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THÈSE

Pour obtenir le grade de

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**préparée dans le cadre d'une cotutelle entre
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ESCOBAR**

préparée au sein du **Laboratoire Institut des Sciences de la Terre**
dans **l'École Doctorale Sciences de la Terre de l'Environnement et
des Planètes** et **l'École Doctorale et l'École de postgrade de la
Pontificia Universidad Católica del Perú.**

Grands glissements de terrain du flanc Ouest des Andes Centrales (15- 20°S): inventaire, caractérisation et contraintes temporelles

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Pontificia Universidad Católica del Perú

Escuela de Posgrado

**Grandes deslizamientos en el flanco occidental de los Andes
Centrales (15-20°S): inventario, caracterización y Factores
temporales**

Tesis para obtener el grado académico de Doctor en Ingeniería
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Lima, 2022

ABSTRACT

Landslides are responsible for economic losses and deaths around the world. Large landslides also play an active role in the erosion and geomorphological evolution of mountains. They can be triggered by multiple factors including climatic and tectonic forcing's. However, the respective roles climate variations and long-term tectonic on landslide processes remain poorly known because of a lack of chronological data on landslide occurrences over suitable time-scales. The western flank of the Central Andes presents interesting possibilities to study those questions because it offers landscapes and old sequences of mass movements that have been well preserved since hundreds of thousand years due to a dominant arid climate. In this context the aim of this thesis was to conduct a pluri-disciplinary work to better understand the factors controlling and triggering the large landslides in the Central arid Andes. For this purpose, we combined field geomorphology, SIG analysis and absolute dating at different spatial scales (i) a regional-scale landslide inventory; (ii) a local focus on an emblematic giant landslide for dating and geomorphological reconstructions, and (iii) a more systematic dating of landslides at the scale of a valley.

Firstly, in order to identify the factors controlling landslide formation at a regional scale along the Central Andes, we inventoried all the large landslides (areas $>0.1 \text{ km}^2$) between the latitude 15 and 20°S . A thousand landslides were mapped, identifying two dominant typologies: rockslides (86%) and rock avalanches (14%). By statistical exploring this landslide database, it was identified a dominant lithological and relief control. The spatial distribution of the landslides reveals the presence of landslide clusters close to the crustal faults.

Secondly, we conducted a focused study on the giant Aricota landslide, located in the southern Peru, in order to know when and in which conditions this large mass movement occurred. Detailed geomorphological mapping and cosmogenic nuclide dating (^{10}Be) were applied revealing the occurrence of two failure events: (i) first a rockslide of $\sim 2 \text{ km}^3$ dated at $17.9 \pm 0.7 \text{ ka}$, which dam the the valley and formed the Aricota lake ($\sim 6 \text{ km}$ long), (ii) second a smaller rock-avalanche dated at $12.1 \pm 0.2 \text{ ka}$, which was deposited on top of the first event. This chronology correlates well with two major paleo wet periods recorded on the Altiplano during the Younger Dryas and the Henrich 1st stadial, suggesting that the transition from arid to more humid climate may have influenced the formation of this landslide.

Thirdly, in order to document more patterns of landslide occurrence though time and to further investigate their triggering, we replicated the dating procedure on eight other large landslides located all around the Aricota rockslide (the Locumba landslide cluster). The results indicated that they all occurred during the Pleistocene. Precise ages were obtained for four cases: the Cotana rock-avalanche at ca. 16 ka, the Antavilca rock-avalanche at ca. 18 ka, the Quilahuani rock-avalanche at ca. 114 ka and the Angostura rockslide at ca. 205 ka. However, strong ages dispersion attributed to problems due cosmogenic nuclide inheritance have affected the others hampering robust dating. Those additional chronological constraints did not favor the hypothesis that the Locumba landslide cluster formed during a single event such as a single mega earthquake. Alternatively, the almost systematic correlation of landslide timing with paleo wet periods, including the "Ouki humid event" (ca. 100-120 ka) during the MIS5, rather support a dominant climate forcing although the co-effect of local seismicity cannot be ruled out.

RÉSUMÉ

Les glissements de terrain sont responsables de pertes économiques et de décès dans le monde entier. Les grands glissements de terrain jouent également un rôle actif dans l'érosion et l'évolution géomorphologique des montagnes. Ils peuvent être déclenchés par de multiples facteurs dont les forçages climatiques et tectoniques. Cependant, les rôles respectifs des variations climatiques et de la tectonique à long terme sur les processus de glissement de terrain restent mal connus en raison du manque de données chronologiques sur les occurrences de glissement de terrain sur des échelles de temps appropriées. Le flanc ouest des Andes centrales présente des possibilités intéressantes pour étudier ces questions car il offre des paysages et des séquences anciennes de mouvements de masse qui ont été bien préservés depuis des centaines de milliers d'années en raison d'un climat aride dominant. Dans ce contexte, l'objectif de cette thèse était de mener un travail pluridisciplinaire pour mieux comprendre les facteurs de contrôle et de déclenchement des grands glissements de terrain dans les Andes centrales arides. Pour cela, nous avons combiné la géomorphologie de terrain, l'analyse SIG et la datation absolue à différentes échelles spatiales : (i) un inventaire des glissements de terrain à l'échelle régionale ; (ii) un focus local sur un glissement de terrain géant emblématique pour la datation et les reconstructions géomorphologiques, et (iii) une datation plus systématique des glissements de terrain à l'échelle d'une vallée.

Tout d'abord, afin d'identifier les facteurs contrôlant la formation des glissements de terrain à une échelle régionale le long des Andes Centrales, nous avons inventorié tous les grands glissements de terrain (surfaces $>0,1 \text{ km}^2$) entre les latitudes 15 et 20°S. Un millier de glissements de terrain ont été cartographiés, identifiant deux typologies dominantes: les éboulements (86%) et les avalanches rocheuses (14%). En explorant statistiquement cette base de données de glissements de terrain, il a été identifié un contrôle lithologique et de relief dominant. La distribution spatiale des glissements de terrain révèle la présence de groupes de glissements de terrain à proximité des failles crustales.

Deuxièmement, nous avons mené une étude ciblée sur le glissement de terrain géant d'Aricona, situé dans le sud du Pérou, afin de savoir quand et dans quelles conditions ce grand mouvement de masse s'est produit. Une cartographie géomorphologique détaillée et une datation par nucléide cosmogénique (^{10}Be) ont été appliquées, révélant l'occurrence de deux événements de rupture: (i) d'abord un éboulement de $\sim 2 \text{ km}^3$ daté de $17,9 \pm 0,7 \text{ ka}$, qui a endigué la vallée et formé le lac Aricona ($\sim 6 \text{ km}$ de long), (ii) ensuite un avalanche rocheuse plus petite datée de $12,1 \pm 0,2 \text{ ka}$, qui s'est déposée sur le premier événement. Cette chronologie est bien corrélée avec deux périodes paléo-humides majeures enregistrées sur l'Altiplano pendant le Younger Dryas et le Henrich 1st stadial, ce qui suggère que la transition d'un climat aride à un climat plus humide a pu influencer la formation de ce glissement de terrain.

Troisièmement, afin de documenter davantage les schémas d'apparition des glissements de terrain dans le temps et d'étudier plus avant leur déclenchement, nous avons reproduit la procédure de datation sur huit autres grands glissements de terrain situés tout autour de l'éboulement d'Aricona (le groupe de glissements de terrain de Locumba). Les résultats indiquent qu'ils se sont tous produits au cours du Pléistocène. Des âges précis ont été obtenus pour quatre cas: l'éboulement de Cotana à env. 16 ka, l'avalanche rocheuse d'Antavilca à env. 18 ka, l'avalanche de Quilahuani à env. 114 ka et l'éboulement d'Angostura à environ 205 ka. Cependant, une forte dispersion des âges attribuée à des problèmes d'héritage de nucléides cosmogéniques a affecté les autres, empêchant une datation robuste. Ces contraintes chronologiques supplémentaires n'ont pas favorisé l'hypothèse selon laquelle le groupe de glissements de terrain de Locumba s'est formé lors d'un événement unique tel qu'un seul mégaséisme. Alternativement, la corrélation presque systématique de la chronologie des glissements de terrain avec les périodes paléo-humides, y compris l'"événement humide d'Ouki" (ca. 100-120 ka) pendant le MIS5, soutient plutôt un forçage climatique dominant bien que le co-effet de la sismicité locale ne puisse être exclu.

RESUMEN

Los deslizamientos son responsables de pérdidas económicas y muertes en todo el mundo. Los grandes deslizamientos también desempeñan un papel activo en la erosión y la evolución geomorfológica de las montañas. Estos pueden ser provocados por múltiples factores, entre ellos los climáticos y tectónicos. Sin embargo, los roles que desempeñan las variaciones climáticas y tectónicas a largo plazo en los procesos de deslizamiento siguen siendo poco conocidos debido a la falta de datos cronológicos sobre la ocurrencia de deslizamientos en escalas de tiempo adecuadas. El flanco oeste de los Andes Centrales presenta interesantes posibilidades para estudiar estas cuestiones porque ofrece paisajes y antiguas secuencias de movimientos en masa que se han conservado bien desde hace cientos de miles de años debido al clima árido dominante. En este contexto, el objetivo de esta tesis fue realizar un trabajo pluridisciplinar para comprender mejor los factores que controlan y desencadenan los grandes deslizamientos en los Andes Áridos Centrales. Para ello, combinamos la geomorfología de campo, el análisis SIG y la datación absoluta a diferentes escalas espaciales: (i) un inventario de deslizamientos a escala regional; (ii) un enfoque local sobre un gran deslizamiento para su datación y reconstrucciones geomorfológicas, y (iii) una datación más sistemática de los deslizamientos a escala de un valle.

En primer lugar, para identificar los factores que controlan la formación de deslizamientos a escala regional a lo largo de los Andes Centrales, se hizo el inventario de todos los grandes deslizamientos (áreas $>0,1 \text{ km}^2$) entre la latitud 15 y 20°S. Se cartografiaron mil deslizamientos de tierra, identificando dos tipologías dominantes: deslizamientos de roca (86%) y avalanchas de rocas (14%). Mediante la exploración estadística de esta base de datos de deslizamientos, se identificó que la litología y el relieve son factores dominantes para su formación. La distribución espacial de los deslizamientos revela la presencia de agrupaciones de deslizamientos cerca de las fallas corticales.

En segundo lugar, realizamos un estudio enfocado en el gran deslizamiento Aricota, situado en el sur de Perú, para saber cuándo y en qué condiciones se produjo este gran evento. Se aplicó un mapeo geomorfológico detallado y datación con nucleidos cosmogénicos (^{10}Be), los resultados revelaron la ocurrencia de dos eventos: (i) primero un deslizamiento de rocas de $\sim 2 \text{ km}^3$ fechado en $17,9 \pm 0,7 \text{ ka}$, que represó el valle y formó el lago de Aricota (de $\sim 6 \text{ km}$ de longitud), (ii) segundo una avalancha de rocas más pequeña fechada en $12,1 \pm 0,2 \text{ ka}$, que se depositó sobre el primer evento. Esta cronología se correlaciona bien con dos importantes períodos paleohúmedos registrados en el Altiplano durante el Younger Dryas y el Henrich 1st stadial, lo que sugiere que la transición de un clima árido a uno más húmedo puede haber influido en la formación de este deslizamiento.

En tercer lugar, para documentar los patrones de ocurrencia de deslizamientos a lo largo del tiempo e investigar más a fondo su desencadenamiento, replicamos el procedimiento de datación en otros ocho grandes deslizamientos situados alrededor del deslizamiento de Aricota (enjambre de deslizamientos de Locumba). Los resultados indicaron que todos ellos se produjeron durante el Pleistoceno. Se obtuvieron edades precisas para cuatro casos: el deslizamiento de rocas Cotana a ca. 16 ka, la avalancha de rocas Antavilca a ca. 18 ka, la avalancha de rocas Quilahuani a ca. 114 ka y la avalancha de rocas Angostura hacia 205 ka. Sin embargo, la fuerte dispersión de las edades, atribuida a problemas debidos a la herencia de los nucleidos cosmogénicos, ha afectado a los demás, dificultando una datación sólida. Estas limitaciones cronológicas adicionales no favorecen la hipótesis de que el conjunto de desprendimientos de Locumba se formara durante un único evento, como un único megaterremoto. Por el contrario, la correlación casi sistemática de la cronología de los deslizamientos con los períodos paleohúmedos, incluido el "evento húmedo de Ouki" (ca. 100-120 ka) durante el MIS5, apoya más bien un forzamiento climático dominante, aunque no se puede descartar el efecto conjunto de la sismicidad local.

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INTRODUCTION

INTRODUCTION

Landslides play an important role in the erosion and geomorphological evolution of mountain ranges. Every year, these processes constitute a major risk to human activities, generating worldwide economic losses and in some cases also human losses (Froude and Petley, 2018; Wallemacq and House, 2018). Landslides form especially along active margins and reliefs such as the Himalayas and also in intertropical regions. Landslides are mainly predisposed by topography and lithology, while their triggering factors are mainly external forcings such as earthquakes (Rosser et al., 2021; Valagussa et al., 2021), precipitation events (Strom, 2013; Qiu et al., 2016) and anthropogenic factors (Lacroix et al., 2020).

Currently, small to moderate-sized landslide formation processes are well known because they are triggered by earthquakes in arid environments (Lacroix et al., 2013) or in locations with rainfall (Zhao et al., 2020), seasonal rainfall (Kirschbaum et al., 2020) and/or anthropogenic factors (Lacroix et al., 2020; Graber et al., 2021), but comparatively few case studies and documentation exist for large landslides (> million cubic metres in volume). This is due to the fact that larger events have longer recurrence times (thousands of years, Zerathe et al., 2017) but there is a lack of chronological data for such large time scales.

Studies were conducted to date landslides on larger time scales in mountain ranges around the world (Dortch et al., 2009; Hermanns et al., 2013; Zerathe et al., 2014; Pánek, T., 2015; Schwartz et al., 2017) in order to investigate possible relationships between landslide formation and climatic and/or tectonic triggers. The dating results show that the landslides are restricted to the Holocene (< 10 ka, Pánek et al. 2017; Pánek 2019). In that sense, there are no morphologies of landslides older than the last glacial advance, because the signal was erased. Similarly, one of the places with more occurrence of landslides is in The Himalayas, in this mountain range landslides are triggered by two factors: monsoon rains that generate slope instability (Dikshit et al., 2019; 2020) and also by tectonic activity such as the landslides that occurred after the 7.8Mw earthquake in Gorka in 2015 (Roback et al., 2018).

On the other hand, focusing on another important mountain range such as the Andes, which is also located on an active tectonic margin where subduction between the Nazca Plate beneath the South American crust is constant and occurs since ~50 Ma (Pardo-Casas and Molnar, 1987) at a convergence rate of ~62 mm.yr⁻¹ (Villegas-Lanza et al., 2016) produces the uplift of the Andes and seismicity. This continuous uplift of the Andes caused this long mountain range to behave as a large orographic barrier that does not allow rainfall from the east and the Amazon to cross to the western flank (Houston and Hartley, 2003, Bookhagen and Strecker, 2008). This lack of rainfall on the western flank of the Andes has been an arid environment for millions of years (Dunai et al., 2005). This arid western fringe has the presence of large landslides where their geomorphological features are preserved. Previous studies on landslides with plurikilometric volumes such as the Chuquibamba landslide (Margirier et al., 2015), Caquilluco (Zerathe et al., 2017), Lluta (Strasser and Schlunegger, 2005), among others, indicate the presence of large paleo-landslides in this part of the Andes. But, although there have been some studies of landslides in the Andes, there are still many questions related to the occurrence and formation of landslides. How many giant landslides are found in this part of the Andes? Or what are the factors that control the formation of such landslides in this sector? Also, there are questions about the distribution of these landslides, whether these landslides follow a common pattern or trigger. Other questions focus on the chronology of the landslides: when did these large paleo-landslides occur, what are the triggers for these landslides, and what are the causes of these landslides? Although some landslides have already been dated, as

is the case of the landslides: Chuquibamba (Margirier et al., 2015), Caquilluco (Zerathe et al., 2017), Lluta (Strasser and Schlunegger, 2005), Miñimiñi and Latagualla (Pinto et al., 2008) and El Magnifico (Mather et al., 2014; Crosta et al., 2017), there are still different points of view. Some researchers point out that landslides in arid environments are linked to the seismotectonic context of the Andes (Mc Philips et al., 2014; Crosta et al., 2017; Junquera-Torrado et al., 2021). In the Andes, seismic activity is an important triggering factor for landslides. In the case of earthquakes linked to subduction dynamics, they generate small landslides (Lacroix et al., 2013). Fault activity related to the development of major fault systems also represents a source for triggering landslides (e.g., the Toquepala fault and the Purgatorio fault that are part of the Incapuquio fault system), but there are no recent records to compare ages. Benavente et al, (2017; 2021) conducted paleosimological studies and detected that these faults can produce earthquakes greater than 7Mw in the last thousand years. Other studies point out that the landslides have correspondences with prolonged climatic events, for example the Chuquibamba landslide (Margirier et al., 2015), the Caquilluco landslide (Zerathe et al., 2017) that can be correlated with the Ouki phase identified in the Altiplano (80-120 ka) (Placzek et al., 2013).

Focusing on the western flank of the Central Andes, there are still many questions regarding landslides: what is the landslide distribution in this part of the Andes?; What are the factors controlling the formation of those landslides?; what is the chronology and frequency of mega-landslides on the western flank of the Central Andes? and What is the role of climate and earthquakes in the triggering of mega-landslides?. In this understanding and with the purpose of contributing to the knowledge of landslides in the Andes, it was proposed to carry out a study of large-scale gravitational processes on the Western Flank of the Central Andes (WFCA). The main objective is to understand what are the conditioning and triggering factors for the formation and/or occurrence of these landslides. The previously mentioned conditions of this part of the Andes and the need for further study to contribute to the knowledge of landslides and disaster risk management, are the main motivation to carry out the thesis project.

The study area of the PhD project is located on the Western Flank of the Central Andes (southern Peru and northern Chile), between 15°-20° South latitudes, from the Pacific coast (0 metres) to the Altiplano (~5000 masl). In order to carry out a study to answer all the questions that motivated this thesis, it was proposed to focus the PhD on three main tasks: (1) To study landslides, carrying out a regional scale mapping and inventory, to understand the factors that control landslide formation. (2) To carry out a detailed study of a landslide and use cosmogenic nuclides to determine the age of exposure of this landslide and determine the triggering factor. (3) To go to an area with a high concentration of landslides to date each landslide using cosmogenic nuclides, with the objective of obtaining a chronology of events in order to have a complete history of landslide formation at this site. In order to perform each task in detail and to answer the scientific questions regarding the landslides, each one was developed in a chapter.

In that understanding, for a better development of the thesis, the manuscript is organised in five chapters:

- **Chapter I: State of the art**

In this first part, an introduction is made on the knowledge of landslides, from a general point of view worldwide then I analyse the current state of knowledge of landslides in the Western

Flank of the Central Andes (WFCA), setting out challenges in the study area and strategies for approaching the scientific questions.

- **Chapter II: Inventory of large landslides along the Central Western Andes (ca. 15°-20°S): Landslide distribution patterns and insights on controlling factors.**

This part is a regional study of landslides located between 15°-20° South latitudes. The objective is to identify which are the conditioning factors for landslides in the WFCA. The methodology applied consists of the recognition and mapping of landslides, using tools such as Google Earth and high-precision DEMs. Based on the inventory, a database is proposed that includes data on typology, dimensions and spatial distribution of landslides, in order to carry out statistical analyses to identify those conditioning factors. More than 1000 landslides were inventoried (Rockslide - 86%; Rock avalanches - 14%). The results indicate that the main factors contributing to slope destabilisation are related to factors including lithology and local relief. Furthermore, by analysing the spatial distribution of landslides, it was possible to identify places where there is a high concentration of landslides. Finally, it is suggested that large landslides cannot form under arid conditions. In order to identify the triggering factor, chronological constraints on large paleolandslides should be provided to explore possible links of their activity with paleoclimatic variations or tectonic events.

- **Chapter III: Giant landslide triggerings and paleoprecipitations in the Central Western Andes: The aricota rockslide dam (South Peru)**

This is a local study focus in the landslide under study is the Aricota landslide which is located on the right flank of the Locumba River. This large landslide filled the Locumba valley, formed an important dam and created a lake of approximately 6 km length. The objective of this study was to find out when this landslide occurred and what was the triggering factor. The methodology applied consisted of detailed geomorphological mapping of the landslide, in order to identify the characteristic morphology and if it has internal landslides. Then, a strategic sampling was carried out to identify the age of exposure using the cosmogenic nuclide methodology (^{10}Be), to then compare results with paleoclimatic and tectonic proxies close to the study area in order to determine the triggering factor. The results suggested two events. The first is a rockslide that is dated at 17.9 ± 0.7 ka, this landslide filled the valley and formed a large dam, the second is rock avalanche dated at 12.1 ± 0.2 ka, this event was deposited on top of the deposits of the first event. Comparison of ages with tectonic and paleoclimatic proxies suggests a correlation with paleoclimatic events identified in the Altiplano (Heinrich's Stadial 1a and the Younger Dryas), suggesting that climate played an important role in triggering these landslides.

- **Chapter IV: Pleistocene chronology of large landslides triggering on the Western Flank of the Central Andes revealed by cosmogenic nuclide dating.**

The study area focuses on a specific location with a high concentration of landslides (Locumba cluster). This area of interest is located in the central part of the Locumba watershed in the WFCA. The objective of this study is to find patterns of landslide occurrence or periodicity, and then to investigate which triggers (earthquakes or paleoclimatic events) have caused these landslides. For this study, 8 landslides were chosen for detailed geomorphological mapping, then boulder sampling was carried out on each landslide to obtain the age of exposure. As a result, the accurate exposure ages were obtained for half of the landslides, while others showed a dispersion of their ages. The landslides occurred during the Pleistocene such as the Cotana rock avalanche (ca. 16 ka), the Antavilca rock-avalanche (ca. 18 ka), the Quilahuani

rock-avalanche (ca. 114 ka) and the Angostura rockslide (ca. 205 ka), have different periods of occurrence. When combined obtained chronologies with paleoseismic events, no correlation could be found, because there are no abroad record. However, regional active faults could be able to generate earthquakes of $M_w \sim 7$. Comparing with paleoclimatic events, the obtained ages are compatible with the Younger Dryas, the Heinrich Stadial 1a and another event during the MIS 5, called the "Ouki event". So we can say that probably wet events were responsible for triggering landslides in arid environments.

- **Chapter V: Conclusions and Perspectives**

This chapter is the last part of the manuscript where the final conclusions obtained during the thesis are presented, as well as some perspectives of future investigations that would complete the studies carried out during this work and would contribute to a better understanding of the activity of large landslides in the Andes.

- **Annexes**

In this part, all the studies in which I participated during the PhD project are included, as well as the abstracts of the congresses in which I participated.

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CHAPTER I:

STATE OF THE ART

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1 Landslides hazards and issues

1.1 Worldwide setting

Landslides are gravitational phenomena that constitute one of the main components of natural hazards. They can be triggered by climatic and/or tectonic events and are responsible for thousands of deaths worldwide (Froude and Petley, 2018). These events also cause substantial economic losses in the billions of dollars (Petley, 2012; Shuster, 1996; Froude and Petley, 2018; Wallemacq and House, 2018). Most studies show a relationship between current climate change (rainfall) and landslides (Gariano and Guzzetti 2016). Froude and Petley (2018) conducted a worldwide database of disasters (landslides resulting in fatalities) between 2004 and 2017 based on media reports, government reports and academic articles. This inventory does not take into consideration landslides triggered by earthquakes. In spite of this, they identified more than 5300 landslides that caused fatalities, the triggers were rainfall, mining and human activity.

According to this worldwide record, Asia is one of the regions with the highest concentration of landslides (~75%) that generated fatalities (Figure 1), other areas most affected are Central and South America, Africa and Europe. Likewise, Froude and Petley, (2018) indicate that anthropogenic activity related to inadequate construction, irrigation and/or logging on slopes influences the increase of current and future landslides (example Lacroix et al., 2020; Graber et al., 2021). Moreover, the landslide activity is located mostly on mountain fronts (Figure 1). These areas present high topographic relief with steep slopes. These places present high seismic activity triggering landslides that generate fatalities (Collins and Jibson 2015; Rosser et al., 2021; Valagussa et al., 2021). In addition, mountain fronts have presence of abundant rainfall in part of the year, this factor increases the risk for villages located in these places (Havenith et al., 2006; Strom, 2013; Qiu et al., 2016). The database made by Froude and Petley, (2018) covers a very short observation time window (<10 years). This database doesn't fit a broader time window associated with the formation of an orogenic zone (> 10⁶yr), because it does not take into account gravity instabilities associated with landform formation related to geodynamic activity in mountain ranges.

More specific studies of historical landslides occurring on different mountain fronts development (Korup (2005); Hewitt et al., (2011); Pánek et al., (2016), Fan et al., (2018); Zhao et al., (2019); Pánek et al., (2019)) have been conducted to understand what are the controlling and triggering mechanisms, landslide types and characteristic morphology.

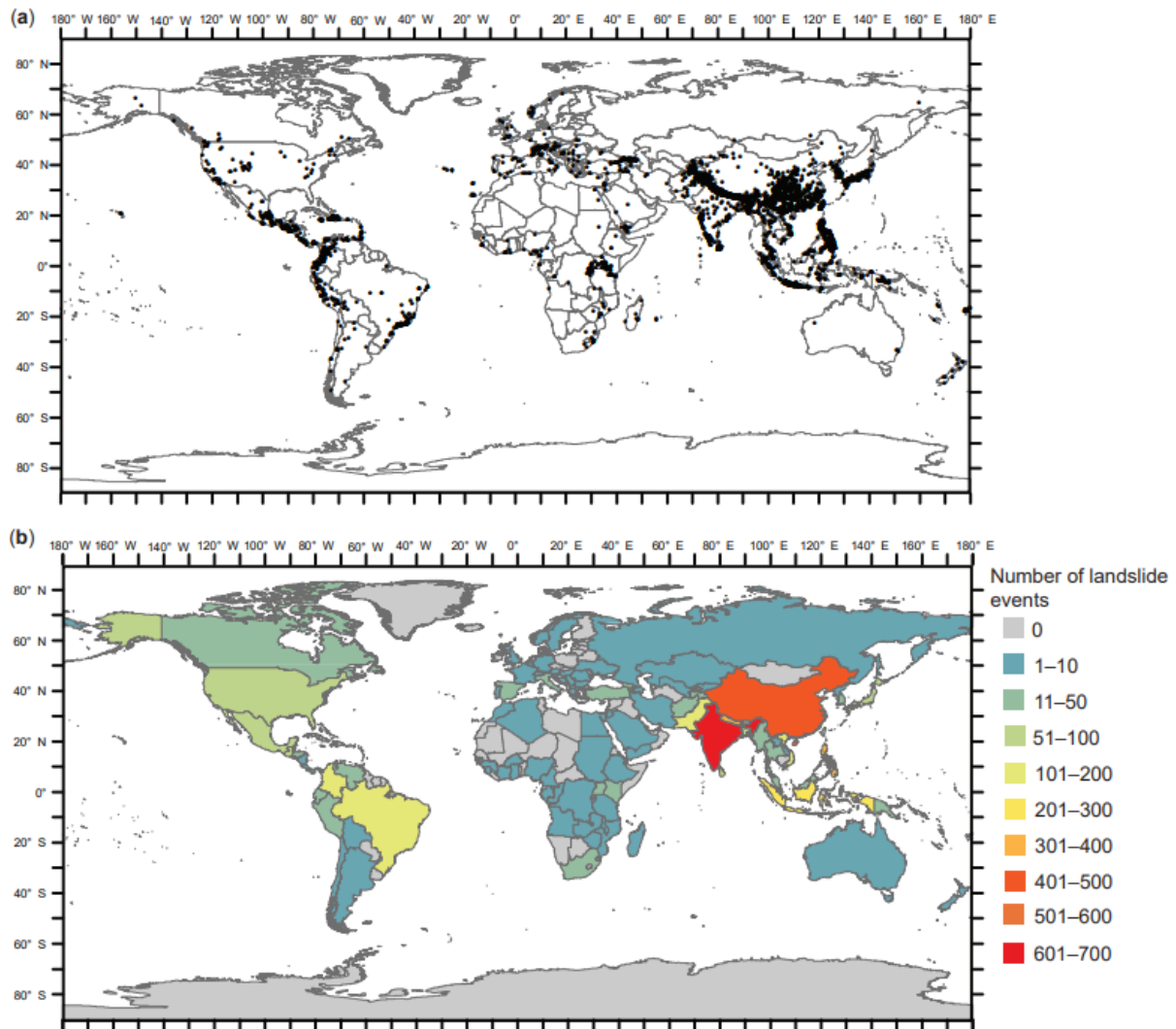


Figure 1. Geographic map of the world with country boundaries (a) The location of non-earthquake triggered fatal landslide events from 2004 to 2016. Individual landslide events shown by a black dot. (b) Number of non-seismically triggered fatal landslide events from 2004 to 2016 by country (Froude and Petley 2018).

According to Froude and Petley, (2018) countries with the highest concentration of landslides that generated fatalities are China and India (Figure 1). At the boundary of these countries are the Himalayan Mountain range and the Tibetan plateau. These two orogenic zones record many landslides, due to extreme precipitation events (Wulf et al., 2010; Van der Geest, 2018). Another important orogenic zone in South America is the Andes, which are located within the intertropical convergence domain. Due to the high temperatures, the air masses ascend forming a lot of cloudiness and ending in abundant rainfall. In this sector there is a moderate concentration of landslides (Figure 1), although we can indicate that the high relief of the Andes Mountain range plays an important role in the amount, intensity, spatial distribution and duration of precipitation for the formation of landslides.

1.2 Focus in South America

The Andes Mountain range is located in South America and corresponds to one of the most important mountain belts in the world, related to the global convergence between the Nazca oceanic plate to the west and the South American plate to the east (subduction process). This shortening in the Andes is accommodated by subduction of the Nazca plate below the South America plate. This subduction process has been active since the Cretaceous period and is responsible for the construction of one of the world's most important mountain ranges. It has a length of ~7500 km and the highest point is located in the snowy Aconcagua at 6961 m asl. The western flank has the presence of important valleys as a result of the incision due to the uplift of the Andes (Thouret et al., 2007). In this place, several natural phenomena occur (mass movements) and landslides are one of the most important hazards affecting society (Schuster et al., 2002; Sepúlveda and Petley 2015), generating deaths and economic losses. The causes of these events are related to heavy rainfall, earthquakes, volcanic eruptions, human activity or the combination of these (Wieczorek, 1996; Sepúlveda and Petley, 2015).

The Andes have an intense seismic activity product of subduction, two types of earthquakes can be evidenced: (i) interplate earthquakes with magnitudes that can be >8 Mw (Pisco earthquake 2007, Mw 8 (Lacroix et al., 2013); Iquique earthquake 2014, Mw 8.2 (Candia et al., 2017)) and (ii) cortical earthquakes due to reactivation of active geological faults with magnitudes up to 7 Mw (Parina earthquake 2016, 6.1Mw, Aguirre et al., 2021). These two types of earthquakes generate different processes such as soil liquefaction, tsunamis and landslides.

The Andes behave as a great orographic barrier that controls the climate (Bookhagen and Strecker 2008). In the western flank of the Andes, the northern part (e.g. 5° south latitude) has areas of high rainfall due to the high concentration of cloud cover, while the central part (ca. 15° to 22° south latitude) has an arid zone without precipitation (Bookhagen and Strecker 2008). Also, these different zones are due to the presence of the Humboldt and El Niño ocean currents (Rossel, 1997; Sanchez et al., 2000; Montes et al., 2011, Sulca et al., 2018). Sepúlveda and Petley (2015) conducted an analysis of non-earthquake-triggered landslides that generated fatalities over a 9-years period (from 2004 to 2013) (Figure 2). Statistical analysis (Figure 3) shows that the main factor controlling the fatal landslide distribution is associated with climatic pulse events like hurricane and heavy rains triggered by El Niño and La Niña phenomena which are warm and cold ENSO events. These phases are believed to arise from ocean-atmosphere interactions in the tropical Pacific Ocean (Wang et al., 1999) and tend to last approximately 1 to 2 years and recur every 3 to 8 years (Okumura and Deser, 2010).

On the other hand, Sepúlveda and Petley (2015) made the relationship with the triggering factors (Figure 3), indicating that more than 85% of the recorded landslides that generated fatalities were caused by extreme weather events (73% torrential rains and 15% by hurricanes or tropical storms) and only 4% of the cases were induced by earthquakes. They also state that human action is causing alterations in the slopes due to excessive irrigation for agriculture or tree cutting, which in the future will cause new landslides due to climatic variations.

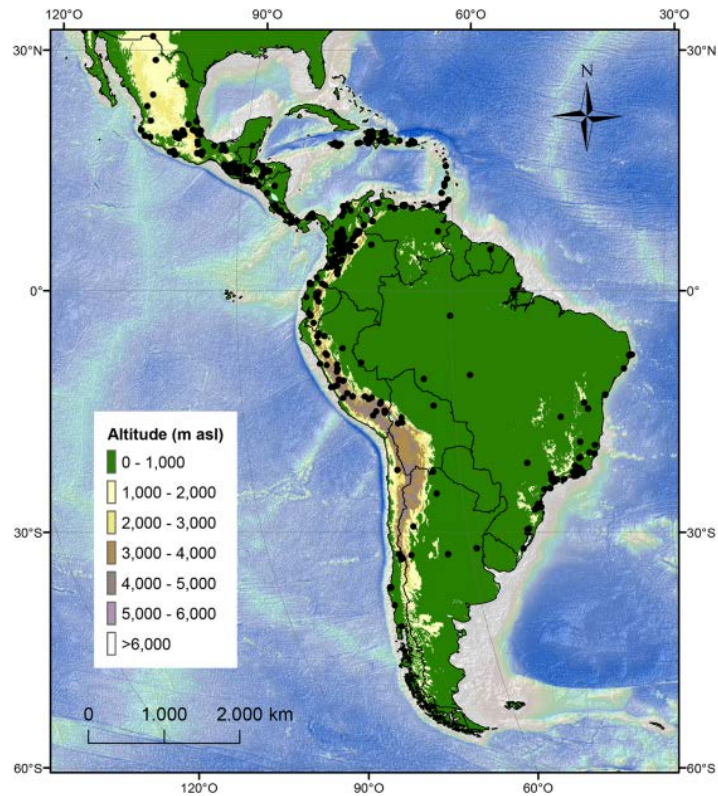


Figure 2. Location of fatal landslides in Latin America and the Caribbean (black dots) in the period 2004–2013 according to the EDFLD. (Sepúlveda and Petley 2015).

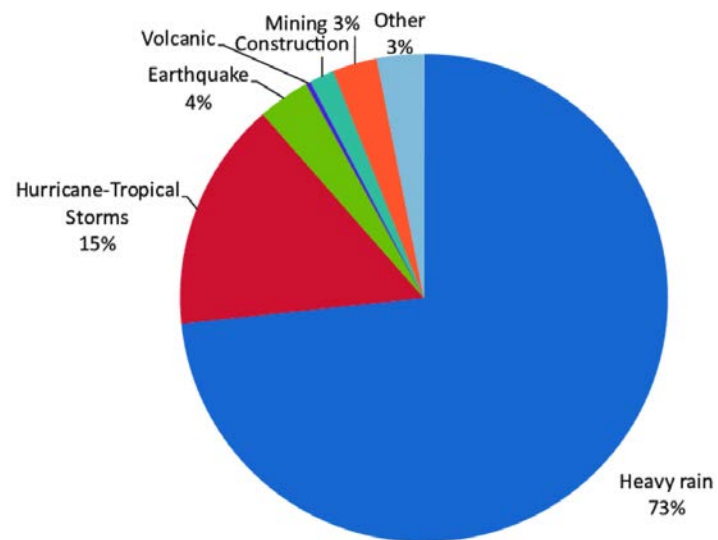


Figure 3. Main triggers of fatal landslides in the period studied (2004-2013). Fatal landslides were mostly triggered by hydraulic controls (torrential rains, hurricanes, tropical storms). A lower percentage (4%) of landslides were triggered by earthquakes. (Sepúlveda and Petley 2015).

As observed in the works of Hermanns et al., (2012), McPhillips et al., (2014) and Sepúlveda and Petley (2015), the Andes register a large number of landslides, the focus should be on studying large landslides, understanding the processes, because they have a great impact on society.

1.3 Large scale historical landslides

Historic chronicals show that landslides are very common in South America (Hermanns et al., 2012). Different types of landslides occur with different sizes from small rockfalls to large landslides that mobilize large volumes of material (millions of m³) and have kilometers of travel length. These large landslides had a great impact on society, causing fatalities and destruction of villages and important infrastructure. One of the extreme events recorded in the Andes is the Huascarán rock avalanche (Peru) that occurred on May 31, 1970 (Figure 4) after the Chimbote earthquake (7.7 Mw), with epicenter on the Peruvian coast. This earthquake triggered the collapse of the northern summit of Huascarán (Plafker & Ericksen 1978). This part of the mountain was weakened by glacial retreat (Broggi, 1943). Plafker & Ericksen (1978) report that ~22000 people died, burying the towns of Yungay and Ranrahirca (Plafker et al., 1971).



Figure 4. Earthquake-induced debris avalanche on Nevados Huascarán in the 1970th (Peru). Town of Yungay is buried beneath the landslide in middle foreground. The rock avalanche had a height difference of ~3,500 m from the rupture zone to the Santa. The displacement of the avalanche was 14 km (Plafker et al. 1971) (Photo courtesy of the National Aerophotographic Service of Peru: June 13, 1970).

To the north of the Andes, one of the most important events was the Ruiz rock avalanche (Mojica et al., 1985; Voight, B. 1990) that destroyed the city of Armero in Colombia (Figure 5), this event occurred on November 13th of 1985, due to the reactivation of the Nevado del Ruiz volcano. This event melted the snow and glaciers on the flanks of the volcano, which triggered lahars. Mojica et al., (1985) indicate that the lahar moved ~ 80 million m^3 generating the death of ~ 25000 people in the valley of Armero and the city of the same name (Figure 5).

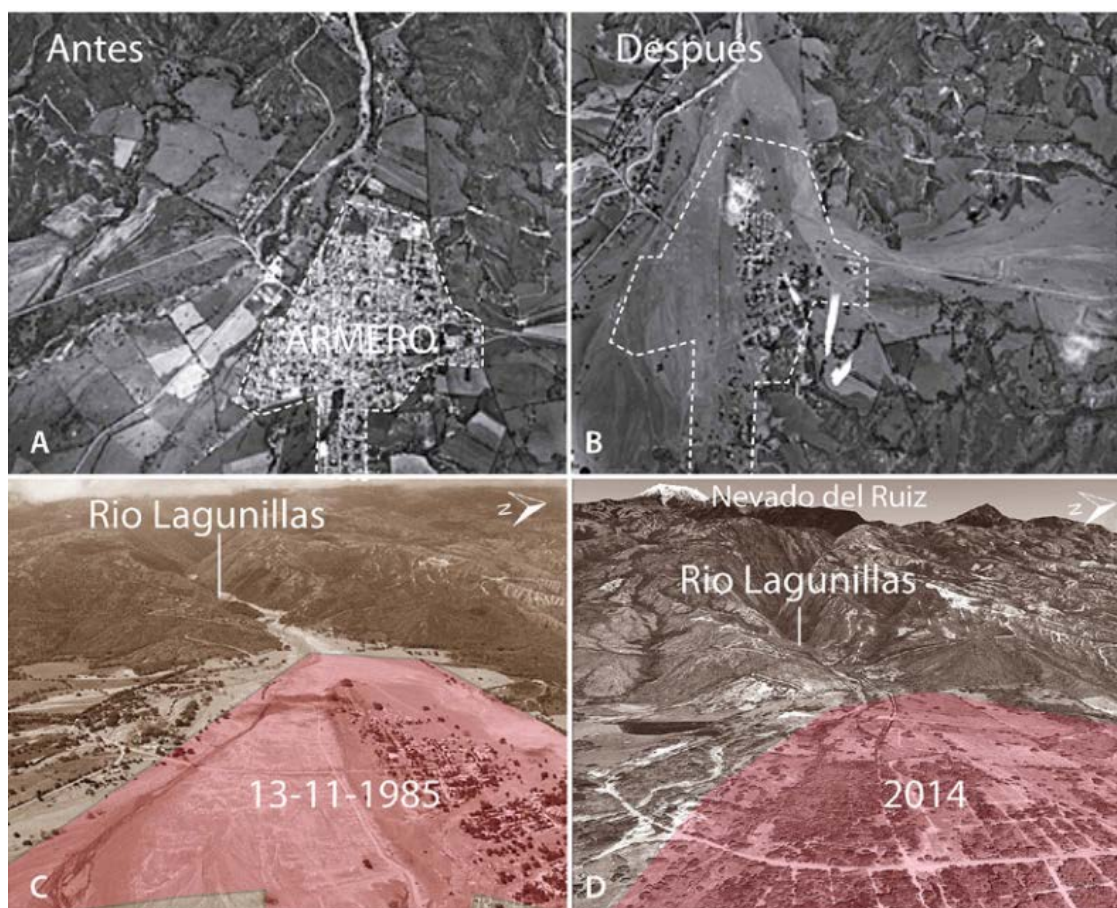


Figure 5. Before (A) and after (B) the lahar of the 1985 eruption of Nevado del Ruiz. The population of Armero (30,000 inhabitants) was almost totally destroyed, causing the loss of some 25,000 people. Situation of the area affected by the lahar just after the eruption (C) and today (D). Since the event the affected land has been used exclusively for agriculture. (Carracedo, J. C. 2015).

Another important landslide that occurred in the Andes was the Mayunmarca landslide in Peru (Figure 6; Galdos, 1975). This event occurred on April 25th of 1974. It displaced ~ 1600 m^3 of material that dammed the Mantaro river (Figure 6; Chang and Alva, 1988) and caused the death of ~ 600 people and the destruction of important infrastructure (houses and roads). The kinematic of the landslide have been characterized by Galdos (1973) that highlights following phenomena such as soil reptation, internal landslides and mudflows before the main triggering of the landslide. The triggering was partly controlled by the poor quality of the rocks, the presence of groundwater and anthropogenic activity due to continuous irrigation for agricultural activity (Vilchez, 2013).

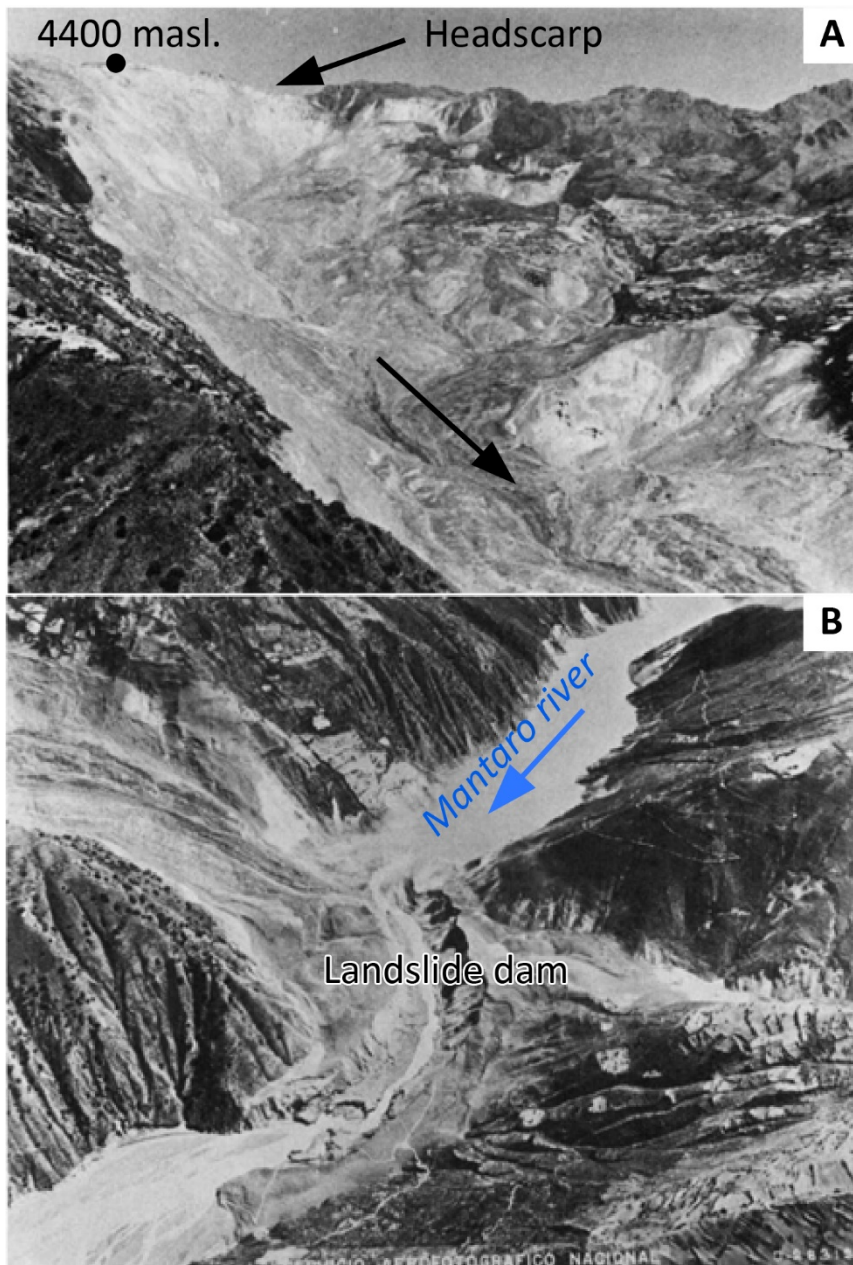


Figure 6. A) Oblique view of slide looking west, showing rockslide source on upper southwest margin, reactivated rotational slides on upper northwest margin, extensive banding in middle reach of debris flow and splatter zone on lower northwest margin (June 1974). B) View to Northwest of breached landslide dam, showing scour zone on right margin of the mouth of the Quebrada Tinte and associated fall-back ridges (Servicio Aerofotografico Nacional, 9 June 1974) (Modified from Kojan and Hutchinson 1978).

In addition to the historical landslides, this year 2022 the Retamas landslide (Figure 7) occurred in the town of Retamas (La Libertad-Peru). This landslide occurred in March. The landslide affected more than 25 houses, many of which were covered by soil and rocks, leaving people trapped in some houses. This landslide is of the rock avalanche type and has a height difference of 100 m from the headscarp to the foot of the landslide (Figure 7a).

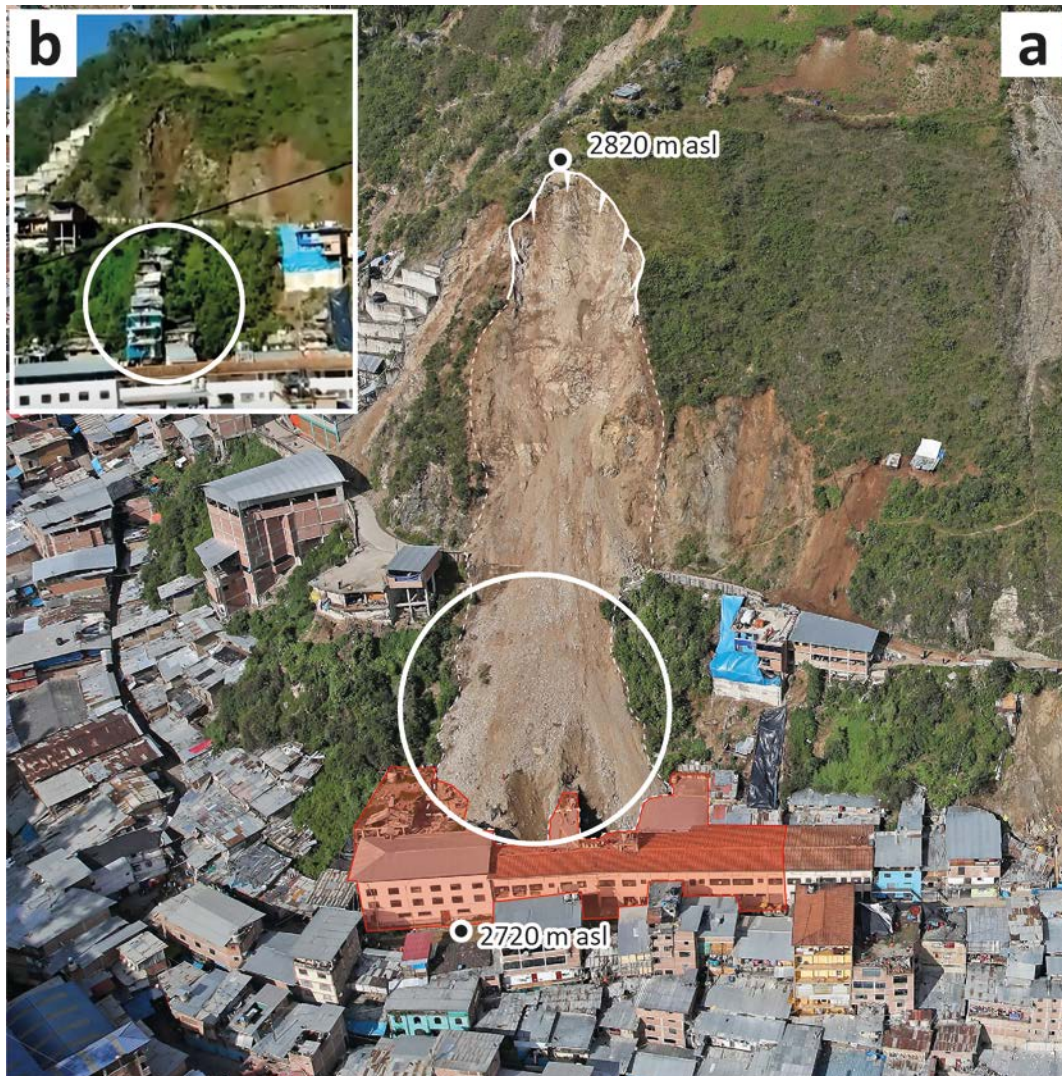


Figure 7. (a) Panoramic view of the landslide that occurred on 15 March 2022 in the village of Retamas. The white line and the dotted line limit the Retamas landslide (Base Photo Aldair Mejia/PRESIDENCIA PERUANA/ AFP). (b) Image of the precise moment that the landslide began (Video capture). The white circle is the location of the houses that were covered by the landslide debris and the red polygon are the houses located at the base of the landslide that were affected.

These four examples of catastrophic landslides in the Andes point out the necessity to bring new informations about the comprehension of the large landslides development and triggering for disaster risk management and land-use planning, because they generate great impact on society-

2 Large landslides: state of the art

2.1 Definition

Large landslides are characterized by a deep failure surface and mobilize large volumes of rocks and/or soils ranging from hundreds of thousands m^3 to hundreds of km^3 . They are mainly located in orogenic belts with a strong tectonic activity in relation to relief formation (Korup, 2005; Dortch et al., 2009;

Pánek et al., 2019). In these sectors the spatial distribution of landslides is related to regional tectonic activity and local structures (Keefer, 1984; Carlini et al., 2016). The constant and rapid uplift during prolonged times of the orogenic belts, increases the tilt angle of the orogenic wedge that can reach the stability angle generating landslides that modify the slope and control mountain growth (Whipple et al., 1999; Montgomery, 2001; Montgomery and Brandon, 2002; Larsen and Montgomery, 2012; Roering, 2012; Li et al., 2014). On the other hand, these major instabilities are the product of the interaction of different controlling factors such as lithology, faults, folds, topographic relief, stress state, weather, climate, seismicity and human activity (Agliardi et al., 2012). All of these factors have a major impact on landslide type, location, and frequency of landslide occurrence (Kellogg, 2001; Břežný and Pánek, 2017; Görum, 2019). But, on a short time scale, earthquakes are the main trigger to induce large landslides (Keefer, 1984; Keefer, 1994; Owen et al., 2008) depending on the magnitude of the earthquake and the degree of rock deformation.

According to the literature, different mechanisms of large landslide formation are proposed (Figure 8, Agliardi et al., 2018). Some of these landslides are associated with the development of joints, faults and folds that limit slope stability by reducing the mechanical characteristics of the rock (Figure 8.g, i, j, s). In these cases, the local relief can exceed 1000m. Another characteristic of landslides is that they present failure surfaces with variable geometries such as curved (Figure 8 a- g), compound (Figure 8 h- l) or planar (Figure 8 m-r; Sjöberg, 1999; Nichol et al., 2002). Large-scale topplings are common on slopes with deep and persistent discontinuities (Figure 8 u-w, Cruden and Hu, 1994; Kieffer, 1998). In conclusion, the type of landslide depends on the degree of resistance of the rock and the type of discontinuities such as fractures, joints, stratification planes, faults and contact zones between different geological formations (Figure 8).

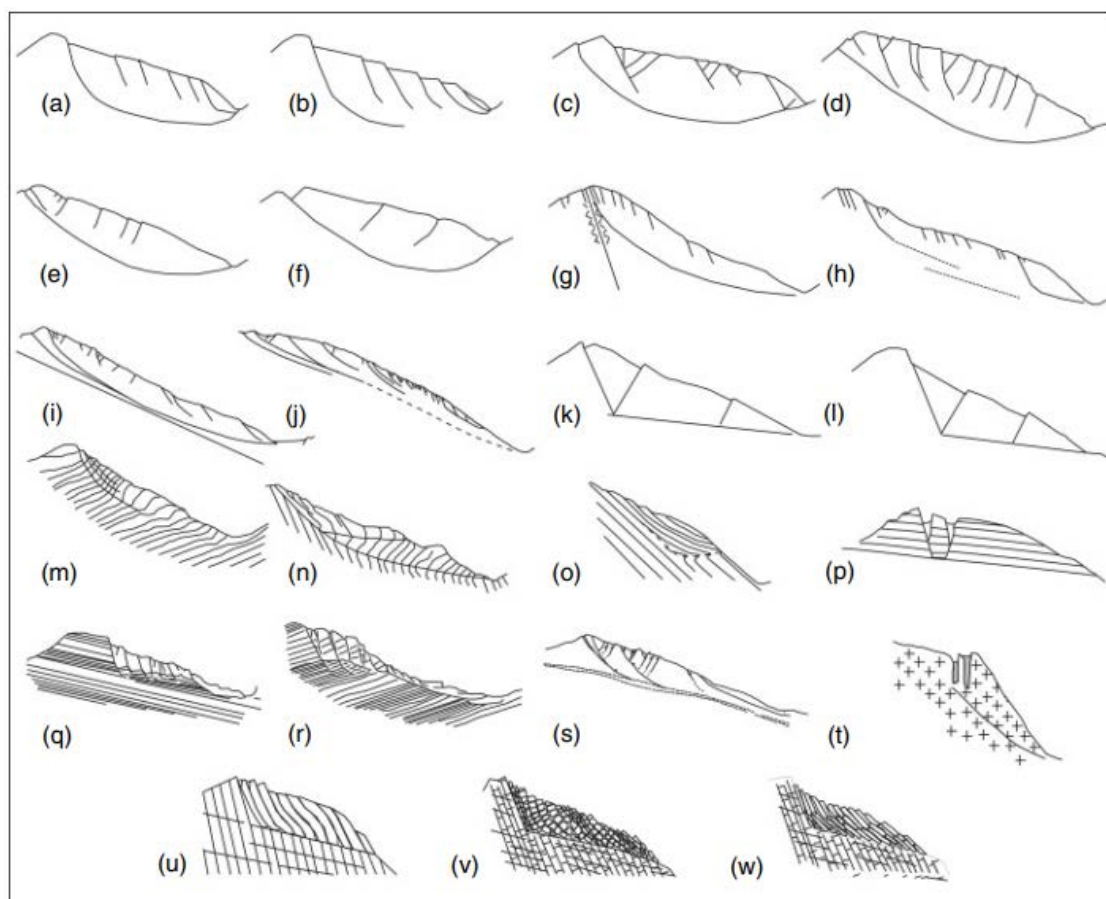


Figure 8. Mechanisms of large scale rock-slope failure proposed in the literature, ordered on the basis of failure geometry and structural controls. (a), (b), (c), (f) Bois et al. (2008); (d) Mahr (1977); (e), (g), (h), (i) Ambrosi and Crosta (2006); (j) Agliardi et al. (2001); (k), (l) Hutchinson (1988); (m), (n) Zischinsky (1966); (o), (p), (t) Chigira (1992); (q), (r) Nemcok (1972); (s) Agliardi et al. (2009b); (u), (v), (w) Kieffer (1998). (Agliardi et al., 2012).

The scale and timing of landslide depend on the interaction between the behavior of the rock mass and the types and histories of external forces such as weather and earthquakes (Agliardi et al., 2012). The result can produce: (1) small ruptures, (2) frequent landslides (e.g., rock falls), (3) sudden or progressive large-scale landslides (e.g., rock falls and rock avalanches), or (4) slow, non-catastrophic deep-seated slope deformations.

2.2 Geomorphology and type

In this part we will focus especially on deep-seated gravitational slope deformation (DSGSD) and deep-seated landslides (DSL), because DSGSD have been documented in many mountain belts around the world (e.g. Pánek et al., 2011). Moreover, DSGSD allow the development of deep-seated landslides (DSL) as indicated by Agliardi et al., (2001) and this fact represents a great risk for cities and people living in the valleys that are located in these mountains.

Deep-seated gravitational slope deformation (DSGSD) are processes that affect the rock mass, generally the slopes of high relief mountains, from valley to ridge, moving and deforming at low rates of movement (mm yr⁻¹) for long periods of time (Varnes et al., 1990; Ambrosi and Crosta, 2006) and moving large volumes (>0.5 km³). DSGSDs reach considerable thicknesses (tens of meters or more) and lateral boundaries are discontinuous and poorly defined (Agliardi et al., 2001; 2012; Crosta et al., 2013).

DSGSDs have relatively deep slip surfaces (Agliardi et al., 2001). Although some authors consider that the slip surface is not always clearly observed (Dramis and Sorriso-Valvo, 1994; Soldati, 2013). However, other works suggest the presence of a well-defined slip plane or that most of the time, DSGSDs are controlled by inherited structures (faults, fold axes, stratification planes) (Agliardi et al., 2001; Agliardi et al., 2009b; Pánek et al., 2011; Pánek and Klimeš, 2016).

The formation of DSGSD is generally related to specific geological and structural features, such as stratification, foliation, joints and faults. They depend also of particular topographic situations associated with local slope changes. They are also common in tectonically active areas such as the Alps and the Himalayan Mountain range (Crosta and Zanchi, 2000; Agliardi et al., 2009b; Ambrosi and Crosta, 2011).

The most common indicator of DSGSD is the presence of surface deformation features of gravity origin (Agliardi et al., 2001). Characteristic morphostructures of DSGSD (Figure 9) include double ridges, trenches, tension cracks, counter-scarps, collapsed blocks, buckling folds, toe bulging, rock fracturing, secondary scarps. However, there may also be associations between DSGSDs and small landslides. These landslides (rockslide or rock avalanche) may occur in the middle and lower part (Figure 9, Agliardi et al., 2001)

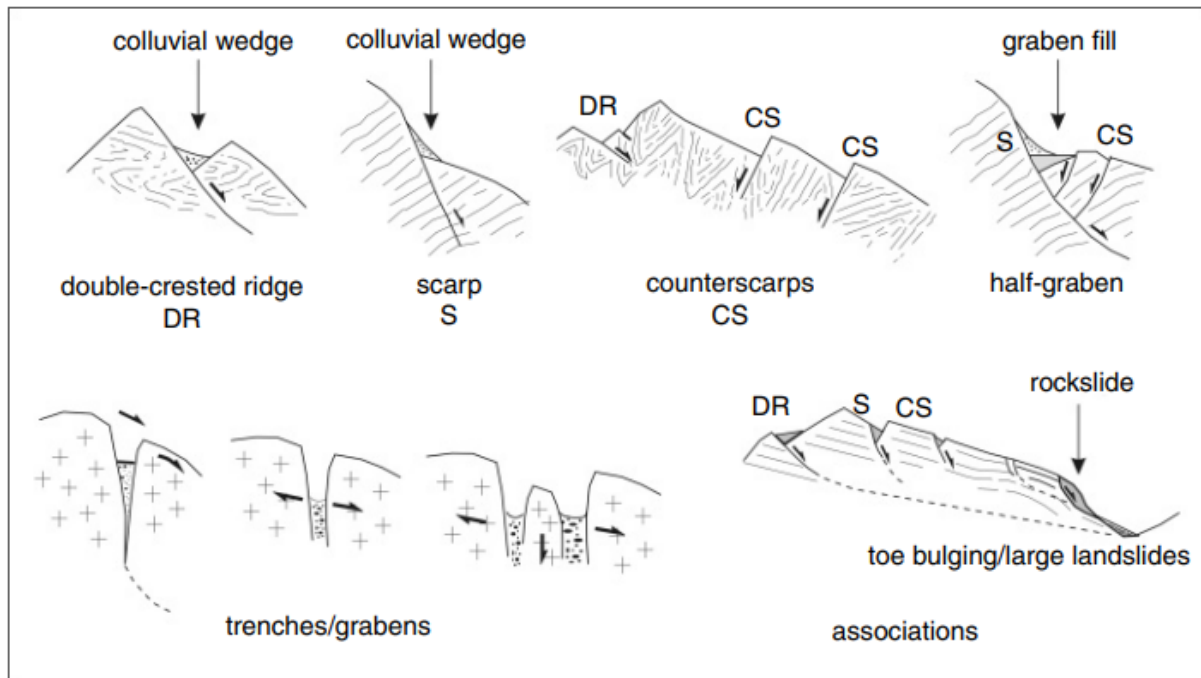


Figure 9. Morpho-structural features diagnostic of deep-seated gravitational slope deformation (DSGSD) phenomena, related kinematic significance, and typical associations (Agliardi et al., 2012).

Most DSGSDs originate as sackungen (Figure 8, see Zischinsky, 1966; Hutchinson, 1988) in metamorphic, igneous or sedimentary rocks. Sackungs were described by several authors (Zischinsky, 1966; Hutchinson, 1988; Varnes et al., 1989; Crosta, 1996; Agliardi et al., 2001). These result from gravitational deformation of the mountains (Radbruch-Hall, 1978), suggest that are due to a long-term (>10³ - 10⁴ years) formation process but with temporal reactivations and/or accelerations (Agliardi et al., 2001; El Bedoui et al., 2009; Hippolyte et al., 2009, 2012; Agliardi et al., 2012; Crosta et al., 2014). Moreover, apart from sackungen there are lateral expansions (Figure 7 p-r; Hutchinson, 1988; Cancelli and Casagli, 1995), these are more common in horizontal or gently sloping areas, where there are sedimentary successions with strongly competing levels (Agliardi et al., 2012).

DSGSD formation depends on stress relief, debuttressing, loss of lateral or frontal support and water pressure in crevasses or diaclases (Pánek et al., 2015), The sackunks are more common in mountainous areas affected by deglaciation processes, rapid river incision, tectonic uplift and seismic events (Agliardi et al., 2001). Sackungs can also occur in non-glacial environments.

Large lateral expansions also form DSGSDs, which can occur in volcanic or compact sedimentary rocks overlying ductile rocks (Dikau et al., 1996). Due to lateral flow of the underlying soft levels or rocks, the more rigid and compact rocks are deformed by the development of tension cracks, trenches and scarps (Pánek and Klimes, 2016), which end up forming surficial topples, rockfalls or landslides. The different structures formed by lateral expansion are similar to those produced by sackungs, which makes it difficult to distinguish them (Pánek and Klimes, 2016).

These processes are globally distributed in mountains that experienced glacial advances. Pánek et al., (2015) performed a compilation of DSGSD in various mountain environments based on studies published since 1990 (Figure 9). The studies used chronological data to differentiate between two types of DSGSD those occurring in glaciated and non-glaciated areas. Those occurring in glaciated areas experienced advances during the Last Glacial Maximum (LGM, Hughes et al., 2013; Agliardi et al., 2013;

Crosta et al., 2013) and DSGSDs at non-glacial sites have paraglacial origins, becoming dated shortly after deglaciation and/or ice retreat (McCalpin and Irvine, 1995; Agliardi et al., 2009a; Hippolyte et al., 2012). For example, in the Alps there is a high concentration of DSGSDs with more than 100 DSGSDs inventoried (Pánek et al., 2015; Crosta et al., 2013).

DSLs are landslides with a relatively deep slip surface compared to DSGSDs. These processes have definite characteristics: (i) a generally horseshoe-shaped scarp, (ii) a main body or sliding mass, (iii) have width, length and height relation, and (iv) high internal deformation (Agliardi et al., 2001). An example of this type is the Rodeopampa landslide located in the department of Cajamarca - Peru (Zavala et al., 2010), this landslide affected the southeast flank of the Rodeopampa hill, has a height difference of ~1 km between the main scarp and the foot of the landslide, the failure surface is deep and the slid mass dammed the Socota river, formed a 100 m high dike and generated a 1.6 km long lake that had an estimated volume of 25 million m³ of water (Figure 10). The main triggering factors for this type of landslide are earthquakes, extreme climatic events, groundwater pressure and anthropogenic activity.



Figure 10. Rodeopampa landslide, this is an example of a DSL. This landslide affected the southeast flank of the Rodeopampa hill, the sliding mass generated a 100 m high dam that dammed the Socota river and formed a lake that accumulated more than 25 Mm³ of water.

DSL can be roughly categorized into two principal typologies: rockslides and rock avalanches. These large events may occur spontaneously or may occur within the body or mass of a DSGSD.

- Rockslides involve the displacement of material along a slip plane or rupture surface (Figure 10). The slip may be of the translational type with displacement along a planar surface, or it may be rotational due to displacement over a concave rupture surface. Slips of this type move in a single block as a coherent or semi-coherent mass with little internal deformation. The displaced mass may have internal planes that tend to tilt backward. These types of events are the ones that mainly trigger the damming of rivers and valleys (Ermini and Casagli, 2003; Fan et al., 2012; Hermanns et al., 2011), as in the case of the La Josefina landslide that occurred in Ecuador in 1993 (Figure 11), this landslide mobilized 20 Mm³, filled the river of the Paute valley and formed a dam 100 m high.
- Rock avalanches are the result of the rapid fragmentation of large rock masses (>1 Mm³) similar to granular flows; associated with very fast transporting material (Hungr et al., 2001), causing drastic and rapid changes in mountain landscapes. These events as highly mobile flows (Hungr et al., 2001) have an increase in velocity related to the increase in volume (Heim, 1932), based on the H/L ratio (ratio of landslide height to horizontal displacement distance) versus volume (V). These events are also considered one of the most dangerous and costly geological hazards because they damage infrastructure and can cause a large number of deaths (Evans et al., 2006; Hewitt et al., 2008). The destabilization begins with the collapse of a large rock mass, then fragmentation and transport (Strom, 2006). This type of landslide can also generate the damming of the valley (Hermanns et al., 2011), as in the case of the rock avalanche that dammed the Melado River (Figure 12), this avalanche occurred in Chile and formed a large dam that gave rise to Dial Lake. The recurrence of this type of event in the same place can occur after thousands of years (Crosta et al., 2004) or can be within weeks (Eberhardt et al., 2004) depending on the rock consistency.

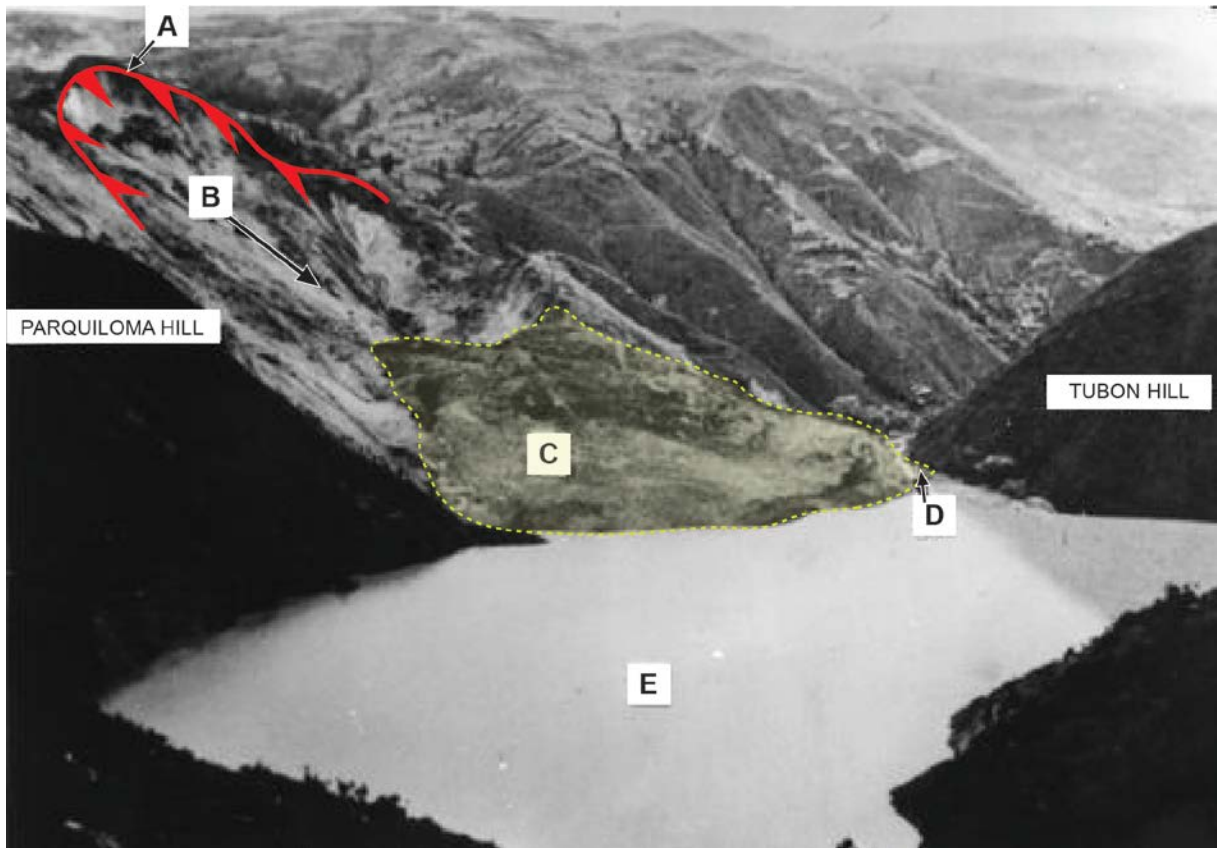


Figure 11. View of the La Josefina landslide that occurred in March 1993 in Ecuador. The landslide of about 20 Mm³ created a natural dam 100 m high, 300 m wide and 1.1 km long. This landslide filled the Paute river valley. (A) Head scarp, (B) Direction of movement; (C) Partial accumulation of debris, (D) Excavated channel, (E) Dammed lake. (Modified from Plaza et al., 2011).

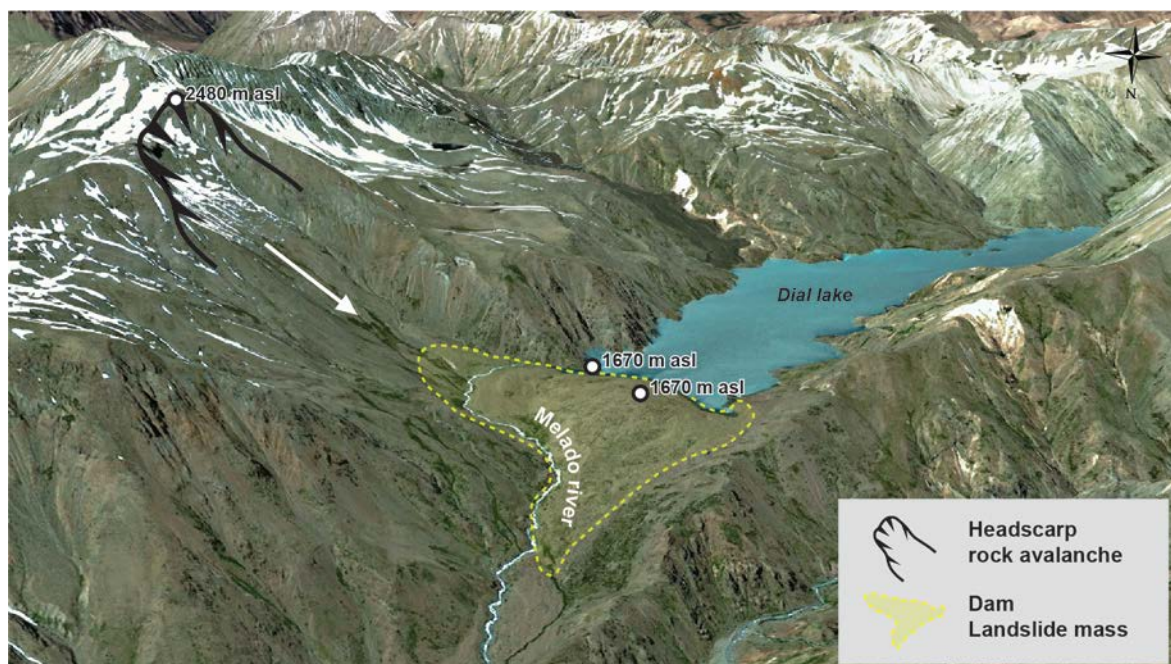


Figure 12. Oblique view of the rock avalanche deposit that fills the valley of the Melado river. The slide mass forms a large dike and gives rise to Dial Lake, Chile (Modified from Hermanns et al., 2011).

2.3 Long term evolution and controlling factors

2.3.1 Concept of progressive failure: creep to collapse

To estimate the movement or deformation of DSGSD at short-term scales, different methods (Klimes et al., 2012) and tools are used, such as geodetic and remote sensing techniques, global positioning systems, and radar interferograms (Colesanti and Wasowski, 2006). However, landslide monitoring is not relevant for long-term study (>100 years). Geochronological and/or stratigraphic methods (Pánek, 2015) are useful to establish the dynamics of destabilizations over the long-term (>100 year; Walker, 2005). The combination of these recent monitoring data and the use of dating techniques allow reconstructing the evolutionary history of DSGSDs (Hermanns et al., 2013).

One of the procedures performed are the excavations of paleoseismological trenches or trenches (McCalpin, 2009) through gravitational scarps, for which dating methods such as ^{14}C or OSL are used. Cosmogenic nuclides ^{10}Be (Sanchez et al., 2010; Hippolyte et al., 2012) and ^{36}Cl (Zerathe et al., 2013; Zerathe et al., 2014) are also used. The results of exposure dating help to know the evolution of DSGSDs (Hippolyte et al., 2009; 2012), for this purpose, samples are extracted from escarpments or cracks and the time of movement onset can be deduced. For DSLs, the use of cosmogenic nuclides helps us to know when these events occurred (Hippolyte et al., 2012; Gutiérrez et al., 2012).

Dating in DSGSDs demonstrates that these processes have long-term motion, comes to be slow and continuous slip (McCalpin et al., 2011; Hermanns et al., 2013), with discrete episodic motions (e.g. Carbonel et al., 2013; Gori et al., 2014). Movements can be steady, accelerated, or decelerated over extended periods of time ($\geq 10^2$ years). Inferred long-term slip rates for DSGSDs range from 0.1 to 5 $\text{mm}\cdot\text{year}^{-1}$ (Gutierrez et al., 2012b), while for DSLs rates can exceed 15 $\text{mm}\cdot\text{year}^{-1}$ and reach up to 80 $\text{mm}\cdot\text{year}^{-1}$ (El Bedoui et al., 2009).

Creep-type landslides can be caused by glacial retreat (McCalpin and Irvine, 1995). McCalpin and Irvine, (1995) in the Colorado sector identified that the movement is not continuous, but rather slowed ($\sim 75\%$) thousands of years after deglaciation began. This long-term deformation is related to the kinematics, the thickness of the rock mass (Hippolyte et al., 2009) and the degree of deformation of the rock. Furthermore, El Bedoui et al., (2009) indicate that post-glacial movements start slow, but during the Holocene they begin to increase the movement, causing the rock to have a progressive decrease in resistance. This fact allows an increase in the rate of deformation that would be the beginning of the rupture and in a short time generate the formation of a rockslide with a movement velocity $>80 \text{ mm}\cdot\text{yr}^{-1}$ (Figure 13; El Bedoui et al., 2009). In conclusion, unlike the evolution of DSGSDs, DSLs are processes that may have a shorter evolution process (tens to thousands of years), or may occur instantaneously, and in other cases may be part of the slipped and deformed mass of a DSGSD.

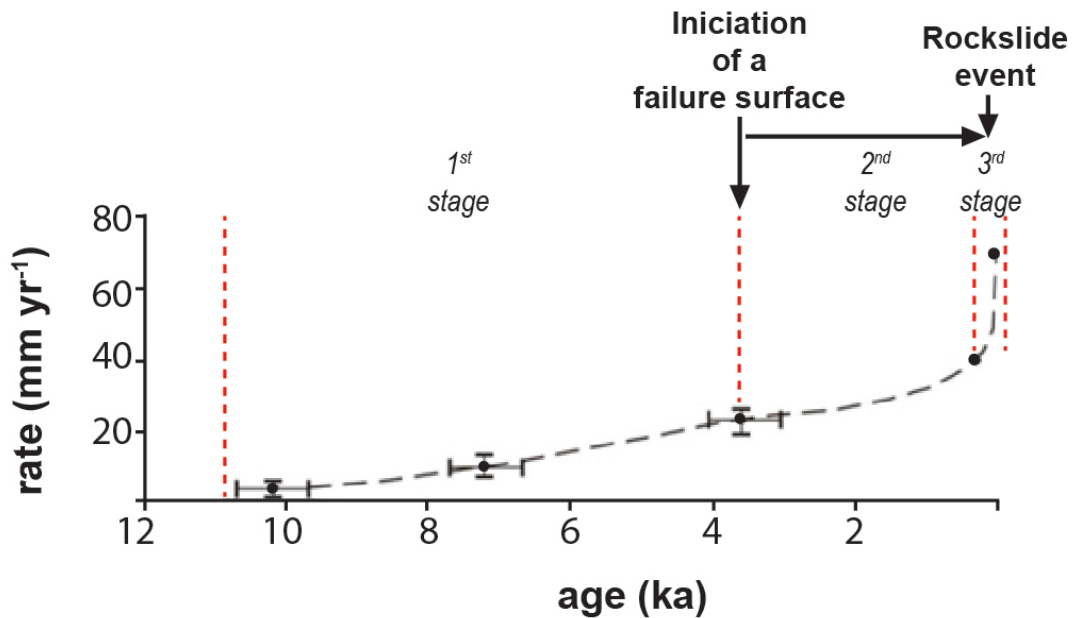


Figure 13. Example of long-lasting horizontal movements and opening of tensile cracks within the La Clapière Sack (French Alps), 3 stages are observed: first a stage of continuous evolution of the landslide that in a second stage (mid-Holocene) transforms into an increase of the deformation rate, finally in the third stage becomes a predominantly vertical and accelerated shearing, which as a result formed a landslide occurred in the last 50 years (Modified from El Bedoui et al., 2009).

2.3.2 Controlling factor (temporal evolution)

The formation of DSGSDs and DSLs is the result of the interaction of different features and controlling processes, including lithology and geological structure such as stratigraphic planes and contacts between geological formations (Agliardi et al., 2001; Ambrosi and Crosta, 2006; Crosta et al., 2013), which are one of the main factors influencing the formation of these processes, but there are also other factors that are: (i) Long-term exhumation controls (Agliardi et al., 2001; Crosta et al., 2013) on active margins such as the Andes where deep valley incision occurs in response to Andes uplift (Thouret et al., 2007), forming steeply sloping hillslopes that can lead to landslides due to rock strength limitation (Schmidt and Montgomery, 1995). (ii) Topographic relief and slope geometry (Ambrosi and Crosta, 2011), influence that above a given slope angle can fail according to rock strength (Schmidt and Montgomery, 1995; Li and Moon, 2021). (iii) Tectonic and topographic stresses and their concentration (Ambrosi and Crosta, 2006; Ambrosi and Crosta, 2011; Crosta, 1996; Martel, 2006; Miller and Dunne, 1996; Molnar, 2004; Savage and Swolfs., 1986), result from the interaction between tectonic and topographic stress that influences rock deformation, weakening the rock and exerting a dominant control on landslide formation and landslide size (Li and Moon, 2021). (iv) Weather and climate (Agliardi et al., 2013; Ballantyne, 2002; Evans and Clague, 1994), comes to be one of the triggers of landslides due to low mechanical properties of rocks or soils, precipitation saturation and changes in the water table (Pánek et al., 2016; Aslan et al., 2021). In the Andes, there are records of landslides correlated with extreme paleoclimatic events recorded in the altiplano (Chuquibamba landslide, Margirier et al., 2015). (v) Glaciation and deglaciation (Augustinus, 1995; Ballantyne, 2002; Cossart et al., 2008; Crosta, 1996; Ustaszewski et al., 2008) are processes that accelerate the development and formation of these processes due to the reduction of glacier ice volume and the recovery of steep valley flanks, leading to landslides and rockfall (Kos et al., 2016). (vi) Seismicity (McCalpin, 1999; Moro

et al., 2007; Radbruch-Hall, 1978; Solonenko, 1977), is one of the triggers for landslide formation. Comparisons were made between magnitude and distance, as well as magnitude and area, suggesting that landslides are generated from magnitudes >5 Mw (Keefer, 1984, 1994; Rodriguez et al., 1999). Examples of landslides induced by earthquakes include the Nepal earthquake of magnitude 7.8 MW in 2015, which caused more than 21,000 landslides (Valagussa et al., 2021b). Another example in the Andes is the 2007 Pisco landslide, which had a magnitude of 8.0 MW and generated the formation of more than 800 landslides (Lacroix et al., 2013). (vii) Changes in the groundwater regime (Crosta, 1996) exert pressure on the cracks and/or escarpments increasing the forces that influence instability, increase the weight of the material by saturation and generate changes in the mineralogical composition of the rock (Gonzales de Vallejo et al., 2002). (viii) Rock dissolution and human activity (Heim, 1932; MacFarlane, 2008; Zangerl et al., 2010) due to irrigation for agriculture and indiscriminate logging influence landslide formation and reactivation (Lacroix et al., 2020).

2.4 Synthesis of large landslide dating in the worldwide (landslide dating in mountainous areas)

Determining the age of landslide exposure is an important step in understanding the causes, recurrence and triggers (Corominas and Moya, 2008). Landslide dating is used to correlate with paleoclimatic events (Placzek et al., 2013), paleoseismic events (Aylsworth et al., 2000) or to estimate the erosion rate of a watershed (Antinao and Gosse, 2009).

Different absolute dating techniques are used to date landslides, because they allow to obtain calculated numerical ages (Walker, 2005). Frequently used absolute dating methods comprise radiometric techniques such as radiocarbon (^{14}C), Cosmic Ray Exposure (CRE), Optically Stimulated Luminescence (OSL), Thermoluminescence (TL) and Uranium-series ($^{234}\text{U}/^{230}\text{Th}$) (Figure 14; Pánek, 2015). For recent events or events that occurred in the last few centuries, tree-ring based dendrochronology is used (Figure 15). Radiocarbon dating (^{14}C) allows dating of organic materials (Wood and paleo-soil) mixed or buried by landslide mass; allowing for landslide chronologies (Borgatti and Soldati, 2010). The Cosmic Ray Exposure allows to know the exposure age of landslides by dating the blocks in the landslide mass and the escarpments or landslide plane (Zerathe et al., 2017). OSL, TL and Uranium series techniques have limitations for dating landslides; fine sediments are required for dating (Li et al., 2008; Prager et al., 2008). Dendrochronology is used to date landslides using trees that were damaged by avalanches or rocks in their path, the tree rings allow determining the age of the landslides with precision (López Saez et al., 2012). One of the relative dating methods for landslides is lichenometry (Figure 14), which is related to specific lichens located on landslide blocks that can give a minimum age of the event (Bull, 2003; Lang et al., 1999). Another relative method is tephrochronology (Figure 15) that can indicate the minimum or maximum age of a landslide depending on the tephra layer that covers or underlies the body of the landslide (Moreiras, 2006; Hermanns and Schellenberger, 2008; Mercier et al., 2013).

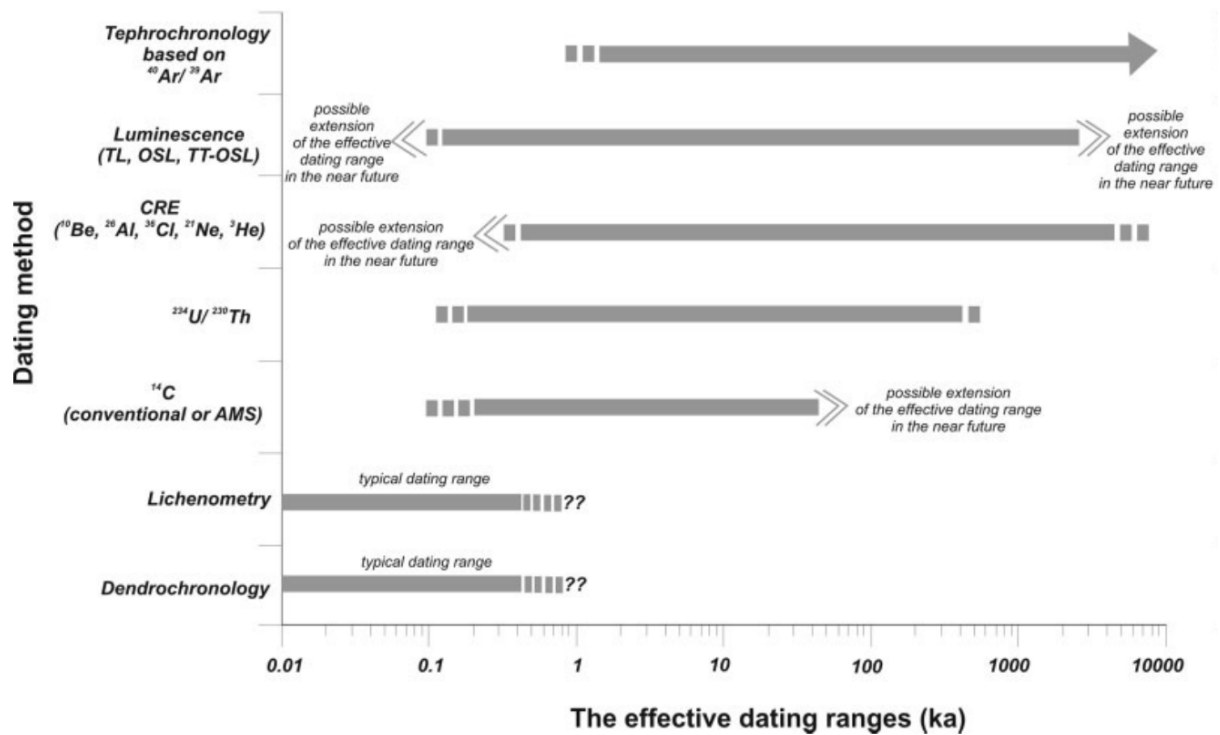


Figure 14. Main dating methods used to date landslides (Modified from Pánek, 2015).

Pánek et al., (2016) conducted a compilation of studies where they used DSGSD and DSL dating methods around the world. They distinguished two groups of events that occurred in glacial and non-glacial environments (Figure 14). The former with ages given between 18 and 10 ka that correspond to deglaciation in mountain belts (e. g. Rocky Mountains, McCalpin and Irvine, 1995; Alaska, McCalpin et al., 2011; Scandinavian Mountains, Hermanns et al., 2013; Alps, Hippolyte et al., 2012; Zerathe et al., 2014; Schwartz et al., 2017; the Pyrenees, Gutiérrez et al., 2008) and the second group that are not related to non-glacial environments, have a longer and more complex evolution, are events prior to the Last Glacial Maximum (Hughes et al., 2013).

Although landslide dating studies have increased worldwide, but regional landslides chronologies are not extensive and are scarce (Figure 15; Pánek, 2015). The glacial advance and retreat, coupled with the presence of intense rainfall in all mountains such as the Alps, the Himalayas, among others, erode and erase the presence of DSGSD and even more the presence of DSL, restricting the study and knowledge of these processes in a short time window (Figure 15). In order to learn more about the behavior, formation and evolution of these large processes, the time window of study must be extended (Figure 15). One of the places in the world that allows the study of these processes is the Western Flank of the Central Andes because it has no rainfall, the surface is preserved and has the presence of large landslides.

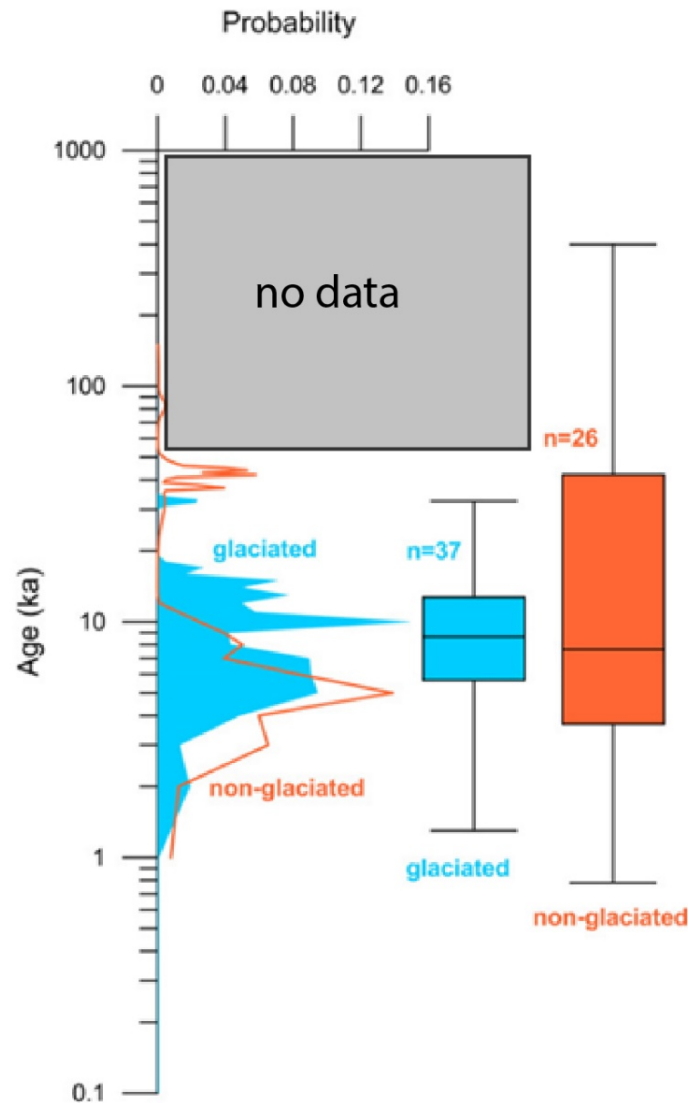


Figure 15. Probability distributions and variability of ages expressed as box-whisker plots for published DSGSDs and DSLs situated in formerly glaciated terrains and in non-glaciated settings. Gray box indicates no data due to lack of landslide studies and dating. (Modified from Pánek and Klimeš, 2016).

3 Western Flank of the Central Andes (WFCA)

3.1 The WFCA a perfect place to study the large landslide activity over 1Ma time window

The western flank of the Central Andes (WFCA) presents from east to west different geomorphological zones. a) a coastal mountain range with a maximum elevation of 1000 m asl, b) a coastal plain or central depression, c) the western cordillera range with elevations between 1000 and 4500 m asl, and d) the Altiplano, which reaches an average elevation of 5000 m asl. (Figure 16)

The WFCA is can be considered as a natural laboratory suitable for the study of the large landslides (Figure 16). Indeed the area presents:

(1) High relief that acts as strong orographic barrier that prevents precipitation from the Amazonian side crossing to the west (Houston and Hartley, 2003; Bookhagen and Strecker, 2008), thus allowing this place to have a hyper-arid climate and very low erosion rates (<0.5 mm/year, Hall et al., 2008) that

allow to preserve the geomorphological markers for millions of years (Kober et al., 2007, Nishiizumi et al., 2005; Dunai et al., 2005), due to the aridity this place is called the Atacama Desert. This place offers the opportunity to trace gravitational processes on an unknown time scale.

(2) The WFCA is carved by deep valleys and canyons that cut through the western cordillera and the central depression and are related to regional uplift (e.g. Thouret et al., 2007), incised and deepened by rivers descending from the altiplano (Evenstar et al., 2017).

(3) The WFCA hosts a large number of fossil mega-slides of plurikilometric cubic volumes as for example Chuquibamba (Margirier et al., 2015), Caquilluco (Zerathe et al., 2017), Lluta (Strasser and Schlunegger, 2005), Miñimiñi and Latagualla landslides (Pinto et al., 2008), El Magnifico landslide (Mather et al., 2014; Crosta et al., 2017). All of these previously studied landslides are located along the western cordillera, with the exception of the El Magnifico landslide, which is located in the coastal cordillera.

(4) In this long term arid climate one of the characteristics of this part of the Andes is the occurrence of intense humid paleoclimatic events in the Atacama Desert (Bartz et al., 2020), producing the formation of temporary paleo lakes (Ritter et al., 2018). Paleo-El Niño events also affect this zone, these were identified by dating debris flows on the Peruvian coastal margin (Wells, 1990; Fontugne et al., 1999; Keefer et al., 2003), suggesting that these events were frequent and severe enough to produce significant erosion and deposition. In the Altiplano shows the occurrence of other recorded paleoclimatic events such as the Tauca phase (18.5 - 14.5 ka) and the Copiasa phase (12.8 - 11 ka) during the Heinrich 1a and Younger Dryas respectively (Placzek et al., 2013) and climatic fluctuations of lake levels and glacial advances during the Tauca phase (Martin et al., 2018) that could have had great impact on landslide formation in this part of the Andes.

(5) The seismicity in this area is due to the convergence between Pacific and the South America plates. This convergence produces uplift related that participate to the construction of the Andes relief. Two types of earthquakes can be distinguished: (i) subduction or crustal earthquakes that generate earthquakes of up to 9 Mw with recurrences every 250 years and (ii) cortical earthquakes due to the reactivation of active geological faults, which generate earthquakes of 7 Mw, these earthquakes are superficial (<30 km deep) and have a recurrence of thousands of years.

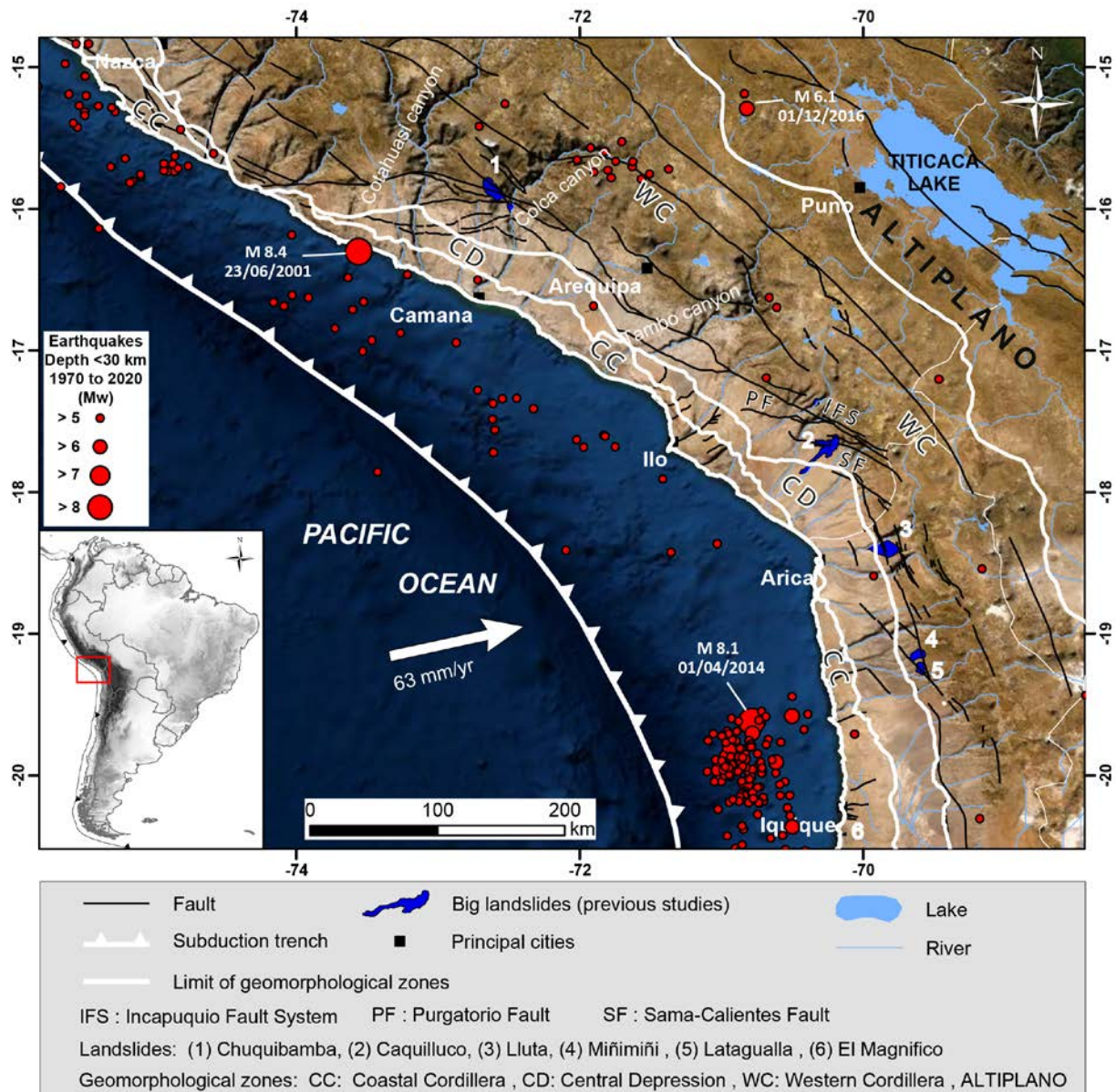


Figure 16. Focus of the Western Flank of the Central Andes divided into geomorphological zones. Large landslides are observed in this part of the Andes: Chuquibamba (Margirier et al., 2015), Caquilluco landslide (Zerathe et al., 2017), Lluta landslide (Wörner et al., 2002; Strasser and Schlunegger, 2005), Miñimiñi and Latagualla landslides (Pinto et al., 2008). There is a rugged topography with mountains, valleys and deep canyons (Cotahuasi, Colca, Tambo). This part has intense seismicity, we consider surface seismicity <30 km (red circle) for subduction and cortical earthquakes (<http://ds.iris.edu/seismon/index.phtml>).

3.2 Geodynamic and tectonic setting

The origin of the Andes is a product of the subduction of the Nazca plate under the South American plate (Pardo-Casas and Molnar, 1987), this process generated the construction of the Andes and gave rise to the formation of successive volcanic arcs. These different arcs were controlled by subduction dip change (Isacks, 1988; Allmendinger et al., 1997; James & Sacks, 1999; Sobolev & Babeyko, 2005; Haschke et al., 2006; Mamani et al., 2008, 2009). These dynamics produced a thickening of the crust,

thus forming the western cordillera. Crustal thickening began in the Upper Cretaceous (Jaillard & Soler, 1996). One of the main volcanic faces corresponds to the so-called Huaylillas arc (24-10 Ma, Quang et al., 2005; Thouret et al., 2007), which produced thick ignimbrite deposits (~300 m thick) on a regional scale. Currently, the western Cordillera is covered by the Huaylillas ignimbrites, being a reference marker. This domain is affected by tectonic shortening, evidencing flexure of the Huaylillas paleosurface and also the presence of crustal fault systems.

The WFCA is deformed and shows important reverse faults due to the crustal shortening and thickening (Armijo et al., 2015) as a result of subduction. In this part of the Andes the tectonic regime is transpressive. Cortical faults generate surface earthquakes with magnitudes up to 7 Mw, the recurrence time of the reactivations of these faults is > 1000 years. One of the last recorded cortical earthquakes was the Parina earthquake with a magnitude of 6.1 MW, which occurred in the Altiplano (Aguirre et al., 2021). In the WFCA the most important structure is the Incapuquio Fault System (IFS), which has a length of more than 200 km with NW-SE direction (Figure 16). This fault system extends along the western cordillera. It is considered as a neotectonic fault because the main surface ruptures have been produced during the Holocene time (Benavente et al., 2021). Another important fault is the Purgatorio Fault (PF), it is a reverse type fault, has an E-W strike and a length ~70 km, this fault shows at least two major ruptures phases that could generate earthquakes up to 7 Mw (Benavente et al., 2017). Another important fault in this part of the Andes is the Sama-Calientes fault (SF), which is considered as a reverse fault. The trace of this fault is located in the central depression with a E-W trending direction and a length of 50 km (Hall et al., 2008).

3.3 Climate and geomorphological setting

The topography of the WFCA results from the competition between erosion processes controlled by climatic conditions and the tectonic context. The western cordillera and the central depression in the WFCA are affected by deep valley incisions and canyons (e.g., Colca Canyon, Cotahuasi Canyon) mainly carved by the regional tectonic uplift (Thouret et al., 2007) related to the formation of the Andes. The estimated uplift rates during the Pleistocene are ranging between 0.2 to 0.4 mm.yr⁻¹ (Hall et al., 2012). This global uplift is due to the shortening and thickening of the continental lithosphere produced by the ongoing subduction of the Nazca plate beneath the South American plate (Isacks, 1988; Horton et al., 2001; Armijo et al., 2015)

Currently, the climate in the WFCA is one of the driest places in the world (Dunai et al., 2005). This place is called the Atacama Desert. This large coastal desert between Peru and Chile has a longitudinal extension of approximately 3500 km and is bounded by the Pacific Ocean to the west and the western cordillera to the east. This narrow topographic zone has a low annual precipitation rate, due to the fact that the Andes Mountain range limits the transfer of precipitation coming from the Atlantic and the Amazon (Bookhagen and Strecker, 2008), and the cold Humboldt current, which is a mass of cold sea water that moves from the South Pacific to the north, covering the coasts of Chile, Peru and Ecuador. It lowers the sea temperature by 5 to 10 degrees, this influences the atmosphere to cool down, limiting evaporation and causing the absence of rainfall, thus creating a strip of sand and coastal desert that becomes the Atacama Desert.

Precipitation during the last decades shows that the main source of moisture for the WFCA comes from the Amazon basin (Figure 17a). Precipitation regime is seasonal with a maximum during the austral summer. Part of this precipitation reaches the upper part of the basins and flows through the rivers to form deep valleys. But the precipitation is restricted to the east (Figure 17 b and c). Thus, the Atacama Desert remains arid, with less than 50 mm/year of precipitation (Strecker et al. 2007).

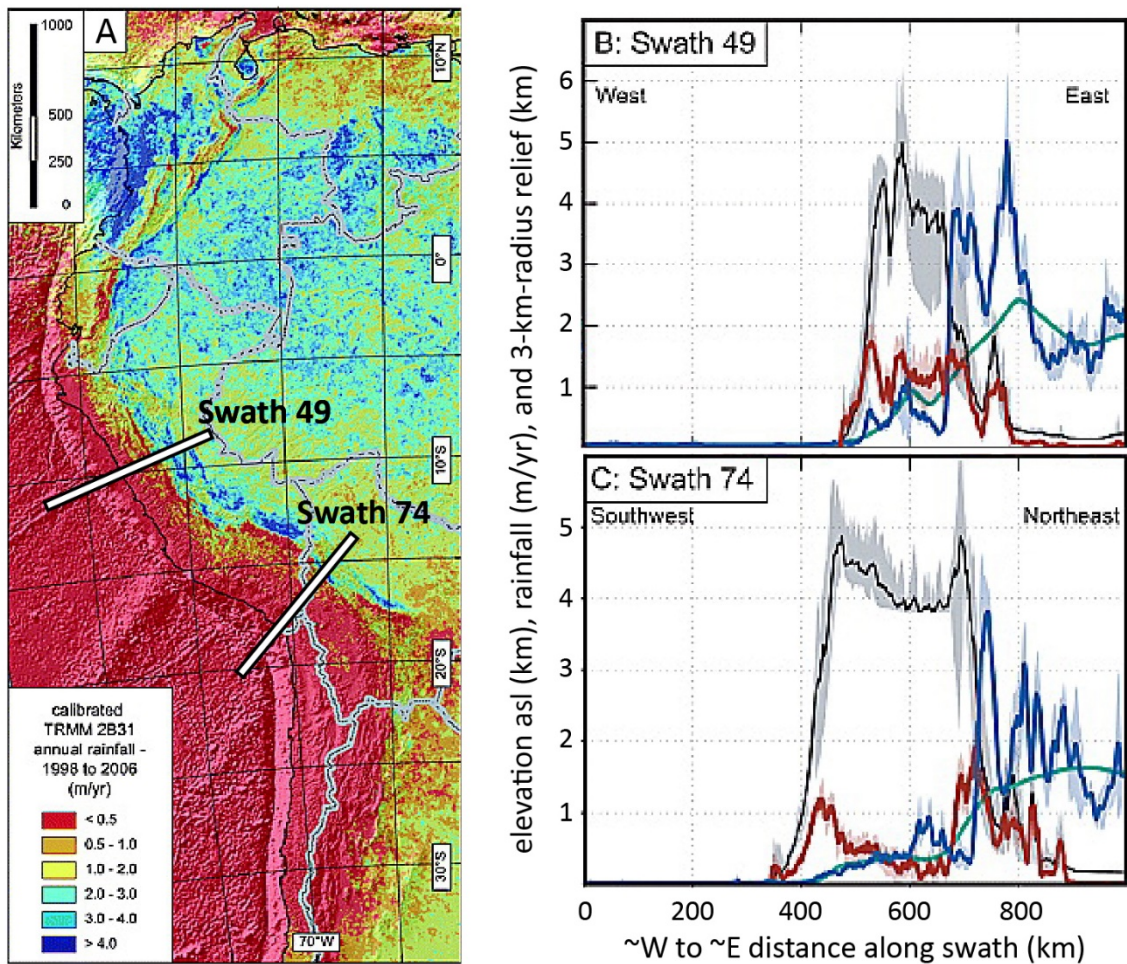


Figure 17. Global precipitation conditions along the Pacific side of the Central Andes. (a) Tropical Rainfall Measuring Mission (TRMM 2B31). The international borders are in grey. The Annual rainfall of the Andes is averaged for the period of 1998 to 2006 (9 years) with a spatial resolution of $\sim 5 \times 5 \text{ km}^2$. We note that the eastern flanks of the Andes represent an important orographic barrier which prevents the overflow of rainfall from the Amazon basin to the west. International borders in gray. (b) and (c) Swath profiles of the Andes, precipitation is in blue (TRMM 2B31) and green (TRMM 3B42); SRTM topography is in black and gray; and 3 km radius relief is in red. (Bookhagen and Strecker, 2008).

The hyperaridity of this site has prevailed for millions of years (Dunai et al., 2005), is responsible for very low denudation rates ($<0.5 \text{ m/Ma}$; e.g. Hall et al., 2008) that allow the preservation of the landscape. Despite aridity, there are studies reporting sparse paleoclimatic records (Bartz et al., 2020) with the presence of paleolakes (Ritter et al., 2017). El Niño phenomenon brings large storms and high amounts of precipitation to the Peruvian coast (Mettier et al., 2009); on the Peruvian coast there is evidence of paleo-floods linked to this phenomenon during the Holocene (Keefer et al., 2003; Lagos et al., 2008; Steffen et al., 2009, 2010), currently these events occur every 2 to 7 years. Paleoclimatic proxies towards the Altiplano are evidenced as periods of higher precipitation recorded in the terraces of the Altiplano paleolake. They show important wet phases between 25 to 11 ka, which is the Tauca Lake period (Baker et al., 2001b; Placzek et al., 2006), as well as this event, there are older events such

as the Ouki cycle (100-120 ka, Placzek et al., 2013) that could also be related to the formation of large landslides (Chuquibamba landslide, Margirier et al., 2015).

3.4 Western Andean large landslides

The WFCA shows the presence of large landslides that imply the gravitational destabilization of large areas greater than 0.1 km². The geomorphological surface of these landslides is well preserved in this part of the Andes due to weak erosion processes controlled by arid climatic conditions over a long period of time (Dunai et al., 2005). Among them the Caquilluco landslide (Figure 18) is a good example. Indeed its main surface is well preserved showing a succession of rock avalanche events with a maximum run out of ~40 km. The main scarp is located at more than 3800 m asl. These types of landslides, due to their large dimensions, disturb the topography, for example the LLuta landslide (Figure 19; Strasser and Schlunegger, 2005), which has a length of ~37 km and it is estimated that the initial collapse mobilized ~26 km³ which modified the topography, filled valleys and changed the course of rivers. This is also observed in the Miñimiñi and Latagualla landslides (Pinto et al., 2008). As well as this landslide there are other landslides where cosmogenic nuclide dating was used to determine the age of exposure (Figure 20); among them the Chuquibamba landslide (100 ka; Margirier et al., 2015; Thouret et al., 2017), Caquilluco landslide (120 - 600 ka; Zerathe et al., 2017; Zerathe et al., 2018), Lluta Landslide (5 - 10 Ma; Wörner et al., 2002; Strasser and Schlunegger, 2005), the Miñimiñi and Latagualla Landslides (8 - 9 Ma; Pinto et al., 2008). A cluster of avalanches from the El Magnifico landslide was also dated, the avalanches are between 4 - 60 Ka (Mather et al., 2014; Crosta et al., 2017).



Figure 18. Caquilluco landslide (Rock avalanche). It has a drop between the headscarp and the foot of the landslide of ~3250 m and a strike length of ~41 km. Note that the landslide mass is preserved.



Figure 19. 3D view of the Lluta landslide, the 37 km long landslide mass disturbed the topography which was probably like the relief of the right flank of the Lluta valley.

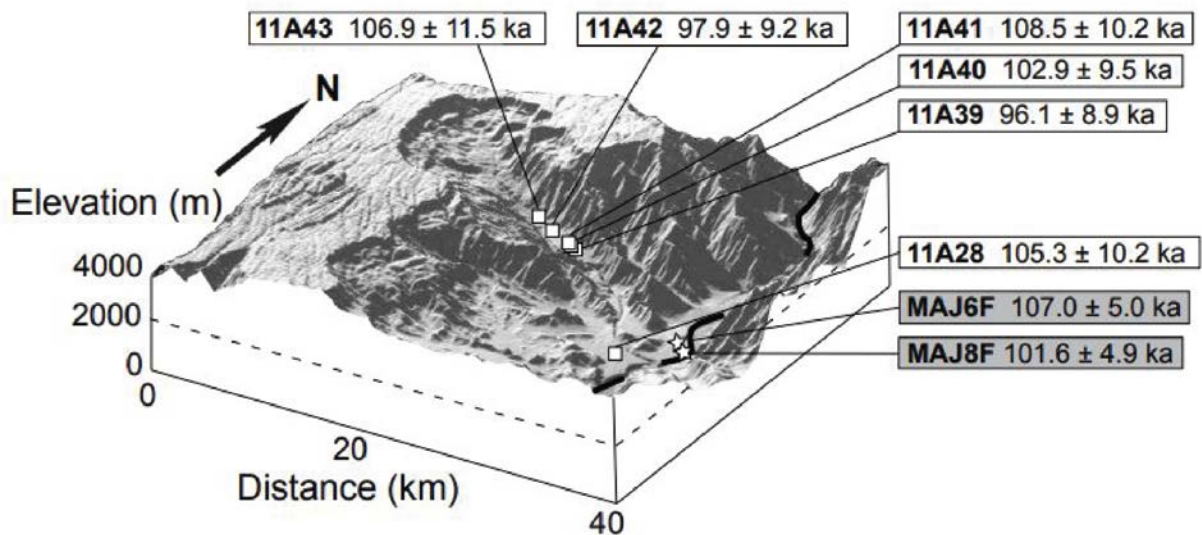


Figure 20. Chuquibamba landslide block diagram (modified Margirier et al., 2015) with digital elevation model (GeoMapApp, SRTM data, 90 m of resolution) and the ages obtained by cosmogenic nuclide dating method.

The question of the triggering of these large surface processes is widely debated at present day. McPhillips et al. (2014) suggest that, for this part of the Andes, the seismic activity plays a predominant role in the triggering of landslides, while climatic conditions have a negligible influence. These

conclusions may be valid for landslides of small volume ($<10^4 \text{ m}^3$) and this is reflected in subduction earthquakes, Lacroix et al. (2013) indicate that the last major earthquake in the Pisco area in 2007 (8 Mw) triggered more than 800 landslides, but all were considered small to moderate ($\sim 10^3 \text{ m}^3$).

In contrast, Margirier et al. (2015) propose that the trigger for the Chuquibamba landslide correlates with a $\sim 100 \text{ ka}$ wet climatic pulse (Ouki episode, Placzek et al., 2013). Similarly, results obtained from the Caquilluco mega-slide (Zerathe et al., 2017) suggest a recurrence of triggers higher than the recurrence times of mega-earthquakes. The last Caquilluco landslide episode (100-120 ka) is synchronized with the "Ouki" climatic event marked by heavy precipitation at the altiplano scale (Placzek et al., 2013).

In this part of the Andes there are numerous large avalanches, in some sectors of the WFCA these events were recognized and mapped (Audin and Bechir, 2006; Crosta et al., 2014, 2015) but are not dated, leaving a gap that the use of cosmogenic nuclide dating, applied to escarpments and blocks, could give a better understanding of the formation and triggers of these large events.

4 Main problematics of the PhD and strategy

4.1 Scientific questions

This thesis project focuses on gravity-driven processes, to characterize them by typology, understand their mechanisms and triggers. The Western Flank of the Central Andes provides an opportunity to study these processes and to broaden the knowledge of the conditions and dynamics of these mass movements. It has a high relief with very deep valleys and erosion is very low in this place for millions of years ($<05 \text{ mm/year}$), this allows the landscape to be preserved, but there are also records of extreme climatic events and seismicity in this part of the Andes is recurrent. The main problematic of my PhD work related to the landslide activity in the WFCA rests on the following main questions:

- How to establish an inventory of large landslides at the regional scale?
- How many other landslides exist in the WFCA?
- Does it exist a specific spatial distribution of landslides in this part of the Andes?
- What is the timing of the landslide activity?
- What can be interpreted for the triggering factors?

In order to respond to these main scientific questions, a working strategy has been deployed using satellite image analysis techniques coupled with cosmogenic nuclide dating.

4.2 Strategy methods and data

In order to respond to the main questions, my PhD manuscript is organized around three main parts which are the following chapters:

- ***Inventory of large landslides along the Central Western Andes (ca. 15°–20°S): Landslide distribution patterns and insights on controlling factors (CHAPTER 2)***

This first part will consist of a large-scale survey of the western flank of the central Andes between latitudes 15 and 20° S, identifying and mapping large landslides including previous work, with the objective of providing a complete and updated database of this part of the Andes. The data to be provided will be about the type of landslide, its size and to verify if there is a spatial distribution. A statistical approach will be used in order to identify the conditioning factors associated with the

landslides activity in this part of the Andes. For the development of this first part we will use images from Google Earth, DEM (TanDEM-X (12m), SRTM (30m)) and GIS support (ArcGIS, QGIS).

- ***Giant landslide triggerings and paleoprecipitations in the Central Western Andes: The aricota rockslide dam (South Peru) (CHAPTER 3)***

This second stage will focus on the study of a specific landslide called the Aricota landslide, the mass of which formed a large dam and gave rise to the Aricota lake. The objective for this part is to determine the age of exposure of the landslide and to investigate the triggering factor. For this part, a detailed mapping of the landslide was made and 17 samples were collected in the field from the main escarpment and the landslide mass. The samples were processed following the cosmogenic nuclide methodology (^{10}Be) in quartz mineral. Exposure ages of the samples were obtained using an online calculator (CREEP program, Martin et al., 2017). The obtained results were compared with paleoclimatic and earthquake proxies close to the study area.

- ***Pleistocene chronology of large landslides triggering on the western flank of the Central Andes revealed by cosmogenic nuclide dating (CHAPTER 4)***

This third stage will focus on a specific place in the western flank of the central Andes with a high concentration of landslides, by carrying out a geochronological study, in order to bring chronological constraints on the landslides activity. The goal is to characterize the patterns of occurrence and/or periodicity of landslide and ultimately to provide new data to investigate their triggering factors (earthquakes or extreme climatic events). For the development of this third part, 8 landslides were chosen, each one was mapped in detail using Pleiades images (2 m resolution), then a sampling strategy was carried out where 52 boulder samples were collected. The samples were processed following the cosmogenic nuclide methodology (^{10}Be) applied on quartz and feldspar minerals. After obtaining the concentrations, using an online calculator (CREP program, Martin et al., 2017) it was possible to obtain the exposure ages, to then compare if there are periodicity patterns and their possible triggers.

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CHAPTER II:
**INVENTORY OF LARGE
LANDSLIDES ALONG THE CENTRAL
WESTERN ANDES (CA. 15°–20° S):
LANDSLIDE DISTRIBUTION
PATTERNS AND INSIGHTS ON
CONTROLLING FACTORS**



Inventory of large landslides along the Central Western Andes (ca. 15°–20° S): Landslide distribution patterns and insights on controlling factors

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ABSTRACT

The western flank of the Central Andes hosts some of the largest terrestrial landslides ($v > \text{km}^3$), which morphologies are particularly well-preserved due to low erosion rates related to the hyper-arid climate prevailing in this region since the Miocene. First-order questions are pending about the factors controlling the development and the triggering of those large-scale slope failures. Previous studies provided some geomorphological analysis and dating on individual study cases, but a regional-scale vision of landslide processes long the Central Western Andes is missing.

Here we report an original inventory of large landslides (areas from 0.1 to 180 km²) established along the western flank of the Central Andes between latitudes ca. 15 and 20° S, and from the Pacific coast to the Altiplano. Based on manual mapping (using satellite images analysis, Google Earth and DEMs analysis) and a compilation of previous works, we inventoried more than a thousand large landslides in this region. We then statistically explored the database according to the landslides typology, size, abundance and relation to geologic, tectonic and climatic settings of the Central Western Andes in order to provide a first insight on their controlling factors. Landslide size-frequency distribution follows a power-law with an exponent of 2.31 ± 0.16 and a cut-off of $4.0 \pm 1.9 \text{ km}^2$ showing a strong contribution of the largest landslides to the cumulated landslide area. We revealed a dominance of rockslide typology (86%) characterized by in-mass slides, the rest being rock-avalanche type (14%) marked by typical granular-flow morphologies. Combination of specific lithology and great local relief emerge as favorable conditioning factor for large landslide initiation, in particular in the case of river incisions through ignimbrites of the Paleogene-Neogene (Huayllillas Formation), concentrating >30% of the landslides. Moreover, landslide clusters tend to follow crustal faults networks suggesting a long-term control of tectonic activity. Most of the identified landslides are paleo events. We tentatively argue that their triggering could not have been possible in the current hyper-arid conditions of the Atacama Desert and its periphery. Future research providing dating on some of the landslide clusters identified in this study is needed to explore possible temporal correlations between periods of landslide activity and external seismic and/or climatic cycles.

1. Introduction

Landslides are ubiquitous gravity phenomena on Earth, found in any environment with slopes. Their triggering is conditioned by the internal mechanical and hydrological properties of geomaterials (Guzzetti et al., 1996; Stead and Wolter, 2015), and may depend on external factors associated with seismotectonic activity (Fan et al., 2019) or climatic variations (Pánek, 2019). They constitute one of the major sources of

hazard, responsible for thousands of victims and billions of dollars in damages each year (Petley, 2012; Froude and Petley, 2018; Wallemacq and House, 2018). The constant growth of the world population associated with the ongoing climate changes are factors that may severely increase the level of risk and hazard related to landslide activity (Gariano et Gariano and Guzzetti, 2016; Haque et al., 2019). In this context, a better understanding of landslide processes and their causative factors is crucial and those questions have received a growing interest (Wu

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et al., 2015). On longer timescales, landslides are recognized as the main erosional process in orogenic zones (e.g. Korup et al., 2007). Landslide rate is thought to mirror the long-term trend of tectonic uplift, landslide continuously affecting steep slopes along the valley flanks of incising rivers (Larsen and Montgomery, 2012). Doing so, landslides are the main agent transporting material from hillslopes to rivers and limiting the elevation and the relief construction in mountain ranges (Whipple et al., 1999; Montgomery, 2001; Roering, 2012).

To disentangle hazard issues and to progress toward a better understanding of landslides processes, research strategies based on landslide inventories have shown interesting potential (Malamud et al., 2004; Guzzetti et al., 2012). Numerous landslide inventories have been built after single storm events or strong earthquakes, using remote sensing approaches to detect the triggered landslides (see reviews in Marc et al. (2018) and Tanyaş et al. (2017), for rainfall-induced and earthquake-induced landslide inventories, respectively). Providing statistics on landslide processes, those inventories can highlight specific patterns and reveal generic landslide properties, such as the earthquake-induced landslide size decreasing with distance from the fault trace (Valagussa et al., 2019), the control of relief on landslide size (Medwedeff et al., 2020) or the influence of total rainstorm on the proportion of large landslides (Marc et al., 2018). However, deciphering landslides patterns on a longer time scale (hundreds to thousands of years) and at a large spatial scale is more complex because erosion continuously removes the geomorphological evidence of past events. Furthermore, automatic detection of past landslides in landscapes is not efficient at present-day and establishing paleo landslides inventory requires a manual mapping based on expert vision (e.g. Pánek et al., 2019; Görüm, 2019). Those inventories allow to understand the relations between large landslides and relief properties at an orogenic scale and to unravel the respective effects of long-term seismotectonic activity and Quaternary climate changes on slope instabilities.

In this study, we focus on large landslides along the western flank of the Central Andes between ca. 15° and 20°S, in both south Peru and north Chile, and we aim at establishing a comprehensive inventory of landslides in this area. This region is an atypical place for several aspects. First, it is particularly active geodynamically, related to the long-term convergence between the Nazca and the South America plates (Armijo et al., 2015; Martinod et al., 2020). This global shortening generates relief construction (Martinod et al., 2020) and produces instantaneous deformation (subduction and crustal seismicity; Villegas-Lanza et al., 2016) coupled with long-term processes of surface uplift (Thouret et al., 2017) and volcanism (Mamani et al., 2009). Second, the climate of this region is specific, with some places being one of the driest worldwide: referred to as the Atacama Desert in Northern Chile and Southern Peru (Hartley and Chong, 2002). This desert, where a hyper-arid climate has been maintained for several millions of years (e.g. Hartley and Chong, 2002; Dunai et al., 2005) is often referred to as a Martian proxy (Valdivia-Silva et al., 2011; Irwin et al., 2014). The long-term aridity is responsible for very low erosion and weathering rates (1–10 mm kyr⁻¹; Nishiizumi et al., 2005), allowing for exceptionally long preservation of landscapes and offering a unique time window to study slope instabilities at geological time scales. At the same time, strong storms can episodically occur during El Niño event. Finally, the western flank of the Central Andes hosts some of the largest landslides ever identified on the emerged Earth surface (e.g. Chuquibamba (Margirier et al., 2015), Caquilluco (Crosta et al., 2015), Lluta (Strasser and Schlunegger, 2005), mobilizing volumes of several cubic kilometers, with kilometeric long run-outs, similar to those reported on the Mars surface (Lucas et al., 2014). Some previous studies have been conducted on those individual slope failures, revealing that the instabilities are ancient with ages ranging from tens to hundreds of thousands of years (Zerathe et al., 2017; Crosta et al., 2017; Delgado et al., 2020; Sánchez-Núñez et al., 2020). However, questions remain about the link between those landslides and the conditioning factors along the Central Western Andes and also with the seismicity and the past climate

variations in this region. Other preliminary works have revealed that much more large landslides may exist there (Audin and Bechir, 2006; Mather et al., 2014; Crosta et al., 2014) but a general view of the distribution of the landslide activity at the scale of the Central Western Andes instabilities is missing.

The scope of the paper is to establish a landslide inventory as exhaustive as possible along the northernmost Central Western Andes (ca. 15° - 20°S), our strategy was based on a review of previous works on landslides existing in the literature for this region and on an original mapping of unrecognized large landslides based mainly on satellite images, Google Earth and DEMs analysis. The finalities of this study are: (1) to provide an updated database of large landslides existing between latitudes ca. 15 and 20°S. This database will be open and may be modifiable; (2) to provide a first-order view of their typology, size, abundance and distribution; and (3) to search for statistical patterns between landslide distribution and background settings in order to better understand their conditioning factors.

2. Settings of the western flank of the Central Andes

2.1. Geodynamic and large-scale morphology

The Andean cordillera is located on an active tectonic margin where the subduction of the Nazca plate beneath the South American plate occurs since ~50 Ma (Pardo-Casas and Molnar, 1987) with a convergence rate of ~62 mm. yr⁻¹ (Villegas-Lanza et al., 2016). This process generates the construction of the Andes and leads to the formation of successive volcanic arcs. Their locations varied in time and were controlled by the change of the dip of the subduction slab (Isacks, 1988; Allmendinger et al., 1997; James and Sacks, 1999; Sobolev and Babeyko, 2005; Haschke et al., 2006; Mamani et al., 2008, 2009). This dynamic produced long-term crustal thickening controlled by magmatic underplating and tectonic shortening. The western flank of the Central Andes is classically subdivided into three main areas (Fig. 1) based on different geological and morphological settings inherited from the long-term geodynamics evolution of the Andes.

The first area corresponds to the Coastal Cordillera (CC) which is mainly characterized by Proterozoic craton (so-called the Arequipa massif, Cobbing and Pitcher, 1972) represented by the association of gneisses and migmatites which have been later intruded by Paleozoic plutons (Cobbing and Pitcher, 1972; Cobbing et al., 1977; Mukasa and Henry, 1990). This Coastal Cordillera forms currently a narrow band reaching 50-km-wide and moderate relief and elevation up to 1000 m a.s.l. along the Pacific coastline.

The second area corresponding to the Central Depression (CD) exhibits Tertiary sedimentary series, the so-called Moquegua formation, unconformably resting above the Proterozoic and Paleozoic bedrock. This area corresponds to a flexural depression located in the front of the volcanic arc. This basin collected the erosional products of the Andean relief under construction. Those detrital sedimentary series can be locally more than 1-km thick (Roperch et al., 2006; Thouret et al., 2007; Schildgen et al., 2007; Garzzone et al., 2008). Their lithologies evolve from thin marine sequences at the base toward conglomeratic continental deposits with interstratified ignimbrites levels at their top. At present-day, this area forms a pediment plain, almost flat with mean elevations ranging from 1000 to 1500 m a.s.l., and locally affected by fluvial incision (Thouret et al., 2007; Schildgen et al., 2007; Garzzone et al., 2008).

The third area corresponds to the Western Cordillera (WC) which presents a higher relief from 1000 to 5000 m a.s.l. It is made of Mesozoic marine sequences and Cenozoic, essentially Paleogene-Neogene, volcano-sedimentary series related to the migration of the successive volcanic arcs (Mamani et al., 2010). One of the last main volcanic phases corresponds to the so-called Huaylillas arc (24-10 Ma, Quang et al., 2005; Thouret et al., 2007). It produced thick ignimbrite deposits (up to 300 m of thickness) at a regional scale. Along the Western Cordillera, the

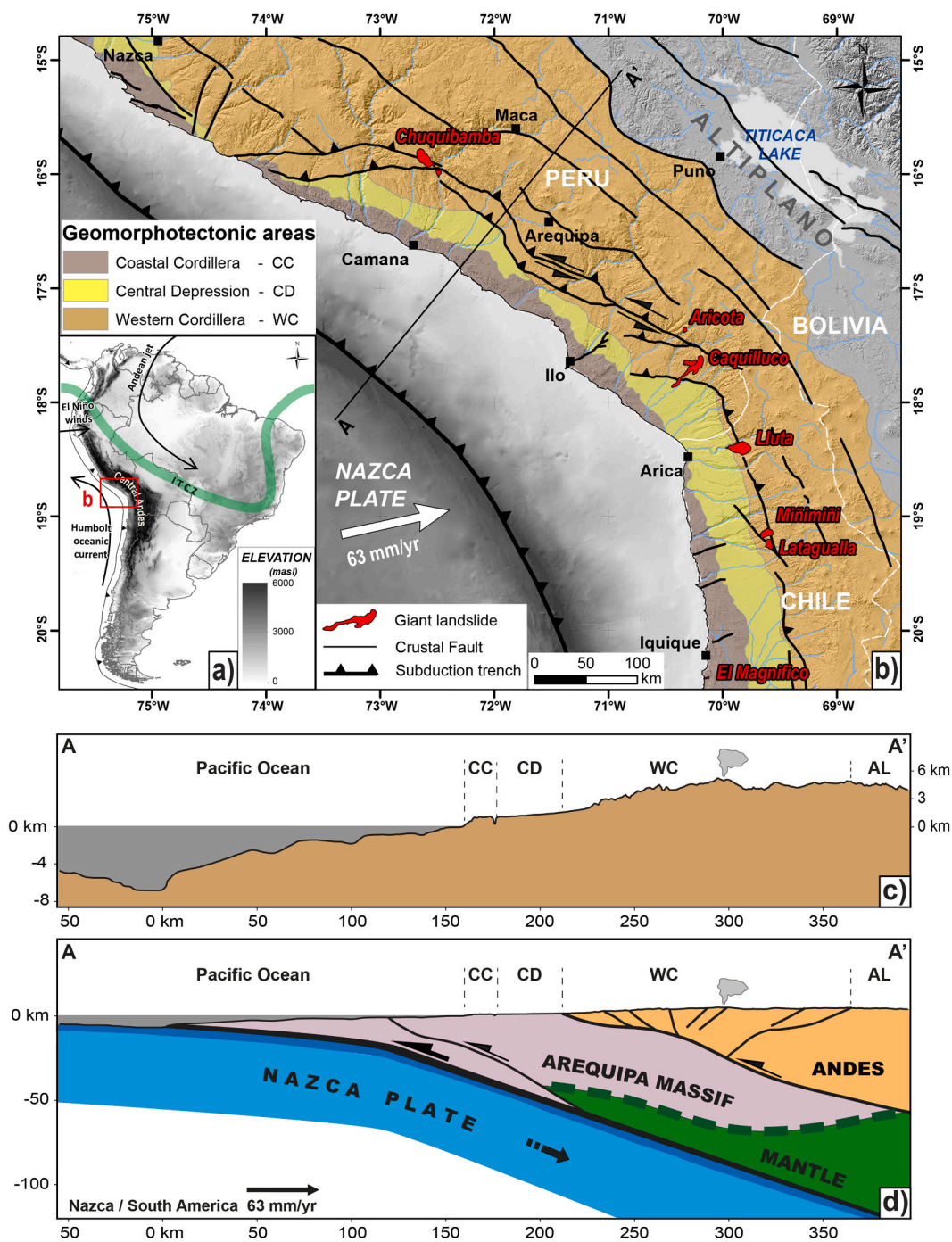


Fig. 1. (a) Study area location and major climatic features of South America showing the Intertropical Convergence Zone (ITCZ), El Niño wings and the Humboldt oceanic current, (b) focus on the study area showing the different geomorphotectonic areas of the Central Western Andes and the location of giant landslides documented in the literature (Chuquibamba landslide - Margirier et al., 2015; Thouret et al., 2017; Aricota landslide - Delgado et al., 2020; Caquilluco landslide - Zerathe et al., 2017; Lluta landslide - Wörner et al., 2002; Strasser and Schlunegger, 2005; Miñimiñi and Latagualla landslides - Pinto et al., 2008; El Magnifico landslide - Mather et al., 2014; Crosta et al., 2017), (c) and (d) AA' topographic profile of the western flank of the Central Andes and its geological interpretation (adapted from Armijo et al., 2015), respectively. CC: Coastal Cordillera, CD: Central Depression, WC: Western Cordillera, AL: Altiplano.

top of the Huaylillas deposits corresponds to a preserved paleosurface used as a reference surface at a regional scale. All this domain is affected by tectonic shortening associated with the development of large-scale anticline geometry, well underline by flexures of the Huaylillas paleosurface, and by pluri-kilometric crustal fault systems.

As previously introduced, among those three sub-areas, the Western Cordillera is the region where some of the largest landslides have been reported in the literature (Chuquibamba landslide - Margirier et al., 2015; Thouret et al., 2017; Aricota landslide - Delgado et al., 2020;

Caquilluco landslide - Zerathe et al., 2017; Lluta landslide - Wörner et al., 2002; Strasser and Schlunegger, 2005; Miñimiñi and Latagualla landslides - Pinto et al., 2008; El Magnifico landslide - Mather et al., 2014; Crosta et al., 2017, Fig. 1). We bring here below further detailed geological and geomorphological descriptions of this key region required to better understand the gravitational destabilization affecting the Central Western Andes.

2.2. Lithostratigraphy

The oldest rocks in the studied area correspond to the Precambrian crystalline basement. It consists of gneiss, migmatites, pegmatites, schists and diorites. This rock assemblage is located between latitudes 15°-18°S, outcropping mainly along the Peruvian Coastal Cordillera along an NW-SE orientation (Fig. 2) and was dated between 1861 ± 32 Ma and 946 Ma by Casquet et al. (2010).

Paleozoic rocks were emplaced in erosional unconformity, their lithostratigraphic units are observed along the Coastal Cordillera (Fig. 2) and are represented by the Marcona (Cambrian), Cabanillas (Devonian), Ambo and Tarma (Carboniferous) formations. These units are mostly made up of limestones, conglomerates, sandstones and shales (Newell, 1945).

The Mesozoic record is characterized by important Jurassic and Cretaceous marine sedimentation, controlled by the tectonic opening of the Arequipa-Tarapacá sedimentary basin (Vicente, 1981). Those deposits outcrop all along the entire western Andean flank and correspond to thick series of limestones (mudstone to grainstone) and marls of the Pelado and Socosani formations (Wilson and García, 1962; Monge and Cervantes, 2000) conformably covered by the Yura Group and the Hualhuani Formation (Wilson and García, 1962; Vicente, 1981) composed of quartz sandstones and black shales interstratified. The top of the Mesozoic series is affected by an erosive discordance, overlain by volcanic and volcano-sedimentary rocks of the Toquepala Group (Bellido Bravo and Guevara, 1963; Bellon and Lefevre, 1916).

The distribution of the Cenozoic lithostratigraphic units is more complex and is related to the formation of the volcanic arc of the Andes, its successive migration and its importance in the creation of forearc, back-arc and intra-arc basins. In the Coastal Depression, deposits of sedimentary sequences accumulated, mainly of marine origin, also from the erosion coming from the proto-Andean under construction, which

generated the almost synchronous creation of the Camaná and Moquegua basins in southern Peru and Azapa in northern Chile. These interstratified sequences of conglomerates with volcanic sequences are called Moquegua Group (Thouret et al., 2007; Schildgen et al., 2007) in Peru while in Chile they correspond to the Azapa Formation (Wörner et al., 2000; Pinto et al., 2007). These sequences, which are up to 800 m thick (Bellido, 1979), are the result of erosion of the Western Cordillera and were deposited from the Oligocene to the late Miocene. From the Eocene onwards, constant volcanic events began and continue to the present day. The Huaylillas formation (Wilson and García, 1962), constitutes a wide surface that extends up to the north of Chile, where it is called Huaylillas surface (Wörner et al., 2000). This formation is a stratigraphic superposition of pyroclastic flows (Wörner et al., 2000; Mamani et al., 2010) developing a thickness between 500 and 600 m (Wilson and García, 1962; Salinas, 1985). This formation is well-preserved due to the hyper-arid climatic conditions and its top surface represents a regional paleosurface. The only forms of erosion are the incision of the valleys produced by the rivers descending from the Altiplano (Evenstar et al., 2017). The northeast is dominated by a large volume of andesites and rhyolites associated with ignimbrites assigned to the Barroso Group (Roperch et al., 2006; Mamani et al., 2010; Acosta et al., 2011), related to the magmatic activity of the Barroso Arc (Mamani et al., 2012). The Quaternary rocks are expressed by Pleistocene lava produced during a recent activity of active volcanoes (e.g. Sabancaya, Ampato, Ubinas) related to the activity of the magmatic arc (e.g. Mariño et al., 2021; Rivera et al., 2020). Quaternary deposits cover a large part of the basement and can reach a few meters thick. These deposits correspond to fluvial and alluvial deposits in the main valley and glacial deposits in high elevation areas that evidence recent climatic fluctuations.

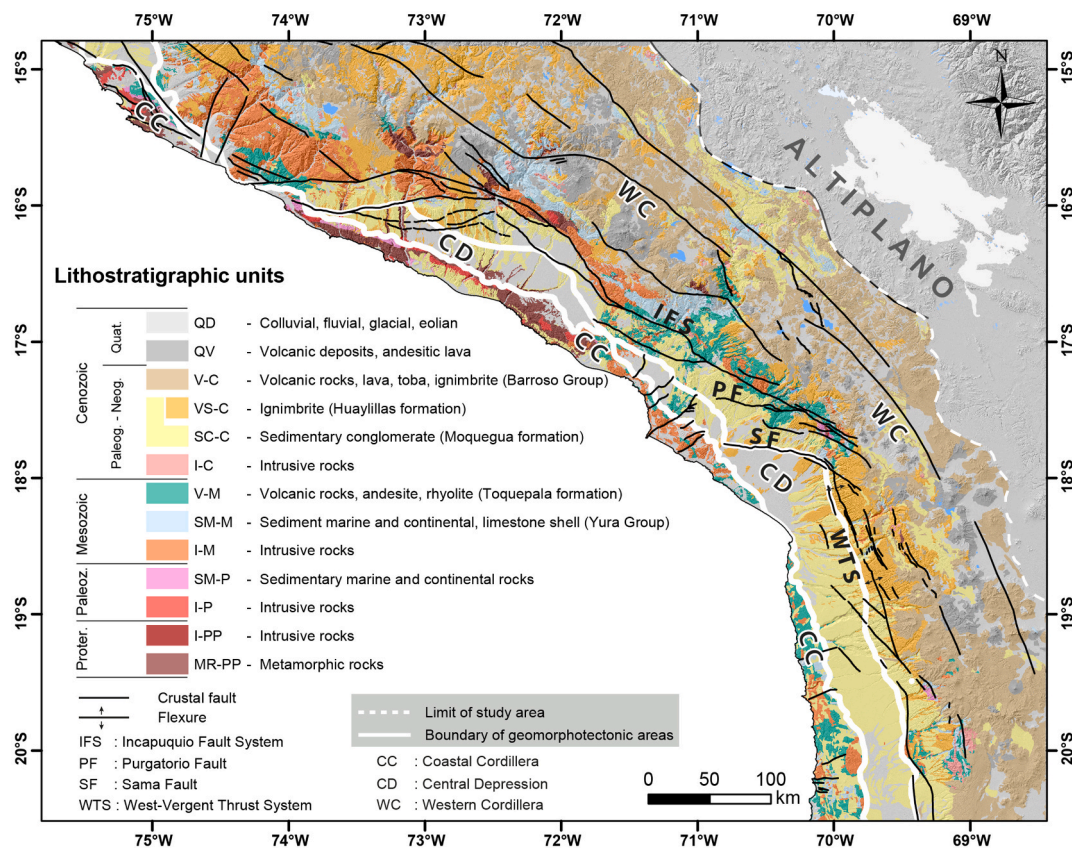


Fig. 2. Lithostratigraphy and main structural features of the Central Western Andes (adapted from <http://geocatmin.ingemmet.gob.pe/geocatmin> for Peru and <https://portalgeominbeta.sernageomin.cl/> for Chile).

2.3. Tectonic setting

Active or neotectonic faults are mostly present along the Western Cordillera area (<http://neotec-opendata.com>; <http://geocatmin.ingemmet.gob.pe/geocatmin>). The width of the Western Cordillera shows important variations being wider in South Peru than along North Chile (Fig. 1). This variation is related to the partitioning of the deformation controlled by the Nazca plate convergence toward a curved shape boundary (Arica bend) of the South American plate (Allmendinger et al., 1997). The Western Cordillera is deformed by intense folding, inverse faults and large overflows due to the shortening and thickening of the crust mainly associated with an increase in the subducted slab angle (Armijo et al., 2015).

In southern Peru, the tectonic regime is transpressive related to the activity of the Incapuquio Fault System (IFS), which extends for more than 200 km along a NW-SE direction (Fig. 2). This crustal-scale fault system displays sinistral displacement affecting mainly the Moquegua Formation and the Toquepala and Yura groups, defining a tectonic contact between them (Jacay et al., 2002). The IFS is considered potentially active as shown by the paleo-seismological studies that

revealed Holocene surface ruptures (Benavente et al., 2021). Other secondary fault systems are connected to the IFS such as: (i) the Purgatorio fault (PF), located between the Pampa Purgatorio and the village of Mirave, striking E-W along 70 km (Benavente et al., 2017b) or (ii) the Sama-Calientes fault (SF), striking E-W along ~50 km (Hall et al., 2008). Both are mainly reverse faults with a slight dextral component and have registered Holocene reactivations and surface failures (Benavente and Audin, 2009; Benavente et al., 2017b).

To the south of the Arica bend (in North of Chile) the tectonic regime becomes compressive and correlated with an important increase in the plate convergence during the last 30-20 Myr (Pardo-Casas and Molnar, 1987; Somoza, 1998). The most important structure corresponds to the West-Vergent Thrust System (WTS) located in the Western Cordillera (Fig. 2) with an N-S trending direction and extending over 450 km in northern Chile (García et al., 2004, 2013; Blanco and Tomlinson, 2013; Valenzuela et al., 2014; Morandé et al., 2015; Tomlinson et al., 2015). This main regional tectonic structure presents W-dipping high angle segments associated with the development of large folds with monoclinical geometry described as regional flexures. These structures present slight variations in the magnitude of displacement along the course

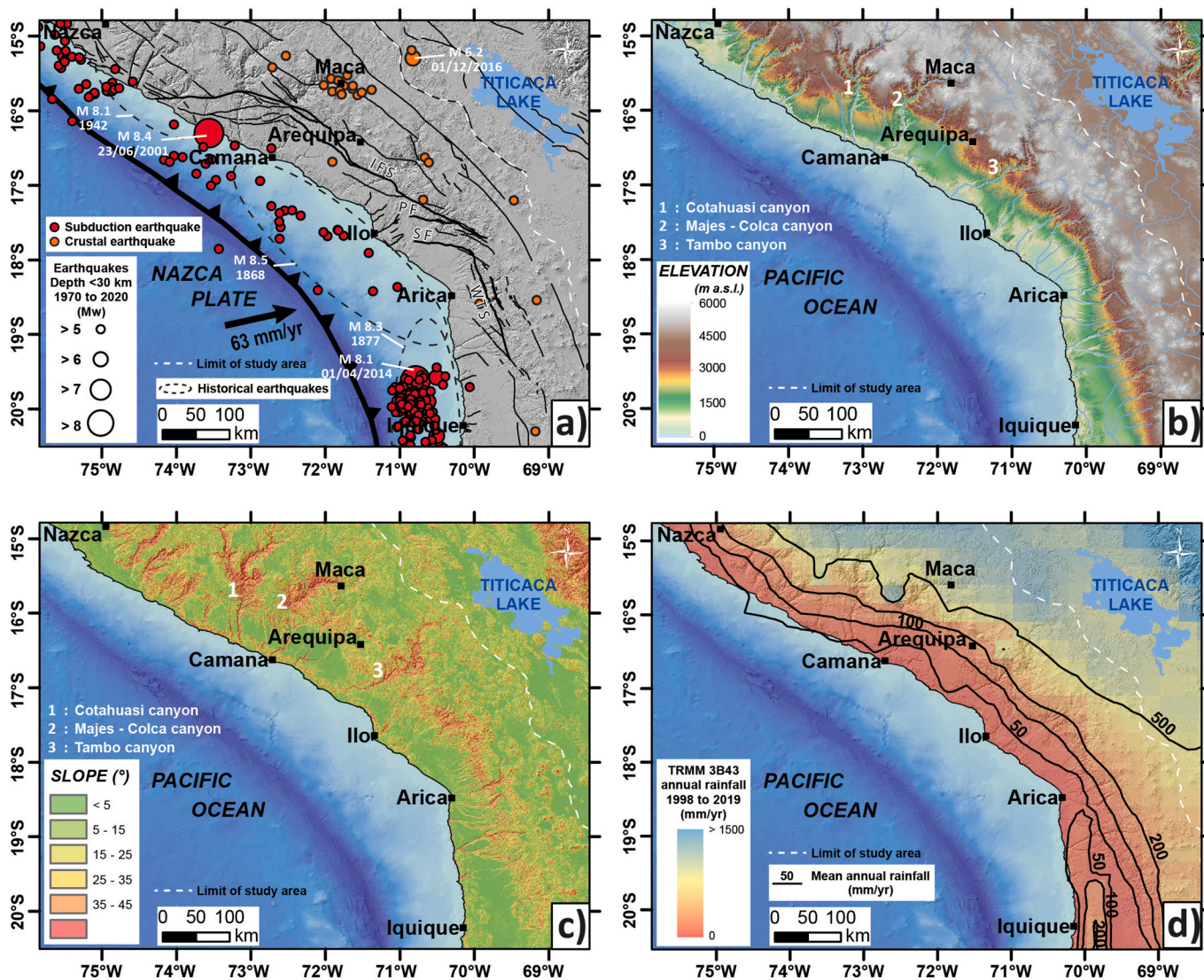


Fig. 3. Settings of the western flank of the Central Andes. (a) fault and seismicity (faults database: <http://neotec-opendata.com> and <http://geocatmin.ingemmet.gob.pe/geocatmin>; instrumental earthquakes from <http://ds.iris.edu/seismon/index.phtml> and historical earthquakes from Villegas-Lanza et al., 2016). (b) and (c) topography and slope, respectively (both derived from SRTM DEM of 30 m of resolution), (d) mean annual rainfall (TRMM 3B43 annual rainfall of the Andes averaged for the period of 1998–2019). The white dashed line marks the eastern limit of our study area.

(Pinto et al., 2004; Farías et al., 2005) and affect rocks of the Moquegua Group and the Huaylillas formation (ignimbrites).

2.4. Seismicity

The western flank of the Central Andes is affected by two types of seismic activity (Fig. 3a). The first one is related to the subduction dynamics that produce earthquakes with magnitudes that could be higher than 8, with slab ruptures of several hundreds of kilometers along the subduction zone (Villegas-Lanza et al., 2016). Recent strong subduction earthquakes include the 2007 Pisco earthquake (Mw 8.0, depth 18 km, ~100 km north to the study area), the 2001 Arequipa earthquake (Mw8.4; depth 30 km) and the 2014 Iquique earthquake (Mw8.1, depth 20 km) (Fig. 3d). Those earthquakes were also associated with swarms of seismicity and aftershocks of moderate to high magnitudes (Fig. 3a). Several historical mega earthquakes are also documented in this area (see Fig. 3a). A recurrence time between 100 and 300 years is proposed for those events for the same slab portion (Kelleher, 1972; Dorbath et al., 1990; Chlieh et al., 2011).

The second one is related to the crustal faults network. The Coastal Cordillera, Central Depression and the Western Cordillera are affected by several major faults (Figs. 2 and 3a) that experienced recent seismotectonic activity (Lavenue et al., 2000; Jacay et al., 2002; Audin et al., 2003, 2006; Barrientos et al., 2004; Lavenue, 2005; PMA, 2009; Leyton et al., 2010; Benavente et al., 2017a, 2017b). The seismic record in the study area is mainly focused on the subduction dynamics because it produces the strongest earthquakes. In contrast, the western cordillera does not benefit from a seismic network allowing the location of earthquakes at crustal-scale depth in relation to the major faults distribution (Figs. 2 and 3d). However, some seismic records over the last 50 years apart from the region of Maca (upper Colca) (Fig. 3a) have been reported that indicate moderate seismicity up to Mw5. Paleoseismological studies show that some of these faults have produced recurrent shallow seismicity during the Holocene. The analyses of the offsets along the rupture surfaces are consistent with earthquake magnitudes up to Mw7.5 (e.g. Benavente et al., 2017a; Santibáñez et al., 2019). These are some examples: the Incapuquio fault (Audin et al., 2008; Benavente et al., 2021), the Purgatorio fault (Benavente et al., 2017b), the Sama-Calientes fault (Audin et al., 2006) and the Bajo Molle fault (González et al., 2015). The length of fault failure is smaller compared to subduction earthquakes, but the energy and the ground acceleration generated by the shallow ruptures along those faults can be very strong (Benavente et al., 2017a). The recurrence period for this type of crustal seismicity is commonly assumed to be about thousand years (Leyton et al., 2010; Benavente et al., 2017b).

2.5. Topography

As shown by Fig. 3b and c, the western flank of the Central Andes is characterized by two main types of topography. First, a large wavelength topography that is directly related to the orogen formation and its evolution. This topography, with elevation ranges between 1500 and 4500 m a.s.l. forms the Western Andean flank itself, striking NW-SE in Peru and NNW-SSE in Chile, roughly parallel to the subduction trench (Fig. 3b). Steep slopes (20–30°) are found at the southern extremity of the Western Cordillera, along the main reverse faults and anticlinal-flexure growth (Fig. 3a). This large-scale wave-length topography is also revealed by a major paleosurface developed above the Huaylillas ignimbrite. This major geomorphological feature exists all along the western flank of the Central Andes (Fig. 2), characterized by a regular primitive drainage network forming a large striped surface. Its mean slope varies between 5° and 20° (mainly toward the South) depending on the local amplitude of the structural flexure and fault-propagation folds (Wilson and García, 1962). Second, a more local but stronger topography corresponds to the deep canyons that dissect the Western Cordillera. They are up to several kilometers deep in some places in

southern Peru (Cotahuasi, Majes, Tambo, see Fig. 3b and c), generating strong local relief and very steep slopes (>30°) along their flanks (Fig. 3c). The formation of those canyons started during the late Miocene and is related to the regional uplift and the specific climate of this region (Thouret et al., 2007; Schildgen et al., 2009, 2010; Gunnell et al., 2010).

2.6. Current and past climate

The Central Western Andes of southern Peru and northern Chile are part of the Atacama Desert, known as one of the driest places worldwide. Several factors are often proposed to explain this extreme lack of precipitation: (1) the mid-latitude of the region (~20°S) located along the sinking branch of the Hadley Circulation generating high pressure of dry air; (2) the oceanic Humboldt Current, characterized by upwelling of cold water along the South American Pacific coast, which cools the air near the surface and prevent moisture evaporation from the Pacific ocean (La Niña-like conditions); (3) the rain shadow effect of the Andes limiting the transfer of moisture coming from the Atlantic and the Amazonia (Houston and Hartley, 2003).

The main source of moisture is coming from the northeast, from the Atlantic Ocean and the Amazonian basin as depicted by a north-south rainfall gradient (Fig. 3d). Precipitations can reach ~1000 mm/yr in the northeastern boundary of our study area (at latitude ~15°S) and along the western boundary of the Central Altiplano (Fig. 3d). Those precipitations are seasonal, occurring mostly during the austral summer, associated with the South American monsoon regime and the seasonal southward shift of the Intertropical convergence zone above the Altiplano. Despite a little of this moisture can reach the upper part of the Pacific watersheds, the Western Cordillera, as part of the Atacama Desert, remains arid receiving less than 200 mm/yr of rain, while the coast and coastal depression receive less than 50 mm/yr of rain (New et al., 2002; Strecker et al., 2007). The hyper-aridity of the Atacama Desert, and such climatic setting, are thought to prevail since at least 10 Ma (Rech et al., 2019 and references therein), responsible for very low denudation rates over the long term (erosion <0.5 m/Ma; e.g. Hall et al., 2008; Placzek et al., 2013) and long-term preservation of landscapes. On the other hand, as the upper of the watersheds received precipitations from Amazonian moisture, the main rivers have strong erosional capacity which produced deep canyon incisions (Cotahuasi, Majes, Tambo; Fig. 3b and c) through the arid Western Cordillera.

The current meteorological conditions can be episodically modulated by El Niño Southern Oscillation (ENSO) which results in a warming of the Pacific Ocean surface related to the Trade winds carrying warm water from the eastern equatorial Pacific towards the South American coast. This can lead to very strong storms such as in March 2015, when up to 40 mm of 1-day accumulated precipitation fed the Atacama region (Bozkurt et al., 2016), triggering strong flash floods and debris flows (Aguilar et al., 2020). Despite paleoclimate records covering the Late Quaternary in the Atacama region being rare and often discontinuous (e.g. Bartz et al., 2020), some evidences of past humid phases has been also reported. They included widespread pluvial stages termed the Central Andean Pluvial Event (CAPE, e.g. Quade et al., 2008; Gayo et al., 2012) recorded as lake extensions and glacier advances in the Central Atacama of Northern Chile. Records of flash floods and debris flows linked to paleo-El Niño events have been reported during the late Pleistocene in Southern Peru (e.g. Keefer et al., 2003). Then evidences of more persistent humid conditions related to ENSO-like climate configuration during the last interglacial periods are recorded as paleolakes extensions (e.g. Ritter et al., 2018; Placzek et al., 2013) and fluvial terraces aggradation in the valleys (Steffen et al., 2010; Litty et al., 2016). Those humid events are thought to have persisted over millennial to pluri-millennial periods (i.e. the Ouki Event (100–120 ka), Placzek et al., 2013; Ritter et al., 2019).

3. Methods

3.1. Landslide mapping strategy

Our main objective was to establish an inventory as exhaustive as possible of large landslides (areas >0.1 km²) along the Central Western Andes in a region bounded to the north and south by the exact latitudes 14.8 and 20.5°S, and to the west and east by the Pacific coast and the western limit of the Altiplano, respectively (Fig. 1b). As detailed here below, our landslide inventory was based on: (1) a review of previous works and mapping of landslides existing in the literature for this region and (2) a manual mapping of newly recognized large landslides based on specific geomorphologic criteria combing GIS analysis (using Google Earth and DEMs (30 m TanDEM-X and 2 m Pleiades). This mapping using remote tools was made possible by the collective expertise of our team acquired during several past field works dedicated to landslide-geomorphology-tectonic in this region for a dozen years. About 10% of the landslides inventoried in this study were visited in the field, several of those being mapped in detail as already published in previous works involving our team (e.g. Zavala et al., 2013; Margirier et al., 2015; Zerathe et al., 2016, 2017; Delgado et al., 2020).

Indeed, the reviews of previous studies included individual landslide case studies (e.g. Strasser and Schlunegger, 2005; Pinto et al., 2008; Hermanns et al., 2012; Zavala et al., 2013; Margirier et al., 2015; Zerathe et al., 2016, 2017; Bontemps et al., 2018; Lacroix et al., 2015, 2019, 2020; Thouret et al., 2017; Delgado et al., 2020; Gaidzik et al., 2020; Sánchez-Núñez et al., 2020). We also revised a few studies including some local landslide databases such as (Audin and Bechir, 2006 and Crosta et al., 2014 for South Peru and Mather et al., 2014 and Crosta et al., 2014 for North Chile). Following this review, we note that two main types of landslide dominate in this region (Fig. 4): (i) coherent landslides for which the slipped mass moved in only one or few packets, typically corresponding to rockslide typology, and (ii) disrupted landslides which evolve as a granular flow of rock and boulders, typically corresponding to rock avalanche typology. In order to decipher if those two landslide types may have different controlling factors, we kept this binary classification for our mapping.

Fig. 4 illustrates the specific geomorphologic criteria that we used for

mapping and classification for both cases. Importantly, a landslide phenomenon was ascribed to a site only if the formal identification of a headscarp associated to a slipped mass was possible. To the contrary, morphologies such as large erosional amphitheatres or slope-break were not mapped as a landslide if a slipped mass was not clearly identified at the scarp base. Finally, we attempted to define a qualitative state of activity for our mapped landslides, trying to distinguish between two main types (Fig. 4). First the recent or active landslides, that are known to affect human infrastructures (agricultural land, road, village, etc.), showing fresh morphologies (fresh scarp, recent river dam, etc.) and/or which are monitored and referred in published papers. Additionally, we attempted to revise each mapped landslide on the Google Earth time-lapse tools, to visually check if some surface large-scale displacements (>100 m) might occur in the last 37-years. The oldest images (from 1985 to ~2005) being of rather poor quality, only displacements of >100 m might have been detectable. Second, the ancient or paleo landslides, being typically characterized by smooth and weathered surface morphologies, partially covered by eolian sand, laharcic flows or which have been significantly re-eroded or re-incised by rivers (see also Hermanns et al., 2012).

In order to carry out the recognition and mapping of landslides as much as possible in an orderly and reproducible way, we gridded our study area (cells of 0.5 × 1°) and we explored and mapped analyzing cell by cell. The grid used is provided in the supplementary data. For each identified landslide, a polygon including the headscarp and the slipped mass was drawn (Fig. 5).

3.2. Dimensional and geological landslide parameters

Understanding the occurrence of landslides requires a thorough knowledge of their initial failure conditions. It thus requires data on the terrain morphology (elevation, slope, local relief) on which landslides has developed, on the lithology and on the morphometric characteristics of the landslide itself. For each mapped landslide, we compiled this data in a database described in detail below (Supplement, Table 1). This database was further used for statistical analysis of landslides patterns. All calculations were made using ArcGIS software and using the SRTM DEM of 30 m of resolution (SRTM, DOI:10.5066/F7K072R7). The

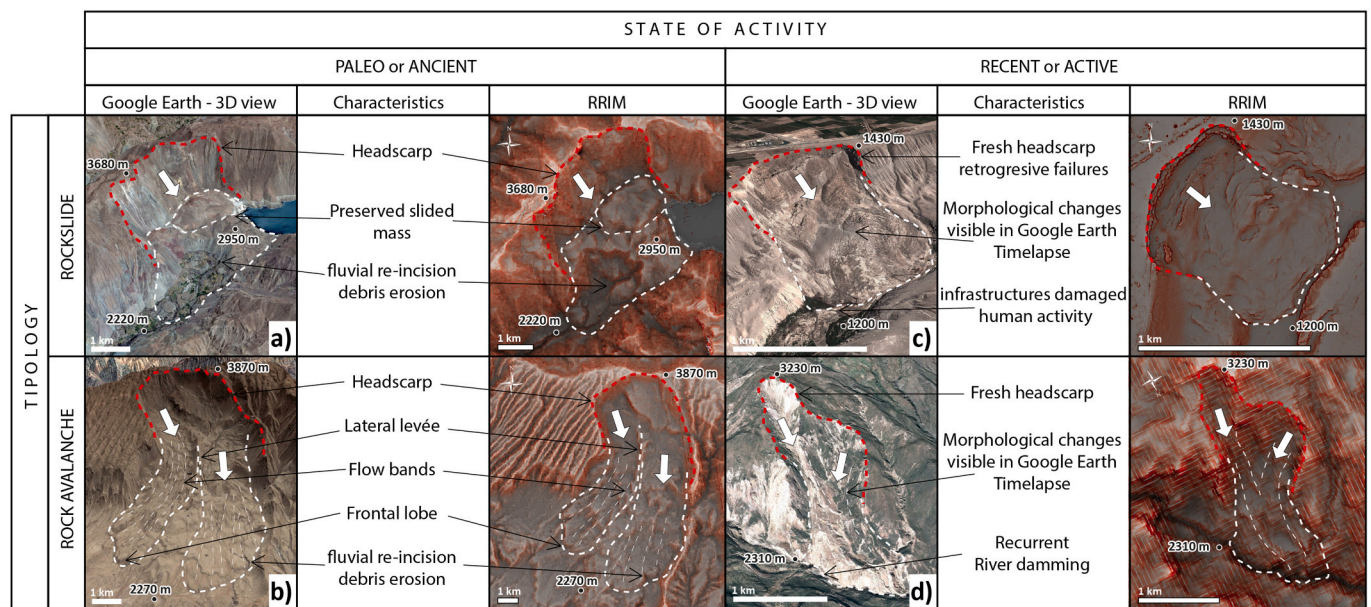


Fig. 4. Morphological criteria used for landslide recognition and mapping along the Central Western Andes. We classified the landslides according to two main typologies (rockslide and rock avalanche) and also attempted to ascribe a qualitative state of activity (paleo or recent) to each identified case (see text for details). Illustrated examples are from (a) the Aricota paleo rockslide (Delgado et al., 2020) (b) the Caquilluco paleo rock avalanche (Zerathe et al., 2017), (c) the Siguas active landslide (Lacroix et al., 2019) and (d) an active landslide from this study (landslide n° 109. RRIM: Red Relief Image Map).

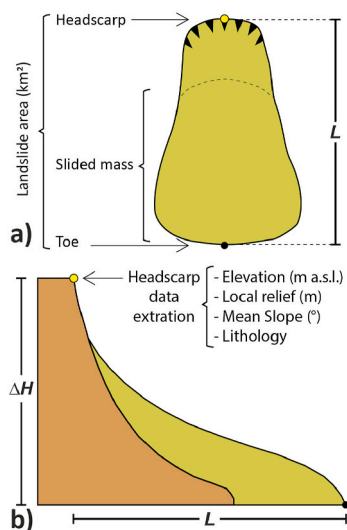


Fig. 5. Landslide sketch illustrating data collection procedure. (a) plan view and b cross-section. The green polygon delimits the whole landslide area (headscarp and slided mass). The yellow dot locates the centroid of the headscarp, considered as the origin of the landslide where several data are extracted (see text for details).

Spatial Analyst tool of ArcGIS toolbox was used to compute slope and local relief map, both calculated considering cells of 2×2 km.

For each landslide, we extracted the area (km^2) of the polygon. Then, two points were set: one located at the center of the headscarp and another one located at the landslide toe, in order to indicate the origin of the landslide and its lower limit, respectively (Fig. 5). At the location of the headscarp point, as recommended by Yilmaz and Ercanoglu (2019), we extracted the lithology in which the landslide developed following the lithostratigraphic layers defined in Fig. 2. We also extracted at this location the characteristic of the topography: the elevation (m a.s.l.), the slope ($^\circ$) and the local relief (m). Finally, using the headscarp point and the toe point, we calculated the landslide length (L in km) and the landslide height (ΔH in km).

All of these morphometric parameters are necessary to perform basic statistical analyses (histograms) of landslide properties in order to better understand their controlling factors. This involves exploring relationships that exist between landslides, topography and lithology through analyzing the frequency distribution of landslides as a function of their area, elevation above sea level, slope and lithology. Through analyzing the relationships ΔH vs L and L vs A, according to the different landslide type, we also explored the mobility of landslide masses and their dimensional properties.

3.3. Landslide spatial density analysis

The activity of landslides is conditioned by different factors among which are for instance the local relief, the slope, the geology of the site (lithology, faults, structures, etc.). In some areas, the interplay of those factors may generate higher landslide susceptibility and thus landslide clustering. In order to identify if the landslide location responds to a clustering in the western flank of the Central Andes, we applied the Ripley's K Function (Ripley, 1977). This function allows determining statistically if the phenomenon appears to be spatially dispersed, clustered, or randomly distributed throughout the study area. It has been often used to explore the spatial pattern of landslides in previous studies (Tonini et al., 2014; Görüm, 2019; Pánek et al., 2019).

Computations were done with the R software (R Core Team, 2019), using the package 'spatstat' (Baddeley et al., 2020). As recommended by Tonini et al. (2014), we applied the "Kinhom" function (Baddeley and Turner, 2005), which is a modification of the original Ripley's

K-function for inhomogeneous point distribution. This variant "Kinhom (r)" allows taking into account the non-stationarity of the studied process due to spatial variability of the geological and topographical characteristics over the studied area (Tonini et al., 2014). The Kinhom(r) function can be defined as (Marcon et Puech, 2009):

$$\hat{K}_{in\ hom}(r) = \frac{1}{A} \sum_{i=1}^N \sum_{j=1, i \neq j}^N \frac{c(i,j,r)}{\lambda(i)\lambda(j)} \quad (1)$$

where r is the radius in m, A is the studied area in m^2 , the indicator C (i,j, r) is the average number of neighbors, being equal to 1 if the distance between points i and j equals at most r, or equals 0 otherwise, and $\lambda(i)$ $\lambda(j)$ are the process density at points i and j, respectively. Theoretically, when $\text{Kinhom}(r) = \pi r^2$, the analyzed points are distributed independently (or randomly) from each other. When $\text{Kinhom}(r) > \pi r^2$, the probability to find a neighboring point at the distance r is greater than the probability to find a point in the same area at any other place, i.e. the points are aggregated. When $\text{Kinhom}(r) < \pi r^2$, the points are dispersed. Final results were plotted as the Linhom function (Besag and Diggle, 1977), which is a normalization of the Kinhom(r) function to get a benchmark at zero and to facilitate visualization:

$$L(r) = \sqrt{\frac{K(r)}{\pi}} - r \quad (2)$$

We used the centroid of the landslide headscarps (Fig. 5) as point input for the Kinhom analysis as recommended by Yilmaz and Ercanoglu (2019) and references therein. In the case of large destabilized areas ($>0.1 \text{ km}^2$), with debris that can have long run-out, the landslide headscarp centroids can provide a better assessment of the geological and topographical conditions of the landslide initiation than any other point located along the debris path or at the landslide toe for instance (Yilmaz and Ercanoglu, 2019). Finally, we used the range of radius obtained from this analysis, to calculate a kernel density of landslides over the studied area and to image the point of the higher frequency distribution of landslides.

3.4. Frequency-area relationships

We first explore the distribution of the mapped landslides according to their area using non-cumulated histograms. Then we compute frequency-area distributions (FAD), which is commonly used to explore the statistical properties of landslide inventories, to compare it with sub-datasets of the same region or with other inventories previously published (e.g. Valagussa et al., 2019). Frequency-area distributions are plotted considering landslide-area bins versus their corresponding non-cumulative frequency-density values. It has been defined by Malamud et al. (2004) as:

$$f(A_L) = \delta N_L / \delta A_L \quad (3)$$

where δN_L is the number of landslides with areas between A_L and $A_L + \delta A_L$, A_L being the area of landslide and δA_L is the width of a given landslide area class (bin). The obtained distributions are often plotted in a doubly logarithmic plot (Tebbens, 2020 and references therein). Classically applied to landslides inventoried after strong earthquakes or storms, this analysis revealed that the frequency of landslide-sizes displays a nonlinear pattern through landslide scales (see recent review in Tanyaş et al., 2019). For large to medium landslide ranges, the frequency strongly increases with the decreasing landslide areas, mimicking a negative power-law and suggesting fractal scaling. Then at a certain range of medium landslide area, the frequency area distribution generally shows an inflexion and the power-law no longer applies. Finally, a rollover is sometimes observed for the smallest landslide ranges for which the frequency decreases (Tanyaş et al., 2019).

Two main strategies and derivative interpretations of those distributions exist. Malamud et al. (2004) considered the inflexion and the rollover to represent the natural landslide distribution and proposed a fit

of the complete distribution with a three-parameter inverse gamma distribution. A second strategy (e.g. Pánek et al., 2019; Görüm, 2019) is to fit solely the tail of the distribution for medium to large landslides using a power-law above a certain cut-off value of landslide size. For landslide sizes smaller than this cut-off, the inventory is considered as incomplete. Here we applied the second strategy because we chose to map landslides starting from areas of 0.1 km² that biases the distribution for small landslide ranges. Moreover, as our inventory stack a large period of time, it is very probable that some of the smallest landslides were eroded.

First, we applied the method of Clauset et al. (2009) focusing on landslide areas only (non-binned). Using the maximum likelihood estimate, it provides the best fit of a power-law, and its exponent labelled alpha, for the landslide-areas higher than a certain cut-off value. To obtain the power-law fit of a frequency-area distribution, the exponent value is converted using the relation beta = alpha + 1 (Guzzetti et al., 2002; Clauset et al., 2009). We computed the FAD using equation (3) and applied log-spaced bins that respect two conditions: (1) a low number of bins according to the scale-range of the database and (2) to avoid empty bins.

The power-law exponent generally varies between 1.5 and 3.5 (Tanyaş et al., 2019). It reveals how much large landslides contribute to the inventory. A lower value of β value means a more important contribution of large landslides to the total inventory (Van Den Eeckhaut et al., 2007).

4. Results

4.1. Landslide inventory, typology and morphology

The landslide inventory obtained in this study is presented in Fig. 6 according to the two typologies and state of activity previously defined. The complete landslide database, including all landslide properties and a kmz file of the landslide polygons, are provided in supplementary data. In total, we have identified and mapped more than a thousand landslides distributed between ca. 15 and 20°S along the Western Central Andes, covering a total area of 3782 km² (Table 1).

Our results show that gravitational destabilizations along the Western Central Andes are dominated by rockslide typology, representing ~86% of the identified landslides while the rest corresponds to rock avalanche type (Fig. 6a). Importantly, we also show that a great majority of landslides (more than 90%) are paleo landslides. The few active

landslides that we identified are located in specific regions such as the upper Colca valley or the Sihuas region (Fig. 6b).

The landslides distribution over the three main geomorphotectonic units of the western Andean flank is summarized in Table 1. The highest percentage of landslides is found along the Western Cordillera and the Central Depression, each holding 76% and 21% of all the mapped landslides, respectively. Regarding the typologies, the Central Depression is strictly dominated by rockslide type (~99%), while the relative amount of rockslide/rock avalanche type is about 20%/80% for both the Coastal Cordillera and the Western Cordillera. We found that the Western Cordillera and the Central Depression present both about 2% of destabilized areas while the Coastal Cordillera have only 0.3% of its areas affected by large landslides.

4.2. Landslide spatial distributions

Results of the Ripley's K Function applied to our landslide database are plotted on Fig. 7 as the Linhom(r) trend for the whole landslide database (n = 1006), the rockslides (n = 866) and the rock avalanches (n = 140) group. Compared to the theoretical Linhom(r) trend for random data, those results indicate that the landslides are not randomly

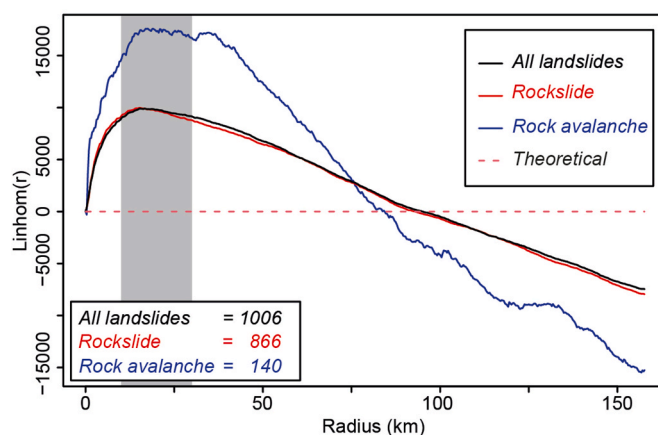


Fig. 7. Results of the Ripley's L-function for our landslide inventory. Grey bar is the range of maximum distribution frequency and is similar for the whole dataset and the two different typologies.

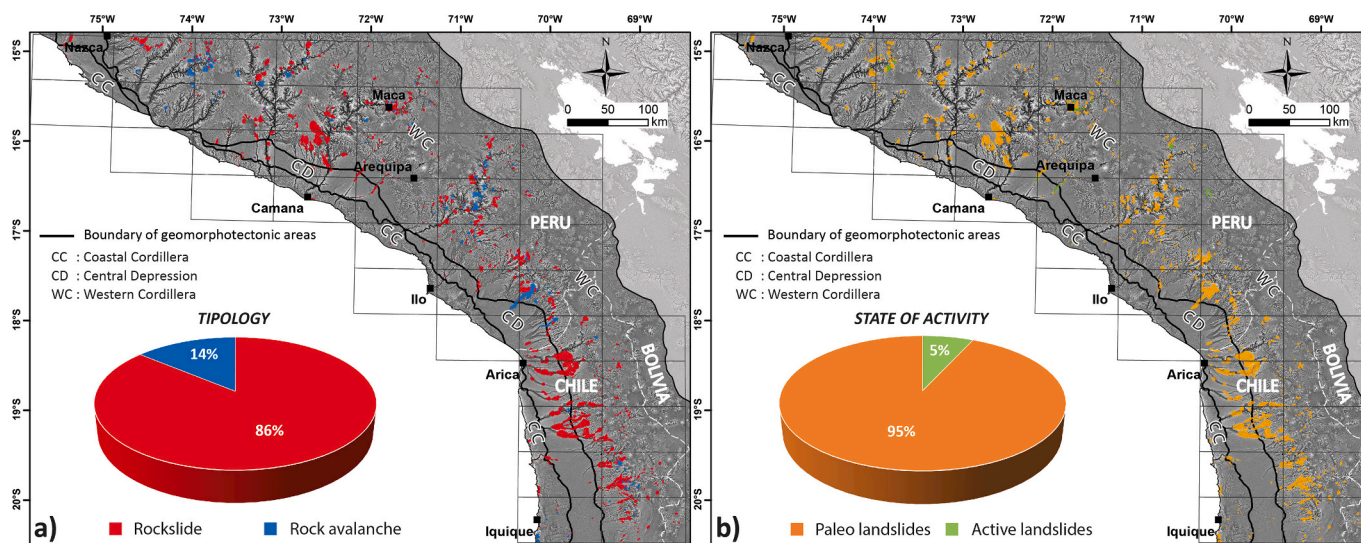


Fig. 6. Landslides inventory along the Western Central Andes between ca. 15 and 20°S. A) Distribution of landslides by typology: rockslide and rock avalanche. B) Landslides distribution according to their state of activity: recent (or active) and paleo. CC: Coastal Cordillera, CD: Central Depression, WC: Western Cordillera. The black grid corresponds to cells of 50 × 100 km that were explored one by one for the landslide mapping (see text for details).

distributed along the western Andean flank, but instead that they display some spatial clustering, with cluster radius up to ca. 100 km. The shape Linhom(r) curves are roughly the same for both the whole dataset and for each individual typology, indicating a similar spatial pattern. The maximum distribution frequency for the different datasets is reached between 10 and 30 km (Fig. 7). This range of radius corresponds to the mean radius of the aggregates of events where the highest number of landslides is found (Goreaud, 2000).

Kernel density maps of landslides were produced using a mean and conservative radius of 20 km (Fig. 8). As expected from the Ripley's K Function analysis, the spatial distribution of large landslides is not homogeneous along the Western Andean flank. Considering the whole landslide database (Fig. 8a), several clusters are revealed, the most significant ones being along the Western Cordillera zone. In particular, we note an important landslide cluster in North Chile at ca. 20°S – 69.5°W between Iquique and Arica latitudes. Three other clusters are located in southernmost Peru, 50 km northeast from Ilo at ca. 17.5°S – 70.5°W, and are aligned along a strike NW-SE. Another cluster is identified 100 km north from Arequipa at ca. 16°S – 71.5°W. This zone corresponds to the upper Colca Valley where numerous landslides have been already reported and studied (e.g. Lacroix et al., 2015). Finally, two smaller clusters are detected at ca. 15°S – 74°W and 15°S - 74.5°W, 50 km east from Nazca (Fig. 8a).

The kernel density distribution of rockslide (Fig. 8b) is similar to the one obtained for the whole database (Fig. 8a) consistently with the fact that rockslide is the dominant typology in this inventory. All the clusters previously listed also exist in the rockslide kernel density map (Fig. 8b).

Then, kernel density of rock avalanche also displays also a clustering mainly located along the Western Cordillera (Fig. 8c). The main clusters of rock avalanches coincide with some of the general clusters at ca. 20°S – 69.5°W, ca. 17.5°S – 70.5°W, and ca. 15°S – 74°W (Fig. 8c). On the other hand, several other clusters identified for the rockslide type do not appear on the kernel density map of rock avalanches. This suggests some specificities of the factors controlling the rock avalanche processes, that may be different from those controlling rockslide occurrences.

4.3. Landslide size distribution

According to the minimal landslide area considered for this inventory (>0.1 km²) all the mapped landslides fall in the category “large landslide”. The histogram of landslide areas (Fig. 9) shows a strong asymmetrical distribution with a decrease of the number of landslides function to the destabilized surface areas. About 93% of the landslides show areas between 0.1 and 10 km² (Fig. 9a). In detail (Fig. 9b), in this range, we still observe this asymmetric trend, the landslide sizes being more represented are the range 0.1–2 km², cumulating 67% of landslides. Fig. 9a evidences the absence of landslides for areas ranging between 80 and 170 km². Beyond 170 km², three giant landslides are recorded (i.e. Chuquibamba, Caquilluco and Lluta). Looking at the cumulative areas, the landslides of the range above 10 km² represent more than 50% of the total landslide area although being less represented (<7%). The 3 largest landslides are contributing alone to 10% of the total cumulative area. In Fig. 9c, it can be observed that the clusters along the Western Cordillera are dominated by landslides with individual areas smaller than 10 km² and located in the headwaters of the main basins and sub-basins. Interestingly, the three largest giant landslides previously mentioned do not belong to the previously described clusters (Fig. 8). Instead, they locate in areas with relatively low to moderate density of landslides. This might suggest that the factors controlling very large landslides are different from those triggering smaller features.

The obtained p-values of the frequency area density distribution of landslides are about ~0.5 (Fig. 10), indicating a good consistency between a power-law model and the tail of our distributions (Clauset et al., 2009). For the whole landslide dataset (ALL), a power-law can be fitted over 2 to 3 orders of magnitude of landslide areas, displaying an

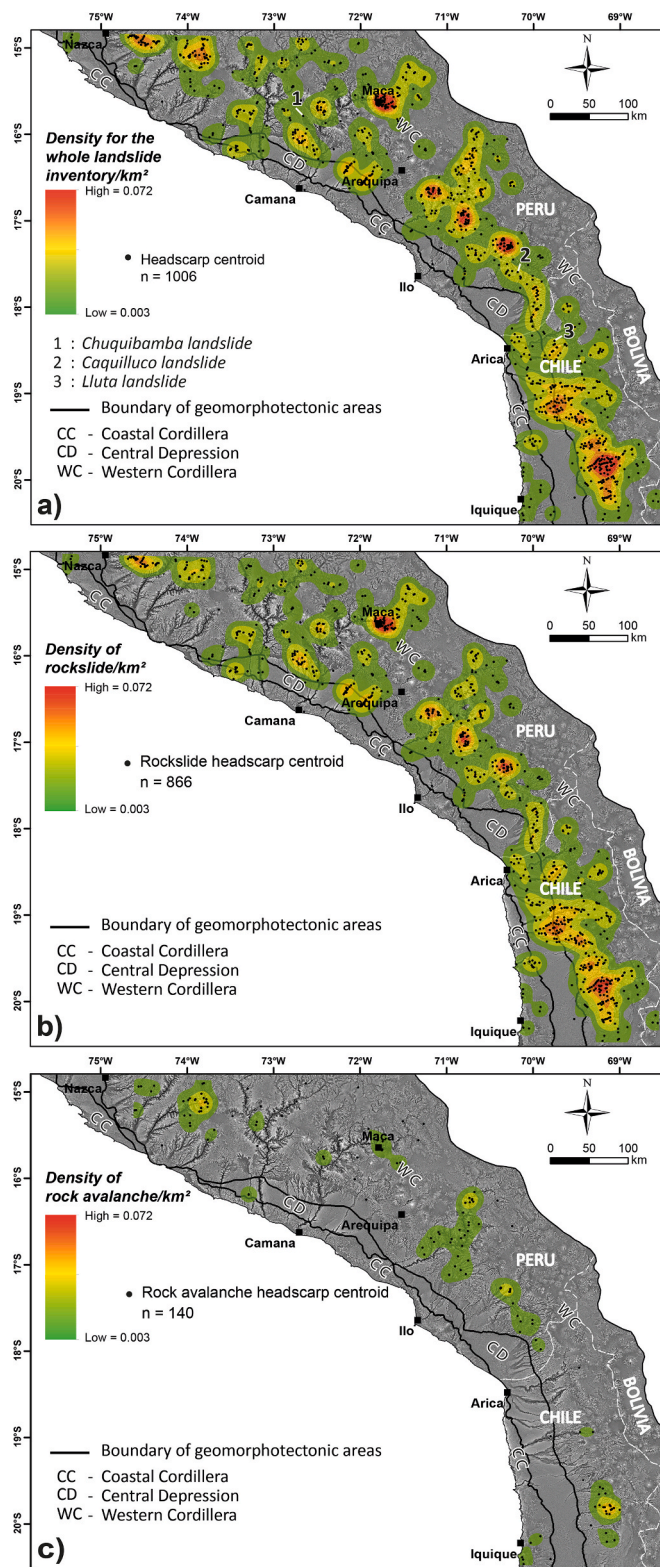


Fig. 8. Spatial distribution analysis of landslides along the western flank of the Central Andes computed through kernel density analysis using a searching radius 20 km for (a) the whole inventory, (b) the rockslide type and (c) the rock avalanche type.

exponent (beta) of 2.31 ± 0.16 and a cut-off value of $4.0 \pm 1.9 \times 10^6$ m². Considering their respective uncertainties, the best-fit parameters of the rockslide and rock avalanche sub datasets remain both almost undifferentiated with those of the whole dataset. We note that the rock

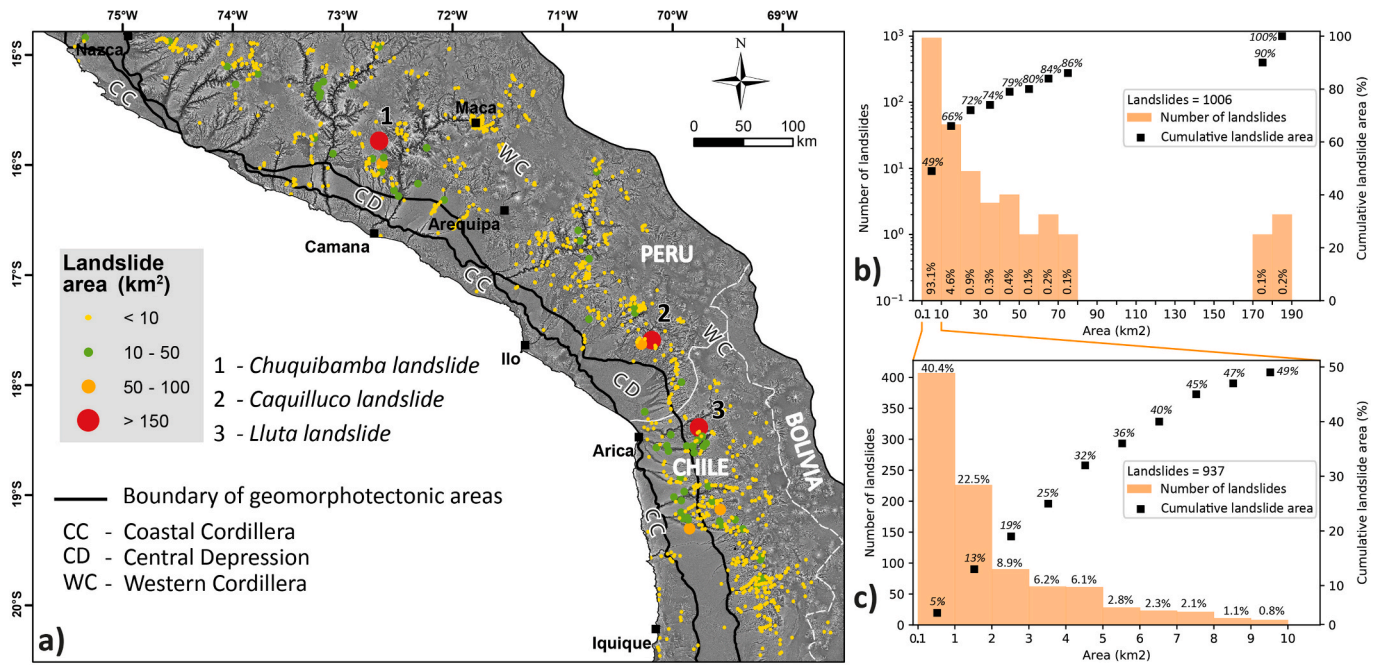


Fig. 9. (a) Spatial distribution of landslides according to their size. Histograms showing the frequency of landslide areas and corresponding cumulative areas in percentage, (b) for the whole dataset using a 10 km² bin width and (c) for the sub-range 0.1–10 km² using a bin of 1 km². CC: Coastal Cordillera, CD: Central Depression, WC: Western Cordillera.

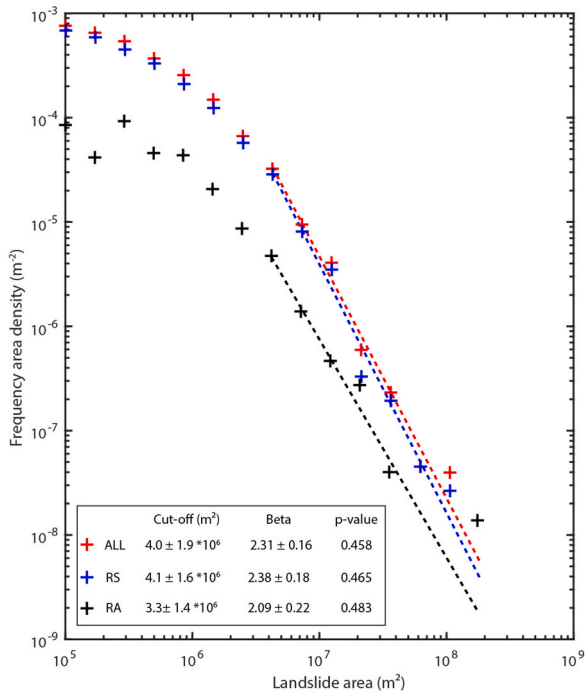


Fig. 10. Frequency area density distributions of landslides in the Central Western Andes given for the whole dataset (ALL) and the sub datasets rockslide (RS) and rock avalanche (RA). The best parameters and associated uncertainties for the power-law fit of the distribution tails are given from the method of Clauset et al. (2009).

avalanche group provides a slight lower power-law exponent (2.09 ± 0.22) which may reflect a dominance of larger landslide features in this typology.

4.4. Landslide morphometry

The analysis of morphometric parameters (ΔH , L and A) associated with the two landslide typologies (rockslide and rock avalanche) provide first order view of the respective landslide dimensions and it highlights some trends (Fig. 11). A correlation ($r = \sim 0.7$) is obtained between landslide height (ΔH) versus landslide run-out (L), for both rockslides and rock avalanches, indicating that higher is the landslide height, longer is the run-out of debris (Fig. 11a). The behavior is similar for both typologies as most of the points overlap. The maximum run-out ~ 41.3 km is obtained for a rock avalanche showing a height of ~ 3.3 km. However, medians reveal the greater size of rock avalanches, which are about two times higher in length and height than the rockslides (Fig. 11a). A good correlation ($r = \sim 0.9$) is also obtained between the landslide run-out (L) and landslide area (A) showing that larger areas are mainly explained by greater landslide lengths (Fig. 11b). Rock avalanches have median areas that are slightly lower than rockslides. Rock avalanches distribution indicates that for the same area than rockslide, rock avalanche debris can reach greater run-out, which is consistent with the highest mobility of granular flows.

5. Interpretation and discussion

5.1. Study limitations

The main limitations of this landslide inventory are the following. 1) Due to the large extension of the study area, it is likely that despite our effort some landslides have been missed during the mapping. We attached a database in .xml format and a file in .kmz format that will serve for future researchers and Peruvian and or Chilean institutions who eventually wish to complete and expand this database. 2) Due to the variability of resolution of the Google Earth images, and sometimes the difficulty leading to the identification of landslide boundaries, we consider that an uncertainty of ca. 100 m applies for the boundary of landslide polygons. This also applies to all the results derived from landslide polygons (landslide area, height, length). 3) In this study, we classified the landslides inventoried into two main categories, rockslide

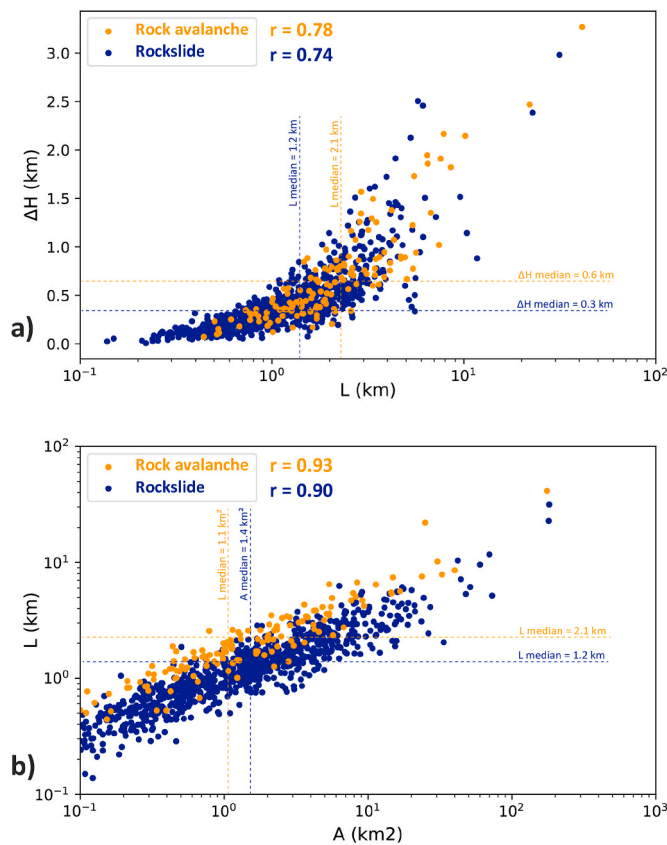


Fig. 11. Morphometric parameters of the landslides for each typology. Relationship between (a) landslide height (ΔH) versus landslide length (L) and (b) landslide length (L) versus landslide area (A). r is the coefficient of correlation of Pearson.

and rock avalanche, as identified by the literature in this region. More details about each landslide feature could be added during future studies, such as to distinguish between planar or rotational failure modes of rockslides to identify their dominant processes. 4) The state of activity of landslides was tentatively defined here according to morphological indices and criteria to differentiate between currently active (or recent) landslides and ancient (or paleo) events. However, the absolute ages of the great majority of the ancient landslides remain unknown and this should be completed with dating methods in future studies. Tracking quantitatively the activity of ongoing landslide failures also would be also very interesting but it requires a dedicated research applying remote sensing methods (e.g. InSAR), applied at a large-scale, which is far beyond the scope of the present study aiming primarily at establishing for the first time a comprehensive inventory of large landslides in the Central Western Andes.

5.2. Landslide controlling factors

In this section we discuss the primary factors that may control or influence landslide susceptibility along the western flank of the Central Andes. We perform comparisons between the landslide frequency distribution and the main settings of this area including the stratigraphy, the relief, the seismotectonic activity and the precipitation patterns.

5.2.1. Landslides versus lithostratigraphy

The type of material (e.g. rock, mud, soil, etc.) is recognized for several decades as one of the first parameters controlling landslide type and their spatial distribution (Varnes, 1978). Several authors further explored the relations between landslides susceptibility and lithology (Hansen, 1984; Guzzetti et al., 1996, 1999; Henriques et al., 2015;

Kumar et al., 2019; Kumar and Gupta, 2021) showing that landslides may vary in typology, dimension and movement rate according to the geomechanical, structural and hydrogeological properties of the material involved (Pradhan and Lee, 2010; Guzzetti et al., 1996). Identifying a specific lithostratigraphic layer prone to landslides can be also useful in terms of hazard management.

Crossing the landslide database with the unified lithostratigraphic map, we explored the relationships between landslides and lithology along the Central Western Andes. In the first order, the results show consistency between the dominant lithologies of the study area and their respective high proportion of landslides (Fig. 12 and Table 2). It concerns mainly: the Quaternary rocks, covering $\sim 27\%$ of the total area and cumulating $\sim 10\%$ of the landslides; the Paleogene-Neogene layers,

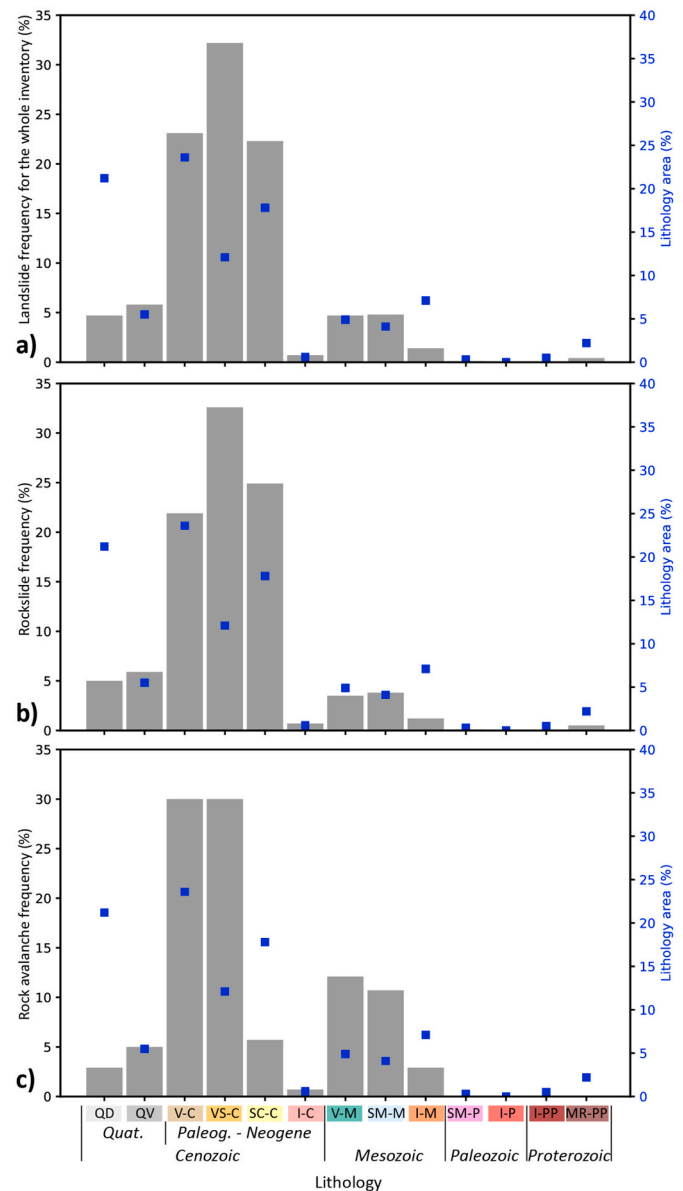


Fig. 12. a) Landslides frequency (in percent) for each lithological unit considering: (a) the whole landslide inventory; (b) the rockslide type and (c) the rock avalanche type. QD: Quaternary deposits (colluvial, fluvial, glacial, eolian); QV: Quaternary volcanic (andesitic lava, volcanic deposits); V-C: Volcanic rock (lava, toba, ignimbrite); SC-C: Sedimentary conglomerate; VS-C: Volcano-Sedimentary (ignimbrite, toba); I-C: Intrusive rocks (granite); V-M: Volcanic rocks (andesite, rhyolite); SM-M: Sediment Marine (limestone and shells); I-M: Intrusive (granite); SM-P: Sedimentary marine; I-P: Intrusive (granite); MR-PP: Metamorphic rocks.

Table 1
Main statistics of the landslide inventory.

| Geomorphotectonic areas | Surface of Geomorphotectonic area (km ²) | Number of landslides | % of landslides | Type of landslides (Number of landslides = Percentage) | Type of landslides (State of activity = Number of landslides = Percentage) | | Total landslide area (km ²) | Percentage covered by landslides (% of total area) |
|-------------------------|--|----------------------|-----------------|--|--|----------------------------|---|--|
| | | | | | Rockslide (RS) | Rock avalanche (RA) | | |
| Coastal Cordillera (CC) | 15620 | 26 | 3% | RS (20 = 77%), RA (6 = 23%) | R = 0 = 0%/P = 20 = 100% | R = 0 = 0%/P = 6 = 100% | 52 | 0.3% |
| Central Depression (CD) | 23198 | 118 | 21% | RS (210 = 97%), RA (3 = 3%) | R = 17 = 8%/P = 193 = 92% | R = 0 = 0%/P = 3 = 100% | 564 | 2.4% |
| Western Cordillera (WC) | 136033 | 862 | 76% | RS (636 = 85%), RA (131 = 15%) | R = 14 = 11%/P = 117 = 89% | R = 14 = 11%/P = 117 = 89% | 3166 | 2.3% |
| Total | 174851 | 1006 | - | - | - | - | 3782 | 2.2% |

State of activity: R: Recent or active, P: Paleo.

Table 2
Statistic of landslides versus lithology.

| | Lithology Code | Lithostratigraphic | Study area | | Landslides statistic | | | | | | | |
|--------------------|-------------------|--|--|--------------|----------------------|--------------|--------------|--------------|----------------|--------------|--------------|-------------|
| | | | Area km ² | % | All landslides | % | Rockslide | % | Rock avalanche | % | | |
| <i>Cenozoic</i> | Quaternary | QD | Quaternary Deposits: colluvial, fluvial, glacial, eolian | 37036 | 21.2% | 47 | 4.7% | 43 | 5.0% | 4 | 2.9% | |
| | | QV | Quaternary Volcanic: andesitic lava, volcanic deposits | 9560 | 5.5% | 58 | 5.8% | 51 | 5.9% | 7 | 5.0% | |
| | Paleogene-Neogene | Cumulative | | | 46596 | 26.7% | 105 | 10.5% | 94 | 10.9% | 11 | 7.9% |
| | | V-C | Volcanic: lava, toba, ignimbrite (Barroso Group) | 41126 | 23.6% | 232 | 23.1% | 190 | 21.9% | 42 | 30.0% | |
| | | SC-C | Sedimentary Conglomerate (Moquegua Formation) | 30950 | 17.8% | 224 | 22.3% | 216 | 24.9% | 8 | 5.7% | |
| | | VS-C | Volcano-Sedimentary: ignimbrite, toba (Huaylillas formation) | 21100 | 12.1% | 324 | 32.2% | 282 | 32.6% | 42 | 30.0% | |
| <i>Mesozoic</i> | I-C | Intrusive rocks: granite | 997 | 0.6% | 7 | 0.7% | 6 | 0.7% | 1 | 0.7% | | |
| | | Cumulative | 94173 | 54.1% | 787 | 78.3% | 694 | 80.1% | 93 | 66.4% | | |
| | V-M | Volcanic: andesite, rhyolite (Toquepala formation) | 8583 | 4.9% | 47 | 4.7% | 30 | 3.5% | 17 | 12.1% | | |
| | SM-M | Sediment Marine: limestone and shells (Yura Group) | 7232 | 4.1% | 48 | 4.8% | 33 | 3.8% | 15 | 10.7% | | |
| | I-M | Intrusive: granite | 12350 | 7.1% | 14 | 1.4% | 10 | 1.2% | 4 | 2.9% | | |
| <i>Paleozoic</i> | Cumulative | | | 28165 | 16.1% | 109 | 10.9% | 73 | 8.5% | 36 | 25.7% | |
| | SM-P | Sedimentary Marine | 576 | 0.3% | 1 | 0.1% | 1 | 0.1% | - | - | | |
| | I-P | Intrusive: granite | 10 | >0.1% | - | - | - | - | - | - | | |
| <i>Proterozoic</i> | Cumulative | | | 586 | 0.3% | 1 | 0.1% | 1 | 0.1% | - | - | |
| | I-PP | Intrusive: granite | 947 | 0.5% | - | - | - | - | - | - | | |
| | MR-PP | Metamorphic Rocks | 3886 | 2.2% | 4 | 0.4% | 4 | 0.5% | - | - | | |
| Cumulative | | | 4833 | 2.7% | 4 | 0.4% | 4 | 0.5% | - | - | | |

covering ~54% of the total area and cumulating ~78% of the landslides; the Mesozoic rocks, covering ~16% of the total area, are cumulating ~11% of the landslides. For the Paleogene-Neogene layers (Table 2), that are dominant in the region, we found that ~23% of landslides are located in volcanic rocks (V-C) corresponding to undifferentiated lava; ~20% of landslides located in the Sedimentary conglomerate (SC-C) corresponding to the Moquegua Formation (Fig. 12); ~32% of landslides originated in the volcanic sedimentary rocks (VS-C) corresponding to ignimbrites layers. These results logically indicate that the common occurrence of the different lithology in the study area is roughly representative of the landslide distribution. Nevertheless, a higher general susceptibility for Paleogene-Neogene volcano-sedimentary rocks (VS-C; Huaylillas formation) is shown (Fig. 12a). Those ignimbrites cumulate >30% of the inventoried landslides whereas they only represent ~12% of the study area.

Then some particularities emerge when looking at the landslide type distribution in detail. While the rockslides follow the same pattern as previously described (Fig. 12b), we observe that the rock avalanches are

more frequent in the volcanic series (Fig. 12c). The lava, toba and ignimbrite sequences of the Quaternary (QV), Paleogene-Neogene (V-C and VS-C) and Mesozoic (V-M) cumulate more >75% of the rock avalanches (Table 2). This finding can be useful for future studies dedicated to rock avalanche hazard management and call for geotechnical works to better understand why those volcanic sequences are much more prone to rock avalanches. Several previous studies reported, through field observations and data, the strong anisotropy of rock strength of the Paleogene-Neogene volcanic sequences (e.g. García et al., 2004; Strasser and Schlunegger, 2005; Pinto et al., 2008; Irwin et al., 2014) that can be a conditioning factor for landsliding. Indeed, those volcanic sequences are made of weak layers (e.g. unwelded pumice, toba, tuff, volcanic ash, epiclastic layers) alternating with much stronger ones (e.g. lava, pyroclastic flow deposits, ignimbrite) that can have a compressive strength that can be multiple times higher (Irwin et al., 2014). This anisotropy affects also the hydrogeological properties of the material, the weaker layers being much more permeable than the stronger layers (Strasser and Schlunegger, 2005). Three main hypotheses, possibly acting at the

same time, were proposed to explain the slope instabilities in this context: groundwater sapping, flood erosion of strong-over-weak stratigraphy, and the toppling of vertically jointed rock (Irwin et al., 2014).

To the contrary, rock avalanche is almost absent (<5%) from the conglomerates of the Moquegua Formation (Table 2), that is rather affected by rockslides (~25%) (Table 2). This may be due to the fact that this formation has fairly similar overall rock strength, as reported by Graber et al. (2020), in addition to being porous and permeable that can favor the development of listric failure planes and subsequent rockslides

such as the Siguas landslide (Lacroix et al., 2019, 2020).

Finally, we note that the intrusive granite and the metamorphic rocks show particularly low susceptibility to large-scale landslides cumulating only <3% of the total landslide database (Table 2).

5.2.2. Landslides versus relief

In order to explore the link between landslides and relief along the western flank of the Central Andes, we analyzed the relationship between the landslides database and elevation, local relief, mean slope and

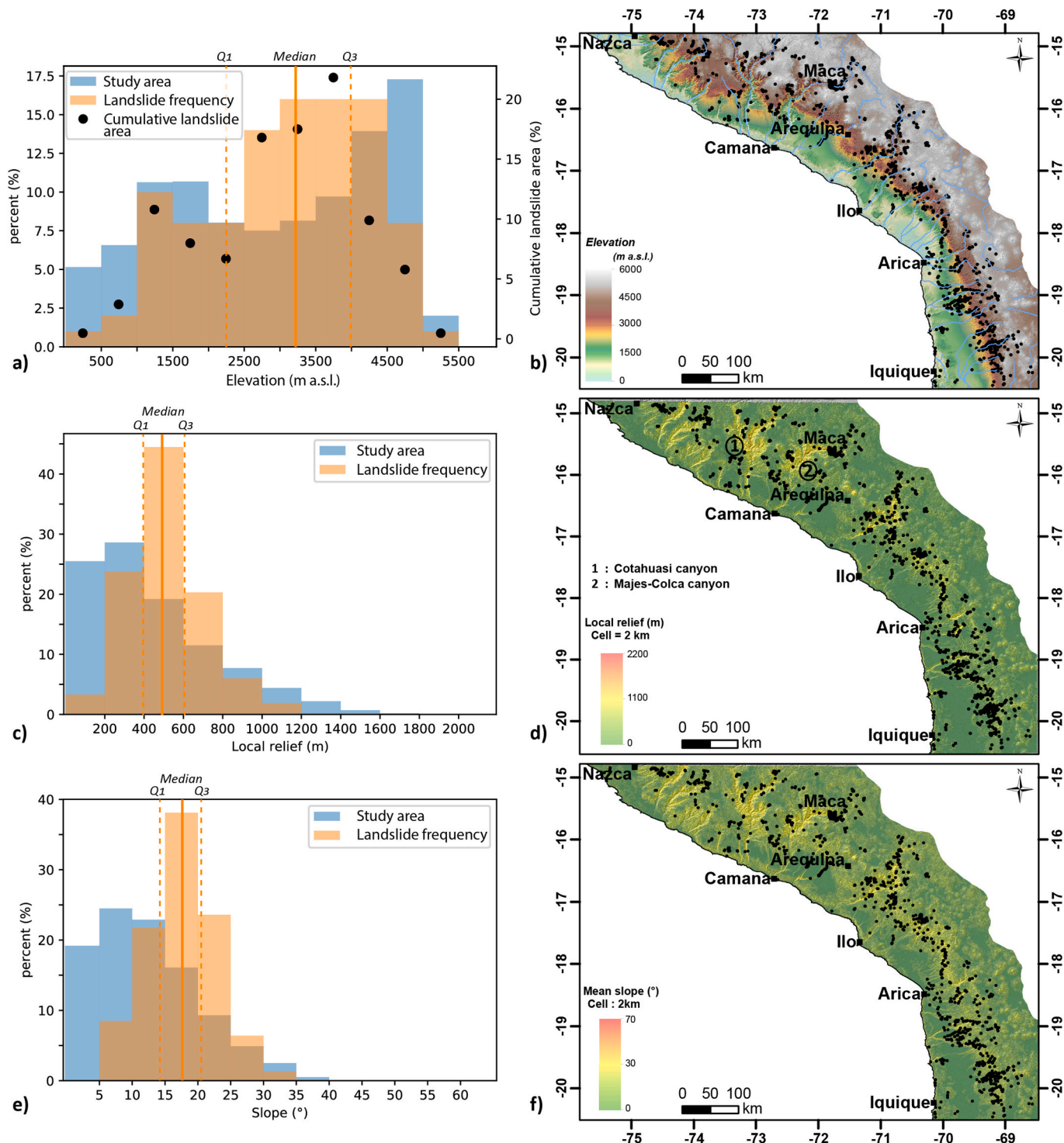


Fig. 13. Landslide statistics versus topography considering (a) and (b) landslide frequency versus elevation, (c) and (d) landslide frequency versus local relief (calculated with cells of 2 × 2 km), (e) and (f) landslide frequency versus slope (calculated with a cell of 2 × 2 km).

river locations. Most of the mapped landslides (~62%) originate in the elevation range between 2500 and 4500 m a.s.l. (Fig. 13a; Fig. 13b) corresponding to the Western Cordillera zone (Fig. 6). Another important range of concentration is between 1000 and 1500 m a.s.l., which corresponds to the Central Depression zone (Fig. 6). Analyzing the cumulative landslide area versus elevation (Fig. 13a; Fig. 13b), we found that >50% of the cumulative landslide areas are between 2500 and 4000 m. a.s.l. (Fig. 13a). This means that landslides are both more frequent and larger in this range of elevation, thus contributing more to the erosion budget. The higher landslide frequency in this elevation range may also be explained by a co-correlation with the lithology of the Western Cordillera unit, that is dominated by volcanic Paleogene-Neogene rocks, that are highly prone to destabilizations as we have previously seen (Fig. 12).

The comparison between landslides and local relief show a unimodal distribution (Fig. 12c). Very few landslides (<5%) are recorded below 200 m of local relief (Fig. 13c). More than 90% of the landslides originate between the local relief ranging from 200 to 800 m (Fig. 13c; Fig. 13d), with the highest frequency peak between 400 and 600 m corresponding to ~50% of the landslides (quartiles Q1 and Q3, Fig. 13c). Then, the frequency of landslides is lower for the greater local relief, <10% of landslides being located in range 800–1000 m. Finally, almost no landslide (<1%) are recorded for the highest local relief ranging from 1000 to 1600 m, despite that they are sharing ~8% of the total study area (Fig. 13c). Those strong reliefs (1000–1600 m) mainly correspond to the deepest and central parts of the Cotahuasi and Majes-Colca canyons, that are almost landslide-free (Fig. 13d). Looking at the mean slope of the study area, the general pattern of landslides distribution previously described is similar, ~80% of the landslides occurring between the range of 10° and 25°, with 50% of those originating on slopes between 14 and 21° (Q1 and Q3 respectively). From slopes >30°, the occurrence of landslides is minimal (<2%).

Those results slightly differ from what is commonly reported from others large landslides inventories, where an asymmetric landslide frequency versus relief (or slope) is often obtained: the highest landslide frequency being concentrated in the highest local relief (e.g. Görüm, 2019; Pánek et al., 2019; Junquera-Torrado et al., 2019). The worldwide compilation of large landslides provided by Korup et al. (2007) also shows this tendency, half of giant landslides occurring in the steepest 15% of mountainous terrain. The higher frequency of landslides in the steepest relief has been related to the threshold hillslope concept (Korup et al., 2007), predicting that above a certain hillslope-angle, or local relief, mountain flanks may fail readily because of the limitation of landscape-scale rock strength (e.g. Schmidt and Montgomery, 1995; Larsen and Montgomery, 2012; Roering, 2012).

In our study area, we interpret the almost absence of large landslides in the areas of extreme relief (1000–1600 m) as due to a lithological effect. Indeed, the deepest sections of the Cotahuasi and Majes-Colca canyons are incised through strong lithologies such as intrusive granite, metamorphic rocks and/or limestone (Fig. 2). Those lithologies having great strength, it is probable that those canyon incisions could reach such depth without occurrence of large to very large landslides. The valley flank erosion in those contexts might be dominated by debris flows, scree, which mobilize smaller volumes of rock that are not documented in this inventory. On the other hand, looking at the general spatial distribution of large landslides at the scale of the study area (Fig. 3d) and excepting the cases the central Cotahuasi and Majes-Colca canyons, we note that the landslides distribution mainly follows the river network and their incisions, where most of the local relief locates (Fig. 3c and d). This suggests that the lithological control on large landslide susceptibility might dominate, whereas the relief would come as secondary.

5.2.3. Landslides versus seismicity and active faults

The link between landslide and seismicity has been well documented by the literature in the Central Western Andes, either for earthquake-

induced landslides activity (e.g. Keefer and Moseley, 2004; Lacroix et al., 2013; Lacroix et al., 2015) or to tentatively link paleo landslide records with the seismogenic context of the Andes (e.g. Mc Phillips et al., 2014; Crosta et al., 2017; Junquera-Torrado et al., 2021). In Fig. 14, we confront the landslide density from this study to the seismicity recorded and the main active faults. To what concern the seismicity related to the subduction, there is no evidence of an increase of landslide density closer to the subduction (Fig. 14). This may be explained by the fact that landslides eventually triggered by subduction earthquakes remain relatively small (e.g. Lacroix et al., 2013). Indeed, the inventory from Lacroix et al. (2013) indicates that the ~866 landslides were triggered during the Pisco mega-earthquake (Mw8.0) were (1) relatively small, with areas ranging between 10^{-4} to 10^{-1} km²; and (2) they mostly corresponded to rockfalls and superficial topples along roads. To explain the fact that a rather low number of landslides were triggered by this Mw8.0 earthquake, while around 10^5 triggered landslides would be predicted for such magnitude (Keefer, 2002), the authors evoked (1) the attenuation of the waves due to the depth of the seismic source and its distance with the relief (>80 km), (2) the climate setting of the region, which long term aridity does not favor soil development and strongly limits the bedrock weathering and the groundwater saturation. Observations were similar for the other historical or recent mega earthquakes of subduction such as the Arequipa Mw8.4 (2001) in southern Peru or the Iquique Mw8.1 (2014) in northern Chile (Fig. 14), for which no observation of triggering, nor reactivation of large landslides (>1 km²) were ever reported (see Borrero 2002; Stirling et al., 2002; Candia et al., 2017). At the plurimillennial-scale, Mc Phillips et al. (2014) suggest a link between landslide triggering and subduction earthquakes in the Pisco region but again it concerns relatively small landslide sizes from 10^{-3} to 10^{-1} km². Those different examples strongly contrast with our mapping showing a thousand of large to giant landslides (areas up to 180 km²) that are well-preserved along the arid Central Western Andes. In summary, given the previous statements, we suggest that while the subduction seismicity can indeed trigger small to moderate superficial landslides and rockfalls, it probably plays a negligible role in forcing large-scale and deep-seated landslides in the arid conditions of the Western Cordillera. On the other hand, frequent and recurrent subduction earthquakes (Mw8 has a recurrence of 100–300 yrs; Chlieh et al., 2011) can contribute to the long-term weathering and rock damage as reported by Keefer and Moseley (2004) observing pervasive coseismic ground cracking and microfracturing of hillslope during the 2001 Arequipa earthquake.

The other source of seismicity along the Central Western Andes is produced by crustal faults activity. In Fig. 14, we confront the landslide density to the neotectonic fault network as well as to the crustal seismicity. As previously stated (62.4), no crustal shallow earthquake of Mw > 6 occurred in this region during the last fifty years. One exception is the region of Maca (Fig. 14) where a seismic swarm (Mw~5) clearly correlates with a landslide cluster. In this region landslides are very specific, developing in lacustrine sediments of a paleolake (Zerathe et al., 2016), where several studies (Lacroix et al., 2015; Lacroix et al., 2019; Bontemps et al., 2018; Gaidzik et al., 2020) already pointed the effect of frequent local earthquakes linked to the volcanic activity.

Another interesting point is the well-marked spatial correlation at large-scale between the landslide clusters and the neotectonics fault pattern (Fig. 14). This correlation can be observed (1) in Peru where several landslides clusters are aligned, from Arequipa to Tacna, with the Incapuquio Fault System (IFS); and (2) in Chile where the West-Vergent Thrust System (WTS) overlaps the main landslide clusters (Fig. 14). Several interpretations can be raised. First, those faults play an important role in the relief building (e.g. Hall et al., 2008), thus the landslide-fault correlation might be indirect, these landslide clusters being rather linked to the relief. Second, those faults are associated with thick damage zones of kilometer width, where the rock strength is decreased and the deep-water circulation along fractures is enhanced. Third, there might be a link between paleoseismicity and paleo landslide

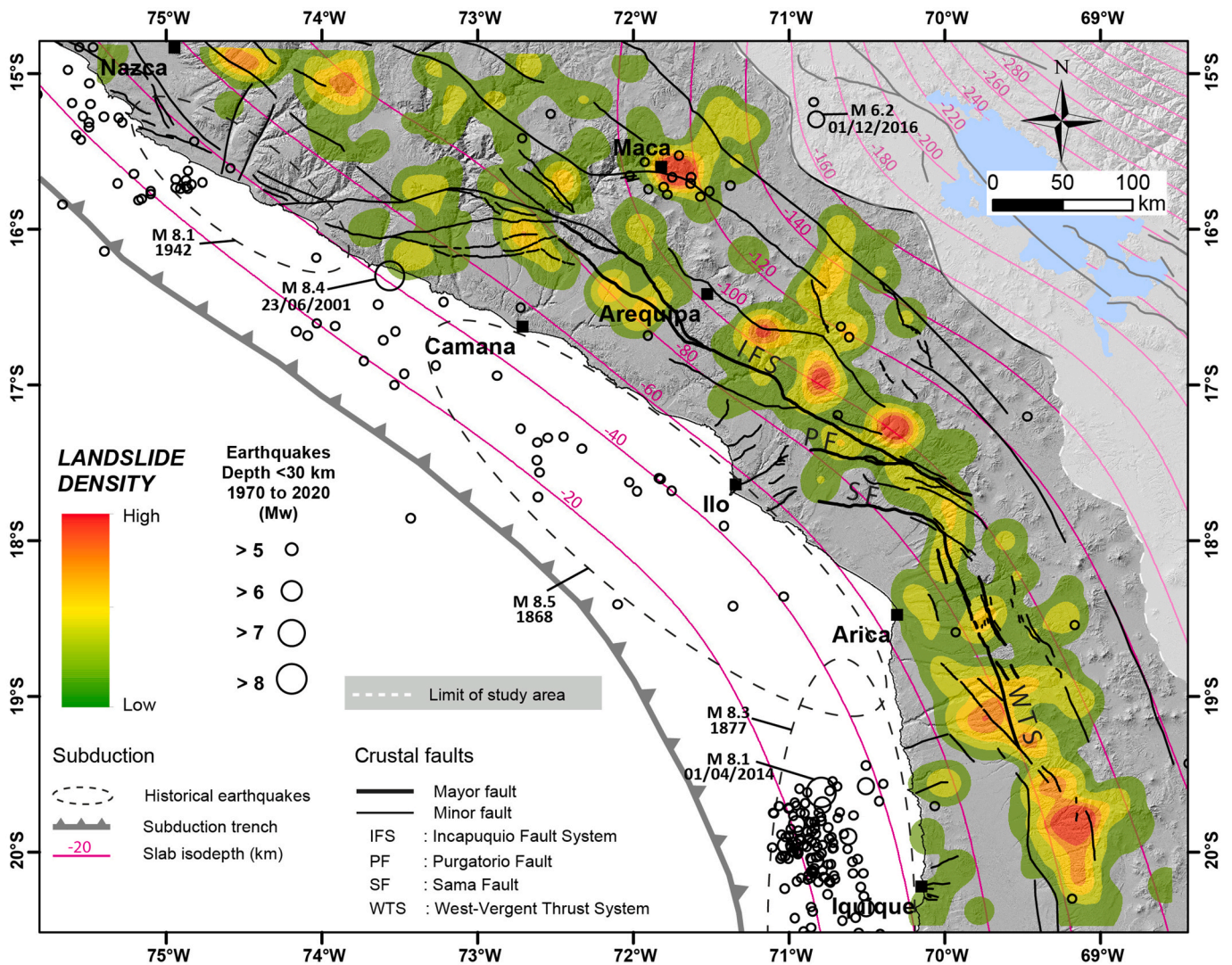


Fig. 14. Landslides density (from Fig. 8a) along the Central Western Andes confronted to the instrumental seismic catalogues for the last 50 years from USGS (earthquakes >Mw5 and depth <30 km), the available historical seismicity and to the main neotectonics crustal faults (see references on the caption of Fig. 3).

triggering. This discussion is speculative because the timing of paleo-earthquakes and paleo landslides remain largely undocumented. However, Benavente et al. (2017b) revealed that tectonic activity occurred along the Purgatorio fault in the last thousand years, showing two ruptures of ~3 and ~2 m of vertical surface offset, equivalent to seismic events of ~Mw7. Evidence of tectonic activities have been also revealed along the ~400 km long IFS (Benavente et al., 2021), where paleo-seismic trenching shows at least 2–3 m of net slip in the last 500 years interpreted as single Mw7.4–7.7 earthquake. Basically, the susceptibility that a bedrock landslide could be triggered or reactivated by an earthquake (Fan et al., 2019) depends on several parameters: (1) the local rock mass properties (linked to the lithology, frequency of fractures and joint discontinuities, etc.) and the level of hillslope stability, and (2) the local ground motion produced by the earthquake that is modulated by the distance from the source and local site effect of wave amplification (topography, lithological contrast, etc.). For crustal earthquakes, relationships between landslide size and ground motion, with larger and deeper landslides associated with higher ground motion, have been reported (Valagussa et al., 2019). Case studies of earthquake-induced landslides inventories after an event of Mw7 and beyond showed that the larger landslides (>0.1 km²) are found generally in areas where the peak ground acceleration exceed 0.5 g, in the close field of the fault (at 10–20 km of the fault) (Valagussa et al., 2019; Junquera-Torrado et al.,

2021). Therefore, it is likely that some of the inventoried large landslides in the western central Andes near the major IFS and WTS faults were triggered by past earthquakes along these faults. There is a need for more research carried out on the timing of both crustal faults and paleo landslides in this part of the Andes.

5.2.4. Landslides versus rainfall

Rainfall is the most frequent forcing and triggering factor of mass movements in mountainous areas. Physical processes related to the addition of water on or below the earth’s surface and their effects on slope instabilities are well described by hydro-mechanical models (e.g., critical soil-state mechanics and rate-and-state friction) developed from numerical theory (Iverson et al., 2000; Baum et al., 2010) coupled to laboratory experiments and confronted to in-situ landslide monitoring and statistics (Glade et al., 2000; Dai and Lee, 2001). The influence of rainfall on landslides differs substantially upon landslide type (typology, dimension, depth), the material involved (mechanical and hydrological properties) and the characteristic of the rainfall (intensity and duration). Groundwater recharge acts as a key factor for slope failures by decreasing the resistance of materials due to pore water pressure variations (Iverson et al., 2000). While shallow landslides (1–2 m depth) are usually triggered a few hours or days after the rainfall onset, depending on the time required for water infiltration and critical pore pressure

increase (Iverson et al., 2000; Baum et al., 2010), larger and deeper landslides (depth >10 m), which are the case of study in this inventory, are more likely to respond to a much longer rainfall duration (months to years). Deep-seated landslides are often in subcritical stability state and subject to long term creep deformation (Lacroix and Amitrano, 2013). These slow movements progressively increase the rock damage and the permeability, reducing the whole landslide strength, until the strain localizes along basal shear failure surfaces (Eberhardt et al., 2004) and a catastrophic collapse can ultimately occur. As shown by recent studies (Handwerger et al., 2019; Agliardi et al., 2020), the conditions for the collapse triggering are often: (1) the presence of a long-term water table water-saturating the basal shear zone; and (2) short-term pore-pressure increase linked to rapid water recharges.

Active landslides are mainly located in the northern part of the study area, where the mean annual rainfall is the highest (Fig. 15a). About 70% of the active landslides are found in areas receiving more than 400 mm/year of rainfall (Fig. 15b). This is consistent with the threshold of 500 mm/yr that have been previously documented for the triggering of the Colca landslides (Zerathe et al., 2016; Bontemps et al., 2018). On the other hand, no active landslides were identified in the desertic south-western part of the study area (Fig. 15). One exception is a group of active anthropic landslides located ~50 km west of Arequipa (Fig. 15; Lacroix et al., 2020; Graber et al., 2021) which develop along the flanks of the Siguas and the Vitor valleys (Fig. 16). They correspond actually to paleo landslides that have been re-activated for ~40 years due to irrigation water input for agricultural lands located just uphill the destabilized valley flanks (Hermann et al., 2012; Araujo et al., 2017; Lacroix et al., 2020). Recently, Graber et al. (2021) demonstrated the critical role played by the anthropic groundwater table rise for those landslide reactivations. Moreover, several other large ancient landslides of the same type are located on the opposite valley flanks and they remain inactive in the absence of irrigation on those sides (Fig. 16). This suggests that the past activation of those ancient landslides could have been linked to climatic conditions that were not the same as nowadays, much more humid, allowing local rainfall and long-term natural recharge of the water table.

At large-scale over the whole study area, the distribution of paleo landslides is not consistent with the current rainfall pattern. They

display an inverse relation with rainfall, drier being the region, higher being the paleo landslide frequency (Fig. 15c). About 70% of the paleo landslides are located in areas that currently receive less than 300 mm/yr of rainfall (Fig. 15c). This distribution might be explained by the fact that drier conditions favor long-term preservation of the paleo-landslide forms. If more humid, younger failures and erosion would have erased those relicts. However, considering the hydro-mechanical conditions required for the triggering of deep-seated landslides, it is on the other hand very improbable that those collapses occurred in such arid conditions. As shown with many examples in the literature (Odin et al., 2018) and the cases of Siguas-Vitor valleys (Graber et al., 2021), the triggering of those large landslides requires a significant recharge of water tables, that are only allowed by perennial rainfall over several months to years. Despite producing very strong storms, the intense rainfalls linked to only few days long El Niño events are very unlikely to feed such groundwater recharge. The rock-hard ground and the lack of vegetation does not allow water absorption and only lead to surficial erosion and flashfloods (Aguilar et al., 2020). On the other hand, ongoing researches on paleoclimate reconstructions in the region show that the Atacama Desert and the Central Western Andes could have experienced more long-term (years to millennial) climate variability during the Pleistocene, as recorded in alluvial fan progradation (Ritter et al., 2019, 2020), paleolake development (Ritter et al., 2019), alluvial terraces sequences (Steffen et al., 2010) and groundwater discharge deposits (Saez et al., 2016). The few giant paleo landslides that were dated have failure ages that are consistent with those events (e.g. Aricota rockslide, ~18 ka with Henrich Stadial (Delgado et al., 2020); the Chuquibamba (~100 ka) and the Caquilluco rock avalanches (100–120 ka) with the Ouki event (Margirier et al., 2015; Zerathe et al., 2017). It is probable that such persistent humid periods have produced sufficient aquifer recharge promoting the triggering of those large landslides. More dating of landslides coupled with local paleo climatic studies are required to disentangle those questions.

6. Conclusion

We report in this paper an original inventory of large landslides (>0.1 km²) along the hyper arid Central Western Andes (latitudes ca.

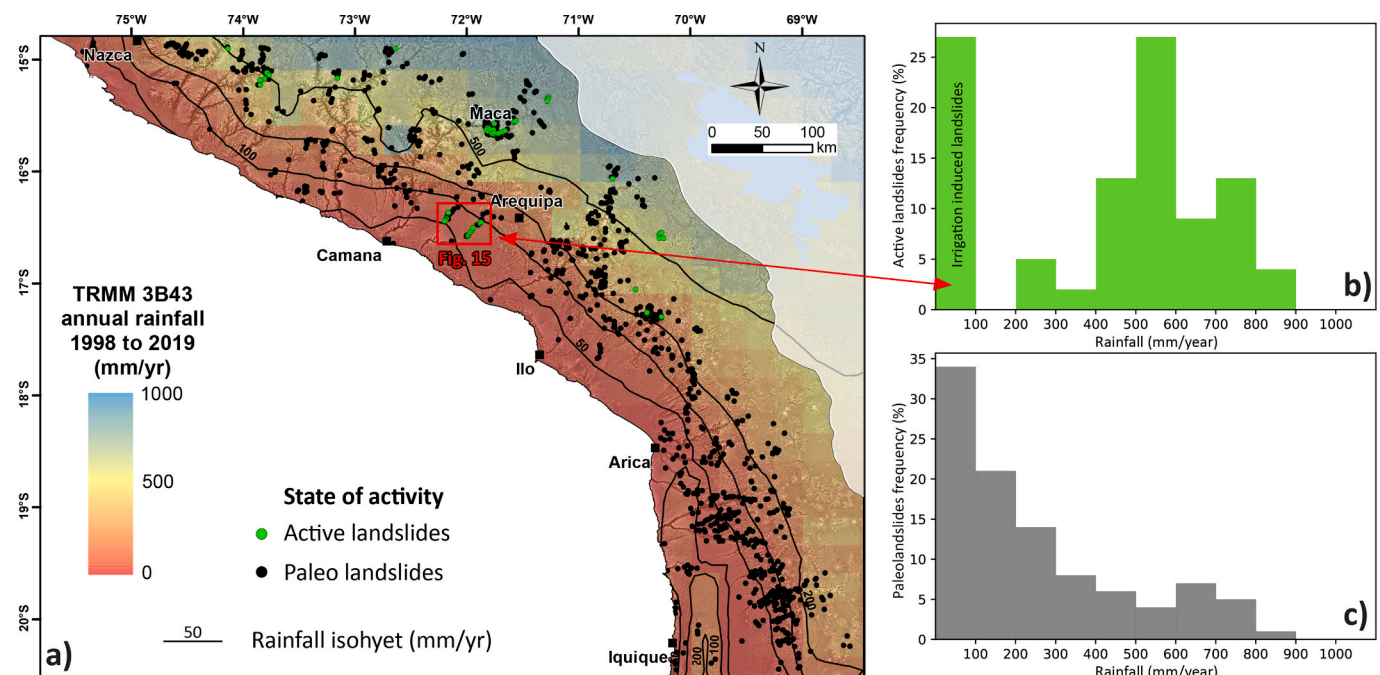


Fig. 15. a) Landslide inventory along the Central Western Andes compared to the mean rainfall of the last two decades; b) and c) Frequency of recent and ancient landslides, respectively, versus rainfall patterns.

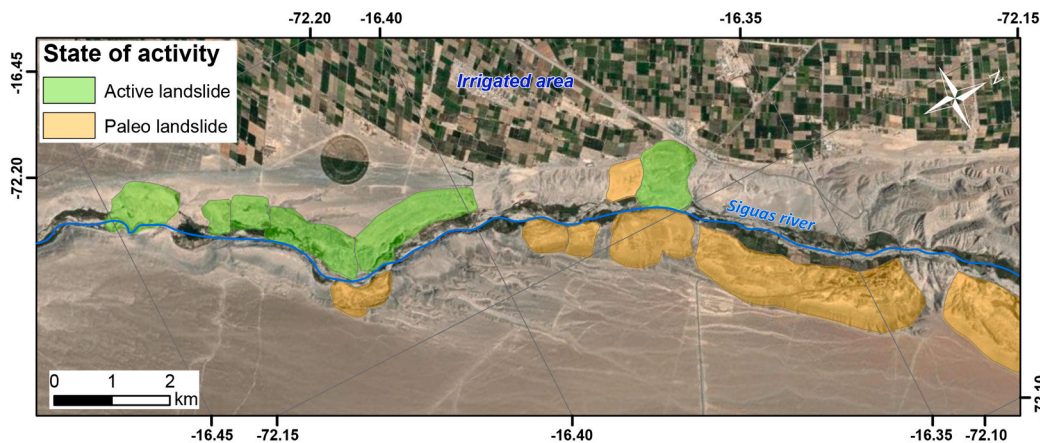


Fig. 16. Anthropic reactivation of paleo landslides induced by irrigation for agriculture along (a) the Sigüas valley modified from Graber et al. (2021). See location on Fig. 13. a. The identification of the landslides reactivated by irrigation comes from Lacroix et al. (2020) while the location of the paleo landslides is from this study. Of importance is the fact that the re-activation of those paleo landslides has need more than 40 years of constant irrigation to increase sufficiently the groundwater level, suggesting that a very different climate must have been acting there at past to produce similar conditions.

15° to 20°S). A systematic mapping of newly identified landslides by satellite images, Google Earth and DEMs analysis, added to the compilation of previous works, allows the inventory of more than a thousand large slope failures. The destabilized area covers $\sim 3782 \text{ km}^2$ and represents about 2% of the whole study area. Landslide size distribution follows a power-law with an exponent of 2.31 ± 0.16 and a cut-off of $4.0 \pm 1.9 \text{ km}^2$, the largest landslides being up to 180 km^2 in size. According to the landslide typologies, the rockslides (or coherent landslides) are the dominant failure mode representing 86% of the inventory while the rock avalanches (granular landslides) represent 14%. The statistical analysis of this landslide inventory confronted to topographical, geological constraints of this region provides first-order understanding about the main conditioning factors of slope failures in the Central Western Andes. We identified a combination of a lithological and relief effects on landslide distribution. Ignimbrites of the Paleogene-Neogene (Hualylillas Formation) concentrate about 30% of the inventoried landslides. The majority of landslides has developed along the flanks of valleys incising through the Western Cordillera. Nevertheless, the deepest areas of two major canyons (Majes-Colca and Cotahuasi) appear less prone to large landslide failure, possibly because they are incising through granite. Finally, we identified a control of fracturing and weathering related to the long-term fault activity suggested by the spatial correlation between landslide clustering and the regional crustal faults network.

This new landslide inventory provides perspectives on the respective roles of climatic and seismotectonic forcing's on the landslide activity in the Central Western Andes. Our dataset suggests that subduction seismicity play a negligible role in forcing those large landslides, while the clustered landslide distribution suggests a more efficient role of crustal seismicity. The majority of the mapped landslides corresponds to paleo landslides (more than 90%), mainly located in the driest areas (rainfall $< 300 \text{ mm/yr}$). On the other hand, the sole active landslides either anthropic, controlled by water infiltration due to irrigation, or either located in the northern part of the study area receiving rainfall from the Amazonian monsoon ($> 400 \text{ mm/year}$). We suggest that the triggering of those paleo landslides could not have been possible in the dry conditions of the Central Western Andes, even during strong earthquakes. Alternatively, the period of activity of those paleo landslides may have been related to long-term (years to millennial) climate shift toward more humid conditions during the Pleistocene, and possibly coupled to seismic effect. Next challenging researches will be to add chronological constraints on this landslide inventory to explore possible temporal correlations between periods of landslide activity and external seismic and/or climatic cycles.

CRedit authorship contribution statement

Fabrizio Delgado: Writing – original draft, Methodology,

Investigation, Formal analysis, Conceptualization. **Swann Zerathe:** Writing – review & editing, Validation, Supervision, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Conceptualization. **Stéphane Schwartz:** Writing – review & editing, Validation, Supervision, Project administration, Investigation, Funding acquisition. **Bastien Mathieux:** Investigation, Formal analysis. **Carlos Benavente:** Supervision, Project administration.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at <https://doi.org/10.1016/j.jsames.2022.103824>.

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Supplementary data: Landslides database

| | |
|------------------------------|------------------------------------|
| | |
| Codigo | Code |
| Type | Type |
| SA | State os activity |
| Area_km2 | Area |
| x_H | Headscarp_coordinate x |
| y_H | Headscarp_coordinate y |
| z_H | Headscarp_coordinate z |
| x_T | Toe_coordinate x |
| y_T | Toe_coordinate y |
| z_T | Toe_coordinate z |
| ΔH | height difference headscarp to toe |
| Strike | Direction of mass slide |
| Local_relief | Local relief value |
| Lithology | Tipe of lithology |
| Mean_slope | Mean slope value |
| GA | Geomorphotectonic area |

| Codigo | Type | SA | Area_km2 | x_H | y_H | z_H | x_T | y_T | z_T | ΔH | Strike | Local_relief | Lithology | Mean_slope | GA |
|--------|------|----|-----------|----------|---------|----------|----------|---------|----------|-------------|------------|--------------|-----------|------------|----|
| 1 | RS | P | 1.201296 | -105434 | 8350418 | 2740.324 | -106153 | 8350646 | 2467.094 | 273.230452 | 287.583450 | 564 | VS-PN | 20.59090 | CO |
| 2 | RS | P | 4.703028 | -92870 | 8349827 | 3290.625 | -94857.1 | 8350884 | 2725.168 | 565.457348 | 298.012103 | 447 | VS-PN | 17.81130 | CO |
| 3 | RA | F | 0.109949 | -110563 | 8349551 | 2560.864 | -111565 | 8350012 | 2232.066 | 230.987820 | 287.619191 | 458 | V-PN | 20.55450 | CO |
| 4 | RS | P | 0.630977 | -107846 | 8350256 | 2615.257 | -107389 | 8348658 | 2183.408 | 328.797645 | 294.700774 | 459 | VS-PN | 16.22330 | CO |
| 5 | RS | P | 1.869201 | 100388.9 | 8349730 | 4878.624 | 102280 | 8348869 | 4217.6 | 431.849715 | 164.050719 | 543 | VS-PN | 19.00840 | CO |
| 6 | RS | P | 1.757089 | -102750 | 8348990 | 2822.003 | -103811 | 8349328 | 2478.53 | 661.024561 | 114.462381 | 762 | VS-PN | 26.02950 | CO |
| 7 | RS | P | 1.696769 | -183036 | 8349175 | 614.9903 | -185368 | 8349593 | 114.0972 | 343.473011 | 287.630690 | 480 | VS-PN | 16.26890 | CO |
| 8 | RS | P | 11.425178 | -105223 | 8349041 | 2644.242 | -106322 | 8349158 | 2293.825 | 500.893102 | 280.150826 | 369 | SC-PN | 9.69144 | PC |
| 9 | RS | P | 0.960470 | -53253.5 | 8348261 | 3424.91 | -52665.6 | 8349617 | 2818.224 | 350.417809 | 276.091358 | 584 | VS-PN | 20.79770 | CO |
| 10 | RS | P | 1.554977 | 104232.7 | 8348964 | 4445.826 | 104143.4 | 8348460 | 4253.868 | 606.685904 | 23.429555 | 700 | VS-PN | 24.30400 | CO |
| 11 | RS | P | 0.511419 | -108843 | 8349278 | 2583.006 | -107887 | 8347991 | 2105.56 | 191.957793 | 190.058830 | 600 | VS-PN | 19.58700 | CO |
| 12 | RS | P | 1.526656 | -93978 | 8347696 | 3152.885 | -96255.3 | 8348952 | 2556.169 | 477.445524 | 143.383023 | 559 | VS-PN | 19.55550 | CO |
| 13 | RS | P | 4.877448 | -112503 | 8347800 | 2384.249 | -112015 | 8346893 | 2110.278 | 596.715867 | 298.870208 | 467 | VS-PN | 18.02110 | CO |
| 14 | RS | P | 0.581463 | -103216 | 8347095 | 2677.652 | -103631 | 8347202 | 2553.44 | 273.970567 | 151.705960 | 438 | VS-PN | 17.60760 | CO |
| 15 | RA | P | 0.212824 | -17284.5 | 8347568 | 3933.527 | -17220.8 | 8346764 | 3781.708 | 185.997312 | 161.735416 | 377 | V-C | 14.85550 | CO |
| 16 | RS | P | 0.289313 | 105225.6 | 8346162 | 4912.061 | 100038 | 8348255 | 4234.998 | 124.211911 | 284.454796 | 453 | VS-PN | 17.34010 | CO |
| 17 | RS | P | 0.429168 | -100646 | 8347924 | 2872.533 | -98706.6 | 8345840 | 2231.553 | 151.819060 | 175.474769 | 379 | V-C | 12.06770 | CO |
| 18 | RS | P | 15.918502 | -20751.1 | 8348005 | 4060.594 | -21553.3 | 8345168 | 3421.654 | 677.063146 | 291.968173 | 591 | V-PN | 19.14910 | CO |
| 19 | RS | P | 11.584197 | -102509 | 8346483 | 2780.404 | -102996 | 8346716 | 2594.493 | 640.979490 | 137.067614 | 469 | VS-PN | 16.56340 | CO |
| 20 | RS | P | 2.878701 | -52690.8 | 8346267 | 3617.681 | -52146.1 | 8347030 | 3425.479 | 638.939687 | 195.788052 | 578 | V-PN | 16.71040 | CO |
| 21 | RS | P | 0.233890 | 174767.5 | 8345691 | 4665.368 | 174041.7 | 8346577 | 4387.068 | 185.911568 | 295.625616 | 441 | VS-PN | 17.30190 | CO |
| 22 | RS | F | 0.278018 | -14058.8 | 8346652 | 4302.686 | -17792.1 | 8345484 | 3635.529 | 192.201763 | 35.524537 | 335 | VS-PN | 11.52930 | CO |
| 23 | RA | P | 0.448064 | -95133.5 | 8345573 | 2994.174 | -97929.4 | 8346705 | 2295.956 | 412.271182 | 162.482705 | 486 | V-C | 19.44190 | CO |
| 24 | RS | P | 0.532963 | 99194.27 | 8346527 | 4342.57 | 100138.1 | 8345697 | 3796.322 | 278.300281 | 320.654477 | 360 | V-PN | 11.61980 | CO |
| 25 | RS | P | 8.548672 | -184191 | 8345376 | 674.7746 | -186136 | 8345431 | 60.45589 | 667.156453 | 252.639972 | 579 | V-C | 17.15960 | CO |
| 26 | RS | P | 6.579523 | 173922.5 | 8344861 | 4667.896 | 173329.2 | 8345434 | 4399.758 | 698.218516 | 292.048555 | 428 | VS-PN | 16.15410 | CO |
| 27 | RS | P | 1.814730 | -38943.8 | 8345014 | 3875.259 | -40176.6 | 8344473 | 3570.655 | 546.247720 | 131.347029 | 883 | VS-PN | 22.53510 | CO |
| 28 | RA | P | 0.283544 | -97003.2 | 8343514 | 2861.385 | -99432.5 | 8345120 | 2183.503 | 286.147619 | 315.254037 | 363 | V-PN | 13.30580 | CO |
| 29 | RS | P | 4.590097 | 102941.1 | 8343410 | 4796.305 | 99342.12 | 8343670 | 3695.742 | 614.318731 | 271.605429 | 389 | SC-PN | 10.80650 | PC |
| 30 | RS | P | 0.421719 | -74199.6 | 8343257 | 3582.524 | -75003.3 | 8343248 | 3372.818 | 268.137996 | 314.016057 | 369 | V-PN | 12.75560 | CO |
| 31 | RS | P | 1.195016 | -75652.4 | 8343304 | 3534.238 | -74896.6 | 8342762 | 3341.275 | 304.603659 | 246.273818 | 415 | V-C | 13.53570 | CO |
| 32 | RS | P | 7.946723 | 41209.32 | 8341644 | 4552.276 | 40792.64 | 8343092 | 4201.515 | 677.882266 | 303.468068 | 513 | VS-PN | 16.42520 | CO |
| 33 | RS | P | 6.837753 | 37931.32 | 8342573 | 4136.428 | 38194.26 | 8342082 | 3881.087 | 1100.562490 | 274.127155 | 660 | VS-PN | 20.05000 | CO |
| 34 | RS | P | 0.585715 | -76412.7 | 8342466 | 3456.428 | -75891.1 | 8341727 | 3214.014 | 209.705915 | 269.319914 | 343 | VS-PN | 16.83580 | CO |
| 35 | RS | P | 1.464418 | -81386.9 | 8343038 | 3323.447 | -81810.4 | 8340782 | 2778.517 | 192.963271 | 125.628835 | 338 | VS-PN | 13.55460 | CO |
| 36 | RS | P | 1.469938 | 39347.88 | 8341553 | 4411.998 | 37910.9 | 8341824 | 3833.771 | 350.761242 | 343.941498 | 624 | VS-PN | 14.76990 | CO |
| 37 | RA | P | 1.234087 | -38741.9 | 8341499 | 3600.824 | -39178.4 | 8341605 | 3408.934 | 120.994209 | 176.653904 | 464 | VS-PN | 18.13380 | CO |
| 38 | RS | P | 0.152773 | -78029.7 | 8341323 | 3399.776 | -79023.8 | 8341010 | 3025.663 | 255.340102 | 151.831801 | 556 | VS-PN | 22.50620 | CO |
| 39 | RS | P | 0.988084 | -94371.1 | 8341643 | 2897.619 | -96283.8 | 8340067 | 2453.305 | 242.413706 | 144.804159 | 365 | VS-PN | 15.47590 | CO |
| 40 | RA | P | 0.675927 | -19233.4 | 8341201 | 3425.576 | -19619.5 | 8339863 | 3234.121 | 180.880983 | 288.383951 | 436 | VS-PN | 17.56020 | CO |
| 41 | RS | P | 1.927005 | -77660.8 | 8340186 | 3179.213 | -78106.8 | 8339519 | 2873.67 | 544.929855 | 190.628959 | 523 | VS-PN | 20.43610 | CO |
| 42 | RS | P | 1.591029 | -91788.5 | 8340935 | 2968.256 | -93684.6 | 8338835 | 2487.674 | 578.227089 | 280.704592 | 661 | VS-PN | 19.12940 | CO |
| 43 | RA | P | 1.901947 | -193166 | 8339989 | 351.5 | -191693 | 8339248 | 32.69329 | 333.546310 | 297.819328 | 432 | VS-PN | 14.67300 | CO |
| 44 | RS | P | 0.275794 | -88023.7 | 8339716 | 3072.75 | -87528.7 | 8338670 | 2711.033 | 191.889915 | 283.722544 | 328 | V-C | 17.68890 | CO |
| 45 | RS | P | 1.723757 | 35483.33 | 8338799 | 3809.406 | 34832.92 | 8339290 | 3350.617 | 374.113177 | 252.504981 | 509 | VS-PN | 19.71410 | CO |
| 46 | RS | P | 4.009498 | -18296.4 | 8339217 | 3282.481 | -18582.3 | 8338890 | 3122.429 | 444.314432 | 230.524562 | 452 | VS-PN | 19.07200 | CO |
| 47 | RA | P | 0.537406 | -40146.6 | 8338101 | 3527.96 | -40897.6 | 8338217 | 3308.748 | 356.394575 | 151.830166 | 659 | VS-PN | 24.03390 | CO |
| 48 | RS | P | 2.357189 | -89369.5 | 8338984 | 3091.234 | -88692.4 | 8337296 | 2565.15 | 191.455792 | 196.100493 | 216 | D-C | 8.71222 | CO |

| | | | | | | | | | | | | | | | |
|----|----|---|-----------|----------|---------|----------|----------|---------|----------|-------------|------------|------|-------|----------|----|
| 49 | RS | P | 0.294629 | -96439.4 | 8338446 | 2715.082 | -96201.2 | 8337286 | 2395.672 | 305.542792 | 213.762523 | 624 | VS-PN | 19.64150 | CO |
| 50 | RS | P | 6.214856 | -91129.4 | 8338586 | 2871.391 | -92650.1 | 8336914 | 2361.472 | 480.581045 | 222.073561 | 465 | VS-PN | 18.38910 | CO |
| 51 | RS | P | 4.195012 | -40789.1 | 8336779 | 3535.221 | -41371 | 8337137 | 3284.092 | 318.806737 | 116.744957 | 339 | D-C | 9.82940 | PC |
| 52 | RS | P | 1.737263 | -90916.7 | 8337486 | 2827.069 | -90313.7 | 8335228 | 2336.257 | 361.716470 | 154.674199 | 490 | VS-PN | 16.32060 | CO |
| 53 | RS | P | 0.290536 | -41474.6 | 8335846 | 3457.102 | -41984.7 | 8336186 | 3263.466 | 458.788599 | 307.027465 | 950 | V-PN | 25.42890 | CO |
| 54 | RS | P | 0.152763 | 103242.7 | 8336117 | 4663.223 | 100696.8 | 8335896 | 3298.66 | 160.051989 | 221.220278 | 436 | V-PN | 16.51960 | CO |
| 55 | RS | P | 0.397730 | 120541.8 | 8335328 | 4846.813 | 121025.3 | 8336162 | 4504.327 | 219.211839 | 278.758209 | 348 | V-C | 17.86900 | CO |
| 56 | RS | P | 2.252191 | -19048.6 | 8335680 | 3080.602 | -18162.5 | 8335961 | 2756.59 | 526.083514 | 158.135881 | 525 | VS-PN | 14.50310 | CO |
| 57 | RS | P | 0.752040 | -20085.7 | 8335956 | 3209.918 | -20162.4 | 8335577 | 3126.786 | 319.410291 | 168.392111 | 408 | VS-PN | 18.93910 | CO |
| 58 | RS | P | 3.788848 | -20859.7 | 8335129 | 3386.975 | -20625.3 | 8335663 | 3226.979 | 509.918890 | 222.288858 | 642 | VS-PN | 18.32460 | CO |
| 59 | RS | P | 0.251582 | 116370 | 8331740 | 4799.266 | 114615 | 8333614 | 4175.651 | 251.129236 | 301.599281 | 293 | V-C | 17.29270 | CO |
| 60 | RS | P | 6.123272 | -29103.8 | 8331769 | 3973.987 | -27919.3 | 8330518 | 3388.046 | 490.811877 | 165.045798 | 591 | VS-PN | 19.60290 | CO |
| 61 | RS | P | 0.343832 | -31794.3 | 8329787 | 3240.763 | -33057.6 | 8328762 | 2752.483 | 193.635873 | 303.657582 | 303 | V-C | 15.93510 | CO |
| 62 | RS | P | 5.427351 | -23700.7 | 8326821 | 2826.638 | -23283.6 | 8327029 | 2619.841 | 1364.562878 | 265.023119 | 805 | VS-PN | 19.46830 | CO |
| 63 | RS | P | 0.595449 | -47515.6 | 8327132 | 3221.258 | -47189.1 | 8326696 | 2985.197 | 342.485703 | 30.096273 | 436 | VS-PN | 15.56420 | CO |
| 64 | RS | P | 1.293033 | -47015.1 | 8326022 | 3245.85 | -47516 | 8326493 | 2968.686 | 324.012292 | 72.425882 | 577 | V-PN | 19.73540 | CO |
| 65 | RS | P | 0.271421 | 54658.42 | 8326629 | 4459.324 | 51939.36 | 8325111 | 3830.916 | 83.131831 | 191.406464 | 584 | V-PN | 16.09040 | CO |
| 66 | RS | P | 0.274859 | -16947.6 | 8324978 | 2667.678 | -17666.3 | 8326375 | 2123.871 | 159.995990 | 23.698783 | 500 | V-PN | 15.76410 | CO |
| 67 | RA | P | 0.298415 | -189121 | 8325549 | 435.3064 | -190193 | 8325018 | 10.56368 | 351.841382 | 285.171083 | 681 | I-M | 18.92740 | CO |
| 68 | RA | P | 5.338033 | -35591.2 | 8325628 | 2824.955 | -35702.3 | 8324813 | 2523.919 | 875.237555 | 99.293354 | 356 | V-PN | 13.56760 | CO |
| 69 | RS | P | 4.329647 | 79641.79 | 8325104 | 4057.071 | 81723.49 | 8324975 | 3284.092 | 623.614407 | 316.872790 | 418 | VS-PN | 13.85120 | CO |
| 70 | RS | P | 1.219831 | -10180.7 | 8325358 | 3254.567 | -10526.9 | 8324373 | 3050.628 | 585.940912 | 136.562754 | 619 | V-PN | 19.17910 | CO |
| 71 | RS | P | 1.472479 | 50368.72 | 8324699 | 4154.914 | 51331.25 | 8323573 | 3653.025 | 488.280077 | 230.937483 | 955 | V-PN | 20.35380 | CO |
| 72 | RA | P | 1.023405 | -35200.1 | 8324050 | 2427.242 | -34863.1 | 8323256 | 2157.091 | 756.904863 | 90.556488 | 615 | V-PN | 20.02680 | CO |
| 73 | RA | P | 5.719666 | 54287.59 | 8323205 | 4565 | 51419.47 | 8323707 | 3663.141 | 659.511241 | 84.625719 | 653 | V-PN | 16.11210 | CO |
| 74 | RA | P | 2.879746 | -35901.5 | 8323204 | 2313.989 | -35408.5 | 8323377 | 2196.494 | 1258.532780 | 338.676859 | 1076 | VS-PN | 27.50310 | CO |
| 75 | RS | P | 0.147130 | 84683.27 | 8322878 | 4274.286 | 81914.52 | 8323483 | 3019.93 | 206.796809 | 63.456349 | 656 | SC-PN | 24.80330 | CO |
| 76 | RS | P | 0.787344 | 79782.39 | 8322795 | 3350.76 | 80309.75 | 8323030 | 3074.626 | 236.061632 | 143.217034 | 343 | VS-PN | 14.31500 | CO |
| 77 | RA | P | 0.437889 | 138189.2 | 8322536 | 4487.72 | 138798 | 8322522 | 4190.213 | 575.261949 | 101.565680 | 854 | V-PN | 22.45310 | CO |
| 78 | RA | P | 0.534941 | 53519.21 | 8321758 | 4291.43 | 51485.77 | 8321675 | 3800.626 | 310.461068 | 128.791209 | 531 | VS-PN | 20.69050 | CO |
| 79 | RS | P | 0.240093 | 132651.5 | 8321032 | 4596.888 | 133504.6 | 8321636 | 4228.552 | 277.163923 | 313.285766 | 340 | SMC-M | 15.37380 | CO |
| 80 | RS | P | 6.042449 | 152690.2 | 8320247 | 4628.58 | 152947.5 | 8319124 | 4180.985 | 628.408432 | 240.819148 | 634 | VS-PN | 17.30530 | CO |
| 81 | RS | P | 1.644078 | 137251.3 | 8320182 | 4375.564 | 138002.3 | 8319146 | 4024.331 | 543.806467 | 332.768290 | 850 | V-PN | 25.30150 | CO |
| 82 | RS | P | 1.913511 | 236075.4 | 8319489 | 4307.962 | 235359.8 | 8319251 | 4176.779 | 424.742710 | 243.675876 | 612 | M-PP | 16.76290 | CC |
| 83 | RS | P | 0.359775 | 151989.9 | 8319499 | 4482.877 | 152049.5 | 8318753 | 4162.087 | 301.036171 | 187.759323 | 765 | V-PN | 22.99770 | CO |
| 84 | RA | P | 2.128280 | 78815.59 | 8318572 | 3444.545 | 80361.97 | 8316707 | 2554.209 | 1254.200971 | 251.120813 | 825 | V-PN | 26.21650 | CO |
| 85 | RS | P | 2.302908 | 237339.1 | 8317396 | 4271.774 | 236938.1 | 8316687 | 4080.994 | 772.978252 | 93.541523 | 1154 | VS-PN | 34.37200 | CO |
| 86 | RS | P | 1.768823 | 69180.36 | 8317672 | 4176.204 | 69127.01 | 8315560 | 3119.514 | 203.939183 | 199.383577 | 436 | D-C | 11.82950 | CO |
| 87 | RA | P | 1.133113 | 98437.23 | 8315755 | 4927.018 | 97866.37 | 8318317 | 3804.683 | 521.727289 | 136.110151 | 805 | D-C | 19.65460 | CO |
| 88 | RA | F | 0.853998 | 236513.6 | 8316222 | 4301.528 | 236909 | 8316723 | 4081.251 | 551.073070 | 29.592419 | 952 | V-PN | 24.39920 | CO |
| 89 | RS | P | 4.972716 | -17024.8 | 8316931 | 3180.179 | -18838.8 | 8316027 | 2600.226 | 501.888889 | 139.480427 | 601 | VS-PN | 15.20940 | CO |
| 90 | RS | P | 0.365912 | 144380.2 | 8317014 | 4413.931 | 144940.4 | 8315291 | 3901.269 | 270.150671 | 156.993349 | 621 | V-PN | 23.31640 | CO |
| 91 | RA | P | 14.890956 | 237240 | 8315748 | 4286.542 | 237760.7 | 8316500 | 4058.903 | 1020.515041 | 96.253083 | 245 | VS-PN | 6.55234 | CO |
| 92 | RS | P | 4.587543 | 238856.2 | 8315233 | 4197.544 | 238160.8 | 8315411 | 4033.264 | 901.858780 | 279.932176 | 650 | D-C | 17.94810 | CO |
| 93 | RS | P | 0.316050 | 83675.62 | 8310590 | 4075.645 | 83637.26 | 8312819 | 3064.106 | 117.494406 | 70.659303 | 551 | V-PN | 22.27210 | CO |
| 94 | RA | P | 2.528482 | 51518.22 | 8310391 | 4494.695 | 46954.77 | 8309145 | 3095.67 | 1293.105701 | 276.799686 | 760 | V-PN | 23.91090 | CO |
| 95 | RS | P | 6.429615 | 234251.5 | 8309269 | 4208.66 | 235463.2 | 8308677 | 3935.123 | 1254.355954 | 282.315352 | 726 | VS-PN | 25.37030 | CO |
| 96 | RS | P | 0.422667 | 245368 | 8309170 | 4184.964 | 245120.5 | 8308683 | 4000.622 | 276.134003 | 65.983420 | 982 | D-C | 28.54710 | CO |
| 97 | RS | P | 0.915713 | 243978.4 | 8308222 | 4332.01 | 244674 | 8309305 | 3988.877 | 297.506840 | 91.357573 | 410 | VS-PN | 15.29040 | CO |

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|-----|----|---|-----------|----------|---------|----------|----------|---------|----------|-------------|------------|------|-------|----------|----|
| 98 | RA | F | 1.664729 | 46276.07 | 8306460 | 4021.608 | 40203.6 | 8307154 | 1564.256 | 296.335585 | 22.910921 | 568 | D-C | 15.63640 | CO |
| 99 | RS | P | 4.447670 | 183977.2 | 8306069 | 4772.677 | 181821.6 | 8306083 | 4390.207 | 490.803903 | 267.681379 | 704 | VS-PN | 21.64030 | CO |
| 100 | RS | P | 1.024526 | 180649.7 | 8305622 | 4545.914 | 180959.8 | 8305007 | 4367.429 | 368.335985 | 54.729974 | 592 | V-PN | 16.43560 | CO |
| 101 | RA | F | 0.324492 | 45495.75 | 8303772 | 4001.519 | 39770.06 | 8303153 | 1496.824 | 216.421832 | 341.641408 | 568 | VS-PN | 20.96850 | CO |
| 102 | RS | P | 1.275324 | 256814 | 8303239 | 4493.254 | 257056.6 | 8302952 | 4438.262 | 447.595564 | 167.098541 | 520 | V-PN | 18.68920 | CO |
| 103 | RS | P | 1.605374 | 257725.2 | 8303386 | 4545.771 | 257206.3 | 8303205 | 4462.75 | 351.233099 | 144.080375 | 453 | VS-PN | 12.56410 | CO |
| 104 | RS | P | 0.563256 | 256592.1 | 8302629 | 4455.393 | 256875.4 | 8302670 | 4414.684 | 131.183005 | 251.637852 | 248 | V-PN | 12.23680 | CO |
| 105 | RS | P | 0.318068 | 230355.4 | 8302273 | 4377.871 | 231011.6 | 8302028 | 4106.154 | 320.789862 | 175.427392 | 545 | V-PN | 20.41730 | CO |
| 106 | RA | P | 14.590193 | 256939.5 | 8301819 | 4402.161 | 256570.8 | 8301923 | 4355.581 | 1224.661235 | 302.733386 | 524 | V-PN | 20.64610 | CO |
| 107 | RS | P | 5.884034 | 256067.2 | 8300497 | 4285.329 | 256249.5 | 8300344 | 4236.337 | 890.336090 | 140.330960 | 1533 | VS-PN | 34.18480 | CO |
| 108 | RS | P | 0.799611 | 234063.9 | 8299689 | 4385.329 | 234631.1 | 8300949 | 3946.334 | 190.780251 | 209.491697 | 371 | V-PN | 13.99830 | CO |
| 109 | RA | F | 2.195741 | 233850.1 | 8299602 | 4330.593 | 232678.2 | 8299712 | 3890.852 | 863.288565 | 14.369131 | 829 | V-PN | 23.67480 | CO |
| 110 | RS | P | 4.979148 | 31142.43 | 8296826 | 3836.137 | 33026.92 | 8298162 | 2930.219 | 1056.689733 | 181.446940 | 735 | VS-PN | 20.11030 | CO |
| 111 | RS | P | 4.542669 | 187305.6 | 8292851 | 5150.694 | 186830.6 | 8292381 | 4758.051 | 1122.335523 | 347.438880 | 598 | V-PN | 19.10830 | CO |
| 112 | RS | P | 0.574943 | 93738.09 | 8289521 | 4271.971 | 93989.48 | 8289793 | 4174.151 | 220.276440 | 38.276427 | 263 | V-PN | 12.85590 | CO |
| 113 | RS | F | 3.192477 | 223405.7 | 8289939 | 4654.311 | 222970.5 | 8289318 | 4456.832 | 579.952186 | 243.492906 | 621 | V-PN | 17.50990 | CO |
| 114 | RS | P | 3.788818 | 94342.98 | 8288830 | 4278.327 | 94799.58 | 8288771 | 3989.784 | 512.661656 | 161.993772 | 489 | V-PN | 13.93950 | CO |
| 115 | RS | P | 0.562611 | 145820.8 | 8289585 | 4360.84 | 146003.8 | 8287585 | 3500.505 | 227.639063 | 34.691301 | 306 | V-PN | 15.84960 | CO |
| 116 | RA | F | 0.389799 | 224460.5 | 8289192 | 4541.496 | 224698.7 | 8287778 | 4235.078 | 287.468285 | 92.655800 | 771 | V-PN | 23.19600 | CO |
| 117 | RS | P | 0.386933 | 243437.5 | 8288100 | 4466.234 | 242591.7 | 8288039 | 4209.595 | 164.280332 | 284.340352 | 443 | V-PN | 15.62540 | CO |
| 118 | RA | F | 8.232869 | 226259.8 | 8288515 | 4500.828 | 226317.2 | 8286756 | 4099.721 | 668.173886 | 20.453063 | 427 | V-PN | 11.97180 | CO |
| 119 | RA | P | 7.882050 | 148635 | 8287557 | 4306.552 | 146238.1 | 8287814 | 3563.895 | 776.390733 | 0.934192 | 293 | VS-PN | 8.57162 | CO |
| 120 | RS | P | 4.522505 | 92705.1 | 8287918 | 4309.232 | 93535.71 | 8286748 | 3762.939 | 1011.538431 | 359.013889 | 697 | VS-PN | 20.58100 | CO |
| 121 | RA | P | 1.147956 | -33647.4 | 8286538 | 3108.723 | -34634.5 | 8286836 | 2652.777 | 714.142676 | 121.894191 | 419 | VS-PN | 10.79000 | CO |
| 122 | RA | P | 2.346211 | 2160.089 | 8285140 | 3728.236 | 521.4614 | 8286217 | 3333.492 | 456.009433 | 215.145021 | 338 | VS-PN | 10.66610 | CO |
| 123 | RS | P | 13.491721 | 147014.9 | 8285713 | 3982.679 | 146310.5 | 8283401 | 3068.707 | 1399.025109 | 254.732673 | 800 | V-PN | 21.17130 | CO |
| 124 | RS | P | 1.105002 | 223769.7 | 8282573 | 4361.222 | 226490.7 | 8281919 | 3876.174 | 273.536309 | 116.011258 | 440 | V-PN | 18.56550 | CO |
| 125 | RA | P | 30.377200 | -28809.5 | 8281258 | 3556.97 | -30208.9 | 8280823 | 2991.282 | 2144.660333 | 317.259972 | 717 | SMC-M | 18.27480 | CO |
| 126 | RA | P | 8.410461 | 248928.6 | 8279805 | 4178.335 | 249237.2 | 8280112 | 4062.699 | 1350.972381 | 351.018197 | 637 | V-PN | 17.29630 | CO |
| 127 | RS | P | 0.222267 | 226303.2 | 8279684 | 3887.753 | 225868.1 | 8279733 | 3720.103 | 184.341999 | 206.912321 | 413 | V-PN | 18.45760 | CO |
| 128 | RA | P | 23.725368 | 224927 | 8278970 | 3769.13 | 225142.9 | 8278620 | 3695.705 | 1910.315692 | 313.785284 | 856 | VS-PN | 23.22430 | CO |
| 129 | RS | P | 1.032415 | 224292.4 | 8278594 | 3743.898 | 224435.1 | 8278239 | 3688.362 | 343.132818 | 32.720190 | 527 | V-PN | 19.71040 | CO |
| 130 | RA | P | 5.369880 | 196990.2 | 8278710 | 4434.897 | 195804.2 | 8277704 | 3734.008 | 1858.938075 | 350.826435 | 481 | SMC-M | 18.39720 | CO |
| 131 | RS | P | 17.263940 | 207789.5 | 8278440 | 4834.211 | 208930.7 | 8277573 | 4440.815 | 2457.351753 | 276.524798 | 789 | V-PN | 23.47990 | CO |
| 132 | RS | P | 2.959800 | 250914.3 | 8276967 | 4348.145 | 251661.5 | 8277397 | 4153.472 | 382.470000 | 270.359128 | 247 | V-PN | 8.53190 | CO |
| 133 | RS | P | 0.352467 | 207469.2 | 8277517 | 4722.362 | 208515.1 | 8276028 | 4277.711 | 178.484589 | 153.229796 | 250 | V-PN | 13.63370 | CO |
| 134 | RS | P | 20.076121 | 171325.2 | 8278960 | 4177.765 | 175136.1 | 8275318 | 2051.692 | 2504.695448 | 263.827144 | 972 | VS-PN | 24.08870 | CO |
| 135 | RS | F | 0.161073 | 206950.1 | 8276391 | 4561.015 | 207793.3 | 8276480 | 4377.509 | 54.992571 | 139.813244 | 256 | SC-PN | 9.44049 | CO |
| 136 | RS | F | 0.380182 | 197224 | 8276739 | 4058.145 | 197628.3 | 8276038 | 3580.181 | 83.020918 | 250.824723 | 262 | D-C | 8.63545 | CO |
| 137 | RS | P | 0.100766 | 218977.6 | 8277422 | 4357.352 | 219742.7 | 8275167 | 3843.588 | 40.709151 | 81.885480 | 259 | SC-PN | 9.19819 | CO |
| 138 | RA | P | 0.787781 | 203400.3 | 8275258 | 4449.26 | 201923.3 | 8275616 | 3880.381 | 726.310491 | 124.894574 | 673 | V-PN | 19.05600 | CO |
| 139 | RS | P | 0.147043 | 180531.1 | 8275954 | 3740.992 | 177245.7 | 8274938 | 2120.841 | 271.717142 | 110.475135 | 671 | SC-PN | 18.72800 | CO |
| 140 | RS | F | 0.235271 | 253287.2 | 8274569 | 4423.379 | 254193.6 | 8275105 | 4223.336 | 46.579997 | 285.758522 | 301 | D-C | 9.49061 | CO |
| 141 | RS | P | 0.143810 | 196706.3 | 8274675 | 3601.083 | 197023.8 | 8273983 | 3176.081 | 48.992405 | 130.035061 | 235 | SC-PN | 9.38184 | CO |
| 142 | RS | P | 1.470295 | 208208.9 | 8274615 | 4310.582 | 209157.1 | 8273421 | 3988.717 | 438.994745 | 24.237126 | 518 | V-PN | 19.35550 | CO |
| 143 | RA | F | 0.100093 | 196507.9 | 8273461 | 3142.912 | 195926 | 8273362 | 3075.481 | 112.593786 | 275.321572 | 243 | SC-PN | 9.81333 | CO |
| 144 | RS | P | 0.604462 | 207771.3 | 8272629 | 4231.749 | 208826.5 | 8272774 | 3844.572 | 439.740420 | 275.336013 | 599 | V-PN | 20.30490 | CO |
| 145 | RA | P | 11.349585 | 205778.7 | 8272890 | 4130.131 | 206527.5 | 8271600 | 3794.227 | 1945.842333 | 263.682220 | 723 | V-PN | 20.58410 | CO |
| 146 | RS | P | 3.967520 | 198539 | 8272168 | 3273.099 | 197569.2 | 8271321 | 3063.227 | 905.917558 | 54.655353 | 720 | V-C | 17.67320 | CO |

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|-----|----|---|-----------|----------|---------|----------|----------|---------|----------|-------------|------------|------|-------|----------|----|
| 147 | RA | P | 14.502745 | 217972.9 | 8271470 | 4053.696 | 217026.1 | 8271336 | 3629.954 | 1728.941448 | 281.119148 | 928 | V-PN | 23.39420 | CO |
| 148 | RA | P | 9.145784 | 207375.8 | 8270957 | 4084.584 | 206335.2 | 8271352 | 3732.378 | 878.460536 | 267.479823 | 606 | SMC-M | 19.70360 | CO |
| 149 | RS | P | 0.303164 | 103953.8 | 8271043 | 4692.159 | 103214 | 8271202 | 4466.995 | 392.643163 | 225.305801 | 557 | V-PN | 21.94100 | CO |
| 150 | RA | P | 0.466853 | 197593.3 | 8270278 | 3392.715 | 197615.3 | 8271250 | 3057.011 | 469.970000 | 224.782308 | 522 | V-PN | 21.41680 | CO |
| 151 | RA | P | 3.043534 | 200946.2 | 8271674 | 3377.398 | 200739.3 | 8269592 | 3136.561 | 412.579918 | 218.855035 | 530 | SMC-M | 18.42510 | CO |
| 152 | RS | P | 0.107082 | 207582 | 8270765 | 4091.158 | 209056.7 | 8270289 | 3595.464 | 97.820587 | 42.730120 | 354 | VS-PN | 10.85060 | CO |
| 153 | RS | P | 0.837944 | 202770.7 | 8270473 | 3320.824 | 202750.1 | 8269403 | 3176.41 | 197.478513 | 215.052408 | 350 | SC-PN | 11.06810 | CO |
| 154 | RS | P | 0.461724 | 204640.8 | 8270459 | 3507.902 | 204530 | 8269387 | 3203.533 | 288.543755 | 97.382362 | 441 | V-PN | 19.59920 | CO |
| 155 | RS | P | 2.923815 | 199608.8 | 8269490 | 3356.316 | 199823.5 | 8270059 | 3108.574 | 860.334443 | 174.774812 | 646 | V-PN | 16.72890 | CO |
| 156 | RS | P | 1.919721 | 127405 | 8269939 | 3674.19 | 127539.6 | 8269203 | 3301.685 | 306.417872 | 170.438620 | 406 | SC-PN | 12.31490 | CO |
| 157 | RS | P | 0.521562 | 215889.8 | 8269862 | 3493.675 | 215814.6 | 8269177 | 3355.252 | 256.638262 | 265.833917 | 743 | V-PN | 21.83520 | CO |
| 158 | RS | P | 1.255203 | 132978.9 | 8269446 | 4243.968 | 133007.2 | 8268625 | 3883.807 | 401.107054 | 178.131927 | 401 | SC-PN | 14.59460 | CO |
| 159 | RS | P | 3.361962 | 131699.9 | 8269251 | 4123.218 | 131642.4 | 8268178 | 3598.46 | 742.657807 | 276.112290 | 823 | SMC-M | 26.69110 | CO |
| 160 | RS | P | 1.540374 | 203303.1 | 8266902 | 3500.037 | 203541.4 | 8269491 | 3191.258 | 546.292923 | 144.606870 | 502 | V-PN | 9.89745 | CO |
| 161 | RS | P | 0.794731 | 205988.3 | 8267735 | 3422.26 | 206079.7 | 8268818 | 3220.307 | 455.946056 | 286.802017 | 583 | VS-PN | 24.07600 | CO |
| 162 | RA | P | 3.294254 | 125476.5 | 8268700 | 3397.477 | 125629.7 | 8267614 | 2773.81 | 758.378942 | 180.732399 | 447 | SMC-M | 14.88250 | CO |
| 163 | RS | P | 2.032731 | 212975.8 | 8268485 | 3571.419 | 212749.1 | 8267474 | 3401.106 | 394.744209 | 303.335546 | 344 | I-PN | 15.59210 | CO |
| 164 | RS | P | 3.380186 | 242327.8 | 8268137 | 4567.259 | 240714.7 | 8267856 | 4154.146 | 913.972373 | 196.942742 | 702 | SMC-M | 20.09120 | CO |
| 165 | RS | P | 4.954393 | 210068.7 | 8267145 | 3392.073 | 209936.1 | 8267464 | 3276.687 | 485.048164 | 103.522169 | 509 | V-C | 14.08000 | CO |
| 166 | RS | P | 0.746547 | 209130.5 | 8266766 | 3364.352 | 209094 | 8267296 | 3274.258 | 565.688910 | 252.712582 | 832 | I-M | 25.24950 | CO |
| 167 | RS | P | 0.285262 | 198762.4 | 8266474 | 4459.024 | 200186.8 | 8266328 | 3875.386 | 115.636457 | 45.147537 | 234 | VS-PN | 11.81650 | CO |
| 168 | RS | F | 0.134840 | 200711 | 8265656 | 4421.277 | 200292.6 | 8266529 | 3834.122 | 167.649791 | 276.382732 | 604 | V-PN | 22.73270 | CO |
| 169 | RS | F | 0.314312 | 49168.38 | 8266494 | 3661.735 | 49793.54 | 8265053 | 3057.25 | 73.425069 | 148.318364 | 731 | D-C | 18.60540 | CO |
| 170 | RS | F | 0.197779 | 221844.4 | 8265104 | 4096.665 | 221030.2 | 8265409 | 3931.737 | 55.536766 | 158.109339 | 705 | D-C | 20.74940 | CO |
| 171 | RA | P | 1.050777 | 217165.8 | 8265330 | 4124.785 | 216408.4 | 8265031 | 3799.323 | 204.864030 | 246.968607 | 281 | VS-PN | 13.06580 | CO |
| 172 | RS | P | 1.538873 | 220582.6 | 8264463 | 4338.992 | 220540.5 | 8265809 | 3846.908 | 700.889700 | 229.689459 | 832 | V-C | 27.49300 | CO |
| 173 | RS | P | 1.557630 | 208519.7 | 8264996 | 3925.952 | 209108.1 | 8264622 | 3716.198 | 393.396256 | 127.211040 | 528 | V-C | 18.81450 | CO |
| 174 | RS | P | 0.483463 | 209744 | 8264208 | 3919.802 | 209250.5 | 8264725 | 3709.047 | 194.673276 | 60.086840 | 275 | VS-PN | 10.82530 | CO |
| 175 | RA | P | 1.853172 | 212056.1 | 8264308 | 3806.22 | 211534.6 | 8264531 | 3634.183 | 792.857736 | 230.186713 | 743 | V-PN | 22.03070 | CO |
| 176 | RA | F | 1.123680 | 218193.8 | 8264655 | 4387.264 | 217707 | 8264287 | 4167.804 | 436.260225 | 280.514270 | 416 | V-C | 15.59160 | CO |
| 177 | RS | P | 1.650162 | 219761.3 | 8263439 | 4555.22 | 219888.6 | 8265448 | 3870.69 | 444.650599 | 144.922671 | 520 | V-C | 18.54580 | CO |
| 178 | RS | P | 8.938608 | 124531.1 | 8263973 | 2897.189 | 125769.7 | 8264119 | 2342.455 | 2126.072868 | 133.704897 | 736 | VS-PN | 26.99730 | CO |
| 179 | RS | P | 0.600674 | 211944.4 | 8263693 | 3884.32 | 211554.7 | 8264007 | 3695.478 | 183.506324 | 83.966338 | 518 | V-C | 14.48760 | CO |
| 180 | RS | P | 0.316372 | 208852.1 | 8262224 | 4254.495 | 208370.5 | 8263914 | 3871.044 | 477.963888 | 150.050507 | 942 | V-PN | 29.03600 | CO |
| 181 | RS | P | 3.128746 | 124641.4 | 8262493 | 2748.076 | 126026.2 | 8262517 | 2182.25 | 513.764234 | 161.253480 | 659 | V-C | 16.44230 | CO |
| 182 | RS | P | 2.159490 | 128968.6 | 8262688 | 3380.383 | 126089.7 | 8261405 | 2104.371 | 568.878847 | 283.639671 | 611 | V-C | 19.26710 | CO |
| 183 | RA | P | 1.788396 | 124209.3 | 8261685 | 2713.862 | 123131.1 | 8260832 | 2129.179 | 758.032078 | 71.858534 | 641 | I-M | 29.88970 | CO |
| 184 | RS | P | 4.465404 | 81299.49 | 8259914 | 3825.994 | 79703.8 | 8257734 | 3035.992 | 1620.150738 | 252.818015 | 1271 | V-PN | 37.28790 | CO |
| 185 | RS | P | 0.783836 | 128912.4 | 8259538 | 2572.519 | 128296.1 | 8258689 | 2012.443 | 200.043402 | 59.377495 | 287 | VS-PN | 10.16290 | CO |
| 186 | RS | P | 0.272616 | 125512.2 | 8259131 | 2286.192 | 125046.5 | 8258859 | 2054.283 | 425.001481 | 155.344243 | 835 | V-PN | 29.02100 | CO |
| 187 | RS | P | 1.627275 | 133251 | 8258364 | 3137.775 | 130327.3 | 8258760 | 2235.086 | 321.865143 | 141.549405 | 452 | V-C | 13.77480 | CO |
| 188 | RS | P | 0.129157 | 88089.47 | 8258332 | 3793.621 | 87281.78 | 8258657 | 3613.469 | 67.431040 | 260.323727 | 449 | V-C | 19.09050 | CO |
| 189 | RS | P | 1.029503 | 83151.55 | 8259502 | 3939.78 | 81188.72 | 8256832 | 3018.081 | 387.177721 | 82.179941 | 484 | V-C | 19.74760 | CO |
| 190 | RS | P | 4.204162 | 27128.64 | 8257594 | 2524.596 | 27932.78 | 8257836 | 2079.433 | 335.903178 | 149.850321 | 495 | V-C | 18.20080 | CO |
| 191 | RS | F | 2.877949 | 28996.55 | 8257851 | 2626.412 | 27985.24 | 8257238 | 2008.972 | 209.872043 | 228.871944 | 434 | D-C | 11.70420 | CO |
| 192 | RS | P | 1.420015 | 134479.6 | 8257678 | 3318.079 | 132816.6 | 8256611 | 2661.812 | 423.741254 | 261.983556 | 533 | V-C | 14.47220 | CO |
| 193 | RS | P | 2.484586 | 83690.39 | 8257504 | 3647.954 | 84680.82 | 8255829 | 3271.44 | 352.206566 | 290.773359 | 384 | V-C | 18.26830 | CO |
| 194 | RS | P | 0.683460 | 45335.72 | 8256915 | 2881.693 | 46770.81 | 8255608 | 2289.946 | 225.163569 | 282.180053 | 411 | V-C | 11.15060 | CO |
| 195 | RS | F | 0.506992 | 33468.64 | 8256448 | 2533.852 | 31791.85 | 8256317 | 2008.024 | 335.704257 | 1.292082 | 866 | D-C | 24.91660 | CO |

| | | | | | | | | | | | | | | | |
|-----|----|---|----------|----------|---------|----------|----------|---------|----------|-------------|------------|------|-------|----------|----|
| 196 | RS | F | 5.162874 | 25059.37 | 8255988 | 2608.907 | 25375.85 | 8256227 | 2294.303 | 240.836586 | 185.673285 | 445 | D-C | 13.76630 | CO |
| 197 | RS | P | 2.013873 | 25482.35 | 8255570 | 2573.695 | 26198.03 | 8255991 | 2126.67 | 495.694401 | 107.910388 | 430 | V-C | 18.71290 | CO |
| 198 | RS | F | 1.038225 | 40734.83 | 8254654 | 2580.051 | 38882.44 | 8251334 | 1843.245 | 144.414141 | 181.105415 | 362 | D-C | 9.77930 | CO |
| 199 | RS | F | 1.226169 | 43818.51 | 8253513 | 2703.711 | 49374.1 | 8251528 | 1757.646 | 304.369428 | 185.899756 | 652 | D-C | 20.84500 | CO |
| 200 | RS | F | 0.434412 | 25792.5 | 8253016 | 2561.05 | 28531.99 | 8251482 | 1902.067 | 247.742181 | 20.687180 | 1127 | SMC-M | 29.44700 | CO |
| 201 | RS | P | 0.447786 | 42159.22 | 8251894 | 2590.965 | 40635.92 | 8252369 | 2135.748 | 372.505294 | 169.642672 | 784 | V-C | 28.02940 | CO |
| 202 | RS | F | 0.562492 | 24664.16 | 8249257 | 2569.595 | 27364.83 | 8249355 | 2018.088 | 138.423038 | 186.261077 | 537 | D-C | 15.27730 | CO |
| 203 | RS | P | 0.979345 | 90427.86 | 8248406 | 3496.313 | 87841.53 | 8248422 | 2959.987 | 360.160850 | 178.029301 | 1200 | D-C | 28.52080 | CO |
| 204 | RS | P | 1.413607 | 225001.1 | 8246548 | 4418.642 | 223992.8 | 8246543 | 4200.775 | 524.757833 | 183.066720 | 1192 | SMC-M | 25.18450 | CO |
| 205 | RS | F | 7.766861 | 41292.8 | 8246473 | 2324.801 | 39150.09 | 8245437 | 1667.689 | 308.778927 | 5.258170 | 952 | D-C | 22.93000 | CO |
| 206 | RS | F | 1.697080 | 91217.61 | 8245642 | 3588.666 | 89682.56 | 8245602 | 3242.908 | 201.952911 | 4.823330 | 494 | V-PN | 14.50340 | CO |
| 207 | RS | P | 0.649935 | 153544.7 | 8245309 | 3708.528 | 150487.5 | 8242632 | 2256.742 | 623.666904 | 171.964832 | 1004 | V-C | 33.15260 | CO |
| 208 | RS | F | 0.603841 | 135000.2 | 8242678 | 1607.129 | 135037.7 | 8244018 | 947.7973 | 170.313186 | 192.642223 | 539 | D-C | 14.90870 | CO |
| 209 | RS | P | 3.004586 | 225415.6 | 8242803 | 4755.873 | 223800.6 | 8243272 | 4063.924 | 413.113602 | 260.136247 | 334 | V-PN | 9.43726 | CO |
| 210 | RA | P | 2.333267 | 107014.3 | 8251371 | 3684.882 | 128227.8 | 8228113 | 701.9663 | 784.738894 | 164.234667 | 492 | VS-PN | 13.16610 | CO |
| 211 | RS | F | 0.245642 | 62213.96 | 8237910 | 1537.007 | 58153.48 | 8237582 | 496.2423 | 115.386342 | 337.439365 | 465 | D-C | 16.12420 | CO |
| 212 | RS | F | 0.377749 | 8184.637 | 8237496 | 1748.566 | 7605.538 | 8236770 | 1389.975 | 90.094374 | 356.060545 | 592 | V-PN | 19.23600 | CO |
| 213 | RA | F | 0.325715 | 183552 | 8236340 | 3908.754 | 183095.3 | 8236191 | 3727.512 | 239.825265 | 68.599458 | 666 | V-PN | 19.58330 | CO |
| 214 | RS | P | 1.954241 | 317146.5 | 8236171 | 4167.799 | 316244.6 | 8235374 | 4020.841 | 583.637559 | 95.855494 | 661 | V-C | 22.60890 | CO |
| 215 | RS | P | 1.239988 | 315729.6 | 8234475 | 4247.97 | 316369.7 | 8235018 | 4005.837 | 587.154301 | 334.387183 | 797 | V-C | 21.27800 | CO |
| 216 | RS | P | 1.260850 | 41439.52 | 8234729 | 1890.786 | 39873.44 | 8233528 | 1454.179 | 604.484368 | 156.543119 | 566 | VS-PN | 16.62170 | CO |
| 217 | RA | P | 0.556024 | 180239.3 | 8234311 | 3781.31 | 181278.4 | 8233674 | 3382.766 | 425.264827 | 66.857476 | 666 | V-C | 19.54710 | CO |
| 218 | RS | P | 0.340667 | 111975.1 | 8234842 | 2960.317 | 115495.8 | 8232672 | 1621.048 | 164.927983 | 290.545088 | 510 | V-PN | 17.82970 | CO |
| 219 | RS | P | 1.036903 | 175887.6 | 8233671 | 3429.346 | 175006.6 | 8233312 | 3111.274 | 325.462575 | 248.485198 | 666 | V-PN | 21.27340 | CO |
| 220 | RS | P | 1.003471 | 324510.1 | 8233729 | 4195.119 | 325403.6 | 8233137 | 3902.003 | 492.083514 | 358.206672 | 707 | V-PN | 20.18710 | CO |
| 221 | RA | P | 5.383979 | 97818.3 | 8233549 | 2979.778 | 96187.43 | 8232528 | 2571.269 | 895.437319 | 180.232883 | 546 | VS-M | 21.98900 | CO |
| 222 | RS | P | 0.581298 | 181427.1 | 8231843 | 3775.066 | 180612.8 | 8232564 | 3265.75 | 209.753736 | 122.450635 | 419 | V-C | 15.62220 | CO |
| 223 | RS | P | 0.403534 | 41087.84 | 8231510 | 1759.104 | 41553.04 | 8232607 | 1447.134 | 210.755614 | 316.348278 | 551 | V-PN | 15.46400 | CO |
| 224 | RS | P | 0.160631 | 322353.1 | 8231990 | 4220.538 | 323649.7 | 8231465 | 3922.745 | 172.037280 | 293.135334 | 510 | V-PN | 16.84200 | CO |
| 225 | RS | P | 0.477314 | 97570.62 | 8230841 | 2856.99 | 96345.69 | 8230712 | 2359.031 | 219.460475 | 232.918293 | 586 | V-PN | 20.28370 | CO |
| 226 | RS | P | 1.687077 | 189241.4 | 8230457 | 3765.151 | 188307 | 8231018 | 3287.651 | 684.529983 | 3.623671 | 516 | V-PN | 15.44170 | CO |
| 227 | RS | P | 1.535831 | 42300.6 | 8230017 | 1680.9 | 42993.04 | 8230270 | 1408.946 | 554.733241 | 83.311193 | 675 | V-C | 20.04790 | CO |
| 228 | RS | P | 0.139209 | 94807.89 | 8230147 | 2580.312 | 96306.57 | 8229443 | 2278.396 | 188.841699 | 308.836326 | 521 | V-PN | 19.23450 | CO |
| 229 | RS | P | 2.752800 | 321341 | 8230304 | 4154.257 | 321524.2 | 8228931 | 3881.559 | 383.451544 | 344.089505 | 418 | V-PN | 13.45720 | CO |
| 230 | RS | P | 2.283081 | 42573.3 | 8228691 | 1643.673 | 43527.03 | 8228649 | 1367.411 | 565.825839 | 89.018241 | 624 | V-C | 22.39830 | CO |
| 231 | RS | P | 6.952133 | 97725.34 | 8228955 | 2667.509 | 96821.31 | 8228502 | 2268.581 | 1276.011674 | 245.979002 | 1007 | SMC-M | 29.19300 | CO |
| 232 | RS | P | 4.360339 | 100713.5 | 8233554 | 2959.75 | 101675.4 | 8223240 | 1817.601 | 584.683787 | 231.656176 | 685 | V-C | 22.99560 | CO |
| 233 | RS | P | 3.297037 | 110494.4 | 8228973 | 2514.743 | 119789 | 8226745 | 998.4555 | 790.002471 | 216.201726 | 631 | VS-PN | 17.06630 | CO |
| 234 | RS | P | 1.555910 | 191001 | 8228014 | 3791.687 | 191719.9 | 8226946 | 3166.971 | 560.075911 | 215.979364 | 1141 | SMC-M | 27.28670 | CO |
| 235 | RS | P | 0.236862 | 94914.37 | 8227299 | 2581.061 | 96835.45 | 8227842 | 2229.832 | 231.909575 | 239.712548 | 770 | V-C | 31.20330 | CO |
| 236 | RS | P | 6.358148 | -4360.83 | 8227028 | 1833.684 | -5076.58 | 8227014 | 1721.459 | 902.689093 | 277.707052 | 830 | SMC-M | 20.87980 | CO |
| 237 | RS | P | 1.296917 | 322649.1 | 8227324 | 4236.525 | 321988 | 8226503 | 3848.471 | 180.151240 | 291.929089 | 355 | V-C | 12.88060 | CO |
| 238 | RS | P | 4.661324 | 318677.5 | 8225011 | 4389.387 | 318678.6 | 8227505 | 3973.954 | 921.699222 | 216.320286 | 536 | VS-PN | 16.45150 | CO |
| 239 | RS | P | 0.425234 | 106775.4 | 8225486 | 2412.444 | 105815.8 | 8225237 | 2067.774 | 445.162412 | 73.231270 | 577 | VS-PN | 19.64070 | CO |
| 240 | RS | P | 3.211734 | 360230.3 | 8224444 | 4910.263 | 361075.5 | 8225139 | 4616.017 | 617.440156 | 238.768890 | 707 | V-PN | 17.19640 | CO |
| 241 | RS | P | 3.631490 | -4547.18 | 8224837 | 1750.826 | -6248.33 | 8224936 | 1581.891 | 656.267043 | 237.311908 | 849 | SMC-M | 19.30380 | CO |
| 242 | RS | P | 3.366916 | 186788 | 8224678 | 3435.156 | 187919.8 | 8223905 | 2742.353 | 376.514682 | 149.406393 | 483 | V-C | 16.51180 | CO |
| 243 | RS | P | 3.708303 | 319583 | 8223531 | 4349.718 | 322383.9 | 8224266 | 3799.571 | 591.747236 | 132.329390 | 569 | VS-PN | 16.05670 | CO |
| 244 | RS | P | 1.459442 | 57700.2 | 8223173 | 1960.528 | 54486.19 | 8223489 | 358.9448 | 525.827156 | 265.510498 | 494 | VS-PN | 13.88960 | CO |

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|-----|----|---|------------|----------|---------|----------|----------|---------|----------|-------------|------------|------|-------|----------|----|
| 245 | RS | P | 0.251482 | 95455.65 | 8222860 | 2375.705 | 96066.49 | 8223391 | 1965.569 | 314.603683 | 53.030541 | 499 | VS-PN | 20.91650 | CO |
| 246 | RS | P | 0.456667 | 344200.6 | 8223182 | 4850.629 | 345204.9 | 8222657 | 4472.545 | 447.025084 | 59.540862 | 590 | VS-PN | 25.24200 | CO |
| 247 | RA | P | 2.859533 | -8676.69 | 8221951 | 1437.506 | -9047.56 | 8221949 | 1309.709 | 1494.372737 | 220.936629 | 837 | SMC-M | 28.95310 | CO |
| 248 | RA | P | 7.634905 | 100433.2 | 8220943 | 1990.991 | 99593.69 | 8220456 | 1720.069 | 902.681493 | 237.509901 | 536 | V-C | 20.55990 | CO |
| 249 | RA | P | 0.439930 | 109882.5 | 8220556 | 2227.549 | 107944.3 | 8219744 | 1627.486 | 778.606500 | 259.842236 | 969 | SMC-M | 25.84070 | CO |
| 250 | RS | P | 6.906192 | 102526.5 | 8218619 | 2181.444 | 100678.3 | 8218593 | 1662.386 | 736.806130 | 209.158759 | 502 | VS-PN | 14.36190 | CO |
| 251 | RS | P | 17.658000 | 107022.5 | 8219375 | 2012.472 | 106201.8 | 8218850 | 1772.526 | 946.064821 | 109.662599 | 446 | VS-PN | 14.34660 | CO |
| 252 | RS | P | 5.464190 | 107133 | 8219139 | 1917.828 | 107958.9 | 8218702 | 1577.088 | 658.982774 | 119.251871 | 413 | SC-PN | 15.36750 | CO |
| 253 | RS | P | 2.309465 | 335264.7 | 8218521 | 4463.563 | 336095.4 | 8218825 | 4127.931 | 455.216906 | 287.318110 | 545 | VS-PN | 14.36220 | CO |
| 254 | RA | P | 2.930059 | 106233.6 | 8218136 | 1724.184 | 105785.4 | 8217823 | 1583.533 | 358.035099 | 36.920874 | 393 | V-PN | 14.70210 | CO |
| 255 | RS | P | 4.872140 | 182688.4 | 8218074 | 2874.032 | 182946.1 | 8217643 | 2680.277 | 551.506684 | 87.922757 | 409 | VS-PN | 12.19790 | CO |
| 256 | RA | P | 0.425117 | 183308.8 | 8217188 | 2811.343 | 182683 | 8217262 | 2619.771 | 245.824569 | 264.117332 | 320 | V-PN | 12.88000 | CO |
| 257 | RS | P | 3.089071 | 105495.9 | 8216861 | 1846.42 | 106217.4 | 8217151 | 1542.682 | 536.325269 | 270.372589 | 438 | SC-PN | 16.04330 | CO |
| 258 | RS | P | 0.709028 | 103034 | 8216826 | 2069.735 | 102296 | 8216759 | 1775.713 | 217.866854 | 269.713954 | 438 | V-PN | 14.67230 | CO |
| 259 | RS | P | 3.778628 | 119778.3 | 8214233 | 1783.752 | 120847.1 | 8214222 | 1526.905 | 657.112619 | 244.212162 | 642 | VS-PN | 16.71350 | CO |
| 260 | RS | P | 2.537621 | 251206.8 | 8214161 | 4124.136 | 252292.9 | 8213475 | 3797.756 | 345.758737 | 268.527984 | 413 | VS-PN | 15.60530 | CO |
| 261 | RS | P | 10.225997 | 317772.5 | 8212184 | 4308.016 | 317267.3 | 8211559 | 3984.392 | 1451.786052 | 228.796254 | 746 | SMC-M | 26.43990 | CO |
| 262 | RS | P | 1.124474 | 112604.2 | 8211400 | 1920.13 | 111277.2 | 8211476 | 1551.098 | 659.331316 | 1.605958 | 1195 | I-M | 29.56140 | CO |
| 263 | RS | P | 1.379977 | 24399.62 | 8211550 | 1340.19 | 23970.11 | 8211708 | 1238.376 | 691.948705 | 286.200364 | 704 | V-PN | 22.65750 | CO |
| 264 | RS | P | 182.024611 | 145623.2 | 8209349 | 1577.273 | 145647.8 | 8212824 | 1102.98 | 2982.915991 | 137.631838 | 656 | VS-PN | 16.32760 | CO |
| 265 | RS | P | 13.025304 | 259172.1 | 8211730 | 4190.897 | 258557.9 | 8211013 | 3859.403 | 1040.764755 | 265.380161 | 702 | SC-PN | 21.92100 | CO |
| 266 | RS | F | 1.119229 | 26221.68 | 8211194 | 1436.344 | 25472.89 | 8211415 | 1347.098 | 358.591383 | 218.568299 | 426 | VS-PN | 20.01800 | CO |
| 267 | RS | P | 0.222837 | 258550.4 | 8210185 | 4128.913 | 259101.3 | 8210498 | 3871.783 | 181.241639 | 251.914920 | 393 | SC-PN | 15.38030 | CO |
| 268 | RS | P | 1.758140 | 259760.4 | 8209464 | 4240.493 | 260035.4 | 8210331 | 3893.677 | 146.957839 | 228.514580 | 293 | SC-PN | 12.01980 | CO |
| 269 | RS | P | 1.658298 | 317411.8 | 8209602 | 4359.94 | 318892.8 | 8210129 | 3686.428 | 242.132702 | 49.707042 | 507 | V-PN | 13.14050 | CO |
| 270 | RS | P | 7.075590 | 125067.9 | 8209141 | 1393.599 | 127019 | 8209968 | 542.762 | 436.607142 | 232.502573 | 441 | VS-PN | 15.66210 | CO |
| 271 | RS | P | 1.495477 | 322046.1 | 8209500 | 3916.478 | 321472.5 | 8208754 | 3678.29 | 398.544712 | 121.510740 | 669 | V-C | 16.27230 | CO |
| 272 | RS | P | 10.158382 | 120786.8 | 8208520 | 1698.822 | 121972.3 | 8209063 | 1221.078 | 1339.269242 | 121.643864 | 445 | VS-PN | 15.47240 | CO |
| 273 | RS | P | 0.843227 | 24430.52 | 8208715 | 1356.967 | 23991.91 | 8208570 | 1275.779 | 318.071269 | 247.802218 | 501 | SC-PN | 19.24010 | CO |
| 274 | RS | P | 1.587303 | 18554.48 | 8207559 | 1094.625 | 17954.32 | 8207532 | 875.7036 | 293.116826 | 123.553304 | 414 | SC-PN | 13.04300 | CO |
| 275 | RS | P | 5.663155 | 121509.6 | 8206810 | 1635.159 | 123548.9 | 8207701 | 1041.735 | 408.508910 | 237.938929 | 490 | D-C | 14.70770 | CO |
| 276 | RS | P | 1.146767 | 39534.64 | 8206639 | 1546.087 | 39325.27 | 8206625 | 1513.514 | 509.316147 | 311.536302 | 801 | VS-PN | 19.84340 | CO |
| 277 | RS | P | 2.006379 | 17465.87 | 8206210 | 1068.201 | 18069.35 | 8206002 | 782.3244 | 311.970120 | 22.970670 | 398 | SM-PN | 13.02430 | CO |
| 278 | RS | P | 2.261804 | 26649.05 | 8206119 | 1275.647 | 26890.89 | 8205700 | 1214.321 | 297.793332 | 112.033312 | 326 | SC-PN | 10.18310 | CO |
| 279 | RS | P | 1.727129 | 193362.9 | 8205888 | 2858.192 | 192908.3 | 8206004 | 2733.26 | 497.958748 | 263.966659 | 524 | SM-PN | 16.25880 | CO |
| 280 | RS | P | 0.953332 | 58310.56 | 8205941 | 1407.806 | 55900.74 | 8205324 | 188.4165 | 477.499934 | 300.976602 | 617 | VS-PN | 23.31390 | CO |
| 281 | RS | P | 1.090705 | 25616.54 | 8205857 | 1291.024 | 25888.63 | 8205261 | 1190.029 | 271.953801 | 69.941394 | 417 | VS-PN | 12.77640 | CO |
| 282 | RS | P | 1.546880 | 24647.52 | 8205207 | 1256.933 | 24095.18 | 8205248 | 1155.719 | 301.916324 | 115.165536 | 422 | SC-PN | 19.11570 | CO |
| 283 | RS | P | 1.237710 | 194571.9 | 8205252 | 2906.372 | 194442.4 | 8204814 | 2726.01 | 272.698018 | 172.397857 | 367 | SC-PN | 14.43350 | CO |
| 284 | RS | P | 1.385820 | 53102.1 | 8204989 | 1369.176 | 55084.33 | 8205025 | 227.5153 | 276.261892 | 92.523441 | 422 | VS-PN | 15.41430 | CO |
| 285 | RS | P | 0.798252 | 343376.8 | 8205223 | 4487.144 | 343102.7 | 8204475 | 4279.884 | 398.928043 | 243.358287 | 555 | SM-PN | 18.68430 | CO |
| 286 | RS | P | 42.082869 | 211278.2 | 8204132 | 2576.851 | 211076.7 | 8204300 | 2470.839 | 1142.149010 | 174.671698 | 444 | VS-PN | 14.51740 | CO |
| 287 | RS | P | 60.067641 | 194499.4 | 8204260 | 2870.517 | 194269.2 | 8203677 | 2637.85 | 1516.287106 | 103.479995 | 539 | VS-PN | 16.07730 | CO |
| 288 | RS | P | 1.379796 | 170648.4 | 8203324 | 1921.595 | 171708.4 | 8202820 | 1573.807 | 624.715511 | 146.065588 | 678 | V-PN | 20.30560 | CO |
| 289 | RS | P | 7.065077 | 122486.1 | 8202432 | 1513.421 | 126470.4 | 8203463 | 665.8484 | 351.228331 | 74.221898 | 440 | VS-PN | 18.84090 | CO |
| 290 | RS | P | 0.575854 | 311098.8 | 8198957 | 3865.797 | 312535.1 | 8199242 | 3340.792 | 112.225055 | 268.889439 | 190 | SC-PN | 10.84200 | CO |
| 291 | RS | P | 0.679728 | 126903.6 | 8196641 | 1190.654 | 128580.9 | 8199225 | 412.1989 | 388.054778 | 218.832972 | 484 | SC-PN | 20.51350 | CO |
| 292 | RA | P | 0.468669 | 348993.8 | 8197642 | 4556.841 | 348811.1 | 8197152 | 4419.313 | 356.059967 | 156.914333 | 501 | SMC-M | 21.61750 | CO |
| 293 | RS | P | 4.937982 | 348465.8 | 8197422 | 4470.139 | 348295.1 | 8196884 | 4358.895 | 415.433628 | 0.024292 | 280 | V-PN | 8.18621 | CO |

| | | | | | | | | | | | | | | | |
|-----|----|---|-----------|----------|---------|----------|----------|---------|----------|-------------|------------|-----|-------|----------|----|
| 294 | RS | P | 2.008805 | 350248.8 | 8196233 | 4606.504 | 348581.3 | 8196947 | 4383.093 | 344.670045 | 255.410408 | 545 | VS-PN | 14.44520 | CO |
| 295 | RS | P | 1.535051 | 22388.33 | 8196543 | 504.5239 | 21862.38 | 8196292 | 199.1816 | 294.245731 | 50.586573 | 432 | V-PN | 16.32810 | CO |
| 296 | RS | P | 5.539941 | 317697.9 | 8194360 | 4187.507 | 317408.6 | 8194663 | 4034.863 | 168.935172 | 273.322994 | 236 | SC-PN | 11.87370 | CO |
| 297 | RS | P | 0.987154 | 171570.9 | 8193306 | 1656.378 | 169236.5 | 8194498 | 1385.419 | 692.802927 | 124.307153 | 728 | V-PN | 22.70970 | CO |
| 298 | RS | F | 12.483615 | 316348.6 | 8194116 | 4054.682 | 314025.7 | 8193884 | 3205.558 | 550.147433 | 75.283483 | 276 | V-PN | 8.35333 | CO |
| 299 | RS | P | 7.967539 | 111205.6 | 8193666 | 1237.256 | 110298.2 | 8193035 | 983.9854 | 1601.582997 | 275.611845 | 820 | SC-PN | 24.58650 | PC |
| 300 | RS | P | 2.665360 | 132503.8 | 8191902 | 1222.249 | 130658.5 | 8192636 | 334.5792 | 410.136046 | 49.018927 | 526 | VS-PN | 14.99420 | CO |
| 301 | RS | P | 1.004613 | 167830.5 | 8191088 | 1552.748 | 167073 | 8191938 | 1311.706 | 378.083784 | 117.598442 | 484 | V-PN | 16.67340 | CO |
| 302 | RS | P | 0.115289 | 303640.1 | 8190309 | 4083.654 | 302926.7 | 8190597 | 3738.338 | 127.796989 | 269.660685 | 279 | SC-PN | 12.67910 | CO |
| 303 | RS | P | 1.412246 | 316029.6 | 8190213 | 4111.776 | 313739.1 | 8190254 | 3287.362 | 270.922085 | 239.898838 | 473 | SC-PN | 25.05700 | CO |
| 304 | RS | P | 14.775536 | 166047.6 | 8188787 | 1480.936 | 165310 | 8189223 | 1252.206 | 600.062649 | 247.251979 | 551 | VS-PN | 17.63970 | CO |
| 305 | RS | P | 6.137640 | 199872 | 8188786 | 1854.494 | 200470 | 8187633 | 1463.404 | 519.058297 | 269.164812 | 512 | VS-PN | 15.60370 | CO |
| 306 | RS | P | 1.639006 | 299818.3 | 8188656 | 3882.009 | 300335.3 | 8187297 | 3383.032 | 239.946135 | 237.410880 | 492 | SC-PN | 20.54030 | CO |
| 307 | RS | P | 1.385820 | 162378.7 | 8187905 | 1424.005 | 163281.7 | 8187204 | 1208.576 | 340.740245 | 117.857567 | 504 | SC-PN | 20.43960 | CO |
| 308 | RS | P | 0.587002 | 162337.3 | 8187024 | 1403.392 | 162867.2 | 8186725 | 1193.096 | 335.632460 | 69.906824 | 460 | SC-PN | 21.08380 | CO |
| 309 | RS | P | 0.326598 | 164042.4 | 8186570 | 1392.427 | 163205.7 | 8186969 | 1206.486 | 140.651396 | 235.116159 | 413 | SC-PN | 19.82950 | CO |
| 310 | RS | P | 0.220277 | 196001.2 | 8186785 | 1648.655 | 196463.5 | 8186597 | 1484.003 | 193.755474 | 149.119646 | 341 | M-PP | 17.30410 | CO |
| 311 | RS | P | 0.468742 | 296936 | 8185525 | 4659.389 | 301311 | 8186593 | 3227.386 | 191.571645 | 276.768862 | 586 | V-PN | 21.71190 | CO |
| 312 | RS | P | 1.453614 | 163406.2 | 8185569 | 1371.356 | 162931.7 | 8185870 | 1178.067 | 303.738155 | 68.075598 | 435 | SC-PN | 23.50980 | CO |
| 313 | RS | P | 0.787707 | 318649 | 8186015 | 4159.359 | 318416 | 8185337 | 3923.583 | 294.022113 | 264.818398 | 509 | VS-PN | 20.12870 | CO |
| 314 | RS | P | 1.353268 | 319884.1 | 8186038 | 4217.647 | 320728.1 | 8184958 | 3985.546 | 256.846862 | 90.593697 | 446 | SC-PN | 20.88040 | CO |
| 315 | RS | P | 1.567440 | 163112.9 | 8185073 | 1308.27 | 162581.4 | 8185275 | 1158.981 | 326.379801 | 122.285903 | 435 | VS-PN | 10.74830 | CO |
| 316 | RA | P | 1.712701 | 205775.6 | 8184251 | 1846.297 | 206250.5 | 8184204 | 1729.549 | 778.835148 | 102.737321 | 793 | SMC-M | 25.15740 | CO |
| 317 | RS | P | 0.454576 | 296988.3 | 8183100 | 4586.029 | 301533.4 | 8184244 | 3280.525 | 323.623972 | 218.956653 | 685 | SMC-M | 24.91210 | CO |
| 318 | RS | P | 1.629834 | 213470.8 | 8183390 | 2020.7 | 213244 | 8183155 | 1930.893 | 369.032169 | 273.252148 | 443 | VS-PN | 20.74590 | CO |
| 319 | RS | P | 0.184523 | 161298 | 8183220 | 1319.337 | 161883.1 | 8183180 | 1122.1 | 101.813886 | 290.177562 | 216 | VS-PN | 9.00185 | PC |
| 320 | RS | P | 15.982592 | 300848.2 | 8181461 | 4166.748 | 303208.5 | 8183226 | 3007.788 | 474.292438 | 0.406754 | 409 | SC-PN | 12.86710 | CO |
| 321 | RS | P | 0.503456 | 194626.2 | 8181759 | 1558.034 | 193769.6 | 8182063 | 1301.213 | 331.493680 | 220.600198 | 447 | V-C | 16.62160 | CO |
| 322 | RS | P | 0.375825 | 162686.6 | 8181673 | 1300.835 | 162235.7 | 8181865 | 1104.581 | 89.246200 | 286.420899 | 131 | SC-PN | 7.25298 | PC |
| 323 | RS | P | 0.198312 | 161009.6 | 8181743 | 1272.569 | 161319.9 | 8181362 | 1080.71 | 257.129113 | 60.429820 | 388 | V-C | 14.58050 | CO |
| 324 | RS | P | 0.745007 | 320696.3 | 8181216 | 3922.723 | 320123.5 | 8181340 | 3694.02 | 346.816571 | 17.610232 | 459 | V-PN | 17.45320 | CO |
| 325 | RS | P | 1.346422 | 160098.7 | 8180919 | 1283.144 | 160565.3 | 8180656 | 1066.227 | 673.512426 | 70.438217 | 656 | SMC-M | 19.65620 | CO |
| 326 | RS | P | 3.817028 | 159924.4 | 8180371 | 1266.573 | 160429.3 | 8180137 | 1053.941 | 850.836848 | 67.031183 | 643 | SC-PN | 21.29570 | CO |
| 327 | RS | P | 1.501713 | 159117.8 | 8179380 | 1260.683 | 159809.4 | 8178908 | 1053.872 | 238.188253 | 217.557493 | 769 | SMC-M | 26.26470 | CO |
| 328 | RS | P | 1.276576 | 303942.2 | 8179564 | 3363.147 | 305037 | 8178056 | 2565.338 | 477.744459 | 65.405655 | 556 | VS-PN | 17.51960 | CO |
| 329 | RS | P | 0.166623 | 193850.4 | 8178574 | 1495.161 | 193351.2 | 8178683 | 1311.934 | 81.188681 | 251.720324 | 205 | SC-PN | 7.57358 | PC |
| 330 | RS | P | 0.201396 | 299084.6 | 8178824 | 4294.878 | 302738.3 | 8177998 | 3327.789 | 218.921732 | 267.434193 | 396 | SC-P | 21.81600 | CC |
| 331 | RS | P | 3.879844 | 303063.6 | 8178803 | 3418.663 | 303860.8 | 8177759 | 2771.548 | 593.423345 | 66.395826 | 534 | VS-PN | 15.43520 | CO |
| 332 | RS | P | 0.131016 | 193206.2 | 8177439 | 1476.562 | 192418.5 | 8177797 | 1230.049 | 32.572453 | 266.175721 | 150 | SC-PN | 8.57111 | PC |
| 333 | RA | P | 0.153262 | 190271.5 | 8175995 | 1346.974 | 190516.8 | 8176399 | 1210.13 | 71.872565 | 245.527262 | 164 | SC-PN | 8.93548 | PC |
| 334 | RS | P | 0.229795 | 191524.6 | 8175928 | 1396.263 | 191368.2 | 8176445 | 1243.308 | 285.876363 | 109.008666 | 432 | VS-PN | 17.28930 | CC |
| 335 | RS | P | 0.104224 | 276442 | 8174737 | 4732.587 | 274316 | 8173798 | 4371.059 | 61.325659 | 149.992374 | 142 | SM-PN | 5.17396 | PC |
| 336 | RS | P | 0.136289 | 186663.8 | 8173130 | 1347.123 | 186148 | 8173430 | 1114.787 | 124.932582 | 284.291657 | 509 | SMC-M | 22.06480 | CO |
| 337 | RS | P | 4.997151 | 186197.3 | 8172342 | 1327.15 | 185598.7 | 8172643 | 1100.641 | 1219.389947 | 255.628637 | 831 | M-PP | 20.83100 | PC |
| 338 | RS | P | 0.518061 | 334401.5 | 8172346 | 4681.17 | 334878.6 | 8171678 | 4331.919 | 100.995379 | 155.453816 | 144 | SM-PN | 6.72730 | PC |
| 339 | RA | P | 0.163592 | 185619.3 | 8170828 | 1310.665 | 184556.3 | 8171263 | 1082.724 | 97.596874 | 214.602210 | 173 | SC-PN | 7.85414 | PC |
| 340 | RS | P | 0.172216 | 183976 | 8168902 | 1158.551 | 183680.1 | 8169085 | 1064.512 | 101.214145 | 274.315930 | 184 | SC-PN | 8.24371 | PC |
| 341 | RS | P | 0.588303 | 365533 | 8169488 | 4727.936 | 365745 | 8168513 | 4562.007 | 180.361635 | 196.470002 | 562 | SMC-M | 22.60460 | CO |
| 342 | RS | P | 2.743339 | 183851.3 | 8168411 | 1207.946 | 183306.8 | 8168578 | 1057.499 | 1141.661158 | 88.957532 | 832 | SC-PN | 19.53490 | PC |

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|-----|----|---|-----------|----------|---------|----------|----------|---------|----------|-------------|------------|------|-------|----------|----|
| 343 | RA | P | 0.794652 | 364237.8 | 8168391 | 4658.193 | 364831.2 | 8167819 | 4503.498 | 681.552731 | 122.374689 | 760 | VS-PN | 24.64060 | CO |
| 344 | RS | P | 0.488349 | 182869.4 | 8166715 | 1195.766 | 182622.8 | 8166971 | 1039.166 | 207.259288 | 200.119906 | 328 | SC-PN | 13.63790 | CO |
| 345 | RS | P | 0.119009 | 181947.8 | 8165548 | 1158.842 | 181516.9 | 8165577 | 1027.05 | 106.012233 | 309.886126 | 310 | V-C | 16.49750 | CO |
| 346 | RA | P | 1.119024 | 180469.8 | 8165689 | 1116.655 | 180646.6 | 8165098 | 1022.049 | 636.248743 | 272.390793 | 707 | V-PN | 18.69050 | CO |
| 347 | RS | P | 0.713572 | 181588.3 | 8164819 | 1164.165 | 181316.6 | 8165052 | 1020.876 | 232.667019 | 201.528829 | 444 | SMC-M | 22.06160 | CO |
| 348 | RS | P | 1.438522 | 364607.8 | 8165067 | 4620.93 | 364201.3 | 8164210 | 4477.253 | 347.787340 | 115.462646 | 429 | SC-PN | 12.84110 | CO |
| 349 | RA | P | 1.305368 | 180329.4 | 8164390 | 1126.352 | 179908.5 | 8164802 | 1012.574 | 760.331078 | 276.069409 | 694 | V-PN | 17.67360 | CO |
| 350 | RS | P | 27.100675 | 368887.2 | 8164547 | 5023.556 | 369483.7 | 8162736 | 4659.684 | 847.572574 | 75.496217 | 540 | VS-PN | 18.69420 | CO |
| 351 | RA | P | 1.668536 | 263306.9 | 8161675 | 3443.328 | 263995 | 8161409 | 3196.129 | 170.926478 | 177.823096 | 322 | V-PN | 10.41330 | CO |
| 352 | RA | P | 0.291649 | 333383.6 | 8161306 | 5085.64 | 332164.4 | 8161552 | 4739.209 | 231.164592 | 244.071896 | 486 | I-M | 16.90000 | CO |
| 353 | RA | P | 3.807330 | 269371.3 | 8161262 | 3600.486 | 267773.4 | 8161297 | 3057.365 | 599.840203 | 225.064644 | 534 | V-PN | 14.46740 | CO |
| 354 | RA | P | 0.125725 | 262406 | 8161268 | 3333.104 | 262180.3 | 8160316 | 2987.236 | 251.464469 | 95.033583 | 759 | VS-PN | 21.33040 | CO |
| 355 | RS | P | 1.026408 | 328141.1 | 8160259 | 4728.254 | 328090.7 | 8161173 | 4475.329 | 525.005147 | 78.743163 | 1073 | SC-PN | 25.35580 | CO |
| 356 | RA | P | 0.211839 | 264258.8 | 8160317 | 3327.156 | 263700.6 | 8160276 | 3121.225 | 311.703146 | 83.760453 | 848 | VS-PN | 21.01840 | CO |
| 357 | RA | P | 1.086566 | 270234.4 | 8161387 | 3621.04 | 270802 | 8158604 | 3020.397 | 612.490541 | 173.606028 | 702 | V-PN | 24.90490 | CO |
| 358 | RS | P | 10.948844 | 261945.4 | 8159967 | 3224.685 | 262296.3 | 8160265 | 2970.426 | 778.454824 | 32.980252 | 617 | SC-PN | 16.40090 | CO |
| 359 | RS | P | 0.241315 | 330119.7 | 8160082 | 4862.427 | 329253.1 | 8159649 | 4612.654 | 137.527510 | 200.450457 | 434 | V-PN | 12.05200 | CO |
| 360 | RS | P | 0.243321 | 263994.4 | 8159552 | 3293.846 | 263689.2 | 8159783 | 3061.4 | 111.244210 | 197.622313 | 310 | SC-PN | 10.16190 | CO |
| 361 | RS | P | 1.434392 | 327333.7 | 8159301 | 4729.773 | 326020.1 | 8159332 | 4511.976 | 223.410571 | 293.181582 | 296 | V-PN | 11.89590 | CO |
| 362 | RS | P | 0.561932 | 166134 | 8159569 | 1036.763 | 166349.2 | 8158961 | 702.617 | 305.342323 | 244.460004 | 605 | M-PP | 23.47050 | CC |
| 363 | RS | P | 0.136045 | 261172.4 | 8159471 | 3423.44 | 262675.9 | 8158896 | 2858.273 | 152.644025 | 316.338043 | 469 | SC-PN | 15.75000 | CO |
| 364 | RS | P | 13.792424 | 269318.2 | 8158841 | 3260.402 | 270383.2 | 8157872 | 2873.785 | 270.959229 | 297.036222 | 232 | SC-PN | 6.78573 | CO |
| 365 | RS | P | 3.483097 | 275598.5 | 8158368 | 3463.265 | 276228.8 | 8157725 | 3067.139 | 849.123182 | 264.297408 | 598 | SC-PN | 20.73570 | CO |
| 366 | RS | P | 2.941049 | 327517.4 | 8157841 | 4874.092 | 326245.1 | 8158081 | 4421.963 | 253.270979 | 235.203224 | 492 | SC-PN | 16.64880 | PC |
| 367 | RS | P | 4.861252 | 276770.6 | 8157508 | 3298.362 | 277755.9 | 8157085 | 2988.892 | 887.669674 | 291.688178 | 595 | SC-PN | 12.75280 | PC |
| 368 | RS | P | 1.850738 | 269027.5 | 8156507 | 2867.965 | 269704.2 | 8155849 | 2629.947 | 241.041539 | 318.288918 | 293 | SC-PN | 8.68034 | CO |
| 369 | RS | P | 0.598590 | 328387.7 | 8156110 | 4961.153 | 325467 | 8155782 | 4246.394 | 345.316676 | 291.951712 | 1097 | VS-PN | 29.58240 | CO |
| 370 | RS | P | 2.019510 | 291364.8 | 8155323 | 2690.889 | 290618.1 | 8155936 | 2285.592 | 824.413544 | 271.015884 | 904 | SC-PN | 24.48700 | CO |
| 371 | RS | P | 3.475697 | 276194.4 | 8155794 | 2808.729 | 275425.2 | 8155704 | 2565.596 | 228.729320 | 300.546359 | 291 | SC-PN | 8.22303 | PC |
| 372 | RS | P | 0.795506 | 110425.9 | 8156352 | 257.3439 | 110225.4 | 8154978 | 8.93034 | 391.089228 | 152.575715 | 532 | I-M | 21.52400 | CO |
| 373 | RS | P | 0.635963 | 263206 | 8156068 | 3179.153 | 261882.7 | 8154679 | 2471.467 | 498.976932 | 159.171695 | 957 | V-C | 25.69450 | CO |
| 374 | RS | F | 0.907323 | 264399.3 | 8155256 | 3011.405 | 265432.6 | 8155081 | 2779.419 | 215.429158 | 127.807447 | 269 | D-C | 7.46436 | PC |
| 375 | RS | P | 0.338374 | 278766 | 8154335 | 3079.063 | 277686.6 | 8154944 | 2554.265 | 210.295912 | 119.468893 | 265 | D-C | 9.41936 | PC |
| 376 | RS | P | 1.155305 | 328694.3 | 8155064 | 4838.244 | 327519.2 | 8153895 | 4309.355 | 185.940959 | 295.450946 | 271 | SC-PN | 9.02725 | PC |
| 377 | RS | P | 0.196496 | 276180.3 | 8154077 | 2527.015 | 275707.5 | 8153886 | 2313.393 | 164.651817 | 112.096036 | 339 | SC-PN | 12.27910 | CO |
| 378 | RA | P | 4.177426 | 264647.2 | 8154028 | 2821.041 | 265535.4 | 8153832 | 2534.027 | 1343.440782 | 257.737439 | 1017 | VS-PN | 31.45680 | CO |
| 379 | RS | P | 8.280703 | 299578.2 | 8153913 | 3120.748 | 299574.7 | 8152866 | 2656.679 | 1432.003721 | 76.280307 | 817 | VS-PN | 22.24030 | CO |
| 380 | RS | F | 0.258316 | 255047.3 | 8152257 | 2925.103 | 253882.6 | 8152199 | 2534.223 | 193.288981 | 302.366218 | 278 | SC-PN | 10.30800 | PC |
| 381 | RS | P | 0.607704 | 328664.9 | 8152745 | 4898.879 | 325794 | 8151244 | 4028.064 | 235.776351 | 198.976967 | 449 | SC-PN | 16.08020 | CO |
| 382 | RS | P | 0.587399 | 254323.3 | 8150513 | 2834.171 | 253582.6 | 8150939 | 2473.542 | 232.100832 | 142.011545 | 353 | SC-PN | 13.90650 | CO |
| 383 | RS | P | 0.370694 | 330670.2 | 8150709 | 5130.927 | 327648.3 | 8150113 | 4330.874 | 149.289092 | 290.816752 | 279 | SC-PN | 11.59980 | PC |
| 384 | RS | P | 0.161383 | 322068 | 8149914 | 3673.901 | 321238.7 | 8150065 | 3242.767 | 116.747239 | 95.678410 | 311 | I-M | 17.43280 | CO |
| 385 | RS | P | 7.904405 | 264135.7 | 8150178 | 2717.809 | 264363 | 8148938 | 2377.267 | 1305.503894 | 75.876089 | 680 | VS-PN | 17.64590 | CO |
| 386 | RS | P | 0.143699 | 242898.6 | 8148909 | 2463.696 | 242751 | 8148885 | 2409.428 | 89.807366 | 223.999083 | 220 | VS-PN | 11.02070 | CO |
| 387 | RS | P | 1.275570 | 287673.7 | 8149416 | 1896.584 | 287580.3 | 8148526 | 1634.047 | 197.236749 | 93.867087 | 255 | SC-PN | 9.13418 | PC |
| 388 | RS | P | 7.213409 | 242579.6 | 8147830 | 2425.374 | 242396.8 | 8148026 | 2298.767 | 1158.960045 | 53.220333 | 956 | V-PN | 22.35520 | CO |
| 389 | RS | P | 0.366705 | 314064.8 | 8147690 | 2585.463 | 314099.9 | 8146782 | 2130.639 | 256.821256 | 289.558274 | 318 | D-C | 10.64520 | CO |
| 390 | RS | F | 0.475184 | 313041 | 8147497 | 2441.169 | 313334.4 | 8146649 | 2085.422 | 196.254382 | 293.142252 | 264 | D-C | 9.29250 | PC |
| 391 | RS | F | 0.923043 | 304656.4 | 8143986 | 2465.224 | 304618 | 8145775 | 1639.294 | 191.859051 | 140.803190 | 258 | SC-PN | 12.26490 | PC |

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|-----|----|---|-----------|----------|---------|----------|----------|---------|----------|-------------|------------|------|-------|----------|----|
| 392 | RS | P | 0.185942 | 294819.8 | 8146808 | 2361.021 | 295435.8 | 8143194 | 1794.645 | 228.702631 | 282.214028 | 619 | SC-PN | 19.43070 | CO |
| 393 | RS | F | 0.350303 | 281211.1 | 8142798 | 2397.501 | 278454.9 | 8144243 | 1149.955 | 216.917401 | 119.375129 | 257 | SC-PN | 10.80540 | PC |
| 394 | RS | F | 0.228020 | 282449.1 | 8142319 | 2743.897 | 280453.9 | 8140991 | 1760.313 | 212.632213 | 114.898771 | 262 | SC-PN | 12.19510 | PC |
| 395 | RS | F | 0.792660 | 312877.6 | 8135581 | 4273.015 | 307728.5 | 8137138 | 3097.812 | 206.810874 | 124.324073 | 259 | D-C | 11.45390 | PC |
| 396 | RS | P | 0.504707 | 273239.4 | 8132329 | 2071.258 | 270360 | 8132735 | 949.7993 | 797.808470 | 143.953365 | 964 | VS-M | 26.50300 | CO |
| 397 | RS | F | 0.437687 | 306765.4 | 8132647 | 3790.3 | 306692 | 8132104 | 3515.738 | 183.226823 | 282.367390 | 296 | D-C | 10.58900 | CO |
| 398 | RS | P | 3.236168 | 309327.1 | 8131518 | 4101.25 | 307830 | 8132585 | 3715.569 | 967.089322 | 102.737245 | 674 | V-PN | 17.41480 | CO |
| 399 | RS | P | 0.446298 | 268060.5 | 8131992 | 1722.851 | 270048.7 | 8131376 | 923.7248 | 647.114565 | 142.629178 | 1083 | VS-M | 25.77190 | CO |
| 400 | RS | F | 0.787059 | 307117.4 | 8130556 | 3948.906 | 306349.4 | 8132067 | 3460.628 | 246.512337 | 294.430212 | 294 | D-C | 12.72720 | CO |
| 401 | RS | P | 0.223738 | 305026.1 | 8129801 | 3774.812 | 304253.8 | 8131527 | 3180.165 | 136.844088 | 31.294153 | 290 | SC-PN | 12.76320 | CO |
| 402 | RS | P | 0.513199 | 242268 | 8129629 | 1533.979 | 241768.7 | 8129755 | 1247.385 | 152.954387 | 343.153712 | 285 | SC-PN | 13.02030 | CO |
| 403 | RA | P | 9.391628 | 272130.1 | 8129026 | 2433.069 | 269663.6 | 8130150 | 923.2989 | 1378.775272 | 70.795215 | 818 | VS-PN | 23.20270 | CO |
| 404 | RS | F | 1.983795 | 267068 | 8128440 | 1612.487 | 265222.9 | 8129001 | 856.5968 | 361.528215 | 246.177938 | 430 | V-PN | 13.75610 | CO |
| 405 | RS | F | 0.447605 | 304489.4 | 8128902 | 3547.248 | 304743.3 | 8128410 | 3388.6 | 232.335655 | 300.129355 | 290 | D-C | 10.74340 | PC |
| 406 | RS | F | 0.722332 | 306269.3 | 8129259 | 3846.131 | 304429.6 | 8128051 | 3302.001 | 226.509049 | 296.713923 | 282 | SC-PN | 8.66631 | PC |
| 407 | RS | P | 0.536732 | 303769 | 8128616 | 3488.061 | 303833.6 | 8127868 | 3253.846 | 349.251117 | 144.471017 | 488 | V-PN | 19.49940 | CO |
| 408 | RA | P | 4.345416 | 304546.5 | 8126826 | 3634.727 | 303901.9 | 8127872 | 3256.802 | 945.353158 | 70.903191 | 728 | VS-PN | 24.47100 | CO |
| 409 | RS | F | 2.094548 | 313223.8 | 8127863 | 4091.654 | 313663.4 | 8126029 | 3718.309 | 227.941026 | 292.256073 | 261 | D-C | 7.81025 | PC |
| 410 | RA | P | 3.507698 | 307042.8 | 8126964 | 3813.683 | 307168.4 | 8125965 | 3472.184 | 720.986201 | 202.033778 | 528 | V-PN | 19.09040 | CO |
| 411 | RA | F | 0.754620 | 311466.2 | 8126922 | 3971.011 | 311721 | 8125824 | 3562.604 | 166.659494 | 199.936778 | 238 | D-C | 7.55519 | CO |
| 412 | RS | F | 0.136200 | 261744.2 | 8124216 | 1768.172 | 261366.1 | 8127221 | 790.6008 | 94.039223 | 301.743113 | 247 | SC-PN | 9.96109 | PC |
| 413 | RS | F | 1.398366 | 304582.4 | 8126219 | 3617.625 | 303819.9 | 8125758 | 3319.729 | 165.928988 | 167.733171 | 226 | D-C | 8.06773 | CO |
| 414 | RS | F | 0.354130 | 335362 | 8122504 | 4797.833 | 335121.4 | 8122294 | 4683.036 | 150.446895 | 287.034276 | 247 | SC-PN | 9.29650 | PC |
| 415 | RS | F | 0.939714 | 327992.1 | 8121854 | 4219.608 | 328256.3 | 8121468 | 3994.334 | 154.695530 | 133.974130 | 256 | D-C | 9.94057 | CO |
| 416 | RS | F | 0.226053 | 310186.6 | 8121206 | 3674.633 | 309648.8 | 8120652 | 3327.402 | 156.599730 | 316.164275 | 227 | SC-PN | 10.06280 | PC |
| 417 | RS | F | 0.162192 | 313546.3 | 8120607 | 3809.19 | 313769.3 | 8120126 | 3572.002 | 131.791810 | 273.930336 | 227 | SC-PN | 10.94820 | PC |
| 418 | RS | P | 0.326263 | 312516.7 | 8120132 | 3729.471 | 312803.2 | 8119501 | 3492.394 | 94.605865 | 163.354071 | 222 | SC-PN | 11.28960 | PC |
| 419 | RS | F | 0.282082 | 299663.8 | 8120596 | 3258.508 | 301443.4 | 8117398 | 2646.658 | 143.288835 | 310.579342 | 217 | SC-PN | 10.13790 | PC |
| 420 | RS | F | 0.853761 | 278627.7 | 8119103 | 2370.644 | 278786.8 | 8117261 | 2054.61 | 143.676759 | 205.387336 | 306 | V-PN | 10.04550 | CO |
| 421 | RS | P | 0.273999 | 313222.3 | 8118774 | 3685.85 | 312903.5 | 8117723 | 3331.326 | 113.777648 | 314.395902 | 221 | SC-PN | 11.68100 | PC |
| 422 | RA | P | 40.006834 | 309652.2 | 8118136 | 3514.215 | 309860.6 | 8117139 | 3086.459 | 1821.792771 | 93.860695 | 1021 | V-C | 24.21130 | CO |
| 423 | RS | F | 3.554964 | 311304.2 | 8116591 | 3511.868 | 310960 | 8117404 | 3176.612 | 363.872135 | 161.762477 | 352 | V-PN | 14.07810 | CO |
| 424 | RA | P | 2.225878 | 308708.2 | 8115642 | 3360.699 | 307974.3 | 8116936 | 2942.788 | 1165.469312 | 203.242256 | 1228 | I-M | 33.11010 | CO |
| 425 | RA | P | 2.303410 | 312891.6 | 8116514 | 3595.642 | 312982.9 | 8115583 | 3136.052 | 1074.282152 | 69.279703 | 862 | V-PN | 24.50170 | CO |
| 426 | RS | P | 0.800658 | 310090.3 | 8115266 | 3403.275 | 310696 | 8114046 | 2969.22 | 247.198303 | 111.136044 | 463 | V-PN | 19.37720 | CO |
| 427 | RS | P | 1.291134 | 302797 | 8113590 | 2706.818 | 302279.6 | 8113063 | 2410.318 | 346.430898 | 281.405925 | 670 | V-PN | 23.07840 | CO |
| 428 | RS | P | 1.413657 | 342368.9 | 8113610 | 5153.555 | 341476.4 | 8112933 | 4719.905 | 543.120894 | 271.246190 | 624 | V-PN | 17.13810 | CO |
| 429 | RS | P | 1.763821 | 260489.9 | 8111504 | 1670.203 | 260530.8 | 8111217 | 1561.127 | 345.868120 | 193.332734 | 549 | V-PN | 21.12680 | CO |
| 430 | RS | P | 0.537869 | 261099.9 | 8111438 | 1679.443 | 261068.2 | 8111136 | 1575.468 | 252.925224 | 356.849248 | 335 | V-PN | 13.62190 | CO |
| 431 | RS | P | 0.357366 | 276237.1 | 8109444 | 2046.557 | 276865.7 | 8108887 | 1834.306 | 205.931059 | 265.833074 | 466 | V-PN | 22.92660 | CO |
| 432 | RS | P | 4.359673 | 321332.7 | 8109363 | 3549.855 | 321196.8 | 8108837 | 3253.182 | 600.642608 | 168.471969 | 584 | V-PN | 17.37890 | CO |
| 433 | RS | P | 0.133532 | 295254.9 | 8108285 | 2236.397 | 295006.6 | 8108945 | 1872.168 | 254.259276 | 49.685337 | 594 | V-PN | 22.13760 | CO |
| 434 | RS | P | 1.481186 | 304635.4 | 8108328 | 2368.731 | 304715.5 | 8107598 | 2168.039 | 249.772540 | 243.421836 | 454 | V-PN | 16.67100 | CO |
| 435 | RS | P | 0.103420 | 243741.1 | 8106831 | 1048.592 | 243870.6 | 8106532 | 979.7783 | 232.445650 | 307.089580 | 504 | V-PN | 21.84910 | CO |
| 436 | RS | P | 2.732825 | 243380.8 | 8106623 | 1040.647 | 243515.1 | 8106258 | 964.9254 | 217.797681 | 271.384915 | 430 | V-PN | 12.47850 | CO |
| 437 | RS | P | 0.266673 | 242102.7 | 8105612 | 1003.891 | 242289.7 | 8105204 | 936.8475 | 334.145515 | 160.516515 | 455 | SC-PN | 21.01210 | PC |
| 438 | RS | P | 1.649543 | 292446.9 | 8105252 | 2327.771 | 294365.2 | 8104262 | 1742.423 | 565.166974 | 110.948356 | 516 | V-PN | 19.59710 | CO |
| 439 | RS | P | 1.637606 | 378865.5 | 8104481 | 4585.59 | 377203.5 | 8104318 | 4267.067 | 386.617066 | 132.283062 | 503 | SC-PN | 19.00580 | CO |
| 440 | RA | P | 0.656978 | 328891.5 | 8102570 | 3900.392 | 328126.8 | 8101684 | 3532.115 | 323.536891 | 175.137144 | 639 | V-PN | 20.81630 | CO |

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|-----|----|---|-----------|----------|---------|----------|----------|---------|----------|-------------|------------|------|-------|----------|----|
| 441 | RS | P | 0.508665 | 204163.1 | 8101922 | 187.0789 | 203879.2 | 8102115 | 36.6079 | 396.126317 | 135.601908 | 711 | V-PN | 23.87340 | CO |
| 442 | RS | P | 0.643251 | 306150.1 | 8098096 | 2434.554 | 305679.5 | 8098594 | 2280.586 | 452.129155 | 280.708467 | 542 | V-PN | 16.87810 | CO |
| 443 | RS | P | 0.855970 | 356135.4 | 8097763 | 3940.711 | 356647 | 8097169 | 3578.754 | 309.469909 | 113.263638 | 672 | V-PN | 22.18770 | CO |
| 444 | RA | P | 2.058224 | 357376.1 | 8096738 | 3948.624 | 356709.8 | 8097156 | 3568.591 | 1568.213193 | 107.990106 | 862 | VS-M | 29.05650 | CO |
| 445 | RS | P | 1.032672 | 355551.5 | 8096695 | 3879.387 | 356287.6 | 8096272 | 3511.653 | 238.017622 | 134.200134 | 605 | SMC-M | 21.45550 | CO |
| 446 | RS | P | 8.388572 | 347309.8 | 8096472 | 4031.59 | 346874.6 | 8096306 | 3876.269 | 714.759250 | 263.585532 | 530 | V-PN | 14.04190 | CO |
| 447 | RS | F | 0.703134 | 354524 | 8096220 | 3909.875 | 355802 | 8095381 | 3432.508 | 405.297744 | 309.404494 | 512 | SMC-M | 22.02390 | CO |
| 448 | RS | P | 0.823152 | 357171.1 | 8095025 | 3917.783 | 355706.8 | 8095090 | 3395.434 | 243.133553 | 263.349072 | 689 | SMC-M | 23.32530 | CO |
| 449 | RS | P | 4.092493 | 354528.5 | 8094837 | 3854.84 | 355133.5 | 8094700 | 3647.511 | 248.413558 | 188.303449 | 293 | SM-PN | 12.11130 | CC |
| 450 | RS | F | 2.611590 | 343588.1 | 8094469 | 4072.791 | 342585.1 | 8093995 | 3714.758 | 707.686017 | 223.615586 | 710 | SC-PN | 24.10950 | CO |
| 451 | RS | P | 1.079954 | 299445.8 | 8093193 | 1993.967 | 298660.6 | 8094248 | 1646.747 | 231.985926 | 99.626797 | 829 | I-M | 22.51960 | CO |
| 452 | RS | P | 1.089652 | 365898.3 | 8091698 | 3676.121 | 367923.8 | 8091592 | 3235.602 | 524.797932 | 299.424579 | 655 | SMC-M | 23.60140 | CO |
| 453 | RS | P | 1.587032 | 357641.9 | 8091249 | 3816.02 | 355908 | 8091945 | 3091.556 | 528.888422 | 225.157540 | 688 | V-PN | 18.25910 | CO |
| 454 | RS | P | 0.235982 | 374199.3 | 8091301 | 3572.071 | 373450.4 | 8090962 | 3298.389 | 213.622086 | 247.957111 | 558 | D-C | 23.51100 | CO |
| 455 | RS | P | 0.696193 | 343839.2 | 8089106 | 3716.952 | 343096.5 | 8089488 | 3373.816 | 287.013861 | 102.465193 | 735 | D-C | 24.61480 | CO |
| 456 | RS | P | 1.117496 | 349124.1 | 8089219 | 3644.879 | 347713.6 | 8088910 | 3193.98 | 464.068309 | 180.193011 | 673 | V-C | 20.14260 | CO |
| 457 | RA | P | 0.707243 | 362874.4 | 8088915 | 3781.203 | 362345.5 | 8088996 | 3597.518 | 648.597653 | 218.257426 | 644 | SC-PN | 20.00760 | CO |
| 458 | RA | P | 1.471417 | 361403 | 8089017 | 3868.372 | 362066.3 | 8088371 | 3532.753 | 340.917338 | 285.415316 | 972 | V-C | 30.05640 | CO |
| 459 | RS | P | 1.028385 | 366648.2 | 8088443 | 3603.551 | 369378.2 | 8088404 | 2985.211 | 390.880143 | 267.142744 | 460 | V-PN | 14.92120 | CO |
| 460 | RS | P | 6.790279 | 362933.1 | 8087989 | 3883.334 | 361980.3 | 8088112 | 3491.354 | 870.815106 | 242.399479 | 603 | V-PN | 22.93090 | CO |
| 461 | RS | P | 0.733662 | 357154.4 | 8087295 | 3857.381 | 353388 | 8089044 | 2841.259 | 360.629643 | 299.895611 | 555 | SMC-M | 21.77200 | CO |
| 462 | RS | P | 5.879711 | 362018.4 | 8086035 | 3841.895 | 361027.3 | 8086511 | 3364.604 | 800.052605 | 258.846502 | 595 | V-PN | 17.80790 | CO |
| 463 | RS | P | 0.266914 | 312118.9 | 8086411 | 2195.344 | 312326.6 | 8086019 | 2087.885 | 431.133876 | 280.319679 | 741 | D-C | 21.48230 | CO |
| 464 | RS | P | 0.749863 | 367457.2 | 8086600 | 3493.613 | 369626 | 8085660 | 2890.097 | 340.542061 | 169.612035 | 578 | SMC-M | 22.62420 | CO |
| 465 | RA | P | 32.695208 | 357904.3 | 8087216 | 3841.157 | 358614 | 8084724 | 3128.263 | 2165.226246 | 180.542936 | 878 | VS-PN | 31.91540 | CO |
| 466 | RS | P | 0.108176 | 352478.2 | 8084682 | 3548.452 | 349475.9 | 8085960 | 2500.588 | 54.268252 | 260.649446 | 451 | V-PN | 18.84640 | CO |
| 467 | RS | P | 0.796046 | 367474.2 | 8085892 | 3425.059 | 367217 | 8084705 | 3084.177 | 262.536892 | 185.997278 | 511 | SMC-M | 21.36790 | CO |
| 468 | RS | P | 0.107588 | 360906.9 | 8083638 | 3783.595 | 359070.7 | 8085040 | 3167.665 | 126.607452 | 316.996306 | 388 | SMC-M | 17.93990 | CO |
| 469 | RA | P | 0.613340 | 280328.4 | 8084422 | 1566.652 | 280699.2 | 8084135 | 1365.262 | 762.060788 | 240.026268 | 1051 | SMC-M | 31.68170 | CO |
| 470 | RS | P | 0.372522 | 317842.8 | 8084149 | 2161.116 | 317424.4 | 8084105 | 2046.52 | 454.823503 | 177.784336 | 782 | V-C | 27.53540 | CO |
| 471 | RA | P | 4.232011 | 383211.3 | 8083266 | 4048.594 | 381853.8 | 8083668 | 3470.915 | 703.778284 | 224.818244 | 449 | V-PN | 16.21800 | CO |
| 472 | RS | P | 0.956152 | 314302.5 | 8083520 | 2069.548 | 314467.4 | 8083086 | 1949.365 | 355.746675 | 160.930844 | 599 | V-C | 25.55020 | CO |
| 473 | RS | P | 1.427830 | 362834.5 | 8084019 | 3872.252 | 364549.9 | 8081641 | 2742.819 | 825.930017 | 358.772711 | 799 | SMC-M | 24.72520 | CO |
| 474 | RA | P | 2.033600 | 322392.2 | 8081783 | 2150.202 | 321924.7 | 8081438 | 2024.725 | 826.832857 | 20.807578 | 982 | SMC-M | 24.59390 | CO |
| 475 | RS | P | 9.220560 | 346777.1 | 8080711 | 2942.546 | 345025.1 | 8081217 | 1918.054 | 566.376017 | 170.326206 | 951 | VS-M | 31.14900 | CO |
| 476 | RS | P | 3.805173 | 357611.1 | 8081923 | 3640.694 | 359831.1 | 8077981 | 2741.764 | 1247.545881 | 297.659454 | 1030 | SMC-M | 28.50270 | CO |
| 477 | RS | P | 2.117710 | 333435 | 8078984 | 2537.115 | 332856.5 | 8079523 | 2203.221 | 983.583246 | 236.352225 | 812 | VS-M | 27.67660 | CO |
| 478 | RA | P | 0.730202 | 322545.2 | 8078538 | 1976.645 | 322959.1 | 8078113 | 1834.173 | 545.284773 | 211.115793 | 515 | SMC-M | 18.50240 | CO |
| 479 | RS | P | 14.113514 | 321842.4 | 8076219 | 1766.225 | 321257.9 | 8076128 | 1690.586 | 1175.202773 | 286.822676 | 495 | VS-PN | 19.52150 | CO |
| 480 | RS | P | 4.705842 | 328793.1 | 8075537 | 1999.289 | 327914.1 | 8076228 | 1703.042 | 1121.458416 | 278.029707 | 631 | SMC-M | 25.03690 | CO |
| 481 | RS | P | 0.293722 | 322891.8 | 8075869 | 1894.989 | 322086.3 | 8075824 | 1673.174 | 274.562179 | 187.699006 | 574 | VS-M | 20.35780 | CO |
| 482 | RS | P | 2.344606 | 401137.3 | 8076152 | 4689.031 | 400495.9 | 8075157 | 4400.902 | 385.681090 | 305.483702 | 422 | VS-PN | 14.52810 | CO |
| 483 | RA | P | 0.992656 | 399301.1 | 8074731 | 4436.452 | 398822.2 | 8074097 | 4132.218 | 378.305513 | 162.990724 | 536 | VS-M | 18.87650 | CO |
| 484 | RS | P | 6.128452 | 353715.7 | 8073463 | 2405.698 | 353082 | 8074973 | 1856.84 | 799.126699 | 107.216972 | 981 | VS-M | 27.77570 | CO |
| 485 | RS | P | 2.761789 | 313123.5 | 8075052 | 1688.424 | 311112.8 | 8069881 | 1185.883 | 488.277642 | 333.047294 | 513 | VS-PN | 17.32360 | CO |
| 486 | RS | P | 5.051281 | 404513.5 | 8073418 | 4889.174 | 404518.7 | 8072420 | 4513.201 | 594.646737 | 335.889897 | 617 | VS-PN | 19.49970 | CO |
| 487 | RA | P | 0.970967 | 402161.4 | 8073033 | 4717.544 | 401669.8 | 8071995 | 4294.633 | 472.448763 | 244.385843 | 651 | VS-M | 25.98460 | CO |
| 488 | RS | P | 0.190197 | 325847.9 | 8070874 | 1818.529 | 325107.8 | 8071299 | 1483.251 | 286.594308 | 284.177124 | 414 | I-M | 24.42080 | CO |
| 489 | RS | P | 4.714921 | 345550.4 | 8069612 | 2222.711 | 344998.3 | 8071044 | 1647.125 | 1509.769844 | 294.499373 | 984 | I-PN | 32.01390 | CO |

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|-----|----|---|----------|----------|---------|----------|----------|---------|----------|------------|------------|-----|-------|----------|----|
| 490 | RS | P | 2.272690 | 327042.8 | 8069316 | 1757.192 | 326656.5 | 8069409 | 1618.394 | 755.890446 | 286.897765 | 907 | VS-M | 29.66730 | CO |
| 491 | RS | P | 0.533547 | 361137 | 8064651 | 2169.726 | 360504.3 | 8065989 | 1591.41 | 158.647233 | 152.685684 | 528 | VS-PN | 18.21180 | CO |
| 492 | RS | P | 1.691403 | 269553.4 | 8063523 | 827.9564 | 268574.5 | 8064045 | 438.2282 | 544.130316 | 236.705694 | 438 | VS-PN | 17.44170 | CO |
| 493 | RS | P | 0.496644 | 386946.9 | 8063775 | 3210.789 | 386380.4 | 8062693 | 2751.789 | 234.215218 | 175.068175 | 534 | VS-PN | 18.71650 | CO |
| 494 | RS | P | 2.345237 | 351298.9 | 8063407 | 2037.165 | 352320.4 | 8061476 | 1229.06 | 377.924699 | 328.363333 | 506 | VS-PN | 16.70530 | CO |
| 495 | RS | P | 3.351561 | 308677.6 | 8058753 | 1101.405 | 308076.4 | 8059148 | 836.6887 | 373.345061 | 166.526881 | 388 | VS-PN | 14.42260 | CO |
| 496 | RS | P | 0.765619 | 362249.5 | 8056304 | 2765.147 | 360728.4 | 8057154 | 2127.156 | 341.498697 | 172.832114 | 509 | VS-PN | 17.62510 | CO |
| 497 | RS | P | 1.735036 | 367424.3 | 8055693 | 3425.156 | 368361.7 | 8057723 | 2690.842 | 408.407085 | 166.940424 | 517 | VS-PN | 19.45560 | CO |
| 498 | RS | P | 7.875639 | 309711.1 | 8055010 | 1093.667 | 308052.9 | 8055739 | 674.7643 | 977.571411 | 352.829570 | 850 | VS-M | 26.22660 | CO |
| 499 | RS | P | 0.580166 | 360727.8 | 8054680 | 2550.704 | 359229.7 | 8055345 | 2084.506 | 297.895360 | 238.867001 | 431 | VS-PN | 16.83500 | CO |
| 500 | RA | P | 1.151793 | 359782.3 | 8052566 | 2309.102 | 358492.8 | 8052748 | 1880.111 | 288.529711 | 168.542417 | 415 | VS-PN | 17.35760 | CO |
| 501 | RS | P | 0.207137 | 309419.8 | 8051824 | 946.1927 | 310931.3 | 8050039 | 539.0551 | 114.796882 | 229.066099 | 398 | V-PN | 13.88050 | CO |
| 502 | RS | P | 0.219442 | 377436.3 | 8048939 | 3308.689 | 376103.8 | 8047770 | 2784.514 | 225.274144 | 145.611943 | 572 | VS-PN | 18.81960 | CO |
| 503 | RS | P | 0.803575 | 364003.4 | 8050379 | 2549.478 | 361227.5 | 8044916 | 1447.298 | 347.230850 | 224.124400 | 565 | VS-PN | 20.32290 | CO |
| 504 | RS | P | 0.156935 | 308003.6 | 8046654 | 604.5866 | 307431.7 | 8046908 | 462.3089 | 237.188000 | 155.159056 | 381 | VS-PN | 16.37570 | CO |
| 505 | RS | P | 1.056419 | 377708.2 | 8046101 | 2953.947 | 375741.1 | 8046087 | 2535.122 | 237.076956 | 155.584222 | 482 | VS-PN | 15.73880 | CO |
| 506 | RS | P | 7.959334 | 306841.2 | 8044882 | 561.3563 | 306447.2 | 8045155 | 432.2943 | 611.849996 | 150.908081 | 468 | VS-PN | 17.55490 | CO |
| 507 | RS | P | 2.797709 | 403801.7 | 8042439 | 4355.211 | 403289.6 | 8043897 | 3608.472 | 316.034027 | 175.064061 | 293 | VS-M | 13.27910 | CO |
| 508 | RS | P | 1.182487 | 385660.7 | 8039195 | 2859.564 | 386866.5 | 8038879 | 2440.702 | 354.523652 | 196.884796 | 561 | VS-PN | 20.58330 | CO |
| 509 | RS | P | 1.729771 | 395708.7 | 8035368 | 3276.476 | 392390.7 | 8036493 | 2497.181 | 427.755886 | 168.196810 | 599 | VS-PN | 16.26750 | CO |
| 510 | RS | P | 2.330805 | 396902.9 | 8035425 | 3451.848 | 397851.6 | 8033733 | 2872.432 | 335.255806 | 337.047503 | 467 | VS-PN | 19.15640 | CO |
| 511 | RA | P | 3.620567 | 393100.8 | 8033001 | 2868.869 | 391210.7 | 8033486 | 2401.235 | 510.419335 | 184.979421 | 415 | VS-PN | 15.69750 | CO |
| 512 | RS | F | 2.296353 | 394166.1 | 8033922 | 3209.268 | 393279.8 | 8031998 | 2561.591 | 417.910441 | 330.437139 | 481 | VS-PN | 13.14340 | CO |
| 513 | RS | F | 0.504092 | 356607.3 | 8032980 | 1184.115 | 356314.4 | 8032482 | 1018.428 | 459.590114 | 174.405550 | 605 | VS-PN | 23.48050 | CO |
| 514 | RS | F | 2.597191 | 397912.9 | 8031276 | 3354.336 | 395917 | 8030446 | 2681.477 | 434.055199 | 153.591314 | 524 | VS-PN | 15.34340 | CO |
| 515 | RS | P | 0.309058 | 399217.2 | 8030075 | 3437.799 | 399137.9 | 8029259 | 3081.513 | 296.499166 | 224.446528 | 451 | SC-PN | 19.44450 | CO |
| 516 | RS | F | 1.305823 | 397832.4 | 8027747 | 3364.642 | 396748.9 | 8029067 | 2720.809 | 433.650139 | 232.831253 | 954 | V-PN | 25.12950 | CO |
| 517 | RA | P | 1.710990 | 399449 | 8025086 | 3358.568 | 398599 | 8026029 | 2679.415 | 386.698810 | 201.506248 | 602 | VS-M | 18.08790 | CO |
| 518 | RS | P | 0.107456 | 398785.8 | 8020023 | 3179.644 | 396381.8 | 8018477 | 2168.613 | 109.076458 | 171.896039 | 223 | D-C | 12.37650 | CO |
| 519 | RS | P | 0.122785 | 395036 | 8015531 | 2502.836 | 395054.3 | 8013246 | 1695.236 | 103.975033 | 185.982878 | 217 | D-C | 12.71110 | CO |
| 520 | RS | P | 0.438095 | 434751.2 | 8014102 | 3911.207 | 435068.1 | 8012488 | 3670.985 | 212.251202 | 131.500081 | 314 | SC-PN | 13.11380 | CO |
| 521 | RS | P | 0.159661 | 435814.3 | 8011503 | 3887.354 | 435143.7 | 8012470 | 3683.996 | 296.672455 | 194.468153 | 716 | VS-M | 23.53190 | CO |
| 522 | RS | P | 0.456688 | 393475.4 | 8010642 | 2006.44 | 392500.9 | 8012452 | 1601.645 | 364.228577 | 339.373729 | 574 | VS-M | 27.33380 | CO |
| 523 | RS | P | 0.297289 | 438802.5 | 8011432 | 3934.722 | 433395.2 | 8010176 | 3598.895 | 200.692317 | 173.727786 | 492 | VS-M | 21.11590 | CO |
| 524 | RA | P | 1.135433 | 398309.8 | 8007883 | 2471.67 | 398247.8 | 8007017 | 2099.665 | 972.586984 | 212.642727 | 796 | VS-PN | 20.91700 | CO |
| 525 | RA | P | 0.316117 | 430419 | 8007800 | 3851.192 | 432168.9 | 8006935 | 3548.857 | 392.646097 | 303.259804 | 544 | VS-M | 24.59470 | CO |
| 526 | RS | P | 0.107976 | 399462.7 | 8007063 | 2513.459 | 398891 | 8007584 | 2213.065 | 68.813307 | 156.560955 | 156 | D-C | 6.62573 | PC |
| 527 | RS | P | 0.127446 | 397084.9 | 8007412 | 2292.992 | 397326.5 | 8006678 | 1974.452 | 75.721140 | 159.834081 | 142 | D-C | 6.46950 | PC |
| 528 | RS | P | 0.163595 | 430610.6 | 8006754 | 3792.362 | 431811.9 | 8005765 | 3526.464 | 67.043915 | 155.369734 | 165 | D-C | 6.98551 | PC |
| 529 | RA | P | 3.714197 | 397319.7 | 8005923 | 2065.352 | 397235.9 | 8005281 | 1849.506 | 777.374840 | 218.740450 | 581 | VS-M | 24.56730 | CO |
| 530 | RS | P | 1.956103 | 436892.9 | 8003717 | 4052.664 | 436665.4 | 8003373 | 3991.008 | 585.347764 | 117.301828 | 725 | VS-M | 25.58840 | CO |
| 531 | RS | P | 2.153554 | 393624.1 | 7999846 | 1625.335 | 393977.7 | 7999136 | 1267.843 | 318.522855 | 264.428934 | 444 | V-PN | 14.94740 | CO |
| 532 | RS | P | 1.587760 | 391766.2 | 7997170 | 1335.676 | 391037.9 | 7997686 | 992.2701 | 368.276466 | 220.808774 | 526 | VS-PN | 19.19370 | CO |
| 533 | RS | P | 0.386928 | 391142.2 | 7996047 | 1349.007 | 390322 | 7996414 | 929.116 | 150.471024 | 304.283099 | 200 | D-C | 7.47886 | CC |
| 534 | RS | P | 0.519211 | 391290.8 | 7993046 | 1220.003 | 391642.3 | 7992182 | 992.3618 | 153.968287 | 316.630989 | 341 | SC-PN | 14.18200 | CO |
| 535 | RS | P | 0.466637 | 392222.7 | 7991615 | 1195.831 | 392328.7 | 7991188 | 997.5533 | 361.956579 | 139.264742 | 488 | VS-PN | 15.41340 | CO |
| 536 | RS | P | 0.304051 | 390942.4 | 7991436 | 1103.523 | 390992.2 | 7990592 | 935.1031 | 380.032572 | 302.109187 | 475 | VS-PN | 16.67350 | CO |
| 537 | RS | P | 0.611182 | 392861 | 798526 | 1377.089 | 393093.3 | 7985238 | 1266.828 | 367.734500 | 119.862284 | 524 | VS-PN | 17.69180 | CO |
| 538 | RS | P | 0.286652 | 393070 | 7984664 | 1378.844 | 392802.3 | 7984953 | 1258.067 | 155.321527 | 249.081918 | 316 | VS-PN | 16.25540 | CO |

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|-----|----|---|-----------|----------|---------|----------|----------|---------|----------|-------------|------------|------|-------|----------|----|
| 539 | RS | P | 1.389149 | 444729.4 | 7984379 | 4415.628 | 441897.3 | 7984439 | 3641.264 | 477.366206 | 123.269665 | 448 | VS-PN | 14.95960 | CO |
| 540 | RS | P | 2.913573 | 440086.7 | 7983800 | 3517.607 | 439487.2 | 7983707 | 3256.801 | 522.349435 | 272.549409 | 504 | VS-PN | 17.55830 | CO |
| 541 | RS | P | 0.588809 | 439454 | 7982051 | 3788.828 | 438977.9 | 7983845 | 3213.682 | 207.328712 | 102.828326 | 601 | VS-PN | 17.79410 | CO |
| 542 | RS | P | 0.612017 | 367732.1 | 7982273 | 518.0536 | 368229.9 | 7980533 | 243.5218 | 358.032434 | 244.692671 | 513 | VS-PN | 16.42950 | CO |
| 543 | RS | P | 2.676355 | 439642.3 | 7981504 | 3876.634 | 438459.8 | 7980363 | 3231.181 | 347.220300 | 323.326093 | 428 | SC-PN | 11.85430 | CO |
| 544 | RS | P | 7.894533 | 474018.5 | 7981162 | 5068.764 | 472901.7 | 7979956 | 4712.95 | 440.518788 | 92.980334 | 358 | VS-PN | 11.75300 | CO |
| 545 | RS | P | 6.318200 | 406096.7 | 7977852 | 2329.539 | 405607.2 | 7978158 | 2125.907 | 724.463341 | 291.879361 | 579 | VS-PN | 13.73420 | CO |
| 546 | RS | P | 1.085740 | 407413.3 | 7976102 | 2366.726 | 407653.7 | 7975411 | 2114.059 | 273.681834 | 245.614210 | 613 | VS-PA | 22.67940 | CO |
| 547 | RA | F | 0.418631 | 371112.6 | 7974900 | 496.6129 | 371411.7 | 7973719 | 337.9648 | 517.451885 | 146.302612 | 888 | VS-PN | 22.41410 | CO |
| 548 | RA | F | 0.297991 | 392470.6 | 7973236 | 1204.523 | 392458.3 | 7974244 | 993.7699 | 301.335043 | 149.115819 | 853 | VS-M | 24.71640 | CO |
| 549 | RA | F | 0.490119 | 378824.8 | 7971270 | 741.0258 | 377739.5 | 7972736 | 485.6181 | 568.203581 | 128.871496 | 1008 | VS-PN | 24.77530 | CO |
| 550 | RA | P | 5.524171 | 484826 | 7971913 | 4804.843 | 484084.7 | 7971770 | 4633.484 | 835.532046 | 86.189693 | 414 | VS-PN | 12.08480 | CO |
| 551 | RS | P | 0.891883 | 374533.1 | 7971159 | 516.798 | 373912.9 | 7971970 | 355.0086 | 343.135808 | 297.221073 | 536 | VS-M | 19.31330 | CO |
| 552 | RS | P | 1.784126 | 367473.4 | 7966657 | 328.8192 | 367459.2 | 7966210 | 152.0894 | 450.899095 | 257.630366 | 619 | VS-PN | 23.38470 | CO |
| 553 | RS | F | 0.179018 | 376412.5 | 7965787 | 558.7281 | 376427.5 | 7964679 | 290.4954 | 183.684864 | 278.686995 | 444 | VS-PN | 15.63890 | CO |
| 554 | RS | P | 1.139419 | 419879.4 | 7966858 | 3268.016 | 397156.3 | 7964969 | 882.2766 | 335.618950 | 134.209973 | 441 | VS-PN | 14.98290 | CO |
| 555 | RS | F | 4.189966 | 370913.1 | 7964868 | 434.9157 | 370986.5 | 7964103 | 212.3423 | 618.339147 | 90.810859 | 575 | VS-PN | 15.91700 | CO |
| 556 | RS | P | 0.861108 | 432582.7 | 7962591 | 3133.13 | 433879.5 | 7962041 | 2558.767 | 391.979892 | 277.358244 | 445 | VS-PN | 14.96060 | CO |
| 557 | RS | P | 16.208025 | 469212 | 7961593 | 4303.214 | 469335.9 | 7961943 | 4246.543 | 1016.121170 | 294.899285 | 364 | VS-PN | 14.13100 | CO |
| 558 | RS | F | 1.377728 | 420201.7 | 7962459 | 3287.646 | 420617.7 | 7960655 | 2614.409 | 477.290483 | 295.644346 | 530 | VS-PN | 17.85890 | CO |
| 559 | RS | P | 0.334906 | 432162.3 | 7962163 | 3157.923 | 432469.3 | 7960923 | 2392.877 | 107.459038 | 152.073635 | 243 | SC-PN | 16.10680 | CO |
| 560 | RS | F | 4.778727 | 434470.7 | 7960461 | 2995.192 | 434519.9 | 7961589 | 2530.212 | 603.516395 | 113.437119 | 480 | VS-M | 17.69690 | CO |
| 561 | RS | P | 13.419785 | 418578 | 7961606 | 3179.638 | 419569 | 7960314 | 2532.197 | 712.893703 | 164.100040 | 395 | VS-PN | 14.19030 | CO |
| 562 | RA | P | 3.611233 | 392832 | 7959442 | 1361.058 | 389174.3 | 7960373 | 598.0123 | 1073.166317 | 140.763182 | 556 | VS-PN | 16.08000 | CO |
| 563 | RS | P | 3.169944 | 384755.5 | 7957458 | 1036.99 | 385354.7 | 7959537 | 518.7319 | 1047.864168 | 293.061141 | 607 | VS-PN | 17.14720 | CO |
| 564 | RS | F | 0.848551 | 422387.5 | 7958280 | 3415.428 | 419489.2 | 7959068 | 2543.447 | 340.881854 | 192.222704 | 535 | VS-M | 17.39190 | CO |
| 565 | RA | P | 0.623576 | 475826.1 | 7956580 | 4400.024 | 474411.1 | 7957258 | 4146.678 | 442.586615 | 111.073968 | 707 | VS-M | 18.01690 | CO |
| 566 | RA | P | 1.294331 | 423050.2 | 7958112 | 3374.975 | 426306.9 | 7955372 | 1966.718 | 809.484261 | 120.654363 | 476 | VS-PN | 14.40650 | CO |
| 567 | RS | P | 3.190040 | 418454.1 | 7954065 | 3302.55 | 412151.3 | 7957432 | 1994.773 | 615.929275 | 307.360819 | 476 | VS-PN | 16.17890 | CO |
| 568 | RS | P | 0.182361 | 479231.9 | 7955226 | 4252.978 | 479087.8 | 7955015 | 4176.397 | 201.389930 | 127.733217 | 434 | SC-PN | 20.13560 | CO |
| 569 | RS | P | 0.109765 | 475868.8 | 7955407 | 4284.748 | 474436.7 | 7954737 | 4118.251 | 114.596187 | 263.964982 | 296 | SC-PN | 14.71530 | CO |
| 570 | RS | P | 1.367502 | 370532.8 | 7954675 | 445.8391 | 370197.6 | 7953942 | 176.3932 | 577.678436 | 286.507441 | 712 | V-PN | 23.72190 | CO |
| 571 | RS | P | 0.331967 | 474528.3 | 7953453 | 4218.531 | 474713.1 | 7953944 | 4119.038 | 120.183472 | 159.203252 | 292 | SC-PN | 17.58170 | CO |
| 572 | RS | P | 7.654203 | 453061.5 | 7953537 | 4710.693 | 452732.2 | 7952800 | 4376.23 | 1129.432666 | 144.185123 | 454 | VS-PN | 15.29150 | CO |
| 573 | RS | P | 0.189364 | 477717.1 | 7953004 | 4265.94 | 476991.7 | 7952806 | 4110.246 | 125.476537 | 233.555547 | 394 | SC-PN | 17.37120 | CO |
| 574 | RS | P | 2.160274 | 473558.1 | 7952524 | 4269.487 | 473548.8 | 7952183 | 4168.372 | 1024.491992 | 286.116425 | 1052 | VS-PA | 28.49420 | CO |
| 575 | RS | P | 14.956786 | 426983 | 7951047 | 3546.716 | 423908.6 | 7953526 | 1825.016 | 898.929996 | 150.611575 | 774 | VS-PA | 28.25070 | CO |
| 576 | RS | P | 0.349902 | 418080.9 | 7953784 | 3163.578 | 418534.6 | 7949557 | 1994.328 | 333.894154 | 312.995069 | 443 | VS-M | 21.43680 | CO |
| 577 | RS | P | 0.576669 | 473677.4 | 7951327 | 4271.9 | 473979.1 | 7951864 | 4160.211 | 142.471506 | 135.737516 | 333 | SC-PN | 17.37780 | CO |
| 578 | RS | P | 0.844028 | 416515 | 7952753 | 2984.272 | 417632.2 | 7946591 | 1477.658 | 75.639741 | 261.134359 | 365 | SC-PN | 18.58390 | CO |
| 579 | RS | P | 1.387080 | 382578.7 | 7949662 | 740.9842 | 381719 | 7948561 | 405.6166 | 296.246913 | 308.191118 | 550 | SC-PN | 19.63130 | CO |
| 580 | RS | P | 0.549627 | 424405 | 7947827 | 3508.683 | 420377.3 | 7949590 | 1596.482 | 221.815279 | 266.777547 | 397 | SC-PN | 19.31800 | CO |
| 581 | RS | P | 1.120672 | 463800.5 | 7948576 | 4890.124 | 465295.5 | 7947836 | 4529.859 | 288.128457 | 212.808446 | 359 | V-PN | 13.28800 | CO |
| 582 | RS | P | 1.672060 | 379184.2 | 7946431 | 782.167 | 380015.5 | 7948361 | 368.9368 | 304.233873 | 217.074274 | 591 | VS-PN | 24.00230 | CO |
| 583 | RS | P | 2.060409 | 389259.4 | 7948573 | 1134.922 | 388288.2 | 7946099 | 632.4362 | 548.857886 | 337.234622 | 726 | VS-M | 31.41840 | CO |
| 584 | RS | P | 15.990278 | 449563.7 | 7947164 | 3564.46 | 449301.8 | 7946957 | 3400.696 | 502.540257 | 201.247483 | 457 | SC-PN | 17.58610 | CO |
| 585 | RS | P | 0.567880 | 414144.4 | 7948392 | 2262.031 | 415339.2 | 7945121 | 1299.19 | 375.972254 | 179.703236 | 436 | V-PN | 15.72400 | CO |
| 586 | RS | P | 0.746472 | 408306.1 | 7948097 | 1862.403 | 407560.4 | 7945095 | 1056.762 | 422.910067 | 205.323483 | 572 | V-PN | 20.23240 | CO |
| 587 | RS | P | 0.562598 | 390712.1 | 7942703 | 1209.063 | 390772.9 | 7944744 | 609.3516 | 335.277970 | 299.881743 | 478 | SC-PN | 21.31040 | CO |

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|-----|----|---|------------|----------|---------|----------|----------|---------|----------|-------------|------------|------|-------|----------|----|
| 588 | RA | P | 0.459535 | 407077.7 | 7943173 | 1749.609 | 407082.2 | 7944853 | 1029.588 | 429.769966 | 284.235728 | 515 | VS-PA | 27.14020 | CO |
| 589 | RS | P | 1.303546 | 409733.5 | 7943031 | 1819.219 | 410061.7 | 7944634 | 1105.263 | 575.585743 | 338.917508 | 1021 | VS-M | 31.41140 | CO |
| 590 | RS | P | 0.104693 | 422263.3 | 7942888 | 3150.349 | 418506 | 7945169 | 1687.925 | 138.797727 | 283.540308 | 351 | SC-PN | 20.18960 | CO |
| 591 | RS | P | 2.333277 | 415518.7 | 7941744 | 2113.317 | 414505.6 | 7944633 | 1393.242 | 578.316460 | 334.688238 | 697 | VS-M | 25.55980 | CO |
| 592 | RS | P | 0.769970 | 447225.8 | 7941683 | 3506.572 | 446677.2 | 7941734 | 3329.14 | 389.728216 | 298.052517 | 586 | VS-M | 24.22110 | PC |
| 593 | RS | P | 1.156337 | 421120.2 | 7940248 | 2839.049 | 421489.1 | 7939689 | 2523.467 | 459.000865 | 207.637504 | 627 | VS-M | 26.43870 | CO |
| 594 | RS | P | 4.112707 | 456993.9 | 7939454 | 3935.64 | 456416.7 | 7939047 | 3686.795 | 808.105800 | 152.116698 | 714 | VS-M | 25.75020 | CO |
| 595 | RS | P | 0.363209 | 372373.4 | 7936930 | 662.3227 | 374132.2 | 7938129 | 352.4463 | 264.716435 | 303.327164 | 413 | SC-PN | 14.81530 | CO |
| 596 | RS | P | 3.054464 | 452329.3 | 7937612 | 3834.878 | 452183.9 | 7937111 | 3683.256 | 637.990821 | 299.171778 | 835 | VS-PN | 24.51610 | CO |
| 597 | RS | P | 4.841104 | 387292.8 | 7932336 | 1044.542 | 386567.3 | 7931216 | 676.8176 | 734.314646 | 24.784063 | 601 | VS-PN | 21.84230 | CO |
| 598 | RS | P | 4.187619 | 385989 | 7929907 | 1040.307 | 386586 | 7931105 | 668.6103 | 418.902255 | 293.732637 | 388 | SC-PN | 15.08470 | CO |
| 599 | RS | P | 4.309330 | 475419.9 | 7928865 | 4612.017 | 474642.8 | 7927775 | 4334.073 | 466.197614 | 293.933707 | 650 | VS-PN | 23.19980 | CO |
| 600 | RS | P | 0.754910 | 453345 | 7924534 | 3824.985 | 453529.2 | 7924040 | 3647.855 | 428.990463 | 278.053021 | 577 | VS-PN | 26.38400 | CO |
| 601 | RS | P | 5.403037 | 453646.2 | 7923733 | 3805.684 | 453421.3 | 7923952 | 3637.632 | 407.137617 | 139.735391 | 398 | SC-PN | 13.61980 | CO |
| 602 | RA | P | 0.989401 | 386682.5 | 7922104 | 1047.496 | 386043.3 | 7920705 | 738.2395 | 596.646465 | 270.664536 | 518 | VS-M | 23.18310 | CO |
| 603 | RS | P | 1.939391 | 389279.5 | 7918281 | 1130.21 | 389568.3 | 7919907 | 811.7245 | 524.174323 | 228.740499 | 718 | VS-PN | 23.61570 | CO |
| 604 | RS | P | 51.266341 | 456152.5 | 7917347 | 3759.11 | 455737.5 | 7916149 | 3431.878 | 1102.180030 | 206.938896 | 583 | VS-PN | 24.54610 | CO |
| 605 | RS | P | 0.871847 | 407117.8 | 7914894 | 1571.322 | 406446.4 | 7915582 | 1202.715 | 142.277657 | 293.943890 | 212 | D-C | 8.13010 | PC |
| 606 | RS | P | 3.533365 | 471686.8 | 7915381 | 4005.493 | 470794.4 | 7915097 | 3787.353 | 418.824711 | 269.591081 | 688 | VS-PN | 24.23390 | CO |
| 607 | RS | P | 0.290852 | 402559.3 | 7916070 | 1534.475 | 403011.2 | 7913497 | 1062.279 | 129.061993 | 304.682090 | 204 | D-C | 7.01175 | PC |
| 608 | RA | P | 2.329532 | 472643.1 | 7914432 | 3982.799 | 471613 | 7914175 | 3762.713 | 862.950436 | 165.080162 | 802 | VS-M | 23.14080 | CO |
| 609 | RS | P | 2.347741 | 474777.3 | 7914232 | 4028.75 | 473646.8 | 7914242 | 3786.344 | 746.739070 | 340.647834 | 867 | SMC-M | 23.06080 | CO |
| 610 | RA | P | 175.299335 | 393721.2 | 7914852 | 1229.101 | 393424.4 | 7913235 | 734.4908 | 3270.163624 | 221.500980 | 529 | VS-PN | 22.88010 | CO |
| 611 | RS | P | 1.116752 | 427532 | 7913066 | 2324.716 | 427082.9 | 7913281 | 2143.422 | 418.862075 | 104.663022 | 544 | VS-PN | 21.90720 | CO |
| 612 | RS | P | 9.329752 | 399924.3 | 7912223 | 1409.906 | 399875.2 | 7913754 | 955.4332 | 779.294894 | 288.742811 | 630 | VS-PN | 18.93880 | CO |
| 613 | RS | P | 2.713573 | 391595.6 | 7911837 | 1239.887 | 391436.7 | 7913963 | 661.2516 | 579.415810 | 150.719920 | 437 | VS-PN | 20.02890 | CO |
| 614 | RS | P | 1.722086 | 398682.4 | 7912146 | 1305.661 | 397765.9 | 7913342 | 894.1992 | 467.634099 | 284.394401 | 660 | VS-PN | 21.00700 | CO |
| 615 | RS | P | 1.224022 | 426970.2 | 7912553 | 2301.879 | 426604.2 | 7912853 | 2085.069 | 647.677007 | 204.735658 | 538 | VS-PN | 23.38340 | CO |
| 616 | RA | P | 6.775901 | 402431.6 | 7911608 | 1543.854 | 402119.9 | 7913811 | 1021.74 | 615.626630 | 232.865723 | 528 | VS-PN | 21.05350 | CO |
| 617 | RS | P | 0.245518 | 393121.5 | 7911385 | 1233.184 | 393467.5 | 7913212 | 731.0251 | 165.686907 | 210.452079 | 325 | VS-PN | 15.13780 | CO |
| 618 | RS | P | 1.473863 | 421157.8 | 7909739 | 1976.551 | 420865.5 | 7909944 | 1816.951 | 672.859290 | 247.418089 | 659 | VS-PN | 20.96140 | CO |
| 619 | RS | P | 0.760509 | 417640.3 | 7909713 | 1827.182 | 417821.1 | 7908669 | 1366.255 | 356.285917 | 185.550862 | 694 | VS-PN | 19.72050 | CO |
| 620 | RS | P | 2.705431 | 436448.2 | 7909060 | 2700.331 | 436255.2 | 7907991 | 2045.164 | 643.833207 | 320.624883 | 548 | VS-PN | 20.92190 | CO |
| 621 | RS | P | 2.761022 | 420010.1 | 7908041 | 1944.117 | 419040.8 | 7908790 | 1515.738 | 679.153671 | 317.955243 | 823 | VS-PN | 21.84680 | CO |
| 622 | RA | P | 0.708918 | 434904.5 | 7908794 | 2557.412 | 435129.1 | 7907062 | 1983.711 | 884.826557 | 325.461774 | 877 | VS-PN | 27.44170 | CO |
| 623 | RS | P | 1.696921 | 418998.6 | 7907084 | 1867.723 | 416393.5 | 7907876 | 1261 | 1011.031095 | 237.260768 | 728 | VS-PN | 23.62060 | CO |
| 624 | RS | P | 5.522049 | 415117.3 | 7907523 | 1493.418 | 415215.2 | 7906500 | 1141.518 | 807.599453 | 179.540418 | 749 | VS-PN | 28.60360 | CO |
| 625 | RS | P | 4.587500 | 441375.4 | 7908659 | 2765.971 | 440734.5 | 7904990 | 1838.076 | 240.222030 | 168.893477 | 221 | V-PN | 7.24832 | CO |
| 626 | RS | P | 4.956596 | 432753.4 | 7908677 | 2536.405 | 433266.1 | 7904954 | 1457.005 | 203.358678 | 325.288073 | 260 | V-PN | 12.10750 | CO |
| 627 | RS | P | 5.541105 | 469181.3 | 7906797 | 3784.338 | 469008 | 7906144 | 3547.444 | 404.795651 | 331.693815 | 723 | VS-PN | 22.40960 | CO |
| 628 | RS | P | 9.102732 | 446335.5 | 7907591 | 3170.7 | 445147.5 | 7905498 | 2216.12 | 335.826947 | 256.922321 | 234 | V-PN | 10.80530 | CO |
| 629 | RA | P | 24.934448 | 454631.1 | 7906582 | 3481.326 | 454481.1 | 7905328 | 2757.536 | 2468.303098 | 244.299987 | 650 | VS-PN | 19.72930 | CO |
| 630 | RS | P | 0.647529 | 416135 | 7905248 | 1767.604 | 415402.8 | 7906559 | 1157.154 | 372.004833 | 184.095636 | 653 | VS-PN | 26.29840 | CO |
| 631 | RS | P | 1.319009 | 429262.4 | 7907885 | 2466.364 | 431009.4 | 7903773 | 1360.041 | 302.334906 | 116.297722 | 248 | V-PN | 6.41523 | CO |
| 632 | RS | P | 0.630720 | 450157.4 | 7906412 | 3258.66 | 450117.1 | 7905033 | 2415.27 | 300.394464 | 312.370543 | 662 | VS-PN | 27.51400 | CO |
| 633 | RS | P | 0.665450 | 456740.2 | 7906115 | 3601.785 | 456310.3 | 7904974 | 2969.076 | 318.539417 | 161.778292 | 691 | VS-PN | 26.03050 | CO |
| 634 | RS | P | 1.782417 | 448443 | 7906594 | 3180.467 | 447758.6 | 7904597 | 2238.799 | 265.898052 | 129.458263 | 306 | SC-PN | 9.12124 | CO |
| 635 | RS | P | 0.685874 | 453059.8 | 7903875 | 3413.949 | 452809.8 | 7905336 | 2615.226 | 215.845442 | 187.446928 | 605 | VS-PN | 22.11610 | CO |
| 636 | RS | P | 0.226455 | 445118.6 | 7902418 | 3044.336 | 444553.4 | 7905058 | 2063.378 | 61.655135 | 213.455827 | 300 | V-C | 9.85064 | CO |

| | | | | | | | | | | | | | | | |
|-----|----|---|------------|----------|---------|----------|----------|---------|----------|-------------|------------|-----|-------|----------|----|
| 637 | RS | P | 0.830324 | 483648.8 | 7902222 | 4708.054 | 483140.9 | 7901273 | 4323.11 | 357.491555 | 153.515201 | 544 | VS-PN | 18.39330 | CO |
| 638 | RS | P | 1.065479 | 406188.1 | 7902360 | 1568.519 | 408559.1 | 7899651 | 836.9583 | 343.405426 | 305.355503 | 525 | VS-PN | 20.30760 | CO |
| 639 | RS | P | 0.481252 | 461905.4 | 7900112 | 3649.13 | 462210.6 | 7900264 | 3477.706 | 419.891097 | 294.146103 | 537 | VS-PN | 18.60010 | CO |
| 640 | RS | P | 1.155423 | 484226.9 | 7898676 | 4478.758 | 485092.6 | 7897889 | 4192.074 | 227.641169 | 157.877819 | 505 | SC-PN | 25.57950 | PC |
| 641 | RS | P | 0.465523 | 485996.8 | 7897579 | 4374.485 | 485480.1 | 7897526 | 4266.614 | 198.278082 | 166.070049 | 512 | SC-PN | 24.68700 | PC |
| 642 | RS | P | 0.853937 | 424476.8 | 7896304 | 2257.483 | 423898.6 | 7897636 | 1697.229 | 168.419819 | 176.622514 | 452 | SC-PN | 24.57320 | PC |
| 643 | RA | P | 5.148483 | 489236.4 | 7897131 | 4946.665 | 488138.4 | 7896404 | 4511.749 | 612.020890 | 283.174399 | 338 | V-PN | 15.56100 | CO |
| 644 | RS | P | 0.203003 | 477854.1 | 7895783 | 4118.006 | 476787.2 | 7896141 | 3903.273 | 110.260948 | 141.186948 | 197 | VS-PN | 11.36290 | PC |
| 645 | RS | P | 0.202191 | 396298.1 | 7896969 | 1339.45 | 397424.9 | 7894472 | 497.3056 | 120.777328 | 317.168132 | 202 | VS-PN | 10.87020 | PC |
| 646 | RS | P | 1.829494 | 432414.7 | 7896354 | 2619.81 | 432576.2 | 7894639 | 2288.355 | 774.364238 | 271.206124 | 597 | VS-PN | 23.80220 | CO |
| 647 | RS | P | 0.321206 | 403369.2 | 7893335 | 1343.748 | 402233.9 | 7896599 | 565.4105 | 260.806141 | 261.231659 | 599 | VS-PN | 22.01750 | CO |
| 648 | RS | P | 1.135638 | 487572.7 | 7894715 | 4490.577 | 487613.9 | 7893961 | 4300.723 | 575.145415 | 345.139490 | 620 | VS-PN | 24.29330 | CO |
| 649 | RS | P | 10.738298 | 474296.5 | 7893660 | 3768.07 | 474548.5 | 7893113 | 3709.103 | 274.531881 | 164.033794 | 245 | SC-PN | 7.47343 | PC |
| 650 | RS | P | 0.925247 | 441604.1 | 7893866 | 2902.823 | 441557.4 | 7892972 | 2648.248 | 645.452489 | 226.004804 | 565 | VS-PN | 24.78840 | CO |
| 651 | RS | P | 1.933872 | 487373.8 | 7892679 | 4423.788 | 486705.1 | 7893579 | 4221.375 | 355.814159 | 222.787942 | 564 | V-PN | 21.59020 | CO |
| 652 | RS | P | 0.302481 | 398192.7 | 7892047 | 1265.03 | 397291.8 | 7893850 | 473.1881 | 203.632303 | 301.994112 | 474 | VS-PN | 18.19050 | CO |
| 653 | RS | P | 0.686670 | 437019.4 | 7893301 | 2748.169 | 436927.2 | 7892740 | 2524.247 | 252.666893 | 160.824414 | 457 | VS-PN | 16.18350 | CO |
| 654 | RS | P | 2.033119 | 470871.4 | 7893156 | 3729.845 | 470673 | 7892481 | 3675.295 | 158.648100 | 165.785644 | 250 | VS-PN | 7.65600 | PC |
| 655 | RS | P | 2.216961 | 439291.6 | 7893069 | 2888.552 | 439518.3 | 7891847 | 2500.818 | 210.753439 | 359.301287 | 344 | SC-PN | 11.62340 | PC |
| 656 | RS | P | 5.126552 | 432632.1 | 7892850 | 2429.295 | 433090.1 | 7891250 | 2179.191 | 255.407735 | 323.493858 | 319 | SC-PN | 8.82159 | PC |
| 657 | RS | P | 0.530421 | 423317.3 | 7892246 | 2019.994 | 424089.6 | 7890759 | 1764.302 | 171.358323 | 259.083807 | 290 | VS-PN | 11.32090 | CO |
| 658 | RS | P | 1.428990 | 437384.5 | 7890615 | 2740.877 | 437203.4 | 7891609 | 2453.528 | 161.789421 | 322.597372 | 295 | VS-PN | 9.66633 | PC |
| 659 | RS | P | 0.525669 | 488188 | 7890797 | 4530.364 | 488718.6 | 7889897 | 4207.797 | 176.729840 | 181.819312 | 292 | SC-PN | 11.96400 | PC |
| 660 | RS | P | 2.645632 | 420265.9 | 7889272 | 1701.342 | 419506.3 | 7889683 | 1416.46 | 268.232650 | 179.224697 | 398 | VS-PN | 10.45840 | PC |
| 661 | RS | P | 180.624400 | 428584 | 7890203 | 2296.612 | 429679.6 | 7888872 | 1872.544 | 2385.739148 | 265.246320 | 698 | VS-PN | 20.24180 | CO |
| 662 | RS | P | 0.598005 | 416084.1 | 7888927 | 1650.523 | 417575.5 | 7887867 | 1298.466 | 222.573430 | 174.525795 | 331 | SC-PN | 11.11290 | PC |
| 663 | RS | P | 1.458476 | 430213.4 | 7887796 | 2240.808 | 429253.1 | 7888725 | 1854.553 | 574.362789 | 112.981263 | 615 | V-PN | 17.92610 | CO |
| 664 | RS | P | 0.228798 | 422757.4 | 7887759 | 1977.623 | 422309.7 | 7886100 | 1580.115 | 56.671350 | 19.474116 | 79 | SC-PN | 5.16076 | CO |
| 665 | RS | P | 3.019913 | 433433.3 | 7887289 | 2476.395 | 434524.5 | 7886337 | 2193.625 | 673.236604 | 167.016763 | 618 | VS-PN | 24.06380 | CO |
| 666 | RS | P | 1.007677 | 459354.9 | 7886683 | 3747.131 | 459934.3 | 7886187 | 3493.856 | 765.045362 | 166.094736 | 824 | V-PN | 22.07200 | CO |
| 667 | RS | P | 1.341493 | 425573.8 | 7887348 | 1953.736 | 425802.3 | 7885614 | 1661.098 | 464.979978 | 2.498415 | 690 | VS-PN | 23.23470 | CO |
| 668 | RS | P | 2.604894 | 413950.4 | 7886997 | 1531.603 | 414963.9 | 7885830 | 1124.226 | 647.441334 | 142.515278 | 701 | VS-PN | 27.53590 | CO |
| 669 | RS | P | 21.214725 | 411738.1 | 7885963 | 1427.32 | 412012.8 | 7884772 | 983.9849 | 763.045430 | 284.282188 | 458 | VS-PN | 17.94920 | PC |
| 670 | RS | P | 5.629820 | 410276.5 | 7884954 | 1380.087 | 410934.5 | 7883969 | 930.4415 | 518.258134 | 16.072890 | 329 | VS-PN | 11.56160 | PC |
| 671 | RS | P | 4.119321 | 420683.7 | 7883474 | 1489.737 | 420684.3 | 7882896 | 1343.355 | 871.980852 | 285.220886 | 617 | VS-PN | 23.67050 | CO |
| 672 | RS | P | 2.453518 | 440742.2 | 7884650 | 2805.47 | 429710.1 | 7880680 | 1923.461 | 253.345936 | 295.592981 | 265 | V-PN | 10.72230 | CO |
| 673 | RS | P | 21.045524 | 418979.5 | 7882584 | 1417.142 | 419239.5 | 7881878 | 1207.042 | 1408.256842 | 130.068654 | 775 | VS-PN | 23.27220 | CO |
| 674 | RS | P | 44.157701 | 407445.9 | 7882371 | 1249.93 | 408890.2 | 7880495 | 791.076 | 1307.776754 | 298.106531 | 631 | VS-PN | 19.42800 | CO |
| 675 | RS | P | 0.194585 | 415138.4 | 7880231 | 1291.315 | 415019.4 | 7881270 | 1011.306 | 76.581285 | 214.324394 | 210 | V-PN | 9.06351 | CO |
| 676 | RS | P | 3.489546 | 403244.5 | 7881660 | 1156.864 | 403419.9 | 7879781 | 635.284 | 166.496734 | 244.925801 | 319 | V-PN | 10.71950 | CO |
| 677 | RS | P | 1.507148 | 427765.9 | 7880990 | 2018.58 | 428720 | 7879906 | 1678.199 | 269.445926 | 204.581543 | 341 | SC-PN | 9.64136 | PC |
| 678 | RS | P | 0.316961 | 429659.8 | 7878583 | 2037.221 | 428484.1 | 7879252 | 1634.626 | 99.492547 | 20.617843 | 184 | SC-PN | 9.19875 | CO |
| 679 | RS | P | 0.353105 | 397930.4 | 7879615 | 1069.172 | 398434.1 | 7878018 | 484.6397 | 334.463071 | 204.078846 | 599 | VS-PN | 20.97480 | CO |
| 680 | RS | P | 1.840932 | 481493 | 7878897 | 4044.819 | 480938.8 | 7878061 | 3810.308 | 155.693562 | 254.744671 | 258 | SC-PN | 9.32343 | CO |
| 681 | RS | P | 0.204574 | 423729.4 | 7879166 | 1759.542 | 424474.9 | 7877706 | 1378.022 | 101.115007 | 181.555637 | 158 | SC-PN | 9.92474 | CO |
| 682 | RS | P | 18.348427 | 426480.8 | 7877313 | 1850.095 | 426351.9 | 7878390 | 1508.73 | 1721.699718 | 308.881136 | 884 | VS-PN | 22.99260 | CO |
| 683 | RS | P | 6.537257 | 404977.6 | 7875540 | 1202.241 | 402568.6 | 7879853 | 603.692 | 1169.250425 | 173.873035 | 683 | VS-PN | 17.84330 | CO |
| 684 | RS | P | 0.926512 | 409089.4 | 7876076 | 1269.182 | 409426.8 | 7878989 | 818.2725 | 111.688712 | 29.331618 | 165 | SC-PN | 7.90534 | CO |
| 685 | RS | P | 6.309795 | 425318.7 | 7876570 | 1756.968 | 424412.9 | 7877530 | 1384.998 | 1506.613754 | 169.723368 | 491 | VS-PN | 18.02840 | CO |

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|-----|----|---|-----------|----------|---------|----------|----------|---------|----------|-------------|------------|-----|-------|----------|----|
| 686 | RS | P | 1.950408 | 401805.6 | 7875669 | 1104.531 | 399167.6 | 7878124 | 506.5477 | 335.367657 | 218.001988 | 513 | SC-PN | 13.43760 | PC |
| 687 | RS | P | 17.164784 | 451632.4 | 7876792 | 3240.938 | 452207.6 | 7876127 | 2927.139 | 1912.200815 | 293.636428 | 790 | VS-PN | 21.10510 | CO |
| 688 | RS | P | 1.276596 | 419064.4 | 7875523 | 1546.85 | 418927.4 | 7876405 | 1149.375 | 360.265371 | 116.327280 | 354 | V-PN | 13.81590 | CO |
| 689 | RS | P | 15.740926 | 422319.5 | 7875068 | 1669.537 | 422060.2 | 7876710 | 1261.672 | 413.230192 | 23.302678 | 328 | SC-PN | 9.28089 | PC |
| 690 | RS | P | 13.526973 | 452601.7 | 7876023 | 3104.31 | 453089.5 | 7875440 | 2838.38 | 502.485918 | 201.430571 | 499 | SC-PN | 14.22210 | PC |
| 691 | RS | P | 0.172288 | 454831.2 | 7874462 | 3266.617 | 453088.4 | 7875325 | 2830.611 | 163.764055 | 231.568131 | 425 | VS-PN | 17.70200 | CO |
| 692 | RS | P | 14.253422 | 476822.8 | 7874750 | 3986.449 | 476360.8 | 7874325 | 3843.009 | 962.840815 | 159.933855 | 655 | VS-PN | 16.58720 | CO |
| 693 | RS | P | 23.527610 | 449137.8 | 7872961 | 3007.488 | 449508.1 | 7872176 | 2735.494 | 805.640440 | 193.948286 | 605 | VS-PN | 16.92890 | PC |
| 694 | RS | P | 33.611745 | 410098 | 7873944 | 1293.633 | 409531.4 | 7871100 | 771.3505 | 599.711489 | 1.705573 | 442 | SC-PN | 17.82280 | PC |
| 695 | RS | P | 4.407410 | 440044.5 | 7872588 | 2551.263 | 434752.2 | 7871908 | 2170.573 | 720.020691 | 0.152645 | 615 | SC-PN | 16.40190 | PC |
| 696 | RS | P | 4.588804 | 420383.3 | 7869230 | 1456.805 | 419565.8 | 7870720 | 1049.341 | 713.955458 | 11.567943 | 675 | VS-PN | 18.30320 | PC |
| 697 | RS | P | 7.964345 | 445427.6 | 7869803 | 2731.94 | 445696.2 | 7869015 | 2417.046 | 1462.423978 | 301.265288 | 779 | VS-PN | 22.15770 | CO |
| 698 | RS | P | 15.648857 | 484717.6 | 7869177 | 4217.737 | 484369.6 | 7868753 | 4051.219 | 720.075247 | 340.674626 | 493 | VS-PN | 14.89510 | CO |
| 699 | RS | P | 0.527238 | 434511.2 | 7868512 | 1939.831 | 433290.4 | 7869320 | 1511.52 | 177.431378 | 275.376277 | 328 | V-PN | 15.69320 | CO |
| 700 | RS | P | 0.686707 | 411313.6 | 7865302 | 1296.195 | 411799.5 | 7870444 | 843.3988 | 315.582155 | 146.544461 | 575 | VS-PN | 23.09390 | CO |
| 701 | RS | P | 0.243896 | 445633.3 | 7867527 | 2706.742 | 444527.7 | 7868522 | 2292.368 | 248.844630 | 234.859232 | 399 | SC-PN | 21.63470 | CO |
| 702 | RS | P | 7.152746 | 423149.2 | 7868782 | 1475.16 | 423091.9 | 7867096 | 1134.996 | 309.876460 | 55.727321 | 258 | D-C | 6.86634 | PC |
| 703 | RS | P | 0.375653 | 441583.9 | 7868692 | 2547.046 | 441990.8 | 7866391 | 1787.582 | 151.621767 | 196.199987 | 266 | V-PN | 11.98470 | CO |
| 704 | RS | P | 2.360665 | 426636.6 | 7865147 | 1777.132 | 425762.5 | 7867254 | 1307.323 | 367.724575 | 212.928239 | 420 | SC-PN | 10.17110 | PC |
| 705 | RS | P | 3.299561 | 447344.2 | 7866483 | 2825.306 | 447111.5 | 7865658 | 2418.235 | 371.697157 | 26.483712 | 390 | SC-PN | 10.44770 | PC |
| 706 | RS | P | 1.446725 | 437860.7 | 7867289 | 2066.425 | 437029.8 | 7864710 | 1559.945 | 277.943966 | 215.489491 | 326 | V-PN | 12.93820 | CO |
| 707 | RS | P | 0.329612 | 423431.6 | 7864764 | 1618.626 | 422783.3 | 7866466 | 1255.98 | 177.130358 | 159.581103 | 378 | VS-PN | 16.28130 | CO |
| 708 | RS | P | 0.349042 | 457450.6 | 7866848 | 3060.103 | 458189.8 | 7864543 | 2486.041 | 168.051923 | 314.223920 | 287 | VS-PN | 13.14980 | CO |
| 709 | RS | P | 3.650585 | 447118.1 | 7865173 | 2529.376 | 446709.8 | 7865539 | 2356.087 | 309.256613 | 204.560975 | 326 | SC-PN | 10.51120 | PC |
| 710 | RS | P | 4.210484 | 462334.8 | 7865005 | 3186.704 | 459113.9 | 7864873 | 2564.73 | 318.485158 | 10.076180 | 260 | SC-PN | 7.63017 | PC |
| 711 | RS | P | 1.076725 | 453583.9 | 7865652 | 2945.899 | 454019 | 7863445 | 2489.931 | 327.231984 | 199.106289 | 648 | V-PN | 19.63410 | CO |
| 712 | RS | P | 0.781507 | 464134.5 | 7863855 | 3292.895 | 463924.3 | 7862288 | 2856.143 | 368.607618 | 315.709952 | 495 | SC-PN | 19.43680 | PC |
| 713 | RS | P | 0.566559 | 450688.7 | 7863296 | 2482.789 | 450990.4 | 7862672 | 2161.149 | 218.139973 | 252.351445 | 304 | V-PN | 14.03130 | CO |
| 714 | RS | P | 12.233624 | 458430.1 | 7863198 | 2720.732 | 457872.2 | 7861602 | 2421.749 | 472.195841 | 170.039704 | 369 | SC-PN | 12.07280 | PC |
| 715 | RS | P | 1.093065 | 466475.9 | 7862813 | 3464.364 | 466055 | 7861600 | 3070.738 | 220.086160 | 256.028500 | 294 | V-PN | 13.42230 | CO |
| 716 | RS | P | 1.874666 | 446751.5 | 7863443 | 2662.982 | 447350.2 | 7860869 | 2003.131 | 242.405467 | 270.536122 | 449 | V-PN | 13.22480 | CO |
| 717 | RS | P | 2.991764 | 450787.9 | 7861716 | 2437.466 | 450425.2 | 7862401 | 2137.251 | 494.610371 | 190.406265 | 423 | SC-PN | 12.10450 | PC |
| 718 | RS | P | 0.244203 | 371883.5 | 7861914 | 1065.631 | 369407.1 | 7860286 | 63.52971 | 181.294372 | 295.592630 | 376 | VS-PN | 18.49760 | CO |
| 719 | RS | P | 1.720458 | 455810.8 | 7859444 | 2885.421 | 455662.1 | 7858547 | 2587.171 | 454.473183 | 358.163120 | 434 | SC-PN | 17.33290 | PC |
| 720 | RS | P | 3.703828 | 469264.7 | 7851354 | 3603.623 | 466382 | 7852007 | 3082.123 | 578.635387 | 355.725140 | 434 | SC-PN | 10.72740 | PC |
| 721 | RS | P | 2.966619 | 459073.5 | 7850894 | 3018.062 | 459967.7 | 7850000 | 2628.617 | 411.462141 | 322.529526 | 485 | SC-PN | 20.11770 | PC |
| 722 | RS | P | 0.388699 | 458775.3 | 7850227 | 2876.875 | 459507.2 | 7849534 | 2592.944 | 216.810321 | 309.314003 | 361 | VS-PN | 18.16280 | CO |
| 723 | RS | P | 7.315726 | 462425 | 7847142 | 3064.677 | 463670.5 | 7845906 | 2637.008 | 522.114043 | 351.946392 | 388 | SC-PN | 15.80870 | PC |
| 724 | RS | P | 3.256862 | 478538.8 | 7845367 | 3514.328 | 477280 | 7847678 | 3111.456 | 502.158565 | 10.728034 | 437 | SC-PN | 14.08110 | PC |
| 725 | RS | P | 0.193437 | 471644.8 | 7846094 | 3025.98 | 470529.4 | 7844892 | 2561.65 | 159.599635 | 305.048852 | 366 | VS-PN | 15.90800 | CO |
| 726 | RS | P | 3.898884 | 475254.9 | 7841839 | 2976.48 | 475211.2 | 7841033 | 2768.99 | 460.926801 | 170.176583 | 723 | VS-PN | 19.35130 | PC |
| 727 | RS | P | 1.012929 | 482857.1 | 7841600 | 3768.689 | 481176.4 | 7840325 | 3290.117 | 655.166952 | 190.226936 | 742 | VS-PN | 23.46250 | CO |
| 728 | RS | P | 1.929968 | 393982.3 | 7841144 | 1003.955 | 393284 | 7839819 | 763.9959 | 428.378731 | 307.690603 | 543 | VS-PN | 14.59470 | CO |
| 729 | RS | P | 3.406609 | 390543.7 | 7839498 | 1028.653 | 391495.4 | 7841102 | 726.0647 | 573.700599 | 172.613719 | 577 | VS-PN | 18.32430 | CO |
| 730 | RS | P | 5.285874 | 481400.1 | 7838510 | 3818.609 | 481772 | 7839866 | 3351.031 | 606.722994 | 286.900585 | 548 | VS-PN | 17.73470 | PC |
| 731 | RS | P | 1.079948 | 480192.2 | 7837146 | 3792.832 | 476276.5 | 7839899 | 2774.096 | 351.900195 | 174.532296 | 752 | SC-PN | 20.29110 | PC |
| 732 | RS | P | 9.971080 | 473536.8 | 7838436 | 2827.487 | 472847.8 | 7838450 | 2632.36 | 927.894921 | 189.908127 | 610 | VS-PN | 20.05970 | CO |
| 733 | RS | P | 7.042680 | 397333 | 7838382 | 1053.342 | 396986.3 | 7838068 | 920.5727 | 1079.399381 | 172.160948 | 512 | VS-PN | 17.29080 | CO |
| 734 | RS | P | 0.381708 | 396714.2 | 7837523 | 1097.075 | 397105.2 | 7837883 | 924.0294 | 236.894811 | 194.863818 | 434 | V-PN | 15.79410 | CO |

| | | | | | | | | | | | | | | | |
|-----|----|---|-----------|----------|---------|----------|----------|---------|----------|-------------|------------|-----|-------|----------|----|
| 735 | RS | P | 7.625544 | 402523.9 | 7837935 | 1141.333 | 402407.5 | 7837450 | 1060.795 | 954.579324 | 209.578163 | 643 | VS-PN | 20.93500 | CO |
| 736 | RS | P | 1.487435 | 384512.7 | 7837402 | 961.9895 | 384461.4 | 7837899 | 855.8061 | 723.789827 | 186.822353 | 780 | VS-PN | 21.13760 | CO |
| 737 | RS | P | 2.874101 | 462238.8 | 7836806 | 2335.278 | 461552.9 | 7836801 | 2086.146 | 610.450026 | 330.820169 | 770 | VS-PN | 23.76660 | PC |
| 738 | RS | P | 19.044596 | 374524.3 | 7835706 | 411.3525 | 373608.5 | 7835689 | 41.29883 | 1106.323141 | 156.983142 | 533 | SC-PN | 19.70880 | CO |
| 739 | RA | P | 0.982490 | 393175.4 | 7834710 | 1145.069 | 393687.4 | 7834827 | 1068.533 | 846.458508 | 173.567583 | 783 | VS-PN | 23.04330 | CO |
| 740 | RA | P | 0.757260 | 471222.6 | 7835439 | 3233.412 | 470073.4 | 7834342 | 2767.429 | 401.217403 | 171.394835 | 467 | V-PN | 15.35720 | CO |
| 741 | RS | P | 2.146912 | 473074.7 | 7835529 | 3223.834 | 473059.8 | 7833905 | 2760.176 | 843.389799 | 181.671750 | 775 | VS-PN | 23.64080 | CO |
| 742 | RS | P | 1.408454 | 465763.8 | 7834038 | 2612.641 | 466505.2 | 7834924 | 2270.525 | 632.708529 | 200.646346 | 689 | VS-PN | 25.08450 | CO |
| 743 | RS | P | 3.224555 | 457269.1 | 7835536 | 2390.137 | 457507.6 | 7833057 | 1914.549 | 941.667679 | 198.918489 | 712 | VS-PN | 20.95520 | CO |
| 744 | RS | P | 6.295475 | 463540.9 | 7833392 | 2556.05 | 462091.5 | 7834685 | 2014.933 | 798.722721 | 350.284512 | 940 | VS-PN | 23.75630 | CO |
| 745 | RS | P | 4.556616 | 522697.8 | 7833946 | 4255.184 | 524208.4 | 7833692 | 4179.523 | 980.958247 | 347.913162 | 703 | VS-PN | 21.14690 | CO |
| 746 | RS | P | 0.588112 | 453351.5 | 7834360 | 2281.874 | 453785.5 | 7832107 | 1778.11 | 384.944231 | 208.169423 | 573 | V-C | 18.62530 | CO |
| 747 | RS | P | 12.442778 | 458773.8 | 7832044 | 2280.999 | 458233.4 | 7833084 | 1911.277 | 731.561077 | 138.798350 | 455 | SC-PN | 12.00930 | PC |
| 748 | RS | P | 0.157288 | 456026.8 | 7832274 | 2057.258 | 455749.6 | 7832918 | 1823.127 | 171.424646 | 63.531412 | 263 | V-PN | 13.05680 | CO |
| 749 | RA | P | 4.951813 | 394440.7 | 7832474 | 1127.959 | 394661.3 | 7832657 | 1083.551 | 1173.844207 | 143.822437 | 606 | SC-PN | 19.91840 | PC |
| 750 | RS | P | 0.511591 | 395439 | 7832117 | 1117.209 | 395447.1 | 7832355 | 1090.318 | 286.683651 | 132.242007 | 413 | V-C | 15.32360 | CO |
| 751 | RS | P | 0.234828 | 458363.6 | 7831838 | 2247.593 | 458338.8 | 7830739 | 1962.326 | 107.870764 | 264.162315 | 563 | V-C | 18.35170 | CO |
| 752 | RS | P | 1.590482 | 452115.7 | 7830190 | 2096.573 | 452690.9 | 7831339 | 1761.876 | 560.253740 | 336.543770 | 665 | SC-PN | 16.94880 | CO |
| 753 | RS | P | 0.876906 | 465923.6 | 7831500 | 2709.218 | 466025 | 7830143 | 2294.12 | 434.915856 | 236.469530 | 610 | V-C | 20.72160 | CO |
| 754 | RS | P | 1.441772 | 464724.4 | 7831106 | 2671.836 | 464363.3 | 7829904 | 2214.828 | 214.732469 | 288.544167 | 497 | V-C | 16.48540 | CO |
| 755 | RS | P | 13.377124 | 455820.4 | 7829032 | 2323.836 | 455564.2 | 7830628 | 1856.656 | 842.144356 | 155.714977 | 648 | SC-PN | 15.46020 | PC |
| 756 | RS | P | 3.194013 | 463091 | 7828951 | 2657.679 | 463525.6 | 7830530 | 2211.639 | 331.454856 | 174.623930 | 315 | SC-PN | 14.71180 | CO |
| 757 | RS | P | 19.307382 | 514542.9 | 7828145 | 4743.663 | 514085.8 | 7826734 | 4571.043 | 778.337292 | 340.819485 | 466 | SC-PN | 12.89470 | PC |
| 758 | RS | P | 0.519088 | 513738.7 | 7827598 | 4687.115 | 513665.6 | 7826715 | 4626.163 | 189.854455 | 176.878485 | 568 | V-C | 20.60010 | CO |
| 759 | RS | P | 0.571899 | 505929.3 | 7825830 | 4265.436 | 505570.9 | 7826193 | 4069.798 | 58.966677 | 155.251633 | 193 | V-PN | 7.30470 | CO |
| 760 | RS | P | 0.834397 | 505337.1 | 7825390 | 4229.162 | 504607.1 | 7825710 | 3952.552 | 254.575189 | 182.990892 | 410 | SC-PN | 21.06390 | CO |
| 761 | RS | P | 1.367819 | 448178.8 | 7823425 | 1976 | 448123.5 | 7823552 | 1951.072 | 202.412527 | 323.400036 | 408 | V-C | 12.83110 | CO |
| 762 | RS | P | 4.705251 | 503848.5 | 7822169 | 4088.631 | 503528.2 | 7822536 | 3889.104 | 791.841854 | 333.447964 | 618 | SC-PN | 13.75830 | PC |
| 763 | RS | P | 0.566203 | 503200.3 | 7821385 | 4081.214 | 502665.5 | 7821758 | 3864.36 | 223.922398 | 189.330355 | 464 | SC-PN | 18.78930 | CO |
| 764 | RS | P | 0.276036 | 514882.9 | 7821366 | 4740.598 | 514777.7 | 7820724 | 4433.925 | 54.550083 | 196.377413 | 87 | V-PN | 5.28131 | CO |
| 765 | RS | P | 2.096761 | 478606.7 | 7819680 | 3241.414 | 478018.7 | 7819448 | 3051.208 | 387.733651 | 169.492040 | 500 | SC-PN | 18.66660 | CO |
| 766 | RS | P | 12.088369 | 498191.4 | 7818142 | 3917.148 | 498571.7 | 7817685 | 3617.293 | 250.103666 | 164.019449 | 419 | SC-PN | 19.07080 | CO |
| 767 | RS | P | 4.380650 | 494991.5 | 7817799 | 3983.836 | 495177.9 | 7817401 | 3782.562 | 255.692363 | 152.560229 | 383 | SC-PN | 18.65040 | CO |
| 768 | RS | P | 2.899474 | 457681.6 | 7817209 | 2193.736 | 456941.9 | 7817502 | 2045.772 | 287.348944 | 349.674918 | 404 | SC-PN | 20.28380 | CO |
| 769 | RS | P | 0.528037 | 499039.6 | 7817106 | 3865.275 | 498219.3 | 7817465 | 3599.551 | 322.566966 | 149.475758 | 347 | V-C | 12.52990 | CO |
| 770 | RS | P | 0.690122 | 484259.9 | 7817459 | 3991.242 | 485103.3 | 7816120 | 3511.101 | 284.881899 | 298.403447 | 492 | VS-PN | 22.42100 | CO |
| 771 | RS | P | 4.706743 | 490413.5 | 7815917 | 3955.39 | 489578.5 | 7816966 | 3639.73 | 424.067686 | 140.556743 | 381 | SC-PN | 14.36640 | CO |
| 772 | RS | P | 6.462532 | 497862.5 | 7815533 | 3813.543 | 497000.9 | 7815728 | 3545.203 | 352.057349 | 125.413971 | 374 | SC-PN | 12.54840 | PC |
| 773 | RS | P | 1.515410 | 474210.6 | 7816216 | 2980.986 | 474718.2 | 7815089 | 2497.76 | 386.255601 | 314.037971 | 508 | SC-PN | 21.46960 | CO |
| 774 | RS | P | 4.075120 | 477137.3 | 7814377 | 2965.198 | 474624.1 | 7814924 | 2486.144 | 397.507994 | 195.095522 | 467 | SC-PN | 18.88650 | CO |
| 775 | RS | P | 3.359974 | 477853.4 | 7815467 | 3121.354 | 478351.9 | 7814802 | 2973.114 | 282.769566 | 131.080341 | 343 | SC-PN | 18.57160 | CO |
| 776 | RS | P | 0.891440 | 488580.2 | 7814931 | 3635.565 | 488190.4 | 7815224 | 3453.005 | 253.275776 | 130.600319 | 368 | V-PN | 16.24360 | CO |
| 777 | RS | P | 5.594107 | 486008.4 | 7815829 | 3862.814 | 486645.9 | 7814467 | 3193.82 | 292.637768 | 172.489679 | 397 | SC-PN | 18.20960 | CO |
| 778 | RS | P | 3.523316 | 472585.4 | 7814606 | 2862.344 | 473508.8 | 7813696 | 2376.163 | 407.377348 | 139.029652 | 413 | SC-PN | 12.09930 | PC |
| 779 | RS | P | 2.352539 | 455948.7 | 7813546 | 2060.597 | 455696 | 7814080 | 1939.832 | 443.334895 | 167.015186 | 511 | SC-PN | 11.91230 | PC |
| 780 | RS | P | 1.101850 | 480709.5 | 7815264 | 3315.808 | 480719.6 | 7811842 | 2623.19 | 449.645251 | 146.236107 | 505 | SC-PN | 12.43070 | PC |
| 781 | RS | P | 0.459524 | 471244.6 | 7812864 | 2763.035 | 472551.2 | 7812121 | 2299.373 | 146.381804 | 179.937815 | 415 | SC-PN | 18.99780 | CO |
| 782 | RS | P | 69.736973 | 483671.7 | 7810786 | 3418.7 | 483395.4 | 7812912 | 2767.31 | 882.008921 | 250.208197 | 558 | V-PN | 17.58570 | CO |
| 783 | RS | P | 1.537585 | 488031 | 7811782 | 3705.414 | 487668 | 7811360 | 3473.385 | 210.100867 | 159.769117 | 380 | SC-PN | 15.49170 | PC |

| | | | | | | | | | | | | | | | |
|-----|----|---|-----------|----------|---------|----------|----------|---------|----------|-------------|------------|-----|-------|----------|----|
| 784 | RS | P | 3.911808 | 527767.6 | 7811505 | 4671.663 | 526969.9 | 7811076 | 4426.458 | 458.853847 | 142.403664 | 437 | SC-PN | 13.08480 | PC |
| 785 | RS | P | 1.728402 | 484648.5 | 7810438 | 3437.201 | 485658.4 | 7811838 | 2906.831 | 280.009552 | 353.468830 | 490 | SC-PN | 20.91740 | PC |
| 786 | RS | P | 15.422940 | 470343.8 | 7811409 | 2740.782 | 471312.9 | 7810442 | 2201.891 | 521.580347 | 174.667636 | 458 | SC-PN | 12.29390 | PC |
| 787 | RS | P | 4.076626 | 489060.2 | 7811592 | 3698.291 | 489469.4 | 7810375 | 3272.059 | 340.381407 | 138.661783 | 361 | SC-PN | 14.34720 | CO |
| 788 | RS | P | 3.531828 | 477895.1 | 7809150 | 3002.517 | 476628 | 7811256 | 2378.06 | 402.594863 | 299.653082 | 487 | SC-PN | 17.85590 | CO |
| 789 | RS | P | 3.385989 | 442032.4 | 7809741 | 1579.464 | 441554.9 | 7810222 | 1513.582 | 584.532150 | 162.493358 | 527 | SC-PN | 22.78460 | PC |
| 790 | RS | P | 1.334145 | 474828.3 | 7808993 | 2898.35 | 474504.2 | 7810636 | 2289.352 | 234.511294 | 213.518403 | 330 | V-PN | 14.31960 | CO |
| 791 | RS | P | 7.126459 | 519717 | 7809243 | 4576.075 | 517951.2 | 7809327 | 4300.853 | 381.519590 | 152.944814 | 437 | SC-PN | 17.17560 | CO |
| 792 | RS | P | 0.975681 | 468495.2 | 7809357 | 2571.229 | 469311.9 | 7807904 | 2274.389 | 341.365610 | 353.169842 | 534 | SC-PN | 20.22270 | CO |
| 793 | RS | P | 24.371492 | 521093 | 7806799 | 4467.308 | 520763.2 | 7807164 | 4387.081 | 598.549047 | 330.816478 | 339 | SC-PN | 10.05660 | PC |
| 794 | RS | P | 15.373712 | 465947.7 | 7807224 | 2400.646 | 466695.2 | 7805953 | 1984.676 | 450.909561 | 6.607732 | 304 | SC-PN | 10.12820 | PC |
| 795 | RS | P | 2.830667 | 476158.7 | 7808044 | 2936.465 | 474903.9 | 7805955 | 2415.535 | 371.969832 | 316.651240 | 520 | SC-PN | 18.63840 | CO |
| 796 | RS | P | 6.937321 | 470782.9 | 7805230 | 2502.918 | 470105.2 | 7806392 | 2175.954 | 597.982981 | 312.943430 | 417 | SC-PN | 11.15840 | PC |
| 797 | RS | P | 1.401086 | 483974.3 | 7806039 | 3386.572 | 484092.6 | 7805617 | 3247.423 | 313.798847 | 139.167550 | 398 | V-PN | 16.40690 | CO |
| 798 | RS | P | 1.014180 | 482997.7 | 7805629 | 3318.54 | 483029.8 | 7805298 | 3168.896 | 397.474855 | 351.176212 | 485 | SC-PN | 15.53430 | PC |
| 799 | RS | P | 5.311770 | 475298.2 | 7804703 | 2884.215 | 475841.9 | 7805826 | 2419.327 | 407.865015 | 351.029741 | 374 | SC-PN | 12.97830 | PC |
| 800 | RS | P | 2.722007 | 463613.6 | 7806336 | 2345.572 | 464837.9 | 7804415 | 1840.979 | 265.929764 | 140.097489 | 465 | SC-PN | 19.81740 | CO |
| 801 | RS | P | 10.374661 | 461075.8 | 7804858 | 2210.4 | 461315.9 | 7803703 | 1757.367 | 436.006529 | 296.339826 | 450 | V-PN | 14.81130 | CO |
| 802 | RS | P | 0.520301 | 452687.9 | 7804282 | 1857.261 | 453132.1 | 7803106 | 1575.136 | 143.440662 | 227.434993 | 355 | V-PN | 13.98040 | CO |
| 803 | RS | P | 1.743799 | 468987.1 | 7803116 | 2521.443 | 468486.2 | 7803887 | 2178.826 | 271.994499 | 154.738862 | 410 | V-PN | 15.50350 | CO |
| 804 | RS | P | 18.893319 | 477108.8 | 7802864 | 2943.97 | 477861.8 | 7803802 | 2598.51 | 522.282835 | 191.267897 | 406 | SC-PN | 10.71560 | PC |
| 805 | RS | P | 47.878537 | 464303.2 | 7802399 | 2315.308 | 463857.4 | 7803890 | 1891.104 | 380.689945 | 262.682003 | 472 | V-PN | 16.04850 | CO |
| 806 | RS | P | 4.349011 | 382881.7 | 7804203 | 883.8886 | 380694.4 | 7803510 | 1.90163 | 407.464032 | 331.257342 | 458 | SC-PN | 19.69360 | PC |
| 807 | RS | P | 1.078865 | 505128.3 | 7802538 | 4150.478 | 505737.6 | 7801991 | 3955.667 | 314.893459 | 161.182398 | 530 | V-PN | 17.82990 | CO |
| 808 | RS | P | 0.490019 | 456550.3 | 7800751 | 1953.399 | 456862.6 | 7801583 | 1757.063 | 166.518149 | 219.348078 | 403 | V-PN | 15.31540 | CO |
| 809 | RS | P | 1.480576 | 475508.5 | 7800928 | 2885.445 | 475374.4 | 7800726 | 2800.015 | 428.311359 | 303.499887 | 493 | SC-PN | 19.72890 | CO |
| 810 | RS | P | 72.987749 | 484516.9 | 7801198 | 3363.601 | 484370 | 7800465 | 3201.491 | 452.796357 | 5.398338 | 290 | SC-PN | 8.71355 | PC |
| 811 | RS | P | 5.370944 | 462660.3 | 7800704 | 2269.672 | 462647 | 7800271 | 2089.281 | 414.373820 | 311.975157 | 578 | V-PN | 18.80540 | CO |
| 812 | RS | P | 6.905324 | 382869.4 | 7798448 | 781.7721 | 380569 | 7797982 | 5.329585 | 340.164599 | 181.946190 | 458 | SC-PN | 15.43300 | PC |
| 813 | RS | P | 11.331291 | 521947.5 | 7797568 | 4245.978 | 519755.4 | 7797823 | 4050.5 | 759.464138 | 169.971369 | 542 | V-PN | 15.14100 | CO |
| 814 | RS | P | 7.870304 | 480714.9 | 7797215 | 3148.251 | 480583.6 | 7796724 | 2955.385 | 469.809184 | 337.475257 | 475 | V-PN | 16.52790 | PC |
| 815 | RS | P | 0.440886 | 476511.5 | 7796736 | 2878.453 | 476451.9 | 7796446 | 2756.904 | 407.070803 | 195.747183 | 601 | V-PN | 17.84150 | CO |
| 816 | RS | P | 6.226438 | 484946.4 | 7795769 | 3394.898 | 484572.9 | 7795062 | 3126.091 | 506.480391 | 197.863466 | 556 | SC-PN | 19.90290 | CO |
| 817 | RS | P | 2.845312 | 491562.6 | 7793418 | 3954.217 | 490141.9 | 7793797 | 3551.043 | 362.645429 | 339.142948 | 428 | SC-PN | 12.28240 | PC |
| 818 | RS | P | 4.247405 | 382320.8 | 7793412 | 597.5982 | 380852.7 | 7793213 | 3.885506 | 574.061194 | 162.215754 | 572 | SC-PN | 18.99960 | CO |
| 819 | RS | P | 0.326258 | 489581.7 | 7792140 | 3784.501 | 488509 | 7793242 | 3497.786 | 173.289685 | 311.808009 | 614 | SC-PN | 20.82240 | CO |
| 820 | RS | P | 17.002598 | 510401.7 | 7792409 | 4501.31 | 508199.1 | 7791450 | 4099.523 | 621.974166 | 267.656700 | 409 | V-PN | 14.98080 | CO |
| 821 | RS | P | 4.068552 | 492674.6 | 7790742 | 3783.186 | 492287.5 | 7789809 | 3489.334 | 455.967872 | 168.848499 | 646 | SC-PN | 16.04980 | CO |
| 822 | RS | P | 1.279518 | 485789.4 | 7790690 | 3531.265 | 486321.3 | 7789457 | 3114.87 | 436.751392 | 187.642294 | 480 | V-PN | 15.43090 | CO |
| 823 | RS | P | 0.422553 | 483504.8 | 7789272 | 3281.048 | 483749 | 7788327 | 2906.353 | 321.639829 | 154.185761 | 776 | VS-PN | 24.10450 | CO |
| 824 | RS | P | 1.359224 | 479652.7 | 7788393 | 3015.462 | 479543.9 | 7787345 | 2675.151 | 298.983084 | 199.264490 | 392 | SC-PN | 15.83840 | CO |
| 825 | RS | P | 4.540534 | 478684.4 | 7788187 | 2963.11 | 478849.9 | 7787150 | 2641.521 | 393.625747 | 199.134891 | 540 | V-PN | 15.25790 | CO |
| 826 | RS | P | 3.542567 | 496613 | 7786666 | 4032.107 | 496315.3 | 7787978 | 3827.12 | 659.851423 | 166.908743 | 591 | V-PN | 19.13880 | CO |
| 827 | RS | P | 0.830735 | 494223.2 | 7786131 | 4167.456 | 495642.9 | 7786924 | 3864.38 | 300.215418 | 332.096257 | 416 | VS-PN | 24.47040 | CO |
| 828 | RS | P | 3.131667 | 480055.7 | 7786348 | 3000.666 | 478327.2 | 7786544 | 2620.729 | 1002.101727 | 236.675744 | 709 | SC-M | 17.79720 | CC |
| 829 | RS | P | 0.787065 | 476385.7 | 7786525 | 2842.112 | 476615.6 | 7785699 | 2526.402 | 298.249461 | 189.415657 | 483 | V-PN | 22.80880 | CO |
| 830 | RS | P | 9.575917 | 478139 | 7784866 | 2920.382 | 477713.9 | 7785970 | 2564.819 | 521.499620 | 282.769020 | 534 | V-PN | 23.02270 | CO |
| 831 | RS | P | 0.797675 | 474089.7 | 7785530 | 2666.768 | 474105.4 | 7785089 | 2469.057 | 389.445223 | 134.986397 | 522 | VS-PN | 21.94550 | CO |
| 832 | RS | P | 0.452675 | 457618.6 | 7784719 | 1837.588 | 457248.4 | 7784704 | 1691.72 | 283.930838 | 133.451103 | 469 | VS-PN | 20.25570 | CO |

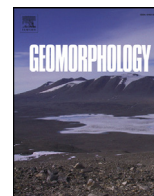
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|-----|----|---|-----------|----------|---------|----------|----------|---------|----------|-------------|------------|-----|-------|----------|----|
| 833 | RS | P | 2.390769 | 459218.6 | 7783339 | 1875.745 | 459017 | 7782921 | 1758.85 | 427.669000 | 134.781160 | 558 | V-PN | 21.23540 | CO |
| 834 | RS | P | 5.016064 | 495828.2 | 7783003 | 4430.107 | 495086.3 | 7782196 | 4006.197 | 402.872150 | 331.421321 | 687 | V-PN | 17.36620 | CO |
| 835 | RS | P | 1.243191 | 404173.2 | 7781669 | 1396.87 | 403904.7 | 7781636 | 1286.572 | 464.330341 | 222.864950 | 643 | V-PN | 18.75300 | CO |
| 836 | RS | P | 0.260186 | 461033.4 | 7781588 | 1942.163 | 461064.5 | 7781230 | 1777.386 | 207.490061 | 183.101197 | 716 | V-PN | 24.48800 | CO |
| 837 | RS | P | 2.184371 | 478379.3 | 7778669 | 2820.316 | 478372 | 7778058 | 2609.143 | 478.572007 | 232.812761 | 557 | V-PN | 17.27480 | CO |
| 838 | RS | P | 4.961884 | 476621.8 | 7777596 | 2671.142 | 476769.4 | 7777104 | 2503.911 | 239.959600 | 207.796615 | 300 | SC-PN | 7.91653 | PC |
| 839 | RS | P | 8.459011 | 403172.7 | 7775887 | 1210.925 | 402782.7 | 7775980 | 1109.51 | 302.588462 | 30.690470 | 253 | SC-PN | 8.03813 | PC |
| 840 | RS | P | 2.242924 | 487538.2 | 7774284 | 3731.626 | 486427.5 | 7773937 | 3345.158 | 467.578017 | 15.338291 | 540 | V-PN | 17.98600 | CO |
| 841 | RS | P | 12.956893 | 486008.6 | 7774522 | 3677.699 | 484602.7 | 7773046 | 3220.296 | 1018.735418 | 305.106792 | 562 | V-PN | 15.19470 | CO |
| 842 | RS | P | 0.407976 | 488408 | 7772915 | 3786.806 | 487940.3 | 7771663 | 3387.553 | 195.127254 | 271.095354 | 354 | V-PN | 16.05970 | CO |
| 843 | RS | P | 0.268372 | 543478.1 | 7771078 | 4302.943 | 542343.6 | 7772163 | 4169.58 | 132.769642 | 227.782554 | 220 | SC-PN | 12.14810 | PC |
| 844 | RS | P | 0.173467 | 488429.9 | 7768533 | 3493.111 | 488851.6 | 7767446 | 3003.353 | 173.045439 | 47.354017 | 252 | SC-PN | 11.34900 | PC |
| 845 | RS | P | 1.101626 | 486560.1 | 7767677 | 3273.384 | 486901.8 | 7766549 | 2815.453 | 80.538534 | 193.515573 | 121 | SC-PN | 6.42379 | PC |
| 846 | RS | P | 0.348318 | 485080.6 | 7766637 | 3118.421 | 485497.7 | 7765704 | 2701.902 | 106.183409 | 354.110519 | 196 | SC-PN | 8.56389 | CC |
| 847 | RA | P | 2.730249 | 444898.2 | 7766045 | 1114.495 | 444790.5 | 7765853 | 1107.987 | 709.147511 | 307.069355 | 601 | V-PN | 18.77000 | CO |
| 848 | RS | P | 0.791321 | 483133.5 | 7766091 | 2926.518 | 483195.7 | 7765259 | 2672.163 | 249.131165 | 269.535167 | 402 | VS-PN | 21.17530 | CO |
| 849 | RS | P | 1.005936 | 478799.8 | 7765674 | 2635.793 | 478707.8 | 7764825 | 2286.628 | 370.053652 | 268.913963 | 506 | SC-PN | 15.01040 | CC |
| 850 | RS | P | 0.754887 | 481274.9 | 7765647 | 2741.167 | 481220.9 | 7764657 | 2437.458 | 76.535337 | 77.204270 | 178 | SC-PN | 6.52907 | CC |
| 851 | RS | P | 1.373239 | 488707.2 | 7764129 | 3429.919 | 488318.4 | 7765332 | 3010.32 | 465.983396 | 226.317363 | 533 | V-PN | 22.38650 | CO |
| 852 | RS | P | 1.716671 | 479796.6 | 7763118 | 2673.219 | 479350.4 | 7762299 | 2358.577 | 463.657699 | 180.526721 | 460 | V-PN | 21.95730 | CO |
| 853 | RS | P | 1.977826 | 480590.2 | 7762229 | 2673.521 | 479916.7 | 7761739 | 2412.276 | 342.115415 | 39.931276 | 579 | VS-PN | 19.43220 | CO |
| 854 | RS | P | 8.040531 | 539988.1 | 7761599 | 4472.13 | 539593.6 | 7761534 | 4342.244 | 475.588437 | 174.505196 | 499 | VS-PN | 18.75590 | CO |
| 855 | RS | P | 4.537322 | 494358.2 | 7760562 | 4138.718 | 494978.2 | 7760613 | 4024.533 | 541.117317 | 311.744813 | 695 | SC-PN | 22.62630 | CO |
| 856 | RA | P | 16.715523 | 545853 | 7760988 | 4221.884 | 545909.3 | 7760036 | 4006.104 | 941.502608 | 271.641077 | 479 | V-PN | 15.61850 | CO |
| 857 | RS | P | 3.870345 | 509269.9 | 7755746 | 4054.911 | 510751.1 | 7754888 | 3825.326 | 75.661063 | 99.561491 | 178 | V-PN | 7.07945 | CO |
| 858 | RS | P | 8.538020 | 383641.7 | 7754871 | 481.3419 | 383215.9 | 7755276 | 178.3118 | 503.763820 | 169.094422 | 394 | VS-PN | 17.50360 | CO |
| 859 | RS | P | 4.242569 | 390358.3 | 7753882 | 876.1342 | 390244.7 | 7753558 | 739.3735 | 369.721922 | 332.548503 | 610 | VS-PN | 18.56220 | CO |
| 860 | RS | P | 0.757584 | 498097.7 | 7753734 | 4225.426 | 498563 | 7753511 | 4155.618 | 234.131255 | 336.723269 | 410 | VS-PN | 17.67150 | CO |
| 861 | RS | P | 0.309097 | 497984.9 | 7749106 | 4039.586 | 498081.8 | 7748870 | 4007.13 | 44.407341 | 50.303000 | 151 | SC-PN | 5.79064 | CC |
| 862 | RS | P | 0.122404 | 420160.8 | 7747833 | 1163.5 | 420784.7 | 7747579 | 1011.845 | 26.891034 | 1.936500 | 84 | SC-PN | 4.46972 | CC |
| 863 | RS | P | 3.624862 | 481296.3 | 7745138 | 2589.793 | 481964.6 | 7744561 | 2487.622 | 285.267192 | 181.292105 | 448 | VS-PN | 17.75120 | CO |
| 864 | RS | P | 2.049642 | 499196.9 | 7740857 | 4057.43 | 499375.6 | 7740634 | 3989.532 | 334.697375 | 26.603005 | 460 | VS-PN | 17.10330 | CO |
| 865 | RS | P | 1.772806 | 497858.5 | 7739812 | 3964.984 | 498081.4 | 7739609 | 3899.003 | 415.098104 | 175.730368 | 451 | VS-PN | 24.13510 | CO |
| 866 | RS | P | 1.656969 | 479323.3 | 7738162 | 2365.137 | 478609.1 | 7738485 | 2103.889 | 457.007416 | 196.723289 | 588 | VS-PN | 25.38680 | CO |
| 867 | RS | P | 8.839273 | -80017 | 8342896 | 3312.788 | -79958 | 8341889 | 3191.794 | 467.179644 | 350.878762 | 344 | SC-PN | 12.65060 | CO |
| 868 | RS | P | 8.046715 | -96486.4 | 8341844 | 2809.325 | -97127.7 | 8342057 | 2628.444 | 446.040509 | 15.387743 | 515 | SC-PN | 15.08950 | CO |
| 869 | RS | P | 1.164463 | -99522.4 | 8341232 | 2548.041 | -100923 | 8341971 | 2214.495 | 172.619838 | 197.953224 | 196 | V-PN | 7.73743 | CO |
| 870 | RS | P | 0.298346 | -20812.2 | 8333684 | 3396.128 | -17377.6 | 8333122 | 2520.89 | 60.951936 | 184.731294 | 255 | V-PN | 8.75476 | CO |
| 871 | RA | P | 1.071004 | -35124.8 | 8327518 | 3044.798 | -32779.8 | 8327739 | 2385.286 | 363.845197 | 243.762966 | 476 | SC-PN | 16.78030 | CO |
| 872 | RA | P | 1.256047 | -43174 | 8323670 | 3264.778 | -35802 | 8322862 | 2244.263 | 565.371716 | 164.161085 | 533 | V-PN | 18.16290 | CO |
| 873 | RS | P | 0.162646 | -12442.3 | 8321400 | 3172.403 | -11776.7 | 8322974 | 2876.068 | 195.638157 | 315.325761 | 469 | V-PN | 15.22220 | CO |
| 874 | RS | P | 0.359430 | -101811 | 8310954 | 2042.503 | -99590.1 | 8309572 | 1328.361 | 276.610088 | 293.641069 | 415 | V-PN | 15.62790 | CO |
| 875 | RS | P | 0.122211 | -103700 | 8310598 | 1986.074 | -104783 | 8309059 | 1530.065 | 24.928455 | 336.416900 | 156 | SC-PN | 7.34800 | CO |
| 876 | RS | P | 0.311716 | 256254.4 | 8299784 | 4317.508 | 255727.7 | 8299833 | 4204.914 | 199.527359 | 318.868376 | 283 | V-PN | 14.53380 | CO |
| 877 | RS | P | 0.362010 | -33936.8 | 8292005 | 3541.288 | -35134.9 | 8290518 | 3128.708 | 216.853588 | 304.882747 | 380 | V-PN | 13.75930 | CO |
| 878 | RS | P | 0.289007 | -68436.8 | 8266090 | 1997.276 | -68451.5 | 8262459 | 1101.838 | 306.673462 | 189.304433 | 520 | V-PN | 19.54680 | CO |
| 879 | RS | P | 0.615210 | 270743.2 | 8148449 | 2966.6 | 268875.6 | 8146570 | 2262.822 | 190.205962 | 248.432051 | 536 | V-PN | 22.03900 | CO |
| 880 | RS | P | 0.465937 | 296998.7 | 8117562 | 3095.121 | 296822.1 | 8115535 | 2584.702 | 299.855364 | 140.252267 | 423 | V-PN | 16.89530 | CO |
| 881 | RS | P | 0.176124 | 377486 | 8034132 | 2386.763 | 375294.6 | 8032473 | 1771.136 | 201.273906 | 154.923023 | 434 | V-PN | 15.51020 | CO |

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|-----|----|---|-----------|----------|---------|----------|----------|---------|----------|------------|------------|-----|-------|----------|----|
| 882 | RS | P | 0.483877 | 403041.7 | 8012164 | 3239.819 | 383199.5 | 8002615 | 771.5163 | 147.964614 | 291.600560 | 308 | SC-PN | 18.16850 | CO |
| 883 | RS | P | 1.301454 | 450209.5 | 7988781 | 4780.829 | 446703.5 | 7989601 | 4168.808 | 265.723586 | 293.646911 | 420 | V-PN | 15.36520 | CO |
| 884 | RS | P | 1.314615 | 479163.8 | 7833976 | 3746.455 | 473534.5 | 7834137 | 2804.952 | 480.141194 | 147.791642 | 687 | V-PN | 26.47510 | CO |
| 885 | RS | P | 1.293264 | 474564.2 | 7826762 | 3299.89 | 473526.5 | 7826250 | 2936.045 | 315.659168 | 321.491370 | 503 | V-PN | 16.82680 | CO |
| 886 | RS | P | 0.471220 | 487575.8 | 7812865 | 3672.789 | 485532.2 | 7811905 | 2873.599 | 268.339743 | 282.785794 | 359 | V-PN | 15.08630 | CO |
| 887 | RS | P | 3.304245 | 475312.7 | 7812747 | 2741.401 | 475057.9 | 7811339 | 2428.273 | 483.226607 | 155.744392 | 603 | SC-PN | 20.58730 | CO |
| 888 | RS | P | 10.393510 | 488502.2 | 7811486 | 3702.275 | 488554.1 | 7810443 | 3316.992 | 479.053901 | 282.284734 | 524 | V-PN | 18.31100 | CO |
| 889 | RS | P | 1.037872 | 481544.8 | 7810319 | 3302.173 | 480962.9 | 7811915 | 2639.475 | 148.239938 | 143.153917 | 447 | V-PN | 17.05700 | CO |
| 890 | RS | P | 0.148106 | 479891.3 | 7810097 | 3185.096 | 479100.7 | 7811657 | 2546.727 | 182.560510 | 306.915532 | 534 | V-PN | 16.86700 | CO |
| 891 | RS | P | 3.622555 | 483094.7 | 7804977 | 3269.083 | 482917.3 | 7803727 | 2927.812 | 668.993728 | 154.908120 | 676 | V-PN | 21.78970 | CO |
| 892 | RS | P | 1.737306 | 483953 | 7801795 | 3304.686 | 483778.5 | 7803180 | 2858.015 | 486.181034 | 134.560704 | 647 | SC-PN | 20.78240 | CO |
| 893 | RS | P | 0.489791 | 487331.4 | 7801355 | 3543.365 | 487277.8 | 7802690 | 3111.69 | 120.765282 | 334.677959 | 303 | VS-PN | 13.28570 | CO |
| 894 | RS | P | 16.216723 | 464886.8 | 7786858 | 2412.078 | 464434 | 7786592 | 2258.243 | 692.618116 | 179.831415 | 613 | V-PN | 18.35170 | CO |
| 895 | RA | P | 1.996969 | 483126.2 | 7777183 | 3238.643 | 481661.1 | 7776343 | 2872.463 | 799.190243 | 244.821190 | 486 | V-PN | 15.81360 | CO |
| 896 | RS | P | 4.034471 | 403681.5 | 7772690 | 1140.137 | 403266.8 | 7772367 | 1032.095 | 463.662200 | 119.626789 | 539 | SC-PN | 17.64550 | CO |
| 897 | RA | P | 1.233699 | 416186.4 | 7743976 | 1469.411 | 417176.3 | 7742951 | 1087.915 | 313.128002 | 190.259501 | 466 | V-PN | 17.76240 | CO |
| 898 | RS | P | 4.677925 | 109118.8 | 8349837 | 4825.825 | 108640.4 | 8349989 | 4594.837 | 651.390652 | 352.593402 | 535 | V-PN | 15.13370 | CO |
| 899 | RS | P | 0.234215 | -17957.5 | 8347617 | 3950.922 | -17661.1 | 8346719 | 3764.924 | 232.028766 | 220.729563 | 727 | V-PN | 20.09820 | CO |
| 900 | RS | P | 1.395443 | -19689.2 | 8346896 | 3929.37 | -19267.3 | 8345559 | 3517.099 | 245.204861 | 241.750335 | 689 | V-PN | 18.08050 | CO |
| 901 | RS | P | 1.769835 | 174282.1 | 8345307 | 4685.349 | 173685.1 | 8345909 | 4399.201 | 530.369860 | 35.817377 | 514 | V-PN | 14.87090 | CO |
| 902 | RA | P | 0.613504 | 36469.49 | 8341443 | 4000.558 | 37030.73 | 8340395 | 3644.163 | 385.283277 | 177.151226 | 675 | V-PN | 19.03490 | CO |
| 903 | RS | P | 1.379959 | -83422 | 8335183 | 2609.982 | -84479.4 | 8335470 | 2258.141 | 538.891282 | 134.927876 | 582 | SC-PN | 19.46830 | CO |
| 904 | RS | P | 1.106910 | -17934.4 | 8328486 | 3045.212 | -15958.9 | 8328467 | 2288.307 | 426.231941 | 161.422986 | 538 | V-PN | 16.34470 | CO |
| 905 | RA | P | 2.147006 | 97981.23 | 8326337 | 4133.801 | 96939.73 | 8329005 | 2875.269 | 662.698601 | 339.967419 | 637 | SC-PN | 18.39560 | CO |
| 906 | RA | P | 1.023376 | -28032.8 | 8326700 | 3181.983 | -26843.5 | 8326457 | 2606.721 | 638.368838 | 333.119575 | 624 | V-PN | 21.21610 | CO |
| 907 | RS | P | 5.783311 | -14389.1 | 8326991 | 2943.741 | -13255.8 | 8326080 | 2633.28 | 624.457276 | 328.964538 | 508 | V-PN | 16.96700 | CO |
| 908 | RA | P | 1.137849 | -28860.8 | 8325529 | 3188.509 | -32168.5 | 8324398 | 1934.308 | 539.716156 | 133.962644 | 563 | SC-PN | 19.54830 | CO |
| 909 | RS | P | 0.855131 | -37186.8 | 8325241 | 2845.817 | -35849.6 | 8323851 | 2324.089 | 65.881972 | 315.191941 | 120 | SC-PN | 4.23784 | PC |
| 910 | RS | P | 2.351883 | -14522.5 | 8323471 | 3038.262 | -13830.7 | 8324689 | 2487.189 | 608.998670 | 348.844722 | 566 | V-PN | 22.48820 | CO |
| 911 | RS | P | 0.979770 | -16258.1 | 8323053 | 3278.686 | -19538.6 | 8323444 | 1985.58 | 275.222096 | 272.712638 | 336 | V-PN | 12.10210 | CO |
| 912 | RA | P | 2.008311 | 53500.85 | 8319372 | 4192.306 | 53193.35 | 8320299 | 3975.885 | 334.877210 | 216.799517 | 448 | VS-M | 18.00150 | CO |
| 913 | RS | P | 5.015375 | -12737.2 | 8316862 | 3904.638 | -17278.7 | 8319781 | 2679.977 | 296.840609 | 150.671101 | 526 | SC-PN | 17.11780 | CO |
| 914 | RA | P | 0.260747 | -21009.8 | 8315884 | 3055.393 | -20473 | 8317980 | 2192.105 | 266.398926 | 140.539153 | 374 | V-PN | 15.60790 | CO |
| 915 | RS | P | 0.266934 | -20568.2 | 8315533 | 3076.957 | -19436 | 8315480 | 2789.488 | 80.227562 | 317.962822 | 430 | V-PN | 12.51520 | CO |
| 916 | RA | P | 0.112005 | -20616.7 | 8311236 | 3270.563 | -18855 | 8315960 | 2602.389 | 320.590010 | 168.435441 | 444 | V-PN | 16.41610 | CO |
| 917 | RA | P | 0.219507 | -22892.1 | 8310923 | 3435.043 | -22803.6 | 8316354 | 2658.652 | 356.740833 | 162.341827 | 435 | V-PN | 17.29170 | CO |
| 918 | RS | P | 2.580203 | -34347.3 | 8305825 | 3647.996 | -41244.2 | 8313288 | 1503.335 | 415.970460 | 149.546256 | 511 | SC-PN | 17.51550 | CO |
| 919 | RA | P | 0.158150 | 18558.52 | 8305726 | 4361.994 | 17510.22 | 8312359 | 3011.022 | 348.330834 | 146.905419 | 484 | V-PN | 19.18430 | CO |
| 920 | RS | P | 26.307838 | 80212.15 | 8307143 | 4167.442 | 74755.68 | 8312372 | 2257.127 | 520.930264 | 210.989931 | 488 | V-PN | 18.70990 | CO |
| 921 | RS | P | 1.905302 | -41421 | 8305461 | 3358.395 | -42453.5 | 8311854 | 1499.457 | 326.964289 | 329.736116 | 587 | VS-PN | 22.94550 | CO |
| 922 | RS | P | 0.430837 | 230266.9 | 8302891 | 4627.523 | 232368.4 | 8301426 | 3901.212 | 139.149078 | 164.340321 | 303 | V-PN | 14.77890 | CO |
| 923 | RA | P | 4.200677 | 48942.28 | 8299041 | 4240.031 | 42542.76 | 8298332 | 2294.188 | 688.361871 | 217.758759 | 605 | V-PN | 18.69190 | CO |
| 924 | RS | P | 0.113727 | 48014.93 | 8295094 | 3665.474 | 42614.37 | 8296156 | 1936.532 | 149.644645 | 174.468007 | 350 | V-PN | 15.11820 | CO |
| 925 | RS | P | 1.934408 | -34389.4 | 8295753 | 3834.802 | -39080.2 | 8295547 | 2956.341 | 464.887923 | 25.848114 | 531 | SC-PN | 17.87460 | CO |
| 926 | RS | P | 5.713398 | 187801.1 | 8292758 | 5245.699 | 187090.5 | 8292042 | 4775.729 | 504.593527 | 147.497646 | 452 | VS-PN | 16.38930 | CO |
| 927 | RA | P | 2.228211 | -3887.61 | 8287914 | 4033.212 | -3926.35 | 8284883 | 3274.833 | 341.270462 | 188.080010 | 488 | SM-M | 18.81320 | CO |
| 928 | RS | P | 0.743256 | 249913.5 | 8278775 | 4282.456 | 248022.1 | 8277971 | 4077.592 | 453.032709 | 168.253638 | 488 | VS-PN | 17.71490 | CO |
| 929 | RS | P | 2.599300 | 199296.1 | 8277936 | 4528.022 | 197726.3 | 8276627 | 3735.164 | 282.125366 | 159.307313 | 341 | SC-PN | 12.53770 | CO |
| 930 | RS | P | 0.492973 | 205567.6 | 8276842 | 4811.278 | 203743.7 | 8277181 | 4375.017 | 342.616422 | 326.962018 | 587 | SC-PN | 17.90350 | CO |

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|-----|----|---|----------|----------|---------|----------|----------|---------|----------|------------|------------|-----|-------|----------|----|
| 931 | RS | P | 4.442289 | -11773.5 | 8274849 | 3163.239 | -9299.02 | 8275659 | 2405.207 | 345.459635 | 38.736494 | 466 | VS-PN | 13.74110 | CO |
| 932 | RS | P | 2.740263 | 50166.05 | 8268286 | 3841.109 | 50878.51 | 8265763 | 3056.37 | 424.204036 | 343.356791 | 480 | SC-PN | 16.66730 | CO |
| 933 | RS | P | 9.642806 | 205371.9 | 8266395 | 3700.825 | 206374.5 | 8266787 | 3461 | 881.986970 | 252.418654 | 690 | VS-M | 18.09810 | CC |
| 934 | RA | P | 2.808776 | 204947.4 | 8265351 | 4045.426 | 206087.8 | 8265838 | 3620.161 | 446.671241 | 352.819251 | 481 | VS-PN | 18.02520 | CO |
| 935 | RS | P | 0.342956 | 131927.5 | 8256008 | 3239.094 | 129729.7 | 8253474 | 1744.721 | 194.810845 | 131.937779 | 315 | V-PN | 13.30160 | CO |
| 936 | RA | P | 0.901678 | 174512 | 8255588 | 4761.158 | 170556.8 | 8253069 | 3858.477 | 431.675137 | 357.703249 | 383 | VS-M | 17.59340 | CO |
| 937 | RS | P | 0.789770 | 133141.8 | 8253474 | 3048.741 | 131285.8 | 8253141 | 2270.135 | 196.335664 | 20.583382 | 372 | V-M | 17.98460 | CO |
| 938 | RS | P | 0.101279 | 227828.7 | 8249867 | 4871.87 | 229093 | 8251550 | 4513.835 | 85.429167 | 213.630947 | 298 | VS-PN | 14.33250 | CO |
| 939 | RS | P | 1.658617 | 223891.9 | 8249067 | 4589.596 | 223127.6 | 8248988 | 4343.772 | 162.110891 | 191.330032 | 353 | VS-PN | 18.42190 | CO |
| 940 | RS | P | 0.398159 | 171703 | 8227387 | 3637.085 | 172158.5 | 8226319 | 3281.026 | 180.391030 | 181.751429 | 326 | VS-PN | 15.43440 | CO |
| 941 | RS | P | 7.404931 | 319939.8 | 8212995 | 4379.929 | 322070.3 | 8212514 | 3601.094 | 776.442495 | 258.546628 | 533 | VS-M | 14.91090 | CC |
| 942 | RS | P | 7.485607 | 40794.42 | 8206230 | 1510.99 | 40392.85 | 8206048 | 1439.117 | 195.477638 | 276.633003 | 175 | V-PN | 10.08610 | CO |
| 943 | RS | P | 0.909322 | 40803.77 | 8205438 | 1491.293 | 40509.86 | 8205012 | 1393.697 | 192.865952 | 194.968073 | 278 | VS-PN | 18.13160 | CO |
| 944 | RS | P | 0.255396 | 313841.5 | 8205283 | 4145.962 | 315183.4 | 8204432 | 3464.409 | 121.549806 | 191.619759 | 287 | VS-PN | 15.97160 | CO |
| 945 | RS | P | 3.066733 | 317190.2 | 8203933 | 4089.044 | 315064 | 8204022 | 3452.796 | 268.806922 | 207.852739 | 394 | VS-PN | 18.77160 | CO |
| 946 | RS | P | 2.480788 | 317087.7 | 8202801 | 4216.627 | 314915 | 8203032 | 3456.296 | 403.174723 | 284.945606 | 421 | SC-M | 19.36340 | CO |
| 947 | RS | P | 3.135038 | 348567.8 | 8202331 | 4587.776 | 348629.6 | 8200706 | 4416.85 | 593.712684 | 262.280549 | 687 | VS-M | 19.54340 | CC |
| 948 | RS | P | 1.430061 | 186380.9 | 8201577 | 2248.604 | 185611.7 | 8201203 | 2017.439 | 286.714920 | 315.767854 | 457 | SC-M | 20.76030 | CO |
| 949 | RS | P | 7.893993 | 318649.2 | 8200694 | 4422.037 | 316279.1 | 8198329 | 3822.197 | 401.787374 | 246.470047 | 316 | V-PN | 13.82410 | CO |
| 950 | RS | P | 1.967775 | 309130.5 | 8199242 | 4189.558 | 309740.7 | 8199189 | 3938.094 | 293.851510 | 202.520246 | 409 | V-PN | 17.43230 | CO |
| 951 | RS | P | 3.086797 | 308872 | 8198915 | 4304.471 | 309688 | 8199004 | 3992.768 | 416.394502 | 156.668432 | 527 | VS-PN | 16.00730 | CO |
| 952 | RS | P | 3.411185 | 314537.2 | 8199677 | 4180.376 | 314752.2 | 8197758 | 3567.885 | 374.694893 | 165.512000 | 518 | VS-PN | 17.02010 | CO |
| 953 | RS | P | 1.035178 | 306416.5 | 8186643 | 4361.848 | 303573.8 | 8186025 | 3018.407 | 340.310616 | 185.924303 | 454 | VS-PN | 16.26750 | CO |
| 954 | RS | P | 0.191717 | 313287.7 | 8173973 | 4880.261 | 317257.9 | 8175355 | 3501.486 | 321.589326 | 170.932517 | 411 | SC-PN | 14.97030 | CO |
| 955 | RS | P | 0.765513 | 313313.8 | 8170619 | 4952.831 | 316952.1 | 8171878 | 4007.478 | 204.987262 | 347.214508 | 599 | SC-M | 16.55270 | CO |
| 956 | RA | P | 0.396477 | 325801.9 | 8172214 | 4342.989 | 324636.3 | 8169334 | 3622.002 | 153.835340 | 239.537924 | 242 | V-M | 12.88430 | CO |
| 957 | RS | P | 2.395761 | 367017.5 | 8169813 | 4774.528 | 366581 | 8168609 | 4607.869 | 303.075899 | 60.812896 | 571 | V-PN | 21.87440 | CO |
| 958 | RS | P | 1.575661 | 302022.5 | 8164204 | 4556.043 | 310554.4 | 8163629 | 2734.251 | 379.937388 | 276.477443 | 421 | SC-PN | 18.34840 | CO |
| 959 | RS | P | 2.530281 | 312344.9 | 8162799 | 3199.186 | 311327.4 | 8160430 | 2033.716 | 315.710046 | 164.450543 | 443 | VS-PN | 15.72280 | CO |
| 960 | RS | P | 4.220614 | 276010.8 | 8161120 | 3949.45 | 278558.8 | 8162084 | 2875.168 | 355.562679 | 338.930771 | 465 | VS-PN | 13.16940 | CO |
| 961 | RS | P | 0.422067 | 277520.7 | 8158536 | 3433.144 | 277600.2 | 8157602 | 3109.607 | 197.711326 | 177.968613 | 454 | V-M | 16.63840 | CO |
| 962 | RS | P | 0.321047 | 308370.5 | 8157416 | 3459.091 | 311143.1 | 8156516 | 1890.877 | 145.868002 | 267.597818 | 279 | VS-PN | 14.29100 | CO |
| 963 | RS | P | 0.409149 | 266826.9 | 8153357 | 2785.348 | 265746.4 | 8151987 | 2136.75 | 116.894998 | 205.773333 | 295 | I-M | 11.43670 | CO |
| 964 | RS | P | 1.133571 | 292378.5 | 8152409 | 2369.622 | 289891.8 | 8153094 | 2028.704 | 423.910381 | 222.577442 | 513 | V-PN | 21.37880 | CO |
| 965 | RS | P | 0.143683 | 303993 | 8153727 | 3791.345 | 303918.6 | 8145876 | 1626.119 | 110.298494 | 263.013160 | 405 | I-M | 14.32740 | CC |
| 966 | RS | P | 0.315502 | 290950.6 | 8148287 | 2628.039 | 289493.9 | 8147447 | 1865.978 | 164.776936 | 175.031833 | 296 | V-M | 14.09770 | CO |
| 967 | RS | P | 0.506715 | 305387.8 | 8143728 | 2511.138 | 306228.8 | 8145941 | 1684.305 | 211.173297 | 180.682070 | 376 | VS-M | 16.23870 | CO |
| 968 | RS | P | 0.208697 | 256511.4 | 8141359 | 2810.236 | 255704.2 | 8140022 | 2264.951 | 167.231438 | 163.313524 | 330 | VS-PN | 16.33940 | CO |
| 969 | RA | P | 1.033932 | 258756.1 | 8132509 | 2337.759 | 259275.5 | 8130811 | 1959.453 | 366.179836 | 240.160830 | 710 | I-PN | 22.64920 | CO |
| 970 | RS | P | 0.208570 | 300423.5 | 8130439 | 3241.182 | 298979.3 | 8129746 | 2768.733 | 101.415018 | 283.443330 | 278 | I-M | 10.21000 | CC |
| 971 | RS | P | 0.746862 | 313091.2 | 8125177 | 3778.137 | 313359.4 | 8123853 | 3489.607 | 386.468373 | 252.670963 | 813 | I-PN | 24.76840 | CO |
| 972 | RS | P | 3.030139 | 304011.6 | 8112773 | 2593.457 | 303385.7 | 8111185 | 2206.758 | 457.403403 | 223.618434 | 747 | I-PN | 22.73790 | CO |
| 973 | RA | P | 0.340349 | 310368.8 | 8107965 | 3249.433 | 309335.3 | 8106352 | 2276.846 | 108.041939 | 232.114788 | 234 | V-M | 9.27206 | CC |
| 974 | RS | P | 1.315779 | 289742.2 | 8106833 | 2402.44 | 288673.1 | 8107534 | 2009.794 | 399.252447 | 200.486469 | 676 | I-PN | 24.14670 | CO |
| 975 | RS | P | 1.943312 | 289783.1 | 8106503 | 2440.561 | 287631.4 | 8103821 | 1663.186 | 133.363152 | 313.702494 | 207 | V-PN | 10.70810 | CO |
| 976 | RA | P | 0.896736 | 353605.3 | 8090884 | 3458.016 | 354272.5 | 8089883 | 2940.564 | 514.963419 | 336.038985 | 561 | V-PN | 18.73440 | CO |
| 977 | RS | P | 1.561439 | 353629.6 | 8090268 | 3230.985 | 354028 | 8089602 | 2929.65 | 489.758051 | 158.790322 | 650 | I-PN | 24.16470 | CO |
| 978 | RS | P | 1.617499 | 352849.8 | 8090033 | 3441.604 | 353744 | 8089312 | 2873.4 | 457.930688 | 163.155294 | 556 | VS-PN | 19.86650 | CO |
| 979 | RS | P | 1.653453 | 365072.8 | 8089352 | 3912.055 | 369193.1 | 8089627 | 3076.523 | 416.519142 | 155.897824 | 530 | VS-PN | 19.15600 | CO |

| | | | | | | | | | | | | | | | |
|------|----|---|----------|----------|---------|----------|----------|---------|----------|------------|------------|-----|-------|----------|----|
| 980 | RS | P | 0.186491 | 364971.4 | 8087181 | 3927.593 | 367702 | 8083838 | 2854.426 | 6.507883 | 209.278410 | 77 | SC-PN | 2.85617 | PC |
| 981 | RS | P | 1.214089 | 364622.8 | 8085455 | 3639.908 | 366021.3 | 8084917 | 3197.322 | 254.355707 | 175.724653 | 458 | VS-PN | 15.18970 | CO |
| 982 | RA | P | 0.507181 | 363896.3 | 8085310 | 3839.97 | 365947.7 | 8084094 | 3030.486 | 380.802589 | 172.229536 | 483 | VS-PN | 16.47520 | CO |
| 983 | RS | P | 3.050761 | 368475.4 | 8070677 | 2845.639 | 367506.5 | 8070922 | 2415.869 | 349.164423 | 186.183038 | 491 | VS-PN | 17.45100 | CO |
| 984 | RS | P | 1.187275 | 392775.1 | 8049817 | 4117.551 | 390769.4 | 8049841 | 3520.904 | 303.708992 | 183.119553 | 512 | VS-PN | 16.66670 | CO |
| 985 | RS | P | 1.752042 | 392672.1 | 8044812 | 3347.621 | 393399 | 8042084 | 2484.67 | 419.599620 | 342.083391 | 652 | V-PN | 19.82560 | CO |
| 986 | RA | P | 0.465126 | 374354.3 | 8054611 | 3841.64 | 346963.2 | 8023652 | 571.476 | 260.402015 | 281.908139 | 323 | SC-M | 14.60390 | CC |
| 987 | RS | P | 0.754941 | 397069 | 8023656 | 3204.573 | 396202.1 | 8024915 | 2319.746 | 314.641652 | 208.569121 | 427 | SC-PN | 18.22240 | CO |
| 988 | RS | P | 1.434132 | 451229.4 | 7906481 | 3357.003 | 451394 | 7905021 | 2510.544 | 261.244490 | 233.932539 | 418 | VS-PN | 17.61880 | CO |
| 989 | RS | P | 0.267631 | 467248.8 | 7906578 | 3895.67 | 467462.2 | 7905168 | 3494.452 | 129.886132 | 260.696421 | 450 | V-PN | 14.17820 | CO |
| 990 | RS | P | 0.625127 | 415543.6 | 7900833 | 2081.878 | 417417.1 | 7898271 | 908.0338 | 114.185040 | 85.327356 | 158 | V-PN | 9.62663 | CO |
| 991 | RS | P | 0.611190 | 475655.6 | 7835968 | 3395.637 | 472913.1 | 7838040 | 2686.489 | 215.780456 | 176.615429 | 513 | V-PN | 12.93210 | CO |
| 992 | RS | P | 4.419042 | 482402.4 | 7827575 | 4126.814 | 483083.8 | 7825173 | 3561.442 | 229.584844 | 120.093836 | 292 | V-PN | 8.50536 | CO |
| 993 | RS | P | 0.277703 | 469801.4 | 7810730 | 2679.154 | 471092.5 | 7809484 | 2139.438 | 303.030085 | 313.631322 | 507 | SC-PN | 11.15170 | CC |
| 994 | RS | P | 0.158309 | 492729.5 | 7809069 | 3865.067 | 491452.7 | 7807362 | 3530.19 | 136.760768 | 199.329689 | 270 | SC-M | 12.20440 | CC |
| 995 | RS | P | 0.282092 | 490440.8 | 7807812 | 3777.807 | 491030.6 | 7807095 | 3511.408 | 69.807409 | 115.563748 | 133 | V-PN | 7.30600 | CO |
| 996 | RS | P | 0.110342 | 489634.7 | 7807130 | 3735.21 | 489788.4 | 7806379 | 3414.62 | 32.455882 | 157.623300 | 164 | V-PN | 7.62596 | CO |
| 997 | RS | P | 0.485729 | 489293.2 | 7807021 | 3756.582 | 489543.9 | 7806234 | 3399.841 | 151.654438 | 112.152904 | 270 | I-M | 11.01260 | CC |
| 998 | RA | P | 4.564294 | 488891.4 | 7806747 | 3729.16 | 489290 | 7806135 | 3380.829 | 901.009794 | 241.692639 | 771 | D-C | 17.86700 | CC |
| 999 | RS | P | 1.737343 | 499694.4 | 7806877 | 4370.386 | 497340.4 | 7803838 | 3682.024 | 102.171679 | 130.770719 | 230 | SC-PN | 7.74422 | CO |
| 1000 | RA | P | 1.274710 | 493348.2 | 7767934 | 3961.694 | 492684.2 | 7769428 | 3446.731 | 381.496142 | 136.005143 | 470 | SC-M | 20.12570 | CC |
| 1001 | RA | P | 5.635952 | 484039.6 | 7766167 | 2998.719 | 484211.3 | 7764909 | 2617.917 | 893.081260 | 250.235526 | 708 | VS-M | 15.95620 | CC |
| 1002 | RS | P | 0.464744 | 392157.1 | 7764104 | 1123.213 | 390484.7 | 7764457 | 862.811 | 67.897507 | 141.281215 | 213 | V-PN | 7.05174 | CO |
| 1003 | RS | P | 0.119602 | 381941.5 | 7745585 | 993.0911 | 379729.2 | 7744394 | 92.08126 | 65.980508 | 132.322086 | 232 | V-PN | 8.29323 | CO |
| 1004 | RS | P | 1.109321 | 383117 | 7743055 | 908.0904 | 378479.5 | 7741389 | 15.00916 | 261.247981 | 294.375064 | 428 | SC-PN | 11.59440 | CO |
| 1005 | RA | P | 4.828010 | 383882.2 | 7736968 | 815.9595 | 379835.3 | 7737719 | 60.14639 | 755.813152 | 280.503242 | 662 | VS-M | 17.08420 | CC |
| 1006 | RA | P | 2.488527 | 378110.8 | 8047726 | 3140.836 | 379492.9 | 8045891 | 2455.907 | 684.929317 | 143.022318 | 730 | VS-PN | 27.04540 | CO |

CHAPTER III:
**GIANT LANDSLIDE TRIGGERINGS
AND PALEOPRECIPITATIONS IN
THE CENTRAL WESTERN ANDES:
THE ARICOTA ROCKSLIDE DAM
(SOUTH PERU)**



Giant landslide triggerings and paleoprecipitations in the Central Western Andes: The aricota rockslide dam (South Peru)

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ABSTRACT

The central part of the Western Andes holds an exceptional concentration of giant paleolandslides involving very large volumes of rock material ($v > \text{km}^3$). While those gravitational slope failures are interpreted consensually as an erosional response to the geodynamic activity of the Andes (relief formation and tectonic activity), the question of their triggering mechanisms remains enigmatic. To clarify the respective roles of climatic versus seismic forcing on the Andean landslides, new temporal constraints on paleo movements are essential. Here, we focus on one of those giant slope failures, the Aricota giant rockslide that damned the Locumba valley in southern Peru. We conducted fieldwork, high-resolution DEM analysis and cosmogenic nuclide dating to decipher its development history and failure mechanisms. Our results point to the occurrence of two successive events. A giant failure mobilizing a rock volume of ca. 2 km^3 first produced a dam at $17.9 \pm 0.7 \text{ ka}$. Considering its height of ca. 600 m, the Aricota rockslide dam is one of the three largest landslide dams worldwide. At $12.1 \pm 0.2 \text{ ka}$, a second event produced ca. 0.2 km^3 of material, and the rock-avalanche debris spread out over the dam. As the chronology of those two events is pointing to the two main paleoclimatic pluvial periods in this region (Heinrich Stadial 1a and Younger Dryas), we favor the interpretation of a climatic forcing. At a regional scale, the concomitant aggradation of alluvial terraces and fan systems along the nearby valleys highlights higher regional erosion, sediments supply and mass-wasting events during those paleoprecipitation events and strengthens this conclusion.

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1. Introduction

The Western flank of the Central Andes (south Peru - north Chile) holds one of the most exceptional concentrations of giant landslides worldwide (Crosta et al., 2014). Those gravitational instabilities mobilize large volume of rock material ($> 10^9 \text{ m}^3$), with debris propagation over long distance ($> 10^3 \text{ m}$) affecting the Western Cordillera from elevations between 4500 m to sea level (e.g. Wörner et al., 2002; Strasser and Schlunegger, 2005; Pinto et al., 2008; Crosta et al., 2014). This Andean area is particularly active geodynamically, related to the long-term convergence between the Nazca and the South America plates. The global shortening is associated

with the relief construction, producing instantaneous deformation (crustal seismicity) coupled with long-term processes of surface uplift and volcanism (Thouret et al., 2017; Benavente et al., 2017). In this region, the large-scale landsliding is suspected to be an efficient relief erosion mechanism at regional scale (Mather et al., 2014).

Additionally, the Western Andean flank presents a climatic setting marked by a dominant hyper-aridity persisting at least since 20 million years (e.g. Dunai et al., 2005). This particular climate environment, with very low denudation rates (typically $1\text{--}10 \text{ mm.kyr}^{-1}$; Nishiizumi et al., 2005; Madella et al., 2018), allows the local preservation of landscape over hundreds of thousands years (e.g. Zerathe et al., 2017). This offers a unique opportunity to track gravitational slope processes over a temporal scale currently unknown, close to the timing of the orogen evolution (Hermanns et al., 2001).

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On the other hand, the development of such giant landslides in a desert environment raise the question of their triggering conditions and failure mechanisms. In the literature, this question is largely debated with two main opposite views implying seismicity versus climatic controls (Moreiras and Sepúlveda, 2015). For examples, McPhillips et al. (2014) suggest that at a millennial-scale, the record of landslides activity in the Andes is mainly consistent with earthquake trigger, whereas Margirier et al. (2015) identified a correlation between the activity phases of a giant paleolandslide (Chuquibamba, south Peru) and wet climatic events on the Altiplano. As pointed by Moreiras and Sepúlveda (2015), in order to push away the limit of this debate and to decipher the respective role of each forcing, new temporal constraints on giant Andean paleolandslides are required. Indeed, while numerous giant landslides have been identified along the western Andean flank (Audin and Bechir, 2006; Crosta et al., 2014), the great majority of them have not been dated yet. In this context, the cosmogenic nuclide dating, applied to either landslide scarps or boulders, is specifically pertinent to constrain the timing of slope evolution (Zerathe et al., 2017; Crosta et al., 2017).

In this paper, we combined geomorphological analysis based on high resolution Pléiades DEMs and geochronological dating using ^{10}Be produced within quartz minerals (in situ-produced ^{10}Be) in order to document the chronology and to determine the context in which the Aricota giant rockslide dam (Central Western Andes, South Peru) occurred.

2. Geological context and landslide setting

The study area is located in the South Peru at $\sim 17^\circ\text{S}$ latitude, along the Western flank of the Central Andean Cordillera (Fig. 1), where ongoing subduction of the Nazca Plate occurs with a convergence velocity of about $62\text{ mm}\cdot\text{yr}^{-1}$ (e.g. Villegas-Lanza et al., 2016). The geomorphology of this region is contrasted and shows from West to East: (1) a coastal cordillera with a maximum elevation of 1000 m a.s.l. , (2) the Western Cordillera with elevations comprised between 1000 and 4500 m a.s.l. , and (3) the Altiplano plateau reaching 5000 m a.s.l. This western flank of the Andes is carved by deep valleys and canyons related to a regional uplift (e.g. Thouret et al., 2007; Schildgen et al., 2009; Gunnell et al., 2010 and references therein). The Western Cordillera is affected by westward major thrusts (Fig. 1) oriented parallel to the subduction trench (Hall et al., 2012; Benavente et al., 2017). The timing and the processes involved in the creation of the Andean relief in this region are still debated. Sempere et al. (2008) propose a rapid uplift of about 2.5 km since the Late Miocene (11 to 6 Ma) in response to a large-scale mantle delamination. Armijo et al. (2015) propose that the topography was controlled by crustal thickening during the Paleogene (50 to 30 Ma) in response to the tectonic shortening of the Central Andes. This process is responsible for aridity increase of the Atacama Desert during the Neogene (Evenstar et al., 2015). Recently, Thouret et al. (2017) provide a compilation of $^{40}\text{Ar}/^{39}\text{Ar}$ and U/Pb dating of ignimbrite deposit covering this region, which helped to decipher the canyon incision chronology. Their dataset suggest that uplift was gradual over the past 25 Ma and accelerated after 9 Ma . The valley incisions start around 11 – 9 Ma and accelerate between 5 and 4 Ma . Pleistocene uplift rates of 0.2 to $0.4\text{ mm}\cdot\text{yr}^{-1}$ have been derived from cosmogenic dating (Hall et al., 2012), and interpreted as a combination of tectonic shortening along steep westvergent faults of the western flank and isostatic responses to fluvial erosion associated with large scale landslide processes. The same conclusion is reached by Viveen and Schlunegger (2018) showing uplift at the Quaternary time scale in the Moquegua region. However, at the scale of the Peruvian forearc, their conclusions open other perspectives showing possible alter-

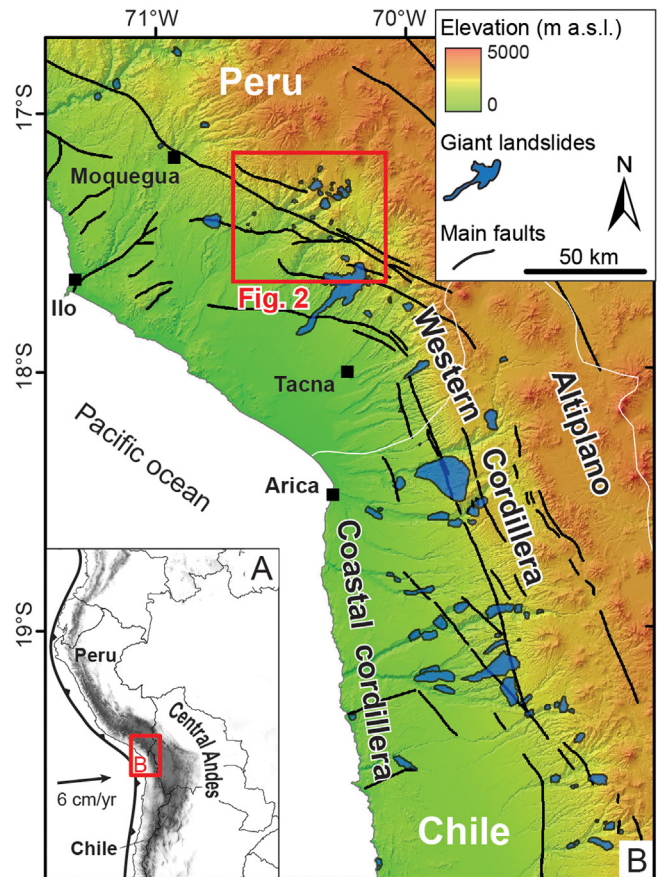


Fig. 1. Morpho-tectonic context of the Central Western Andes and location of the study area. Hillshade and elevation are produced using the ASTER DEM (resolution 30 m). Main faults are reported from Hall et al. (2012); Armijo et al. (2015) and Benavente et al. (2017). The database of giant landslides is compiled from Audin and Bechir (2006); Crosta et al. (2014); Mather et al. (2014); Zerathe et al. (2017) and adding personal mapping from this study.

nating phases of compressional and transtensional tectonics during the Cenozoic.

The progressive Cenozoic onset of the Andean relief acted as an important topographic barrier impeding the cross of cloud currents and precipitation from the Amazonian basin (Houston and Hartley, 2003). As a result, hyper-arid conditions have developed and still currently prevail in the so-called Atacama Desert, along the Western Central Andes, allowing for long-term preservation of landscapes (up to several millions of years, e.g. Dunai et al., 2005). As contrasting with this long-term dry climate, the flank of Western Central Andes, between latitudes 17°S and 20°S , holds an exceptional concentration of some of the largest landslides identified at the Earth surface (Fig. 1). The imprint of those giant landslides have been progressively identified and mapped since a decade (e.g. Audin and Bechir, 2006; Crosta et al., 2014). From North to South, some impressive examples among others are: the Chuquibamba landslide - 40 km^3 (Margirier et al., 2015; Thouret et al., 2017), the Caquilluco landslide - 15 km^3 (Zerathe et al., 2017), the Lluta landslide - 26 km^3 (Wörner et al., 2002; Strasser and Schlunegger, 2005), the Minimini landslide - $>5\text{ km}^3$, the Latagualla landslide - 5.4 km^3 (Pinto et al., 2008) or the Magnifico landslide - 0.2 km^3 (Mather et al., 2014; Crosta et al., 2017). Only few of those giant landslides have been precisely dated (e.g. Zerathe et al., 2017; Crosta et al., 2017). Paleo-climatic variations and/or active tectonic and seismicity are considered both as possible factors of forcing. However, mainly because of the lack precise of chronological constraints on

these events, there is no consensus to date about the reason of their triggerings (McPhillips et al., 2014; Margirier et al., 2015).

In this paper, we focus on one of those giant landslides, the Aricota rockslide dam. It developed in the middle of the Locumba valley whose basin extends across the whole Western Cordillera, from the Altiplano down to Pacific Ocean. The Aricota rockslide generated a large dam in the Locumba valley, forming a 6 km-long lake. The lithology observed around the valley is dominated by volcano-sedimentary rocks (Fig. 2). The Aricota rockslide affects geological series that are almost horizontal. From the valley bottom to the plateau, we observe the following stratigraphic cross section: Cretaceous andesite and rhyolite of the Quellaveco formation, Paleogene silt and shales of the Tarata formation and Neogene ignimbrite of the Huaylillas formation unconformably covering the former (Fig. 2). The Cretaceous layers are cut by intrusive granite at the north-east of the Aricota rockslide zone. Neotectonic faults activities have been described recently south-west of the Aricota rockslide, mainly along the Incapuquio fault system and the Purgatorio fault (Hall et al., 2012; Benavente et al., 2017). The Incapuquio fault system is a sub-vertical lineament of ~400 km in length with a northwest-southeast trending direction and accommodates left lateral transpressive displacement. The Purgatorio fault accommodates right lateral transpressive displacement which has produced at least two ruptures during the last thousands years with superficial offsets of several meters (Benavente et al., 2017).

On the Aricota rockslide dam site, two hydroelectric plants, Áricota I and II (35 MW) were built in 1967. The continuous pumping of water caused a drop of the lake level of ~100 m in the last 50 years, which allow studying paleo shorelines revealed by diatomite deposits (Placzek et al., 2001). Placzek et al. (2001) obtained radiocarbon calibrated ages ranging between ca. 300 and 7000 yr B.P., pointing to high lake levels around 6100 yr B.P. and 1700–1300 yr B.P. and giving a minimum age of ca. 7 ka for the rockslide-dam emplacement. They identified in the morphology the existence of two successive failure events. However, the precise chronology of this rockslide, the failure and triggering mechanisms remain unknown yet.

3. Methods

3.1. *Pléiades* DEM elaboration and mapping

To identify and map the structures and deposits associated to the Aricota giant rockslide activity, we combine geomorphic and tectonic observations based on field data, analyses of high-resolution Digital Elevation Model (DEM) and Google Earth images. A high-resolution DEM was derived from two stereo images acquired by the *Pléiades* satellites on October 2015. The full resolution of these optical images is 0.7 m and their orientation was assessed using the Rational Polynomial Coefficient (RPC) provided in their ancillary data. We generated the DEM using the open source software Ames Stereo Pipeline (ASP) developed by NASA (Broxton and Edwards, 2008) and followed the three-step procedure. First, each image was map-projected using the low-resolution (30 m) SRTM DEM. Then the two images were bundle-adjusted based on automatically extracted tie points, before finding the disparities. The third step involved finding the intersection of all the rays coming from the homologous points of the image pair. This step leads to a point cloud of the surface topography, which is then converted onto a 2-m resolution grid (Fig. 3A). Field campaigns were conducted in 2014 and 2015 to (1) validate the observations/interpretations made about the different deposits and related events within the rockslide mass, and (2) to sample boulders and scarps for cosmogenic nuclide surface exposure dating.

3.2. Cosmogenic nuclide surface exposure dating

In order to determine the ages of the different events that occurred on the Aricota rockslide area, a sampling strategy was designed according to our geomorphological mapping. Seventeen samples were selected (Fig. 3B). In order to constrain an accurate long-term and local denudation rate, one sample (AR1) was taken on the eroding surface (presumed at steady state) that is located on the plateau above the rockslide scarp at ca. 3700 m a.s.l.. Three samples (AR3, AR4 and AR5) were extracted from the free-face of two preserved sub vertical scarps (bedrock). Thirteen samples were extracted from boulders distributed all over the rockslide mass, including six samples (AR14 to AR21) from the main dam and seven others (AR6 to AR12, and AR27 to AR29) from a rock-avalanche deposit located on top of the dam (Fig. 3B). A last boulder, AR29, has been taken tentatively to estimate past variations of the Aricota lake level (Fig. 3B). Indeed, despite belonging morphologically to the rock-avalanche deposit, this boulder stands at an elevation that is of about 40 m below the pre-1967 lake level (date of artificial lake lowering by pumping). In other words, before 1967, tens of meters of water, sufficient to protect quasi-completely the AR29 boulder from cosmic ray primary and secondary particles, were covering it. Thus, any concentration measured in this sample might represent periods of past lake level drop that would be large enough to allow exposing the AR29 boulder to cosmic ray particles (at ten meters depth, the cosmogenic nuclide production rates are less than 0.2% that at the surface, Gosse and Phillips, 2001).

In general, we paid special attention to select boulders whose height and length were higher than 2 m and with no trace of post-deposition toppling, nor large desquamations. Elevation, latitude and longitude were recorded with a handle GPS. Pictures of the boulders are provided in the supplementary material.

Sample preparation and ^{10}Be chemical extraction were achieved following routine procedure, which is detailed in the supplementary information, at the GTC Plateform, ISTERRE laboratory (Grenoble, France). $^{10}\text{Be}/^9\text{Be}$ measurements were performed at the French AMS National Facility, located at CEREGE in Aix-en-Provence (Arnold et al., 2013). $^{10}\text{Be}/^9\text{Be}$ ratios were calibrated against the in-house standard STD-11, using an assigned $^{10}\text{Be}/^9\text{Be}$ ratio of $(1.191 \pm 0.013) \times 10^{-11}$ (Braucher et al., 2015). Uncertainties on ^{10}Be concentrations (reported as 1σ) are calculated according to the standard error propagation method using the quadratic sum of the relative errors and include a conservative 0.5% external machine uncertainty (Arnold et al., 2010), a 1.08% uncertainty on the certified standard ratio, a 1σ uncertainty associated to the mean of the standard ratio measurements during the measurement cycles, a 1σ statistical error on counted events and the uncertainty associated with the chemical and analytical blank correction.

Denudation rates and exposure durations were both calculated using the MATLAB®-based CRONUScalc program, developed by Marrero et al. (2016). We applied a globally calibrated ^{10}Be spallation production rate of $4.09 \pm 0.35 \text{ at.gr}^{-1}.\text{yr}^{-1}$ (sea level and high latitude; Borchers et al., 2016) which was scaled at the geographical and altitudinal location of each sampling site using the LSD scaling scheme (SF; Lifton et al., 2014; see details in the supplementary information).

We initially calculated long-term denudation rates for this area. As this will be detailed in the following results, in addition to the dedicated sample AR1, two other samples (AR14 and AR15) were considered for denudation rates calculation.

Finally, exposure duration calculations were performed considering this locally constrained denudation rate. Both analytical and total uncertainties (1σ) are reported. Analytical age uncertainties (i.e. internal) include uncertainties of the measured ^{10}Be concentrations (Table 1, supplementary data), pressure ($\pm 5 \text{ hPa}$), sample thickness ($\pm 1 \text{ cm}$), shielding factor (± 0.01), denudation

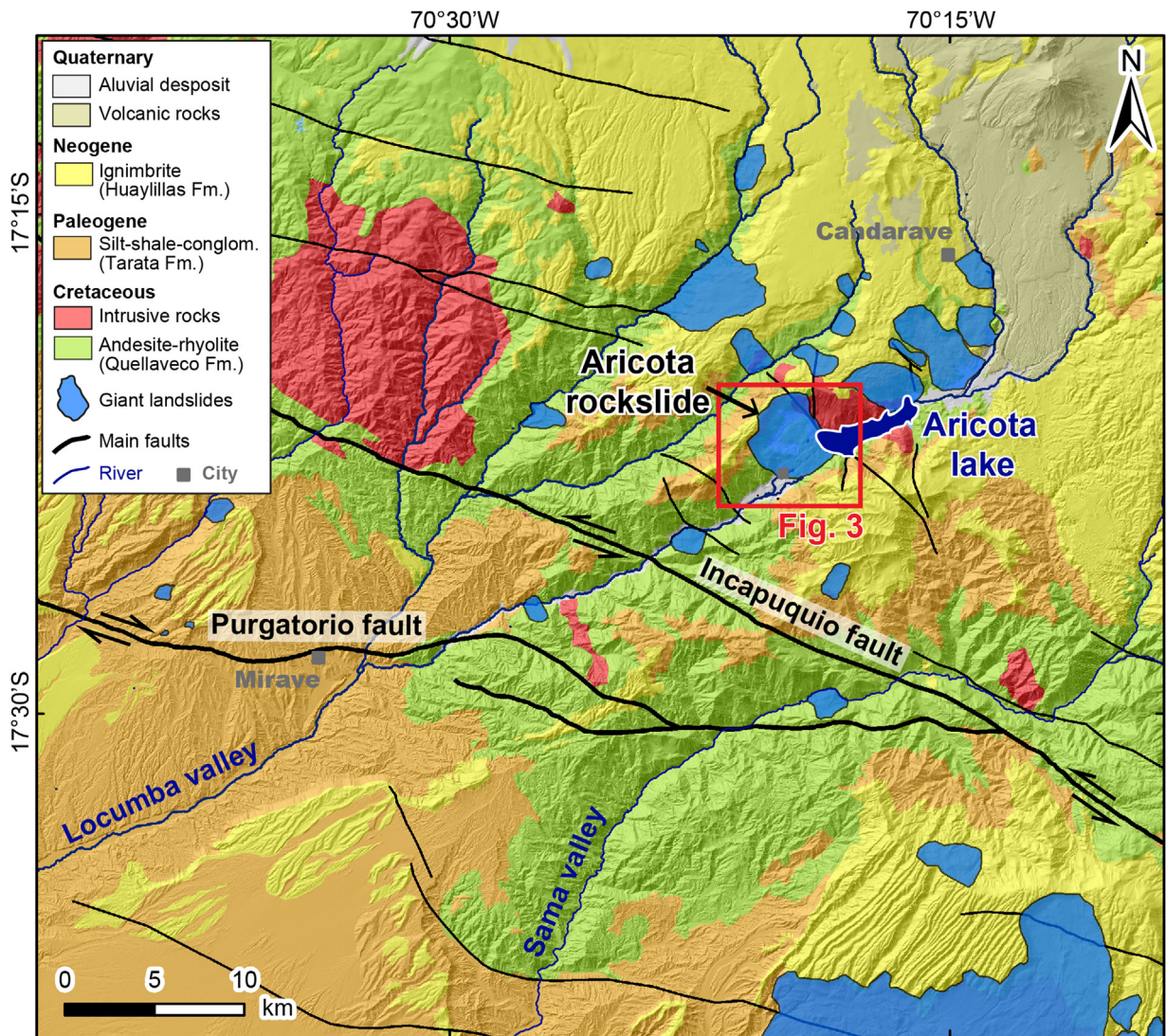


Fig. 2. Geological settings around the Aricota rockslide (see frame location on Fig. 1). The geological map is adapted from INGEMMET (2011) and draped above hillshade produced using the TanDEM-X DEM (resolution 12 m). Quaternary crustal faults are reported (e.g. Incapuquio-Purgatorio fault system; Hall et al., 2012; Benavente et al., 2017). Giant landslides reported were mapped during this study.

rate ($\pm 0.4 \text{ mm.ka}^{-1}$) and attenuation length ($\pm 10 \text{ g. cm}^{-2}$). Total age uncertainties (i.e. external) include contributions from the analytical method and production rate uncertainty (Marrero et al., 2016). All results are presented in Table 1 (supplementary data).

4. Results and interpretations

4.1. Rockslide morphology

The failure of the Aricota giant rockslide has left a spectacular morphological imprint in the Locumba valley and has deeply modified the surrounding landscapes (Figs. 3–4A). It generated a natural dam of about 600 m of height impounding a lake of $\sim 0.8 \text{ km}^3$ with a length of $\sim 6 \text{ km}$ (Aricota lake) and produced a large scar of about 4 km of width along the northern flank of the valley (Fig. 3A). As it is visible on the Fig. 3A, the main scarp intercepts a plateau, corresponding to a paleo ignimbrite surface (Huaylillas formation, Fig. 2), at an elevation of ca. 3700 m a.s.l. According to the geomorphological description proposed by Placzek et al. (2001), two successive deposits can be distinguished in the rockslide mass. The dam itself and a subsequent rock-avalanche deposit overlying

its northern part. The whole destabilized area extends over $\sim 3 \text{ km}$ of length towards the south until the opposite valley slope.

We observe in the central part of the dam a continuous lithological succession, locally fractured, composed from bottom to top by the Huaylillas ignimbrites (Fig. 5A), overlying the metasediment (silts-shales) and pyroclastics of the Tarata formation. This lithological succession is comparable with the one outcropping along the stable valley slopes (Figs. 3B and 4). On southern extremity of the dam (i.e. the most distal part), we observe a dominance of andesite from the Quellaveco formation (Fig. 3B), derived from the lower most layer of the original slope, with a high degree of destruction, also mixing all the other lithologies (Fig. 4B). According to those observations, the dam was likely produced during a first large and “in mass” rockslide failure that have affected the whole valley flank.

The western side of the dam (downstream side) shows a large amphitheater (Fig. 3A), affected by gullies and landslides with scarps of several hundred meters in length (Fig. 6A). Water seeping is also observable at the base of the dam (see location of current and paleo springs on Fig. 3B). We interpret this morphology as regressive erosion processes affecting the dam due to its steep topography and to the high level of rock fracturing produced during the rock-

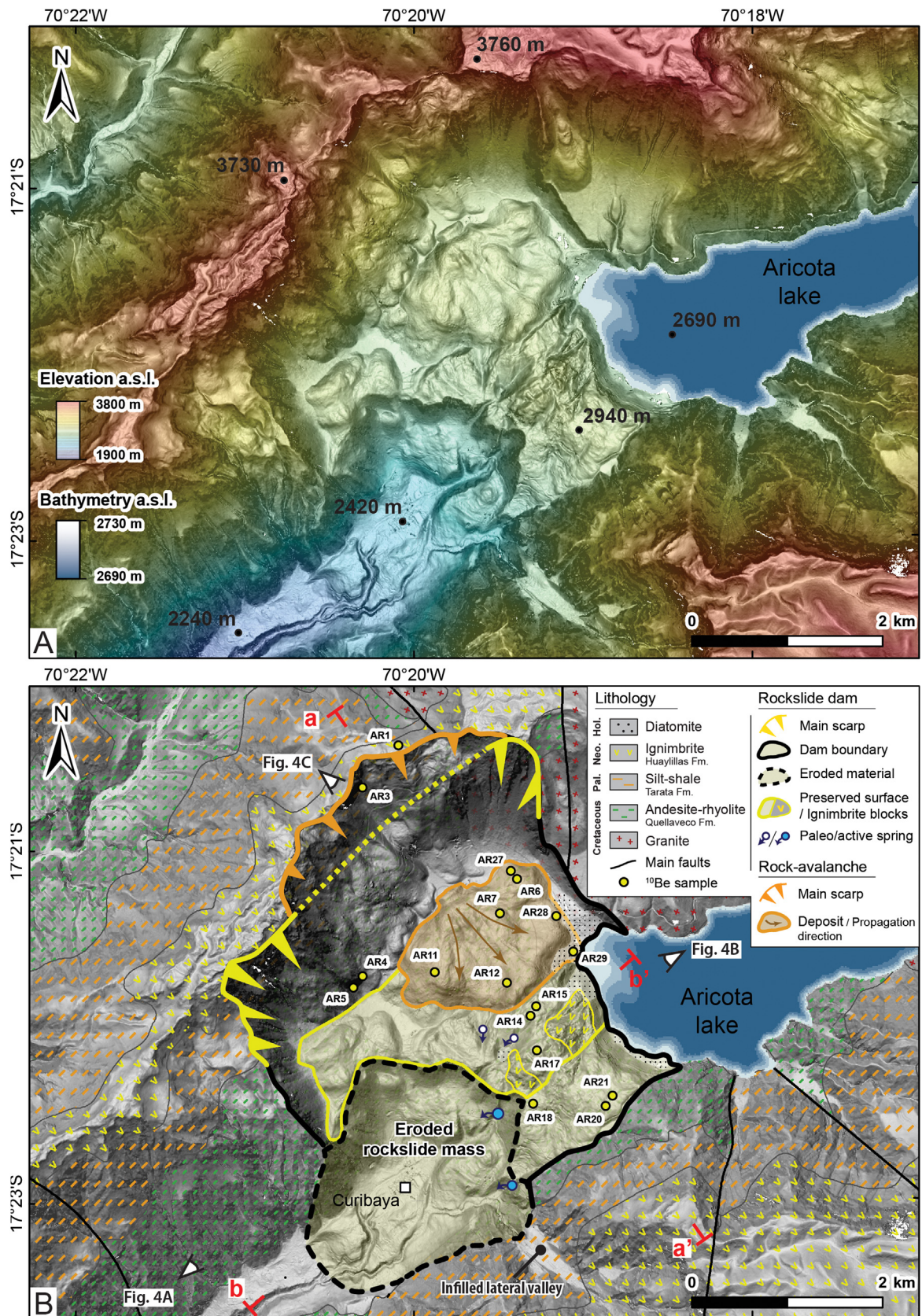


Fig. 3. The Aricota giant rockslide (see frame location on Fig. 2). (A) Raw hillshade and elevation image derived from high resolution (2 m) Pléiades DEM (see text for details). The bathymetry of the Aricota lake (resolution 1 m) has been provided by the company EGESUR. (B) Geomorphological map of the Aricota rockslide showing the two failure events. The first and main event that generated the dam in the valley is mapped in yellow. Note the regressive erosion affecting southwestern part of the slipped mass and the infill of the secondary valley located at the southern center of the map. The second event, a rock-avalanche that have affected the main scarp of the first event, is depicted in orange. Yellow points correspond to samples extracted for ¹⁰Be cosmic ray exposure dating (1 above the rockslide scarp, 3 on the free face of the rockslide scarp and 13 on boulders distributed over the landslide mass). Outside of the rockslide area, the geology is the same as Fig. 3.

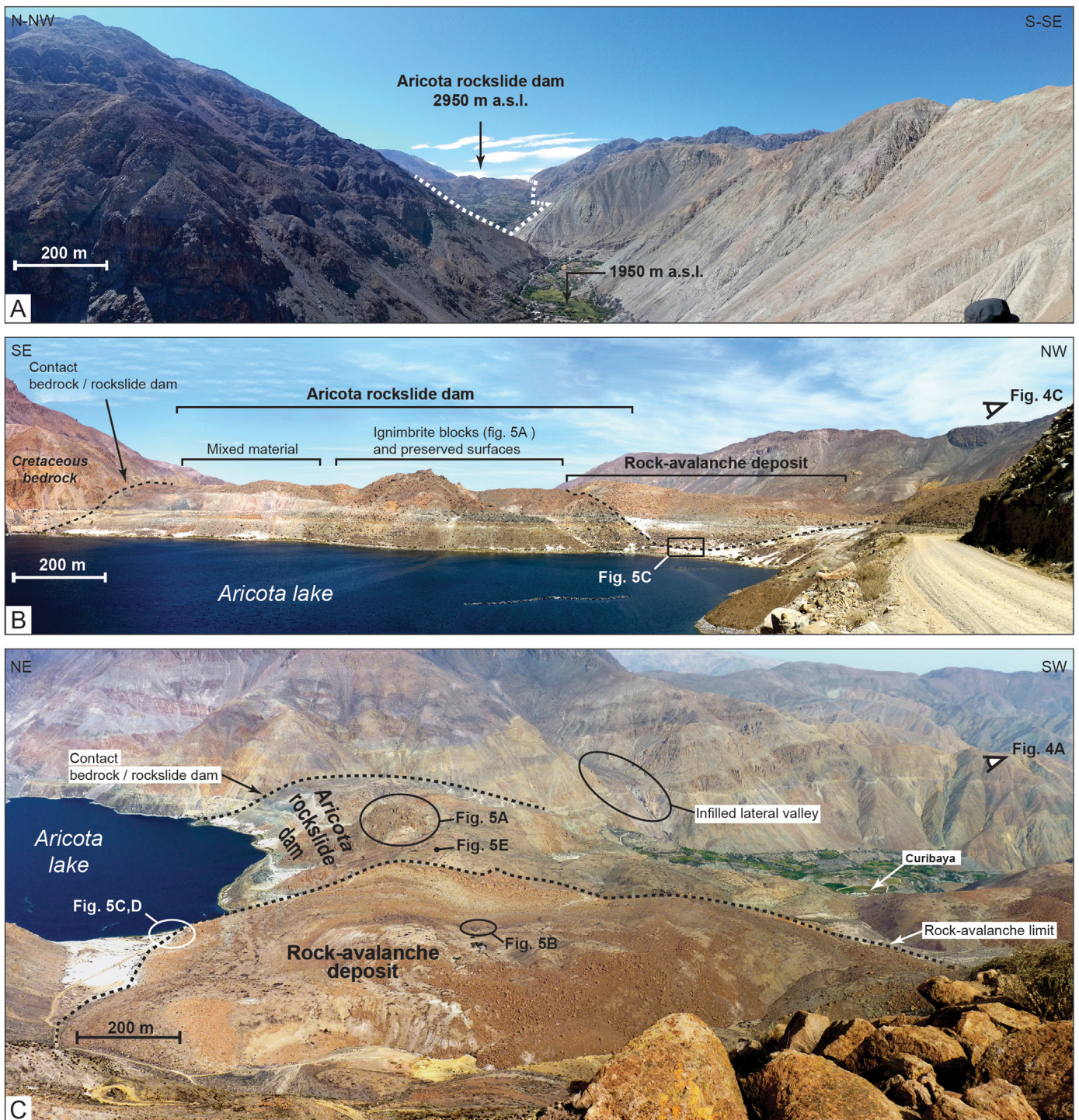


Fig. 4. Panoramic views illustrating the main structures of the Aricota giant rockslide area. (A) Panoramic view from the downstream part of the Locumba valley (see location on Fig. 4C). Note the general V-shape of the valley and the contact between the giant Aricota rockslide and the flank underlined by a dotted white line. (B) Westward view taken from the road along the lake (see location on Fig. 3B) and showing the dam generated by the first giant event. Along the dam, two bodies can be discriminated. On the central part, pre-rockslide topographic surfaces and large ignimbrite blocks are preserved (see also Fig. 5A). On the south-eastern part, mixed and highly deformed material are outcropping. Rock-avalanche deposits overly the top the rockslide dam. (C) Southward view of the whole rockslide area taken from the top of the scarp (see location on Fig. 4B). Note on the opposite Locumba valley flank, the lateral valley infilled by accumulation of deposits reflecting its obstruction by the main Aricota rockslide dam.

slide propagation. On the opposite Locumba valley flank (southern flank), our DEM (Fig. 3A) highlights a flat and perched surface, at the same elevation than the Aricota dam (ca. 2700–2800 m a.s.l.), infilling a small lateral valley (Fig. 4C). This morphology suggests that the former dam reached this area before being eroded.

Postulating that before the rockslide triggering, the valley had a typical v-shaped morphology (Fig. 4A) we reconstructed a pre-

failure topography. Then taking into account the strike and dip of the main scarp, we estimate a volume of ca. $2 \pm 0.3 \text{ km}^3$ for the Aricota rockslide dam, which includes an estimation of the volume eroded since it emplaced.

On its northern part, the dam is covered by a secondary rock-avalanche deposit constituting a circular lobe of debris of 800 m of radius (Fig. 3A). The contact between the dam and this rock-



Fig. 5. Detailed morphologies of the Aricota rockslide. (A) Preserved large ignimbrite boulders outcropping in the central part of the rockslide dam. (B) Large boulders from the Tarata formation (bedded silt and shales) aligned in the rock-avalanche deposit. (C) Boulders of the rock-avalanche partially covered by diatomite. This zone was immersed before the hydroelectric lake drop. (D) Boulder (AR29) sampled to tentatively track the paleo-lake level variations. (E) Boulder of sample AR15. (F) Ignimbrite surface located on the plateau at the top of rockslide scarp and sampled to estimate the long-term local denudation rate (see location on Fig. 3B). On all pictures, see the persons for scale and their location on Fig. 4.

avalanche deposit is delineated on the DEM by a slope break (Fig. 3). On the field, it corresponds to a clear contact between a chaotic deposit of blocs of thickness of 60 to 100 m overlying the oldest dam surface. Taking into account the area covered by the rock-avalanche and its mean thickness; we estimated a volume $\sim 0.2 \text{ km}^3$ for this

second event. Above this rock-avalanche deposit, we observe a high cliff of more than 200 m of elevation, cutting through the intercalations of silts and shales from the Tarata formation (Fig. 6C). This cliff crosscuts morphologically the main scarp left by the first fail-

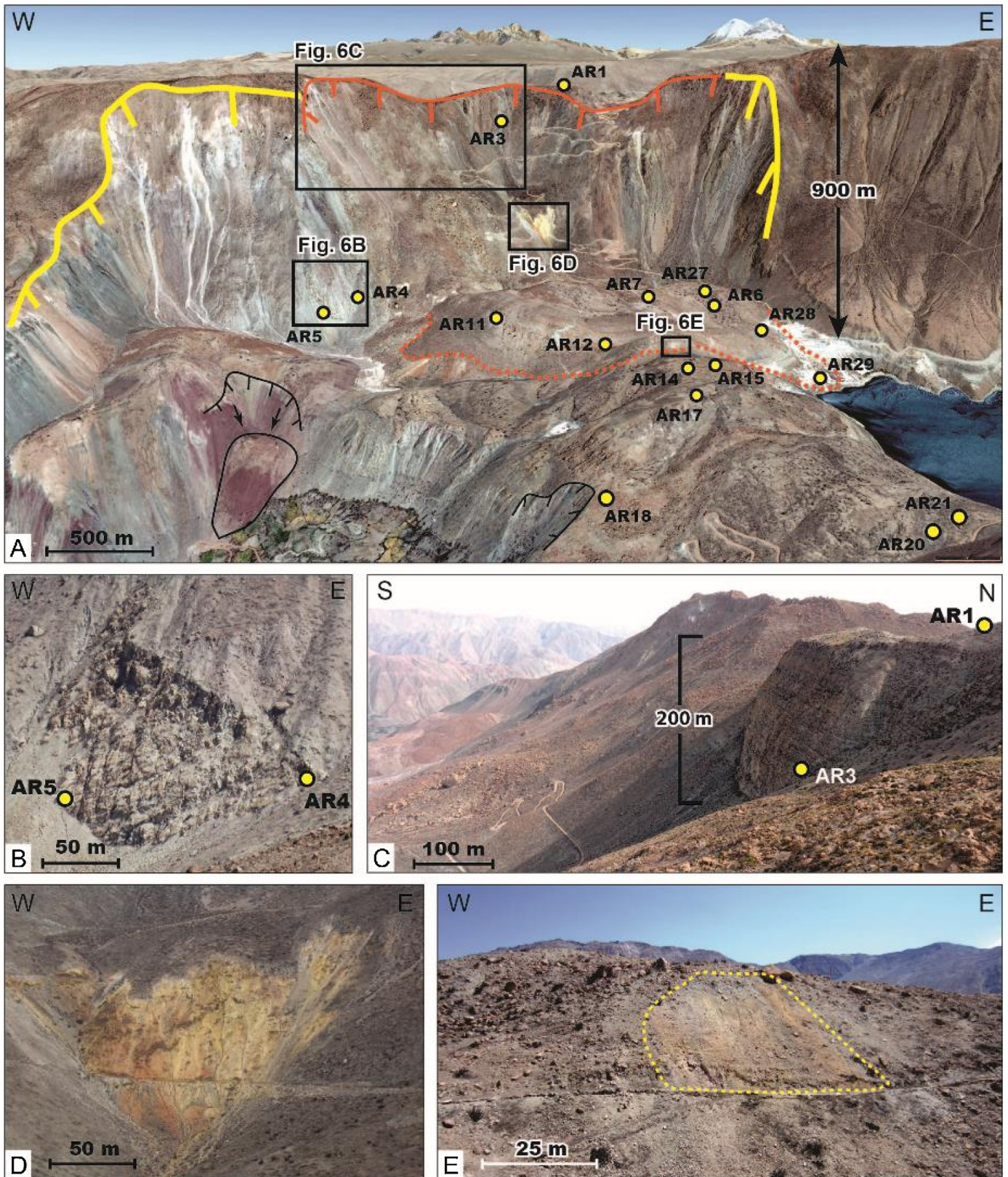


Fig. 6. Main scarp morphologies of the Aricota rockslide. (A) 3D view of the Aricota rockslide area (Google Earth). The scarp of the rockslide dam (first event) is depicted in yellow while the rock-avalanche scarp (second event) is in orange. Dashed orange line highlights the boundary of the rock-avalanche deposit. Small landslides (in black) affect the southwestern slope of the rockslide dam. (B) Preserved scarp surface of the first failure event and location of samples AR4 and AR5. (C) Vertical scarp generated by the second failure event and cutting through alternating silts and black shales of the Tarata formation. Sample AR3 was extracted from the scarp toe. See also location of the sample AR1 at the top of the slope, dedicated to constrain long-term denudation rate. (D) Layer corresponding to a regional paleo weathering profile interbedded in Cretaceous series. (E) Same weathered material (yellow) reworked and transported by the rock-avalanche.

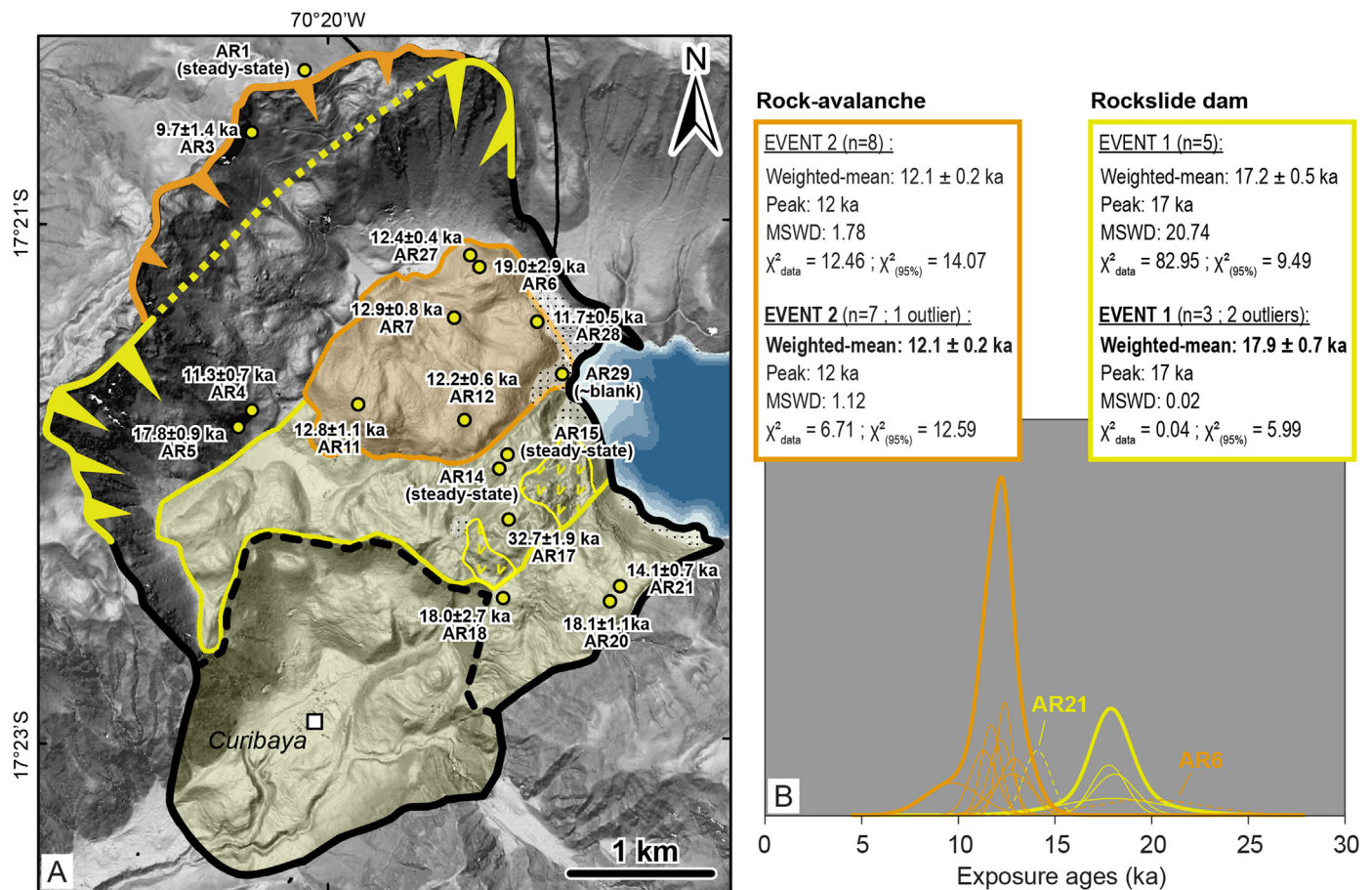


Fig. 7. Exposure durations results on the Aricota giant rockslide. (A) Rockslide map and sample ages (1σ internal uncertainty, Table 1, supplementary data). Legend is the same as Fig. 3B. (B) Probability density plot and statistics over exposure durations (1σ internal uncertainty, Table 1, supplementary data). Yellow curves and orange curves correspond to the rockslide dam (event 1) and the rock-avalanche (event 2), respectively. Thin lines correspond to individual exposure durations. Dashed lines refer to exposure durations interpreted as outliers (see text for details). Exposure duration from sample AR17 (32.7 ± 1.9 ka) is considered as an outlier (out of frame). Thick curves refer to the summed probability density function for each event (excluding outliers).

ure over a width of ~ 3 km (Figs. 3B and 6 A) inducing a regression toward the north of about 600–700 m.

Two types of structures can be distinguished in the rock-avalanche deposit. The firsts ones correspond to radial structures in the morphology (Fig. 3A), which directions point mainly toward the southeast. They are interpreted as an indication of the main direction of debris propagation toward the southeast. The second types of structures are concentric and are revealed by several bands of colors (black, brown and white) that are alternating in the deposit (Fig. 4C and Fig. 6A). Those colors correspond to different lithology of boulders. Indeed, from the northern to the southern part of the deposit, we can recognize boulders of ignimbrite and weathered material from the Huayllilas formation, followed by alignment of black silt-shale boulders from the Tarata formation (e.g. Fig. 5B) and finally very large boulders (up to 25 m in length) of andesitic breccia from the Quellaveco formation. The eastern side of the rock-avalanche deposit is composed of granitic boulders such as they outcrop above and along the top of the scarp (Fig. 3B). At the front of the rock-avalanche deposit (Fig. 6A), we observed an outcrop of weathered yellow material that originates from the middle part of the upper slope (Fig. 6D).

As a whole, those morphologies and such spatial distribution of boulders indicate that the former lithological succession of the slope was not mixed during the rock-avalanche and debris transport. The failure mode probably follows a translational failure allowing the bottom part of the slope to be projected in the distal part of the deposit.

4.2. Denudation rate and exposure duration results

Denudation rate and exposure durations derived from ^{10}Be data are reported in Table 1 (supplementary data). As previously mentioned, our first objective was to constrain the local denudation rate of the Aricota rockslide area in order to derive accurate exposure durations. The sample AR1, extracted on the ignimbritic plateau for this purpose, provided a high concentration of $38.00 \pm 1.36 \times 10^5$ at. g^{-1} . This indicates a saturation of ^{10}Be , i.e. a steady state, which is reached after an exposure duration greater than 1 Ma (Gosse and Phillips, 2001) at this latitude and elevation (17°S and ca. 3700 m a.s.l.) and corresponds to a denudation rate of 3.1 ± 0.6 $\text{mm} \cdot \text{ka}^{-1}$. Unexpectedly two other samples, AR14 and AR15, taken at the top of the Aricota rockslide dam also provided steady-state concentrations of $43.78 \pm 1.42 \times 10^5$ and $50.49 \pm 1.47 \times 10^5$ at. g^{-1} , corresponding respectively to denudation rates of 2.6 ± 0.5 and 2.2 ± 0.4 $\text{mm} \cdot \text{ka}^{-1}$. The presence of those steady-state surfaces in the main rockslide body suggests that a part of the original topography of the plateau was preserved during the mass movement. The implications of that result for the understanding of the failure typology will be more specifically discussed hereafter. All agreeing within uncertainties, those three denudation rates success a chi-2 test (1.39/5.99 (95%)) and belong to the same population whose weighted mean is 2.6 ± 0.4 $\text{mm} \cdot \text{ka}^{-1}$ (uncertainty attached is 1 sigma weighted standard deviation).

Exposure durations were then calculated using this mean denudation rate. In general, as shown on the Fig. 7B, exposure dura-

tions obtained are in good agreement with the geomorphological settings and they allow discriminating the two successive events that occurred on the Aricota rockslide. In the following, the exposure durations are reported with one sigma internal uncertainty.

The youngest exposure durations correspond to boulders of the rock-avalanche deposits, corresponding to the second event. Five exposure durations over six (samples AR7, AR11, AR12, AR27 and AR28) range between 11.7 ± 0.5 and 12.8 ± 1.1 ka (Table 1 (supplementary data) and Fig. 7B). The sample AR6 (19.0 ± 2.9 ka) is the only one age of this lobe of deposit falling out of this range, and for which we suspect likely inheritance. Comparing with exposure durations of ca. 12–13 ka, the excess of ^{10}Be concentration in this sample would be about 1×10^5 at g^{-1} . Along a depth profile that is theoretically at the equilibrium, and considering the denudation and the production rate conditions of the plateau (mean denudation rate of $2.6 \pm 0.4 \text{ mm} \cdot \text{ka}^{-1}$, “infinite” time, and production scaling of sample AR1), this concentration would be achieved at depth of 4 to 6 m. It is thus probable that the boulder AR19 comes from this pre-failure depth location and then was deposited in the debris with non-zero initial ^{10}Be concentration, giving an apparent older exposure duration. The sample AR3, picked at the foot of the vertical scarp located directly above the debris lobe (Fig. 6A and C), provided an exposure duration of 9.7 ± 1.4 ka, not significantly different from the previous ones considering the uncertainties. It confirms the relation between this secondary scarp and the rock-avalanche deposits.

Finally, the sample AR4, that was extracted from the northern part of the scarp presented on Fig. 6B (see also location on Fig. 3B), provided an exposure duration of 11.3 ± 0.7 ka that also agree with the one's previously listed. It is likely that the rock-avalanche failure has rejuvenated this side of the main scarp during its propagation. A probability density plot including all those samples (Fig. 7B) highlights a unimodal distribution (chi-2 test (95%): 6.71/12.59), the weighted mean of which is 12.1 ± 0.7 ka (uncertainty attached is 1 sigma weighted standard deviation). Considered or not, the AR4 and AR6 samples do not affect the result (Fig. 7B).

Exposure durations obtained from the five samples picked on the dam area (AR5, AR17, AR18, AR20, AR21), and its corresponding scarp, are significantly older. They range between 14.1 ± 0.7 and 32.7 ± 1.9 ka (Table 1, supplementary data). The probability density distribution provided on Fig. 7B shows that three of those ages (AR5, AR18 and AR20) agree within uncertainties (chi-2 test (95%): 0.04/5.99) and point to a weighted mean of 17.9 ± 0.7 ka. Inheritance is inferred in the sample AR17 (32.7 ± 1.9 ka) leading to a significantly older apparent exposure duration than the mean duration. This is fairly concordant with the fact that (1) the sample AR17 was extracted on boulders close to the samples AR14 and AR15 at steady state, and (2) all those samples are all standing in an area of preserved surface (Figs. 3B and 7) representing pre-rockslide topography.

The ^{10}Be concentration of sample AR21 (14.1 ± 0.7 ka) leads to a significantly younger apparent exposure duration. We interpret this younger apparent age as the consequence of a desquamation process of the boulder surface following the typical onion-skin weathering of the Atacama desert.

We measured in the sample AR29 (Fig. 5C and D) a $^{10}\text{Be}/^9\text{Be}$ ratio of $0.56 \pm 0.08 \times 10^{-14}$ that is equivalent to the corresponding blank value for this run ($0.52 \pm 0.23 \times 10^{-14}$, Table 1, supplementary data). This means that the ^{10}Be concentration in this sample is close to the detection limit, implying an exposure duration close to zero. The Fig. 8 shows the morphological context of the boulder AR29. It stands at an elevation of 2760 m, while the pre-1967 level was at 2790 m and the highest level deduced from diatomite deposit (Placzek et al., 2001) was estimated at ca. 2830 m (Fig. 8B). As this boulder belongs morphologically to the second event (mean age of deposition is 12.1 ± 0.7 ka), its very low ^{10}Be concentra-

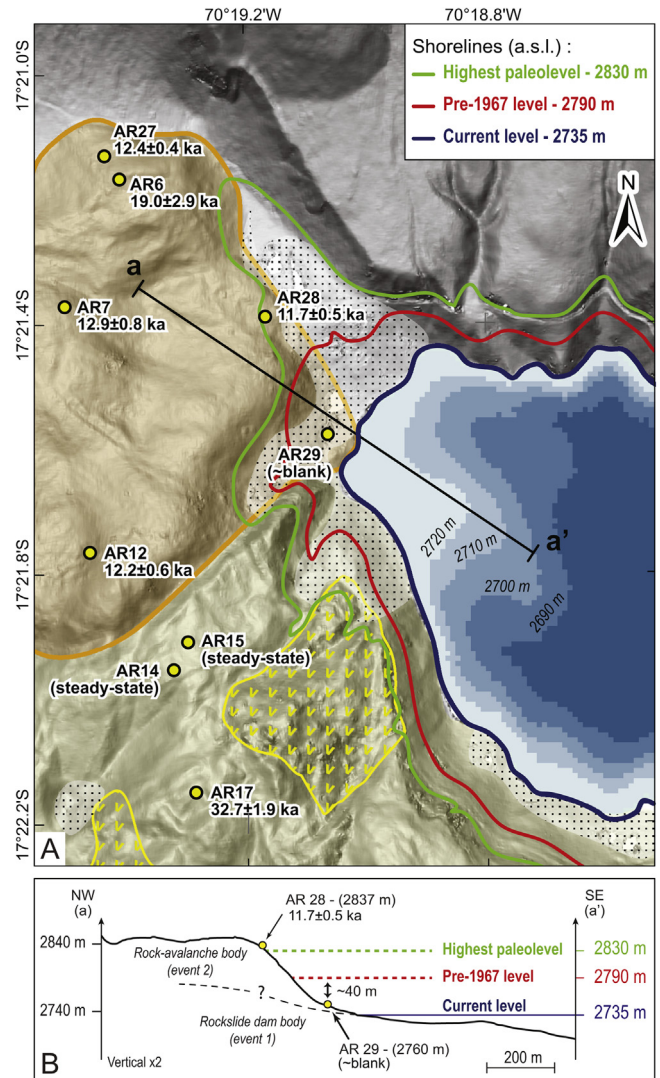


Fig. 8. Morphological context around the sample AR29. (A) Geomorphological map of the north-eastern part of the Aricota dam showing the location of the sample AR29 and the main variations of the Aricota lake shorelines (the probable highest paleo-lake level was reconstructed according to diatomite deposits (Placzek et al., 2001)). (B) Topographic profile extracted from the Pléiades DEM (see location on Fig. 8B). The legend of the rockslide morphologies is the same as Fig. 3B.

tion suggests that during the rock-avalanche, the boulder likely fell directly in deep water, thus shielded from the incident cosmic ray particles up to now.

5. Discussion

Most of the large landslides identified in the Central Western Andes, including the Aricota rockslide, have developed along the flank of deeply incised canyons (Fig. 1; e.g. Crosta et al., 2014; Thouret et al., 2017). In those canyons, the incision can locally exceed 1500 m (Thouret et al., 2017) suggesting that the topography is probably the first preconditioning factor for those giant gravitational failures. The same conclusions were made by Strasser and Schlunegger (2005), and Wörner et al. (2002) regarding the Lluta landslide. The deep incision of those canyons is the result of the peculiar conditions prevailing along the Central Western Andes since several millions of years (Schlunegger et al., 2006; García et al., 2011; Gunnell et al., 2010; Bissig and Riquelme, 2010; Jeffery et al., 2013). It is first related to the uplift of the region since the Cenozoic (e.g. Schildgen et al., 2009; Thouret et al., 2007). Second, it is related

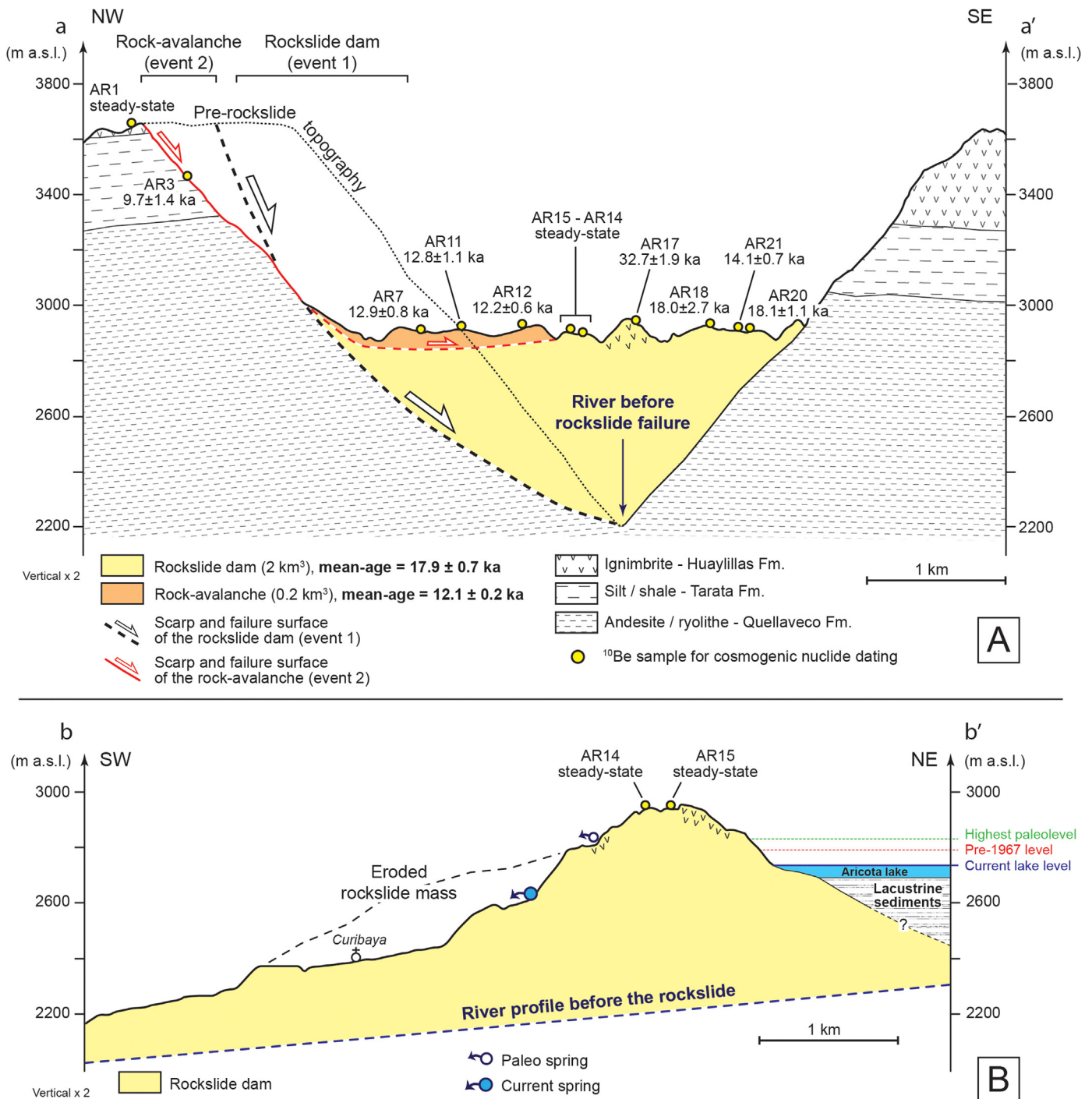


Fig. 9. Interpretative cross-sections of the Aricota giant rockslide. See locations on Fig. 3B. (A) Perpendicular to the Locumba valley. The pre-rockslide topography, before the first event, is reconstructed considering the volume estimation of the rockslide dam and interpolating the slope of the valley flanks (Delgado et al., 2018). Samples for ¹⁰Be cosmic ray exposure dating are projected on the cross-section. (B) Parallel to the Locumba valley. The pre-rockslide dam river profile is indicated from Delgado et al. (2018).

to the specific climate condition marked by a long lasting hyper-aridity affecting all the Central Western Andean flank (Atacama desert) until elevations of about 3000 m a.s.l., and, on the other hand, precipitations from the easterlies that reached the upper part of the western watersheds (Altiplano and Western Cordillera). Indeed, after Huffman et al. (2007), while current mean precipitation are ~0 mm/yr along the coast and the Western Cordillera, about 800 mm/yr of precipitation in average are recorded on the Altiplano. This rain shadow effect started possibly at 12/10 Ma (e.g. Ehlers and Poulsen, 2009; Insel et al., 2012; Rech et al., 2019). This

way, while the western flank of the Andes remains hyper-arid, the upper catchments collect a significant amount of water, flowing then throughout the Cordillera toward the Pacific (Litty et al., 2017). This discharge has maintained a constant incision in the valleys thus contributing to maintain very steep canyon flanks and critical topographic wedges highly prone to large-scale landslide failure (Thouret et al., 2017). As it was globally reported by Korup et al. (2007), and locally by Wörner et al. (2002) in the Lluta valley, this suggests that the critical relief (see also Blöthe et al., 2015) that can be close, or even beyond, to its proposed upper strength limit may

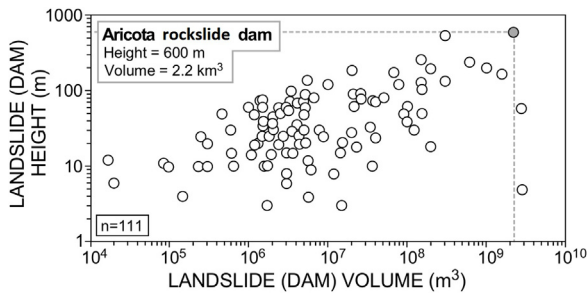


Fig. 10. Worldwide compilation of landslide dams modified from Korup et al. (2004) showing the relations between the landslide volumes and heights (n is the number of landslides of the database). The Aricota rockslide (grey circle) stands within the 3 largest landslide dams and the highest height reported worldwide.

be one of the primary factor controlling the development of large landslides in the Andean canyons.

In the Locumba valley, the gravitational failure of the canyon flank was deep and large enough to produce a massive dam generating upstream a lake more than 6 km long. As shown by our morphological analysis, two successive failure events occurred at the Aricota site (Fig. 3 and Fig. 9). A first main event, of rockslide typology, created the dam and then a second event occurred, of rock-avalanche typology, which deposits spread out on top of the first ones, reinforcing the initial dam. Taking into account the height of the dam (~600 m), its volume ($2 \pm 0.3 \text{ km}^3$) and the pre-rockslide valley morphology, we propose that the first event (rockslide dam) has affected the ignimbritic plateau over a maximal width of 400–500 m (Fig. 9A). The failure allowed the collapse of a part of this plateau originally located at ca. 3650 m a.s.l. Ignimbritic rock volume outcrops at the present-day at the top of the rockslide dam at ca. 2900 m a.s.l. (Fig. 9A). Translational movements probably dominated the failure type as the vertical distribution of the stratigraphy is preserved in the dam. This morphological characteristic has been already described in various study cases of large slope destabilizations (Shreve, 1968; Strom, 2006; Humair et al., 2013). According to the classification of Hermanns et al. (2011), the distribution of the Aricota rockslide deposits in the Locumba valley corresponds to a type “IV a” in plan view. Indeed, the run-out of the debris was long enough (~3 km) to reach the opposite valley flank and to dam a small tributary valley (Fig. 3). As shown on the geological cross-section Fig. 9A, along a cross-valley profile, the deposit profile is roughly flat and symmetric to the original valley profile. This would correspond to a type “i” of cross-valley profile in the classification of Hermanns et al. (2011). The cross-section of the rockslide deposit, parallel to the valley (Fig. 9B), highlights the large thickness of the dam (600 m) and shows similarities with the type “2” of the along-valley profile classification of rockslide dams that is associated with a large lake (Hermanns et al., 2011). The great depth of the failure surface and the confined setting of the original Locumba valley may explain the high thickness of the deposit (Fig. 9B).

As shown on Fig. 10, comparing with the compilation of landslide dams established by Korup (2004), the Aricota rockslide dam stands among the largest worldwide. To explore the geotechnical stability of this dam, we compiled the two indexes developed by Casagli and Ermini (1999). They are based on geomorphometric parameters of the site: (1) the Blockage Index $I_b = \log(V_D * A_C^{-1})$ and (2) the Impoundment Index $I_i = \log(V_D * V_L^{-1})$, where V_D and V_L are the volumes of the rockslide dam and the lake [in m^3], respectively, and A_C is catchment area upstream of the blockage [in km^2]. The values obtained for the Aricota rockslide dam are $I_b = 6$ and $I_i = 3.4$ (taking $V_D = 2 * 10^9 \text{ m}^3$, $A_C = 1600 \text{ km}^2$ and $V_L = 8 * 10^5 \text{ m}^3$ (Placzek et al., 2001)) indicating the stability of the site. Indeed Korup et al. (2004) shown that below $I_b = 2$ no landslide-dammed lakes formed,

whereas unstable lakes form at $I_b < 4$ and that impoundments with $I_b > 7$ have remained stable. Similarly, sites where $I_i > 1$ have all retained existing lakes, whereas locations with $I_i < 1$ comprise both stable and unstable landslide dams. Since the dam emplacement, the progressive infilling of the lake by lacustrine sediments (Fig. 9B) have also decreased the water volume and therefore reduced the pressure imposed to the dam. More generally, megatsunami is another hazard potentially linked to mountain lakes (either natural, landslide dam or artificial lakes) that can be triggered by slope failures around the lake (Hermanns et al., 2004). Taking into account the steep slope around the Aricota lake, this hazard cannot be excluded and deserve to be studied.

In the case of large landslide processes, Glade and Crozier (2005), or Hermanns et al. (2006) introduce that both preparatory factors (static and dynamic) and triggering factors are often interdependent and play crucial role in the slope failure evolution. In our study the geomorphological observations combined with cosmogenic nuclide dating obtained on the Aricota rockslide area show clearly two stages of destabilization at $17.9 \pm 0.7 \text{ ka}$ and $12.1 \pm 0.2 \text{ ka}$, corresponding to the main rockslide dam event and to the secondary rock-avalanche, respectively (Fig. 9A). This timing of events provides a frame to discuss the nature of forcings that may have triggered the two slope failures. However, we do not have any constraints to discuss the preparatory phases and their related factors, thus the following discussion focuses on triggering factors only.

According to the literature, most of the contemporaneous, or historical landslide dams, have been triggered by earthquakes. Some of the most impressive cases are the Usoy landslide (volume = 2.4 km^3 , impounding a lake of a 17 km^3), triggered in 1911 by an earthquake of $M_w 7.7$ (Ambraseys and Bilham, 2012), the Tortum landslide (0.18 km^3) in Turkey (Duman, 2009), or the numerous landslide dams in southeastern Italy which triggered by earthquakes of intensity VII to X during the 17th (Nicoletti and Parise, 2002). In the Andes, mostly in the NW Argentina, numerous paleo-landslide dams were reported and attributed also to past earthquakes (Wayne, 1999; Hermanns and Schellenberger, 2008; Moreiras et al., 2015).

Considering that the Aricota rockslide is located in a tectonically active region, with two large crustal fault systems (Incapuquio and Purgatorio faults) located from 10 to 20 km south of the rockslide (Fig. 2), a coseismic triggering of the Aricota slope failures is probable. Indeed, Benavente et al. (2017) revealed Holocene seismotectonic activity of the Purgatorio fault, showing at least two ruptures of ~3 and ~2 m of vertical offset at the surface, equivalent to $> M_w 7$ shallow seismic events. However, even if those faults represent high seismogenic potential in the close field of the rockslide, it does not exist for the moment any paleoseismic records as old as the Aricota slope failures that would corroborate a coseismic trigger. Another observation is that several landslides, including the Aricota ones, seem to cluster spatially on the hanging wall of the Incapuquio fault (transpressive senestral, Fig. 2). Similarly to what was reported by Gorum et al. (2011) in the Sichuan after the 2008 Wenchuan earthquake, such a landslide distribution could reflect a coseismic “hanging wall” effect. Indeed, Gorum et al. (2011) noticed that most of the landslides triggered during the Wenchuan earthquake occurred on the hanging wall block of the Wenchuan-Maowen fault. This massive landslide triggering was interpreted as a site effect and a probable amplification of ground motion in this area (Chiou and Youngs, 2014). Over the long-term, a higher concentration of slope failures on the hanging wall of the Incapuquio fault (Fig. 2) can be interpreted also as the effect of the river incision into the uplifting block, which may have increased and steepened the relief there.

On the other hand, several studies reported that in northwestern Argentinian Andes many landslide producing dammed lakes may have formed during wet periods (e.g. Trauth et al., 2003). Moreiras

and Sepúlveda (2015) provide an up-to-date inventory of mega paleolandslides in the Central Andes at 32–34°S and discuss traditional hypotheses used to explain landslide occurrences. Whereas earthquakes have been widely proposed as the main triggering mechanism of the Chilean slope failures, paleoclimatic conditions are considered as the main cause of mega-landslides in Argentina. However, Moreiras and Sepúlveda (2015) also insist on the fact that local evidences and geological records of those wetter periods are often lacking. On our study area at 17°S, it is striking to note the synchronicity between the chronic of failures of the Aricota rockslide and the two latest humid periods recorded at the scale of the Central Altiplano since 20 ka, pointing to a potential climatic control on the Aricota rockslide triggering. Those humid periods, documented since the 80 S' (e.g. Blodgett et al., 1997), are characterized mainly by two major expansions of the Altiplano lakes: the Tauca (18.5–14.5 ka) and the Coipasa (12.8–11 ka) phases (Placzek et al., 2013), during the Heinrich Stadial 1a and the Younger Dryas, respectively. Recently Martin et al. (2018) explored in details the past climate conditions during the Tauca phase by simultaneously reconstructing the fluctuations of lake levels and glacier advances in the Altiplano region. They found that during this period, on the northwestern edge of the Altiplano and the upper Locumba basin, the paleoprecipitations were amplified by 2–3 times compared to the present day precipitation. At a regional scale, the occurrence of such drastic increases of the paleoprecipitation is corroborated also by the concomitant aggradation of alluvial terraces and fan systems on valley floors along the western Peruvian margin. For instance, in the Majes river, located at about 300 km northwest to the Locumba valley, Steffen et al. (2010) pointed to the occurrence of major periods of aggradation at ca. 20 ka and between 12–8 ka. In the Moquegua valley (50 km northwest to Aricota), Keefer et al. (2003) reported the existence of extensive flood and debris flow deposits dated between 12 and 8.4 ka, and at least ten severe events that took place between 38 and 13 ka. At a larger scale along the western margin of the Andes in Peru, Litty et al. (2017) highlighted changes in precipitations patterns during the last 100 ka through shifts of the sediment provenance. In the Pisco valley, 700 km northwest to the Locumba valley, Steffen et al. (2010) and Bekaddour et al. (2014) conclude that phases of sediment aggradation and accumulation were triggered by shifts toward a more humid climate conditions during the Tauca paleolakes maximal expansions.

As a summary, several lines of evidences point toward significant increase of paleoprecipitation regime along the Central Western Andes during the periods 18.5–14.5 ka and 12.8–11 ka (Placzek et al., 2013). Given the correlation between those wet events and the timing of the Aricota rockslide (17.9 ± 0.7 ka and 12.1 ± 0.2 ka, Fig. 7); we tentatively propose that the generation of catastrophic mass movements in the Locumba valley was firstly climatically driven. Prolonged periods of increased precipitation may have reduced thresholds for slope instabilities by increasing water content in the unstable masses, decreasing the effective friction over the sliding planes, and eroding slope foots because of higher river discharge.

6. Conclusions

In this paper, we provide a geomorphological analysis and dating of the Aricota giant rockslide, located in the Central Western Cordillera of southern Peru (17°S). Our results indicate the occurrence of two successive events. A giant failure producing a rockslide dam occurred first at 17.9 ± 0.7 ka. This first destabilization event mobilized a rock volume of ca. 2 km³ and affected the northern flank of the Locumba valley. As shown by the presence of large preserved ignimbrite blocks overlying mixed and fragmented material in the dam, this first failure event was “in mass”. It gener-

ated an impressive dam in the main valley with a height of about 600 m, impounding a lake of approximately 6 km long upstream that remains until today. At 12.1 ± 0.2 ka, a second event of destabilization cross-cutting the initial scarp produced a rock-avalanche of ca. 0.2 km³ which debris spread out at the top of the northern part of the dam formed by the first event. The chronology of those two events of destabilization is compatible with the main paleoclimatic events of this region during the Heinrich Stadial 1a and the Younger Dryas, both characterized by paleoprecipitation increases. Furthermore, aggradation of alluvial terraces and fan systems are concomitant along the valley floors of the western Peruvian margin highlighting higher regional erosion, sediments supply and mass-wasting events during those two periods. This temporal correlation suggests that the climate has played a preponderant role on the triggering of the Aricota rockslide. However, additional and/or concomitant effect of crustal earthquakes on the rockslide initiation cannot be ruled out considering the seismotectonic setting of this Andean region. Future studies related to paleoseismicity would help to clarify this debated question. At the scale of the Central Andes, although numerous giant paleolandslides are recognized on its western arid flank, their understanding still suffers of a lack of time constraints, either in term of climatic events or in term of their individual geomorphic description.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary material related to this article can be found, in the online version, at doi:<https://doi.org/10.1016/j.geomorph.2019.106932>.

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2 **Sample preparation**

3 Sample preparation and ^{10}Be chemical extraction were achieved following routine procedure at the
4 GTC Plateform, ISTerre laboratory (Grenoble, France). The samples were crushed and sieved to obtain
5 a grain-size of 0.2–0.8 mm. Then pure quartz was obtained by successive magnetic separations using
6 a Frantz magnetic separator and subsequent leaching in a mixture (1:2) of hydrochloric and
7 hexafluorosilicic acids. After atmospheric ^{10}Be decontamination (by 3 sequential HF leaching), ^9Be
8 carrier solution (1000 mg.l^{-1} , Scharlab Be batch 14569501) was added and the sample was then
9 dissolved in 40% HF. Beryllium was isolated using anion and cation exchange columns followed by
10 selective pH precipitation techniques (Brown et al., 1991). The beryllium hydroxides were precipitated,
11 dried, and calcined at 850 °C to BeO . $^{10}\text{Be}/^9\text{Be}$ measurements were performed at the French AMS
12 National Facility, located at CEREGE in Aix-en-Provence (Arnold et al., 2013). $^{10}\text{Be}/^9\text{Be}$ ratios were
13 calibrated against the in-house standard STD-11, using an assigned $^{10}\text{Be}/^9\text{Be}$ ratio of (1.191 ± 0.013)
14 $\times 10^{-11}$ (Braucher et al., 2015). Uncertainties on ^{10}Be concentrations (reported as 1σ) are calculated
15 according to the standard error propagation method using the quadratic sum of the relative errors and
16 include a conservative 0.5% external machine uncertainty (Arnold et al., 2010), a 1.08% uncertainty on
17 the certified standard ratio, a 1σ uncertainty associated to the mean of the standard ratio
18 measurements during the measurement cycles, a 1σ statistical error on counted events and the
19 uncertainty associated with the chemical and analytical blank correction. The $^{10}\text{Be}/^9\text{Be}$ blank correction
20 values were $5.21 \pm 2.30 \times 10^{-15}$ for the run of samples AR27, AR28 and AR29, and $2.77 \pm 0.47 \times 10^{-15}$ for the
21 other samples (Table 1).

22 Denudation rates and exposure durations were both calculated using the MATLAB[®]-based CRONUScalc
23 program, developed by Marrero et al. (2016). This production rate was scaled at the geographical and
24 altitudinal location of each sampling site using the LSD scaling scheme (SF) of Lifton et al. (2014) which
25 is a time-dependent model based on equations from a nuclear physics model and incorporating dipole

26 and non-dipole magnetic field fluctuations and solar modulation (Marrero et al., 2016). Atmospheric
27 pressure at the sampling site was derived from the ERA-40 atmosphere model (Uppala et al., 2005).
28 We applied a density estimate of 2.6 g.cm^{-3} for the ignimbrite and an attenuation length of 160 g.cm^{-2}
29 for the neutron component (Dunne et al., 1999). For the muons scheme, we kept the default
30 parameters of CRONUScalc program (Marrero et al., 2016). Snowfall almost never occurred in this
31 semi-arid area, thus this correction was neglected. Data templates including all the parameter
32 previously listed are provided in the supplementary data for any recalculation.

33 Table 1: Samples parameters, cosmogenic ^{10}Be data and results. Z is the sample thickness, S is the topographic shielding factor, Pn and P μ are the
 34 contemporary depth average production rate outputs from the CRONUS Earth Web Calculators (version 2.0; Marrero et al., 2016) for the neutrons and
 35 slow/fast muons, respectively. All the uncertainties reported are 1 sigma.

| Morphology | Sample | Latitude (S°) | Longitude (W°) | Elevation (m a.s.l.) | Z (cm) | S | Mass (g) | ^9Be carrier (10^{19} atoms) | $^{10}\text{Be}/^9\text{Be}$ (10^{-14}) | ^{10}Be ^a (10^5 at.g $^{-1}$) | Pn (at.g $^{-1}$.yr $^{-1}$) | P μ (at.g $^{-1}$.yr $^{-1}$) | Exposure ^b ages (ka) | Denudation rates (mm/ka) |
|------------|------------------|------------------|-------------------|-------------------------|-----------|-------|-------------|---|--|--|-----------------------------------|--|------------------------------------|-----------------------------|
| Scarps | AR3 | 17.34418 | 70.33860 | 3488 | 6.0 | 0.494 | 1.73 | 2.04 | 1.21 ± 0.09 | 1.10 ± 0.12 | 11.95 | 0.09 | 9.7 ± 1.4 (1.7) | |
| | AR4 | 17.36217 | 70.33842 | 2870 | 5.5 | 0.792 | 4.87 | 2.04 | 3.64 ± 0.17 | 1.41 ± 0.08 | 13.50 | 0.11 | 11.3 ± 0.7 (1.3) | |
| | AR5 | 17.36312 | 70.33930 | 2856 | 1.5 | 0.591 | 5.45 | 2.04 | 4.82 ± 0.22 | 1.70 ± 0.08 | 10.32 | 0.08 | 17.8 ± 0.9 (1.7) | |
| Boulders | AR6 | 17.35278 | 70.32345 | 2933 | 3.0 | 0.976 | 6.34 | 2.03 | 9.99 ± 1.74 | 3.11 ± 0.56 | 17.62 | 0.14 | 19.0 ± 2.9 (3.2) | |
| | AR7 | 17.35618 | 70.32500 | 2918 | 4.0 | 0.971 | 4.46 | 2.03 | 4.79 ± 0.25 | 2.05 ± 0.12 | 17.24 | 0.14 | 12.9 ± 0.8 (1.4) | |
| | AR11 | 17.36170 | 70.33145 | 2935 | 5.5 | 0.984 | 2.76 | 2.03 | 3.07 ± 0.21 | 2.05 ± 0.16 | 17.44 | 0.14 | 12.8 ± 1.1 (1.6) | |
| | AR12 | 17.36274 | 70.32433 | 2907 | 5.0 | 0.925 | 5.12 | 2.02 | 4.90 ± 0.22 | 1.82 ± 0.09 | 16.18 | 0.13 | 12.2 ± 0.6 (1.2) | |
| | AR17 | 17.36917 | 70.32143 | 2928 | 3.5 | 0.995 | 1.08 | 2.05 | 3.35 ± 0.18 | 5.83 ± 0.36 | 17.84 | 0.14 | 32.7 ± 1.9 (3.2) | |
| | AR18 | 17.37422 | 70.32235 | 2822 | 2.5 | 0.992 | 0.45 | 2.09 | 0.90 ± 0.09 | 2.89 ± 0.47 | 16.84 | 0.14 | 18.0 ± 2.7 (3.0) | |
| | AR20 | 17.37403 | 70.31420 | 2909 | 5.5 | 0.981 | 8.10 | 2.06 | 11.55 ± 0.75 | 2.87 ± 0.19 | 17.12 | 0.14 | 18.1 ± 1.1 (1.8) | |
| | AR21 | 17.37372 | 70.31408 | 2907 | 5.0 | 0.987 | 5.07 | 2.06 | 5.76 ± 0.28 | 2.23 ± 0.11 | 17.27 | 0.14 | 14.1 ± 0.7 (1.4) | |
| | AR27 | 17.35217 | 70.32387 | 2925 | 3.0 | 0.964 | 8.58 | 4.10 | 4.58 ± 0.15 | 1.98 ± 0.06 | 17.32 | 0.14 | 12.4 ± 0.4 (1.2) | |
| | AR28 | 17.35647 | 70.31943 | 2837 | 3.8 | 0.980 | 8.70 | 3.42 | 5.06 ± 0.22 | 1.79 ± 0.07 | 16.61 | 0.14 | 11.7 ± 0.5 (1.2) | |
| | AR29 | 17.35985 | 70.31778 | 2750 | 3.5 | 0.969 | 3.12 | 3.39 | 0.56 ± 0.08 | - | - | - | - | - |
| Boulders | AR1 | 17.34085 | 70.33488 | 3674 | 2.0 | 1 | 3.07 | 2.03 | 57.81 ± 2.05 | 38.00 ± 1.36 | 24.93 | 0.19 | 3.1 ± 0.6 | |
| | AR14 | 17.36590 | 70.32203 | 2923 | 4.0 | 1 | 0.75 | 2.08 | 16.12 ± 0.51 | 43.78 ± 1.42 | 24.93 | 0.19 | 2.6 ± 0.5 | |
| | AR15 | 17.36515 | 70.32163 | 2910 | 3.0 | 1 | 5.59 | 2.04 | 138.70 ± 4.04 | 50.49 ± 1.47 | 24.93 | 0.19 | 2.2 ± 0.4 | |
| | BI1 ^c | - | - | - | - | - | - | 2.03 | 0.28 ± 0.47 | - | - | - | - | - |
| | BI2 ^d | - | - | - | - | - | - | 3.37 | 0.52 ± 0.23 | - | - | - | - | - |

^a Uncertainties reported include the counting statistics, the machine stability (~0.5%) and the blank correction.

^b Exposure ages are reported with analytical and total uncertainties (the total uncertainty is in parentheses), that both include the propagation of uncertainties of each parameters by partial derivatives such as described in Marrero et al. (2016). Exposure ages were calculated with a locally estimated mean denudation rate of 2.6 ± 0.5 mm.ka $^{-1}$ (see text for explanations).

^c This sample was extracted from the top of a boulder that morphologically belongs to the deposit of the secondary rock-avalanche event, but which was located below the lake surface before 1967 (see text for details). As the concentration measured in this sample is equivalent to the blank value measured during this run (BI2), we did not calculated a corresponding exposure age.

^d This blank corresponds to the first run of measurements done in 2014 and its correction was applied to samples: AR1, AR3, AR4, AR5, AR6, AR7, AR11, AR12, AR14, AR15, AR17, AR18, AR20 and AR21.

^e This blank corresponds to the second run of measurements done in 2018 and its correction was applied to samples: AR27, AR28 and AR29.

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CHAPTER IV:
PLEISTOCENE CHRONOLOGY OF
LARGE LANDSLIDES TRIGGERING
ON THE WESTERN FLANK OF THE
CENTRAL ANDES REVEALED BY
COSMOGENIC NUCLIDE DATING

Pleistocene chronologies of large landslides triggering on the Western Flank of the Central Andes revealed by cosmogenic nuclide dating

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Abstract

The Western flank of the Central Andes presents a high concentration of giant paleo-landslides that are well preserved due to the long-term aridity of the region. Based on an exhaustive inventory established at the scale of the Western Cordillera in South Peru and North Chile, a previous study indicates that the formation of those giant paleo-landslides was favored by coupled conditioning factors including lithology and strong local relief generated by the incision of deep canyons. In particular, spatial clustering was highlighted by the presence of dozens of large landslides spatially concentrated within a few kilometers. In this part of the Andes, the strong seismic activity linked to the ruptures of crustal faults and past climatic changes could have played a major role in the triggering of these large gravity instabilities. However, the precise timing of most of these landslides remains unknown, hampering our understanding of their frequency of occurrence. Thus, additional data are required to further investigate the question of their factor of trigger through time.

To shed new light on those questions, we focus in this study on one of those previously identified clusters: the “Locumba cluster”. The largest landslide in this area corresponds to the Aricota rockslide dam. A previous study shows that two failure events occurred at the Aricota site, a rockslide dam of $\sim 2 \text{ km}^3$ at ca. 18 ka and then a secondary rock-avalanche of $\sim 0.2 \text{ km}^3$ at ca. 12 ka, the timing of which suggests a correlation with humid episodes in the high central Andes. Our aim here was to date several other large landslides, located near and around the Aricota rockslide, to explore their possible correlation in time. We selected 8 paleo-landslides, including paleo-rockslide’s dams and rock-avalanches, distributed all along the Locumba river and its neighboring valleys: the Huanara and the Ilabaya rivers. On each site, we conducted a detailed mapping of the landslide’s morphologies using a high-resolution DEM (TanDEM-X and Pléiades), Google Earth images, and fieldworks to define a geological and geomorphological model of the landslides and to identify, when this applies, their successive internal failure events. Then, based on those frameworks, we used cosmogenic nuclide exposure dating to constrain their timing of failure, sampling 52 boulders in total. We used alternatively $^{10}\text{Be}/\text{quartz}$ or $^{10}\text{Be}/\text{feldspar}$ depending on the lithology available.

For half of the landslides, the exposure ages that we obtained show a strong scattering, including very old apparent ages up to ~1 Ma, which does not allow to determine the precise date of their triggering. For those cases, probable time ranges of landslide occurrence could be proposed only. We discuss and attribute this age-scattering mainly due to the inheritance problem. Indeed, inheritance is expected to be very strong in these arid regions where most of the slopes are slowly eroding, likely at steady-state equilibrium, and thus with a very high cosmogenic nuclide concentration at surface and at shallow depth (first 20 m). Nevertheless, we obtained good constraints for four of the landslides. All occurred during the Pleistocene with mean ages of ca. 16 ka, 18 ka, 114 ka, and 205 ka. So far, despite the spatial clustering of those landslides, their chronological constraints suggest that their triggering was related to various events, that spread through time. When comparing this to the previous dating in the region and other climatic proxies, the time ranges of 16-18 ka and 100-120 ka correspond to two well-defined humid periods, known as the Henrich stadial 1a and the Ouki event (during MIS5), respectively. These results suggest that past climate changes corresponding to the shift from hyper-arid to prolonged wetter conditions played a primary role in large landslide activity.

Keywords: Central Western Andes, Peru, Large paleo-landslides, Locumba cluster, Cosmogenic nuclides dating, Triggering factors.

1. Introduction

Landslides are gravitational phenomena that can be observed worldwide in various environments, from areas with strong topographic gradients such as orogenic and/or volcanic zones to oceanic slopes. In the continental domain they constitute one of the most important hazards generating loss of human lives and infrastructure (Petley, 2012; Froude and Petley, 2018; Wallemacq and House, 2018). On a longer time scale, large landslides are recognized as an efficient mechanism of regional-scale relief erosion in orogenic zones (e.g. Korup et al., 2007). The rate of landsliding is thought to reflect the long-term trend of tectonic uplift, with mass movements continuously affecting steep slopes along the flanks of incised river valleys (e.g. Larsen and Montgomery, 2012). Thus, landslides are the primary agent of material transport from hillslopes to rivers, limiting the relief construction in mountain ranges (Whipple et al., 1999; Montgomery, 2001; Roering, 2012).

During the last decades, studies of landslides on long-time scales (eg., hundreds to thousands of years), through the use of various dating approaches, have increased in different mountain ranges around the world (e.g., Dortch et al., 2009; Hermanns et al., 2013; Zerathe et al., 2014; Pánek, T., 2015; Schwartz et al., 2017) with the purpose of investigating potential relations between landslides activity and past climate oscillations or with long-term seismotectonic forcing. For instance, those results documented possible correlations between paleo-earthquake and landslide (e.g. Lebourg et al., 2014; Oswald et al., 2021), between last glacier retreats, permafrost melting, and slope debuttressing although with possible time-lags (e.g. Bigot-Cormier et al., 2005; Sanchez et al., 2010; Cossart et al., 2013; Lebrouc et al., 2014; Grämiger et al., 2017), and also between enhanced landslide activity and humid periods (e.g. Zerathe et al., 2014; Pánek, 2019). Nevertheless, as shown by a recent review from Pánek et al. (2017) and Pánek (2019), most of those landslide dating is restricted to the Holocene, very rarely to the Late Pleistocene. Our ability to document older landslide sequences is strongly hampered by the fact that landslide morphologies older than the last maximum glacial advance were not

preserved in the high mountains because of glacial and then fluvial erosion. Thus, up to now, very little is known about the effect of Quaternary climate oscillations on landsliding rates.

The Central Western Andes shows an interesting potential to study landslide chronicles on such long and undocumented time scales. Indeed, the Western flank of the Central Andes presents a high concentration of giant paleo-landslides (Figure. 1; Crosta et al., 2014; Delgado et al., 2022), and these large instabilities show exceptionally good states of preservation due to the low erosion and weathering related to the hyper-arid climate of the Atacama Desert since the Miocene (Dunai et al., 2005). As such, pioneered studies in this region were able to document landslide ages up to hundred thousand years (e.g. Margirier et al., 2015; Thouret et al., 2017; Crosta et al., 2017) or more (e.g. Pinto et al., 2008; Zerathe et al., 2017). However, first-order questions regarding the triggering of these large landslides remain pending. In particular, the respective roles of the strong and frequent seismicity along the Andean plate margin (either from subduction or crustal faults), as well as the effect of variations in precipitation patterns associated with past climate change, are debated.

Based on a landslide inventory elaborated in South Peru and North Chile, Delgado et al. (2022) documented about a thousand large landslides along the western flank of the central Andes. They made the correlation between favorable conditioning factors for the slope failures including lithology and strong local relief related to the incision of deep canyons. They also highlight spatial clustering of landslides, with several clusters grouping dozens of large landslides over radiuses of a few kilometers (Figure 1). Since most of these landslides remain undated, the main questions to be addressed now concern the temporal evolution setting of these landslide clusters. Do these clusters form during a single and strong triggering event, as in the case of a major earthquake (e.g. Valagussa et al., 2019; Junquera-Torrado et al., 2021)? Or do these clusters correspond to the accumulation of several slope failures spread over a long period of time interrupted by periods of quiescence?

In this study, we focus on one of these clusters, the Locumba cluster (Figure 1 and Figure 2) located in southern Peru. At the center of this cluster, the large Aricota rockslide was previously dated revealing two major slope failures, at about 18 ka and 12 ka (Delgado et al., 2020), possibly synchronous with wetter climate phases in the high central Andes (Martin et al., 2018). Our aim here was to constrain the ages of more landslides of the Locumba cluster around the Aricota rockslide, to explore their possible correlation in time. From perspective, we selected 8 paleo-landslides, including paleo-rockslide's dams and rock-avalanches, distributed all along the Locumba river and its neighboring valleys, the Huanara, and the Ilabaya rivers. Our detailed objectives were: (1) to perform a detailed mapping of those landslides and their internal events; (2) to constrain their age; (3) to look for patterns of occurrence and/or periodicity; (4) to explore the question of climatic or seismic triggering under the light of those new chronological constraints.

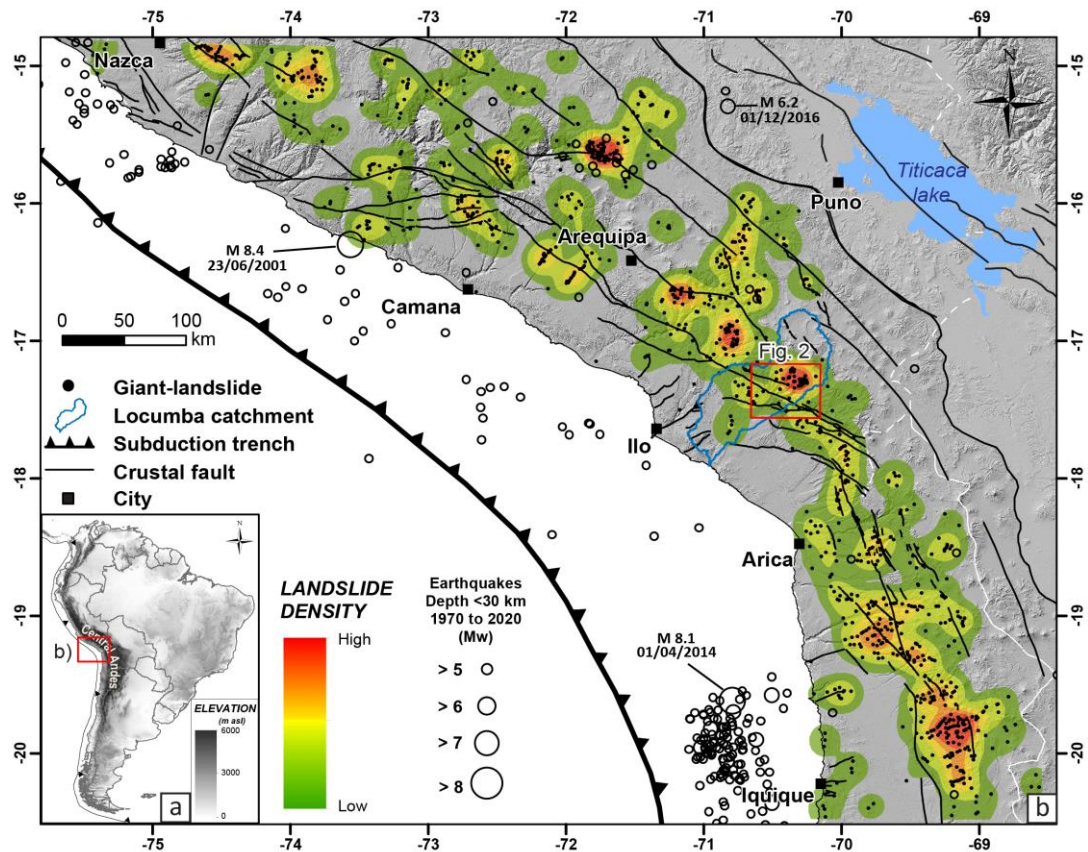


Figure 1. a) Location of the study area in the Central Andes. b) Density of large landslides along the Western flank of the Central Andes compared with the seismic catalog of the last 50 years by USGS (earthquakes > 5 Mw and depth < 30 km) and the main active crustal faults (from Delgado et al., 2022). The study area, located in the central part of the Locumba catchment (blue outline) is indicated by a red box.

2. Settings

2.1. Geological context

The orogenic zone of the Andes is located on an active tectonic margin, where the Nazca plate subducts below the South American plate with a convergence rate of $\sim 62 \text{ mm}\cdot\text{yr}^{-1}$ (Villegas-Lanza et al., 2016) producing long-term crustal thickening and uplift of the Andes range. The western flank is carved by deep valleys and canyons related to regional uplift (Thouret et al., 2007; Schildgen et al., 2009; Gunnell et al., 2010), it is also affected by important fault system oriented parallel to the subduction trench (Hall et al., 2012; Benavente et al., 2017, 2021). The study area is located on the Western Flank of the Central Andes, in the central part of the Locumba catchment at $\sim 17.5^\circ \text{ S}$ latitude (Figure 1).

In the study area, the lithology corresponds to a thick sequence of Mesozoic to Cenozoic volcano-sedimentary rocks (Figure 2). The Mesozoic sedimentation was controlled by the tectonic opening of the Arequipa-Tarapacá sedimentary basin (Vicente, 1982; Armijo et al., 2015). This tectonic context allows the sedimentation of thick series of limestones (mudstone to grainstone) and marls of the Pelado and Socosani formations (Wilson and García, 1962; Monge and Cervantes, 2000) along the entire Western Flank of the Andes. This formation is conformably covered by the Yura Group and the Hualhuani Formation (Wilson and García, 1962;

Vicente, 1982) composed of quartz sandstones and interstratified black shales; small outcrops are observed in south part of the study area. The top of the Mesozoic series is affected by an erosional unconformity, overlain by volcanic and volcano-sedimentary rocks of the Toquepala Group (Bellido and Guevara, 1963; Bellón and Lefèvre 1976), which outcrop in the central part.

The distribution of the Cenozoic lithostratigraphic units is divided into Paleogene, Neogene rocks, and Quaternary deposits. These rocks are related to the migration of the active Andean volcanic arc controlled by the variation of the dip of the Nazca subducting slab (Mamani et al., 2008). The migration of the volcanic arc controls the location of forearc, back-arc, and intra-arc basins. In the Coastal Depression, deposits of sedimentary sequences accumulated, mainly of marine origin, and the erosion of the proto-Andean under construction, which generated the almost synchronous creation of the Moquegua basin. These interstratified sequences of conglomerates with volcanic sequences are called the Moquegua Group (Thouret et al., 2007; Schildgen et al., 2007). These Oligocene to the late Miocene sequences, up to 800 m thick (Bellido, 1979), are the result of erosion of the Western Cordillera. From the Eocene onwards, constant volcanic events began and continue to the present day. The Huaylillas formation (Wilson and García 1962), constitutes a wide ~600 m thick ignimbrites succession (Wilson and García, 1962; Salinas, 1985). It is a stratigraphic superposition of pyroclastic flows (Wörner et al., 2000; Mamani et al., 2010). This formation is well preserved due to hyper-arid conditions and its upper surface represents a regional paleosurface. The only forms of erosion are valley incision produced by rivers descending from the Altiplano (Evenstar et al., 2017). This sector is also dominated by a large volume of andesites and rhyolites associated with ignimbrites assigned to the Barroso Group (Roperch et al., 2006; Mamani et al., 2010; Acosta et al., 2011), related to the magmatic activity of the Barroso Arc (Mamani et al., 2012). The rocks from the Quaternary correspond to the large volume of lava flows produced during the Pleistocene in relation with the active volcanoes (e.g., Yucamane; Rivera et al., 2020). These volcanic rocks are associated with fluvial and alluvial deposits in the main valley and glacial deposits in the higher areas such as the headwaters of the Locumba catchment. These deposits cover a large part of the basement and can reach a few meters thick in response to recent climatic fluctuations (Keefer et al., 2003, Engel et al., 2014; Bookhagen and Strecker, 2008). Regarding the landslides of the Locumba cluster, these have their starting zone or headscarp in the Huaylillas ignimbrites (Delgado et al., 2022). This suggests that the lithology is an important factor in the formation of these large events, however, the age of occurrence of these processes is still unknown.

In the study area, the structural setting is marked by the presence of major faults that are part of the Incapuquio Fault System where neotectonic fault activities have been recorded mainly along the Toquepala fault and the Purgatorio fault (Figure 2; Hall et al., 2012; Benavente et al., 2017; 2021). The Incapuquio fault system is a set of subvertical faults ~400 km long with NW direction and hosts left-lateral transpressional displacement. The recent study by Benavente et al, (2021) evidences a last reactivation of the Toquepala fault during the XV century that generated an earthquake of magnitude >7. The Purgatorio fault hosts a right-lateral transpressional displacement that has produced at least two ruptures during the last thousand years with surface displacements of several meters (Benavente et al., 2017).

More than 30 large landslides of the Locumba cluster occur close to these faults. Thus, it is not excluded that the probable trigger of these landslides is due to the reactivation of one of these faults. To define the probable triggering factor, it is necessary to date the landslides and correlate them with climatic or tectonic events.

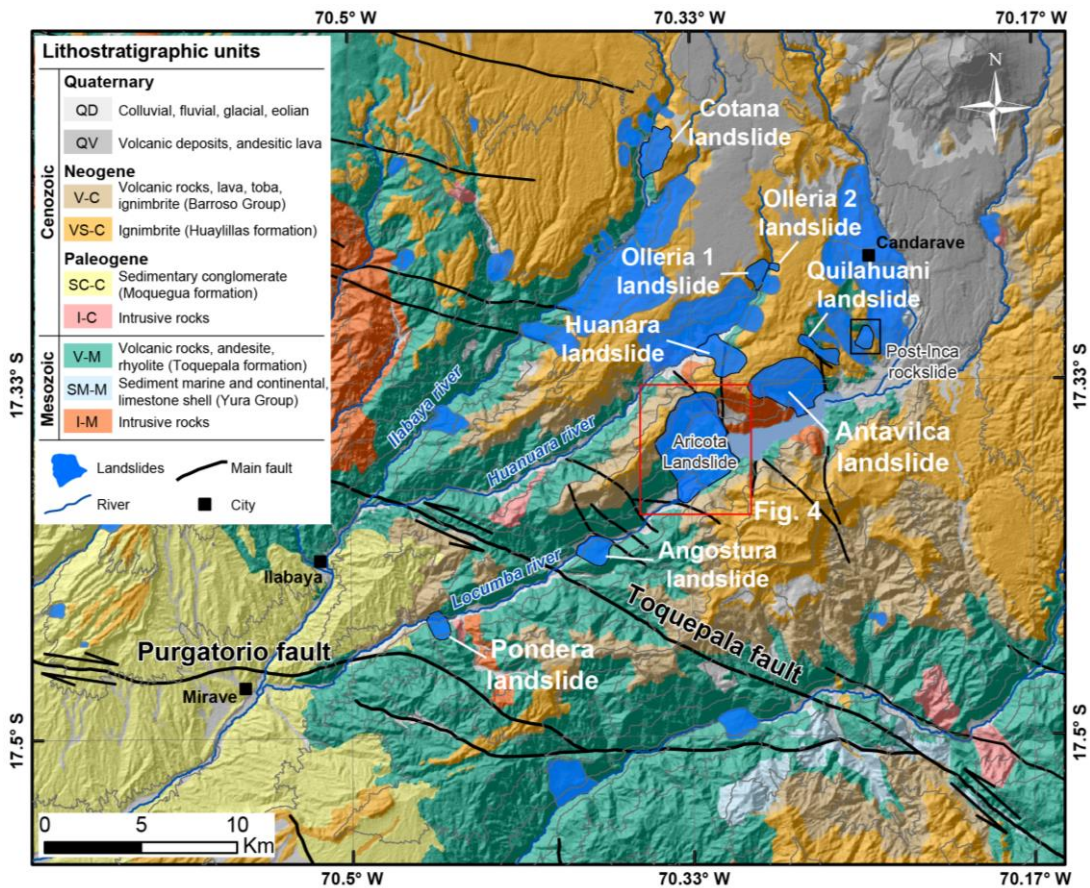


Figure 2. Lithostratigraphic map of the study area, where the Locumba cluster is located, with more than 30 landslides inventoried (Delgado et al., 2022). Eight landslides (Pondera, Angostura, Antavilca, Quilahuani, Huanara, Olleria 1, Olleria 2 and Cotana) were chosen for study. The red box marks the Aricota landslide (Delgado et al., 2020) and the other Black box shows the post-Inca rockslide.

2.2. Geomorphology and landslides of the Locumba region

The highest point of the Locumba catchment is at 5700 m asl. and the lowest point is at the confluence of the Locumba river and the Pacific Ocean. The main river is the Locumba river. The catchment is characterized by deep valleys with steep slopes due to the incision caused by the Locumba river that transports the water coming from the precipitation in the Altiplano. Several giant landslides were identified in this catchment (Delgado et al., 2022). Knickpoints observed on the swath profile of the Locumba river (Figure 3A, 3B; Mathieux, B. 2021) correspond to the location of landslides mapped by Delgado et al. (2022) (Figure 3B). In addition, landslides identified by Delgado et al. (2022) coincide also with areas of higher incisions (Figure 3c).

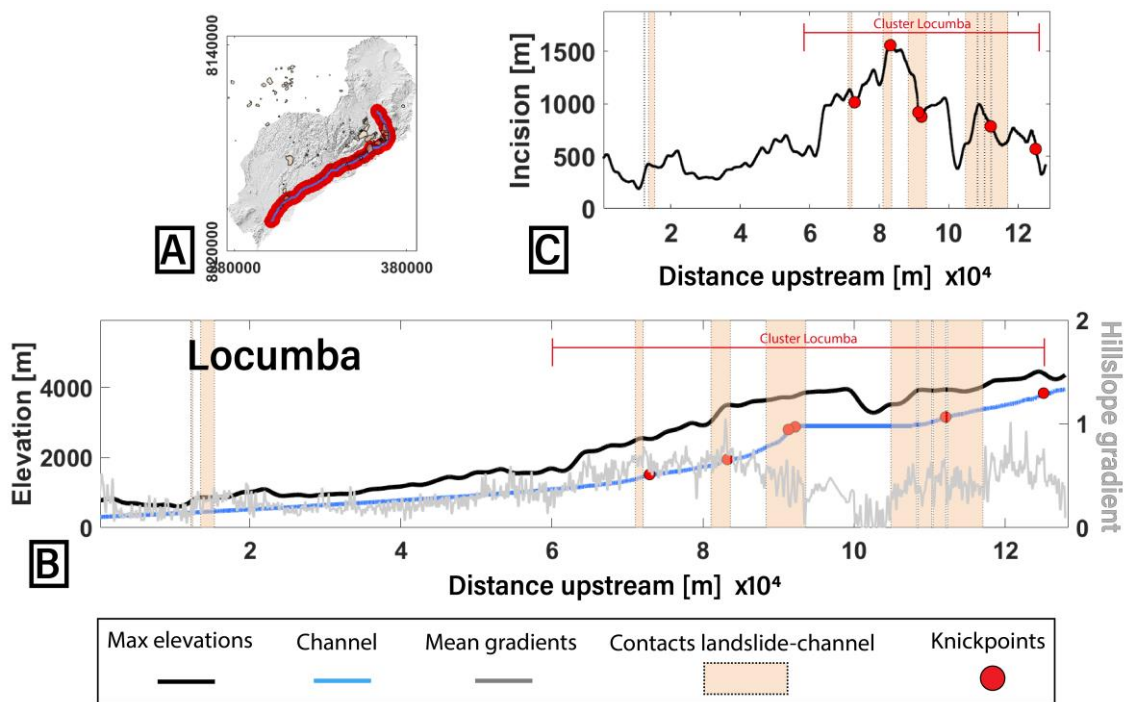


Figure 3. (A) Locumba catchment, the red stripe is the swath profile box. (B) Swath profile of the Locumba river, showing the correlation between knickpoints and landslides. (C) Relationship between landslide location and valley incision. (modified from Mathieux, B. 2021).

Delgado et al., (2020) conducted a geochronological study of the Aricota rockslide (part of the Locumba cluster) by cosmogenic ^{10}Be dating (Figure 2, Figure 4). This landslide mobilized $\sim 2.2 \text{ km}^3$, formed a large dam that blocked the Locumba river valley, and gave rise to the Aricota lake. The landslide occurred in two major events of destabilization (Figure 4), the first was a rockslide ($17.9 \pm 0.7 \text{ ka}$) that dammed the Locumba river valley and formed a dam, and the second event was a rock avalanche ($12.1 \pm 0.2 \text{ ka}$) that was deposited on top of the first event. Based on the obtained exposure ages, these events may be related to climatic changes associated with maximum expansions of Altiplano lakes during the Heinrich Stadial 1a and Younger Dryas, respectively (Placzek et al., 2013; Martin et al., 2018). The Aricota rockslide is a first advance to define/recognize the age of deformation and the triggering factor in the Locumba cluster. Still, a larger area must be analyzed, and more landslides must be studied to identify patterns in the age of formation, the triggering factor and whether these landslides occur simultaneously. The study of landslide clustering based on a detailed study of the Locumba cluster will help to answer these main questions. For that, eight landslides were chosen that show the following characteristics: 1) the origin of the landslides is located in similar lithologies, and 2) the main escarpment is located between 2000 and $\sim 4000 \text{ m asl}$. All selected landslides are distributed along the Locumba, Huanuara, and Ilabaya rivers. This division will help to identify if there are any patterns of their formation in each valley.

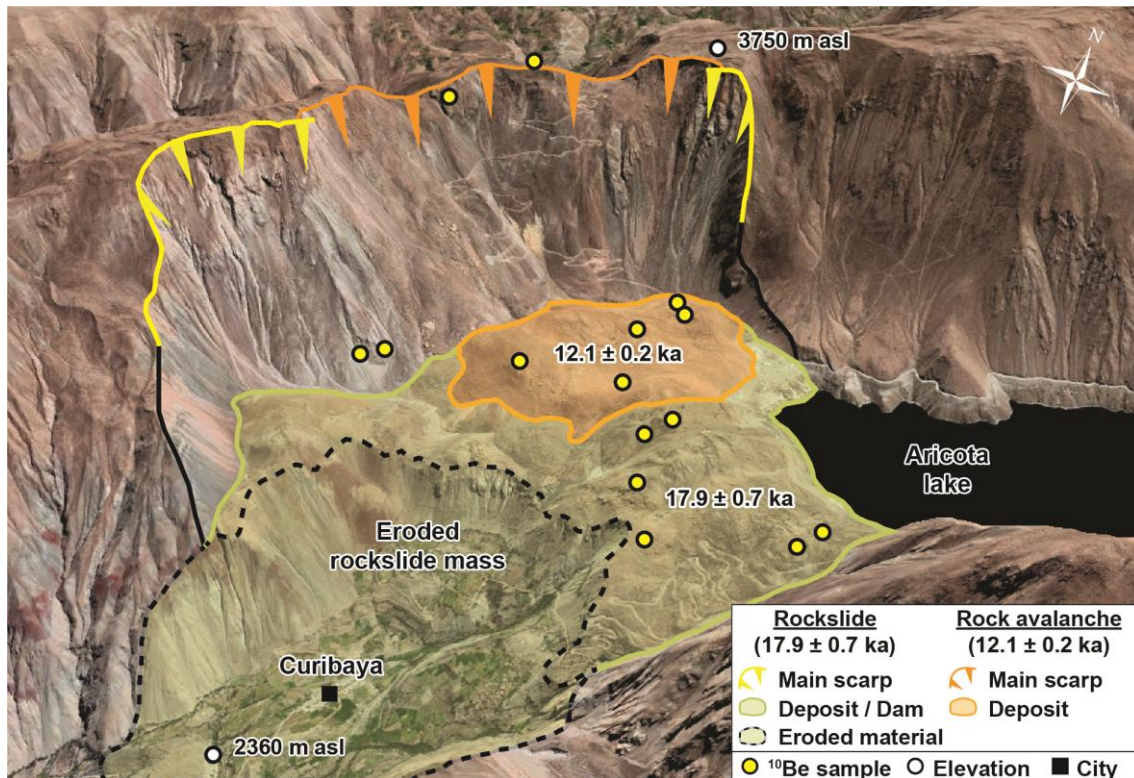


Figure 4. 3D Google Earth view of the Aricota rockslide (modified from Delgado et al., 2020). It is observed that the first event (17.9 ± 0.7 ka) filled the valley and formed a big dam and the second event (12.1 ± 0.2 ka) was deposited on top of the first event.

3. Methodology

3.1. Mapping of landslides

Detailed mapping of the selected landslides (headscarps, sliding-mass, and debris deposits boundary, etc.) in the Locumba watershed is based on geomorphological and structural observations (headscarps and tension cracks) from high-resolution Digital Elevation Model (DEM) analysis, Google Earth images and fieldwork. This geomorphological characterization is essential in the case of landslides presenting multiple events of mass mobilization because it facilitates the interpretation of cosmogenic ages in terms of destabilization dynamics. In order to have a high-resolution DEM of the Locumba cluster, eleven stereoscopic images covering the study area were obtained. These images were acquired by the Pléiades satellites in June 2020. The full resolution of these optical images is 0.7 m. We generated the DEM using the open-source Ames Stereo Pipeline (ASP) software developed by NASA (Broxton and Edwards, 2008) and followed the recommended three-step procedure: i) each image was projected onto the map using the low-resolution (30 m) SRTM DEM, ii) the two images were adjusted based on the automatically extracted tie points before finding disparities, iii) finding the intersection of all the rays coming from the homologous points of the image pair. This step leads to a point cloud of the surface topography, which is then converted to a 2 m resolution grid.

Fieldwork was conducted in 2019, in order to (1) validate the Google Earth and DEM observations/interpretations previously made on each site, and (2) sample boulders for cosmogenic nuclides dating.

3.2. Cosmogenic nuclide surface exposure dating

To determine the ages of the eight landslides selected in the Locumba cluster, a sampling strategy was designed according to the detailed geomorphological mapping of each landslide. When sampling, special attention was paid to selected reliable boulders, having heights and lengths both larger than ~ 2 m and, as far as possible, with traces of post-depositional movements, weathering, or desquamation. Elevation, latitude, and longitude data were recorded with a handheld GPS. In total, 52 samples were collected and processed (Table 1), with at least three samples collected per landslide.

Sample preparation and ^{10}Be chemical extraction were performed at the GTC Platform laboratory, ISTERre (Grenoble, France), following the ^{10}Be /quartz (Corbett et al., 2016) and ^{10}Be /feldspar (Zerathe et al., 2017) procedures depending on the mineralogical composition of the sample. The $^{10}\text{Be}/^9\text{Be}$ measurements were performed at the French national accelerator ASTER, located at CEREGE in Aix-en-Provence (Arnold et al., 2013). The $^{10}\text{Be}/^9\text{Be}$ ratios were calibrated against the internal standard STD-11, using an assigned $^{10}\text{Be}/^9\text{Be}$ ratio of $(1.191 \pm 0.013) \times 10^{-11}$ (Braucher et al., 2015). Uncertainties in the ^{10}Be concentrations (reported as 1σ) are calculated according to the standard error propagation method using the quadratic sum of the relative errors and include a conservative 0.5 % external uncertainty in the machine (Arnold et al., 2010), a 1.08% uncertainty in the certified standard ratio, a 1σ uncertainty associated with the mean of the standard ratio measurements over measurement cycles, a 1σ statistical error in the counted events, and the uncertainty associated with the chemical and analytical correction of the blank.

Exposure ages were calculated using the CREP online calculator developed by Martin et al. (2017). For the quartz targets, we applied a globally calibrated ^{10}Be spallation production rate of $4.09 \pm 0.35 \text{ at.gr}^{-1}.\text{yr}^{-1}$ (sea level and high latitude; Borchers et al., 2016) that was scaled to the geographic and altitudinal location of each sampling site using the LSD scaling scheme (SF; Lifton et al., 2014). For feldspar targets, we applied a calibrated ^{10}Be spallation production rate of $3.57 \pm 0.21 \text{ at.gr}^{-1}.\text{yr}^{-1}$ (Zerathe et al., 2017).

The CREP program assumes that denudation is constant over exposure time (Martin et al., 2017), but for this site, we used a denudation rate of $2 \times 10^{-5} \text{ cm.yr}^{-1}$ (Delgado et al., 2020). Analytical age uncertainties (i.e., internal) include uncertainties on the measured ^{10}Be concentrations. Total age uncertainties (i.e., external) include the production rate uncertainty. All data are presented in Table 1.

4. Results and interpretations

4.1. Locumba river

4.1.1. Pondera landslide

The Pondera landslide is a rockslide with headscarp located on the left flank of the Locumba River (Figure 5a) at 17.45° S latitude, at an elevation of >2220 m asl. It has an escarpment of ~ 1 km wide. The headscarp developed in Mesozoic volcanic rocks (Figure 2, Figure 5b). According to our geomorphological analysis, only one event occurred, that filled the valley forming a dam ~ 200 m high and ~ 0.9 km long to the north. The dam has been re-incised and largely eroded by the Locumba river (Figure 5a, 5b, Figure 6a). Only relicts of the deposit remain visible on both

flanks of the valley (Figure 5a). The profile of the eroded dam shows very large rock blocks (Figure 5a, Figure 6a). These dam blocks correspond to andesites which is the lithology observed on the valley flanks in this part. Northeast of the dam, DEM highlights a flat surface that is at the same elevation as the dam (between 1580-1640 m asl; Figure 5a, Figure 6a). This surface corresponds to a tributary valley dammed by the rockslide and subsequently filled by lacustrine deposits (Figure 5a, Figure 6c). On the right flank of the Locumba River, ~2 km east of the landslide, other thick lacustrine deposits were mapped. These correspond to lacustrine deposits that were deposited in the Locumba river. These deposits show some folds and deformations that are interpreted as slumps (Figure 5a, Figure 6d). The top of these deposits stands at ~1700 m asl (Figure 5a, Figure 5b).

Three blocks (PO-01, PO-02, PO-03) were sampled on the top of the dam relic to determine their surface exposure ages (Figure 5a, Figure 7). They yielded exposure ages of 100 ± 6 Ka, 68 ± 6 ka, and 180 ± 10 ka (Table 1). Whereas a single age should be obtained as the geomorphology indicates only one failure event, the ages obtained are scattered, which does not permit to point to a weighted-mean age for this failure (Figure 7). Both strong differential erosion between the boulders, or variable amount of ^{10}Be inheritance, can explain this scattering. This will be discussed in the discussion part. Without any additional age on the Pondera rockslide, only a probable period of occurrence can be proposed between ca. 62 and 190 ka (Figure 7).

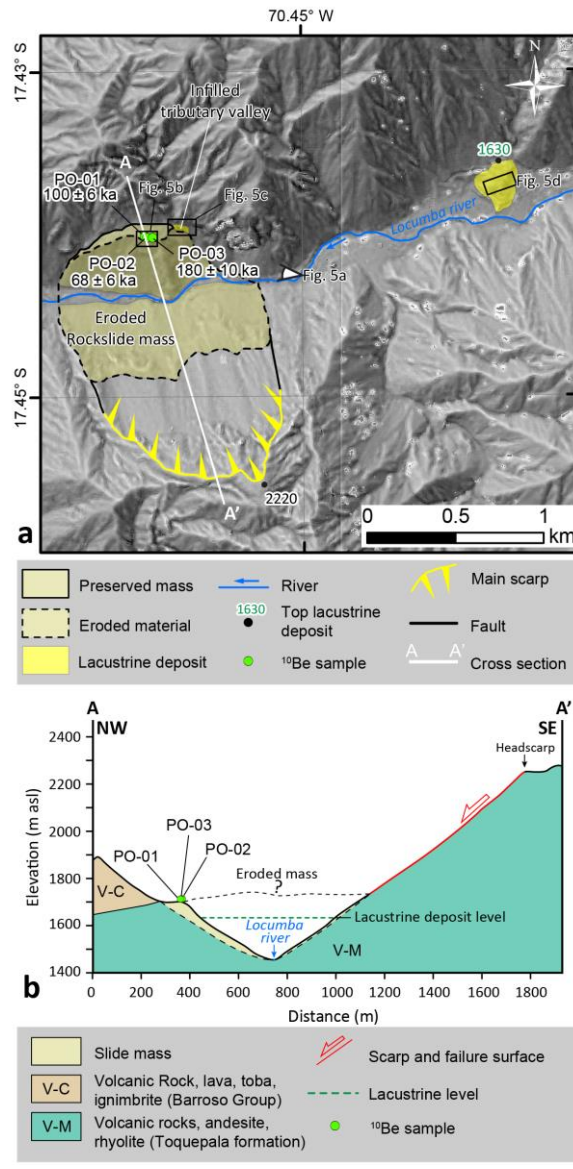


Figure 5. (a) Geomorphological map of the Pondera rockslide that filled the valley and formed a large dam. This is currently eroded. (b) Cross section of Pondera rockslide.

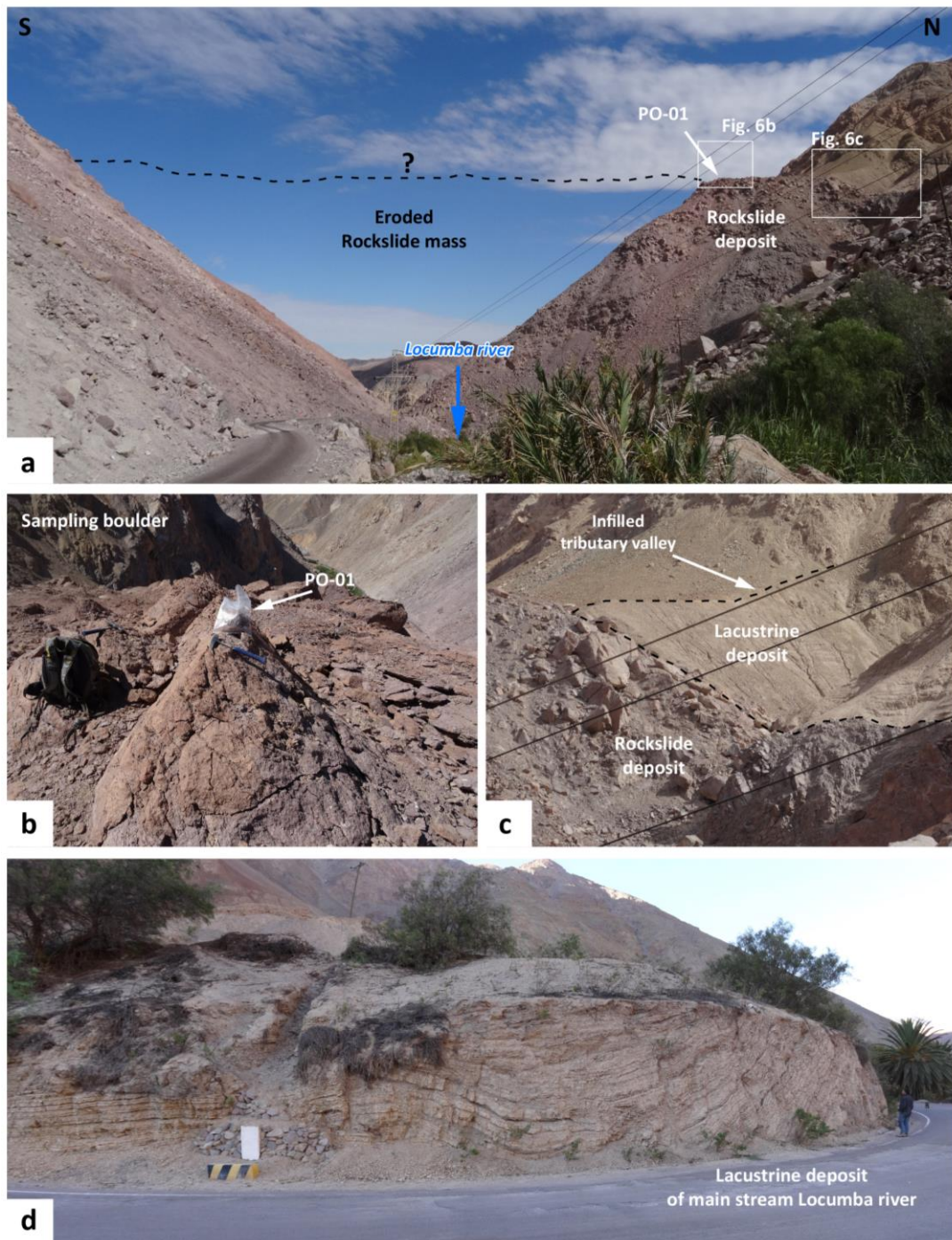


Figure 6. (a) Panoramic view of the eroded dam of the Pondera rockslide. Note to the north, the perched lacustrine deposits that are outcropping along a tributary dammed by the rockslide deposit, (b) Samples collection for cosmogenic nuclide dating (^{10}Be), (c) Close up on the perched lacustrine deposits, (d) Thick lacustrine deposits located along the main stream, ~ 2 km upstream to the dam along the Locumba valley.

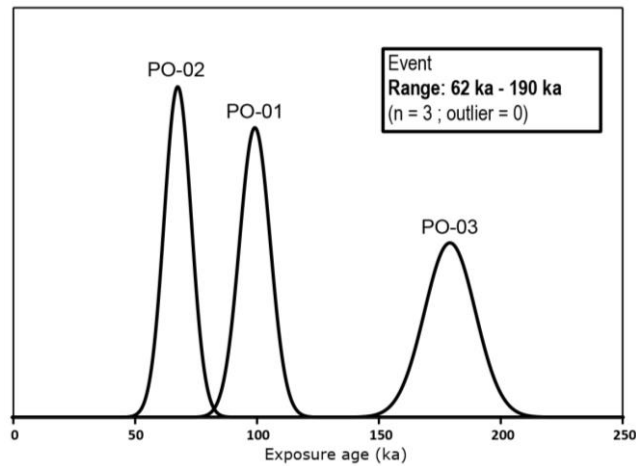


Figure 7. Probability density plot of the exposure ages obtained on boulders on top of the Pondera rockslide deposits.

4.1.2. Angostura landslide

The Angostura landslide is of a rockslide typology. It is located on the left flank of the Locumba River (Figure 8a) at 17.42° S latitude, at an elevation of ~2450 m asl (headscarp). It has an escarpment of ~1.5 km wide. The headscarp originates in Mesozoic volcanic rocks (Figure 2, 8b). Geomorphological mapping shows a single event that filled the Locumba valley forming a dam ~400 m high and ~2 km long to the north (opposite slope). Part of the dam is eroded and re-incised by the Locumba river activity (Figure 8a, Figure 9a). The incision profile in the dam shows that it is formed by blocks of Mesozoic volcanic rock corresponding to the rocks that outcrop on the stable slope of the valley (Figure 8b). On the right flank of the Locumba River, next to the dam and upstream (~ 2km), lacustrine and fluvial deposits are observed that correspond to the lake formed by the dam (Figure 8a, Figure 9b, 9d). The top of these deposits culminates at an altitude of ~2130 m asl (Figure 8a, 8b).

Seven boulders were sampled at the top of the Angostura slided mass (AA-01, AA-02, AA-03, AA-04, AA-05, AA-06, AA-07) (Figure 10). Four exposure ages (AA-02, AA-03, AA-04, AA-06) range from 178 ± 15 ka to 238 ± 17 ka (Table 1), which are compatible with a unique event (chi-2 test (95%): 7.07/7.81) and point to a weighted mean of 205 ± 9 ka (Figure 10). Three others exposure ages are significantly older: AR-01 (318 ± 39 Ka), AR-05 (330 ± 23 ka), and AR-07 (703 ± 51 ka). They are likely attributed to inheritance. See discussion hereafter.

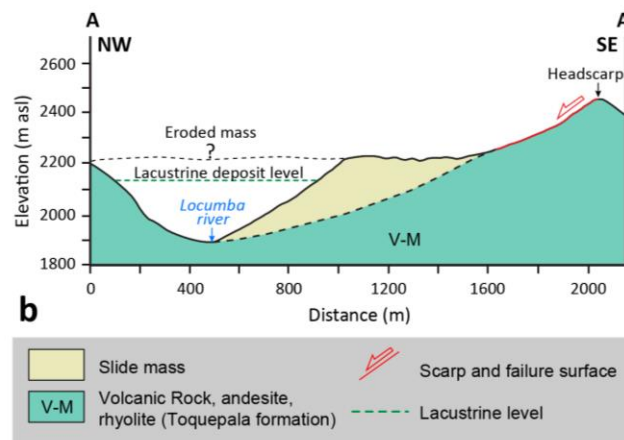
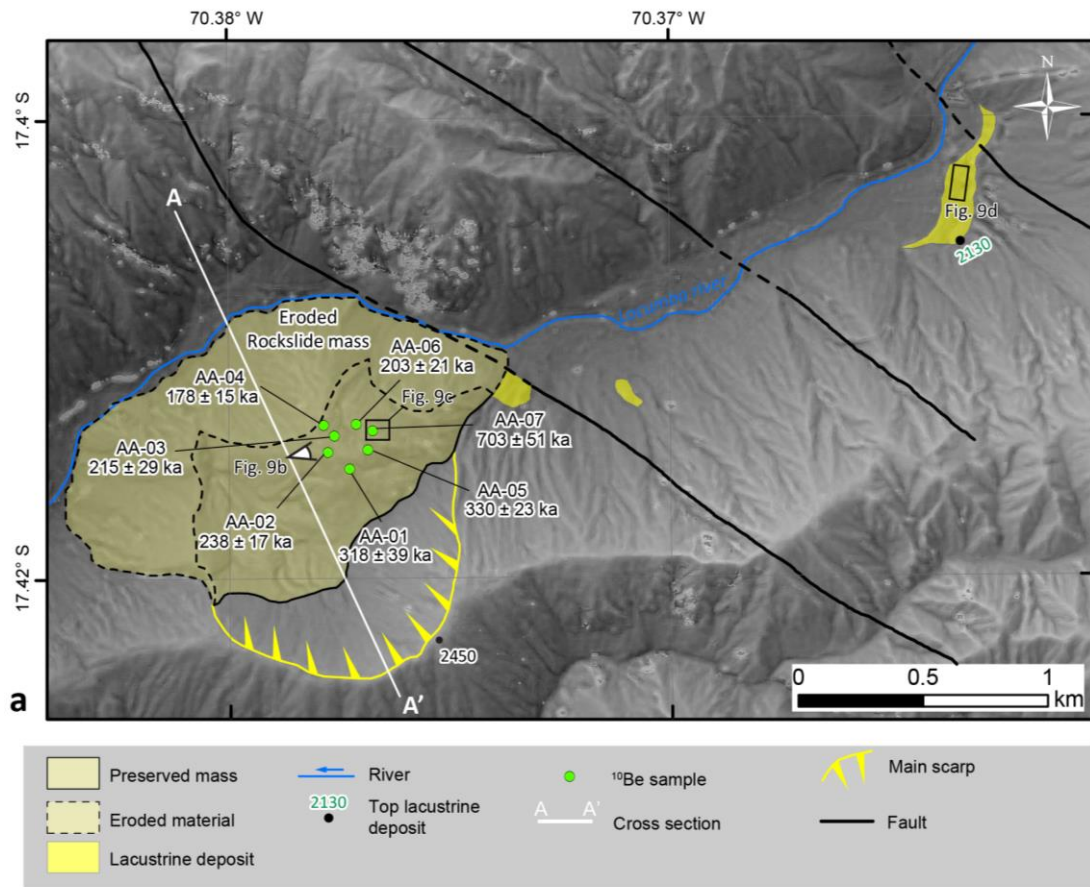


Figure 8. (a) Geomorphological map of the Angostura rockslide that filled the valley and formed a large dam. Part of this rockslide dam is currently eroded. (b) Cross section of the Angostura rockslide.

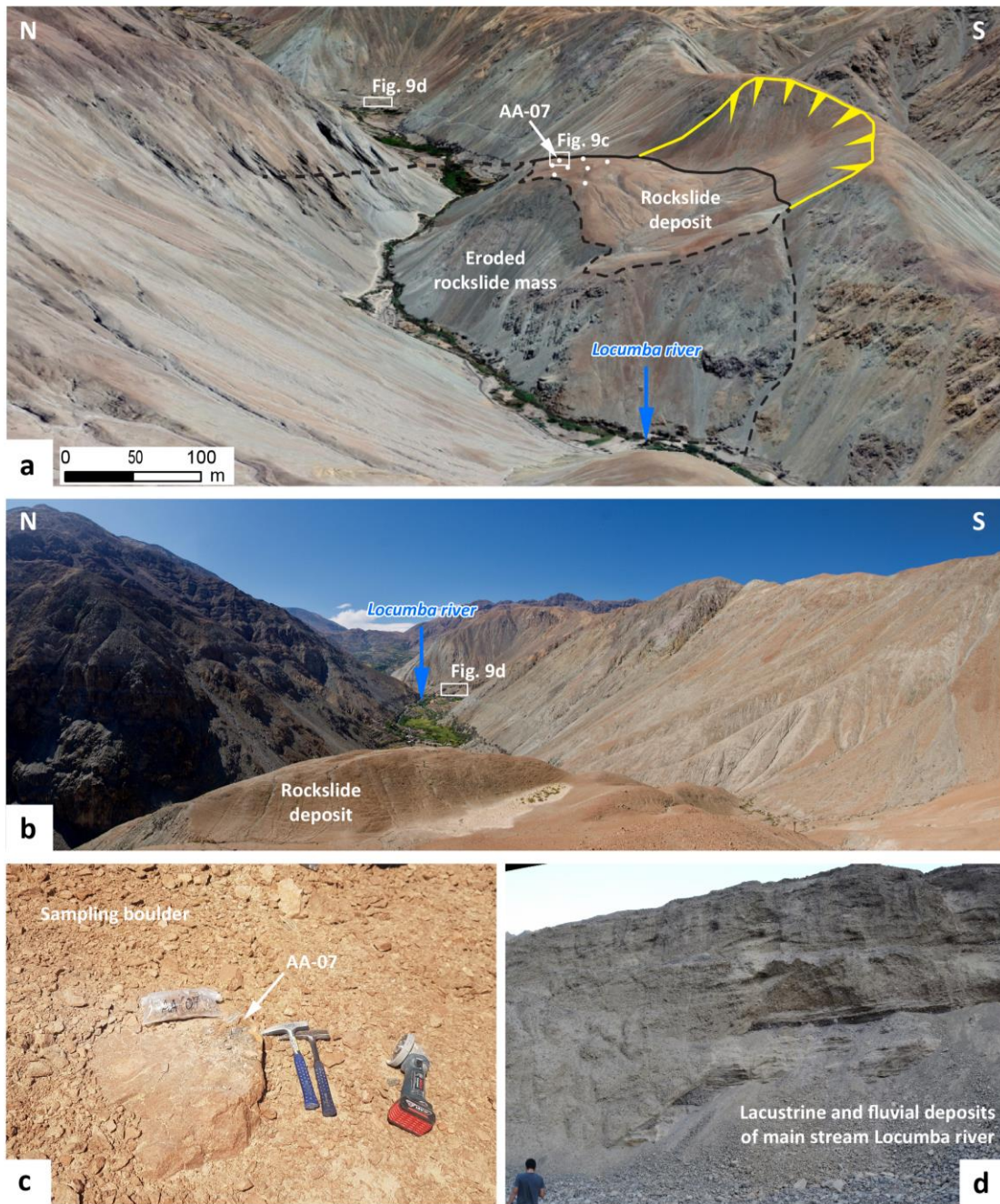


Figure 9. (a) Google Earth 3D image, showing the Angostura rockslide, the preserved deposit, and the eroded mass by the Locumba river, (b) Panoramic view to the northeast, upstream of the dam, location of lacustrine deposits ~2km away, (c) Samples collection for cosmogenic nuclide dating (^{10}Be), (d) Thick lacustrine and fluvial deposits located along the main stream, ~2km upstream to the dam along the Locumba valley.

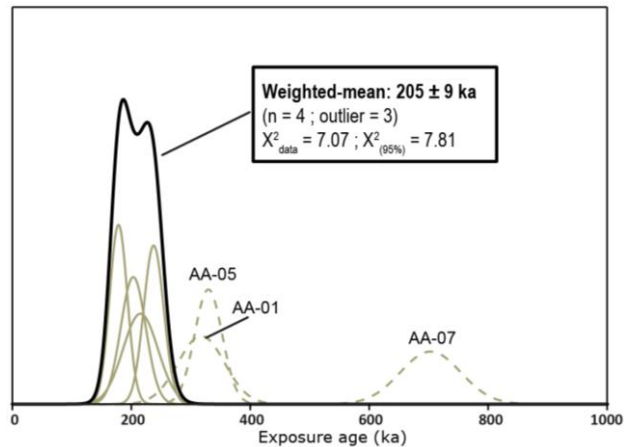


Figure 10. Probability density plot of the exposure-ages obtained on boulders on top of the Angostura rockslide deposit.

4.1.3. Antavilca landslide

The Antavilca landslide is located on the right flank of the Aricota lake (Figure 11a) at 17. 33° S latitude, at an altitude of ~3890 m asl. (headscarp), the base of this landslide is at 2750 m asl (Aricota lake level). A sequence of scarps in this landslide may indicate a progressive failure that took place over a prolonged period of time. In addition, numerous tension cracks above the main scarp and other cracks in the landslide mass are observed. These cracks indicate a movement of the landslide mass toward the south (Figure 11a, Figure 12a). All these characteristics suggest that it is a deep-seated gravitational slope deformation (DSGSD). On the southern side of this large DSGSD, some sliding mass converted into two rock-avalanches that reached the Aricota lake (Figure 11a, 11b, Figure 12a). The first event is an avalanche that mobilized a large part of the body of the Antavilca landslide (Figure 12a, 12b), the avalanche deposits reached the Aricota lake (travel length of >3km) (Figure 11b). The second event is an internal avalanche that mobilized part of the avalanche deposits of the first event (Figure 11a, 11b).

We focus on the second avalanche because it is the last event to occur. The avalanche surface has large boulders (boulders >2m, Figure 12c, 12d) that allow us to perform characteristic sampling and then determine the age of exposure using cosmogenic nuclides ¹⁰Be (Figure 12c, 12d). Six samples (AN-06, AN-07, AN-08, AN-09, AN-10, AN-11) were collected from boulders found on the avalanche surface (Figure 11a). Four exposure ages (AN-07, AN-08, AN-10, AN-11) range from 16 ± 1 ka to 17 ± 1 ka (Table 1). Samples AN-06 (19 ± 1 Ka) and AN-09 (6.1 ± 0.2 Ka) can be called outliers because these ages are outside the range. We suspect that sample AN-06 has an inheritance from the first event, while sample AN-09 may be a block displaced after the emplacement.

The ages obtained from four samples (AN-07, AN-08, AN-10, AN-11) of the rock avalanche deposit are tightly grouped (Figure 13), pointing to a weighted-mean age of 16.3 ± 0.3 ka (chi-2 test (95%): 3.44 / 7.81).

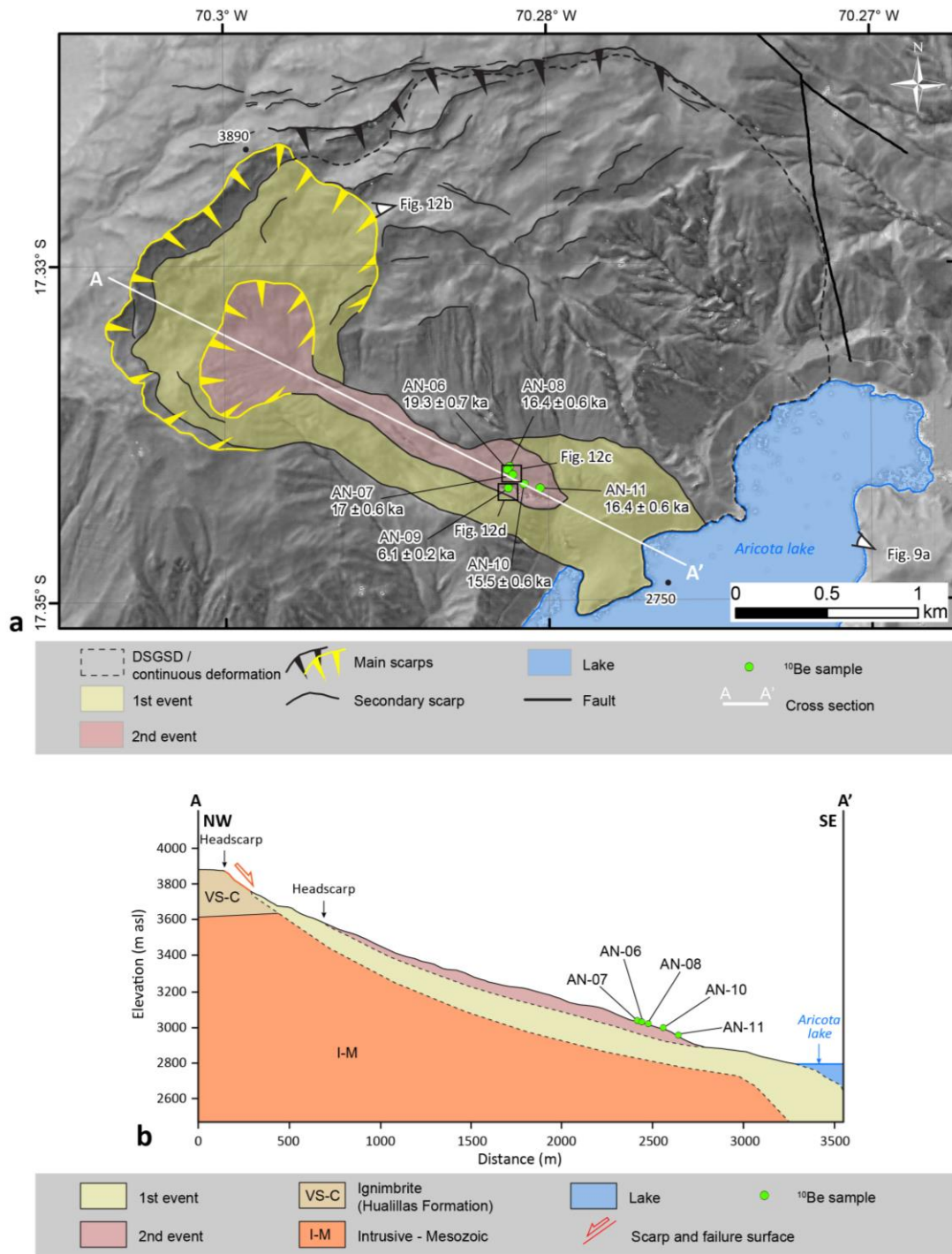


Figure 11. (a) Geomorphological map of the Antavilca landslide showing the typical morphology of DSGSD, as well as the two rock avalanches that have developed at the southern extremity of the landslide. (b) Cross section of the Antavilca landslide, showing the first and second rock-avalanche.

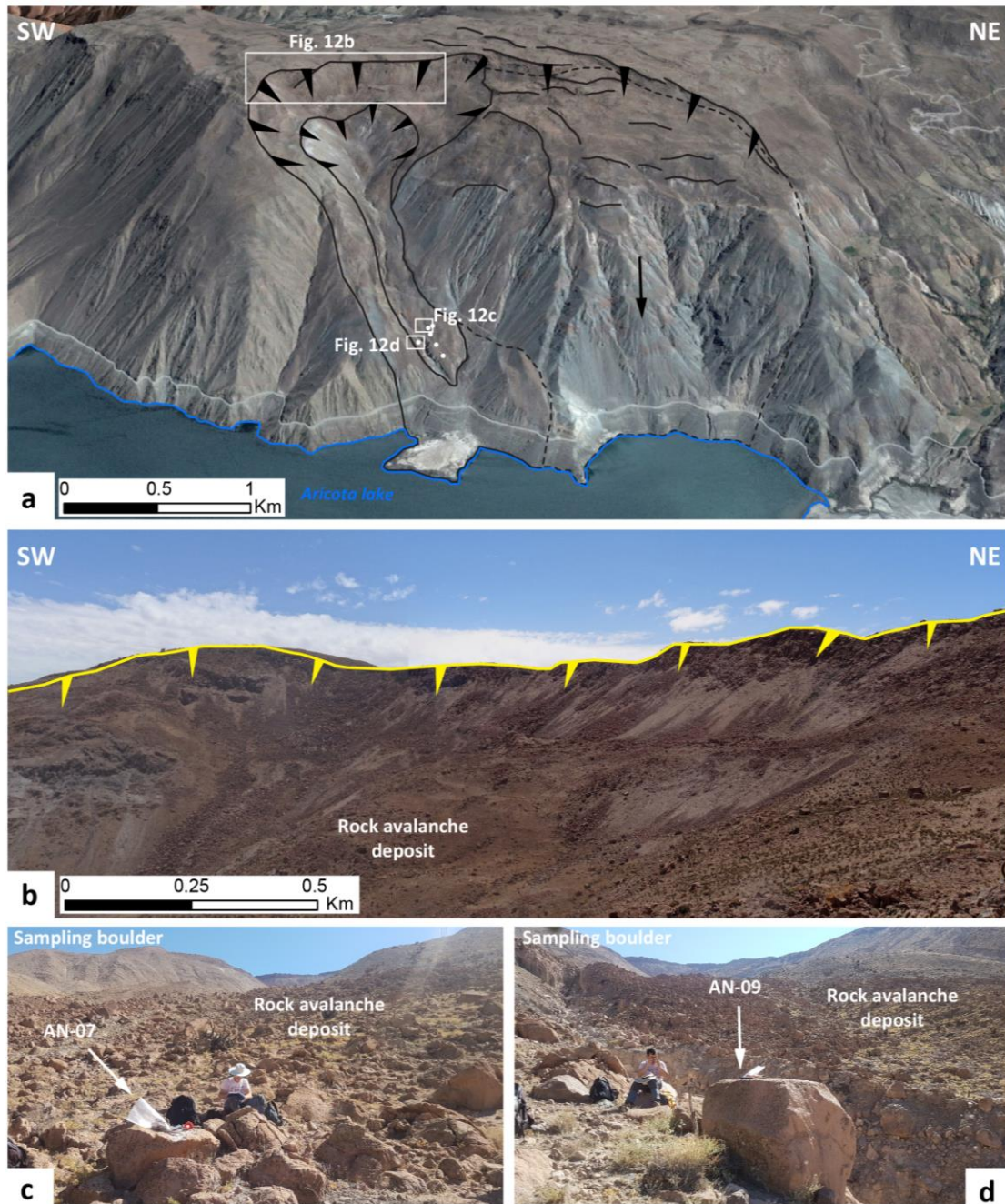


Figure 12. (a) Google Earth 3D image, showing the Antavilca landslide (DSGSD), and two rock avalanches located to the south of the landslide, (b) view of the headscarp of the first event and the deposit of the first avalanche. (c) and (d) Samples collection for cosmogenic nuclide dating (^{10}Be).

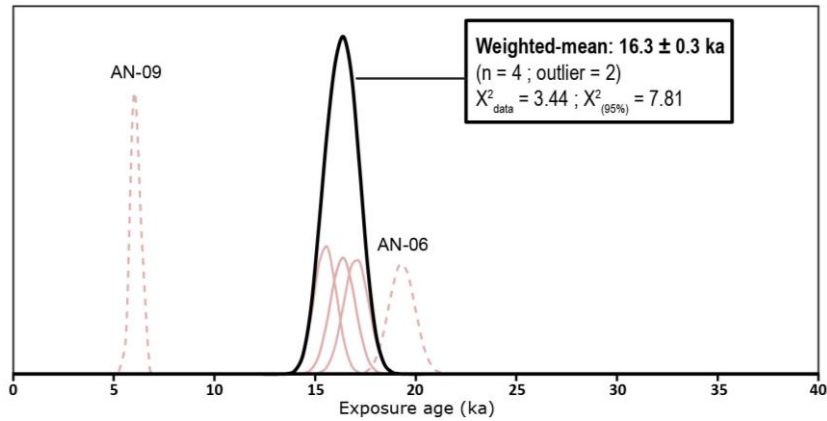


Figure 13: Probability density plot of the exposure ages obtained on boulders on top of the second rock avalanche deposit.

4.1.4. Quilahuani landslide

The Quilahuani landslide is a rock avalanche located on the right flank of the Quilahuani river (Figure 14a), i.e., a tributary of the Aricota lake, at 17.32° S latitude, at an altitude of 3870 m asl. (headscarp). It has an escarpment of ~0.5 km wide, and the toe of the avalanche deposits stands at ca. 3000 m asl. The headscarp developed within ignimbrites of the Huaylillas formation (Figure 2, figure 14b). There is an event with a length of ~2 km towards the southeast (Figure 14a), there are lateral and frontal levees that channel and limit the avalanche path (Figure 14a, figure 15b). The avalanche boulders correspond to the ignimbrites of the Huaylillas formation (Figure 14b, figure 15a). The deposit is currently eroded and re-incised at the foot of the avalanche (Figure 14a).

Ten boulders distributed all along the avalanche deposit were sampled to determine the timing of the failure (Figure 14a). Five exposure ages (QL-02, QL-04, QL-07, QL-09, QL-10) range from 109 ± 4 ka to 120 ± 4 ka (Table 1). Those ages show a single gaussian distribution (chi-2 test (95%): 5.72/9.49), pointing to a weighted-mean age of 114 ± 2 ka (Figure 16). Five other ages are more scattered, corresponding either to younger (QL-01A: 65 ± 2 Ka; QL-05: 70 ± 4 ka; QL-08: 60 ± 2 ka), or older ages (QL-03: 170 ± 4 ka; QL-06: 192 ± 5 ka). As only one main rock-avalanche event can be observed in the morphology, we favor the interpretation of a failure event at 114 ± 2 ka (Figure 16). Younger and older scattered ages are likely attributed to post-depositional erosion of the boulders and to inheritance, respectively.

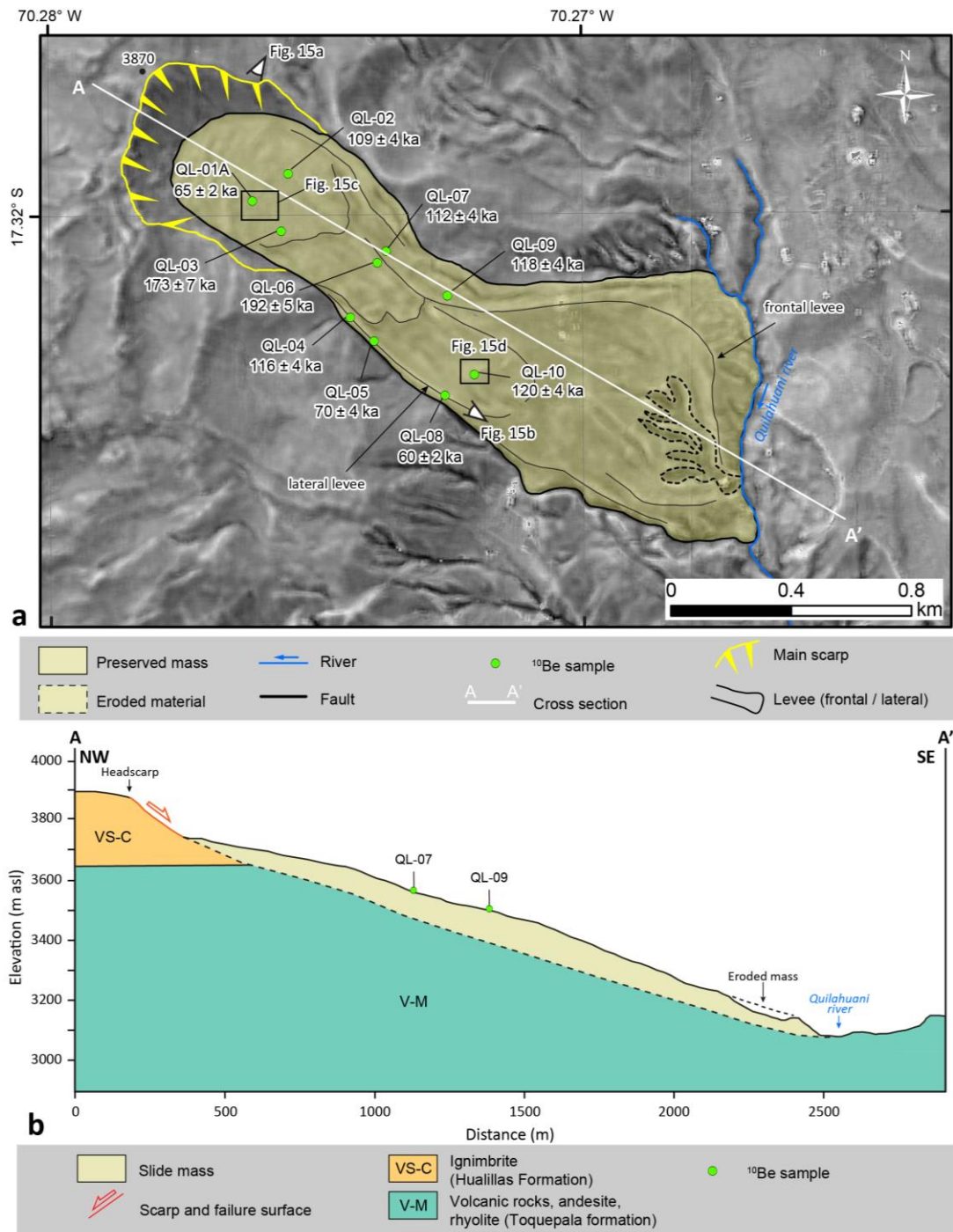


Figure 14. (a) Geomorphological map of the Quilahuani rock avalanche. We observed levees (frontal and lateral) and an erosional process at the foot of the avalanche. (b) Cross section of the Quilahuani rock avalanche.

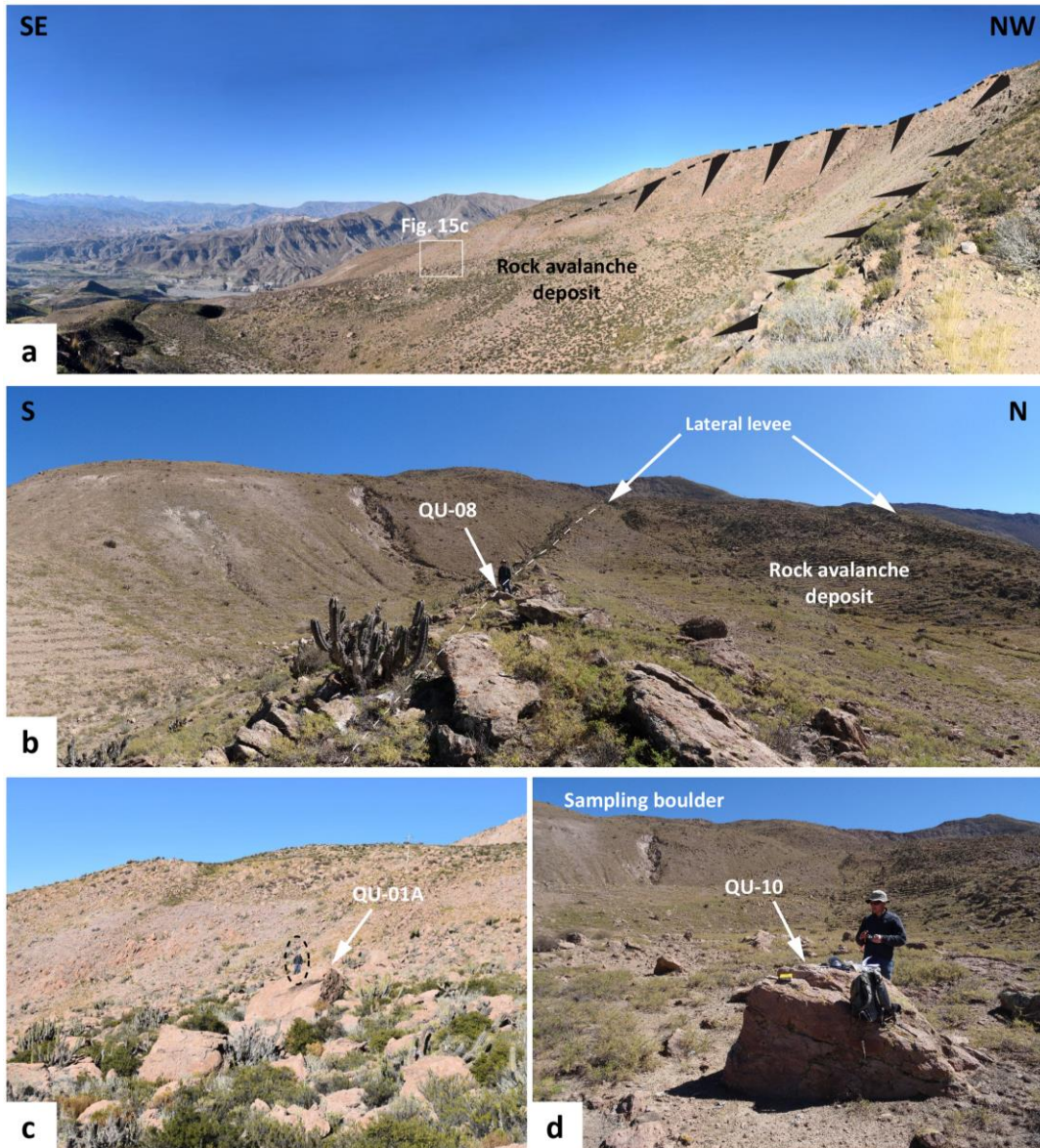


Figure 15. (a) Panoramic view of the Quilahuani rock avalanche main scarp and the avalanche deposit, (b) Lateral levees channeling the rock avalanche deposit, (c) Detail of the size of ignimbrite blocks, (d) Boulder sampled for cosmogenic nuclide dating (^{10}Be).

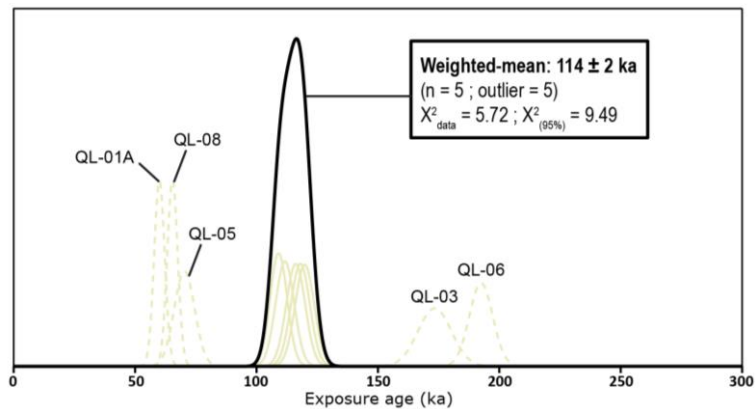


Figure 16. Probability density plot of the exposure ages obtained on boulders on top of the Quilahuani rock avalanche deposit.

4.2. Huanuara river

4.2.1. Huanuara landslide

The Huanuara landslide has a rock avalanche typology. It is located on the left flank of the Huanuara River (Figure 17a) at 17.33° S latitude, at an elevation of 3780 m asl. (headscarp). It has an escarpment of ~2 km wide, and the foot of the avalanche is at 3150 m asl. This landslide presents several internal events (Figure 17a), the first event corresponds to an old avalanche that deposits reached the Huanuara river. The avalanche deposit is strongly eroded, part of the avalanche has been reactivated and is cut by river (Figure 17a, figure 18a). On the left flank of this landslide, there is a sequence of events subsequent to the main event (Figure 17a) and this sector is the area of greatest interest because it presents recent events. A second avalanche was identified (Figure 17a, 17b) that originated in the headscarp and has a length of ~2.2 km; it is a retrogressive process that also mobilized part of the avalanche deposit of the first event. The headscarp originates in Mesozoic intrusive rocks (Figure 2, 17b). Levees can be observed as a product of the avalanche path (Figure 17a, figure 18a, 18c). Also the deposit is eroded. A third event occurred in the avalanche deposit of the second event (Figure 17a, 17b, figure 18b). This event corresponds to an internal avalanche and has a travel length of ~0.7 km. Finally, a fourth event was identified that corresponds to an avalanche, the headscarp is located at ~3730 m asl., the deposits of this avalanche cover part of the second and third event and show a travel length of ~0.7 km (Figure 17a). The boulders of these avalanches correspond to intrusive rocks and ignimbrites of the Huaylillas formation.

After the identification of internal events, a systematic sampling was carried out and 12 boulder samples (>2m, Figure 18d, 18e) were collected. These samples are equitably distributed in each deposit (Figure 17a). Five samples (HU-08, HU-09, HU-10, HU-11, and HU-12) were collected from the second avalanche, of which four exposure ages range from 682 ± 50 ka to 1261 ± 75 ka (Table 1). The exposure age of sample HU-08 (318 ± 22 Ka) we qualify as an outlier because it is outside the range. This sample is probably a block moved later at the site. From the third avalanche, three samples were collected (HU-01, HU-06, and HU-07), and the exposure ages are between 369 ± 28 ka and 499 ± 31 ka (Table 1). For the fourth avalanche, four samples were collected (HU-02, HU-03, HU-04, and HU-05), and the exposure ages of these samples are between 177 ± 5 ka and 325 ± 28 ka (table 1). The ages obtained in the three deposits are scattered and a weighted mean age could not be obtained (Figure 19), but a range of occurrence could be determined by taking into account the ages and their uncertainties. For this reason, we argue that: i) the second avalanche occurred in the range between 632 ka and 1336 ka, ii) the third avalanche occurred between 341 ka and 530 ka, iii) the fourth avalanche is the most recent event occurred in the range between 172 ka and 353 ka (Figure. 19).

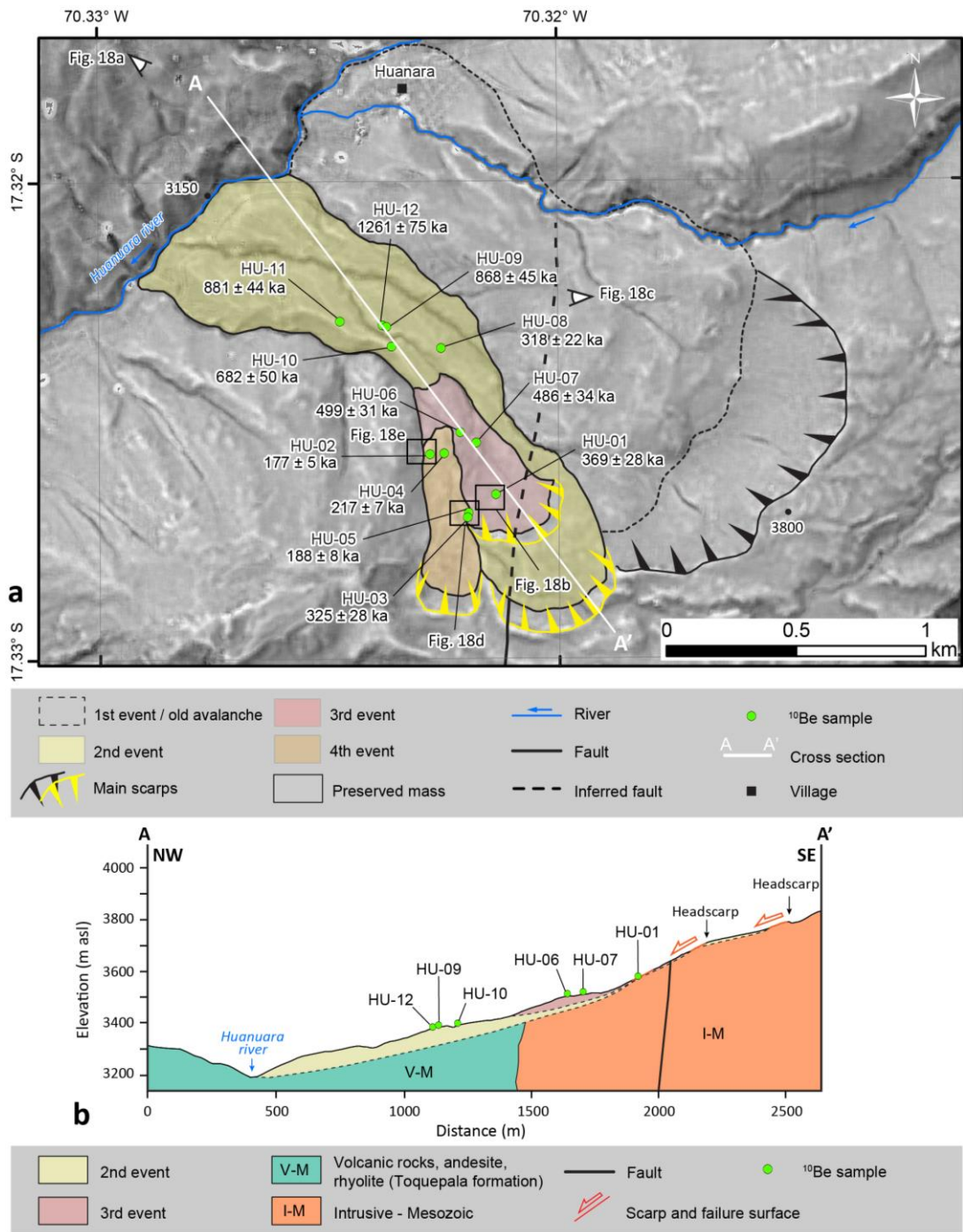


Figure 17. (a) Geomorphological map of the Huanara landslide, four internal events were identified as rock-avalanche. (b) Cross section of the internal avalanches (second and third event) of the Huanara landslide.



Figure 18. (a) Panoramic view of Huanara landslide, showing the deposits of the successive rock-avalanche generations, (b) Headscarp and slide surface of the third event, (c) Lateral levee channeling the deposits from the second rock-avalanche, (d) and (e) Sampling on top of boulders for cosmogenic nuclide dating (^{10}Be).

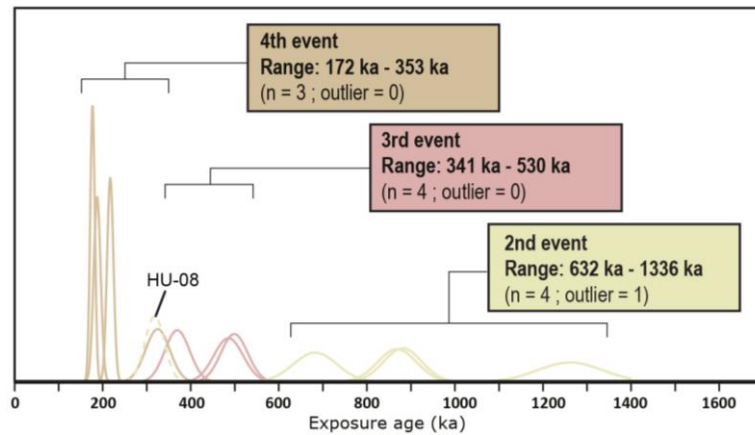


Figure 19. Probability density plot of the exposure-ages obtained on boulders from rock avalanche deposits.

4.2.2. Olleria 1 landslide

Olleria 1 landslide is a rockslide located on the right flank of the Huanuara River (Figure 20a) at 17.28° S latitude and an elevation of ~3890 m asl (headscarp). It has a ~1 km wide headscarp and the foot of the landslide is at 3450 m asl. In the detailed mapping of the landslide, we were able to identify three internal events (Figure 20a). The first event corresponds to the main event. This is a rockslide which deposits reached the Huanuara river. The headscarp originates in the ignimbrites of the Huaylillas formation (Figure 2, figure 20b). The second event corresponds to a rockslide. It is a reactivation of the rockslide deposits of the first event. This rockslide is small but fills and obstructs the Huanuara river (Figure 20a, figure 21a). This filling generated an epigenetic wedging of the river, modifying the normal course, causing the river to generate a rapid erosion and incision of the bedrock (Figure 21d). A third event was identified that corresponds to a rock avalanche, that originated in the headscarp and the deposits were accumulated on the mass of the first event (Figure 20a, figure 21a, 21b). The boulders visible on the surface of these events correspond to ignimbrites of the Huaylillas Formation.

After identifying all the internal events, a sampling was carried out to determine the exposure ages of the first and second events. Five samples (EP-01, EP-02, EP-03, EP-04, EP-05) were collected on large boulders (boulders >2m, Figure 21b, 21c) to determine the exposure age using cosmogenic nuclides ¹⁰Be. For the first event three samples were collected (EP-03, EP-04, EP-05), the exposure ages of these samples are between 295 ± 8 ka and 840 ± 22 ka (table 1). For the second event, two samples were collected (EP-01, and EP-02) that yielded ages between 52 ± 3 ka and 64 ± 2 ka (table 1). The ages obtained are scattered and a weighted mean age could not be obtained (figure 22), but a range of occurrence could be determined by taking into account the ages and their uncertainties. The first event, called the main event, occurred between 295 ka and 840 ka. The second event, which corresponds to the recent landslide that modified the course of the Huanuara river, occurred between 49 ka and 66 ka (Figure 22). Although the age scattering, the relative age of the event is in agreement with the mapping, i.e., the deposits with older ages, being overlaid by the deposit with the younger ages.

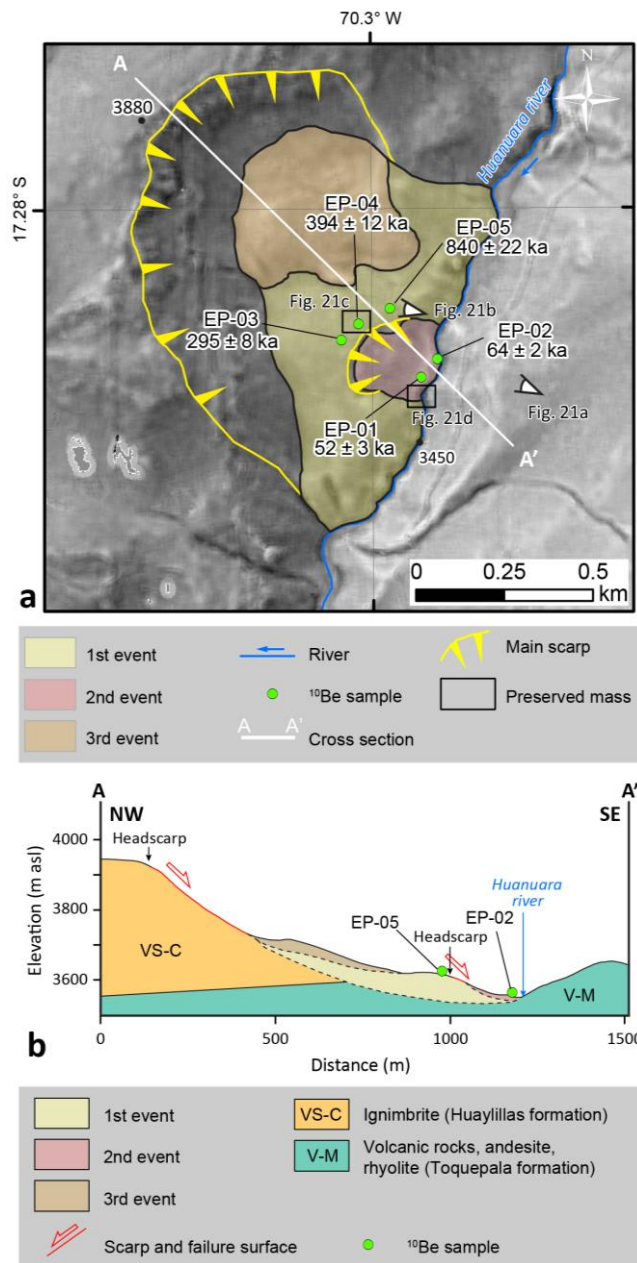


Figure 20. (a) Geomorphologic map of the Olleria 1 landslide, three internal events were observed, the first and second event are rockslides and the third event corresponds to a rock avalanche deposited on top of the first event. (b) Cross section of the internal events.

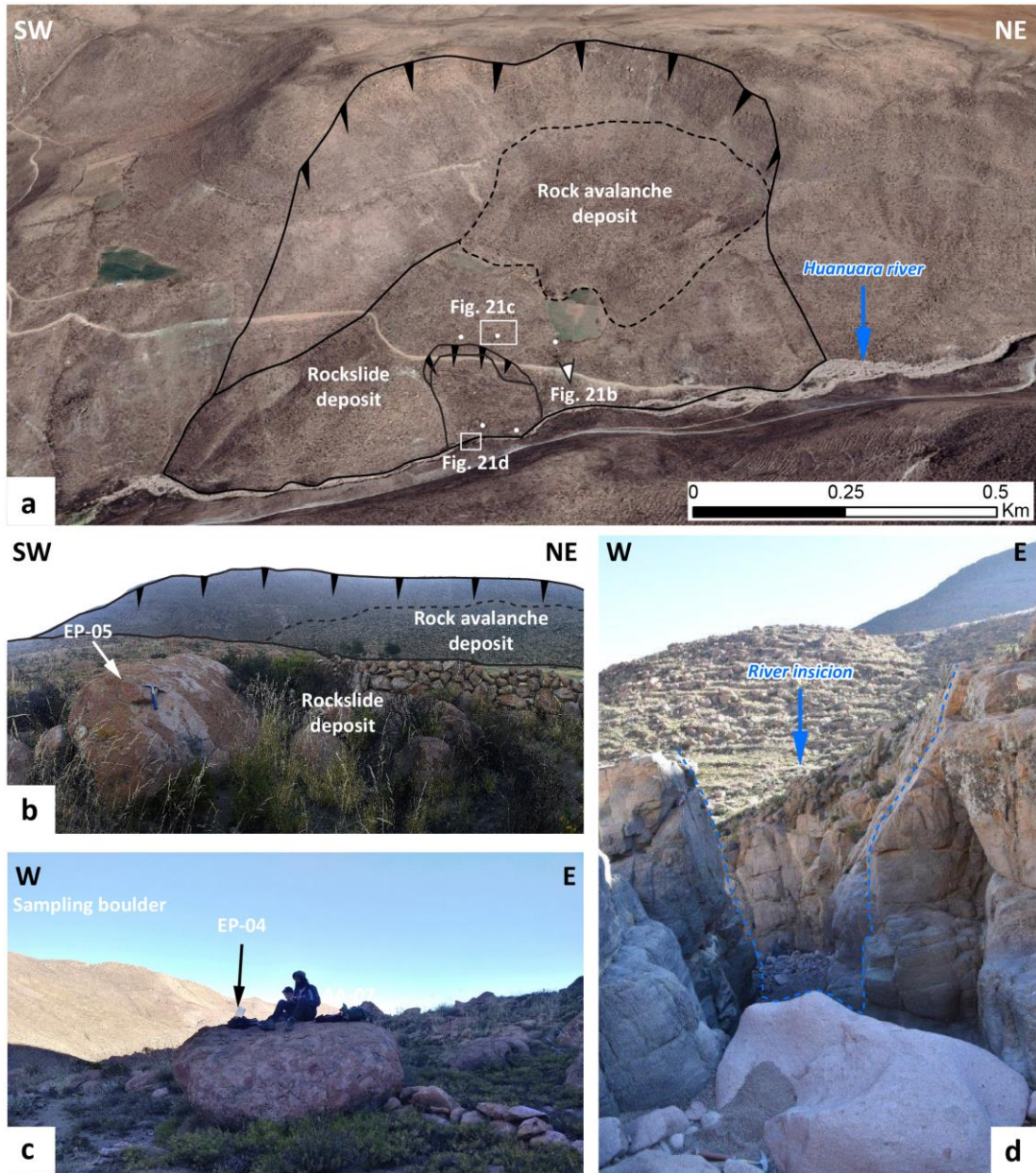


Figure 21. (a) Google Earth 3D image of the Olleria 1 landslide where the three internal events are observed, (b) view of the headscarp of the Olleria 1 landslide. The deposits of the first event (rockslide) and the third event (avalanche rock) can be observed (Figure. 15a). (c) sample collection for cosmogenic nuclide (^{10}Be) dating. (d) Epigenetic process and river incision of bedrock due to blockage of the main channel of the Huanuara river.

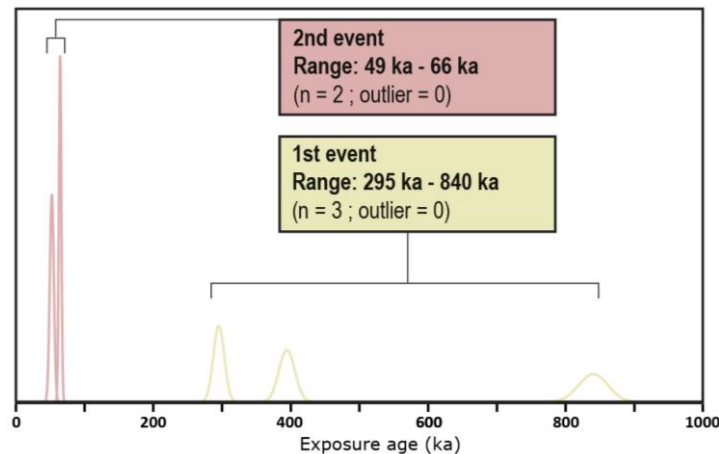


Figure 22. Probability density plot of the exposure ages obtained on boulders from rockslide deposits.

4.2.3. Olleria 2 landslide

The Olleria 2 landslide is a rockslide located on the left flank of the Huanuara river (Figure 23a) at 17.28° S latitude and at an elevation of ~3800 m asl (head scarp). It has an escarpment ~0.45 km wide. The headscarp originates from ignimbrites of the Huaylillas formation (Figure 2, Figure 23b). We performed detailed mapping and identified a unique event that formed a small dam blocking the Huanuara river. The height of the dam is ~10 m and it has a length of ~0.6 km towards the northwest (opposite slope).

Currently, part of the dam is incised and eroded by the activity of the Huanuara river (Figure 23a, Figure 24a, 24c). The profile of the eroded dam shows that the slipped mass is formed by ignimbrite blocks corresponding to the rocks that outcrop on the slopes of this part of the valley (Figure 23b). Also, attached to the eroded dam are lacustrine deposits corresponding to the lake formed by the landslide (Figure 23a, Figure 24d), this lake was small ~0.3 km long. The upper part of these deposits is at an altitude of ~3700 m asl (Figure 23b).

Large boulders (>2m, Figure 23a, Figure 24b) were selected for TCNs dating. Six samples (KS-01, KS-02, KS-03, KS-04, KS-05, KS-06) were collected (Figure 23a). The age shows a strong scatter and a weighted average age cannot be obtained (Figure 25). The exposure ages of these samples are between 56 ± 2 Ka and 682 ± 21 Ka. This landslide has a height difference of 200 m from the headscarp to the Ilabaya river, it is likely that the landslide mass was not modified at the time of the event. We believe that some of the boulder ages are inherited (Figure 23a). From the results obtained it is not possible to define an average age, only that the Olleria 2 landslide occurred between the range 52 ka and 703 ka (Figure 25).

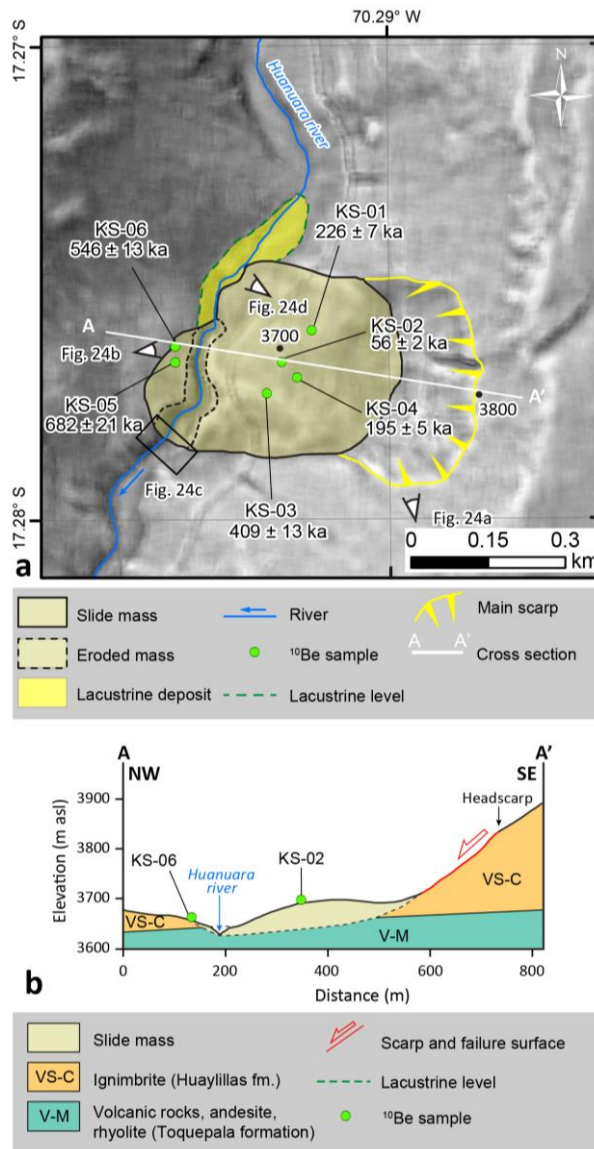


Figure 23. (a) Geomorphological map of the Olleria 2 rockslide. The rockslide deposit that filled the valley and formed a dam are observed, also the lacustrine deposits of the formed palaeolake are observed, (b) Cross section of Olleria 2 rockslide.

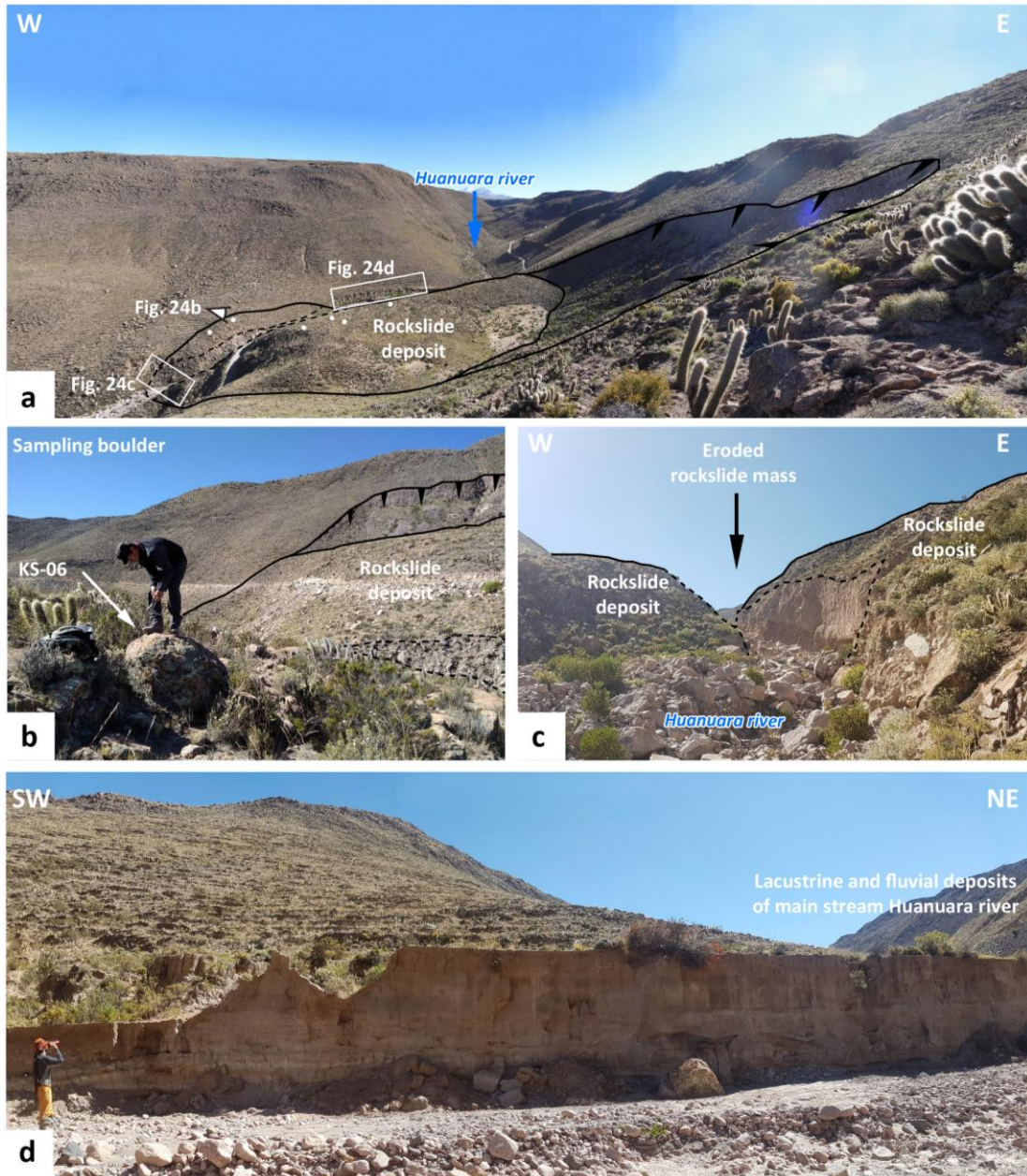


Figure 24. (a) Panoramic view to the north of the Olleria 2 rockslide, showing the landslide mass. The deposits are observed on the opposite flank of the river and the dam is eroded, (b) sample collection for cosmogenic nuclide dating (^{10}Be) dating. (c) Detail of the rockslide dam incised and eroded by the Huanuara river, (d) lacustrine deposits located along the main stream. The lake is formed by the Olleria 2 rockslide.

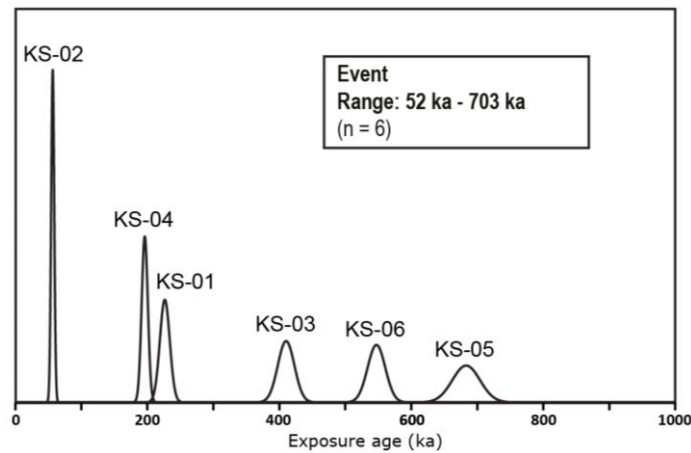


Figure 25. Probability density plot of the exposure ages obtained on boulders on top of the Olleria 2 rockslide deposit.

4.3. Ilabaya river

4.3.1. Cotana landslide

The Cotana landslide has several internal events. This large landslide is located on the left flank of the Ilabaya River (Figure 26a) between latitudes 17.22° S and 17.23° S. This landslide has a headscarp >2 km wide (Figure 26a). The landslide mass modified the channel and direction of the Ilabaya River. Four events could be identified by detailed mapping (Figure 26a, Figure 27a): The first event is a rockfall, the deposits reached the Ilabaya river. The escarpment originated in the ignimbrites of the Huaylillas formation (figure 2, figure 27b). The second event is a rock avalanche deposited on top of the first event (Figure 26a, Figure 27a). The third event is a rock avalanche affecting both previous events (Figure 26a, Figure 27a, 27c). This avalanche has a length of ~1.3 km. The fourth event is also a rock avalanche that originates from the avalanche deposits of the second event (Figure 26a). All boulders observed at the surface of these processes correspond to ignimbrites of the Huaylillas Formation (Figure 26b).

Of these four events, we choose to preliminary determine the exposure age of the second event for accessibility reasons on the field. Three samples were collected from boulders on top of the rock-avalanche (Figure. 19d). The samples yielded the following ages AB-02: 19 ± 1 ka, AB-03: 17 ± 1 ka, AB-04: 42 ± 1 ka (Table 1). The first two ages are compatible within uncertainties, corresponding to a mean age of 18 ± 0.4 ka (Figure 28). The third and older age is likely attributed to inheritance.

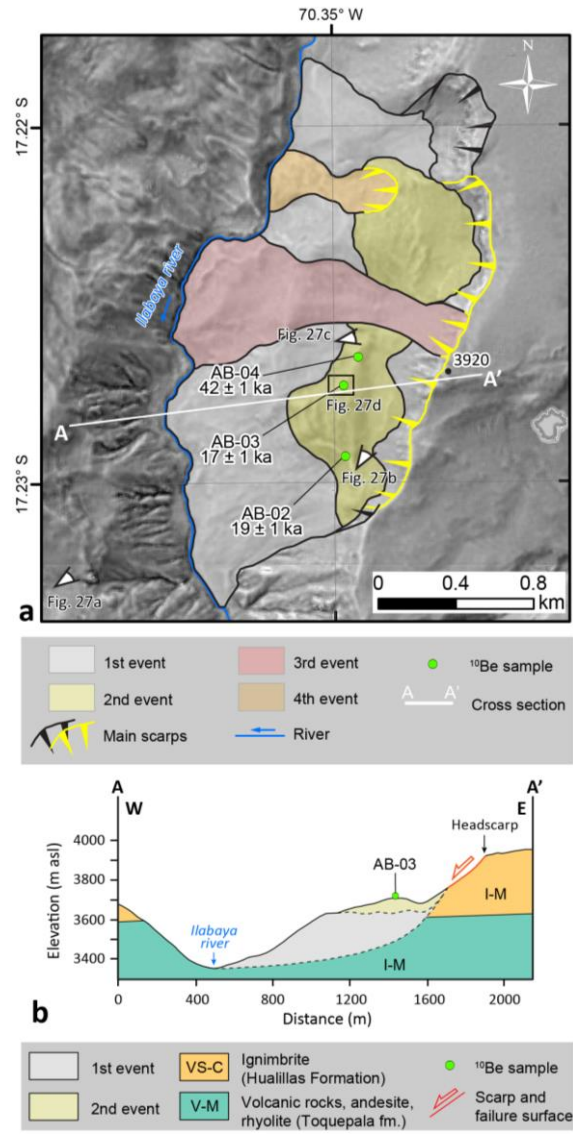


Figure 26. (a) Geomorphological map of the Cotana landslide, up to four events are observed: the first event corresponds to a rockslide and the other three events are rock avalanches, (b) Cross section showing the first (rockslide) and second event (rock avalanche).

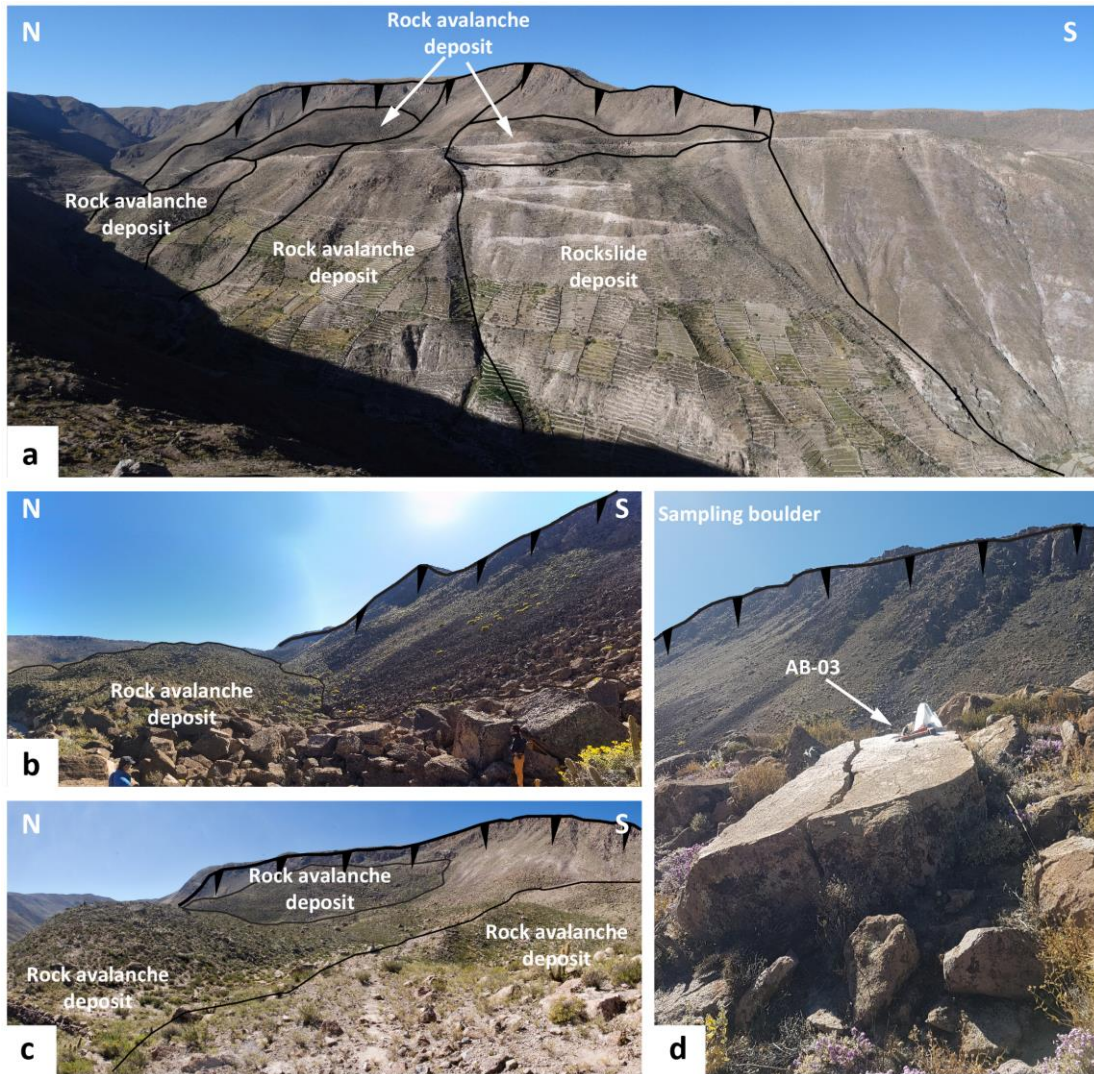


Figure 27. (a) Panoramic view to the Cotana landslide, this landslide has several internal events, the main event is a rockslide and the others are rock avalanches, (b) Detail of the headscarp and rock avalanche deposit of the second event, (c) Detail of the avalanches of the second and third events (Figure 18a), (d) sample collection for cosmogenic nuclide dating (^{10}Be).

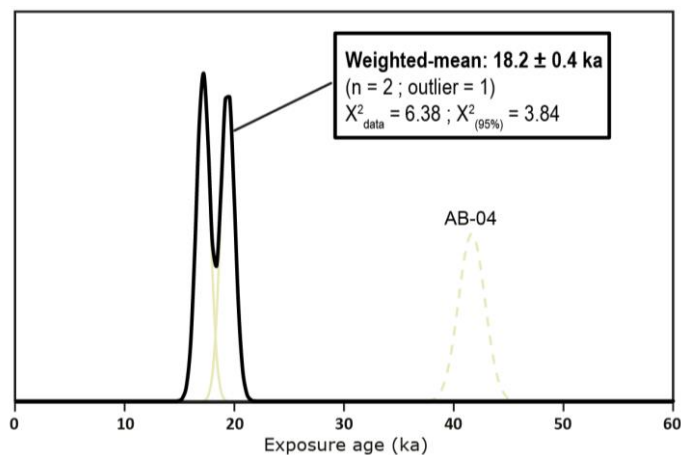


Figure 28. Probability density plot of the exposure ages obtained on boulders on top of the second event (rock avalanche).

Table 1: Samples parameters, cosmogenic ^{10}Be data and results. Z is the sample thickness, St is the topographic shielding factor. All the uncertainties reported are 1 sigma (σ).

| Landslide | Sample | Latitude (S°) | Longitude (W°) | Elevation (m a.s.l.) | Z (cm) | St (%) | Mass (g) | ^9Be carrier (10^{19} atoms) | $^{10}\text{Be}/^9\text{Be}$ (10^{-14}) | ^{10}Be (10^5 at.g $^{-1}$) | Age (ka) | 1 σ (ka) | 1 σ without PR error (ka) |
|----------------------|--------|---------------|----------------|----------------------|--------|--------|----------|--|---|--|----------|-----------------|----------------------------------|
| Locumba river | | | | | | | | | | | | | |
| Pondera | PO-01 | 17.44175 | 70.45839 | 1836 | 1.0 | 0.979 | 5.18 | 3.47 | 12.62 \pm 0.66 | 8.04 \pm 0.42 | 100 | 6 | 4 |
| | PO-02 | 17.44182 | 70.45827 | 1836 | 3.0 | 0.979 | 5.23 | 3.39 | 8.98 \pm 0.60 | 5.41 \pm 0.33 | 68 | 6 | 4 |
| | PO-03 | 17.44183 | 70.45795 | 1835 | 4.0 | 0.973 | 5.21 | 3.48 | 21.61 \pm 0.81 | 13.99 \pm 0.50 | 180 | 10 | 5 |
| Angostura | AA-01 | 17.41267 | 70.37878 | 2235 | 2 | 0.988 | 2.16 | 3.45 | 21.14 \pm 2.24 | 32.27 \pm 3.47 | 318 | 39 | 34 |
| | AA-02 | 17.41207 | 70.3796 | 2235 | 3 | 0.990 | 4.07 | 3.44 | 30.27 \pm 1.00 | 25.10 \pm 0.77 | 238 | 17 | 8 |
| | AA-03 | 17.41148 | 70.37935 | 2228 | 3.5 | 0.988 | 2.42 | 3.46 | 16.60 \pm 2.17 | 22.90 \pm 2.99 | 215 | 29 | 27 |
| | AA-04 | 17.41108 | 70.37975 | 2214 | 3 | 0.987 | 1.91 | 3.43 | 10.89 \pm 0.85 | 18.40 \pm 1.43 | 178 | 15 | 12 |
| | AA-05 | 17.41199 | 70.37809 | 2244 | 3 | 0.988 | 1.73 | 3.45 | 17.51 \pm 0.56 | 33.70 \pm 1.06 | 330 | 23 | 11 |
| | AA-06 | 17.41106 | 70.37853 | 2204 | 3 | 0.983 | 2.67 | 3.45 | 17.08 \pm 1.89 | 21.30 \pm 2.20 | 203 | 201 | 18 |
| | AA-07 | 17.41130 | 70.37789 | 2225 | 3 | 0.976 | 3.75 | 3.47 | 62.62 \pm 1.96 | 57.30 \pm 1.74 | 703 | 51 | 22 |
| Antavilca | AN-06 | 17.34334 | 70.28532 | 3008 | 3 | 0.955 | 5.58 | 3.43 | 6.53 \pm 0.21 | 3.59 \pm 0.11 | 19.3 | 0.7 | 0.5 |
| | AN-07 | 17.34349 | 70.28542 | 3007 | 3.5 | 0.955 | 5.21 | 3.42 | 5.40 \pm 0.18 | 3.10 \pm 0.09 | 17.0 | 0.6 | 0.5 |
| | AN-08 | 17.34375 | 70.28516 | 2972 | 3 | 0.974 | 6.02 | 3.43 | 5.91 \pm 0.19 | 2.98 \pm 0.09 | 16.4 | 0.6 | 0.5 |
| | AN-09 | 17.34441 | 70.28538 | 2971 | 2 | 0.984 | 7.18 | 3.42 | 2.80 \pm 0.13 | 1.01 \pm 0.04 | 6.1 | 0.2 | 0.2 |
| | AN-10 | 17.34421 | 70.28457 | 2964 | 2 | 0.984 | 7.37 | 3.43 | 6.79 \pm 0.21 | 2.85 \pm 0.09 | 15.5 | 0.6 | 0.4 |
| | AN-11 | 17.34441 | 70.28376 | 2935 | 2 | 0.975 | 5.31 | 3.43 | 5.23 \pm 0.18 | 2.94 \pm 0.09 | 16.4 | 0.6 | 0.5 |
| Quilahuani | QL-01A | 17.31622 | 70.27694 | 3649 | 3.5 | 0.986 | 8.04 | 3.41 | 46.38 \pm 1.53 | 19.46 \pm 0.59 | 65 | 2 | 2 |
| | QL-02 | 17.31540 | 70.27582 | 3642 | 1.5 | 0.958 | 8.12 | 3.43 | 77.29 \pm 2.45 | 32.47 \pm 0.99 | 109 | 4 | 3 |
| | QL-03 | 17.31714 | 70.27605 | 3626 | 2 | 0.988 | 8.08 | 3.43 | 121.74 \pm 3.97 | 51.41 \pm 1.54 | 173 | 7 | 5 |
| | QL-04 | 17.31974 | 70.27391 | 3544 | 4.5 | 0.985 | 8.25 | 3.45 | 79.80 \pm 2.60 | 33.14 \pm 1.00 | 116 | 4 | 3 |
| | QL-05 | 17.32046 | 70.27317 | 3515 | 3.5 | 0.979 | 8.16 | 3.39 | 46.85 \pm 2.82 | 19.24 \pm 0.92 | 70 | 4 | 4 |
| | QL-06 | 17.31776 | 70.27277 | 3505 | 3.5 | 0.992 | 7.87 | 3.44 | 124.99 \pm 5.56 | 54.38 \pm 1.63 | 192 | 5 | 4 |
| | QL-07 | 17.31810 | 70.27304 | 3510 | 3.5 | 0.990 | 7.86 | 3.43 | 72.65 \pm 2.54 | 31.52 \pm 1.01 | 112 | 4 | 3 |
| | QL-08 | 17.32210 | 70.27096 | 3454 | 2 | 0.989 | 8.13 | 3.43 | 37.98 \pm 1.29 | 15.83 \pm 0.51 | 60 | 2 | 2 |
| | QL-09 | 17.31910 | 70.27087 | 3468 | 2.5 | 0.996 | 8.13 | 3.43 | 79.29 \pm 3.12 | 33.20 \pm 1.01 | 118 | 4 | 3 |
| | QL-10 | 17.32148 | 70.27004 | 3445 | 3 | 0.986 | 7.94 | 3.44 | 76.39 \pm 2.50 | 32.88 \pm 1.00 | 120 | 4 | 3 |

| Huanuara river | | | | | | | | | | | | | |
|-----------------------|-------|----------|----------|------|-----|-------|------|------|---------------|---------------|-------|----|-----|
| Huanuara | HU-01 | 17.32761 | 70.31892 | 3524 | 2 | 0.969 | 5.56 | 3.43 | 128.48 ± 4.48 | 78.93 ± 2.38 | 369 | 28 | 14 |
| | HU-02 | 17.32619 | 70.32131 | 3480 | 2.5 | 0.988 | 3.52 | 3.44 | 50.03 ± 1.02 | 48.12 ± 0.92 | 177 | 5 | 3 |
| | HU-03 | 17.32840 | 70.31995 | 3548 | 5 | 0.970 | 4.33 | 3.45 | 90.18 ± 6.43 | 71.48 ± 3.98 | 325 | 28 | 19 |
| | HU-04 | 17.32616 | 70.32079 | 3486 | 2 | 0.985 | 2.97 | 3.43 | 53.54 ± 1.15 | 61.08 ± 1.18 | 217 | 7 | 4 |
| | HU-05 | 17.32824 | 70.31991 | 3546 | 3.5 | 0.970 | 4.36 | 3.45 | 55.37 ± 1.81 | 43.29 ± 1.30 | 188 | 8 | 3 |
| | HU-06 | 17.32544 | 70.32020 | 3465 | 2.3 | 0.985 | 5.31 | 3.46 | 148.77 ± 4.45 | 96.54 ± 2.33 | 499 | 31 | 11 |
| | HU-07 | 17.32580 | 70.31962 | 3471 | 4 | 0.972 | 4.22 | 3.45 | 113.47 ± 4.08 | 92.19 ± 3.14 | 486 | 34 | 17 |
| | HU-08 | 17.32249 | 70.32088 | 3386 | 4.5 | 0.971 | 5.68 | 3.43 | 107.22 ± 4.62 | 64.44 ± 2.46 | 318 | 22 | 12 |
| | HU-09 | 17.32243 | 70.32268 | 3348 | 4.5 | 0.977 | 4.41 | 3.46 | 169.06 ± 3.54 | 132.06 ± 2.45 | 868 | 45 | 11 |
| | HU-10 | 17.32169 | 70.32300 | 3356 | 4 | 0.992 | 5.51 | 3.44 | 182.44 ± 5.67 | 113.46 ± 3.38 | 682 | 50 | 21 |
| | HU-11 | 17.32154 | 70.32456 | 3315 | 4 | 0.977 | 4.51 | 3.45 | 173.05 ± 3.64 | 131.78 ± 2.61 | 881 | 44 | 14 |
| | HU-12 | 17.32173 | 70.32287 | 3343 | 1 | 0.992 | 4.30 | 3.46 | 218.24 ± 7.83 | 174.86 ± 5.30 | 1,261 | 75 | 36 |
| Ollería 1 | EP-01 | 17.28764 | 70.29868 | 3514 | 4.5 | 0.982 | 5.79 | 3.43 | 24.65 ± 0.80 | 14.19 ± 0.41 | 52 | 3 | 2 |
| | EP-02 | 17.28718 | 70.29824 | 3519 | 3 | 0.954 | 5.09 | 3.42 | 26.30 ± 0.78 | 17.21 ± 0.47 | 64 | 2 | 1 |
| | EP-03 | 17.28668 | 70.30079 | 3589 | 1 | 0.970 | 4.96 | 3.42 | 122.19 ± 2.08 | 83.87 ± 1.30 | 295 | 8 | 4 |
| | EP-04 | 17.28627 | 70.30033 | 3583 | 3 | 0.973 | 5.19 | 3.42 | 156.86 ± 2.54 | 102.91 ± 1.50 | 394 | 12 | 6 |
| | EP-05 | 17.28588 | 70.2995 | 3578 | 2 | 0.979 | 5.47 | 3.43 | 289.40 ± 4.22 | 180.86 ± 2.20 | 840 | 22 | 10 |
| Ollería 2 | KS-01 | 17.28000 | 70.29306 | 3688 | 3 | 0.961 | 7.85 | 3.43 | 156.67 ± 2.69 | 68.27 ± 0.91 | 226 | 7 | 3 |
| | KS-02 | 17.28056 | 70.29361 | 3678 | 4 | 0.968 | 8.68 | 3.44 | 41.22 ± 1.00 | 16.13 ± 0.36 | 56 | 2 | 1 |
| | KS-03 | 17.28111 | 70.29389 | 3680 | 1 | 0.964 | 8.53 | 3.44 | 279.81 ± 4.74 | 112.82 ± 1.54 | 409 | 13 | 6 |
| | KS-04 | 17.28083 | 70.29333 | 3684 | 3 | 0.961 | 7.84 | 3.45 | 136.07 ± 3.49 | 59.67 ± 1.12 | 195 | 5 | 2 |
| | KS-05 | 17.28056 | 70.29556 | 3638 | 2 | 0.974 | 9.95 | 3.41 | 466.13 ± 6.84 | 159.78 ± 1.85 | 682 | 21 | 8 |
| | KS-06 | 17.28028 | 70.29556 | 3643 | 2 | 0.967 | 8.82 | 3.44 | 352.26 ± 5.75 | 137.09 ± 1.78 | 546 | 13 | 6 |
| Ilabaya river | | | | | | | | | | | | | |
| Cotana | AB-02 | 17.23211 | 70.34943 | 3626 | 3 | 0.977 | 5.28 | 3.43 | 8.75 ± 0.28 | 5.24 ± 0.16 | 19 | 1 | 0.5 |
| | AB-03 | 17.22879 | 70.34951 | 3652 | 2.5 | 0.991 | 5.15 | 3.44 | 7.71 ± 0.24 | 4.70 ± 0.14 | 17 | 1 | 0.5 |
| | AB-04 | 17.22746 | 70.3488 | 3658 | 2 | 0.974 | 5.74 | 3.44 | 22.39 ± 0.68 | 13.03 ± 0.39 | 42 | 1 | 0.9 |
| | BI1 | | | | | | | | | | | | |
| | BI2 | - | - | - | - | - | - | | | | - | - | - |
| | BI3 | - | - | - | - | - | - | | | | - | - | - |

5. Discussion

5.1. Exposure ages scattering

In summary, we were able to reach robust dating constraints in agreement with the geomorphological mappings, for four over eight of the landslides sampled for cosmogenic nuclide dating. For half of the landslides, the obtained exposure ages show a strong dispersion, including very old apparent ages up to ~ 1 Ma, which are incompatible with their failure scenarios (one or more successive events) deduced from the morphology analysis.

One of the most outstanding examples is the Olleria 2 rockslide (Figure 23 and Figure 24). At this site, we obtained six ages ranging from 52 to 703 ka (Table 1), being all incompatible with each other's (Figure 25), while the geomorphology of the rockslide favors the interpretation of a single and simple failure event (Figure 23).

The scattering, or the incompatibility, of cosmogenic nuclide exposure ages with scenarios inferred from geomorphological observations, or other independent dating constraints, has been frequently reported in the literature. It concerns various topics such as the dating of terraces and alluvial deposits (e.g. Litty et al., 2019), the dating of glacier retreat and moraine abandonment (e.g. Heyman et al., 2011; Larsen et al., 2021), the dating of rock-glacier (e.g. Çiner et al., 2017), the dating of fluvial gorge incision (e.g. Cardinal et al., 2021); the dating of landslides, either sampling boulders (e.g. Ivy-ochs et al., 2009) or headscarps (e.g. Le Roux et al., 2009; Zerathe et al., 2014; Böhme et al., 2019). Too young or too old ages (Heyman et al., 2011) have been respectively related to two main factors: (i) incomplete exposure, yielding exposure ages that are too young, either due to post-depositional boulder rotation, shielding by shallow soil or moraine deposits, scarp rejuvenation; and (ii) inheritance, or prior exposure, yielding exposure ages that are too old (see references listed above). All of this is related to the main specificity of the cosmogenic nuclide dating tool: the exponential attenuation of incident cosmic ray particles when they cross the matter (Lal, 1991; Gosse and Phillips, 2001).

Hilger et al. (2019) explored recently the question of the significance of the inheritance when dating landslide boulders with terrestrial cosmogenic nuclide dating (TCN). According to this study the probability of sampling a boulder that may contain a non-negligible amount of inherited TCN concentration (Figure 29a and 29b) depends on two main parameters: (1) the amount of inherited TCN in the pre-failure hillslope and (2) the ability of the landslide in mixing and disintegrating the rock mass, further exposing boulders that were previously either deeply buried, or located at shallow depth below the pre-failure hillslope. Of course, the situation can be even more unfavorable if the dated landslide is young ($< \text{few ka}$, Hilger et al., 2019), implying a lower ratio between the concentration acquired by direct exposure, and the inherited component one's (Zerathe et al., 2014).

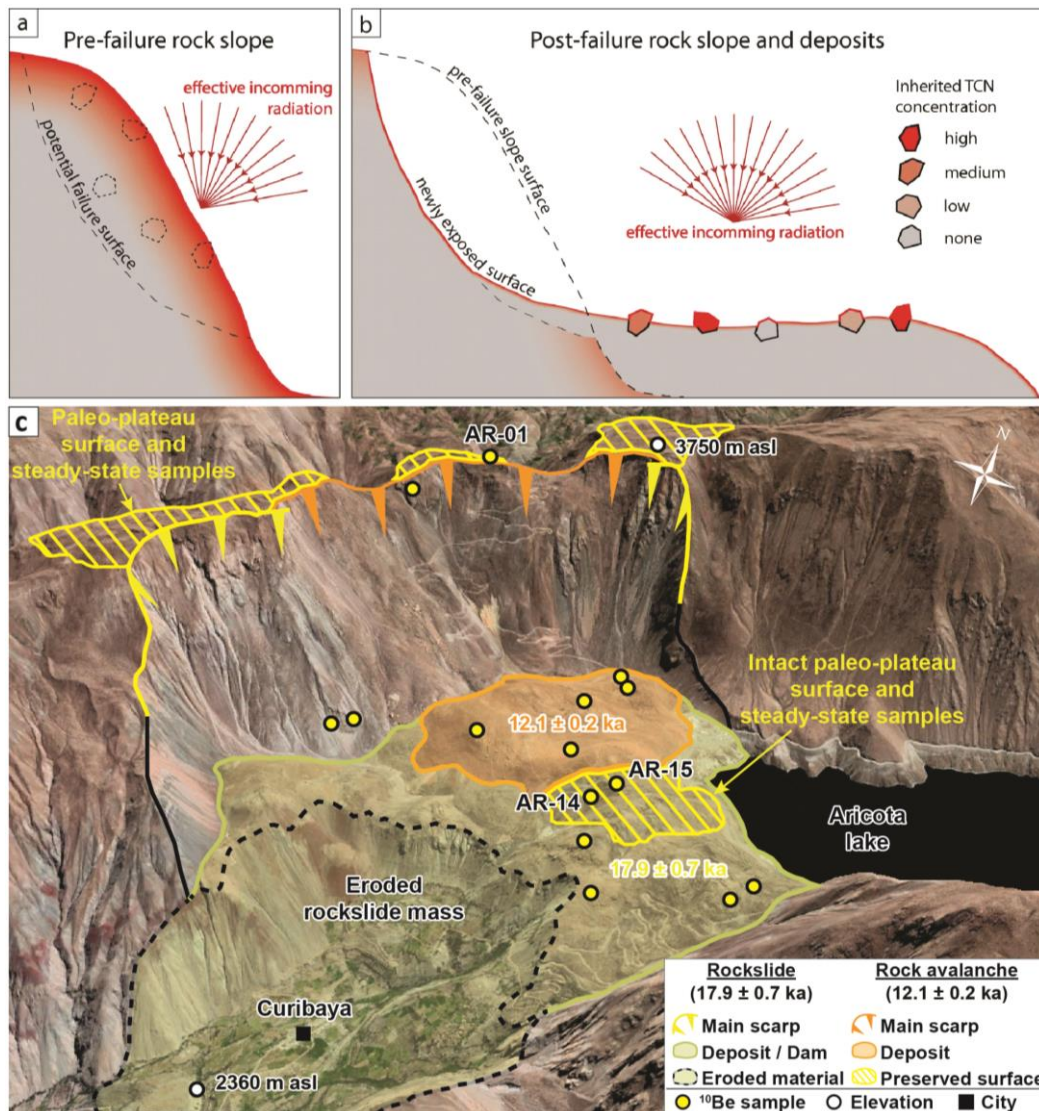


Figure 29. (a) and (b) Setting the inheritance problem from Hilger et al. (2019), (c) the Aricota rockslide dam (modified from Delgado et al., 2020) where steady-state concentration was measured on the plateau at the landslide top (AR1) and where an intact relict of this paleo-plateau was mapped in the slid-mass and on which sampled boulders (AR14 and AR15) provided steady-state similar concentrations.

To what concerns the first parameter, arid hillslopes of the Central Andes offer a strongly unfavorable context in comparison to high latitude mountains that were glaciated during the Last Glacial Maximum (LGM). Indeed, in the domains covered by ice during LGM, hillslopes were ice-shielded for a long time and completely rejuvenated by glacier erosion. Thus, in these contexts, the inheritance calculation has to be integrated over ca. 20 ka only (Schwartz et al., 2017; Hilger et al., 2019). As shown in Figure 30, this implies inherited TCN concentrations ranging from 10^3 to 10^5 at.g^{-1} , corresponding to apparent exposure ages ranging from 1 to 20 ka in the first 2 meters, which then become negligible at greater depth. On the other hand, in the arid Central Andes, Quaternary glaciers only affected the higher elevations (>5000 m asl) and the hillslopes below have been shaped by a very low erosion for millions of years, with surfaces being most of the time at steady-state equilibrium (e.g. Placzek et al., 2009). An example is the

Aricota rockslide, where we measured concentrations of more than 10^7 at.g⁻¹ along the pre-failure slope, at the top of the landslide plateau (Figure 29; sample AAR1; Delgado et al., 2020). In this context, an “infinite time” must be considered when calculating the profile of inherited TCN concentrations, which strongly increases the concentrations of TCN produced and also generates significant content of TCN at great depths, down to 20 m. As shown in Figure 30, this implies TCN concentrations from 10^5 to 10^7 in the first 20 meters of depth, corresponding to apparent exposure ages between 20 ka to 1 Ma. In this context, if one samples a landslide boulder that was previously located in the first 20 meters below the pre-failure hillslope, the inferred exposure age may be erroneously overestimated by 1 to 3 orders of magnitude.

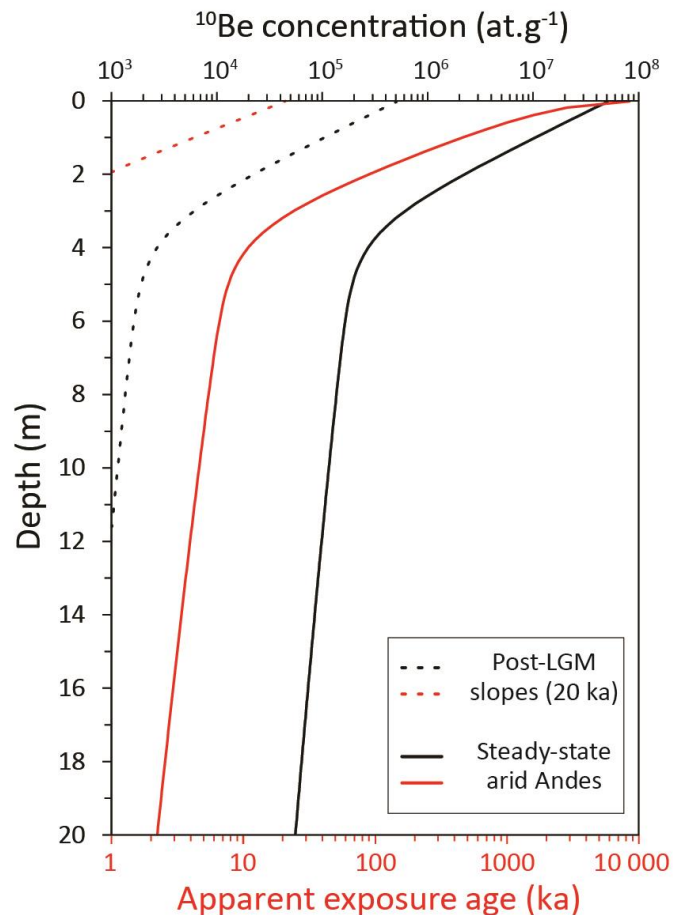


Figure 30. Theoretical depth profiles and related apparent exposure ages (adapted from Hilger et al., 2019) calculated for two different configurations: i) hillslopes after LGM glacier retreat, considering an exposure duration of ~20 ka; ii) the steady-state arid Andes, considering an « infinite time ». ¹⁰Be concentrations and exposure ages were calculated following equations described in Martin et al. (2017), parametrization described in Delgado et al. (2020), using production rate scaled at the elevations and latitude of the Locumba cluster and accounting for the muogenic productions.

Regarding the ability of the landslide to mix the rock mass, this parameter depends on the slope failure mechanisms and landslide typology, which play a major role in exposing boulders that were previously either deeply buried or located at shallow depth below the pre-failure hillslope (Hilger et al., 2019). The situation can be critical for “in-mass” rockslides, as shown in the Aricota

rockslide case (Delgado et al, 2020), where almost intact relict surfaces of the pre-failure plateau were mapped and sampled on the slided-mass (Figure 29c). As another example, for a post-Inca rockslide near Candarave (Figure 31A), several field evidences indicate almost complete preservation of the pre-failure slope in the slided-mass. Indeed, tilted Inca terraces were found in the landslide, despite having moved for ~300 meters downward (Figure 31C). We can expect a similar effect on the Olleria 2 rockslide (Figure 31B), where suspiciously old, and strongly scattered, exposure ages can be attributed to the preservation of the steady-state pre-failure hillslope. In the case of rock-avalanche type, because the movement is typically a granular-flow, and as the run out of material is often longer, at higher level a mass-destructuration can be expected.

In summary, strong caution should be taken when sampling landslide boulders for TCNs dating in regard of mentioned inheritance problems, especially in arid environments. Boulder selection should be based on careful evaluation of the degree of preservation of the pre-failure hillslope. We also recommend to multiple the dating, sampling the headscarp if possible, using multiple dating techniques to ensure to reach robust conclusions.

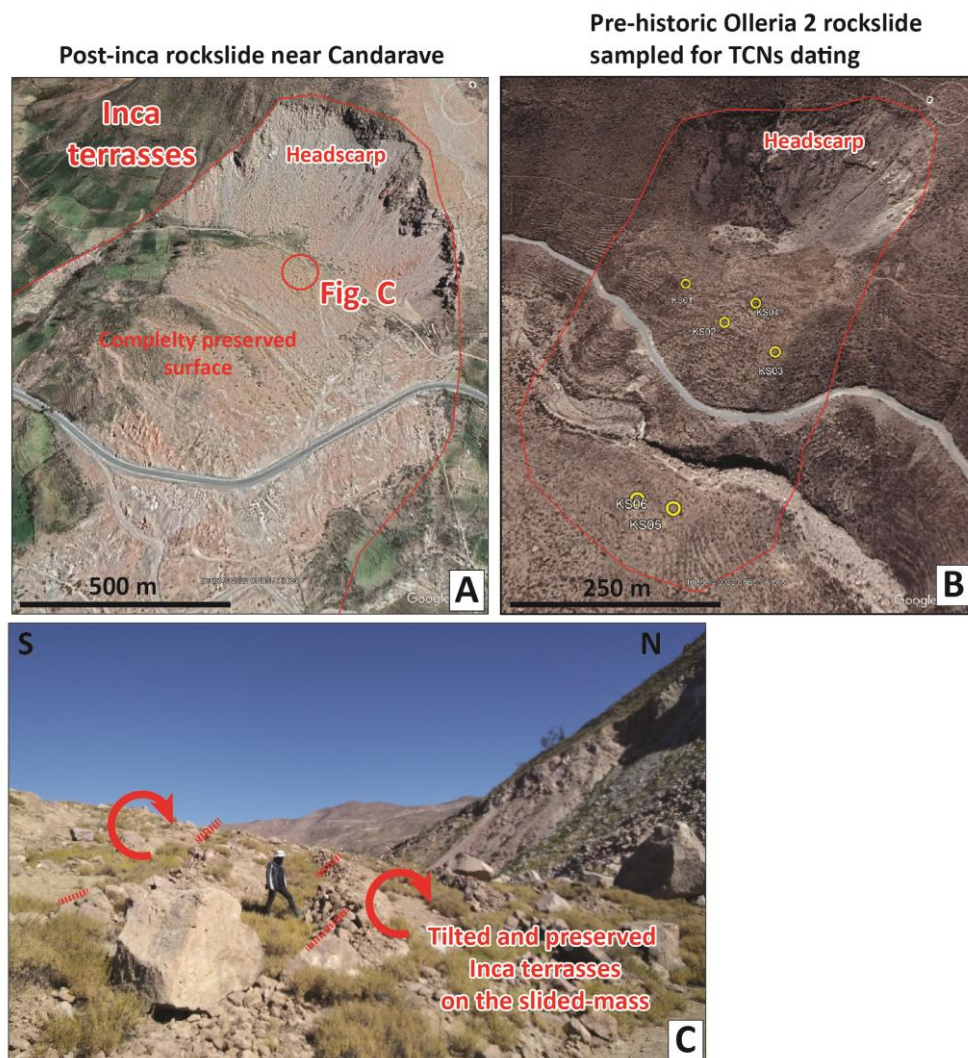


Figure 31. Morphological similarities between (A) a post-Inca rockslide mapped near Candarave (see location in Figure 2) and (B) the Olleria 2 paleo-rockslide sampled for TCN dating. (C) Tilted, but preserved, Inca terraces as evidences of preserved pre-failure hillslope in the slided-mass.

5.2. Implication of landslide timings for the triggering factors

One of the main purposes of applying the cosmogenic nuclide dating was to constrain the age of failure of a significant amount of the paleo-landslides composing the Locumba cluster in order to investigate their possible triggering factor. Of the eight landslides sampled, robust mean ages could be obtained for four landslides only (Angostura (205 ± 9 ka), Antavilca (16.3 ± 0.3 ka), Quilahuani (114 ± 2 ka), Cotana (18 ± 0.7 ka), Figure 32). For the rest of the landslides, because of age scattering, as mentioned above, only the potential range of time of occurrence was documented.

The map Figure 32 shows a synthesis of the dating at the scale of the Locumba cluster. On the basis of our data, we can say that the spatial distribution of landslide ages does not reveal any specific pattern. For instance, large landslides with different time ranges (ca. 12-18 ka; 100 and 200 ka) co-exist along the Locumba river. We do not observe any signal of upward knickpoint propagation in the valley, young and old landslides dam being located indifferently at the upper and the lower part of the catchment.

Figure 32 allows also to discuss the possible co-seismic triggering of those landslides. Two active crustal faults that are part of the Incapuquio fault system bound the Locumba cluster to the south: 1) the Toquepala fault, which is ~ 170 km long, dominated by sinistral transpression (Benavente et al., 2021), and 2) the Purgatorio fault, which is ~ 70 km long, is a dextral reverse fault (Benavente et al., 2017). These faults are continuous and are preserved in the terrain, affecting the drainage network and alluvial deposits. Recent paleoseismological studies were carried out along those faults indicating: (i) on the Purgatorio fault, sampling profiles were carried out on the fault scarp, dating was performed using cosmogenic nuclide methodology (^{10}Be), it was possible to identify at least two earthquakes of ca. Mw 7 in the last thousand years, with very shallow epicenters as they involved surface ruptures with offset of several meters (Figure 33, Benavente et al., 2017); and (ii) for the Toquepala fault they performed paleoseismological trenches, radiocarbon dating was performed (C^{14}), as a result at least one earthquake of Mw 7.4-7.7 occurred during the last five hundred years was identified, this event is related to surface ruptures of kilometers in length and offset scarps between 2-4 meters. In addition, this earthquake coincides with the collapse of the pre-Inca civilization (Benavente et al., 2021). Those results of the activity of these faults (Toquepala y Purgatorio) are a support to say that the triggering of landslides by past earthquakes is likely to occur in the Locumba area because most of the landslides investigated are located in the field very close (< 20 km) of those active fault segments. Some of the landslides affecting Inca terraces, such as the example illustrated in Figure 31A, may have been directly related to those historical earthquakes. On the other hand, in the absence of older paleoseismic records, no definitive conclusions can be reached on the link between Pleistocene giant landslides and earthquakes. We can nevertheless notice that those large landslides seem to have a relatively lower frequency of occurrence (ca. 10 to 100 ka) than the crustal seismicity in this region (ca 100 to 1000 years). Moreover, according to the recurrence of earthquakes (< 1000 years), we can indirectly say that between each dated landslide many seismic events may have occurred that have contributed to slope instability.

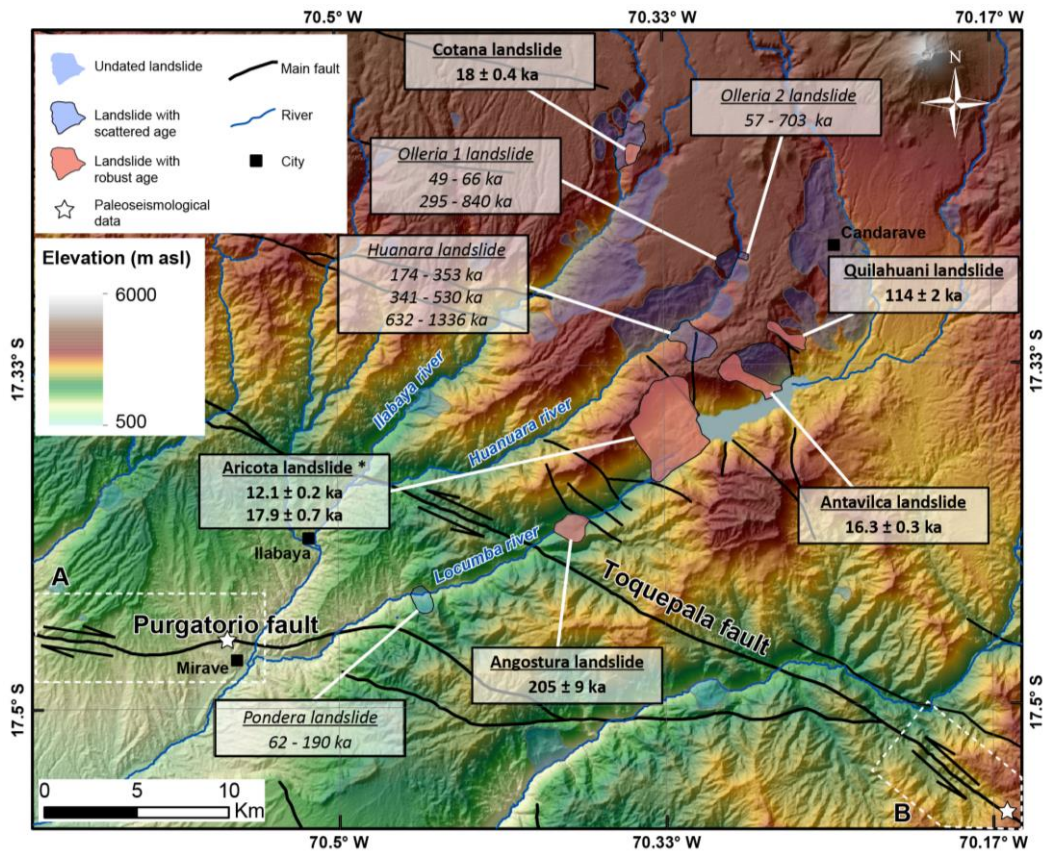


Figure 32. Summary map of landslide dating in the Locumba cluster. Paleoseismological studies (Benavente et al. 2017; 2021) with (A) Purgatorio fault (figure 33) and (B) Toquepala fault. (*) Previous study (Delgado et al., 2020).



Figure 33. Purgatorio fault scarp. (a) Panoramic view of the Purgatorio fault and the location of the sampled profile. Note the person to scale. (b) fault scarp where the yellow stars show the location of the sampled boulders. (Benavente et al., 2017).

In Figure 34, we propose a compilation of dated landslides along the Central Western Andes. The four landslides dated in this study are compared with previous studies on landslides in this part of the Andes such as the Chuquibamba landslide (Margirier et al., 2015), the Caquilluco

landslide (Zerathe et al., 2017, 2018), and the Aricota landslide (Delgado et al., 2020). Those landslide chronicles are then compared to local climate reconstructions and other climatic proxies such as alluvial terraces aggradation or paleolakes records.

The Western Flank of the Central Andes has a hyper-arid climate (Dunai et al., 2005), but there is evidence of past humid phases recorded during the Pleistocene as lake extensions and glacial advances (Quade et al., 2008; Gayo et al., 2012; Placzek et al., 2013; Martin et al., 2018, 2020; Bromley et al., 2016; Ritter et al., 2018). Also, towards the coast, records of alluvial terraces have been reported (Hall et al., 2008 and 2012; Steffen et al., 2010; McPhillips et al., 2013; Litty et al., 2018) and debris flows corresponding to Paleo-El Niño events have been dated (Keefer et al., 2003). Even, deposits from a blocked endorheic basin correlated with extreme climatic events (Ritter et al., 2019).

Starting with the youngest event, the Aricota rock avalanche (12.1 ± 0.2 ka). This landslide correlates with a lacustrine expansion in the Altiplano called the Copiasa phase (Bloggett et al., 1997) during the Younger Dryas (Placzek et al., 2013). It also correlates with dated terraces in the Majes valley (Steffen et al., 2010) and the Pisco river (McPhillips et al., 2013). Then there are three events, the Antavilca rock avalanche (16.3 ± 0.3 ka), the Pondera rock avalanche (18.2 ± 0.4 ka), and the Aricota rockslide (17.9 ± 0.7 ka). These events correlate with a large lacustrine expansion in the Altiplano known as the Tauca phase or Heinrich Stadial 1a (Placzek et al., 2013; Martin et al., 2018) that occurred between 14.5 - 18.5 ka (Figure 33e, 33f). Moreover, these landslides also correlate with 16-24 ka terraces on the Pisco river (Steffen et al., 2009; McPhillips et al., 2013) (Figure 34i). The Quilahuani rock avalanche (114 ± 2 ka) can be correlated with the Ouki phase identified in the Altiplano (80-120 ka) (Placzek et al., 2013) (Figure 34e). The age of this landslide can also be correlated to one of the terraces dated by Hall et al., (2008) in Mirave in Tacna (129 ± 24 ka; Figure 34g), and terrace in the Majes river (approx. 100 - 110 ka; Figure 34h) dated by Steffen et al., (2010). Older feature, i.e., Angostura rockslide (205 ± 9 ka), can be correlated with one of the terraces dated by Hall et al., (2008) in Palpa (Nazca). The age of this terrace is 203 ± 32 ka (Figure 34g).

All these results suggest that the major Pleistocene landslides along the arid central Andes occurred during the main humid periods. We thus propose that landslide formation in the Locumba cluster was triggered primarily by climate. During those periods of prolonged rainfalls (ie. month to years) the increase of water content in the slopes through cracks and fractures permeability and can have reduce slopes stability. Moreover, associated river discharge increase could have produce erosion at the foot of the slopes increasing slope instability.

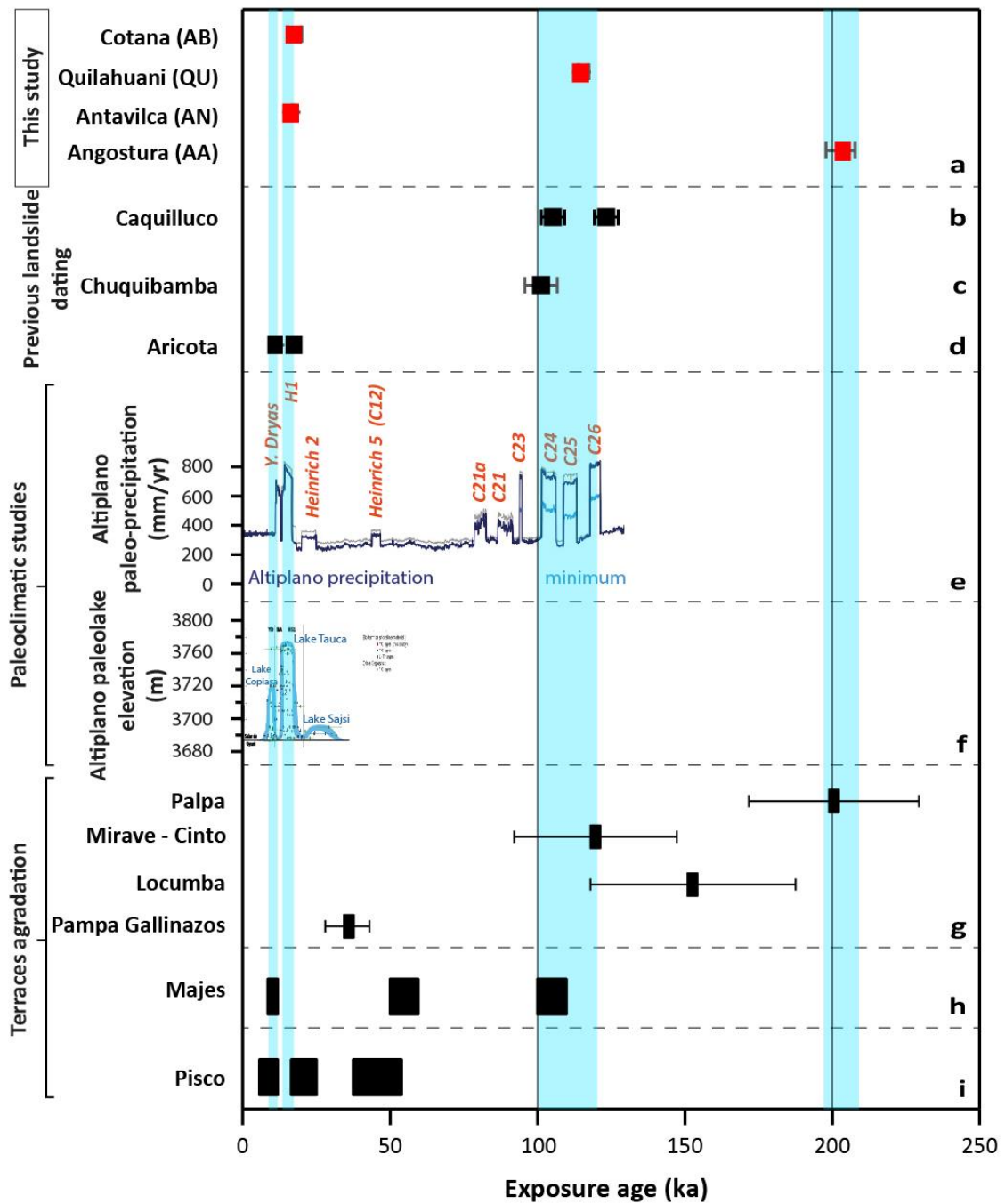


Figure 34. Compilation of landslide exposure ages for the Locumba cluster and comparison with climatic proxies. (a) Exposure ages of the present study. (b, c, d) Previous landslide studies (Caquilluco landslide - Zerathe et al., 2017, 2018; Chuquibamba Landslide - Margirier et al., 2015; Aricota landslide - Delgado et al., 2020). (e) Paleoclimatic study in the Altiplano (Placzek et al., 2013). (f) Paleoclimatic study in lakes in the Altiplano (Martin et al., 2018, 2020). (g, h, i) dated terraces on the western flank of the Andes (Hall et al., 2008; Steffen et al., 2010; McPhillips et al., 2013).

6. Conclusion

In this study, we focused on a spatial cluster of large paleo-landslides located along the Western Flank of the Central Andes, in the Locumba catchment, southern Peru. Selecting eight large landslides, distributed all around the giant Aricota rockslide (Delgado et al., 2020), we conducted field mapping and applied cosmogenic nuclide exposure dating on each site in order to reconstruct their failure history. Both rockslides and rock-avalanches were identified and the detailed geomorphological reconstructions of failure events were used as a basis for the sampling strategy and for the subsequent interpretation of exposure ages. Reliable timing of the triggering could be obtained for half of the studied landslides, while for the others, incompatibilities between dating and geomorphology as well as age scattering were attributed to inheritance problems. The landslides occurred during the Pleistocene with mean ages of ca. 16 ka for the Cotana rockslide, ca. 18 ka for the Antavilca rock-avalanche, ca. 114 ka for the Quilahuani rock-avalanche, and ca. 205 ka for the Angostura rockslide. Despite the fact that all those landslides are spatially clustered in a radius of less than 10 km, their chronological constraints highlight that they were triggered at different periods of time, with time lags up to several tens of thousands of years between each event. A seismic trigger is a possible interpretation for those collapses as the Locumba landslide cluster is bounded by two active crustal faults, that produced surface ruptures equivalent to several earthquakes of $M_w \sim 7$ during the last thousand years. However, the frequency of earthquake recurrence (hundreds to thousand years) differs from the timing of the landslides documented in this study. When comparing the chronicle of landslide episodes in the Locumba cluster, with the other mass movements previously dated in the Central Western Andes, as well as with Quaternary paleoclimate reconstructions and climatic proxies, some correlations emerge. Three periods characterized by mass movements activities synchronous with wet events or periods of enhanced precipitations are identified: the younger Dryas (ca. 12 ka), the Henrich stadial 1a (ca. 16-18 ka), and the MIS5, locally named "Ouki event" (100-120 ka). These results suggest that past climate changes corresponding to the shift from hyper-arid to prolonged wetter conditions played a primary role in large landslide activity in the Central Western Andes.

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CHAPTER V:

CONCLUSIONS AND PERSPECTIVES

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1. Conclusions

Landslides are gravitational phenomena that affect society, in many cases resulting in economic loss and people death. These processes can be triggered by climatic, tectonic or anthropogenic events. Some of the largest landslides, and that are among the most destructive, occur mostly on mountain fronts such as the Andes, Himalayas, Alps (and others) because these places cumulate strong reliefs, steep slopes, active tectonics and frequently strong seasonal precipitations. The main reasons that motivated a focus on the Central Western Andes during this PhD thesis include the facts that (1) since now, those processes were only poorly studied and misunderstood in this region despite a strong level of hazard ; (2) that, due to its low erosion and dominant aridity, the Central Andes offers an interesting case of study to improve our knowledge on landslides evolution and triggering on long time-scales (i.e. beyond the Holocene) In this context, first order questions have guided our research during this PhD project : What are the characteristics of the large landslides (type, size, abundance, spatial, distribution, etc.) along the Western flank of the Central Andes? What can we learn from those characteristics about the factors that conditioned their developments? What is the chronology of these landslides and what can be deduced from this chronology to better understand their factors of triggering?

To answer those questions, our research was based on a pluridisciplinary approach which included (1) geomorphological studies combining field mapping and analyses, study of satellite images and digital elevation models, and (2) geochronological studies based on cosmogenic nuclide dating.

Our strategy was based on three scales of study: i) a regional-scale through the inventory of large landslides along the south Peru and the north Chile, ii) a local-scale (slope-scale) with a detailed analysis and dating of an emblematic large landslide of the southern Peru and iii) an intermediate-scale with the dating of several landslides in an area of high concentration of landslide. The results were presented through three main chapters based on two published papers (Delgado et al., 2020 and Delgado et al., 2022) and a third one currently ready for submission (Delgado et al., in prep).

In the first part, our regional-scale study focused on mapping and inventorying all major landslides along the western flank of the Central Andes between latitudes 15 and 20° S (Delgado et al., 2022). The main objective was to search for control patterns for landslide formation. The mapping was carried out using satellite imagery, Google Earth, DEM and field verifications. We inventoried more than a thousand large landslides $> 0,1 \text{ km}^2$, identifying two main types of mass movements: rockslides (86% of the inventory) and rock-avalanches (14% of the inventory). Most of the mass movements mapped were identified as paleo slope-failures (>90 %). Crossing this landslide database with geological background settings, a combination of primary conditioning factors including lithology and local relief produced by the main valleys was identified, revealing in particular a strong susceptibility of the ignimbrites of the Paleogene-Neogene (Huayllillas Formation) to generate large-scale slope failures. Analyzing the spatial distribution of landslides at the regional scale, we highlighted several landslide clusters, grouping dozens of large slope failures in radiuses of $\sim 20 \text{ km}$. According to this landslide distribution and its spatial concordance with the main crustal faults of the Western Cordillera, we discussed the possible role played by those tectonic structures for the initiation of landslides (relief construction, long term rock weathering, seismic trigger). Finally, comparing the location paleo-landslides, that are dominant along the arid Western Cordillera, with the location of active landslides, that are more frequent in the northern regions receiving seasonal rainfall, we suggested that the triggering of paleo-

landslides was unlikely to occur in such very arid conditions, calling for more absolute dating of landslide to explore the question of their possible link with past climate variations.

In the second part, we focus on one of the largest landslide of the southern Peru: the Aricota rockslide dam, located in the Locumba valley (Delgado et al., 2020). Detailed geomorphological mapping was combined with cosmogenic nuclide dating to document the timing of those failures and to provide the necessary temporal frame for discussing the context their triggers. The results indicate the occurrence of two events. The first was a rockslide, dated at 17.9 ± 0.7 ka, that filled the Locumba valley and formed a dam with a height of ~ 600 m, generating a lake reservoir of ~ 6 km long. The second event was a rock avalanche, dated at 12.1 ± 0.2 ka, which debris were deposited on top of the rockslide dam of the first event. The chronology of these successive slope failures coincides with paleoclimatic events recorded on the Altiplano: the Heinrich Stadial 1a and the Younger Dryas. Both events were characterized by increased precipitation, leading to glacier advances and Altiplano lakes water level increase. This correlation suggested that climate may have played an important role in the triggering of the Aricota landslide, however, the effect of concomitant earthquake could not be ruled out.

In the third part, making use of the expertise and the knowledge acquired on the Aricota rockslide, we expanded our dating approach to several others large landslides identified all around the Aricota site that we named the "Locumba landslide cluster". Eight landslides of different typologies (rockslides and rock-avalanches) were selected. The main objective of this study was to test whether the landslides forming the Locumba spatial cluster occurred synchronously or not, further exploring the condition of landslide triggering in this valley. On each site, we performed geomorphological reconstructions, with mapping of the successive internal events, completed by cosmogenic nuclide exposure dating. A reliable chronology could be obtained for half of the studied landslides, while for the others, the results showed an overdispersion of ages interpreted as problems related to cosmogenic nuclide inheritance. The dated landslides occurred all during the Pleistocene: the Cotana rock avalanche at ca. 16 ka, the Antavilca rock-avalanche at ca. 18 ka, the Quilahuani rock-avalanche at ca. 114 ka and the Angostura rockslide at ca. 205 ka. Consequently, although being spatially clustered, the chronology of these landslides indicates different periods of occurrence of slope failures revealing a long history of triggering. It could be argued that a seismic trigger could have been the cause of these events, since these landslides are located close to two neotectonics crustal faults (Toquepala fault and Purgatorio fault) that produced $M_w \sim 7$ earthquakes in the last thousand years, but, there is no record of seismic events during the Pleistocene to make a comparison with the ages obtained from each landslide. On the other hand, comparing the landslide chronology of this PhD with other landslide dating published in previous studies, with Quaternary paleoclimatic reconstructions and with climatic proxies, more systematic correlations were observed. Once again, compatible timing was found between the Heinrich 1a stadial (ca. 16-18 ka) and the occurrence of two additional large landslides in the Locumba valley. Moreover, we found a synchronicity between another older wet event during the MIS 5, called the "Ouki event" (100-120 ka), and the triggering of the Quilahuani rock-avalanche (ca. 114 ka), the Chuquibamba landslide (ca. 102 ka; Margirier et al., 2015) and the latest events of the Caquilluco rock-avalanche complex (ca. 100-120 ka; Zerathe et al., 2017). Altogether, those results favor a vision where temporary, but strong, environmental and climatic changes, from arid to more humid weather, were responsible for the triggering of large landslides, erosion pulses and significant landscape perturbations in the Central Western Andes during the Quaternary.

2. Perspectives

We propose here below some perspectives in the continuity of the research developed during this PhD.

- **The potential of Artificial Intelligence for automatic recognition and mapping of large landslides**

Recent studies have reported the use of Artificial Intelligence (AI) and deep learning systems to automatically map landslides. For example, Prasad et al., (2021) used AI to prepare landslide susceptibility maps in India. They divided the mapped landslides into two groups, the first was for training purposes for the program and the second group of landslides was for validation of the results. They conclude that this new methodology is effective and promising for landslide susceptibility assessment. Schönfeldt et al. (2022) trained two Convolutional Neural Networks (CNNs, AlexNet and U-Net) to detect large landslides in Patagonia. They used optical data (Sentinel-2) and topographic data (TanDEM-X) on elevation, surface roughness and curvature to train the program. Confronting results to field evidences they conclude that CNNs can be a good and powerful tool for detecting large landslides at regional-scales although visual inspection should be still recommended for validation and to correctly delimit landslides.

The use such automated AI systems could be very interesting in the case the arid Central Western Andes. According to the previous attempts cited here above, we can expect that this methodology would be particularly efficient on our study area because the morphologies are very well preserved (almost intact) due to the aridity and the absence of vegetation. Using the landslide database that we built, we could train the CNNs and then run it again on our study area to detect more landslides. Then, once the systems trained, this would also allow to extend the landslide mapping to north and to the south of the study area of this PhD. Such an automatic mapping could strongly reduce the mapping time in comparison to manual mapping only. Additionally, the deep learning based on our database of landslides, acquired in arid environments such as the western flank of the Central Andes, could be a useful base for landslide recognition in other arid environments of the World and even on other telluric planets such as Mars.

- **Criteria and improvement for landslide dating**

During the application of the Cosmogenic Nuclide (CN) dating tool to constrain the timing of landslides, we encountered some problems with the inherited content of CN at shallow depth. As previously discussed, the strong presence of inheritance in our cases seems to be specific to the areas that experienced long-term aridity, such as the Central Andes, because it strongly limits erosion and because Quaternary glaciations almost never reach elevations below 5000 m there. Thus, on one hand such regions offer a strong potential to study long term evolution of landscape, but on the other hand inheritance problem with the CN can arise, limiting its use. In order to get around this problem, we would recommend to (i) combine CN sampling with Schmidt hammer that allow to test the relative age of the boulders according to its state of erosion; (ii) to combine boulders and scarp samples if possible; (iii) to combine multiple dating techniques (Pánek, T., 2015) such as OSL on lacustrine deposits that are trapped behind the slided mass, for example one of the places to apply this technique would be on the lacustrine deposits of the Olleria 2 landslide; (iv) study the lacustrine deposits because they are places that record evidence of the seismic activity of the site and these could be dated. In this way, one will be able to improve the methodology by cross-checking information and it will ensure a more complete history of the landslide.

- **Progressive landslide failure and link with ultimate collapse triggering**

In chapters 3 and 4, the dated landslides were mass movements that have already collapsed. It would be interesting to investigate and to date landslides that have not yet collapsed, but that are in the process of formation, affected by progressive failure. The landslide to be studied could be the Antavilca rockslide. This landslide has the same dimensions as the Aricota rockslide (width and height). In a first stage of this PhD, we were thinking to included this case in our dating strategy. Thus this rockslide was sampled but, because of covid crisis and lack of time, we were not able to process the samples. Sampling profiles were made along the main escarpments of the landslide (Figure 1), with the aim of finding out when the landslide began to form, estimating the speed of its movement and identifying the stages in which the movement of the landslide accelerated. This could be another interesting contribution to better understand the evolution and triggering of large landslides in the Central Andes.

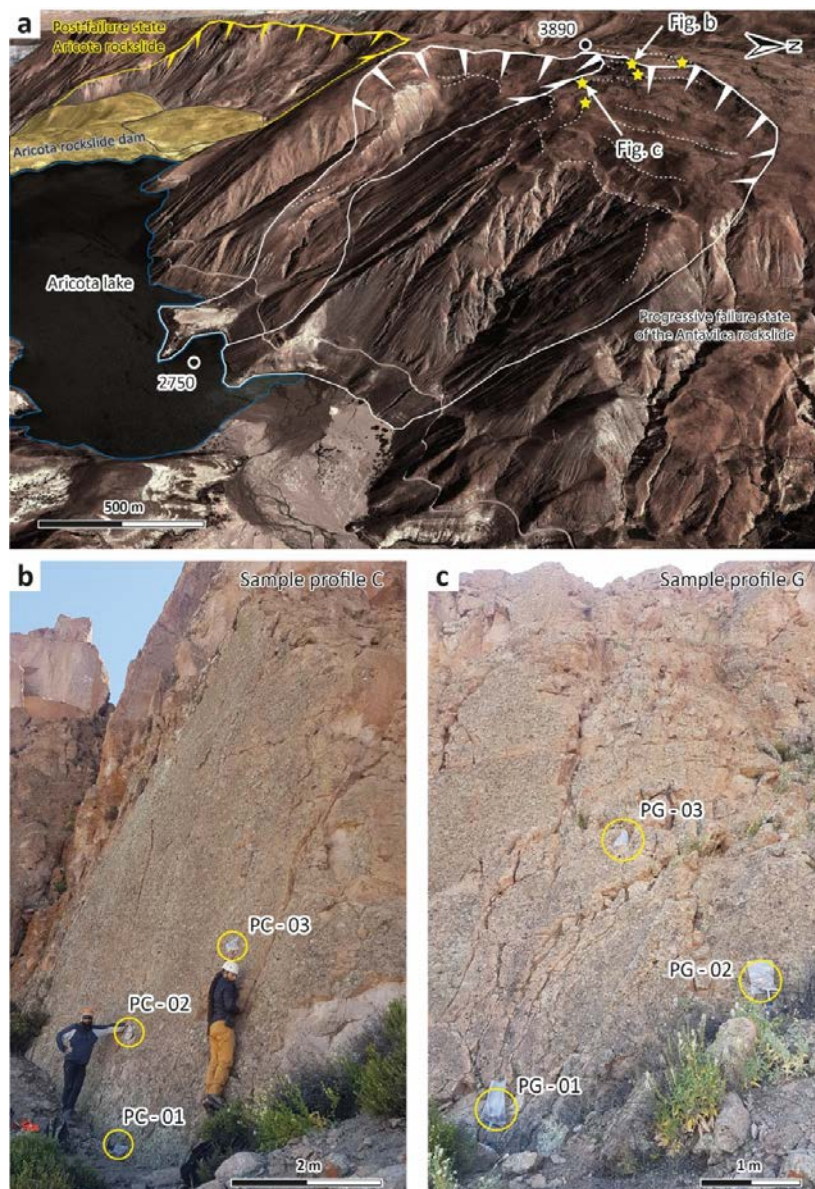


Figure 1. (a) Google Earth perspective view of the Antavilca rockslide, the dotted lines are main scarp though the mass affected by progressive failure. The yellow stars are the locations where sampling profiles were performed. (b) and (c) examples of sample collection along the scarps of the Antavilca rockslide.

- **Toward a better mitigation of landslide hazard in Peru**

In order to contribute to landslide risk management plans in Peru, the inventory and database of landslides on the western flank of the Peruvian Andes could be expanded. The first part of the landslide inventory for the western flank of the Central Andes should be used in the work of INGEMMET, the Peruvian Geological Survey. In addition, it could be proposed to implement a paleo-landslide inventory layer in the GEOCATMIN - INGEMMET viewer, as these are potential instability zones for the future. Our regional-scale landslide mapping also reveals an increased susceptibility of some lithological layers which should now be considered in the hazard maps.

Another complementary approach could be the use of InSAR (Interferometric Synthetic Aperture Radar) to detect active landslides. The InSAR methodology is based on the phase difference measurement between two or more SAR images of the same location, but from different time periods of acquisition. It allows to detect very small surface displacements (few mm/yr) whereas larger displacements can be revealed by InSAR decorrelation. Currently, a great opportunity is offered by the products provided by the ForM@Ter Large-scale Sentinel-1 Multi-Temporal Interface Sentinel-1 (FLATSIM) service which processed a massive quantity of multi-temporal Sentinel-1 data (Thollard et al., 2021). In particular, they covered most of the Central Andes of Peru and Chile, providing a map of surface displacement cumulated over the period 2014-2021 (see example on Figure 2A). Those data look very promising as we can see on this displacement map the signal from large-scale plate convergence, the continuous uplift of some volcanos, the impact of anthropogenic projects such as open mining extraction, the surface ruptures of some faults associated to the last earthquakes and also several landslides (Figure 2A and 2B). First steps that could be conducted about landslides could be : (1) to compare this displacement map with our landslide database to check the state of activity of the landslide inventoried, (2) to verify our classification of active and paleo-landslides; (3) to explore whether other slopes could have been affected by slow deformations missed during our mapping. Additionally to the cumulated surface displacement, each pixel contains time-series of displacement covering the 6 years of study (Thollard et al., 2021) and which could allow to study the response of landslides to specific forcing such as contemporaneous earthquakes or strong rainfall.

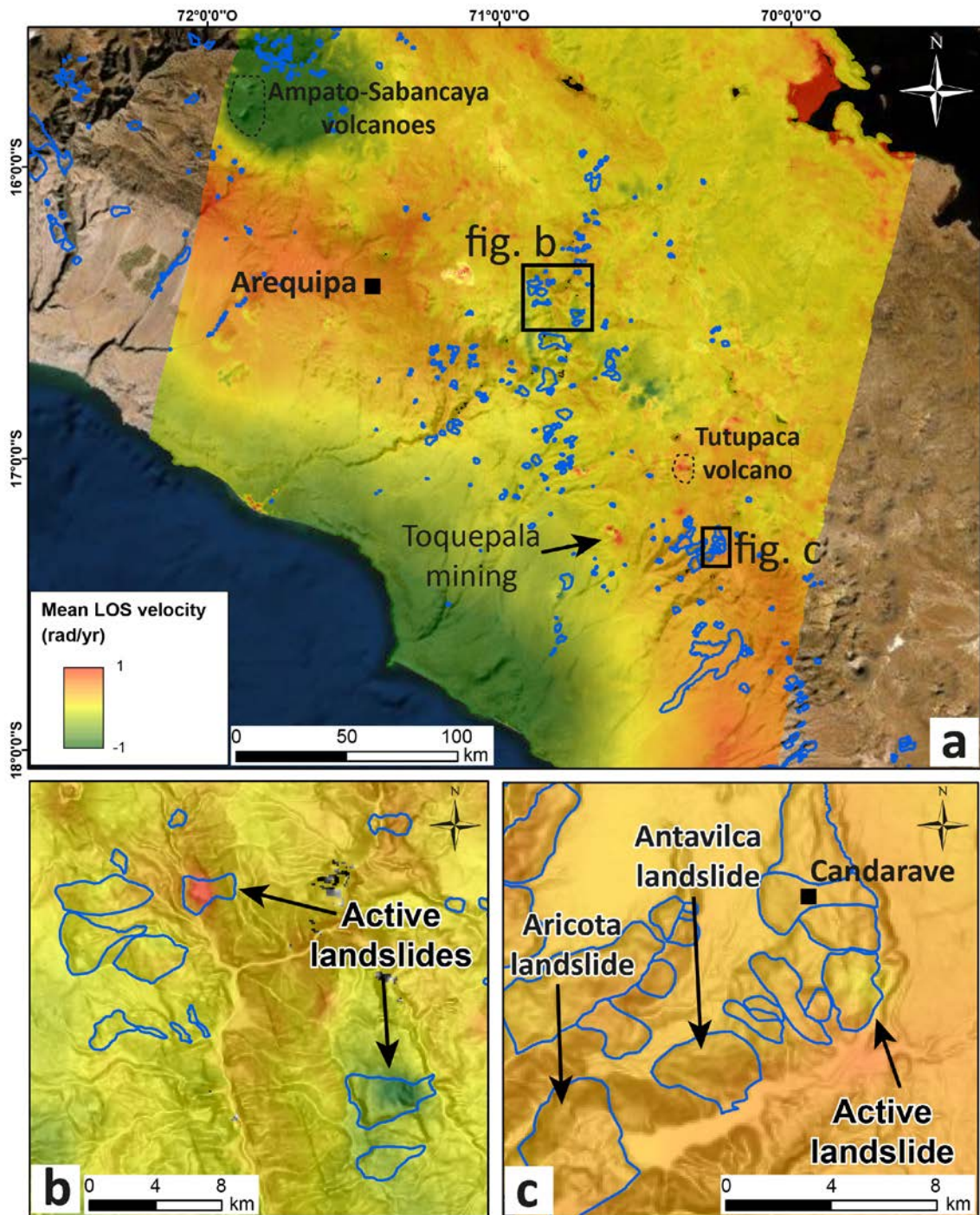


Figure 2. (a) Example of surface displacement map produced by FLATSIM by the massive processing of multi-temporal Sentinel-1 data (positive displacements are away from the satellite). Landslide polygons (in blue) are reported for comparison from Delgado et al. (2022). (b) Close up view on some large landslides where InSAR results indicate some active cases. (c) Close up view on the Locumba landslide cluster where a large landslide below orrelation of landslide mapping with deformation areas recorded in the InSAR model.

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ANNEXES

Participation in conferences:

Delgado, F., Zerathe, S., Schwartz, S., Benavente, C., Robert, X., Gaidzik, K., ... & Team, A. (2021, April). 10Be dating reveal a one-million-years records of landslide activities in the Central Western Andes. In EGU General Assembly Conference Abstracts (pp. EGU21-13580).

Fabrizio, D., Swann, Z., Stéphane, S., & Carlos, B. (2020). Large landslides database along the Central Western Andes (15°-20° S): constraints on mass-movement development and implications on relief evolution (No. EGU2020-10169). Copernicus Meetings.

Delgado Madera, G. F., Zerathe, S., Schwartz, S., Benavente Escobar, C. L., Audin, L., Carcaillet, J., & Team, A. (2019). What are the main factors that trigger the giant-landslides in the Peruvian western Andes? The Aricota giant-landslide case study. 8th International Symposium on Andean Geodynamics (ISAG).

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¹⁰Be dating reveal a one-million-years records of landslide activities in the Central Western Andes

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The western flank of the Central Andes shows a high concentration of giant landslides (Strasser and Schlunegger, 2005; Audin & Bechir 2006; Pinto et al., 2008; Matther et al., 2014; Crosta et al., 2014, Margirier et al., 2015; Zerathe et al., 2017; Delgado et al., 2020) related to specific characteristics such as a strong local relief (canyons, structural-flexures, etc.), strong and recurrent seismo-tectonic activities, and atypical climate combining long-term hyper-aridity and punctual extreme precipitation events. In this context, ongoing studies inventorying more than one-thousand giant paleo-landslides in this region underline their spatial clustering that is controlled by coupled conditioning factors including high topographical gradients and specific lithology (Delgado et al., 2020).

The purpose of this study is to constrain now the kinematics of landsliding and ultimately to get time-frequency law of the gravitational slope destabilizations of this Andean region. For this, we focus on the Locumba valley (south Peru) where more than 30 giant landslides are clustered and distributed in two main typologies (rockslide and rock-avalanche). We applied cosmogenic nuclide dating to 8 paleo-landslides, sampling 52 boulders. We used alternatively ¹⁰Be/quartz or ¹⁰Be/feldspar depending on the available lithology.

Our dataset opens an unprecedented opportunity for paleolandslides studies and reconstructions. Indeed, the exposure-ages obtained range from the Holocene to the Pleistocene, the oldest ages reaching one-million years. This new temporal-scale allows to address and discuss triggering processes in the context of seismo-tectonic activities and Quaternary climate changes. Exposure-ages distribution shows several time-frequency peaks suggesting that gravitational destabilizations are episodic phenomena with time recurrence on the range of ~100 ka. Additionally, our time-constraints indicate that most of the current landscapes along this Western

Andean flank are older than one-million years. Especially, fluvial incision and valley deepening processes are currently very low as testified by relicts of landslide dams and associated lacustrine sediments of hundred's thousand years old that are preserved along the main canyons and still not fully re-incised.



Large landslides database along the Central Western Andes (15° - 20° S): constraints on mass-movement development and implications on relief evolution

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The western flank of the central Andes presents an exceptional concentration of large paleo-landslides ($v > 100 \times 10^6 \text{ m}^3$), most of which being well-preserved morphologies due to low erosion and weathering related to the hyper-arid climate of the Atacama Desert since the Miocene. First order questions are pending about the triggering of those mass-movements, their dynamics, their locations and their roles on the Andean relief evolution. Previous studies included geomorphological analysis and few dating on individual landslides (e.g. in Peru: Margirier et al., 2015; Crosta et al., 2014; Zerathe et al., 2017; Delgado et al., 2020; e.g. in Chile: Strasser and Schlunegger, 2005; Pinto et al., 2008; Crosta et al., 2017). Preliminary regional mapping have been attempted in Peru (Geocatmin-INGEMMET and Audin & Bechir 2006) and in Chile (Matther et al., 2014 and Crosta et al., 2014).

Here we proposed a new and exhaustive mapping of large landslides of the Western Andes updating and homogenizing the previous works. The considered area locates between latitude 15° and 20°S, from the coast to the mean elevation of the Altiplano (~5000 m a.s.l). The landslide mapping was done by using Google Earth and DEMs (TanDEM-X and Pléiades). We mapped polygons (surface area $> 0.1 \text{ km}^2$) corresponding to destructured areas and strictly including the evidence of major landslide scarps (cliffs, unusual slope-breaks, etc.) and its sliding mass (offset lithology, boulders fields, etc.).

We identified more than 700 landslides, distributed into three main typologies: (1) deep-seated rockslide (DSR) showing “in-mass” displacement; (2) rock-avalanche (RA) with typical granular-flow morphologies (e.g. levees, boulders fields) and (3) destabilizations associated with both dynamics. This GIS database allows statistical analysis and interpretations crossing the landslide distribution and typologies versus relief properties, geology-lithology, long-term uplift, dating, etc. Preliminary analysis of this database shows that spatial distribution of mass-movements is not homogeneous. Instead, we observed cluster of mass-movements following the main valleys or canyons. They mainly located at elevation between 1500 and 2000 m a.s.l. Interestingly, the largest landslides

(surface area > 50 km²) are disconnected to fluvial incision. They occurred within interfluvial areas. Few of the largest landslides cover alone more than 30 % of the total cumulated landslide area in this region and, on their own, might contribute at a first order to the relief erosion.

What are the main factors that trigger the giant-landslides in the Peruvian western Andes? The Aricota giant-landslide case study.

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The central part of western Andes concentrates giant paleo-landslides that mobilized large volumes of rock, well preserved due to hyper arid climate of this region (Audin and Bechir, 2006; Pinto et al., 2008; Crosta et al., 2014; Crosta et al., 2015; Crosta et al., 2017; Mather et al., 2014; Zerathe et al., 2017) and bring us the opportunity to study the sequence of ancient events.

The main goal of this study is to identify the role of climate and tectonics phenomena's on the triggering of giant-landslides in Peruvian western Andes. We realized a multidisciplinary study on the Aricota landslide by using high-resolution DEM derived from Pléiades satellite image (Lacroix et al, 2016. Zerathe et al, 2016.) and coupled with cosmogenic nuclide methodology, We realize dating on the main body of landslides and main scarps in order to obtain chronological constraints of the gravitational destabilization events.

We identified two events: (1) a first event with an estimated volume of ~2 km³ that event generated an impressive dam in the main valley and formed a lake approximately 6 km long upstream; and (2) a second event of rocks avalanche with an estimated volume of ~0.3 km³. 10Be dating (17 samples) suggest ages of 17.9 ± 0.7 ka and 12.1 ± 0.2 ka (weighted mean and 1 sigma uncertainty of the weighted mean) for these two events. Comparing those mean ages with local paleoclimatic reconstructions, we noticed that the failures match well with two important wet events of the Altiplano: Heinrich 1 (14 - 18 ka) and Younger Dryas (11 - 13 ka), which correspond to the formation of the Taucu and Copiasa lakes respectively (Placzek et al., 2013). This suggests that the climate probably played an important role in the triggers of landslides. However, as several neotectonic faults also affect this area (in the 50 km of radius, e.g. Incapuquio fault or Purgatorio fault), we can't rule out a possible seismic trigger or even an earthquake/climate coupling.

On the western flank of the Andes, the Aricota landslide is one of the few dating events. Although there are numerous recognized paleo-landslides. So, other new landslides ages, should also allow us to know more about the origin of these phenomena in this arid region.

Differential exhumation driven by Tectonic processes in the Abancay deflection (Peruvian Andes)

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The Abancay deflection (12-13.5°S), forming the northern edge of the Altiplano in the Central Andes of Peru, is a remarkable geomorphologic feature marking the along-strike segmentation of the Andes (Dalmayrac et al., 1980). Little is known about the timing and spatial distribution of exhumation in this peculiar part of the Eastern Cordillera for the last 40 Ma; however, it is characterized by 4 km-high relief and 2 km-deep gorges suggesting significant recent incision. To better constrain the exhumation and incision history of this northern edge of the Altiplano, we present apatite and zircon (U-Th)/He and fission-track data from 6 steep altitudinal profiles collected within the deflection (40 sampling sites). Thermochronology results highlight differential exhumation episodes between the Eastern Cordillera and the Altiplano with young thermochronological ages (<10 Ma) and older ones (>15 Ma) respectively. We processed these ages into QTQt (Gallagher, 2012) and PECUBE (Braun, 2003) to discuss and unravel the exhumation timing, magnitude and settings of this area. Data inversion reveals the (re)activation of the crustal scale Apurimac fault system tilting the entire deflection like a pop-up structure (< 10 Ma) leading to differential exhumation between the Eastern Cordillera and the Altiplano. We speculate that the Abancay deflection, with its “bulls-eye” morphology and the abrupt increase in exhumation rate < 10 Ma, may represent an Andean proto-syntaxis, somewhat similar to the syntaxes described in the Himalaya or Alaska (Zeitler et al., 2001).

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ANNEXES

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Cosmogenic ^3He and ^{10}Be denudation rates in the Central Andes: Comparison with a natural sediment trap over the last 18 ka



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ABSTRACT

It is of major importance for Earth surface sciences to reconstruct denudation rates in the most precise and accurate way. For this, it can be useful to test on the same setting methods based on different assumptions, such as those relying on geomorphological and geochemical observations. Here, we use an exceptionally suited setting in the Locumba catchment (southwestern Peruvian Andes) that offers the unique opportunity to compare denudation rates derived from *in situ* cosmogenic ^3He and ^{10}Be with a geomorphological sediment budget integrated over the last 18 ka. The sediment budget is estimated by determining the volume of sediment trapped in the Aricota lake that formed 18 ka ago after the occurrence of a giant rockslide dam. We reconstructed the topography of the Locumba valley before the dam emplacement and established that the captured sediment volume is $0.8 \pm 0.1 \text{ km}^3$. Considering that the lake-water output is restricted to seepage through the dam and that overflow above the dam never occurred, this volume correctly represents the sediment flux integrated over the last 18 ka. Integrating this volume over the upstream catchment area ($\sim 1500 \text{ km}^2$), we derived a corresponding mean erosion rate of $30 \pm 9 \text{ mm.ka}^{-1}$. Fluvial sediments feeding the Aricota lake were sampled to derive denudation rates from *in-situ* cosmogenic ^{10}Be in the silicates and from *in-situ* cosmogenic ^3He in the ferromagnesian minerals. Cosmogenic nuclide denudation rates from the main stream are 30 ± 2 , 33 ± 2 , 21 ± 1 and $82 \pm 5 \text{ mm.ka}^{-1}$ for the ^{10}Be -quartz, the ^{10}Be -feldspar, the ^3He -amphibole and ^3He -pyroxene, respectively. The consistency between the cosmogenic nuclide denudation rates derived from ^{10}Be in the silicates and the erosion rate derived from our sediment budget shows that the ^{10}Be accurately estimates of the sediment flux. Additionally, this work provides the first successful application of ^{10}Be -feldspar nuclide-mineral pair to derive catchment-mean denudation rate and demonstrate that ^{10}Be -feldspar can thus be a good alternative in catchments dominated by volcanic rocks with no quartz. The discrepancies observed between the denudation rates derived from the ^3He -amphibole and ^3He -pyroxene couples require further studies.

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1. Introduction

Reconstructing denudation rates at different timescales in hyper-arid climates and tectonically active settings like the western flank of the Peruvian Andes are particularly valuable. Indeed, this allows to address the impact of climate and tectonic on de-

nudation rates, a topic that motivated long-standing debates (e.g. Herman and Champagnac, 2016; Willenbring and Jerolmack, 2016). Additionally, the impact of climate and tectonic on erosion is often cited as a driver for important feedbacks in the landscape and mountain structure evolution (e.g. Whipple and Meade, 2004). Although observations suggest correlations between erosion rates and precipitation rates or uplift rates, the respective amplitude of climatic and tectonic forcings require more geological data to be properly documented. In this context, accurate estimates of denudation rates at the millennial timescale are important (e.g. Mariotti et al., 2021). Recording denudation at such timescales

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indeed offers the advantage to average and buffer the natural variability of tectonic and climatic forcings. Moreover, this timescale is too short to be affected by variations of the internal geodynamic flux.

To quantify long-term denudation rates, different methods are often applied, including: thermochronology (0.1 to 100 Ma; e.g. Herman and Champagnac, 2016), cosmogenic nuclides applied to modern or old sediments (1 to 1000 ka; e.g. Carretier et al., 2013; Madella et al., 2018), determination of solid and solute sediment fluxes in a drainage basin (day to years; e.g. Guyot et al., 1993), estimates of total volume of sediment deposited in lakes (years to millions of years; e.g. Svendsen et al., 1989) and reconstruction of pre-eroded surfaces from Digital Elevation Models (last ~10 Ma; Riquelme et al., 2008). However, only a few studies have used more than one of these techniques on the same setting to compare and validate the obtained denudation rates results over long-time scales (e.g. Carretier et al., 2013; Aguilar et al., 2011 and 2014).

Denudation rates determined from cosmogenic nuclides have been mainly based measuring ^{10}Be concentrations in quartz, as quartz rich lithologies are common on the Earth's surface (e.g. Dunai, 2010). Only few studies have used other minerals than quartz to calculate denudation rates (e.g. Ferrier et al., 2013; Litty et al., 2021) and, to our knowledge, no study has used more than one mineral or multiple cosmogenic nuclides in the same watershed. In the Andes, denudation rates were mostly determined using ^{10}Be -quartz (e.g. Reber et al., 2017; Carretier et al., 2018).

On the southwestern flank of the Peruvian Andes, at latitude ~17°S, the Aricota lake offers an ideal opportunity to obtain and compare basin wide denudation rates using a several cosmogenic nuclides and techniques. A giant landslide blocked the Locumba valley ~18 ka ago, generating a large dam that triggered the formation of a 6 km long and 1.5 km wide lake (Fig. 1; Delgado et al., 2020). Since the formation of the lake, two main tributary rivers, the Callazas and Salado rivers, have transported sediments drained from a 1500 km² watershed. These sediments have not been able to pass through the dam, and have thus continuously filled the lake. Since the Aricota lake can be considered as an efficient sediment trap, the totality of its sediment infill represents an accurate record of the denudation rate of the upstream catchment integrated over the last 18 ka.

The purpose of this study is to compare the denudation rates obtained by two different techniques: (1) the estimation of the total volume of the sediment accumulated in the Aricota lake since its formation, 18 ka; (2) the cosmogenic ^{10}Be and ^3He concentrations measured in different detrital minerals sampled in the main present-day rivers (quartz, feldspar, amphibole and pyroxene).

2. Geological settings

The Locumba valley is located in the South Peru at ~17°S latitude, along the Western flank of the Central Andean Cordillera (Fig. 1A). The geomorphology of the Central Cordillera shows from West to East: (1) the coastal cordillera with elevation ≤ 1000 m a.s.l., (2) the Western Cordillera with elevations comprised between 1000 and 4500 m a.s.l., and (3) the Altiplano plateau reaching 5000 m a.s.l. The western flank of the Andes is carved by deep valleys and canyons related to a regional uplift and erosion (e.g. Thouret et al., 2017). The progressive onset of the Andean relief during the Miocene acted as an important topographic barrier prevented the crossing of cloud and precipitations from the Amazonian basin (Houston and Hartley, 2003). As a result, hyper-arid conditions have developed and still currently prevail in the so-called Atacama Desert (e.g. Dunai et al., 2005). This context induces very low erosion rates (1–10 mm.ka⁻¹; Madella et al., 2018 and references therein) which allows an exceptional preservation of landscapes over several millions of years (e.g. Dunai et al.,

2005). Contrasting with these dominantly dry conditions, records of extreme erosional events, such as flash floods, debris flows or landslides linked to El Niño-La Niña oscillations (ENSO) have been reported during the late Pleistocene in Southern Peru (e.g. Keefer et al., 2003). Other evidences of more persistent humid conditions related to ENSO-like climate configuration during previous interglacial periods are recorded as paleolakes extensions (e.g. Ritter et al., 2018), alluvial fan (e.g. Ritter et al., 2019; Litty et al., 2019) and fluvial terrace aggradations (e.g. Litty et al., 2018). The timings of some of the largest landslides inventoried in this region are thought to have been synchronous with those wet events (e.g. Delgado et al., 2020).

In the Locumba valley, the giant Aricota rockslide occurred ~18 ka ago (Delgado et al., 2020), creating a ~2 km³ and 600 m high dam (Fig. 1B) and 6 km long and 1.5 km wide lake. No trace of overflow, nor of fluvial incision exist above the rockslide dam and the maximum elevation of paleo shorelines remains several dozen meters below the minimum elevation of the dam crest (Placzek et al., 2001; Delgado et al., 2020). The lake outflow occurred strictly via seepage through the 1-km-wide dam (Placzek et al., 2001). Thus, the Aricota dammed lake has acted as an efficient sediment trap since its formation. The two rivers feeding the lake are the Callazas and Salado rivers (Fig. 1B and Fig. 2) which joined just upstream to the current lake delta. The Locumba basin ranges from 2000 to 5900 m a.s.l., covering a total area of ~1500 km². The Callazas and Salado sub-basins have areas of 1118 km² and 357 km², respectively (Table 1). A hydroelectric plant that siphons water from Lake Aricota to provide power for the surrounding cities induced a lake level lowering of ~50 m since 1967 (creation of the plant), that modified the base level of the river and induced a regressive incision of the lake delta and a loss of agricultural surfaces (Fig. 1B and Fig. 2A).

The lithology of the upstream Locumba basin is dominated by Tertiary and Quaternary volcanic and volcano-sedimentary rocks (Fig. 2B). The following stratigraphic succession outcrops from the valley bottom to the 4,500 m plateau: the lower unit, the Quellaveco formation, is made of Cretaceous andesites, rhyolites and an intrusive granite (outcropping north of the Aricota rockslide dam); then, the upper Tarata formation is composed of Paleogene silt and shales; and, finally, the Neogene ignimbrites of the Huaylillas formation unconformably covers these units and represents the majority of the outcrops (Fig. 2B). This sequence is complete in the Salado tributary basin (eastern tributary), while, in the lower part of the Callazas tributary basin (western tributary), the Miocene Huaylillas ignimbrite is directly deposited on the Cretaceous Quellaveco andesite-rhyolite. The mechanical contrast between the two lithologies favor the development of landslides that can reach the Callazas river (Fig. 2B, Delgado et al., 2020). The upper part of the Callazas tributary basin is incising into Pliocene andesitic lithologies that belong to the upper Barroso formation, unconformably covering the sequence previously described. Finally, two active volcanos belong to the Aricota lake basin: the Tutupaca (5815 m), in the western part of the Callazas sub catchment, and the Yucamane (5550 m) that belongs to both sub-catchments (Fig. 2). Those volcanos show large conic edifices that have been built by discontinuous volcanic activity from the middle Pleistocene to the Holocene. Their lithologies are dominated by andesitic to dacitic lava sequences (Rivera et al., 2020 and Mariño et al., 2021) characterized by a mineral assemblage of plagioclase (10–20%), amphibole (3–15%), pyroxene (2–10%), accessory minerals and quartz (< 1%). The ignimbrite of the Huaylillas formation is the only layer that contains significant amounts of quartz (5–15%), along with plagioclase (10–30%), pyroxene (1%), biotite and accessory minerals (< 1%).

The detailed chronologies of lava and eruptions were established by Mariño et al. (2021) and Rivera et al. (2020) for the

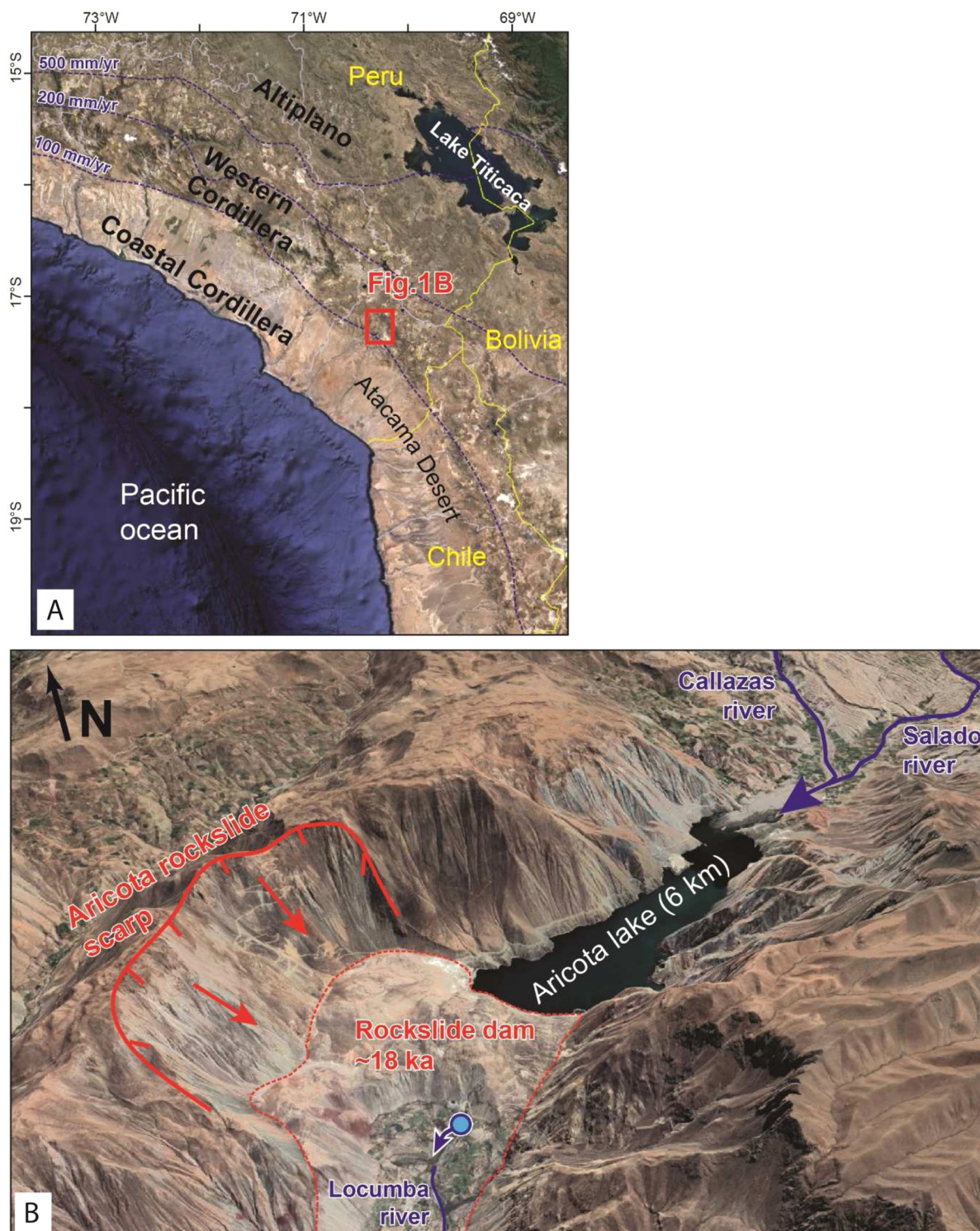


Fig. 1. A) Study area location in the Central Western Andes and isohyets of annual precipitation; B) 3D GoogleEarth view of the Aricota rockslide dam and its lake (modified from Delgado et al., 2020). The blue circle locates a spring corresponding to the main seepage of the lake through the dam, feeding the lower Locumba river. Overflow of water above the dam never occurred since the dam emplaced (Placzek et al., 2001). (For interpretation of the colors in the figure(s), the reader is referred to the web version of this article.)

Tutupaca and the Yucamane volcanos, respectively. During the Holocene, the Yucamane volcano experienced at least 4-5 explosive events, with pyroclastic flows and tephra's ejecta that probably reached a height of 4-5 km above the volcano (Rivera et al., 2020). The Tutupaca volcano produced a large debris avalanche at 6-8 ka which spread over 2-3 km on its south-eastern flank (Mariño et al., 2021). Later, 218 ± 14 yr BP (C-14), the Tutupaca produced

an historical eruption that triggered a debris avalanche ($<1 \text{ km}^3$) associated to a pyroclastic eruption which spread over few kilometers along the eastern flank of the volcano, up to the Callazas river (Samaniego et al., 2015).

Larges moraines can be identified at the head of the Callazas and Salado catchments (Mariño et al., 2021; Fig. 2B). To our knowledge, no dating of paleo glacier was reported for this basin. Nev-

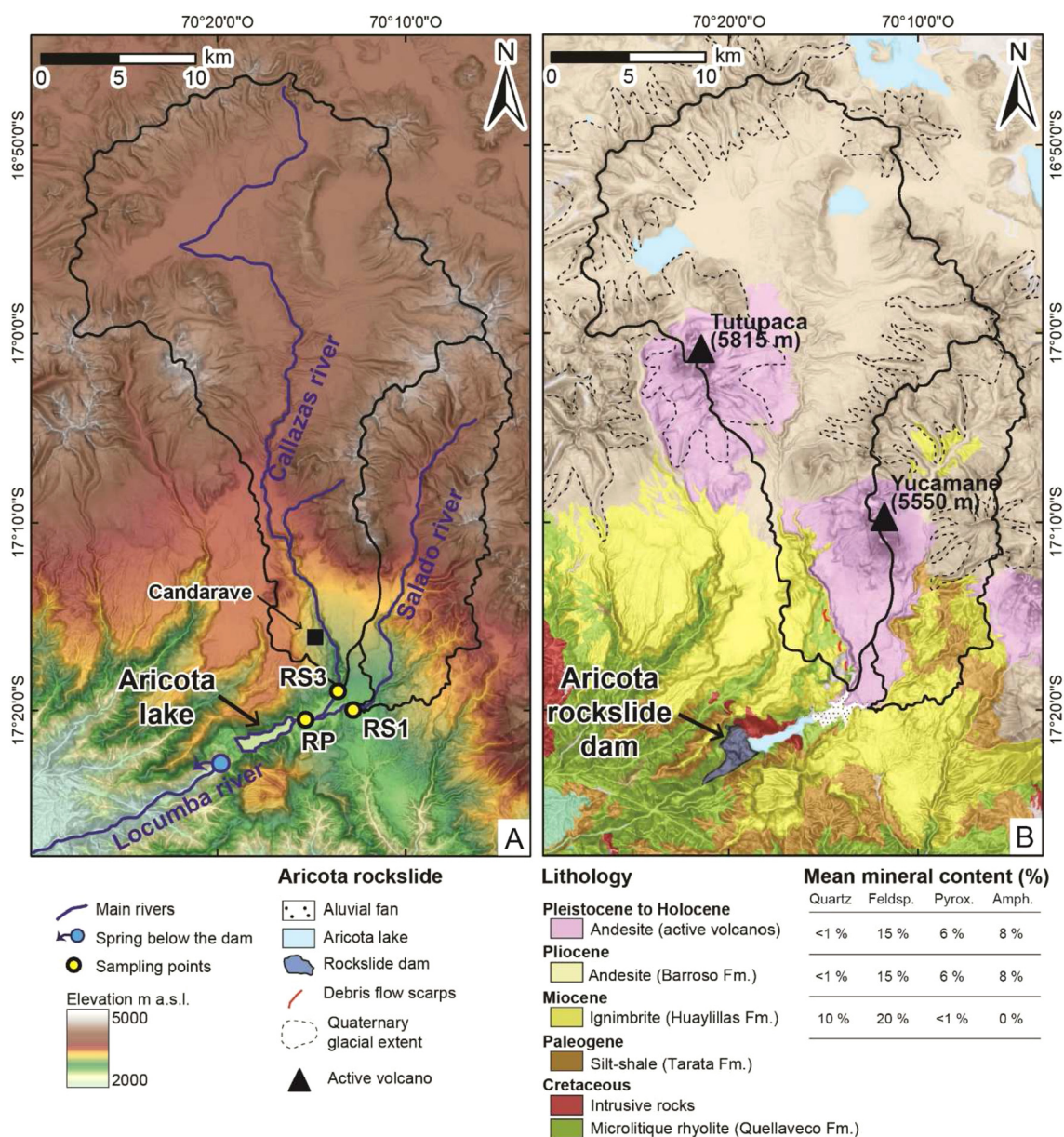


Fig. 2. Settings of the upper Locumba basin. A) Hillshade map and elevations from the TanDEM-x DEM (12 m) showing the two tributaries of the upper Locumba basin, upstream to the Aricota lake. Three samples were collected: RP from the main stream, just above the current lake, and RS1 and RS3 from the eastern (Salado river) and the western (Callazas river) tributaries respectively. B) Lithological map of the area from the INGEMMET also showing the late Quaternary glacial extent through moraines mapping. Mineral content of the lithologies are from Rivera et al. (2020) and Mariño et al. (2021). Note that Paleogene Silt and Shale, as well as Cretaceous microlitic rhyolite, do not contain any phenocrysts larger than 100 microns.

ertheless, those moraines are likely associated to the Last Glacial Maximum, which is dated in the Peruvian Andes between 25 and 17 ka at similar elevations (~4500 m a.s.l.; e.g. Martin et al., 2020 and references therein). A previous catchment-averaged denudation rate of $12.5 \pm 3.2 \text{ mm.k}^{-1}$ was obtained at the mouth of the Locumba river with the Pacific Ocean, while values ranged from 10 to 30 mm.k^{-1} were obtained in the adjacent valleys (Reber et al., 2017).

3. Methods

3.1. Estimation of the sediment volume accumulated upstream the Aricota rockslide dam

The volume of sediment trapped in the Aricota lake was computed by reconstructing the former pre-dam V-shape fluvial valley (Fig. 3C). Bathymetry was provided by the hydroelectric company

EGESUR (acquisition in October 2014, resolution 10 m). The lake currently reaches 45 m deep, with a relatively flat lake bottom (Fig. 3A). We used the Tandem-X DEM (TerraSAR-X add-on for Digital Elevation Measurements, acquisition in 2014, resolution 12 m) merged with the bathymetry to create a S1 DEM. We mapped the limit of the accumulated sediments, including the emerged delta. In the lake, the bedrock-sediment limit corresponds to the abrupt slope change between the steep valley flank and the flat bottom, that is also visible in seismic profiles (Delgado et al., 2020). Then, we extracted 25 topographic profiles from the S1-DEM, perpendicularly to the lake elongation length and to the delta (Fig. 3A). Considering that the Locumba valley has a typical V-shape fluvial profile (Fig. 3C), we performed a linear fit on each valley flank until their intersection at depth (Fig. 3B). The intersection points correspond to the former valley bottom (Fig. 3B). Then we used these points to rebuild the former river profile and to create the synthetic

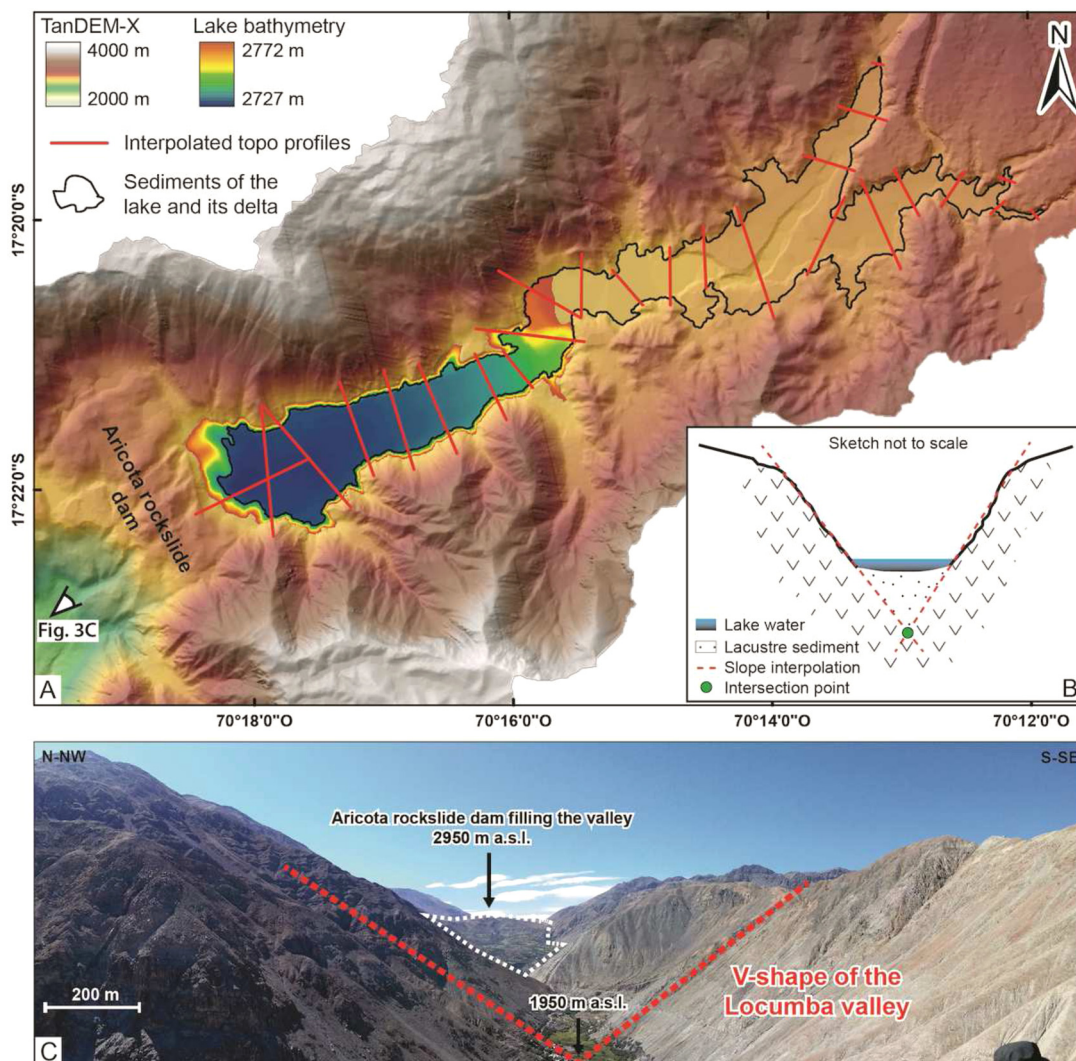


Fig. 3. Methodology followed to estimate the volume of sediment trapped in the Aricota lake. A) Tandem-X DEM of the Locumba valley around the Aricota lake and lake bathymetry (provided by the company EGESUR). The red lines are the profiles used to interpolate the valley flanks below the lake bottom and the sediment delta. B) Sketch illustrating the valley slope interpolations allowing the reconstruction of the former valley shape (theoretical green intersection point). C) Panoramic view of the Aricota valley, downstream the Aricota rockslide dam, showing its V-shape (modified from Delgado et al., 2020).

surface (S0) of the paleo-valley. Finally, we obtained the sediment volume by subtracting S1-DEM by S0-DEM. The uncertainty on the vertical location of the intersection points was propagated to derive an uncertainty on the sediment volume.

3.2. Catchment-averaged denudation rates from cosmogenic ^3He and ^{10}Be

In situ cosmogenic nuclides are produced in minerals of the Earth's surface, and this production decrease quickly below the air-rock interface (by an exponential factor each ~ 50 cm) (e.g. Dunai, 2010). These nuclides represent an accurate mean to determine denudation rates in a landscape that is eroded at secular equilibrium (Dunai, 2010; equation (4)). Such reconstructions were mainly based on ^{10}Be measured in quartz-rich lithologies. However, the upstream basin of the Aricota lake is mainly composed of basic and intermediate volcanic lithologies that are relatively poor in quartz. To obtain a better representativeness of the denudation rate over the entire catchment, we measured the ^{10}Be concentrations in quartz, but also in feldspar (Zerathe et al., 2017) and ^3He in amphibole and pyroxene (e.g. Litty et al., 2021).

3.2.1. Sampling

We collected three samples (Fig. 2A, Table 1): RP are sediments representing the main Locumba river, just before its outlet in the Aricota lake, while samples RS1 and RS3 were collected few kilometers upstream, in the two tributaries of the Locumba river. Sediment sample RS1 is representative of the Salado river draining the eastern sub-basin and sample RS3 is from the Callazas river, draining the western sub-basin (Fig. 2A). About 3 kilograms of bedload sands were collected for each sample to ensure enough material for the separation of the different minerals. The samples were sieved to retain the 0.2–0.5 mm granulometric window. Then successive magnetic separations with a Frantz magnetic separator yielded different fractions enriched in amphibole - pyroxene and quartz - feldspar, respectively.

3.2.2. In-situ ^{10}Be in quartz and in feldspar

The chemical extraction of ^{10}Be from quartz and feldspar was done at the GTC Plateform of the ISTERre laboratory (Grenoble, France). Quartz and feldspar were separated using the HF-etching magnetite approach (Zerathe et al., 2017). Grains were leached in HF-2% for 2h, before being rinsed with water and dried. We then added about 100 mg of fine powder of pure magnetite for ~ 100 gr of grains. The samples were then shaken and homoge-

Table 1Sample location, corresponding catchment size and mineral-bearing areas in km² and corresponding percentage of the total catchment area.

| Sample label | Latitude (°S) | Longitude (°W) | Elevation (m a.s.l.) | Total catchment areas (km ²) | Mean catchment elevation (m a.s.l.) | Areas bearing quartz (km ²) | Areas bearing feldspar (km ²) | Areas bearing pyroxene and amphibole (km ²) |
|--------------|---------------|----------------|----------------------|--|-------------------------------------|---|---|---|
| RP | 17.34030 | 70.24937 | 2790 | 1470 | 4490 | 113 (8%) | 1409 (94%) | 1280 (85%) |
| RS1 | 17.33285 | 70.21022 | 2880 | 357 | 4390 | 69 (19%) | 328 (92%) | 259 (73%) |
| RS3 | 17.30760 | 70.22480 | 2882 | 1118 | 4561 | 44 (4%) | 1081 (97%) | 1021 (91%) |

nized, the general colors of the grains turning to light brown. At this stage, the feldspar minerals are partially covered by magnetite powder while the quartz remains clean. Then, the Frantz magnetic separator permitted to separate feldspar from quartz. Finally, the magnetite powder was removed from the feldspar surfaces by dilute HCl leaching. Obtained separates were carefully checked under binocular to ensure that they were almost pure minerals. Samples were labeled RP-Q, RS1-Q, RS3-Q and RP-F, RS1-F, RS3-F for quartz and feldspar sub-samples, respectively. Typical treated sample size of pure quartz and feldspars was ~10 g (Table 2). After atmospheric ¹⁰Be decontamination (by 3 sequential HF leaching), ~0.5 ml of ⁹Be carrier solution (998 ± 3.5 mg.L⁻¹, Scharlab Be batch 14569501) was added and the samples were dissolved in 40% HF.

Then beryllium was isolated following routine procedure using anion and cation exchange columns followed by selective pH precipitation techniques for quartz. For feldspar, we applied the updated protocol of Zerathe et al. (2017), which considers the high cationic content of feldspar. This protocol notably uses sequential centrifugations after HF dissolution to remove fluorides precipitates, pH-4 separation to remove Titanium and sequential repetition of cation columns to ensure to reach a Be fraction of high-purity.

The beryllium hydroxides were precipitated, dried, and oxidized at 850 °C during 6 hours into BeO. ¹⁰Be/⁹Be ratio were measured at the French AMS National Facility, located at CEREGE in Aix-en-Provence (Arnold et al., 2013). ¹⁰Be/⁹Be ratios were calibrated against the in-house standard STD-11, using an assigned ¹⁰Be/⁹Be ratio of (1.191 ± 0.013) × 10⁻¹¹ (Braucher et al., 2015). Measured blank ¹⁰Be/⁹Be ratios of the chemical procedure were (5.2 ± 2.3) × 10⁻¹⁵ for the run of samples RP-Q, RS3-Q, RS1-F and (5.7 ± 0.5) × 10⁻¹⁵ for RS1-Q, RP-F and RS3-F, being one to two orders of magnitude lower than the ¹⁰Be/⁹Be ratios of the measured samples. This implies that blanks do not represent a significant source of uncertainty. Uncertainties on ¹⁰Be concentrations (reported as 1σ) are calculated according to the standard error propagation method using the quadratic sum of the relative errors and include a conservative 0.5% external machine uncertainty (Arnold et al., 2013), a 1.09% uncertainty on the certified standard ratio, a 1σ uncertainty associated to the mean of the standard ratio measurements during the measurement cycles, a 1σ statistical error on counted events and the uncertainty associated with the chemical and analytical blank correction.

3.2.3. In-situ ³He in pyroxene and in amphibole

After a density separation in heavy liquids, pyroxenes and amphiboles were hand-picked under a binocular microscope to obtain around 200 to 500 mg of pure minerals. Samples were labeled RP-P, RS1-P and RP-A, RS1-A, RS3-A for pyroxene and amphibole separates respectively. Unfortunately, we did not retrieve sufficient amount of pyroxene for the sample RS3-P, that finally could not be processed. ³He and ⁴He concentrations were measured at the CRPG noble gas platform, using an in house-tuned Helix SFT, following the procedures previously described in Litty et al. (2021). For each sample, between 50 and 200 mg of pure mineral phenocrysts (pyroxenes or amphiboles) were weighted and wrapped in tin foils. Each sample was then fused in-vacuo for 15 min at 1400 °C, using an in-house-built single vacuum induction furnace.

³He and ⁴He blanks of this hot furnace procedure were (3.6 ± 1.1) × 10⁴ at. and (1.8 ± 0.2) × 10⁹ at., respectively, two to three orders of magnitude lower than the value of the measured samples. This implies that blanks do not represent a significant source of uncertainty. The SFT sensitivity was calibrated using a known amount of helium gas standard with a ³He/⁴He ratio of 20.63 Ra (1 Ra = 1.384 × 10⁻⁶ is the atmospheric ratio) (Matsuda et al., 2002). Additionally, two aliquots of the CRONUS-P pyroxene standard were analyzed during the same analytical session and yielded a mean ³He concentration of (5.04 ± 0.07) × 10⁹ at.g⁻¹, in good agreement with the average value reported from an inter-laboratory comparison (Blard, 2021).

The ³He_{tot} measured by fusing the minerals is a three-component system that can be written e.g. (Blard, 2021):

$${}^3\text{He}_{\text{tot}} = {}^3\text{He}_c + {}^3\text{He}_{\text{nucl}} + {}^3\text{He}_{\text{mag}}, \quad (1)$$

where indices *c*, *nucl* and *mag* refer to the cosmogenic ³He, the nucleogenic ³He and the magmatic component, respectively. To calculate the nucleogenic ³He production rate (P_{3nucl}) and its contribution (³He_{nucl}) for each sample we use the excel spreadsheet of (Blard, 2021), considering 1) the mean age of the lava crystallization determined here by (U-Th)/⁴He dating, 2) the concentration of Li in each mineral sample measured by ICPOES, and 3) the major and trace element concentrations measured in the bulk rock. Major, trace element and Li concentrations in the pyroxene, amphibole and in the bulk sand were measured at the SARM-CRPG facility (Nancy, France). The ⁴He_{tot} in both pyroxene and amphibole is a two-component system (Blard, 2021):

$${}^4\text{He}_{\text{tot}} = {}^4\text{He}_{\text{rad}} + {}^4\text{He}_{\text{mag}}, \quad (2)$$

where the indice *rad* refers to the radiogenic component. The mean age of the lava outcropping in the catchment was evaluated using the (U-Th-Sm)/⁴He_{rad} method (Blard, 2021). Assuming that the magmatic component is negligible in those lithologies (Blard, 2021 and references therein), the calculated ages are maximum. ⁴He production rate (P₄) was estimated for each sample from the equations of Farley (see in Blard, 2021). Mean lava ages (t_{eruption}) were then computed using:

$$t_{\text{eruption}} = {}^4\text{He}_{\text{rad}}/P_4 \quad (3)$$

where ⁴He_{rad} = ⁴He_{tot}. Corrections for α ejection and implantation between the phenocrysts and the lava were applied (Blard, 2021).

3.2.4. Denudation rates calculation

The relationship between measured cosmogenic-nuclide concentration (C) and mean catchment denudation rate (ε) can be expressed, in its simplest form, as (Brown et al., 1995):

$$C = \sum P_i \Delta_i / \varepsilon(3) \quad (4)$$

where P_i and Δ_i are the mean catchment production rate and the attenuation length, respectively, of each particle (*i*: neutron, fast muon and slow muon) that contribute to the production. Using Eq. (4) to quantify the mean denudation at catchment scales

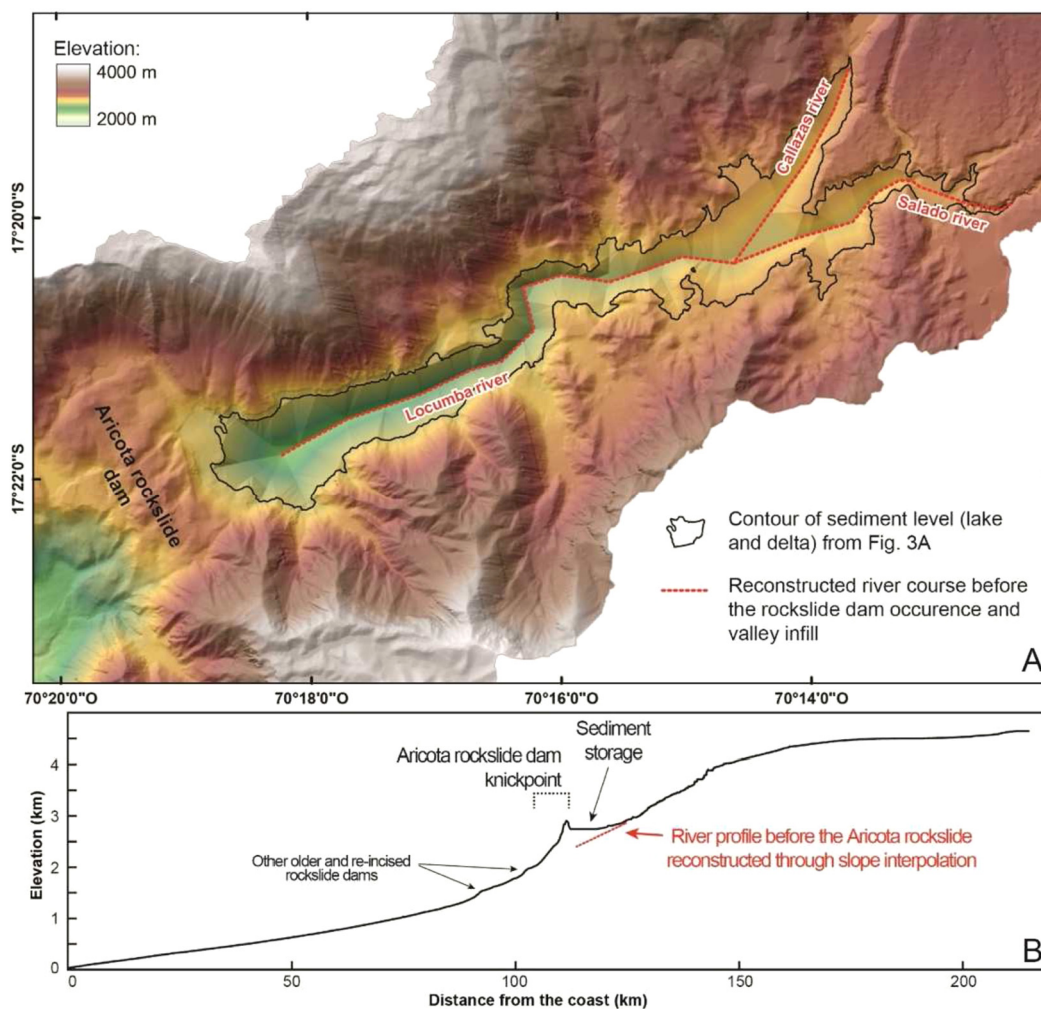


Fig. 4. Reconstruction of the Locumba valley and river profile before the valley infill behind the Aricota rockslide dam. A) Hillshade view (TanDEM-X dem) showing the reconstructed valley flanks through slope interpolations below the current sediment level. B) Reconstructed river profile (in red) plotted along the long profile of the Locumba river.

implies two assumptions: (1) sediment storage within the catchment is limited and (2) loss induced by radioactive decay of ^{10}Be is negligible since both the erosion time and the residence time of sediment within the fluvial system are short. This is a reasonable assumption in high-relief mountain settings such as the high elevation Peruvian Andes, where fluvial transport is expected to be relatively rapid. In order to deduce catchment-wide denudation rates, a spatially averaged cosmogenic nuclides production rate has been computed using Basinga software (Charreau et al., 2019), based on a cell-by-cell approach with a 30 m digital elevation model. As recommended when the used minerals are not homogeneously distributed over the catchment (Charreau et al., 2019), we applied geological masks according to the mineralogical assemblages known in the catchment in order to compute accurate production rates (Fig. 2B and Table 1). For all minerals, Paleogene and Cretaceous lithology were excluded from the production rate calculation as they do not contain any phenocryst. Feldspars are almost homogeneously distributed so no additional area was removed from the calculations. For quartz, we selected only the areas corresponding to the Miocene ignimbrites of the Huaylilas formation containing most of the quartz in the basin. Pyroxene and amphibole dominate in the Pliocene and Pleistocene volcanic series (Fig. 2B). Denudation rates for each nuclide-mineral pair have been also computed without applying any mask for comparison. We used the modern world-wide spallogenic production rate (i.e. induced by neutrons) at sea level and high latitude of $4.11 \text{ atoms.g}^{-1}.\text{yr}^{-1}$ for ^{10}Be in

quartz (Martin et al., 2017), $3.49 \pm 0.5 \text{ atoms.g}^{-1}.\text{yr}^{-1}$ for ^{10}Be on feldspar (Zerathe et al., 2017) and $122 \pm 12 \text{ atoms.g}^{-1}.\text{yr}^{-1}$ for ^3He in both pyroxene and amphibole (Martin et al., 2017). To compute the spatial correction factor, we used the time dependent Lal-Stone scaling scheme, as implemented in CREP (Martin et al., 2017). If the LSD scheme is used in place of the Lal-Stone scaling, differences in denudation rate range between 2 and 9% (see Supplementary Material and discussion in Charreau et al., 2019). Such a bias is comparable with the analytical uncertainties and do not affect our data interpretation.

4. Results

4.1. Sediment budget and derived catchment-averaged erosion rate

The reconstructed DEM of the Locumba valley before the sediment accumulation is shown on Fig. 4A. To check the accuracy of this reconstruction, we plotted the portion of the river profile reconstructed along with the current river profile of the whole Locumba basin (Fig. 4B). We can observe a clear knickpoint produced by the Aricota rockslide dam in the center of the current river profile. Downstream of this major knickpoint, smaller ones can be observed, corresponding to older and partially re-incised rockslide dams (Delgado et al., 2020). The portion of the river profile that has been reconstructed shows a good coherence and good continuity with the longitudinal profile upstream and downstream

Table 2
¹⁰Be measured in quartz and in feldspar.

| Sample | Mineral | Mass (g) | ⁹ Be carrier (10 ¹⁹ atoms) | Total ¹⁰ Be counts | ¹⁰ Be/ ⁹ Be ratio (10 ⁻¹³) | ¹⁰ Be ^a (10 ⁵ at.g ⁻¹) |
|--------------------|----------|----------|--|-------------------------------|--|---|
| RP-Q ^b | Quartz | 8.5780 | 3.3675 | 1271 | 1.789 ± 0.057 | 6.82 ± 0.24 |
| RS1-Q ^c | Quartz | 6.0263 | 3.4129 | 1235 | 1.483 ± 0.051 | 8.07 ± 0.29 |
| RS3-Q ^b | Quartz | 8.9790 | 3.3955 | 833 | 0.410 ± 0.029 | 1.36 ± 0.14 |
| RP-F ^c | Feldspar | 3.6429 | 3.3942 | 222 | 0.826 ± 0.058 | 7.16 ± 0.55 |
| RS1-F ^b | Feldspar | 6.6360 | 3.3648 | 478 | 0.943 ± 0.068 | 4.52 ± 0.36 |
| RS3-F ^c | Feldspar | 14.2379 | 3.4156 | 259 | 0.825 ± 0.057 | 1.84 ± 0.13 |

^a Concentration corrected from the blank, analytical uncertainties are 1σ and include the counting statistics, the machine stability (~0.5%) and the blank correction.

^b The ¹⁰Be/⁹Be blank ratio for those samples was (5.2 ± 2.3) × 10⁻¹⁵.

^c The ¹⁰Be/⁹Be blank ratio for those samples was (5.7 ± 0.5) × 10⁻¹⁵.

Table 3

Cosmogenic nuclide denudation rates in mm.ka⁻¹ derived from the different nuclide-mineral pairs. Note that denudation rates for ¹⁰Be/feldspar were not recalculated with geological mask as the feldspar are homogeneously distributed over the Locumba catchment.

| | Sample | ¹⁰ Be denudation rates (mm.ka ⁻¹) | | ³ He denudation rates (mm.ka ⁻¹) | |
|-------------------------|--------|--|----------|---|-----------|
| | | Quartz | Feldspar | Pyroxene | Amphibole |
| With geological mask | RP | 30 ± 2 | 33 ± 3 | 21 ± 1 | 82 ± 5 |
| | RS1 | 26 ± 2 | 51 ± 5 | n.a. | 57 ± 4 |
| | RS3 | 147 ± 18 | 130 ± 12 | 21 ± 1 | 68 ± 4 |
| Without geological mask | RP | 40 ± 3 | 33 ± 3 | 18 ± 1 | 79 ± 4 |
| | RS1 | 33 ± 2 | 51 ± 5 | n.a. | 53 ± 3 |
| | RS3 | 208 ± 25 | 130 ± 12 | 21 ± 1 | 67 ± 4 |

of the Aricota rockslide, validating the accuracy of our paleo-valley reconstruction.

We calculated a total volume of sediment (V_{sed}) of 0.8 ± 0.1 km³ accumulated behind the dam by subtracting the S1-DEM by the S0-DEM. To derive an erosion rate from this volume, a porosity correction can be applied. The porosity of the river sediment was measured on samples RS1 and RS3 (following Missimer and Lopez, 2018) and yielded a value of $40 \pm 10\%$. This value should be considered as a maximum estimate for the mean porosity in the lake sediment because: (1) some finer sand fraction may have remained in suspension in the river, but be deposited into the lake therefore reducing the mean porosity, and (2) sediment compaction into the lake may further reduce the porosity. However, following the literature, the porosity of the volcanic rocks outcropping in the Locumba catchment (i.e. mainly andesite and dacite) have values that can range between 20 and 50% (Heap et al., 2016 and references therein). Considering that the porosity of the lake sediment and the eroded source rocks are both in the same range, we assume that the volume of sediment trapped in the lake roughly equals the volume of rock eroded in the catchment. To consider the any possible uncertainty associated to the differential porosity, we propagated 10% of additional uncertainty on the sediment volume. Assuming an age of 17.9 ± 0.7 ka for the Aricota rockslide dam (Delgado et al., 2020), corresponding to the lake initiation and thus the beginning of sediment accumulation (t), the catchment-scale mean erosion rate (ε_{sed}) can be derived from the volume of eroded sediment (V_{sed}) and the catchment area upstream to the dam ($A = 1470$ km²) such as $\varepsilon_{sed} = (V_{sed})/(t \times A)$. We obtained an erosion rate of 30 ± 9 mm.ka⁻¹.

4.2. Cosmogenic nuclides-based catchment-averaged denudation rate

4.2.1. ¹⁰Be results

Measured ¹⁰Be concentrations range between $(1.36 \pm 0.14) \times 10^5$ and $(8.07 \pm 0.29) \times 10^5$ at.g⁻¹ in quartz and between $(1.84 \pm 0.13) \times 10^5$ at.g⁻¹ and $(7.16 \pm 0.29) \times 10^5$ at.g⁻¹ in feldspar (Table 2).

Taking into account geological masks, we obtained denudation rates of 30 ± 2 mm.ka⁻¹ and 33 ± 3 mm.ka⁻¹ for the main stream (RP) on quartz and feldspar, respectively (Table 3). For the two tributary rivers: 1) denudation rates of 26 ± 2 mm.ka⁻¹ and 51 ± 5 mm.ka⁻¹ have been calculated for RS1 (Salado River) on quartz and feldspar, respectively; 2) denudation rates of 147 ± 18 mm.ka⁻¹ and 131 ± 13 mm.ka⁻¹ have been calculated for RS3 (Callazas River) on quartz and feldspar, respectively.

4.2.2. ³He results

³He and ⁴He results are presented in Table 4. Measured total ³He concentrations range between $(4.06 \pm 0.12) \times 10^7$ and $(4.57 \pm 0.13) \times 10^7$ at.g⁻¹ in pyroxene and between $(1.04 \pm 0.03) \times 10^7$ and $(1.50 \pm 0.06) \times 10^7$ at.g⁻¹ on amphibole. Measured total ⁴He concentrations range between $(3.17 \pm 0.03) \times 10^{12}$ and $(5.85 \pm 0.05) \times 10^{12}$ at.g⁻¹ in pyroxene and between $(1.41 \pm 0.01) \times 10^{12}$ and $(5.95 \pm 0.05) \times 10^{12}$ at.g⁻¹ in amphibole. Assuming that the magmatic ⁴He component is negligible, we derived from the total ⁴He concentration and from the U-Th-Sm content of target minerals and of the bulk sand (supplementary data), mean eruption ages ranging between 0.3 ± 0.1 and 1.6 ± 0.1 Ma. Those relatively young eruption ages are in good agreement with the dominance of Pleistocene to Pliocene lava sequences in the upper Locumba basin (Fig. 2B; Rivera et al., 2020 and Mariño et al., 2021). Such young lava ages resulted in low contributions of nucleogenic ³He (³He_n), representing less than 1% of the total ³He concentrations.

Considering geological masks, we calculated denudation rates of 21 ± 1 and 82 ± 5 mm.ka⁻¹ for the main stream (RP) from pyroxene and amphibole, respectively (Table 3). For the two tributary rivers: 1) a denudation rate of 57 ± 4 mm.ka⁻¹ has been calculated for RS1 (Salado River) from amphibole (the pyroxene was not measured due a lack of material); 2) denudation rates of 21 ± 1 and 68 ± 4 mm.ka⁻¹ have been calculated for RS3 (Callazas River) from pyroxene and amphibole, respectively.

Table 4
 ^3He and ^4He measured in pyroxene and amphibole.

| Sample | Mineral | Mass (mg) | $^4\text{He}_{\text{tot}}$ (10^{12} at.g $^{-1}$) | $^3\text{He}_{\text{tot}}$ (10^7 at.g $^{-1}$) | P_4^a (10^6 at.g $^{-1}$.yr $^{-1}$) | (U-Th-Sm)/ ^4He eruption age (Ma) | P_3^b (at.g $^{-1}$.yr $^{-1}$) | $^3\text{He}_n^c$ (10^5 at.g $^{-1}$) | % $^3\text{He}_n^c/{}^3\text{He}_t$ | $^3\text{He}_c^d$ (10^7 at.g $^{-1}$) |
|--------|-----------|--------------|---|--|---|--|-------------------------------------|---|-------------------------------------|---|
| RP-P | Pyroxene | 49.10 | 3.17 ± 0.03 | 4.57 ± 0.13 | 2.4 ± 0.4 | 1.3 ± 0.3 | 0.087 | 1.5 | 0.3 | 4.56 ± 0.13 |
| RS1-P | Pyroxene | Not measured | | | | | | | | |
| RS3-P | Pyroxene | 52.70 | 5.85 ± 0.05 | 4.06 ± 0.12 | Not measured | | | | | 4.06 ± 0.12 |
| RP-A | Amphibole | 199.2 | 1.41 ± 0.01 | 1.04 ± 0.03 | 2.9 ± 0.4 | 0.5 ± 0.1 | 0.082 | 0.4 | 0.4 | 1.04 ± 0.03 |
| RS1-A | Amphibole | 58.00 | 1.65 ± 0.01 | 1.50 ± 0.06 | 6.6 ± 0.2 | 0.3 ± 0.1 | 0.057 | 0.2 | 0.2 | 1.50 ± 0.06 |
| RS3-A | Amphibole | 158.70 | 5.95 ± 0.05 | 1.27 ± 0.04 | 3.8 ± 0.1 | 1.6 ± 0.1 | 0.063 | 1.0 | 0.8 | 1.26 ± 0.04 |

^a Calculated using equations of Farley (see in Blard, 2021), the U, Th and Sm content measured in phenocrysts targets and bulk rock (supplementary data) and assuming a mean phenocryst radius of 250 ± 100 μm , which was evaluated under a binocular microscope.

^b Calculated using the Li content of pyroxene and major and trace composition of the bulk rock and assuming an eruption age obtained from the calculation of the radiogenic ^4He (Blard, 2021).

^c ^3He concentration ($^3\text{He}_n$) obtained from P_3^b .

^d ^3He concentration ($^3\text{He}_c$) obtained after subtracting the nucleogenic ^3He component ($^3\text{He}_n$)^c to the total measured ^3He component ($^3\text{He}_t$). The magmatic component was neglected.

5. Discussion

5.1. Erosion rate derived from sediment budget versus cosmogenic nuclide denudation rates in the main stream

Denudation rates derived from cosmogenic nuclides integrate both mechanical erosion and chemical weathering (e.g. Dunai, 2010), while the erosion rate derived from sediment budget integrates the mechanical erosion only. As the chemical weathering of rocks occurs mainly by water–rock interactions at the Earth's surface, the short travel time of the sediments in the Locumba basin, the young lithologies (mainly < 2 Ma), plus the semi-arid condition of this region (rainfall < 500 mm.yr $^{-1}$) are in favor of a negligible weathering. Moreover, The Chemical Index of Alteration (CIA) can be used to quantitatively evaluate the weathering (Nesbitt and Young, 1982). CIA is defined as $\text{Al}_2\text{O}_3 / (\text{Al}_2\text{O}_3 \times \text{CaO} \times \text{Na}_2\text{O} \times \text{K}_2\text{O}) \times 100$ to consider the elements that are easily leached from rocks. CIA values of about 50 indicate virtually no weathering, whereas the value of 100 indicates intense weathering with complete removal of alkali and alkaline earth elements. In our case, we obtained a CIA of ca. 59 using major element compositions of rocks of the Locumba basin provided by Rivera et al. (2020) and Mariño et al. (2021). These values indicate a negligible weathering. Therefore, erosion rate from the lake sediment budget and cosmogenic nuclide denudation rates should be comparable as they both integrate the mechanical erosion only.

As shown on Fig. 5, the denudation rates derived from the main stream (samples RP) from ^{10}Be -quartz (30 ± 2 mm.ka $^{-1}$) and from ^{10}Be -feldspar (33 ± 3 mm.ka $^{-1}$) are indistinguishable within uncertainties with the erosion rate based on sediment budget (30 ± 9 mm.ka $^{-1}$). Integration times (t_i) associated with cosmogenic nuclide denudation rates (ε) can be calculated by ($t_i = (\Lambda / \rho) / \varepsilon$) where Λ is the neutron attenuation length (160 g.cm $^{-2}$) and ρ the material density fixed at 2.7 g.cm $^{-3}$ here. This implies integration times of about 20 and 18 ka for the denudation rates from quartz and feldspar, respectively. Given that this time range is similar to the age of the Aricota dam emplacement (ca. 18 ka; Delgado et al., 2020), the sediment storage in the Aricota lake and those cosmogenic-nuclide derived denudation rates represent the same integration time.

As feldspar is the mineral mostly represented and homogeneously distributed over the Locumba catchment (Fig. 2B), the consistency between the erosion rate from sediment budget and the denudation rates from ^{10}Be -feldspar strongly suggests that a denudation rate of ca. 30 mm.ka $^{-1}$ is accurate for the Locumba basin over the last 20 ka. The consistency with the denudation rates derived from ^{10}Be -quartz (30 ± 2 mm.ka $^{-1}$) also shows that the Miocene ignimbrite (bearing quartz mostly) are eroding at almost the same rate than the Pliocene lava outcropping upstream.

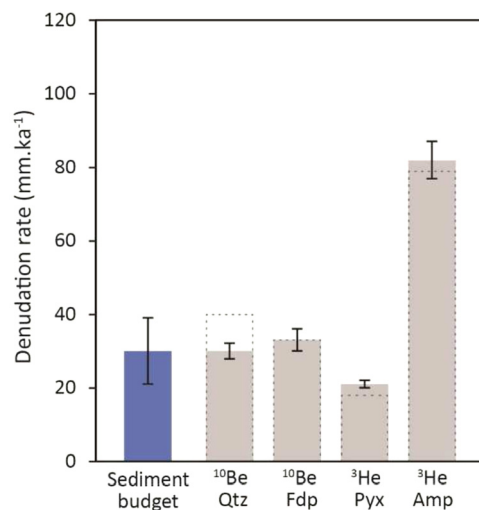


Fig. 5. Erosion rate derived from sediment budget (in blue) compared to denudation rates derived from cosmogenic nuclide measurements (in gray) from the different nuclide-mineral pairs in the main stream (samples “RP”) and including geological masks (Table 3). Dashed bars indicate corresponding denudation rates calculated without considering geological masks. Acronyms Qtz, Fdp, Pyx and Amph stand for Quartz, Feldspar, Pyroxene and Amphibole, respectively.

The denudation rates deduced from ^3He in pyroxene and amphibole provided more contrasted results. The denudation rate from ^3He -pyroxene are lower (21 ± 1 mm.ka $^{-1}$), although being also compatible within uncertainties with the previous ones (Fig. 5). Contrariwise, the denudation rate derived from ^3He -amphibole are significantly higher (82 ± 5 mm.ka $^{-1}$). Considering that the lava bearing the pyroxene and the amphibole also contains feldspar, the ^3He denudation rates are at odd with the denudation rate of ca. 30 mm.ka $^{-1}$ established from ^{10}Be -feldspar. While the ^3He -pyroxene denudation rate is in reasonable agreement with those deduced from ^{10}Be in quartz and feldspars, the ^3He -amphibole denudation rates hence seems to be overestimated. Several hypotheses can be explored to explain this discrepancy. i) This might be explained by differences between ^3He production rates in pyroxene and in amphibole. There are only few studies that documented ^3He production rate in amphibole (e.g. Amidon and Farley, 2012) and this mineral may have a highest Li-content and thus highest unrecognized nucleogenic contribution (Blard, 2021), especially when the mineral is hosted in U-rich bulk rock. ii) Another possible explanation can be that amphibole has a lowest ^3He retentivity than pyroxene but this should be further studied by acquiring specific additional experimental diffusion data. iii) Fi-



Fig. 6. Google Earth view of the lower Callazas basin where debris flows might supply quartz and feldspar with low ^{10}Be content (deeply buried) to the Callazas river.

nally, this ^3He high denudation signal could be biased by a peculiar unknown amphibole-rich watershed area that buffers the signal.

5.2. Variability of denudation rates derived from sub-catchments

Looking at ^{10}Be -quartz and ^{10}Be -feldspar results, the denudation rates obtained for the tributary rivers show some variability. The values from the Salado river ($\text{RS1-Q} = 26 \pm 2 \text{ mm.ka}^{-1}$ and $\text{RS1-F} = 51 \pm 5 \text{ mm.ka}^{-1}$, Table 3) are relatively close to the mean denudation rate of ca. 30 mm.ka^{-1} previously reported for the main stream. However, the denudation rates from the Callazas river are much higher, with values of 147 ± 18 and $131 \pm 13 \text{ mm.ka}^{-1}$ for RS3-Q and RS3-F , respectively. The mixing of cosmogenic nuclide concentrations at the scale of the basin is based on the hypothesis that individual mineral grains supplied at different rates from different source areas within the basin will be collected by the fluvial network, mixed in the sediment load through fluvial processes and carried towards the basin outlet. Therefore, if this mixing is satisfied, the cosmogenic nuclide concentration measured in an amalgam of alluvial grains will likely represent the spatially averaged denudation rate over the upstream catchment (Dunai, 2010). In that sense, downstream to a river junction theoretical denudation rate ($\varepsilon_{\text{theo}}$) should equal to the average of the denudations obtained in each tributary and weighted by their areas (e.g. Binnie et al., 2006) such as $\varepsilon_{\text{theo}} = (\varepsilon_1 \times A_1 + \varepsilon_2 \times A_2) / (A_1 + A_2)$, where the subscripts correspond to each tributary basin. Applying this to our case, it returns theoretical denudation rates for the main stream of 73 ± 8 and $112 \pm 11 \text{ mm.ka}^{-1}$ for $\text{RP-Q}_{\text{theo}}$ and $\text{RP-F}_{\text{theo}}$, respectively, that are not in agreement with the measured ones (Table 3). This suggests that denudation rates derived from ^{10}Be -quartz and ^{10}Be -feldspar on the Callazas river are affected by local processes and that ^{10}Be concentrations are anomalously low in those samples.

One possible explanation can be the presence of landslides and debris-flows that we identified in the downstream part of the Callazas basin (Delgado et al., 2020 and 2022). Those landslides involve material from the quartz- and feldspar-bearing Miocene ignimbrite (Fig. 2B and Fig. 6). Analysis of Google Earth images shows that those debris flows are connected to the Callazas river (Fig. 6), and that they may episodically supply quartz and feldspar with very low ^{10}Be concentration to the river. This interpretation can be also supported by the fact that such high denudation rate is not

recorded by the ^3He -pyroxene proxy ($\text{RS3-P} = 21 \pm 1 \text{ mm.ka}^{-1}$), that comes from other lithologies of the upper part of the basin, where no landslide is reported. Sediment supply from landslides and mass-wasting processes is often mentioned to discuss anomalously low cosmogenic nuclide concentrations in river sediment and inferred high denudation rates (e.g. Niemi et al., 2005). In our study case, we acknowledge that we do not know much about the timing and frequency of those debris-flows. However, the fact that this signal of high-denudation rate was not measured in the main stream below the river junction suggests that the landslides are either recent (few hundred's years) or very episodic. This conclusion is also supported by the very good agreement between the ^{10}Be -derived denudation rates and those determined by the sediment budget of the Aricota lake investigated over $\sim 20 \text{ ka}$. Another possible interpretation for the lower ^{10}Be concentrations of the Callazas catchment can be an anthropogenic effect, as mentioned by similar studies (e.g. Brardinoni et al., 2020 and references therein). Together with the development of the Candarave village (Fig. 1 and Fig. 6) during the last century, agriculture and new road openings were conducted in this area that may have accelerated physical erosion, providing shielded, low ^{10}Be -bearing material, to the fluvial network. For all these reasons, denudation rate derived from sample RS3 should be considered as a non-representative outlier.

5.3. Geomorphological implications

The good agreement between (1) the sediment budget established in the Aricota lake trap and (2) the denudation rates derived from different pairs of cosmogenic nuclide-mineral sampled in its tributary, validates a mean denudation rate value of ca. $20\text{--}30 \text{ mm.ka}^{-1}$ for the upper Locumba catchment, this value being integrated over the last 18 ka. Moreover, our results confirm that the ^{10}Be -quartz, ^{10}Be -feldspar and ^3He -pyroxene couples can accurately measure a catchment-mean denudation rate. Denudation rates of $20\text{--}30 \text{ mm.ka}^{-1}$ are of the same magnitude as those documented by previous works in this area, which measured mean catchment denudations between 10 and 50 mm.ka^{-1} , based on ^{10}Be -quartz in the southern Peru (Reber et al., 2017 and Starke et al., 2020). Reber et al. (2017) collected a stream-sediment sample in the same catchment as our study, at the mouth of the Locumba valley (sample PRCME-401, lat.-long. $17.90^\circ\text{--}70.95^\circ$, elevation $\sim 400 \text{ m a.s.l.}$), reporting a mean ^{10}Be -quartz denudation

rate of $12.5 \pm 3.2 \text{ mm.ka}^{-1}$ for the whole Locumba catchment. The difference between our result (^{10}Be -quartz $30 \pm 2 \text{ mm.ka}^{-1}$; Table 3) and the value of Reber et al. (2017) may result from the fact that this previous study did not account for the presence of the Aricota dam in the middle part of the catchment, hence ignoring the signal from upper part of the basin and the sediment flux produced by the volcanos located upstream. Furthermore, it may have induced errors in the estimation of the catchment mean production rate.

The respective roles of climate and tectonic on the geomorphological evolution of the Central Andes, have been thoroughly discussed by Carretier et al. (2018). It is interesting to note that our new denudation rates from the Locumba catchment are close to those measured in the arid Cordillera segments of northern Chile and southern Atacama, both from modern (e.g. Aguilar et al., 2014) and Miocene sediments (Madella et al., 2018). Our data are also comparable to erosion budget deduced from geomorphic markers that integrate denudation over several millions of years (Riquelme et al., 2008; Aguilar et al., 2011). This similarity of methods encompassing different time scales supports the hypothesis of a relative stability of erosion and related geomorphic processes in the arid central Andes, at least since the Plio-Pleistocene (Aguilar et al., 2014). Despite the existence of sporadic landslide (e.g. Niemi et al., 2005), such as the shallow debris flows of the upper Locumba basin, our results also suggest that the cosmogenic nuclides are robust over a large range of timescales (few ka to few Ma). However, this conclusion can be paradoxical given that our study site has itself been formed by a large deep-seated landslide. A recent inventory of paleo landslides established at the scale of Central Andes (Delgado et al., 2022), showed that very large mass movements (volume of 10^7 to 10^{10} m^3), such as the Aricota rockslide, are frequent along the canyons of the Western Cordillera. However, little is known about their timing, their frequency, and the mixing time between landslide material and other sediments in the valleys, requiring further research to better understand the role of large landslides in the landscape evolution (Carretier et al., 2018). In the future, the joined use of multiple nuclide-mineral pairs, as achieved here, has the potential to better understand such complex processes and denudation histories. This approach offers the possibility to track the variability of the sediment source lithology (e.g. Hidy et al., 2018) and to pursue current efforts to resolve complex burial-transport histories by comparing different radiogenic and stable cosmogenic nuclide isotopes in sediments (e.g. Wittmann and von Blanckenburg, 2016; Hippe et al., 2021).

6. Summary and conclusion

We compared denudation rates derived from multiple cosmogenic nuclide-mineral pairs with an estimation of fluvial sediment volume trapped behind the giant Aricota rockslide, that completely dammed the Locumba valley (Central Andes) about 18 ka ago. Reconstruction of the Locumba valley topography before the rockslide dam emplacement and estimation of the sediment infill yield a total sediment volume of $0.8 \pm 0.1 \text{ km}^3$, implying a mean erosion rate of $30 \pm 9 \text{ mm.ka}^{-1}$ when integrated over the upstream catchment area and an accumulation period of 18 ka. The fluvial sediments currently feeding the Aricota lake were sampled in the main stream and in its two upstream tributaries to derive cosmogenic nuclide denudation rates from ^{10}Be in both quartz and feldspar and ^3He in both amphibole pyroxene. Inferred denudation rates from the main stream were 30 ± 2 , 33 ± 2 , 21 ± 1 and $82 \pm 5 \text{ mm.ka}^{-1}$ for the ^{10}Be -quartz, the ^{10}Be -feldspar, the ^3He -amphibole and ^3He -pyroxene, respectively. The consistency between the denudation rates derived from ^{10}Be cosmogenic nuclide and the erosion rate derived from the Aricota sediment budget shows that the ^{10}Be can accurately estimate the sediment flux in this vol-

canic catchment. On the other hand, the discrepancies obtained for the denudation rates derived from ferromagnesian, especially from the ^3He -amphibole, as thought to be related to specific ^3He production-diffusion mechanisms. Denudation rates derived from the two tributaries return more contrasted results, showing either denudation rates fully compatible with those obtained from the main stream, or either significantly higher denudation rates that should be considered as probable outliers. Finally, our results provide the first successful use of ^{10}Be -feldspar to derive catchment-mean denudation rate which can be an alternative in catchments where volcanic lithologies do not contain quartz and offer a new nuclide-mineral pair to explore complex denudation histories.

CRedit authorship contribution statement

S.Z. and L.A. designed the project. S.Z., F.D., J.C., and the ASTER Team produced the ^{10}Be data. C.L. and P.H.B. produced the ^3He data. F.D. did the sediment volume analysis. S.Z., C.L., P.H.B., and J.C. contributed to the data interpretation, the paper writing and edition. All authors have approved the final version of the manuscript.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

Acknowledgements

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Appendix A. Supplementary material

Supplementary material related to this article can be found online at <https://doi.org/10.1016/j.epsl.2022.117869>. These data include the Google map of the most important areas described in this article.

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Earthquake surface ruptures on the altiplano and geomorphological evidence of normal faulting in the December 2016 (Mw 6.1) Parina earthquake, Peru

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ABSTRACT

The 2016 Mw 6.1 Parina earthquake ruptured a shallow-crustal normal fault within the high Andes of south Peru. We use high-resolution DEMs and field mapping of the surface ruptures generated by the earthquake, in combination with **co-seismic** and **post-seismic** InSAR measurements, to investigate how different features of the geomorphology at Parina are generated by the earthquake cycle on the Parina Fault. We systematically mapped 12 km of NW-SE trending surface ruptures with up to ~27 cm vertical displacement and ~25 cm tensional opening along strike, separated by a gap with no observable surface ruptures. Co- and post-seismic InSAR measurements require slip below this gap in surface ruptures, implying that surface offsets observed in paleoseismic trenches may not necessarily be representative of slip at seismogenic depths, and will typically yield an underestimate of paleo-earthquake magnitudes. The surface ruptures developed along 10–20 m high cumulative scarps cutting through late Quaternary fluvio-glacial deposits and bedrock. The 2016 Parina earthquake did not rupture the full length of the late Quaternary scarps, implying that the Parina Fault does not slip in characteristic, repeat earthquakes. At Parina, and across most of the Peruvian Altiplano, normal faults are most-easily identified from recent scarps cutting late Quaternary moraine crests. In regions where there are no **recently-deposited** moraines, faults are difficult to identify and lack time constraints to quantify rates of fault slip. For this reason, current fault maps may underestimate the seismic hazard in the Altiplano.

1. Introduction

On the December 1, 2016 a rare, shallow M_w 6.1 earthquake was recorded in the Altiplano of southern Peru near the village of Parina (Fig. 1). The epicenter was located ~50 km west of Lampa village in a remote region of the plateau, though three fatalities and damage to local infrastructure were recorded (Llontop and Marrou, 2016). Body-waveform seismology and radar geodetic measurements have revealed that the earthquake ruptured a ~15 km-long, NW-SE striking normal fault, which trends sub-parallel to a well-documented system of normal faults cutting across the Altiplano known as the Cusco-Lagunillas Fault System (CLFS) (Fig. 1a; Wimpenny et al., 2018; Xu et al., 2019; Sébrier et al., 1985a,b; Benavente et al., 2013). Although an active fault map for the Peruvian Andes has been released by INGEMMET (Macharé et al., 2009; Benavente et al., 2013; 2017; INGEMMET, 2017), the Parina earthquake ruptured a previously-unmapped structure. This event provides a unique

opportunity to assess how key features of an earthquake, such as the fault location and the slip distribution, are related to the geomorphology and surface ruptures in the epicentral region, and to examine how earthquakes are preserved in the Altiplano landscape.

Whether fault-related geomorphology, such as fault scarps, accurately reflect the distribution of slip in past earthquakes is a particularly pertinent question for seismic hazard assessment in slowly-deforming regions like the Peruvian Altiplano. Seismicity in southern Peru is infrequent enough that the modern instrumental catalogue is a poor representation of the spatial distribution of active faults and the possible maximum magnitude of earthquakes on these faults, therefore paleoseismological methods must be used to complement the modern and historical catalogues (e.g. Schwartz, 1988). However, there are a number of limitations to using paleoseismological methods to infer past earthquake slip distributions and magnitudes (e.g. Ainscoe et al., 2018). For example, the fault

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scarps generated by the two moderate-magnitude earthquakes to have occurred in the Peruvian Andes prior to the Parina event – the 1946 Ms 6.4 Ancash earthquake and the 1969 Mw 6.9 Huaytapallana (Pariahuanca) earthquake – both produced highly-segmented surface rupture traces with cumulative lengths far shorter than might be expected for earthquakes of their size (Wells and Coppersmith, 1994). The Ancash earthquake produced two 5 km-long sections of normal-faulting surface ruptures along the crest of Cerro Llamacorral, separated by a 12 km gap coincident with intervening river valleys (Bellier et al., 1991). Whilst the surface ruptures along the Huaytapallana Fault consisted of distinct segments 10 km-long and 6 km-long, separated by a 4 km-wide gap (Philip and Megard, 1977). From these rupture observations alone, it would not be possible to tell whether the gaps in the surface rupture traces reflected real along-strike variations in fault slip (e. g. due to a rupture barrier), erosional features, or a change in the material properties of the near-surface material. One way to assess

this particular limitation is by studying how slip in modern earthquakes relates to their surface ruptures and cumulative fault scarps.

In this study, we use new field measurements of the Parina earthquake surface ruptures, coupled with high-resolution DEMs of the cumulative fault scarps formed using drone photogrammetry, to examine the geomorphological evidence for faulting at Parina. We compare our scarp observations with previously-published measurements of co- and post-seismic ground deformation in the 2016 Parina earthquake from interferometric synthetic aperture radar (InSAR), to investigate how fault slip at depth relates to scarp formation and fault-related geomorphology at the surface. The accuracy and relative completeness of the surface rupture dataset, including field measurement and high-resolution DEM, also provides a unique opportunity to enrich the worldwide dataset of surface ruptures (SURE) (Baize et al., 2020).

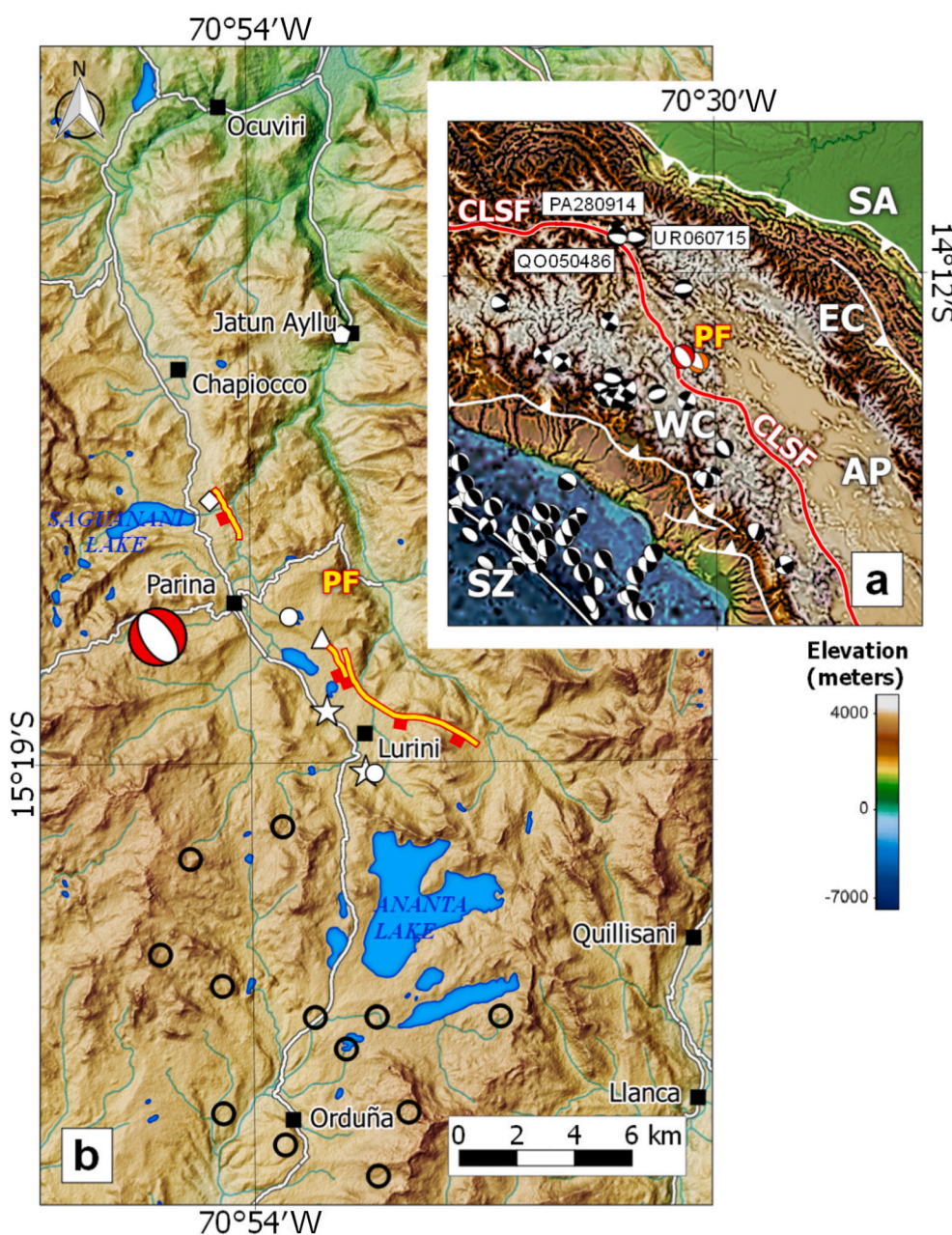


Fig. 1. a) Overview map of the Parina Fault scarp (in red). Inset (upper right) shows plate boundary setting, where (SA) Sub-andean zone, (EC) Eastern Cordillera, (AP) Altiplano, (WC) Western Cordillera, (SZ) Trench, (CLFS) for Cusco-Lagunillas Fault System and (PF) Parina Fault. The focal mechanisms seismic events shallower than 40 km hypocenter depth, with the red focal mechanism corresponding to the Parina earthquake, and the orange focal mechanism being an aftershock the next day. Note the events of Qoricocha (QO050486), Paruro (280,914) and Urcos (060,715) next to Cusco-Lagunillas Fault System (CLFS). All mechanisms are taken from the GCMT catalogue of Ekström et al. (2012) b) Close up view of the Parina Fault. White markers show the location of coseismic rock falls (pentagon), landslides (rhombus), soil liquefaction (circle), jumping stones (triangle) and crack openings (five-pointed star). Earthquake epicenters and aftershocks of the 2016 earthquake are shown as open circles. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

2. Geological and seismotectonic setting

The Parina earthquake occurred within the northern Altiplano, a 350-450 km-wide plateau that extends ~1800 km along the backbone of the Andes, from southern Peru to northern Argentina. The Peruvian Altiplano is a low-relief basin at an average elevation of ~4500 m filled with Cenozoic sedimentary and volcanoclastic rocks that have been faulted and folded throughout the Miocene. Internal drainage and low topographic gradients in this region have precluded any deep fluvial dissection of the landscape, though periodic glaciation over the last ~100 ka has formed U-shaped valleys, moraines and drift sheets that dominate the surface morphology.

One of the most prominent structural features of the Peruvian Altiplano is the Cusco-Lagunillas Fault System (CLFS) (Ellison et al., 1989; Jaillard and Santander, 1992; Carlotto, 1998). The CLFS consists of a series of ~10–20 km-long, NW-SE trending normal faults (Fig. 1a) recognizable from their narrow hangingwall basins bound by uplifted and incised footwalls, as well as through Holocene fault scarps that often cut the Late Glacial Maximum moraines (Sébrier et al., 1985b; Mercier et al., 1992; Benavente et al., 2013a; Wimpenny

et al., 2020). Modern seismicity along the CLFS is sparse. Previous seismotectonic studies indicated that the northern section of the CLFS near Cusco had undergone extension in a Mb 5.3 normal-faulting earthquake that generated minor surface ruptures in 1986 (Cabrera and Sébrier, 1998) (see focal mechanism QO050486 in Fig. 1a). The only other moderate-magnitude (i.e. $M_w > 5$) earthquakes along the CLFS in the instrumental catalogue did not generate observable surface ruptures (see focal mechanism PA280914 and UR060715 in Fig. 1a). There have also been a number of historical reports of significant earthquakes along the CLFS, with Cusco being severely damaged in 1650 and 1950, as well as a cluster of earthquakes between 1939 and 1943 that damaged settlements further south-east along the Vilcanota river valley section of the CLFS (Erickson et al., 1954; Silgado, 1978). The Parina earthquake is the first known $M_w > 6$ earthquake to rupture the CLFS in the modern instrumental era.

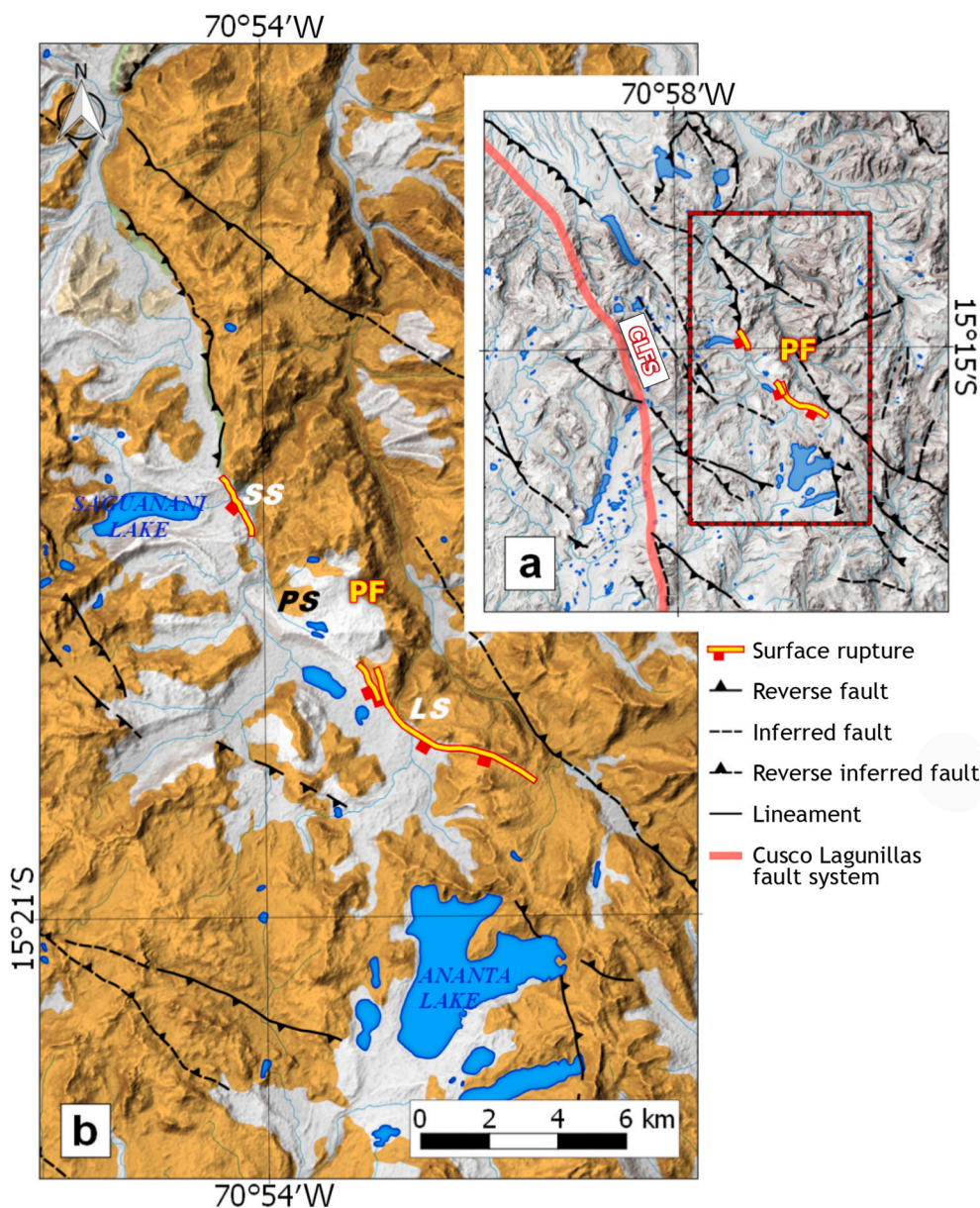


Fig. 2. a) Structural map in the Parina epicentral region. Inset (upper right), shows the Parina fault location respect to Cusco-Lagunillas Fault System (CLFS). b) Geology setting map (modified from INGEMMET, 2017). The yellow color represents Cenozoic volcanic rocks, while the gray color represents Quaternary deposits. Reverse faults are toothed black lines and the location of the surface rupture of 2016 event is shown by red and yellow line. Also shown are the segments of Parina Fault, Saguanani segment (SS), Parina segment (PS) and Lurini segment (LS). (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

3. Methods

3.1. Fieldwork

Three days after the earthquake in Parina, we organized a **post-seismic survey** of the epicentral area. On site, we mapped the surface ruptures generated by the earthquake, measured their height and tensional opening, collected an inventory of coseismic shaking effects along-strike (Fig. 3) and collected low-altitude drone imagery to form a high-resolution Digital Elevation Model (DEM), covering a surface area of $\sim 36 \text{ km}^2$ with detailed field inspection. The field evidence of earthquake-related shaking includes tensional cracks, liquefaction, and jumping stones. No rainfall occurred within the period between the earthquake and our first field study, thus both climate and limited anthropogenic activity in the area led to excellent preservation of the earthquake surface ruptures.

3.2. DEM construction and resolution

To examine the link between the surface ruptures and the cumulative fault scarps on the Parina Fault, we constructed a high-resolution DEM along the surface-rupture trace using the structure-from-motion technique with photographs collected from an eBee senseFly drone. The photographs were processed with the photogrammetry software Agisoft Photoscan (Agisoft, 2017). Ground control points were measured using differential GPS and used to guide the image matching and georeferencing. The resulting DEM has a 20 cm horizontal resolution and a $\sim 1 \text{ cm}$ vertical resolution between adjacent points (Westoby et al., 2012), and is complemented with orthomosaic color imagery at 4 cm/pixel resolution along the whole length of the surface ruptures (see Fig. 3b and c).

4. Observations

4.1. Surface ruptures and environment effects of the 2016 Parina earthquake

The surface ruptures generated by the Parina earthquake consisted of two NW-SE trending segments separated by a gap of 4 km, which we call the **Parina Gap** (Fig. 3a). The northern segment of surface ruptures (the Saguanani Segment, SS) is $\sim 2 \text{ km}$ long, whilst the southern segment (the Lurini Segment, LS) is $\sim 6 \text{ km}$ long, with both being defined by a semi-continuous trace of ruptures offsetting the surface sediment and bedrock.

4.1.1. Saguanani and Lurini segments

The Saguanani Segment, located at the northern end of the Parina Fault, displayed average vertical offsets across the surface ruptures of 3 cm, with maximum vertical offsets up to 8 cm (Figs. 4c and 5). The surface ruptures formed a series of sub-parallel, overlapping **strands that are best preserved** in sag ponds formed in the interfluvial crests between E-W trending moraine crests. The surface ruptures terminate at their southern end where they intersect a \sim NW-SE trending stream, and their northern termination occurs at the northern-most limit of lateral moraines around Lake Saguanani.

The Lurini Segment preserved far larger vertical and tensional offsets across the ruptures of up to 27 cm (Fig. 4a and b). Vertical and horizontal displacements across the ruptures decrease from a maximum in the middle of the Lurini Segment to a minimum at the tips of the segment with a slip-length ratio of 5×10^{-5} , matching the classic triangular shape expected for active normal faults (Cowie and Scholz, 1992) (see Fig. 5a and b). The northern $\sim 750 \text{ m}$ of the Lurini Segment consists of overlapping, sub-parallel strands of ruptures, whilst towards the south-east the remaining $\sim 5 \text{ km}$ of ruptures follow a single, curvilinear trace. The northern termination of the ruptures in the Lurini Segment occurs in a region coincident with sag small ponds and evidence for liquefaction, whilst the southern termination of the surface ruptures occurs where the fault trace crosses a stream.

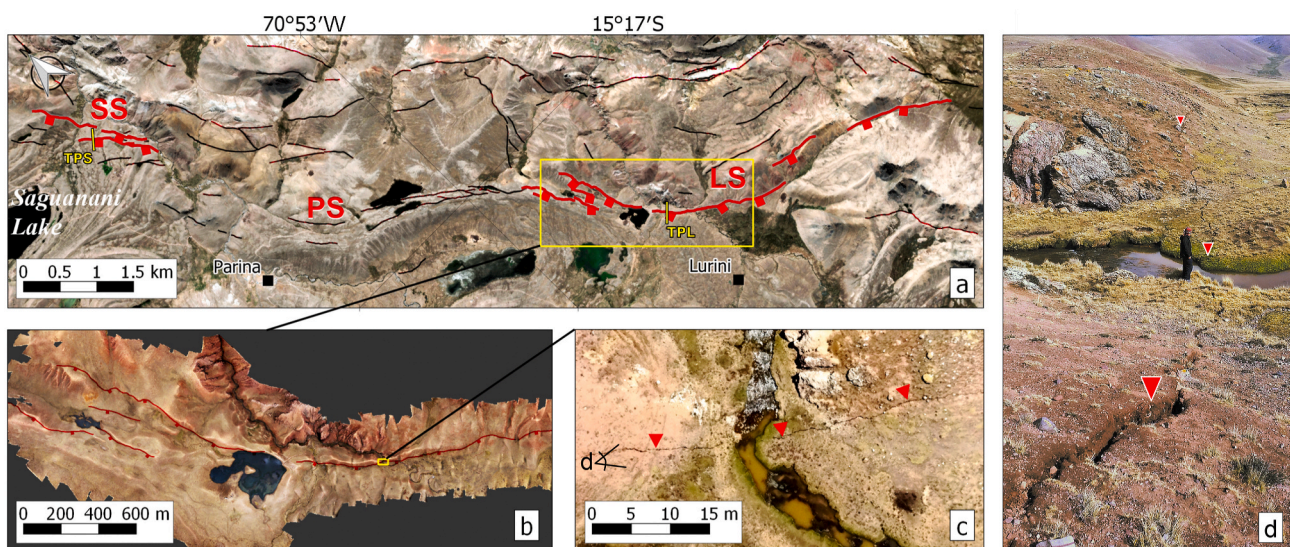


Fig. 3. a) Optical satellite imagery (from Google, DigitalGlobe) showing in red lines the Parina fault segments: Saguanani segment (SS), Parina segment (PS) and Lurini segment (LS). Black lines are Holocene tectonics scarps mapped during field work. Note that in the Parina segment there is no surface rupture trace. b) Red relief image map (RRIM) derived from the DEM (Chiba et al., 2007, 2008), built with photogrammetric surveyed data along the surface rupture (this study). Red lines are highlighting the surface rupture surveyed by foot along the fault trace. The location of the high-resolution DEM is highlighted by the yellow box in (a). c) Aerial photograph from the flying Ebee (4 cm in resolution). The footwall (top) and hanging wall (bottom) are limited by the scarp indicated by red triangles, note the scarp is cut by a stream, its flow direction is from south to north. The location of this drone image is outlined as a yellow box on (b). d) Surface offset associated to Parina earthquake; picture taken from western stream margin looking south-east along the scarp. Location is displayed in "d" letter in (c). (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)



Fig. 4. Field photographs of coseismic surface ruptures and associated shaking effects. a) ~10 cm surface rupture, located in Lurini segment. b) ~27 cm surface rupture, located in Lurini segment. c) ~20 cm crack opening, located in Lurini segment. d) Sand boils west of the lake in Parina segment. e) Jumping stones, which are co-located with the sand boils, in Parina segment. f) Rockfall, which dammed the Jatun Ayllu River, some 12 km north of the epicenter. Note that near to surface rupture there is no more rock fall, probably due to the limited relief. See the yellow circle for the scale. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

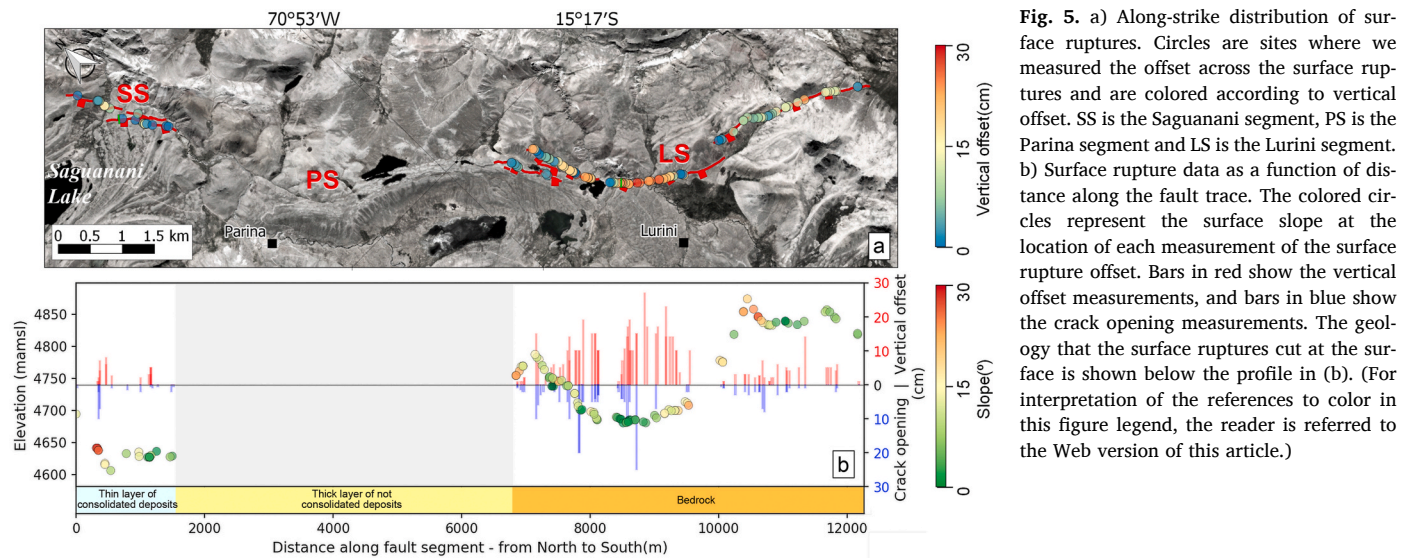


Fig. 5. a) Along-strike distribution of surface ruptures. Circles are sites where we measured the offset across the surface ruptures and are colored according to vertical offset. SS is the Saguanani segment, PS is the Parina segment and LS is the Lurini segment. b) Surface rupture data as a function of distance along the fault trace. The colored circles represent the surface slope at the location of each measurement of the surface rupture offset. Bars in red show the vertical offset measurements, and bars in blue show the crack opening measurements. The geology that the surface ruptures cut at the surface is shown below the profile in (b). (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

Along the Saguanani and Luruni Segments, the landscape has a low relief, and we did not observe any superficial mass movements with uphill extensional scars and downhill compressional bulges. A slope map generated from the high-resolution DEM shows that the slopes around the surface ruptures are below 15° on average, and that at Luruni, where vertical displacement is greatest, the topographic slope is at its lowest $<10^\circ$ (Fig. 5b). As slopes in granular material are generally stable at angles of repose $<30^\circ$, and the observation that regions with the highest slope angle have the smallest offsets across the surface ruptures, we believe that the first-order variations in displacement across the surface ruptures reflect variations in slip on the shallow portion of the Parina Fault, and not surface slope instability.

4.1.2. Parina Gap

Between the Saguanani and Luruni Segments there is a distinct gap in the mapped rupture trace. Although this gap does not show any evidence of surface rupture, we mapped several features that are commonly associated with near-field ground shaking within this region, such as sand boils (Fig. 4d and e) and jumping stones (Fig. 4e).

The sand boils are found within the hanging wall of the Parina Fault in areas of dry lake beds (Fig. 4d), are ~ 30 cm in diameter and are formed of medium-to-fine grained brown sands. In other settings, sand boils typically form through the ejection of fluidized sand through the shallow clay-rich sediments as a result of the shaking generated during an earthquake. This behavior of the near-surface sediment can last for a significant time after the seismic shaking, as the fine-grained sediments relax into a stable packing configuration and continue to expel pore waters (see Rodríguez-Pascua et al., 2015). The presence of sand boils within the Parina Gap is indicative of seismically-induced liquefaction around the Parina Fault in this area.

Jumping stones are volcanic boulders of ~ 20 – 30 cm diameter that are displaced laterally from their original resting place with no evidence of rolling along the sediment surface (Fig. 4e), indicating they have been lifted vertically and translated relative to the ground surface whilst in the air (e.g. King et al., 2018). We observe the jumping stones within the uplifted footwall of the Parina Gap and find they are consistently translated ~ 20 – 30 cm towards the south-east, which is roughly parallel to the fault trace inferred from the Saguanani and Luruni surface ruptures. For the stones to leave the ground surface means that the vertical ground acceleration exceeded 1 g during the earthquake. In addition, there must have been some horizontal component to the ground velocity either during the instant the stones left the ground surface, or whilst the stones were in the air.

4.1.3. Landsliding and rockfalls

The area near Parina is characterised by gentle relief. Nonetheless, we observed gravitational processes such as rock falls and small landslides in the epicentral region, in particular the Jatun Ayllu ravine (Fig. 1). This rockfall was located 13 km from the epicentral and covered a total area of ~ 0.60 km² (Fig. 4f). Rock falls were constituted of individual boulders or disrupted m-scale boulders (up to 10 m high) that descended slopes by rolling, jumping or free fall. This type of landslide was less common in comparison to shallow, disrupted landslides.

4.2. Late quaternary fault scarps on the Parina Fault

The surface ruptures formed in the 2016 Parina earthquake consistently follow ~ 5 to 20 m-high, pre-existing scarps cutting bedrock, alluvium and glacial deposits along the base of a ~ 150 m-high escarpment that marks the footwall of the Parina Fault. If these metre-high scarps are formed by repeated slip on the Parina Fault, the scarp heights correspond to a minimum vertical tectonic offset since the last period of glacial resurfacing and moraine formation at Parina. Exposure and radiocarbon dating of moraines in the nearby Cordillera Vilcanota suggest the last major episode of moraine deposition occurred during the Last Glacial Maximum ~ 10 – 45 ka (Clapperton, 1983), roughly placing the moraines and scarps as late Quaternary in age.

We used the high-resolution DEM to map the late Quaternary fault scarps and find that their along-strike distribution is similar to the surface ruptures generated by the 2016 Parina earthquake, but with some subtle differences (Fig. 7a,7 b). At Saguanani, the late Quaternary scarps form a series of sub-parallel strands that have offset the crests of nested lateral moraines and are directly coincident with the surface ruptures. We did not identify any late Quaternary scarps preserved in the Parina Gap – the same region there were no surface ruptures. In the Luruni Segment, late Quaternary fault scarps do outcrop along much of the surface rupture trace, but extend ~ 1 km further north-west than the 2016 surface ruptures, and do not occur along the ~ 1.5 km of the south-eastern end of the rupture trace.

We also extracted a series of topographic profiles across the late Quaternary fault scarps from our high-resolution DEM, in order to compare the along-strike scarp height distribution to the surface rupture heights. We calculate the scarp heights by using least-squares regression to fit lines to points above and below the scarp, and calculated the vertical separation of these lines. In many

places the scarp height variations may not reflect variations in fault throw, as erosional scouring within the hanging wall by axially-draining streams and deposition within small sag ponds may mask fault throw variations. We therefore only estimated scarp heights on selected surfaces that could be reliably correlated across the fault, such as moraine crests and abandoned fan surfaces (Fig. 6). As a result of this selective sampling, the along-strike distribution of late Quaternary scarp height measurements is far sparser than the surface rupture height distribution (compare Fig. 7d and e).

In the Saguanani Segment, we summed the vertical offsets across the sub-parallel fault scarps cutting late Quaternary moraine crests to estimate the cumulative vertical offset is between 5 and 15 m at different points along-strike. In the Luruni Segment

there are fewer places to make reliable scarp measurements, but the scarps are between 5 and 10 m-high. In contrast with the along-strike distribution of surface rupture heights in the 2016 Parina earthquake, the late Quaternary scarp heights do not increase towards the center of the Luruni Segment (Fig. 7d and e). Areas where the surface ruptures had the highest vertical offset and tensional opening do not necessarily correspond to where the Quaternary fault scarps were highest.

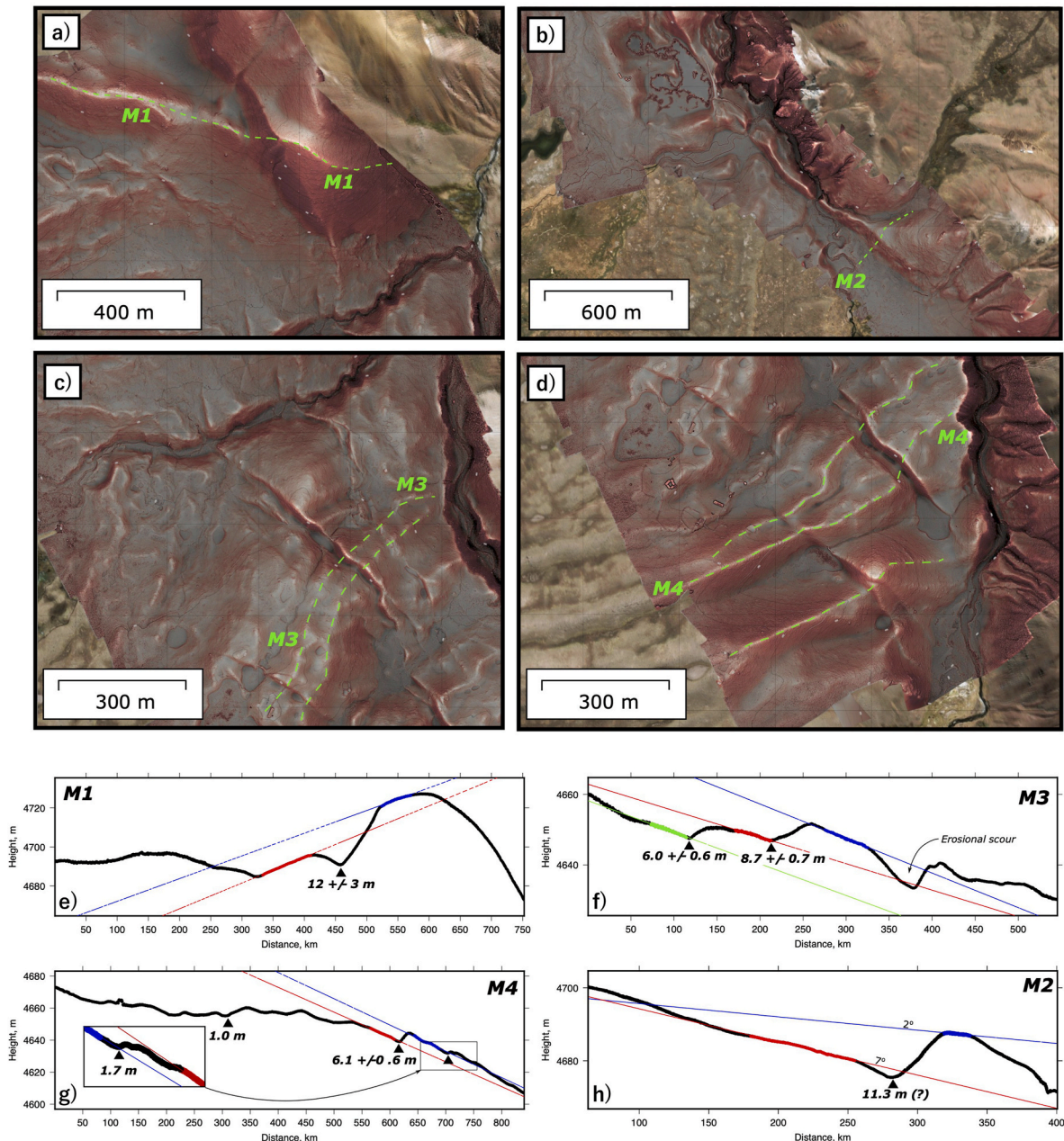


Fig. 6. Topographic profiles across the late Quaternary fault scarps extracted from high-resolution DEM. (a–d) Relief maps of the Parina late Quaternary scarps in the Saguanani (a,c,d) and Luruni (b) segments. Dashed green lines indicate profiles along surfaces or moraine crests that have been offset by the fault. Example topographic profiles are shown below. On the profiles, lines have been fit in a least-squares sense to points in the hanging wall (red) and footwall (blue), and the scarp height is measured as the vertical offset between these lines at the foot of the scarp. On low-dip angle surfaces ($<10^\circ$), the scarp height is similar to the fault throw to within $\pm 15\%$. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

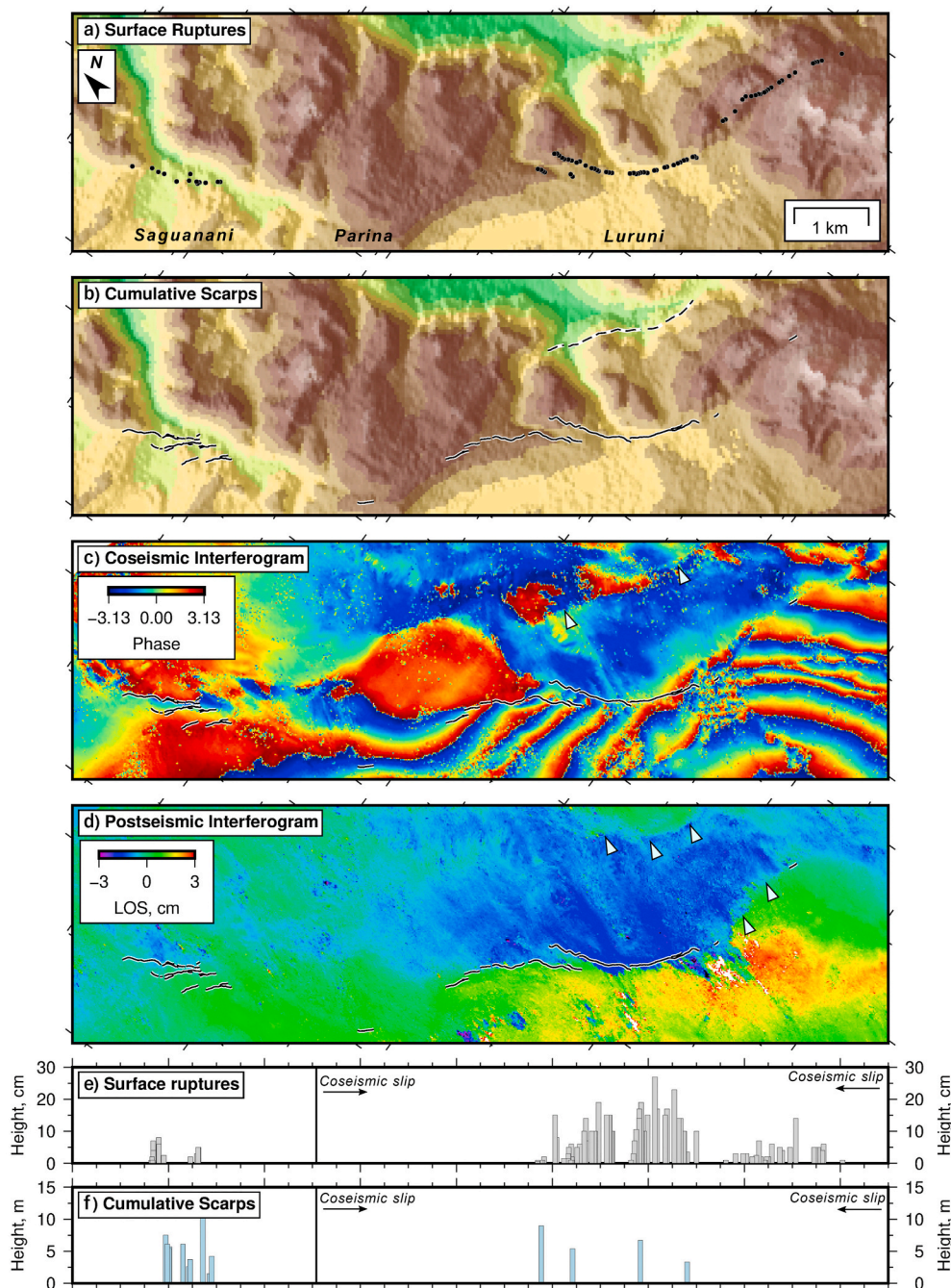


Fig. 7. Comparison of the topography with the surface ruptures, late Quaternary scarps, coseismic and **post-seismic** surface displacements. (a) SRTM 30 m topography with the mapped surface ruptures shown as black dots. (b) The same topography with mapped late Quaternary scarps shown as black lines. (c) Wrapped descending-track coseismic interferogram. (d) Unwrapped descending-track **post-seismic** interferogram between December 20, 2016 and June 30, 2017. (e) Along-strike distribution of coseismic surface rupture heights. (f) Along-strike distribution of cumulative scarp heights measured from offset moraine crests and fan surfaces using the high-resolution DEM.

5. Discussion

5.1. Surface ruptures, late quaternary scarps and slip on the Parina Fault

In this section we present a comparison between the surface ruptures and late Quaternary scarp heights mapped in this study, and the co- and post-seismic surface deformation recorded by InSAR from [Wimpenny et al. \(2018\)](#) to study how co- and post-seismic fault slip contribute to surface rupture formation and fault scarp growth.

The coseismic interferograms captured a relatively smooth pattern of surface displacement in the earthquake with 5–6 concentric fringes in the interferometric wrapped phase to the southwest of the mapped surface ruptures corresponding to ~15–20 cm of line-of-sight motion. Patches of low coherence in the interferogram visible as speckle within the fault hangingwall coincide with a marshy area that may have

undergone significant liquefaction ([Fig. 7d](#)). Interferogram fringes are truncated in the location of the surface ruptures on the Luruni Segment, but not on the Saguanani Segment, indicating that more slip reached the shallow fault zone at Luruni than Saguanani. In addition, the peak line-of-sight displacement at the center of the fringe pattern directly correlates with the location of the highest surface ruptures ([Fig. 7c,e](#)).

[Wimpenny et al. \(2018\)](#) and [Xu et al. \(2019\)](#) inverted the coseismic InSAR measurements for the geometry of the Parina Fault and the distribution of fault slip in the earthquake. Both studies found that the majority of fault slip (~50–70 cm) occurred between 3 and 10 km depth beneath the central Luruni Segment, whilst the InSAR data do not require any coseismic fault slip beneath the Saguanani Segment. Neither study required there to be slip within the top 2 km of the fault zone at any point along-strike, leading to the inference of a ‘shallow slip deficit’ (e.g. [Fialko et al., 2005](#); [Xu et al., 2019](#)). However, the fault dip

determined from the kinematic slip inversions (40°) and the maximum surface rupture height (27 cm) requires there was at least 35 cm of slip in parts of the shallow fault zone, highlighting the widely-recognized limitation of kinematic slip inversions using an elastic half-space Green's Function to accurately capture small-scale variations in near-surface fault slip.

Post-seismic slip may also contribute to the formation of surface ruptures and scarps. Post-seismic surface displacements measured from InSAR (Fig. 7d) indicate that the Luruni segment experienced ~7 cm of shallow afterslip between 0 and 3 km depth in the year following the earthquake coincident with the surface rupture trace (Wimpenny et al., 2018). Beneath the central part of the Parina Gap, ~2–4 cm of afterslip remained buried between ~2 and 5 km and did not reach the surface (Xu et al., 2019). There is little evidence for post-seismic deformation in the Saguanani Segment that could be related to shallow afterslip (Fig. 7d).

The comparison between the InSAR measurements, surface ruptures and fault scarps highlights a number of key features: (1) co- and post-seismic fault slip did occur at depth beneath the gap in the surface rupture trace, but this slip did not propagate to the surface in the 2016 earthquake, or in any scarp-forming earthquakes in the late Quaternary, (2) despite there being no resolvable co- or post-seismic slip beneath the surface ruptures of the Saguanani segment, late Quaternary scarps cutting lateral moraine crests in this area indicate there has been significant slip on this section of the Parina Fault in the late Quaternary, and (3) shallow post-seismic deformation can contribute a significant fraction (~20%) of fault scarp and surface rupture heights.

5.2. Preservation of surface ruptures, late quaternary scarps and surface geology

The kinematics and distribution of the surface ruptures and fault scarps at Saguanani and Luruni are independent of the topography, but vary along-strike in a manner that is not related to the first-order variation of slip at depth derived from the InSAR measurements. The prime example of this behavior is beneath the Parina Gap. There are subtle differences between the surface geology and conditions in the Saguanani-Luruni segments and the Parina Gap that may account for the along-strike variations in surface rupture and fault scarp preservation. At Saguanani and Luruni the surface geology consists of a thin veneer of unconsolidated sediments, including Last Glacial Maximum moraines and Pleistocene fluvio-glacial deposits that cover the bedrock, which can be seen exposed where streams cut through the fault footwall (Fig. 2b). In contrast, along the central Parina Gap, the extrapolated fault trace would cut through depressions filled with lacustrine and fluvio-glacial sediments dotted with small water bodies, suggesting the ground may be saturated in the near surface. We found evidence for this saturation when we attempted to trench a section of the fault near the north-western tip of the Luruni segment.

It seems likely that the 2016 Parina earthquake and previous late Quaternary earthquakes did not propagate to the surface in the Parina segment, either because of the quasi-plastic mechanical properties of the unconsolidated fluvio-glacial deposits, or because much of the near-surface material in the Parina segment liquefied during the earthquake, both of which prevent discrete ruptures forming. The observation that surface ruptures are absent in regions where liquefaction features are present suggests the latter of these two suggestions may be the dominant control at Parina.

The control of surface geological conditions on coseismic surface rupture patterns is well-documented. Khajavi et al. (2014) proposed that the thickness of the cover deposits or unconsolidated sediment is an important control on surface rupture on the Hope Fault, New Zealand. During the 2016 Amatrice-Norcia earthquake sequence, Pucci et al. (2017) and Civico et al. (2018) observed this same effect along the Laga Mts Fault and the Monte Vettore faults. Similarly, Moss et al. (2013) and Stanton (2013) concluded that the likelihood of rupture propagation to the surface is controlled by parameters such as the thickness and

stiffness of the surface cover.

Just as the surface ruptures are not formed everywhere up-dip of the main coseismic rupture area at depth, the late Quaternary scarps are also discontinuous along-strike and are only preserved in certain settings. At Parina, the best-preserved fault scarps are in the Saguanani Segment, where the fault has cut late Quaternary lateral moraines. This is a pattern recognized across much of south Peru and offers a general rule for mapping faults in the region: recently-active faults are best preserved in regions affected by recent glaciation. As the active normal faults have accommodated little finite extension, their footwalls are not always elevated relative to their hangingwall basin, and therefore the standard morphology associated with normal faults in faster-deforming parts of the world (e.g. Greece, western Turkey; Jackson et al., 1982; Hubert-Ferrari et al., 2002) is difficult to identify in the Altiplano of southern Peru. In addition, a previous phase of shortening in the late Miocene (Perez and Horton, 2014) has left remnant topography associated with upright anticlinal folding and footwall ridges that is often larger in amplitude than that formed by normal faulting meaning faults can be nearly impossible to identify from the regional topography alone. As a result, if most faults are only being preserved where they cut recently-deposited moraines, there is significant difficulty in understanding the along-strike continuity of the normal faults in the Peruvian Altiplano from geomorphology alone. Similarly, there is probably a significant sampling bias in fault mapping in the region related to where late Quaternary moraines are well preserved in the Altiplano.

5.3. The Parina earthquake surface ruptures and scaling relationships

In seismic hazard analyses, the maximum magnitude of a potential earthquake on a mapped fault is determined by comparing field observations of fault lengths and slip during individual events to empirical scaling relationships between M_w and length or slip (e.g. Wells and Coppersmith, 1994, hereafter W&C94). Such relationships are obtained after statistical analysis of a large number of previous events. However, there is a significant spread in the data used to construct these empirical relationships, and along-strike variations in near-surface geological conditions can significantly affect the size and outcrop of surface ruptures (Champenois et al., 2017; Ritz et al., 2020). Here, we compare our observations from the Parina earthquake to the W&C94 predictions.

The different values of surface rupture length (SRL), average displacement (AD) and maximum displacement (MD) for individual and combined segments are reported in Table 1. Note that to calculate the fault length including the Parina Gap, we argue that the fault remained buried at shallow depth because of the unfavorable surface geology, as suggested by the InSAR-derived coseismic source model. The final length is 12 km and we consider this to be representative of the surface rupture length in the scaling relationships.

Table 1

Data referring to the average displacement (AD), maximum displacement (MD) and the length of the surface rupture (SRL), in order to estimate the magnitude with Wells and Coppersmith (1994) approach for Saguanani (SS) and Luruni (LS) segments independently, totally with both segments and plus with Parina segment (PS).

| Segments | AD (cm) | MD (cm) | SRL (km) | M_w from AD (Normal Fault, WC94) | M_w from MD (Normal Fault, WC94) | M_w from SRL (Normal Fault, WC94) |
|--------------------|---------|---------|----------|------------------------------------|------------------------------------|-------------------------------------|
| | | | | (±0.33) | (±0.34) | (±0.34) |
| LS | 6.8 | 27 | 6 | 6.0 | 6.2 | 5.9 |
| Total SS + LS | 6 | 27 | 7.7 | 6.0 | 6.2 | 6.0 |
| Total SS + PS + LS | 5.3 | 27 | 12 | 6.0 | 6.2 | 6.3 |

This simple analysis shows that the *Wells and Coppersmith (1994)* empirical scaling between fault slip, length and the resulting earthquake magnitude is accurate when using maximum displacement, giving Mw values close to actual instrumental measurement; total surface length at the surface and shallow subsurface fault (SS + PS + LS) scenario also gives a reasonable value. Using AD provides systematically lower prediction of the earthquake magnitude (Mw 6). Our conclusion is that, for moderate magnitude earthquakes such as that at Parina, the MD or SRL parameters of W&C94 appear to provide a reasonably accurate way of estimating the possible magnitude of earthquakes along faults.

5.4. Lessons for seismic hazard assessment

Two key results have come out of this study that provide new lessons on seismic hazard assessment from paleoearthquake data in the Peruvian Altiplano.

Firstly, there may be a significant preservation bias associated with Holocene normal faults in the Altiplano. Pleistocene glaciation deposited lateral moraines and drift sheets across much of the Altiplano that provide ideal marker surfaces to study faulting, and most of the active faults mapped to date are identified based on offset glacial deposits (e.g. *Benavente et al., 2013; Wimpenny et al., 2020*). In places where there are no glacial deposits, faults are far more difficult to identify as they have accommodated little finite slip, and fault maps may underestimate the number of potentially seismogenic faults in these areas.

Second, any along-strike variability and segmentation of paleoseismic surface ruptures may not accurately reflect along-strike variations in the earthquake rupture at depth. The surface scarps generated by the Parina earthquake were clearly split into two sections, separated by a gap of ~4 km, despite the slip at depth extending beneath the surface rupture gap. Therefore estimates of the size of past earthquakes based on the along-strike length of their rupture trace must take into account possible gaps caused by near-surface geology.

Surface rupture on shallow, continental faults poses a significant threat for transport infrastructure, villages and critical facilities such as gas pipelines (*Baize et al., 2020*). In Peru, this surface rupture hazard is rarely taken into account in hazard analyses. Probabilistic and empirical approaches to assessing hazard suffer due to the scarcity of data in the low-to-moderate magnitude range for shallow continental events, and often only consider the effect of the seismic waves. The lack of detailed surface rupture description thus results in poorly-constrained hazard assessment in the high Andes (*Yepes et al., 2016*) in comparison to our understanding of the hazard posed by megathrust ruptures on the subduction zone (*Audin et al., 2008*).

6. Conclusions

In this study, we have analysed the heterogeneous surface displacements generated by the moderate-magnitude Parina earthquake in the high Peruvian Andes through a combination of high-resolution DEMs, InSAR data and geological field investigation. We have demonstrated that both late Quaternary slip and the recent Mw 6.1 earthquake have occurred along a newly-identified normal fault, known as the Parina Fault. Similar faults elsewhere in the Peruvian Altiplano may pose a significant seismic hazard to the local population from the effects of shaking on infrastructure and from the secondary hazards of liquefaction and landsliding or rock falls, **particularly in towns and villages sat within hangingwall basins**. However, these faults may be difficult to map in regions where there has been no late Quaternary sedimentation, as the finite extension on the normal faults in the Altiplano is small owing to a recent change in the style of deformation in the region. **In regions where recent fault scarps can be identified**, detailed mapping of the coseismic surface ruptures highlighted that significant along-strike variability in the rupture heights can occur that is not correlated with along-strike changes in the **coseismic slip pattern** at depth, which would imply that trenching a single section of a fault may not accurately

reflect the magnitude of paleo-earthquake offsets on this fault, but could provide evidence on earthquake chronology.

The Parina event is a reminder that **shallow** earthquakes of moderate magnitude pose a real hazard to communities and infrastructure in the Altiplano – possibly greater than megathrust earthquakes on the subduction interface (*Costa et al., 2020*). The Parina event taught us that the reactivation of these intra-continental faults generates local accelerations >1 g. Many regions exist in the same regime, with little or no geodetically-measurable horizontal deformation, minimal current seismic activity, no documented paleoseismicity and geomorphology that has been shaped by many competing processes – not just faulting (for instance, in the French Alps: *Nocquet et al., 2016* or in Central USA: *Calais et al., 2016*). To better assess the seismic hazard in these regions, we must first develop an understanding of how active faulting is recorded in the landscape, both at long and short term.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Pliocene river capture and incision of the northern Altiplano: Machu Picchu, Peru

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Abstract: The Abancay Deflection, forming the northern edge of the Altiplano in the Peruvian Andes, is a remarkable geomorphological feature marking the along-strike segmentation of the Andes. Little is known about the timing and spatial distribution of exhumation in this area. To constrain the exhumation history of the Abancay Deflection and its drivers, we present apatite (U–Th)/He and fission-track thermochronology data from samples collected along an elevation transect at Machu Picchu. Geomorphological analysis demonstrates recent and continuing drainage reorganization recorded by the spatial distribution of the normalized steepness index (k_{sn}) and normalized integrated drainage area (χ) parameters. Thermochronologically derived cooling rates are converted into exhumation using regionally constrained geothermal gradients between 16 and 26°C km⁻¹. Time–temperature inversions imply steady and slow exhumation (<0.05 km Ma⁻¹) between 20 and 4 Ma, followed by rapid exhumation (>0.9 km Ma⁻¹) since 4 Ma. The timing of rapid exhumation, combined with the geomorphological analysis, suggests that fluvial capture of the previously endorheic Altiplano by the Urubamba River drove recent incision and exhumation. Depending on the value of the geothermal gradient used, total exhumation since 4 Ma can be explained by river incision alone or requires additional exhumation driven by tectonics, possibly associated with movement on the Apurímac fault.

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The Central Andes contain the second-highest and -widest plateau on Earth: the Altiplano. Topographic building-up of the Andes has occurred since at least the Cretaceous (*c.* 120–110 Ma; Jaillard and Soler 1996); the northern Altiplano acquired its modern elevation during the Miocene (Barnes and Ehlers 2009; Garzzone *et al.* 2017; Schildgen and Hoke 2018). Tectonic, climatic and erosional interactions affecting the Altiplano and its eastward border, the Eastern Cordillera (Fig. 1), have been extensively studied in the southern Central Andes of Bolivia and Argentina (e.g. Strecker *et al.* 2007). Pliocene canyon incision, potentially induced by global climate cooling, has been inferred for the Eastern Cordillera in southernmost Peru (Lease and Ehlers 2013). In contrast, the evolution of the northern edge of the Altiplano and the Eastern Cordillera further north in Peru remains poorly documented. This area is formed by the Abancay Deflection (Fig. 1; Dalmayrac *et al.* 1980), a major Andean transition zone that separates the wide Bolivian orocline (Central Andes) to the south from the narrower Northern Andes to the north. The Abancay Deflection has higher (*c.* 0.3 km) average elevation and is much more incised than the low-relief and internally drained Altiplano to the south (Fig. 1c). Palaeoaltimetry data (Picard *et al.* 2008; Sundell *et al.* 2019) and biodiversity records (Hoorn *et al.* 2010) suggest that the study area acquired its modern elevation of *c.* 4 km before 5 Ma. At the scale of the Central Andes, different potential uplift mechanisms have been proposed, including crustal shortening (Barnes and Ehlers 2009), lithospheric delamination (Garzzone *et al.* 2006) and crustal flow (Husson and Sempere 2003; for a review see Garzzone *et al.* 2017). Tectonic shortening was

transferred from the Altiplano to the Subandes of central Peru during the mid- to late Miocene (Horton 2005; McQuarrie *et al.* 2005; Espurt *et al.* 2011). The lack of structural, geomorphological and thermochronological data from the Eastern Cordillera, with only a few previous studies distributed around our study area (Fig. 1), however, renders the mode and timing of deformation transfer unclear (Gautheron *et al.* 2013). The mechanisms driving exhumation and surface uplift in the Abancay Deflection also remain enigmatic. The Machu Picchu Batholith, in the core of the Abancay Deflection, has been deeply incised by the Urubamba River and appears as a prime location to investigate the exhumation history of the Abancay Deflection and its drivers (Fig. 1). Here we present new apatite (U–Th)/He (AHe) and apatite fission-track (AFT) dates from the Machu Picchu Batholith. We use age–elevation relationships (AER; e.g. Fitzgerald and Malusà 2019) and inverse time–temperature modelling (QTQt; Gallagher 2012) to unravel the cooling and exhumation history of the core of the Abancay Deflection. As exhumation is generally driven by surface erosion, investigating the geomorphological evolution of an area is crucial to assess potential exhumation drivers. We couple the exhumation history to landscape evolution by extracting normalized steepness (k_{sn}) and the χ indices (Kirby and Whipple 2012; Perron and Royden 2013; Willett *et al.* 2014; Whipple *et al.* 2017) for the Urubamba drainage basin. These indices allow identification of slope anomalies (knickpoints) in the river profile and reorganization patterns between drainage basins, respectively. We combine these data to discuss potential mechanisms of Miocene to present exhumation in the Abancay Deflection.

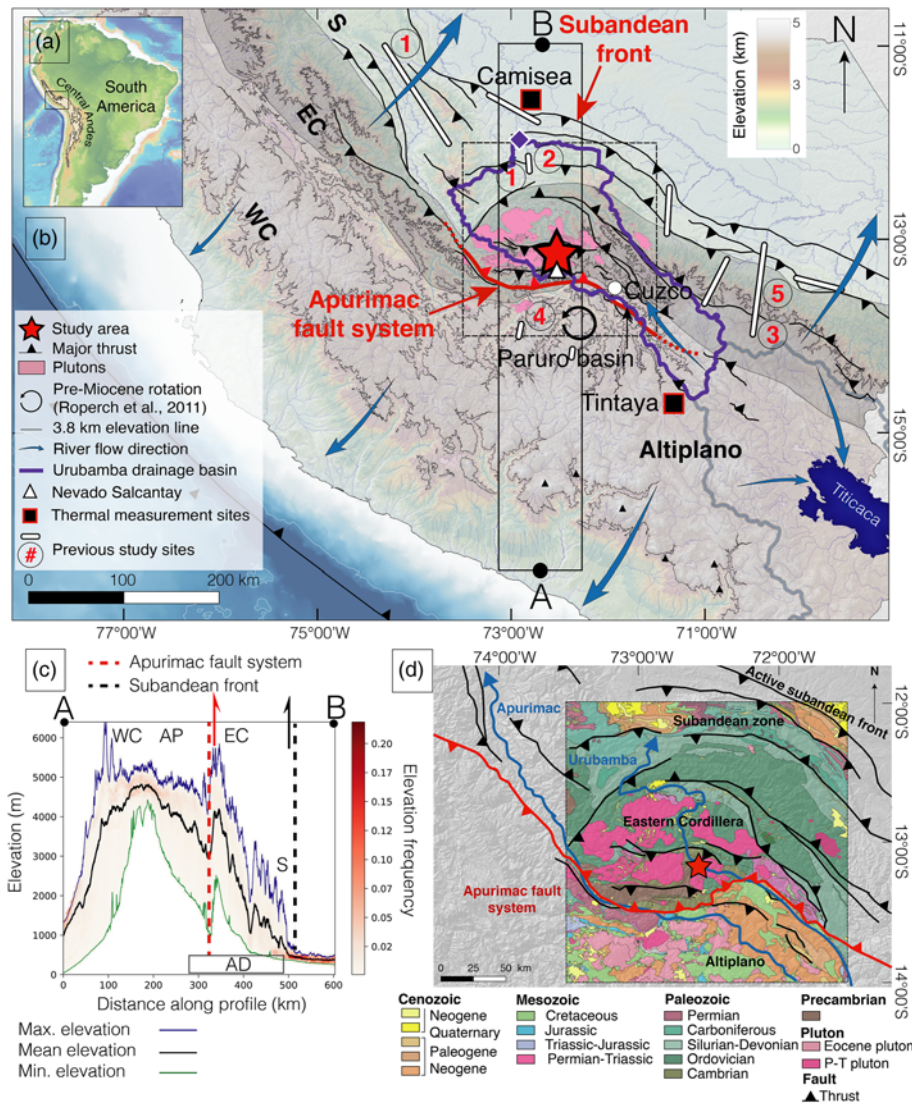


Fig. 1. Topography of the southern Peruvian Andes. **(a)** Location of the Central Andes within South America. The black line is the 3.8 km elevation contour outlining the Altiplano. **(b)** Study area (Abancay Deflection; black dashed square) showing location of sampling profile at Machu Picchu (red star) and major city (white circle). Pink areas correspond to Permo-Triassic intrusive rocks, including the sampled Machu Picchu Batholith. Grey shading indicates the Eastern Cordillera (EC). The rectangle AB is the location of the topographic swath profile displayed in (c). The Urubamba drainage basin is outlined by the purple contour and its outlet is indicated by the purple diamond. Geology was extracted from 1:100 000 scale INGEMMET maps. Red numbers refer to previous thermochronological studies. 1, Gautheron *et al.* (2013); 2, Espurt *et al.* (2011); 3, Lease and Ehlers (2013); 4, Ruiz *et al.* (2009); 5, Perez *et al.* (2016). **(c)** Abancay Deflection topography and relief: 100 km wide north-south-trending swath profile in southern Peru crossing the Abancay Deflection perpendicular to major east-west faults. A noteworthy feature is the abrupt morphological transition when crossing the Apurimac fault system (red dashed line) between the high and relatively flat Altiplano (AP) and the higher and much more incised Eastern Cordillera (EC) through the Abancay Deflection (AD). **(d)** Geological map of the Abancay Deflection. Geological map was compiled from 1:100 000 INGEMMET maps available at <http://geocadmin.ingemmet.gob.pe/geocadmin> and personal field observations. Other abbreviations: WC, Western Cordillera; S, Subandes.

Geological setting

The Abancay Deflection connects the Central and Northern Andes in Peru; its hinge-like character is emphasized by the $>45^\circ$ deflection of its fault pattern from the overall NNW-SSE axis of the range (Fig. 1; Marocco 1971). The Abancay Deflection records up to 65° of Eocene–Early Miocene (*c.* 40–20 Ma) rotation and marks the tectonic limit between the Bolivian orocline and the straight and narrow Northern Andes (Roperch *et al.* 2011). In the core of the Abancay Deflection, The Inca citadel of Machu Picchu is built on the Permo-Triassic granitic Machu Picchu Batholith (Eastern Cordillera; Fig. 1), emplaced at 222 ± 7 Ma (Carlier *et al.* 1982). The regional crustal-scale Apurimac fault system, *c.* 15 km south of the Machu Picchu Batholith, delimits two lithospheric blocks (Carlier *et al.* 2005) corresponding to two distinct lithotectonic domains: the Eastern Cordillera and the Altiplano (Fig. 1). The Altiplano is characterized by gentle relief and consists of Eocene plutons (50–30 Ma; Mamani *et al.* 2010) emplaced into Meso-Cenozoic sediments (Carlier *et al.* 1996; Fig. 1d). This domain was exhumed steadily at moderate rates (*c.* 0.2 km Ma^{-1}), at least between 38 and 14 Ma (Ruiz *et al.* 2009). In contrast, in the higher and deeply incised Eastern Cordillera, numerous Permo-Triassic batholiths emplaced into Paleozoic rocks (Mišković *et al.* 2009; Fig. 1d) crop out. The Eastern Cordillera is characterized by high elevation and relief, and contains the highest peaks east of the

Altiplano (e.g. Salcantay; 6.3 km a.s.l.; Fig. 1b). On average, the area presents elevation amplitude >1 km for a relief wavelength of *c.* 25 km (Supplementary Fig. 1). The lack of a Meso-Cenozoic sedimentary cover suggests that the Eastern Cordillera has been a long-lived structural high (Perez *et al.* 2016). Preliminary AFT ages of *c.* 2 Ma from two samples from the Machu Picchu Batholith, however, suggest unexpected rapid and recent exhumation (Kennan 2008).

The Urubamba River, flowing at the foot of Machu Picchu, drains both the Altiplano and the Eastern Cordillera towards the Amazon foreland (Figs 1b and 2a). The present-day climate of the Abancay Deflection is characterized by an abrupt latitudinal precipitation gradient, with rainfall decreasing from $>2.5 \text{ m a}^{-1}$ in the Subandean domain to $<0.5 \text{ m a}^{-1}$ in the Altiplano (Supplementary Fig. 2). The topography of the Abancay Deflection constitutes an effective orographic barrier causing this change in precipitation regime (Bookhagen and Strecker 2008; Insel *et al.* 2010), which has probably been in place since the late Miocene (Poulsen *et al.* 2010).

Methods

AHe and AFT systems record the thermal evolution of the upper *c.* 4 km of the crust, given their thermal sensitivity ranges spanning *c.* 40–80°C (e.g. Flowers *et al.* 2009; Gautheron *et al.* 2009; for a

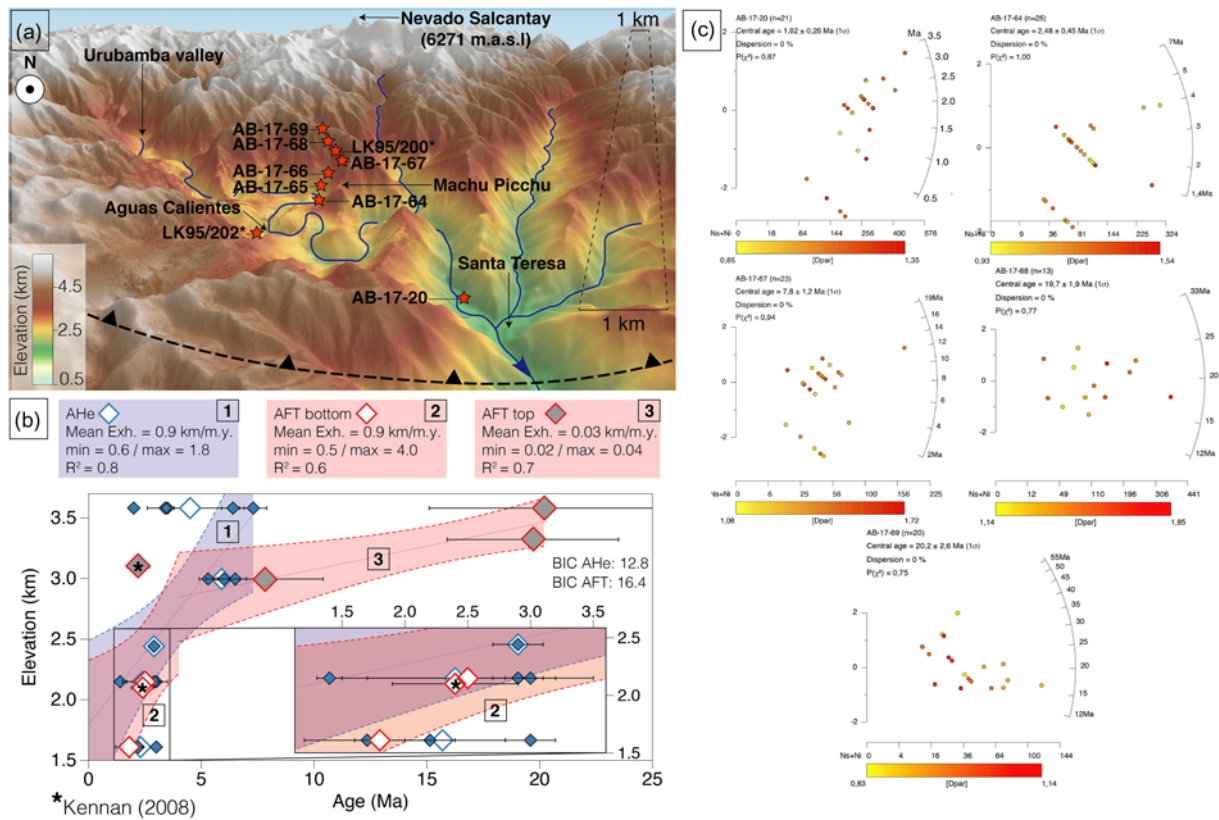


Fig. 2. Thermochronological data. (a) DEM (12 m resolution TanDEM-X data) focusing on the sample locations (red stars). The view is southward with the Urubamba River flowing toward the NW (blue arrow). The blind-thrust plotted is documented as an inherited structure into Paleozoic rocks. (b) Age v. elevation plot for AHe (blue diamonds), AFT bottom (white with red outline diamonds) and AFT top (grey with red outline diamonds). For AHe, filled diamonds represent single-grain ages and open diamonds represent mean AHe ages for each sample. Starred points are from Kennan (2008). Exh., exhumation rates inferred from the age–elevation relationship (AER; coloured dashed lines) with minimum and maximum values indicated by blue and red dotted lines (2σ confidence intervals) for AHe and AFT respectively. R^2 (correlation coefficient) for each segment and the Bayesian Information Criterion (BIC) are also indicated (see Glotzbach *et al.* 2011 for method). (c) AFT single-grain radial plots for each sample.

review see Ault *et al.* 2019), and *c.* 75–125°C (e.g. Brandon *et al.* 1998; Reiners and Brandon 2006), allowing the deciphering of exhumation linked to rock uplift and landscape evolution (e.g. Reiners and Shuster 2009; Ault *et al.* 2019). Here, we combine these data with geomorphological analyses to address landscape evolution and drainage reorganization in response to climatic and/or tectonic perturbations (e.g. Burbank and Anderson 2012).

Sampling strategy and sample preparation

Seven samples were collected from the Machu Picchu Batholith along the Inca trail from the town of Santa Teresa to the Phuyupatamarca Inca site, forming a 1.9 km elevation profile in the vicinity of Machu Picchu (Fig. 2a; Table 1). We sampled the freshest possible *in situ* outcrops encountered (Supplementary Data). Rock samples were crushed and sieved to extract the 100–

160 μm fractions, after which apatite crystals were concentrated using standard magnetic and heavy-liquid techniques.

Apatite (U–Th)/He (AHe) dating

Euhedral apatite crystals were carefully selected for AHe dating under a binocular microscope to identify minerals without fractures and/or inclusions that would skew the AHe age (Farley 2002). Among the seven samples, five yielded sufficient suitable apatite crystals for AHe dating, from which we extracted 15 single-grain ages. AHe measurements were performed at GEOPS (Université Paris Saclay, France). We determined the individual grain geometry and calculated the alpha-ejection correction factor using the Qt_FT program (Gautheron and Tassan-Got 2010; Ketcham *et al.* 2011). Individual apatite crystals were encapsulated in platinum tubes and were heated twice for 5 min under ultra-vacuum conditions at high temperature ($1050 \pm 50^\circ\text{C}$) using an infrared diode laser. The extracted ^4He gas was mixed with a known amount of ^3He ; the gas mixture was purified and analysed using a Prisma Quadrupole mass spectrometer. Subsequently, apatite crystals were dissolved in 50 μl of 5N HNO_3 solution containing known amount of ^{235}U , ^{230}Th , ^{149}Sm and ^{42}Ca ; an additional 50 μl of 5N HNO_3 was added to the solution. The solution was heated to 70°C for 3 h; after cooling, 900 μl of distilled water was added. The final solution was analysed using an ELEMENT XR inductively coupled plasma mass spectrometry system; the ^{238}U , ^{230}Th and ^{147}Sm concentrations were determined and apatite weight was estimated using the Ca content, following the method proposed by Evans *et al.* (2005). Standard Durango apatite crystals were analysed alongside the

Table 1. Sample locations and lithologies; all samples are from the Triassic granitic Machu Picchu pluton

| Sample number | Latitude ($^\circ\text{S}$) | Longitude ($^\circ\text{W}$) | Elevation (m) |
|---------------|-------------------------------|--------------------------------|---------------|
| AB-17-20 | 13.14182 | 72.58376 | 1610 |
| AB-17-64 | 13.18747 | 72.52931 | 2149 |
| AB-17-65 | 13.18833 | 72.53428 | 2441 |
| AB-17-66 | 13.19034 | 72.5369 | 2719 |
| AB-17-67 | 13.19288 | 72.54157 | 2996 |
| AB-17-68 | 13.2029 | 72.53497 | 3322 |
| AB-17-69 | 13.20652 | 72.53204 | 3581 |

Table 2. QTQt parameters for data inversion

| Parameters | Values or flags | References or justifications |
|---|--------------------------------|---|
| Explored time interval (Ma) | 0–50 | Encompassing AHe and AFT data range |
| Explored temperature interval (°C) | 0–140 | Encompassing AHe and AFT closure temperature |
| Explored $\delta T/\delta t$ range (°C Ma ⁻¹) | 1000 | Maximum exploration; no constraints |
| Geothermal gradient (°C km ⁻¹) | 25 ± 15 | Broad range; the geothermal gradient measured at the site closest to our sampling is 16 ± 2°C km ⁻¹ (Henry and Pollack 1988) |
| Present-day surface temperature (°C) | 25 ± 10 | Gonfiantini <i>et al.</i> (2001) |
| Surface-temperature lapse rate (°C km ⁻¹) | 6 ± 2 | Estimated from Klein <i>et al.</i> (1999) and Gonfiantini <i>et al.</i> (2001) |
| Allow geothermal gradient to vary over time | Yes | Inversion output consistent with our geothermal gradient assumption |
| Reheating | No | No evidence for reheating event considering the time period explored |
| Number of iterations | 300 000 | |
| Etchant | 5.5M | Sample preparation protocol |
| AFT annealing model | Ketcham <i>et al.</i> (2007) | Taking into account kinetic variability characterized by <i>D</i> _{par} |
| AHe radiation damage model | Gautheron <i>et al.</i> (2009) | Taking into account kinetic variability characterized by eU |

eU, concentration of effective uranium.

unknowns to ensure data quality (Supplementary Table 1). The 1 σ error on each single-grain AHe age amounts to 8%, reflecting analytical error and uncertainty on the FT ejection factor correction. More details on the analytical procedure have been given by Recanati *et al.* (2017).

Apatite fission track (AFT) analysis

For AFT dating, apatite crystals were manually selected, mounted in epoxy resin and polished at the GTC platform (ISTerre, Grenoble, France). Among the seven samples, five presented sufficient suitable apatite crystals for AFT dating. AFT dating was performed using the external-detector method and ζ -calibration approach (Hurford and Green 1983). Spontaneous fission tracks were revealed by etching at 21°C for 20 s using a 5.5M HNO₃ solution. Induced tracks were implanted in an external mica-sheet detector by thermal-neutron irradiation at the FRM II reactor (Munich, Germany). Tracks were counted and lengths were measured at 1250 \times magnification under a Zeiss microscope. Simultaneous measurement of five Durango and five Fish Canyon Tuff age standards allowed a ζ -value of 275 ± 12 to be constrained for the operator, Benjamin Gérard. We used the BINOMFIT program (e.g. Ehlers *et al.* 2005) to calculate AFT central ages (Supplementary Data).

Interpreting age–elevation relationships (AER)

Age–elevation relationships (AER) provide a first-order estimate of apparent exhumation rates without requiring information on the thermal structure of the crust, with breaks in slope in AER allowing identification of changes in exhumation rate through time (e.g. Wagner *et al.* 1977; Fitzgerald and Malusà 2019). This approach, however, does not take into account potential inter-sample AHe/AFT kinetic variability and assumes a quasi-vertical profile (Stüwe *et al.* 1994). We fitted single- and multi-tier regressions to the AFT and AHe data from the altitudinal profile data using a Bayesian approach (Glotzbach *et al.* 2011); the best-fit AER was determined by minimization of the Bayesian Information Criterion (BIC; Schwarz 1978).

Time–temperature modelling

Time–temperature modelling with QTQt (Gallagher 2012) allows thermal histories to be inferred for individual samples, with the possibility of combining and processing multiple samples from an altitudinal profile. Parameters used for QTQt data inversion are

detailed in Table 2. We processed all AHe aliquots displayed in Table 3 and all AFT data presented in Table 4, including track-length measurements for sample AB-17-69 together. We extracted best-fitting thermal histories for the combined samples from the Machu Picchu profile, exploring the T – t space by calculating the likelihood for 300 000 iterations. We implemented the annealing model of Ketcham *et al.* (2007) and the radiation-damage model of Gautheron *et al.* (2009) for AFT and AHe respectively. We tested the influence of the AHe diffusion model on the inferred cooling history and found that this is insignificant in our case (Supplementary Fig. 9). We allowed the geothermal gradient to vary over time between commonly inferred values for the Eastern Cordillera (Henry and Pollack 1988; Barnes *et al.* 2008; Lease and Ehlers 2013); that is, between 10 and 40°C km⁻¹. The explored timespan starts at 50 Ma, twice the oldest thermochronological age, to take into account the earlier history. We implemented a surface-temperature lapse rate of *c.* 6°C km⁻¹, as determined for the eastern flank of the inter-tropical Andes (Gonfiantini *et al.* 2001).

Geomorphological analysis

For our geomorphological analysis, we used a 1 arc-second (*c.* 30 m) digital elevation model (DEM) derived from the Shuttle Radar Topography Mission (SRTM V4; Reuter *et al.* 2007) and 12 m resolution TanDEM-X data where available (Rizzoli *et al.* 2017). We extracted the Urubamba drainage basin, its associated drainage network and river longitudinal profiles with Whitebox GAT 3.4 (Lindsay *et al.* 2015; Fig. 1). We fixed the Urubamba basin outlet location to the Eastern Cordillera–Subandes boundary to avoid potential perturbations in the downstream river profile owing to surface uplift in the Subandean zone (e.g. Gautheron *et al.* 2013) and in the Amazon foreland (Fitzcarrald arch uplift; Espurt *et al.* 2007).

The normalized steepness index (k_{sn}) quantifies river gradients corrected for upstream drainage area and allows identification of abnormally steep river reaches or knickzones (Kirby and Whipple 2012). The map pattern of k_{sn} values in a catchment area is a powerful tool to determine active tectonic boundaries and/or edges of a metastable plateau consumed by regressive erosion with knickpoint retreat (Kirby *et al.* 2003; Wobus *et al.* 2006). We used Topotoolbox v.2 (Schwanghart and Scherler 2014) to extract k_{sn} values for the entire hydrographic network of the Urubamba, imposing a mean concavity value $\theta_{ref} = 0.45$ (Wobus *et al.* 2006).

The variable χ represents normalized integrated drainage area at any point in the river and has units of length (Perron and Royden

Table 3. Apatite (U–Th–Sm)/He data

| Sample number | Morphology | Length (µm) | Width (µm) | Thickness (µm) | R_s (µm) | Weight (µg) | F_T | ^4He (ncc STP g ⁻¹) | ^{238}U (ppm) | ^{232}Th (ppm) | ^{147}Sm (ppm) | eU Th/U (ppm) | Age (Ma) | Corrected age (Ma) | $\pm 1\sigma$ | |
|---------------|------------|-------------|------------|----------------|------------|-------------|-------|--|------------------------|-------------------------|-------------------------|---------------|----------|--------------------|---------------|------|
| AB-17-20A | 2b | 156 | 115 | 107 | 74 | 4.3 | 0.81 | 15 283 | 47.4 | 193.0 | 59.0 | 4.1 | 94.0 | 1.4 | 1.7 | 0.1 |
| AB-17-20B | 1b + 1py | 259 | 101 | 94 | 60 | 4.8 | 0.77 | 17 371 | 39.6 | 94.6 | 59.8 | 2.4 | 62.6 | 2.3 | 3.0 | 0.2 |
| AB-17-20C | 2b | 126 | 120 | 99 | 69 | 3.1 | 0.80 | 16 046 | 76.4 | 3.3 | 58.1 | 0.0 | 77.5 | 1.7 | 2.2 | 0.2 |
| AB-17-20 | | | | | | | | | | | | | | | 2.3* | 0.5* |
| AB-17-64D | 1b + 1py | 209 | 113 | 89 | 57 | 3.7 | 0.75 | 9015 | 21.3 | 53.5 | 80.2 | 2.5 | 35.0 | 2.2 | 2.9 | 0.2 |
| AB-17-64E | 1b + 1py | 179 | 96 | 90 | 56 | 2.9 | 0.75 | 9430 | 23.7 | 44.4 | 54.1 | 1.9 | 35.0 | 2.3 | 3.0 | 0.2 |
| AB-17-64H | 2b | 102 | 118 | 139 | 70 | 3.6 | 0.80 | 5789 | 28.4 | 54.3 | 62.0 | 1.9 | 41.5 | 1.1 | 1.4 | 0.1 |
| AB-17-64* | | | | | | | | | | | | | | | 2.4* | 0.7* |
| AB-17-65D | 2b | 205 | 151 | 141 | 97 | 9.6 | 0.85 | 3491 | 7.4 | 17.7 | 46.2 | 2.4 | 11.9 | 2.5 | 2.9 | 0.2 |
| AB-17-65* | | | | | | | | | | | | | | | 2.9* | 0.2* |
| AB-17-67C | 2b | 154 | 108 | 84 | 58 | 2.8 | 0.76 | 14 056 | 17.5 | 48.1 | 53.8 | 2.7 | 29.3 | 4.0 | 5.3 | 0.4 |
| AB-17-67D | 1b + 1py | 154 | 96 | 97 | 57 | 2.6 | 0.75 | 16 427 | 16.1 | 48.8 | 71.2 | 3.0 | 28.2 | 4.9 | 6.5 | 0.5 |
| AB-17-67F | 2b | 104 | 112 | 72 | 72 | 3.6 | 0.80 | 45 191 | 69.1 | 33.5 | 19.3 | 0.5 | 77.2 | 4.8 | 6.0 | 0.4 |
| AB-17-67* | | | | | | | | | | | | | | | 5.9* | 0.4* |
| AB-17-69B | 1b + 1py | 202 | 104 | 97 | 61 | 3.8 | 0.77 | 18 879 | 35.6 | 92.6 | 32.8 | 2.6 | 58.0 | 2.7 | 3.5 | 0.3 |
| AB-17-69D | 1b + 1py | 212 | 92 | 66 | 43 | 2.2 | 0.68 | 17 806 | 16.6 | 55.8 | 82.4 | 3.4 | 30.4 | 4.9 | 7.3 | 0.6 |
| AB-17-69E | 1b + 1py | 116 | 75 | 80 | 45 | 1.2 | 0.69 | 9998 | 11.1 | 31.5 | 47.1 | 2.8 | 18.9 | 4.4 | 6.4 | 0.5 |
| AB-17-69I | 2b | 109 | 122 | 126 | 75 | 3.6 | 0.81 | 8191 | 14.2 | 42.2 | 74.1 | 3.0 | 24.4 | 2.7 | 3.4 | 0.2 |
| AB-17-69J | 2b | 125 | 128 | 136 | 85 | 5.0 | 0.83 | 5001 | 13.9 | 45.1 | 78.1 | 3.2 | 24.8 | 1.6 | 2.0 | 0.1 |
| AB-17-69* | | | | | | | | | | | | | | | 4.5* | 1.9* |

Morphology refers to the apatite geometry. 2b, two broken faces; 1b + 1py, one broken face and one hexagonal pyramid. F_T , ejection correction factor; R_s , sphere equivalent radius of hexagonal crystal (Ketcham *et al.* 2011; Gautheron *et al.* 2012).

*AHe arithmetic mean value calculated for plotting (Fig. 2b) with associated error (standard deviation).

2013; Whipple *et al.* 2017). As it is predicted that drainage divides will migrate in the direction from lower to higher χ values, the pattern of χ values across drainage divides can be used to assess their present-day stability or evolution (Willett *et al.* 2014; Whipple *et al.* 2017). Combined with independent geomorphological evidence, such patterns can be extrapolated to infer recent drainage migration. We used Topotoolbox v.2 to calculate χ for the endorheic Altiplano and the neighbouring Urubamba basin, upstream of the 3.8 km elevation contour, and focus on the drainage divide equilibrium between these two drainage basins.

Results

Thermochronology data and modelling

We report 15 single-grain AHe ages (Table 3) and five AFT ages (Table 4) from five samples. We included two published AFT ages from the same zone (Kennan 2008) in our models (Table 4). Single-grain AHe and central AFT ages range from 1.4 ± 0.1 Ma to 7.3 ± 0.6 Ma ($\pm 1\sigma$) and from 1.8 ± 0.6 Ma to 20.2 ± 5.1 Ma ($\pm 2\sigma$), respectively (Tables 3 and 4; Fig. 2b and c). There is a consistent

increase in both AHe and AFT ages with elevation (Fig. 2b), with the AFT ages of the two highest samples being much older than all other AFT and AHe ages. AFT ages present a notable dispersion but pass the χ^2 test owing to the small number of spontaneous fission tracks in the crystals (Table 4). Only three track lengths were measured because of the young AFT ages and associated low track counts. Only the upper sample provided a mean track length (MTL) of *c.* 12 µm (Table 4; Supplementary Table 2). Etch-pit widths (D_{par}), measured as a proxy for apatite composition, range between 0.97 and 1.46 µm (Table 4), suggesting that the analysed apatites are fluorapatites, characterized by rapid annealing compared with apatite crystals with higher D_{par} values (Donelick *et al.* 2005).

Bayesian AER modelling reveals that AHe ages are best fit by a single AER with a slope of $0.9^{+0.9}_{-0.3}$ km Ma⁻¹ between *c.* 4 and *c.* 2 Ma (Fig. 2b). In contrast, the AFT ages require a two-tier fit, with the higher elevation samples showing an AER with a slope of 0.03 ± 0.01 km Ma⁻¹ (*c.* 20 to *c.* 4 Ma; Fig. 2b) and the lower elevation samples an AER with a slope of $0.9^{+3.1}_{-0.4}$ km Ma⁻¹ (*c.* 4 to *c.* 2 Ma; Fig. 2b); the latter is compatible with the AHe results.

Time–temperature inversions with QTQt reveal slow continuous cooling from *c.* 20 to 4.0 ± 0.6 Ma at a rate of 0.7 ± 0.2 °C Ma⁻¹,

Table 4. Apatite fission-track data

| Sample number | n | ρ_s (10 ⁵ cm ⁻²) | N_s | ρ_i (10 ⁵ cm ⁻²) | N_i | ρ_d (10 ⁵ cm ⁻²) | P (χ^2) | Dispersion (%) | Central age (Ma) | U $\pm 2\sigma$ (ppm) | $N \pm 1\sigma$ (D_{par}) | $M D_{\text{par}}$ (µm) | n TL | MTL (µm) | | |
|---------------|-----|--|-------|--|--------|--|------------------|----------------|------------------|-----------------------|--------------------------------------|-------------------------|--------|----------|------|-------|
| AB-17-20 | 21 | 0.49 | (51) | 50.3 | (5297) | 13.8 | 87.5 | 0.4 | 1.8 | 0.6 | 55 | 2 | 67 | 1.16 | n.d. | n.d. |
| AB-17-64 | 25 | 0.25 | (31) | 19.6 | (2451) | 14.2 | 99.8 | 0.2 | 2.5 | 1.0 | 21 | 1 | 76 | 1.21 | n.d. | n.d. |
| AB-17-67 | 23 | 0.57 | (41) | 14.3 | (1029) | 14.3 | 93.5 | 0.6 | 7.8 | 2.6 | 15 | 1 | 89 | 1.35 | n.d. | n.d. |
| AB-17-68 | 13 | 5.46 | (154) | 54.7 | (1541) | 14.3 | 76.8 | 0.2 | 19.7 | 3.8 | 57 | 3 | 74 | 1.46 | n.d. | n.d. |
| AB-17-69 | 20 | 1.32 | (78) | 12.9 | (763) | 14.4 | 74.9 | 0.3 | 20.2 | 5.1 | 14 | 1 | 42 | 0.97 | 3 | 11.92 |
| LK95/200* | 30 | n.r. | n.r. | n.r. | n.r. | n.r. | 46.5 | n.r. | 2.2 | 0.5 | n.r. | n.r. | n.r. | n.r. | n.r. | n.r. |
| LK95/202* | 30 | n.r. | n.r. | n.r. | n.r. | n.r. | 97.0 | n.r. | 2.4 | 0.5 | n.r. | n.r. | n.r. | n.r. | n.r. | n.r. |

Fission-track age is reported as central age (Galbraith and Laslett 1993). Samples were counted dry with a BX51 Olympus microscope at 1250× magnification. Ages were calculated with the BINOMFIT program (Ehlers *et al.* 2005), using a zeta value of 275.18 ± 11.53 and the IRMM 540 uranium glass standard (15 ppm U). n , number of analysed grains; ρ_s , spontaneous track density; N_s , number of spontaneous tracks; ρ_i , induced track density; N_i , number of induced tracks; ρ_d , dosimeter tracks density; P (χ^2), probability of obtaining the χ^2 value for n degree of freedom (n = number of crystals – 1); $n D_{\text{par}}$, number of D_{par} measured; $M D_{\text{par}}$, mean D_{par} value (i.e. average etch pit diameter of fission track); n TL, number of track lengths measured; MTL, mean track lengths of horizontally confined tracks; n.d., no data; n.r., not reported.

*Previously published data (Kennan 2008). For samples LK95/200 and LK95/202, elevations are respectively 3.1 km and 2.1 km.

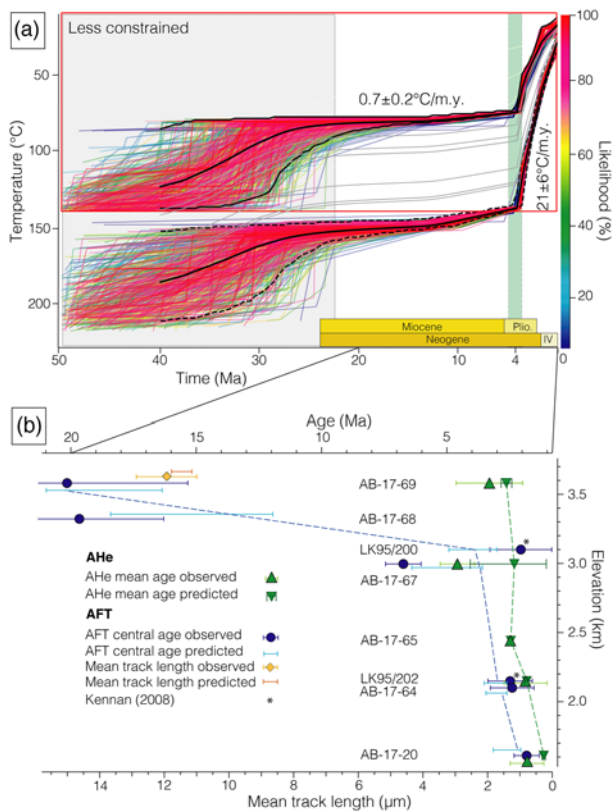


Fig. 3. Time–temperature ($T-t$) modelling. (a) Time–temperature paths obtained by inversion of AHe and AFT thermochronology data using QTQt. The red rectangle shows the explored $T-t$ range for inversion. Coloured lines show the $T-t$ paths for the top and the bottom samples with their respective likelihood (colour scale on right). Continuous and dashed black lines show the expected model and its 95% reliable interval for the thermal histories of the top and bottom samples, respectively. Grey lines represent the expected cooling paths for intermediate samples. The green vertical band indicates acceleration of cooling at 4.0 ± 0.6 Ma. Cooling rates derived from QTQt are indicated on the graph. (b) Fit of best-fit QTQt model predictions to the data for the Machu Picchu elevation profile.

increasing to $21 \pm 6^\circ\text{C Ma}^{-1}$ since *c.* 4 Ma (Fig. 3). AHe and AFT ages predicted by the best-fit model fit the observed ages within error.

Geomorphological analysis

The highest k_{sn} values ($>1000 \text{ m}^{0.9}$) in the Urubamba drainage basin are focused along a SW–NE band orthogonal to the drainage direction (Fig. 4b). This zone of high k_{sn} corresponds to kilometre-scale knickzones in the Urubamba main stem and its tributaries, where the rivers actively incise bedrock (Fig. 5c). In contrast, alluvial portions upstream (Fig. 5d) correspond to the lowest k_{sn} values ($<10 \text{ m}^{0.9}$; Fig. 4b). Along the drainage divide between the endorheic Altiplano and externally drained Urubamba drainage basins, χ values (calculated from a base level at 3.8 km) are noticeably higher in the Altiplano (*c.* 10^5 m) than in the Urubamba basin (*c.* 10^3 m ; Fig. 4c).

Discussion

Miocene–Present exhumation of the Machu Picchu Batholith

The data for both thermochronometric systems suggest rapid cooling starting at *c.* 4 Ma. It is reasonable to assume that the Machu Picchu Batholith did not experience reheating since the Miocene, considering the lack of evidence for volcanic activity and/or sedimentary burial (Perez *et al.* 2016). Magmatic activity in the Abancay Deflection ceased after *c.* 30 Ma (Mamani *et al.* 2010); any potential associated thermal perturbation would not have affected the Miocene thermal history. Nonetheless, to explore potential temporal variability of the geothermal gradient, we allow it to vary over time in the range $25 \pm 15^\circ\text{C km}^{-1}$ during time–temperature inversions. The model does not converge to a single range of palaeo-geothermal gradient estimates. As it is not possible to estimate the geothermal gradient accurately in the past, we consider it constant in time and space in the following calculations, following previous work (e.g. Barnes *et al.* 2012; Perez *et al.* 2016).

The value of the geothermal gradient is a crucial choice when translating cooling rates (inferred from time–temperature modelling) into exhumation rates. As the Abancay Deflection is devoid of direct measurements of its thermal structure, we explore two options

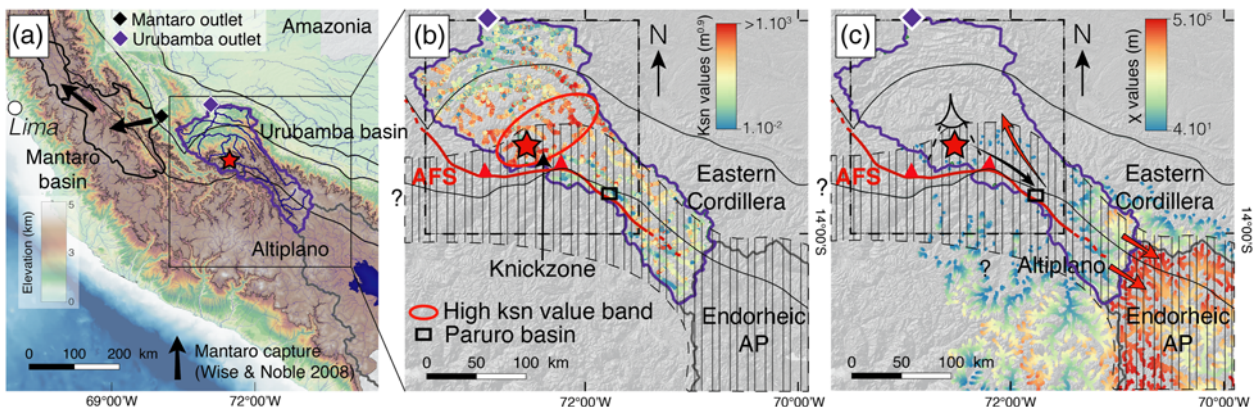


Fig. 4. Quantitative geomorphology of the Urubamba River drainage basin. (a) Urubamba (purple) and Mantaro (black) watershed locations in southern Peru. Blue lines are rivers. (b) k_{sn} map for the Urubamba drainage basin. Higher k_{sn} values (in warm colours) are aligned in a band orthogonal to the main elongation axis of the Urubamba drainage basin, suggesting capture of a palaeo-Altiplano (Wobus *et al.* 2003, 2006). (c) χ map for the Urubamba drainage basin. χ values were calculated with an elevation threshold of 3.8 km corresponding to the endorheic Lake Titicaca base level. The χ gradient across the drainage divide between the Urubamba and the endorheic Altiplano suggests that it is actively migrating southward (red arrows), implying continuing capture of the plateau. The black and the red curved arrows represent respectively the drainage direction for 9–7 Ma (Sundell *et al.* 2018) and for the present day. The ‘eye’ icon represents the view direction of the 3D DEM in Fig. 2a. In (a–c), the red star is the sample location close to Machu Picchu and the dashed black square is the Abancay Deflection. The grey polygon outlines the present-day endorheic Altiplano and the black-hatched polygon represents the ante-4 Ma northern extension of the palaeo-endorheic Altiplano. AFS, Apurimac fault system.

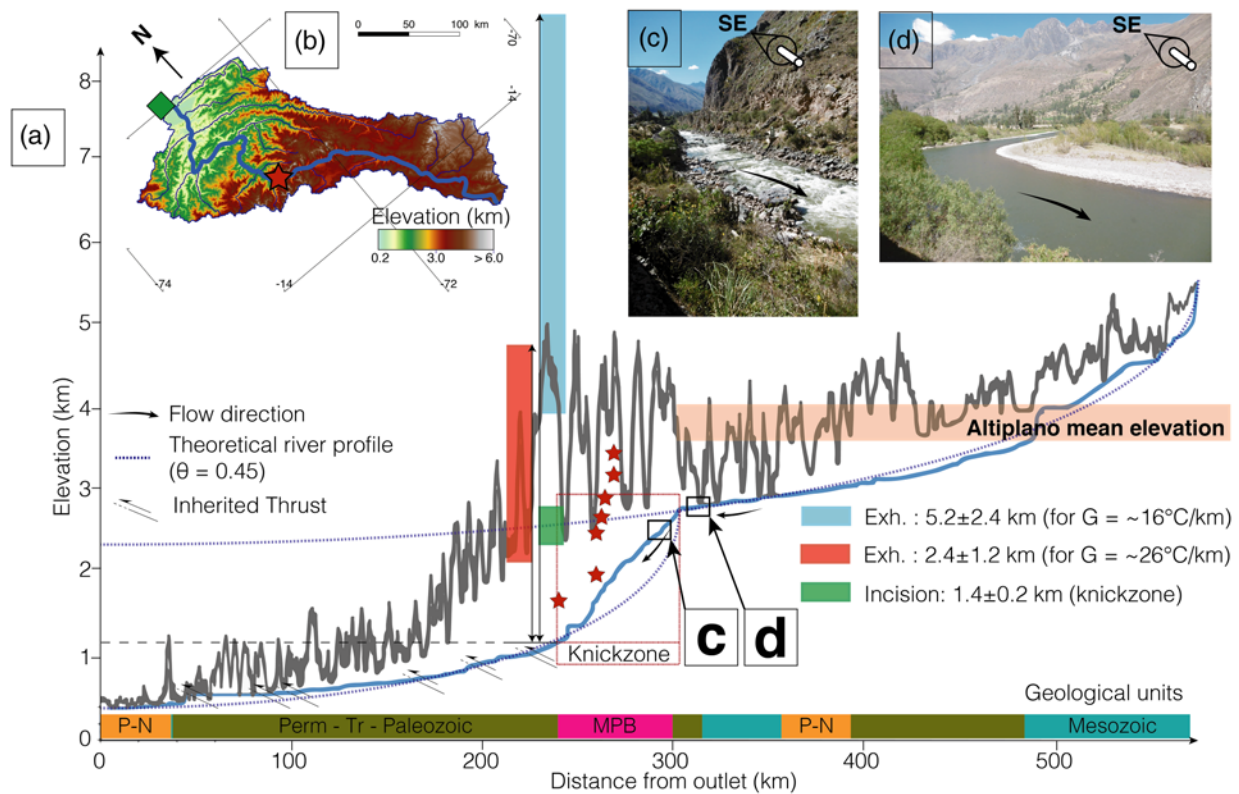


Fig. 5. (a) Urubamba river profile (blue) crossing the Machu Picchu Batholith. Red stars show projected location of the samples collected in this study. The orange horizontal band represents the mean elevation of the Altiplano (calculated from a swath profile) and the dark grey line is the mean topography in a 5 km swath following the Urubamba River. The blue and red vertical bands show the estimated total exhumation since 4 Ma for an assumed ‘cold’ and ‘warm’ geotherm, respectively, at the same location at the base of the knickzone. The green vertical band shows the minimum incision of the Urubamba River computed by the difference between the theoretical river profile reconstructed from the river profile above the knickzone and the present-day river profile at the foot of the knickzone. Vertical exhumation or incision rectangles are slightly shifted to avoid overprinting the signals displayed. Total exhumation is calculated taking into account minimum and maximum values for exhumation rates and timing of acceleration. The error on the incision estimate for the knickzone is propagated from a 15% uncertainty in the concavity value (θ) derived from river-profile fitting (Kirby and Whipple 2012). (b) DEM of the Urubamba drainage basin with its outlet (green diamond). The main Urubamba river (thick blue curve) is plotted in (a). The red star indicates the location of the knickzone and sampling profile. Inset photographs (c) and (d) show the morphological change of the Urubamba River from meandering upstream (d) to rapids in a canyon (knickzone; c). MPB, Machu Picchu Batholith; P-N, Paleo-Neogene.

to estimate the geothermal gradient in our study area. The first consists in using the nearest available measurements. Henry and Pollack (1988) reported a measured modern-day geothermal gradient of $c. 14^{\circ}\text{C km}^{-1}$ from the Tintaya mine on the Altiplano (Fig. 1), whereas Espurt *et al.* (2011) inferred a Miocene geothermal gradient of $c. 17^{\circ}\text{C km}^{-1}$ in the Camisea area in the Subandean domain (Fig. 1), leading to an estimated geothermal gradient of $16 \pm 2^{\circ}\text{C km}^{-1}$. The second option is to take into account more distant data available for the Eastern Cordillera of Bolivia, which suggest a somewhat higher geothermal gradient of $26 \pm 8^{\circ}\text{C km}^{-1}$ (Barnes *et al.* 2008). We will refer to these two estimates of the geothermal gradient as ‘cold’ (based on local data) and ‘warm’ (based on Barnes *et al.* 2008). Considering stable, linear and spatially uniform geothermal gradients of $16 \pm 2^{\circ}\text{C km}^{-1}$ or $26 \pm 8^{\circ}\text{C km}^{-1}$ (‘cold’ v. ‘warm’), we can translate the cooling rates from the time-temperature inversions to exhumation rates. Between $c. 20$ and $c. 4$ Ma, exhumation rates were $0.05 \pm 0.02 \text{ km Ma}^{-1}$ (‘cold’ gradient) or $0.03 \pm 0.01 \text{ km Ma}^{-1}$ (‘warm’ gradient); that is, very similar independent of the chosen geothermal gradient. For the period from $c. 4$ Ma to present day, however, the choice of geothermal gradient leads to significant differences in predicted exhumation rates. If the ‘cold’ gradient is used the exhumation rate is $1.3 \pm 0.6 \text{ km Ma}^{-1}$, whereas for the ‘warm’ gradient the exhumation rate decreases to $0.9 \pm 0.3 \text{ km Ma}^{-1}$. Both values are consistent within errors with those inferred from the AER analysis ($0.9_{-0.3}^{+0.9} \text{ km Ma}^{-1}$ for the AHe

data; Fig. 2b). In the following discussion, we will interpret exhumation rates values computed from QTQt cooling dynamic.

The local relief may also influence estimated exhumation rates, as topography deflects isotherms with an exponentially decreasing influence downward (Braun 2002; Braun *et al.* 2006). Therefore, the closure depth of thermochronometric systems is relief dependent, in particular for the lowest-temperature system (i.e. AHe). Using a relief wavelength $\lambda = 25 \pm 8 \text{ km}$ and relief amplitude $>1 \text{ km}$ (Supplementary Fig. 1) and the calculation method of Mancktelow and Grasemann (1997) (see also Braun *et al.* 2006), leads to deflections of the 100°C isotherm of 280–570 m depending on the chosen exhumation rate but does not significantly affect the exhumation-rate estimates.

Thus our thermochronology data from the Machu Picchu Batholith clearly show an $c. 30$ -fold increase in exhumation rate in the Pliocene, from <0.05 to $>0.9 \text{ km Ma}^{-1}$. Although the exact rate and amount of exhumation since this time depend on assumed values for the geothermal gradient and the influence of relief, the relative increase as well as its timing at $4.0 \pm 0.6 \text{ Ma}$ is robust.

Geomorphological evidence for capture of Altiplano drainage

The modern Abancay Deflection is externally drained and has anomalously high topography, high relief and outcropping

basement batholiths, in contrast to the neighbouring low-relief Altiplano (Fig. 1c). The Machu Picchu area is set within a SW–NE-trending band of high k_{sn} values (Fig. 4b), with much lower k_{sn} values found upstream in the Altiplano region. The Urubamba River, draining the Abancay Deflection, is one of the most distant tributaries of the Amazon. From its source in the Altiplano, it flows parallel to the Andean range at 3.8 km elevation for *c.* 150 km before it cuts the Machu Picchu Batholith in a >1 km deep canyon, associated with a major knickzone (Fig. 5). This knickzone appears to be confined to the Machu Picchu Batholith (Fig. 5a), which presumably has greater rock-strength than surrounding units. Although the SW–NE band of high k_{sn} values is mostly contained within intrusive rocks and metamorphic sediments (Fig. 1), these rocks also occur widely outside this band. Therefore, the band of high k_{sn} values does not appear to be purely lithologically controlled and presumably reflects a geomorphological or structural transition. In the absence of a major tectonic structure associated with it, we interpret the major knickzone associated with this band by base-level fall in the Urubamba river system owing to capture of a former endorheic catchment (which would have been a northward extension of the Altiplano; Fig. 4). Although we cannot determine the exact location of the river capture, it must have happened downstream of the present-day location of the knickzone. Capture is a continuing process, as shown by the pattern of χ values that points to drainage-divide migration toward the SE; that is, expansion of the Urubamba catchment to the detriment of the endorheic Altiplano (Fig. 4c). Although lithology does not appear to be a primary control on the pattern of k_{sn} values, headward propagation of incision from the foreland into the highlands may be stalling within the hard rocks of the Machu Picchu Batholith, limiting incision further upstream, as suggested by the alluvial river channels found upstream of the knickzone (Fig. 5c).

Miocene surface uplift of the northern Altiplano without exhumation

Our data imply slow exhumation between 20 and 4 Ma (*c.* 0.6 km in *c.* 16 myr), consistent with the record from the Altiplano to the south that suggests steady and moderate exhumation between 38 and 14 Ma (Ruiz *et al.* 2009; Supplementary Fig. 10). In contrast, the Eastern Cordillera record to the SE suggests significant Miocene exhumation (Lease and Ehlers 2013; Perez *et al.* 2016). Several palaeo-elevation estimates (e.g. Sundell *et al.* 2019) indicate that the elevation of both the Eastern Cordillera and the neighbouring Altiplano grew by *c.* 2 to *c.* 4 km between 20 and 5 Ma; the Abancay Deflection must have reached its present-day elevation before 5 Ma. Thus, slow exhumation of the core of the Abancay Deflection during the Miocene appears to be coeval with surface uplift of the northern Altiplano. Although a pulse of exhumation would be expected to accompany surface uplift, both the Abancay Deflection (this study) and the northern Altiplano (Ruiz *et al.* 2009) record steady and moderate exhumation rates. There are two potential explanations for diminished Miocene denudation within this rising orogen: (1) establishment of aridity owing to the development of an orographic barrier (Strecker *et al.* 2007), and/or (2) a high-elevation endorheic local base level. Provenance studies in the Paruro basin south of Cuzco, based on detrital zircon U–Pb dating (Sundell *et al.* 2018), suggest that the Machu Picchu area (specifically the Ollantaytambo Formation into which the Machu Picchu Batholith intruded; Bahlburg *et al.* 2006) was one of the numerous sources for late-Miocene (*c.* 9 to *c.* 7 Ma) Altiplano basin sediments. In contrast, rocks from the Machu Picchu area are currently exported toward the Amazon foreland via the modern Urubamba drainage network (Fig. 4c). This contrast implies a major drainage reversal since the late Miocene. The combined data strongly suggest that the Abancay Deflection (including the Machu Picchu Batholith) was

part of a slowly eroding endorheic environment during the Miocene, undergoing rock and surface uplift but little exhumation, as it was associated with a high-elevation local base level comparable with the present-day endorheic Altiplano.

Drivers of Pliocene exhumation

Our data suggest that exhumation rates increased dramatically at 4 Ma (Figs 2b and 3a). The total amount of exhumation since that time, however, depends on the assumed geothermal gradient. If the ‘cold’ Altiplano option is considered, total exhumation since *c.* 4 Ma amounts to 5.2 ± 2.4 km; in contrast, if the ‘warm’ Eastern Cordillera option is used, this number decreases to 2.4 ± 1.2 km. Regardless of the choice of geothermal gradient, these values are higher than those obtained in the Eastern Cordillera further south in Bolivia for the same period (*c.* 0.6 km Ma⁻¹; Lease and Ehlers 2013; Fig. 1, reference 3).

Fitting equilibrium profiles to the reaches of the Urubamba River above and below the knickzone (Kirby and Whipple 2012) allows us to derive a minimum depth of incision of 1.4 ± 0.2 km at the base of the knickzone (Fig. 5). This amount represents the height of the rock column above the present-day knickzone before incision. We suggest that the Urubamba River captured a former *c.* 3.8 km high endorheic drainage system of the Altiplano, initiating canyon carving at *c.* 4 Ma (Fig. 4). A similar scenario of endorheic basin capture and opening to the Amazon is recorded in the adjacent Mantaro River catchment to the north (Fig. 4a; Wise and Noble 2008).

Either climatic or tectonic changes could have further amplified incision. Two major but diachronous climatic events affected the Central Andes since the Miocene, both linked to emplacement and/or intensification of the South American monsoon leading to climate-driven incision of the Eastern Cordillera. The first is global Pliocene cooling between 4 and 2 Ma (Zhang *et al.* 2001), which has been interpreted as the remote driver for incision of canyons cutting perpendicularly through the Eastern Cordillera in southern Peru and Bolivia (Lease and Ehlers 2013). This cooling signal is even documented in northern Peru in the Cordillera Blanca area (Margirier *et al.* 2015). An older and more regional climatic event involves increased precipitation and possibly related intensified erosion in the Eastern Cordillera owing to surface uplift in the Central Andes during the Late Miocene (*c.* 10 to 6 Ma; Uba *et al.* 2007; Poulsen *et al.* 2010). This precipitation gradient pattern is still valid at present (Supplementary Fig. 2).

Whether incision was climatically amplified or not, a first-order observation from our data is that the reconstructed amount of incision (1.4 ± 0.2 km) overlaps the lower end of our exhumation estimate for a ‘warm’ geothermal gradient (2.4 ± 1.2 km; Fig. 5) but if a ‘cold’ geothermal gradient is assumed, the amount of canyon incision is significantly smaller than total exhumation at river level since 4 Ma (5.2 ± 2.4 km; Fig. 5). Some additional uplift will be caused by the isostatic response to mass removal by river incision. Zeilinger and Schlunegger (2007) quantified the maximum deflection owing to isostatic rebound to river incision for the Rio La Paz in the Bolivian Eastern Cordillera, a system similar in scale to the Urubamba River, and found that for an elastic thickness of 17.5 ± 2.5 km (Pérez-Gussinyé *et al.* 2008) this would be *c.* 0.2 km; that is, a negligible amount. Furthermore, glaciations could also promote erosion and incision. Postglacial isostatic rebound could potentially accelerate the surface uplift and exhumation. These observations are particularly true for fully glaciated area such as the Cordillera Blanca in northern Peru (Margirier *et al.* 2016). In contrast, present-day glaciers represent an insignificant part of our study area, as they occupy only >4.5 km elevation zones (Licciardi *et al.* 2009). In this intertropical context, they did not reach <4 km elevation in the past, with drier climatic conditions limiting their

spatial extent (Pleistocene; Fox and Bloom 1994). We thus do not take into account potential glacial influence on exhumation for the Machu Picchu region. A substantial amount of exhumation since 4 Ma (1.0 ± 1.4 km for the ‘warm’ geotherm case; 3.8 ± 2.6 km for the ‘cold’ geotherm case) thus has to be tectonic in origin. Knowledge of the (active?) tectonics of the Abancay Deflection remains limited because of its complex structural setting, dense vegetation and difficult access. Initiation of compression in the Subandean fold-and-thrust belt to the NE of the Abancay Deflection at *c.* 14 Ma is associated with thick-skinned tectonics (Espurt *et al.* 2011) that potentially could affect the basement of the Abancay Deflection. The diachronous *c.* 4 Ma acceleration of exhumation recorded in the Machu Picchu Batholith, in either of the hypotheses, suggests that the Abancay Deflection is tectonically decoupled from its surroundings. We propose activity of the Apurimac fault system to explain the additional post-Miocene exhumation (not explained by incision). Inherited normal faults reactivated as thrusts affecting the Eastern Cordillera are already documented further south in Bolivia (Perez *et al.* 2016), which could be comparable with the Apurimac fault system context. The structure of the Abancay Deflection developed by horizontal strike-slip faults with limited vertical motion during the Miocene (*c.* 20 to 4 Ma; Dalmayrac *et al.* 1980; Roperch *et al.* 2011; this study). A change to a more compressional setting at 4 Ma may have led to significant exhumation of the Abancay Deflection along the Apurimac fault system.

Conclusion

The opportunity to sample in the Machu Picchu Geopark provides a unique insight into a key area of the segmented Andean orogen: the Abancay Deflection. Our new thermochronology data and modelling from the Machu Picchu Batholith in the core of the Abancay Deflection reveal slow exhumation during the Miocene, despite evidence for both contemporaneous surface uplift and tectonic shortening of the northern Altiplano. This temporal decoupling of uplift and exhumation supports the hypothesis of an endorheic northern Altiplano prior to the Pliocene, as previously suggested from provenance data. Sediments seemed to be transported from the Eastern Cordillera toward the Altiplano in the late Miocene (Sundell *et al.* 2018) whereas the modern drainage direction is reversed toward the Amazon foreland. Geomorphological analysis of the Urubamba drainage basin suggests that it evolved through capture of an endorheic drainage system. At *c.* 4 Ma, drainage capture occurred close to our sampling location, resulting in base-level fall and causing a knickzone associated with significant incision to form at the point of capture. As a result of this increased focused incision, exhumation in this area increased since 4 Ma. The knickpoint has retreated toward the SE with the granite exposed all along the high-relief knickzone. The process driving exhumation is, however, probably more complex. As the total amount of exhumation may be larger than the maximum allowable amount of incision, depending on assumptions on the value of the geothermal gradient, additional tectonic uplift may be controlled by the Apurimac fault system.

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(equal), funding acquisition (lead), supervision (equal), visualization (equal), writing – review & editing (equal); CG: investigation (equal), writing – review & editing (equal); PvdB: investigation (equal), visualization (equal), writing – review & editing (equal); MB: investigation (equal), writing – review & editing (equal); CB: resources (supporting), writing – review & editing (supporting); FD: resources (supporting), writing – review & editing (supporting)

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Hazardous faults of South America; compilation and overview

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ABSTRACT

The heterogeneous South American geology has coined a wide variety of neotectonic settings where crustal seismogenic sources do occur. This fact has led to different approaches for mapping and inventory neotectonic structures. The South American Risk Assessment project promoted the discussion and update under uniform standards of the available information on neotectonic deformation, for its application in regional Probabilistic Seismic Hazard Assessments. As a result, 1533 hazardous faults have been inventoried onshore South America, 497 of them qualifying to feed the engine model driving probabilistic maps.

Main hazardous structures are concentrated throughout the eastern boundary of the Northern Andean Sliver and along the foreland-facing Andean Thrust Front. Space geodesy and seismicity illuminate the seismogenic significance of these deformation belts, although few neotectonic surveys have been conducted to date in the latter region. The characteristics of the main structures or deformation zones are here outlined according to their filiation to neotectonic domains, which are dependant on the geologic, seismotectonic, or morphotectonic settings in Andean and extra-Andean regions.

The knowledge accrued on the hazardous faults in South America here compiled, reinforces the fact that some of these structures constitute significant hazard sources for many urban areas and critical facilities and should be incorporated in seismic hazard assessments. However, the available fault data are insufficient in many cases or carry significant epistemic uncertainties for fault source characterization. This contribution aims to summarize the present knowledge on the South American hazardous faults as well as the main challenges for successful fault data incorporation into seismic hazard models.

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1. Introduction

The location and displacement record of fault sources constitute basic insights for seismic hazard assessment (SHA), helping to conduct more appropriate evaluations for a specific structure or region. This information is particularly relevant for areas where the recurrence interval of destructive earthquakes is larger than the time coverage provided by the seismic catalog, or whose slip rates can be barely measurable by instrumental networks. Thus, inventories under common compilation criteria of geologic structures with seismogenic significance in South America, constitute a basic supply for sound regional SHA which may also spotlight departure points for more detailed fault characterization studies.

The different seismotectonic and morphoclimatic settings in South America have traditionally resulted in heterogeneous criteria for mapping and interpreting neotectonic structures, particularly regarding the fault source geometry and activity rates. Many neotectonic or Quaternary-active structures have very limited information to date on their precise geometry, kinematics, and slip rates. Moreover, these attributes have usually been identified or suspected merely by fault/fold-related landforms or expert judgment, whereas no other data related to their activity or hazard are available. Accordingly, key parameters for fault source characterization such as slip rate and the 3D fault geometry (e.g. Basili et al., 2008; Haller and Basili, 2011; Pagani et al., 2015) carry high epistemic uncertainties or are absent for a significant number of structures.

A timely opportunity to update and review the existing data on the nature and distribution of onshore hazardous faults in South America has been the launching of the South America Risk Assessment project (SARA) (<https://sara.openquake.org/>), under the sponsorship of the Global Earthquake Model initiative (<https://www.globalquakemodel.org/>). The project was operative from 2014 to 2016 and aimed to estimate the regional hazard and risk through a probabilistic engine. The ultimate goal was to visualize the factors that increase the physical damage and decrease the resilience of populations to respond to and recover from damaging earthquake events.

The seismic hazard component of SARA addressed the harmonization of critical earthquake data sets, including crustal hazardous faults (SARA Topic 2), as one of the input layers of the SARA seismic hazard source model (SHSM) to calculate hazard and risk. The hazard or seismogenic capability of neotectonic structures (namely, those which have or are suspected to have slipped during the Quaternary), has been approached through characterization of their geometry, kinematics, and activity rate as main parameters. The other layers were historical and instrumental earthquake catalogs and recordings of local/national strong-motion. The project's main outcome has been the first regional probabilistic seismic hazard assessment (PSHA), with all data and tools placed in the public domain for data capture and representation (https://sara.openquake.org/hazard_rt7).

The SARA Topic 2 project activities have been focused on compiling the existing databases and in bridging the gap, whenever possible, between neotectonic information and the necessary data of faults sources required by the SARA SHSM. This contribution aims to summarize the main neotectonic settings in continental South America, relevant as to the occurrence of significant hazardous crustal structures, and to describe the criteria and strategies for data compilation. Such a goal implied to review and update the existing databases; to compile and elaborate new information and to upgrade many data by populating the required parameters for fault source modeling under homogeneous standards. The project also aimed to set up basic criteria to capture new GIS-based data, which can provide guidance for future research on these topics.

2. Tectonic outline of South America

As a response to contemporary geodynamical processes, neotectonic

deformation in South America is concentrated along the Andes (Fig. 1). Intraplate low strain regions comprising cratonic areas and related basins in extra-Andean South America constitute the major domain in terms of areal representation, but with few occurrences of hazardous faults in comparison to the Andes and peri-Andean regions.

The inherited geological and structural patterns and discontinuities of the Andes orogen, as well as the present plate tectonic setting, cause a wide variety of neotectonic environments in terms of both structural styles and strain rate, under different morphoclimatic conditions. These settings vary from an active subduction megathrust and onshore interplate borders, to slowly deforming internal regions. As for its present geodynamics, the Andean chain is characterized by the prevalence of strike-slip tectonics at its northern and southern extremes and by a typical oceanic-continental plate boundary throughout the Central Andes (Fig. 1).

The Andes have traditionally been divided into three main sectors, namely the Northern Andes, the Central Andes, and the Southern Andes (e.g. Gansser, 1973; Ramos, 1999) (Fig. 1). The Northern Andes, located north of the Gulf of Guayaquil (Fig. 2) are the result of the interactions between the Nazca, South American and Caribbean plates, involving a complex framework of tectonic blocks also related to the collision of island arcs (e.g. Ramos, 1999, 2009; Taboada et al., 2000; Audemard and Audemard, 2002; Audemard, 2014a; Arcila and Muñoz-Martin, 2020). Strike-slip tectonics is dominant near these plate boundaries throughout the Caribbean coast. Of particular relevance for the



Fig. 1. Main plate boundaries and geotectonic features of the continental South American Plate. Opposite red arrows point out boundaries between the Northern, Central, and Southern Andes domains. Yellow quadrangles show figures location. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

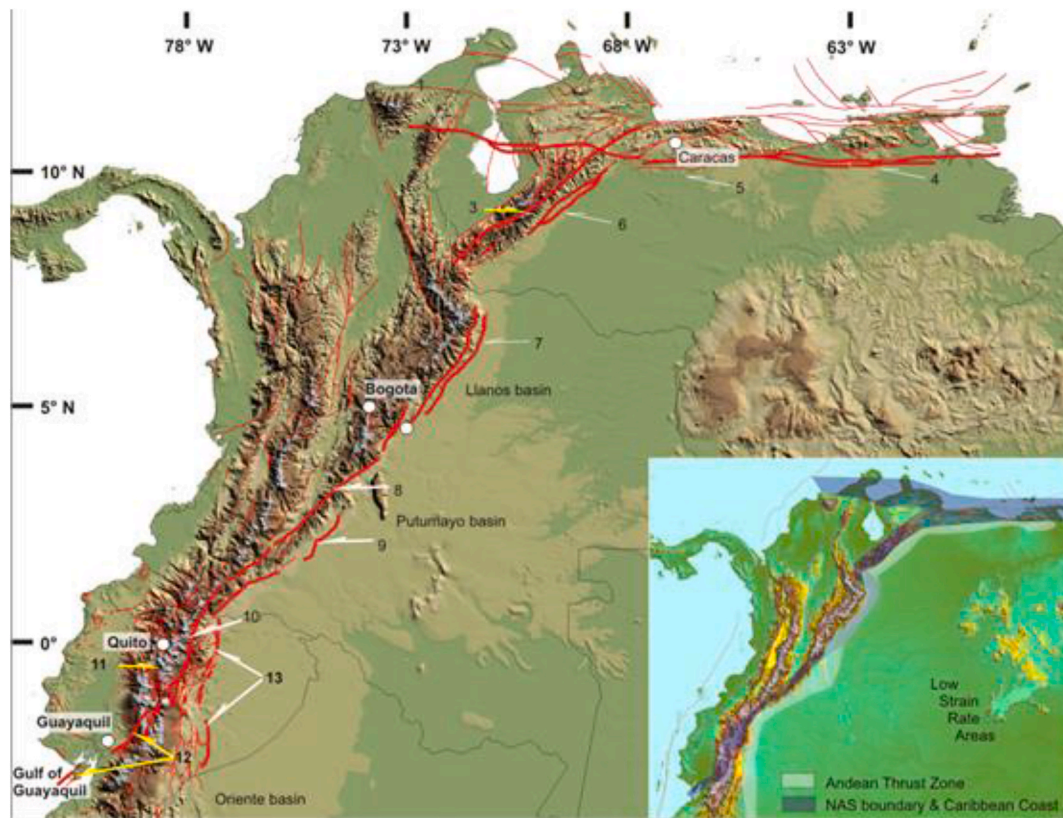


Fig. 2. Outline of the main hazardous fault systems (tick red lines) of the Northern Andes. 1. Oca-Ancón, 2. San Sebastian-El Pilar, 3. Boconó-Morón, 4. Campo Texas-Pedernales-Jusepin, 5. Frontal Thrusts, 6. South Andean Flexure Zone, 7. Eastern Frontal Thrust System, 8. Algeciras, 9. Amazonian Border, 10. Cosanga-Chingual, 11. Inter Andean Depression and Quito-Latacunga, 12. Pallatanga-Puná, 13. Subandean Thrust Zone. The inset shows the main neotectonic domains sketched in the text. See the location in Fig. 1. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

occurrence of hazardous faults is the eastern boundary of the North Andean Sliver (NAS) or North Andean Block. This first-order deformation belt concentrates the escape to the north of the NAS as to stable South America (Pennington, 1981; Stephan et al., 1990; Bellier et al., 1989; Freymueller et al., 1993; Audemard, 1998; Nocquet et al., 2014; Alvarado et al., 2016; Mora-Páez et al., 2019a, 2020).

The Central Andes, between 4°S and 46°30' S are regarded as the typical Andean orogen, where mountain building and related processes are mainly driven by type-B subduction (Ramos, 1988, 1999; Gutscher et al., 2000) (Fig. 1). The main control of location and style of Quaternary deformation is exerted by the geometry of the subducted Nazca plate, determining several regions with distinct characteristics. Latitudinal segments with normal subduction angles show noticeable differences in spatial distribution and tectonic style of Quaternary deformation as regards to flat-subduction segments. This is mainly because neotectonic deformation is more efficiently transmitted to the foreland region in the latter (e.g. Jordan et al., 1983; Jordan and Allmendinger, 1986; Gutscher et al., 2000; Ramos et al., 2002).

South of 46°30'S, the Southern Andes are associated with ridge collision and kinematic interaction among the South American, Antarctica, and Scotia plates, determining the concentration of strike-slip deformation at the southern end of the continent (Dalziel et al., 1975; Cunningham, 1993; Klepeis, 1994; Ramos, 1999; Kraemer, 2003; Smalley et al., 2003) (Fig. 1).

Recent and ongoing deformation in the Pacific lowlands and Andean Forearc is a direct manifestation of interplate processes and seismicity at the Benioff zone (e.g. Allmendinger et al., 2005; Audin et al., 2008; Allmendinger and González, 2010; González et al., 2015; Benavente et al., 2017a). Major Quaternary structures at the eastern slope of the Andes instead, are related to crustal weaknesses rather than to interplate processes (Costa et al., 2006a and references therein).

The intraplate regions of cratonic South America expose a long-evolved Precambrian basement coexisting with sedimentary rocks deposited in pericratonic and rift basins. Neotectonic deformation has been described located on shear zones of pre-existing anisotropies of the basement rocks (e.g. Bezerra et al., 1998; Riccomini and Assumpção, 1999; Bezerra and Vita Finzi, 2000; Nogueira et al., 2010; Coelho et al., 1997; de Menezes et al.; Ramos et al.). Other neotectonic faults cut across pre-existing basement structures and form new faults (Bezerra et al., 2011).

3. Neotectonic domains

The diversity of geodynamic and geologic settings in space and time, determine a wide variety of neotectonic scenarios in continental South America. Similarities in the structural style of inventoried hazardous fault systems usually show a dependence upon the regional geology or their occurrence being constrained by morphostructural units. Such discrete areas are here conceived as *Neotectonic Domains*. This discrimination does not intend to cover the entire region or the occurrence of all hazardous faults known. It aims to introduce a geographic-based sketch to link the occurrence of main hazardous faults and neotectonic deformation zones with particular geologic, seismotectonic, and/or morphotectonic settings. Some domains are restricted to specific areas or major morphostructural provinces, whereas others overlap over different geologic and geodynamic environments.

The main *Neotectonic Domains* arising from the compiled data can be outlined as follows;

3.1. The Andean thrust zone

Although resulting from very variable geology, geologic evolution,

and plate interactions, the Andean foothills facing to the continental interiors from Venezuela to the Southern Patagonian Andes are characterized by an almost continuous zone with localized neotectonic crustal compression. Essentially a fold and thrust belt (FTB) of variable width, thickness, and net shortening (Figs. 1–6), only interrupted in the northern Pampean-Chilean flat-slab (27°–30°S).

Most structures are derived from FTB geometries, in some cases rooted in basement rocks and evolving from inverted Mesozoic faults (e.g. Fabre, 1983; Baby et al., 1992, 1997; 2018; Audemard and Audemard, 2002; Audemard, 2003; Mora et al., 2006, 2009, 2019; Zamora et al., 2009; Giambiagi et al., 2015; Folguera et al., 2015; Villegas-Lanza et al., 2016; McClay et al., 2018). These FTB have usually been formed from ~10 Ma to Present along the active Andean orogenic front (e.g. Mora et al., 2006, 2014; Ramos, 2009; Horton, 2018). Subandean thrust faults are commonly blind and related to piedmont anticlines. Although barely exposed at the surface, they can be imaged through gentle up-bulges or suspected from tilted alluvial surfaces in the piedmont alluvial planes and drainage anomalies (Dumont et al., 1991; Dumont, 1996; Audemard, 1999; Bes de Berc et al., 2005; Mugnier et al., 2006). The underlying causative structures have usually been illuminated through oil industry seismic lines.

In Venezuela, mountain building along the NE-SW trending Merida

Andes has been mainly driven by complex interactions between the Caribbean, South American, and Nazca plates with recent deformation concentrated along the Boconó Fault System (Fig. 2) (e.g. Pennington, 1981; Schubert, 1982; Freymueller et al., 1993; Audemard and Audemard, 2002; Trenkamp et al., 2002). However, the southeastern foothills of this mountain range are bounded by the South Andean Flexure Zone (Audemard and Audemard, 2002), which is rooted under this mountain range (Fig. 2). These contractional blind structures result from a complex flat and ramp geometries generally SE-vergent, which deform Quaternary alluvial terraces along the piedmont area (Audemard, 1999, 2003; Audemard et al., 2000; Audemard and Audemard, 2002) (Fig. 2). Similar thrust systems with opposite vergence appear at the northwestern foothills of the Merida Andes (De Toni and Kellogg, 1993; Audemard and Audemard, 2002; Duerto et al., 2006).

To the east of the Merida Andes and not directly related to the Andean chain, a main thrust boundary zone with general E-W trend results from shortening linked to the Caribbean-South America plates interaction along the Caribbean coast. In central-northern Venezuela, it is the southern boundary of the Caribbean nappes that overrode the continent in the Paleogene. Discontinuous reverse faults systems, such as Cantagallo and Frontal thrusts in central Venezuela (Audemard et al., 1988), and Campo Texas-Pedernales-Jusepin faults in eastern Venezuela

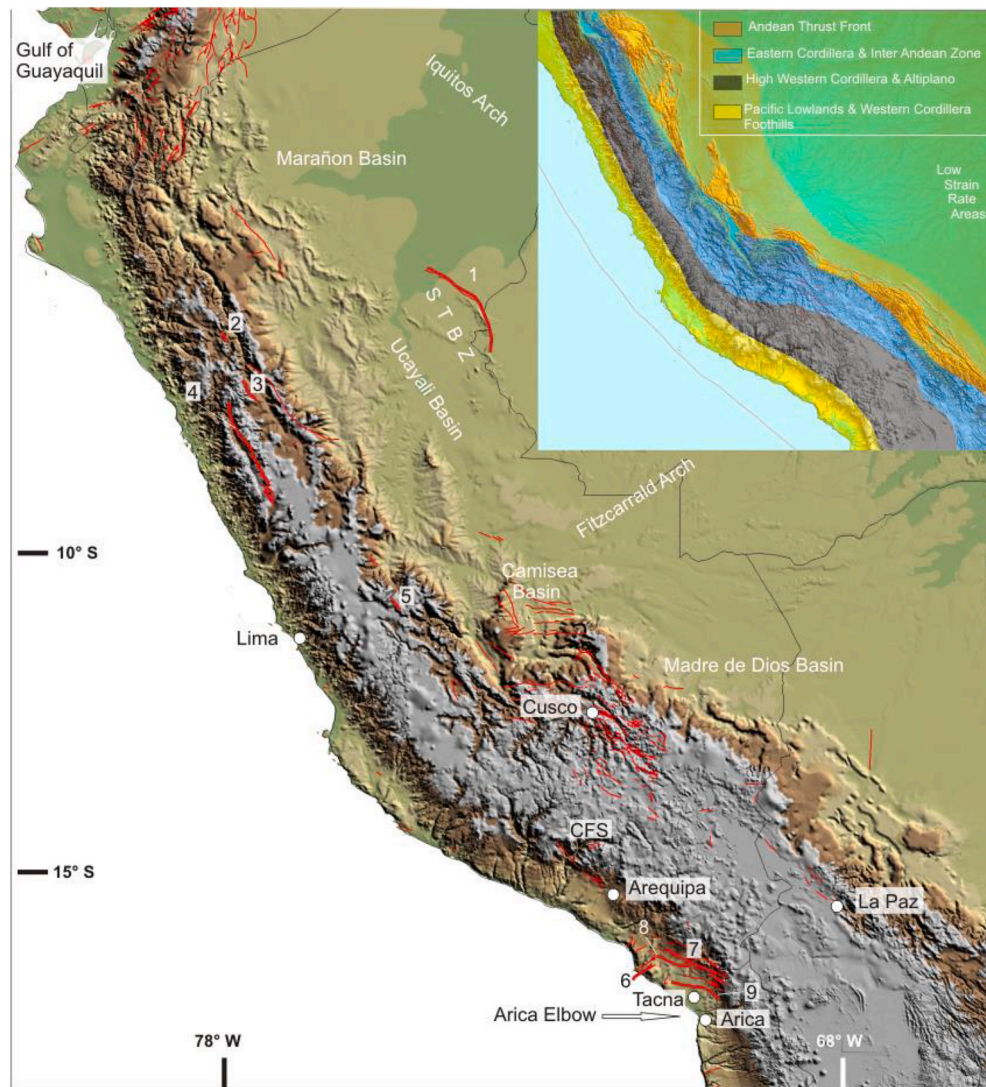


Fig. 3. Main hazardous faults and fault systems in the northern section of the Central Andes. 1. Subandean Tilted Block Zone, 2. Chaquilbamba, 3. Quiches, 4. Cordillera Blanca, 5. Huaytapallana, 6. Chololo, 7. Incapuquio, 8. Purgatorio, 9. Sama-Calientes. The inset displays the neotectonic domains corresponding to this region. See the location in Fig. 1.

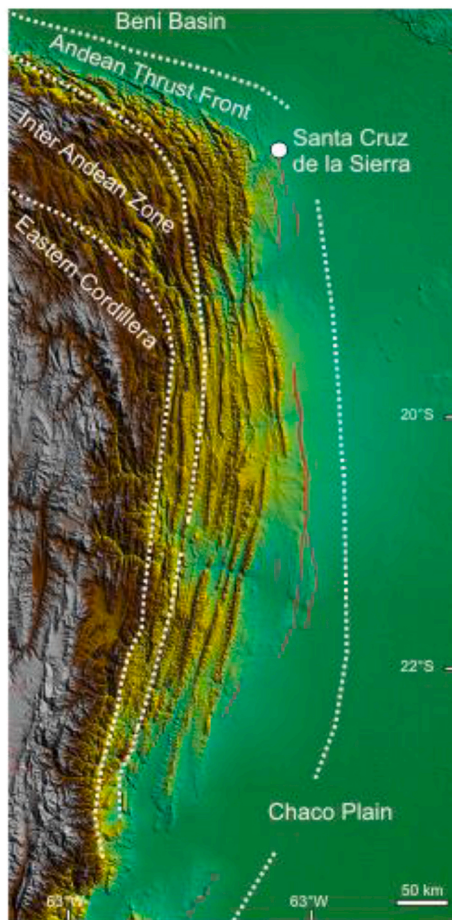


Fig. 4. SRTM image of the Andean Thrust Front and related neotectonic domains in the Bolivian Andes, depicting the Mandeyapécu Thrust System. Thrust traces according to the SARA T2 database and Weiss et al. (2015). See the location in Fig. 1.

(FUNVISIS, 1994; Singer et al., 1995; Wagner, 2004; Fajardo, 2015), extend up to the Atlantic coast and bound the southern coast of Trinidad (Fig. 2). In eastern Venezuela and southern Trinidad, this belt is accompanied by a trend of active oil-seeping mud volcanoes.

The Mérida Andes meets the Eastern Cordillera of the Colombian Andes in a structurally complex zone, where the Andean chain experiments two opposite right-angle bends as the dextral motion of the Boconó Fault System is being transferred into the Eastern Frontal Thrust System (EFTS) of the Eastern Cordillera in Colombia (Fig. 2). After a first bend to the south, this transfer is made possible by east-verging NNW trending thrusts in Colombia (Rodríguez et al., 2017). And after a second opposing bend, they connect with the EFTS through the NE trending Guaicaramo Fault System and related anticlines. These structures deform Pleistocene alluvial terraces (Paris and Sarria, 1986; Robertson, 1989, 2007; Vergara et al., 1995; Audemard, 1999; Diederix and Romero, 2009) with slip rates ~ 1.5 mm/a (Mora et al., 2010; Veloza et al., 2012; 2015, among others). This value is not much different from the one obtained for the South Andean Flexure Zone in Venezuela (Fig. 2), where Guzmán et al. (2013) estimated an uplift rate of 1.1 mm/a for the last 70 ka. Assuming a typical average dip of 30° for the master thrust zone, thus a slip rate ~ 2.5 mm/a can be expected. Historic and recent crustal earthquakes have occurred along this active front in Colombia such as the 1995 Mw 6.5 Tauramena earthquake (Dimaté et al., 2003).

Current tectonic activity is completely partitioned in the Mérida Andes (Audemard and Audemard, 2002; Audemard, 2009a). The Boconó fault takes most if not all the dextral slip while the South Andean

Flexure Zone and the northern FTB and the chain itself accommodate across-strike shortening. Dextral and reverse slip at the EFTS (Guaicaramo, Cusiana, Yopal, and others thrusts) in Colombia are not as clearly dissociated along the southern foothills of the Eastern Cordillera north of 4° N.

At $\sim 4^\circ$ N this compressive-transpressive bends slightly again to the NE-SW and Quaternary-active fault traces have been mapped through the inner Eastern Cordillera, merging with the dextral Algeciras Fault System (AFS) (Pennington, 1981; Taboada et al., 2000; Diederix and Romero, 2009; Diederix et al., 2019; Bohorquez et al., this volume), where Gómez et al. (2015) documented a transpressive duplex system between the AFS and the Guaicaramo Fault system. However, south of $\sim 4^\circ$ N, contractional neotectonic structures have also been reported along the Subandean zone, bounding the Garzón Massif on the east with the Putumayo basin (Mocoa and Amazonian Border Faults) (Paris and Romero, 1994; Paris et al., 2000; Robertson and Castiblanco, 2011; Veloza et al., 2012; Saeid et al., 2017; https://sara.openquake.org/hazard_rt2), indicating the southward continuation of the foothills contractional belt (Figs. 2 and 3).

Thrust faults, most of them blind, also prevail along the Ecuadorian foothills. These neotectonic structures are the outer bound of the Subandean Thrust Zone or Eastern Sub-Andean Thrust-and-Folds Belt (ESB), *sensu* Yepes et al. (2016), highlighted by bedrock uplifts, such as the Napo (i.e. Payamino, Pusuno and Sumaco faults) and Cutucú (Cutucú, Cangaime faults) uplifts (Fig. 3). Quaternary tectonic activity has been reported based on secondary evidence, drainage control, and coincidence with Neogene underlying structures (Ego et al., 1996; Egüez et al., 2003; Bès de Berc, 2003; Bès de Berc et al., 2005; Bernal et al., 2012).

South of the Gulf of Guayaquil (4° S), where the Carnegie ridge meets the trench, to $\sim 46^\circ$ S, the Andean Thrust Front lies in the Central Andes setting (Fig. 1). The thrust front has been migrating eastwards during the Cenozoic and in the Andes of Perú, Bolivia, and Argentina. Main Neogene shortening is recorded at the Eastern Cordillera but particularly at the Subandean zone (Fig. 3). The latter is the locus of active Andean growth and mountain building processes, as underlined by geodetic and seismologic data (Ramos, 1988, 1999; Kendrick et al., 1999, 2006; Gutscher et al., 2000; Taboada et al., 2000; Brooks et al., 2011; Nocquet et al., 2014; Alvarado et al., 2016).

The Central Andes of Perú exhibits a general NNW-SSE trend south of the gentle Huancabamba deflection (Fig. 3). The thrust front here lies above the Peruvian flat-slab segment (4° – 14° S), although the Subandean zone exhibits similar structural style as to the Northern Andes of Ecuador (Oriente basin) (Ham and Herrera, 1963; Ego et al., 1996; Baby et al., 1997). These areas are poorly surveyed as for neotectonic structures and the few ones compiled have insufficient and low-reliability data. Dumont et al. (1991) and Dumont (1996) outlined the Subandean Tilted Block Zone (STBZ) parallel to the Peruvian Subandean FTB, which is partly bounded by the Tapiche fault (Macharé et al., 2003, 2009a) (Fig. 3). According to these authors, neotectonic thrust activity along the STBZ controls major rivers patterns and migration, such as the Pastaza and Ucayali rivers to flow parallel to the STBZ, before merging into the Amazonas river and overpassing the forebulge of the Iquitos arch (Fig. 3).

The Peruvian flat-slab extends down to $\sim 14^\circ$ S, flanked to the south by major crustal-scale features, such as the Abancay deflection, the Camisea Subandean zone (Espurt et al., 2011) and the Fitzcarrald arch (Regard et al., 2009) (Fig. 3). Here, the Andean Thrust Front undergoes a local right angle deflection with many structures suspected to have sustained Quaternary activity (Ham and Herrera, 1963; Baby et al., 1997; Macharé et al., 2003, 2009a; Mora et al., 2009; Benavente et al., 2013; Regard et al., 2009; McClay et al., 2018, <https://www.ingemmet.gob.pe/mapa-neotectonico>; https://sara.openquake.org/hazard_rt2; <http://neotec-opendata.com/>).

The Andean chain notably widens south of the Abancay deflection above a normal subduction segment (14° – 27° S) (Fig. 4) and the Subandean thrust zone describes a gentle arc concave to the southwest with

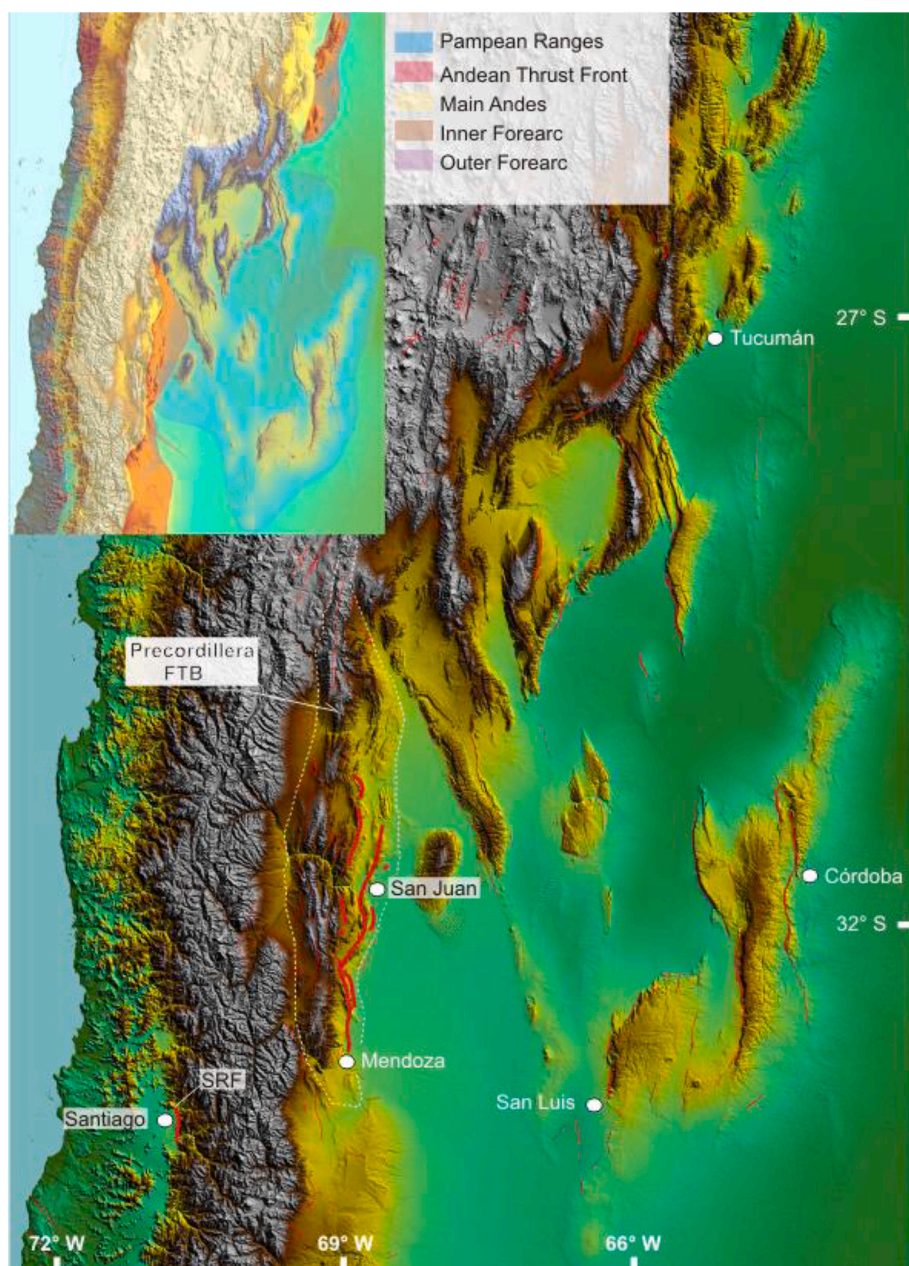


Fig. 5. The Andean broken foreland represented by the basement uplifts of the Pampean Ranges stands out in peri-Andean regions above the Pampean-Chilean flat subduction segment (27°–33°S). The main bounding faults compiled in this domain appear in thin red lines. The Andean Thrust Front is here located in the eastern part of the Precordillera FTB. SRF, San Ramón Fault. The inset shows the main neotectonic domains in this latitudinal section. See the location in Fig. 1. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

a general NW trend. Almost none neotectonic structures have been compiled at the orogenic front between 14° and 18°S, a latitudinal segment coincident with the northern part of the Altiplano plateau and also characterized by an FTB style of Neogene deformation. Quaternary-active structures propagating eastward into flat Neogene sediments of the Beni basin has been suspected from subsurface data (Dumont, 1996; Baby et al., 1997; Gautheron et al., 2013; McClay et al., 2018; Rojas Vera et al., 2019) (Fig. 4) and suggested by the dynamics and adaptation of major (Dumont, 1996; Regard et al., 2009).

The Subandean zone of the Bolivian orocline bends to a general NNE direction in coincidence with the Arica elbow south of 18°S and extends down to 23°S (Argentina-Bolivia frontier zone). This segment corresponds to the widest, highest, and thickest Andean segment, whose retroarc orogenic belt has also accrued the highest Cenozoic shortening (Horton, 2018) (Fig. 4). The frontal deformation zone of the Andes can be recognized in the topography by a series of thin- and thick-skinned fault-related folds with parallel trends (Baby et al., 1992; Leturmy et al., 2000; Rocha and Cristallini, 2015; McClay et al., 2018; Giampaoli

and Rojas Vera, 2018; Rojas Vera et al., 2019). The outer thrust of this FTB corresponds to the Mandeyapecua Thrust System (MTS) (Moretti et al., 1996; Lavenu et al., 2000; Brooks et al., 2011; Weiss et al., 2015) (Fig. 4). Brooks et al. (2011) have suggested that the master faults underlying the orogenic wedge have the capability of producing large ($M_w > 8$) earthquakes. These authors derived a slip rate ~ 10 mm/a from geodetic data, corresponding to the locked portion of the detachment zone beneath the subandean zone. Weiss et al. (2015) refined Holocene dip-slip rates for the MTS, suggesting values of ~ 4.6 mm/a. This indicates that $\sim 1/2$ of both the mean geologic and geodetic shortening rates (~ 7 – 13 mm/a) are accommodated by dip-slip motion at the wedge-front, highlighting the significant threat that the MTS poses for this region.

Neogene shortening decrease from north to south along the Bolivian subandean zone (McClay et al., 2018; Giampaoli and Rojas Vera, 2018; Rojas Vera et al., 2019), although Holocene deformation has also been described at its southern tip in Argentina (Ramos et al., 2006).

The Andean Thrust Front progressively loses its typical topographic

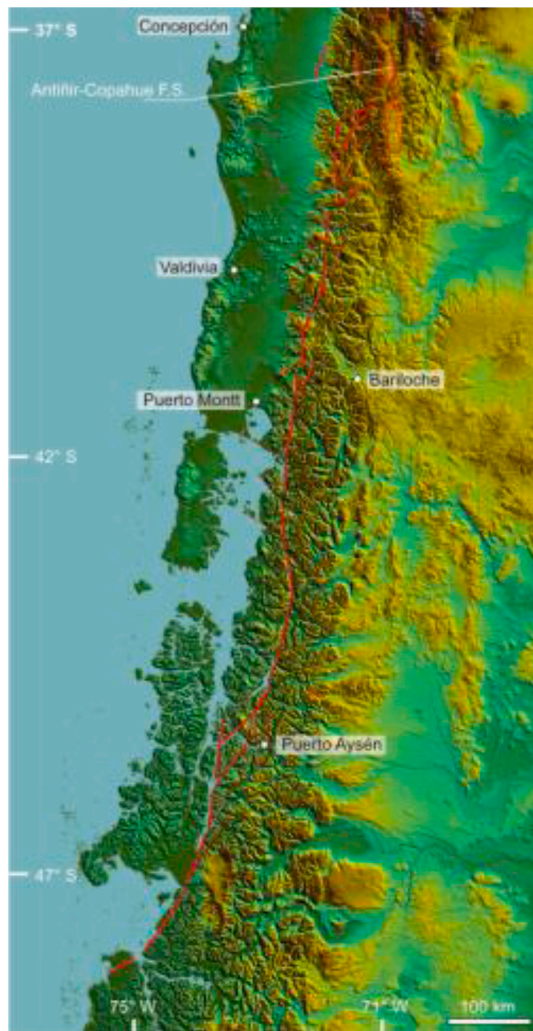


Fig. 6. SRTM image sketching the general trace of the Liqueñe Ofqui Fault System and its proposed continuation to the north into the Antifir-Copahue Fault System. See the location in Fig. 1.

imprint at the northern part of the Pampean-Chilean flat-slab (27°–33°S), where extra-Andean mountain building has been characterized by widespread Neogene broken-foreland basement uplifts (Pampean Ranges) during the last ~8Ma (Fig. 5) (e.g. Jordan and Allmendinger, 1986; Ramos et al., 2002; Costa, 1999; Costa et al., 2006a; Davila and Carter, 2013).

From a morphotectonic point of view, two main domains can be recognized along the Pampean-Chilean flat-slab. North of 29°–30°S, the Pampean Ranges are assembled to the Andean edifice, some of the uplifted basement blocks achieving an orogenic relief similar or even higher than the main Andean peaks (Ramos et al., 2004). The pattern of Quaternary faulting, characterized by short, distributed and not well spatially organized traces, suggests that the orogenic front is here characterized by a wide diffuse deformation zone (Costa et al., 2000a; García et al., 2013, 2017; Hongn et al., 2014; <https://sigam.segemar.gov.ar/visor/>) probably involving a thicker seismogenic crust. Conversely, south of 29°–30°S the frontal deformation zone of the Andes is concentrated at the Precordillera FTB foothills (Fig. 5), where an arid climate and suitable morphotectonic conditions favor the best exposures of the active orogenic front along the entire Andean chain (e.g. Bastías et al., 1984; Martos, 1987; Costa et al., 2000b, 2014a; 2015, 2019; Ahumada and Costa, 2009; Costa, 2009; Schmidt et al., 2011; Perucca and Onorato, 2011; Perucca et al., 2013; Audemard, 2014b; Audemard et al., 2016; Richard et al., 2019; Rimando et al., 2019). In this southern

part of the flat-slab segment, the Andean building is separated from the Pampean uplifts by a foreland basin (Fig. 5).

The Argentine Precordillera is a Palaeozoic orogen whose neotectonic deformation styles have been controlled by pre-Cenozoic structures, which result in a sharp change in the geometries and vergences of active thrusting north and south of 32°15'S (Cortés et al., 1999, 2006; Ahumada and Costa, 2009; Giambiagi et al., 2015; Costa et al., 2014a, 2019). Geodetic data suggests shortening rates of 4–7 mm/a (Kendrick et al., 1999, 2006; Brooks et al., 2003), although Quaternary shortening rates are variable, even within individual thrusts (Siame et al., 2002, 2005; 2006a; Schmidt et al., 2011; Rockwell et al., 2014; Costa et al., 2019; Richard et al., 2019; Rimando et al., 2019), highlighting the complexities for activity rates evaluation in these thrust systems. Most surveyed individual thrusts reveal shortening rates ~1 mm/a, suggesting that several active structures are accommodating the transient strain signal depicted by space geodesy. Geodetic data has also led to argue that the Andean hinterland behaves as a microplate at these latitudes (Brooks et al., 2003), although this interpretation is not necessarily endorsed by geologic data (García Morabito et al., 2020).

South of 33°S, another segment of normal subduction develops and the orogenic front becomes markedly less-well exposed and characterized by east-directed blind thrusts (Cortés et al., 1999, 2006; García and Casa, 2014; Moreiras et al., 2014). An FTB style also characterizes the Andean foothills between 33° and 38°S with sparse evidence of neotectonic activity (Messenger, 2010; Messenger et al., 2010; Galland et al., 2007; Sagripanti et al., 2017, 2020; Colavitto et al., 2019; Mescua et al., 2019).

Neogene shortening in the Central Andes orogen decreases gradually to the south (Ramos et al., 2004). Between 38°S and the Fuegian Andes, the characteristics of the Andean front as for the occurrence of Quaternary fault activity has been poorly documented, except for the Antifir-Copahue Fault System (ACFS) in the northern Patagonian Andes and other isolated minor faults (Fig. 6) (https://sara.openquake.org/hazard_rt2). It has been claimed that the dominantly compressive ACFS merges to the south with the Liqueñe-Ofqui Fault System (Folguera et al., 2004, 2006; 2015; Melnick et al., 2006; Colavitto et al., 2020). At the southern continental end, the evolution of the Fuegian Andes foothills is closely related to the dynamics of the South America-Scotia plate margin (Fig. 7).

3.2. The North Andean Sliver boundary and the caribbean coast

Most significant hazardous faults in northernmost South America result from the complex interaction between the Caribbean, South America, and Nazca plates, involving the North Andean Block *sensu* Pennington (1981) or North Andean Sliver (NAS) *sensu* Nocquet et al.



Fig. 7. Main fault traces compiled for the Magallanes-Fagnano Fault System and modified after Sandoval and De Pascale (2020). See the location in Fig. 1.

(2014), where strike-slip faults largely prevail. This crustal block is escaping to the NNE concerning stable South America, involving a wide deformation belt where several minor blocks can be recognized mostly through tectonic geodesy data (Pennington, 1981; Aggarwal, 1983; Stephan et al., 1990; Audemard, 1993, 1998, 2002, 2009b, 2014; Freymueller et al., 1993; Kellogg and Vega, 1995; Taboada et al., 2000; Trenkamp et al., 2002; Alvarado et al., 2016; Mora-Paez et al., 2019a, 2020; Arcila and Muñoz-Martin, 2020). The main motion of the eastern NAS boundary and current interactions with the Southamerican plate is being accommodated onshore by several strike-slip fault systems running from the Caribbean coast down to the Ecuadorian-Colombian trench at the Gulf of Guayaquil (Stephan et al., 1990; Audemard, 1993, 2002, 2009b, Audemard, 2014a; Taboada et al., 2000; Dumont et al., 2005; Alvarado et al., 2016; Yepes et al., 2016; Baize et al., 2014, 2020).

In Venezuela, a significant part of this right-lateral motion takes place along the dextral Boconó- San Sebastián-El Pilar Fault System (Fig. 2) (Molnar and Sykes, 1969; Minster and Jordan, 1978; Schubert, 1979, 1982, 1984; Pérez and Aggarwal, 1981; Aggarwal, 1983; Soulas, 1986; Beltrán and Giraldo, 1989; Stephan et al., 1990; Audemard et al., 2006; Audemard, 2007). The strike-slip El Pilar-San Sebastián fault system runs mostly offshore with E-W general trend along the Venezuelan coastline with slip rates $\sim 9\text{--}10$ mm/a (Audemard et al., 2006 and references therein). Several historic earthquakes have taken place along them, being the last significant one, the Ms 6.8 1997 Cariaco earthquake (Audemard, 2002). These coastal fault systems bend into the NE-SW trending Boconó Fault System (BFS) (Schubert, 1980a, 1980b, 1982, 1984) (Fig. 2) which runs with a fairly axial position along the Andes of Mérida with Quaternary slip rates varying from 4 to 11 mm/a (Audemard, 1997; Audemard et al., 1999; Pouse-Beltrán et al., 2017, and references therein). Structural complexities along these major wrench fault systems determine transtensional and transpressional zones (Audemard et al., 2006), which have nested historic earthquakes (Audemard, 1997, 2002; 2007, Audemard, 2014a; Rodríguez et al., 2017).

The dextral motion of the BFS is being transferred by complex kinematic interactions at the Pamplona indenter to the Eastern Frontal Thrust System (EFTS) of the Eastern Cordillera in Colombia (Audemard, 2014a; Rodríguez et al., 2017), where this domain overlaps with the Andean Thrust Front domain from $7^{\circ} 30'$ to 4°N (Fig. 2). South of this latitude this fault system bends to the NNE as it enters into the Eastern Cordillera, resuming the prevalence of dextral slip through the Algeciras Fault System (AFS) (Gómez et al., 2015; Diederix et al., 2019; Bohorquez et al., this volume, and references therein). This fault system as the main part of the NAS boundary is considered to continue through the Afiladores-Sibundoy faults (Paris et al., 2000; Velandia et al., 2005) and Chingual fault in Ecuador (Soulas et al., 1991; Egüez et al., 2003; Alvarado, 2009; Alvarado et al., 2016; https://sara.openquake.org/hazard_rt2; <http://neotec-opendata.com/>). The Chingual fault system is characterized by Quaternary slip rates ranging from 7 to 10 mm/a (Ego et al., 1995; Tibaldi et al., 2007).

According to Alvarado et al. (2016) and previous contributors, the eastern boundary of the NAS in the Ecuadorian Andes is constituted by the Chingual-Cosanga-Pallatanga-Puná (CCPP) fault systems (Fig. 2), which links different transpressive and contractional subsystems. West of the Cosanga and Pisayambo faults, the Interandean Depression (IAD) (Soulas et al., 1991; Lavenu et al., 1995; Egüez et al., 2003; Alvarado, 2009b; Alvarado et al., 2014) hosts contractional Quaternary deformation (Quito-Latacunga fault-fold system), where shortening rates of 1–4 mm/a have been estimated (Fiorini and Tibaldi, 2012; Alvarado et al., 2014; Champenois et al., 2017) (Fig. 2).

The Cosanga fault and the Quito-Latacunga faults and folds are almost N–S striking and are considered a transpressive segment of the NAS boundary. The former fault nucleated an Mw 5.0 earthquake in 2010 which ruptured at the surface (Champenois et al., 2017).

South of the IAD, the CCPP exposes dominant dextral strike-slip

along the Pallatanga fault (Soulas et al., 1991; Winter et al., 1993; Ego et al., 1996; Egüez et al., 2003; Alvarado, 2009c) where Holocene slip rates of 2.5–4.6 mm/a have been estimated (Winter et al., 1993; Baize et al., 2014, 2020). Paleoseismological investigation revealed large prehistoric earthquakes along the Pallatanga fault zone, bearing also records of the historic 1797 Riobamba event (Baize et al., 2014, 2020).

It is worth mentioning that even if the NAS eastern boundary concentrates the most significant hazardous faults in the Northern Andes, many other structures with documented Quaternary activity do occur in wide areas, particularly in western Colombia. Faults such as the Bucaramanga-Marta, Ibagué and Romeral Fault System, among other structures, play a role in accommodating neotectonic deformation with a prevalence of strike-slip movements (e.g. Diederix et al., 1987, 2011; Paris and Romero, 1994; Paris et al., 2000; Tibaldi and Romero, 2000; Diederix et al., 2006; Diederix et al., 2009; López, 2006; Osorio et al., 2008; Diederix and Romero, 2009).

In summary, the NAS east boundary constitutes a major tectonic feature in South America, particularly for hazardous faults occurrence and capability for generating large shallows crustal earthquakes. This deformation belt displays a general NE trend with dextral slip dominance, whereas, in areas with a dominant N–S strike, compressive sections prevail, like the EFTS in Colombia and the IAD-Cosanga fault in Ecuador.

3.3. The pacific lowlands and foothills of the Western Cordillera of the Central Andes

The peri-Andean zone from the pacific coast to the Andean foothills constitutes the main part of the Central Andes forearc (Fig. 1). This domain is very heterogeneous in terms of its geology, geomorphology, and occurrence of neotectonic structures. It overlaps several Andean segments with different subduction angles and orientations of the slip subduction vector. Certainly, it cannot be ascribed to a single domain and thus, the following outline merely constitutes a simplified approach for summarizing the occurrence of main hazardous faults throughout this environment.

Only a few data on the potential occurrence of hazardous faults have been compiled so far north of 17°S , although between 17°S and the Arica elbow in the Perú-Chile border ($18^{\circ}30'\text{S}$) several neotectonic structures have been described depicting dominant NW striking faults with different kinematics. Some faults transversal to the coastline exhibits normal slip, such as the Chololo fault, which are thought to be related to the subduction dynamics (Audin et al., 2006, 2008, 2009a; Benavente et al., 2017a, 2017b) (Fig. 3). In the Western Cordillera foothills and nearby piedmont, compressive and transpressive fault systems have been reported (Incapuquio, Purgatorio, and Sama-Calientes fault systems), with slip rates $\sim 0.2\text{--}0.5$ mm/a, linked to the Andean chain bend at the Arica elbow (Audin et al., 2006, 2008, 2009b, 2009c, this volume; Hall et al., 2012; Benavente et al., 2017a, 2017b) (Fig. 3).

South of the Arica elbow in Northern Chile, regional-scale neotectonic deformation is characterized by N–S striking structures. First-order latitudinal tectonic segments occur throughout Chile, mostly due to subduction dynamics and inherited bedrock geology, resulting in different neotectonic deformation styles (Gutscher et al., 2000; Tassara and Yañez, 2003; Yañez et al., 2001; Yañez and Cembrano, 2004; Ramos, 2009).

Santibañez et al. (2019) divided the occurrence of Chilean neotectonic crustal faults in three longitudinal domains (N–S trending strips); namely the Outer-Forearc (OF), the Inner-Forearc (IF) and the Volcanic Arc (VA).

The Atacama Fault System (AFS) stands out in the OF domain (Fig. 8). This fault system, composed by multiple fault sections, runs ~ 1000 km in northern Chile from 20°S to 30°S . It has a general N–S trend and an arcuate pattern concave to the west, sustaining locally Pliocene to Quaternary displacement mainly of extensional nature (Arabasz, 1968; Okada, 1971; Hervé and Thiele, 1987; Naranjo, 1987;

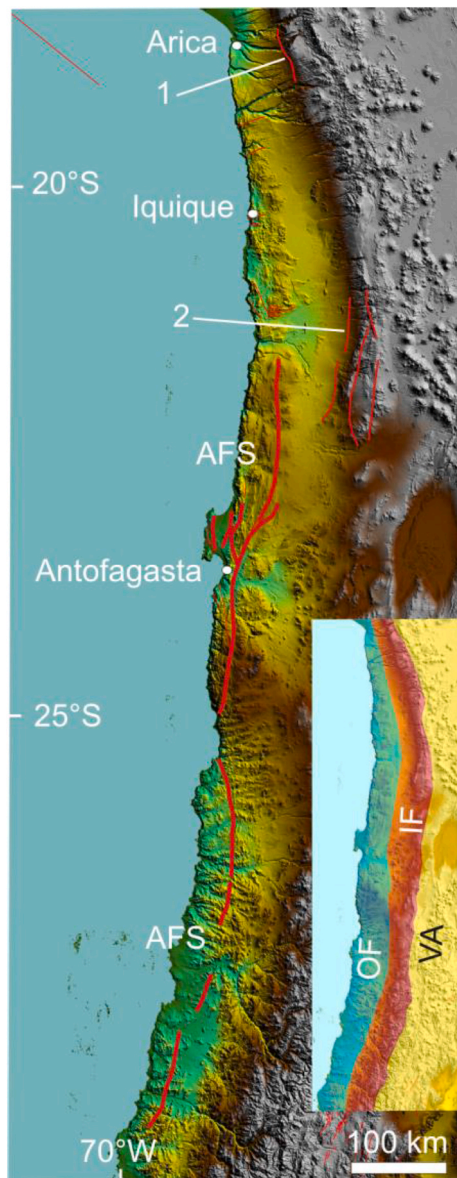


Fig. 8. Main traces compiled for the Atacama Fault System (AFS). 1. Western Andean Thrust, 2. Domeyko Fault System. Neotectonic domains in the inset. OF, Outer forearc, IF, Inner forearc, VA, Volcanic arc. See the location in Fig. 1.

González et al., 2003, 2008; Allmendinger and González, 2010; Cortés-Aranda et al., 2012). The best-known fault sections correspond to the Salar del Carmen and Mejillones faults, where Pleistocene-Holocene slip rates <1 mm/a and maximal magnitude $\sim M 7$ for paleo-earthquakes occurrence have been estimated (González et al., 2006; Cortés-Aranda et al., 2012; Ritz et al., 2019). South of Iquique (21°S), Pliocene to Quaternary strike-slip displacements along two NW-SE fault branches of the AFS have been documented by Carrizo et al. (2008). Furthermore, the Coastal Cordillera in northern Chile, between 19°S to 21° 30' S, exposes E-W reverse faults with neotectonic cumulative displacements up to 300 m. Some of these faults deform marine terraces and have been the locus of an Mw 6.7 earthquake (González et al., 2015). This N-S contraction is linked to the Nazca plate subduction along a concave to sea margin given by the Orocline bend of the Andes at this latitude (Allmendinger et al., 2005; González et al., 2015).

Trench-parallel normal faulting along the Coastal of Central Chile (34° 30'S) has been recently revealed by the reactivation of the Pichilemu Fault right after the 2010 Mw 8.8 Maule Earthquake. This extension is thought to be connected with coseismic and postseismic upper

plate extension promoted by unclamping of the megathrust (Aron et al., 2013, 2015). This fact underpins that independently of the local geological setting, hazardous faults located in the OF domain show a strong dependence on the subduction cycle.

The IF domain, according to Santibañez et al., (2019), extends along the Andes foothills and Chilean Precordillera (Fig. 8) through the Western Thrust System or Western Andean Thrust (WAT) (Muñoz and Charrier, 1996; David et al., 2005; García and Herail, 2005; Farías et al., 2005; Armijo et al., 2010; García et al., 2011) (Fig. 8). These structures are thought to have played an important role in the Altiplano uplift (Muñoz and Charrier, 1996), being its potential hazard underlined by historic earthquakes (Santibañez et al., 2019 and references therein). According to Armijo et al. (2015), the WAT is represented by discontinuous fault and fold systems, whose tectonic activity get younger to the south, involving neotectonic structures such as the Oxaya anticline, the Copaquilla-Tignamar thrusts, the Domeyko Fault System in northern Chile (Fig. 8), and the San Ramón Fault (SRF) further south (Fig. 5). The latter lies near the Santiago urban area in Central Chile exhibiting west-facing thrust scarps, at the boundary between the Central Depression and the Andes foothills (Lavenu et al., 2000; Rauld et al., 2006; Rauld, 2009; Armijo et al., 2010). Paleoseismological studies account for the occurrence of Late-Pleistocene-Holocene $\sim M 7.5$ earthquakes that ruptured along this fault, posing a significant threat for Santiago de Chile (Armijo et al., 2010; Vargas et al., 2014; Estay et al., 2016).

Further south, the most significant crustal neotectonic structure is developed in the VA domain and represented by the Liquiñe-Ofqui Fault System (LOFS) (Fig. 6). This NNE-striking fault system exhibits conspicuous regional-scale fault arrays, including horse-fault terminations and a central strike-slip duplex structure. The LOFS is a major crustal fault system with associated seismicity (e.g. Barrientos and Acevedo, 1992; Lange et al., 2008; Mora et al., 2010; Legrand et al., 2011; Agurto et al., 2012; Sielfeld et al., 2019), which accommodates dextral strike-slip displacement related to slip partitioning along more than 1200 km. (Hervé, 1976; Lavenu and Cembrano, 1999; Cembrano et al., 1996, 2002; Cembrano and Lara, 2009; Lara, 2009; Vargas et al., 2013).

Challenging morphoclimatic conditions and a dense vegetation cover have determined very scarce exposures along the LOFS, hampering to date a detailed mapping regarding its neotectonic activity. Numerical modeling of current slip rates led to estimate values in the order of 1–10 mm/a (Stanton-Yonge et al., 2016; Iturrieta et al., 2017), although field data suggest Late Quaternary slip rates in the range of 12–25 mm/a, meaning the LOFS being the fastest-moving crustal fault onshore South America (De Pascale et al., 2018; Astudillo et al., 2018). Apparent discrepancies with GPS velocities need to be yet accurately assessed, to unravel a possible slip deficit along the LOFS concerning its seismic cycle.

3.4. The high Western Cordillera of the Central Andes and the altiplano plateau

This domain comprises the high Western Cordillera and extends from the northernmost Central Andes in Perú down to the Arica elbow (Fig. 3), hosting some of the highest Andean peaks in the Cordillera Blanca of Perú. Normal faults highly prevail in the compiled Quaternary deformation, whose occurrence and evolution in these high-altitude areas is still a matter of debate (e.g. Dalmayrac and Molnar, 1981; McNulty and Farber, 2002; Margirier et al., 2017).

The Cordillera Blanca Fault System (Fig. 3) bounds the western flank of the homonymous cordillera, exhibiting outstanding examples of mountain front-scale morphologies driven by normal faulting (Sebrier et al., 1988; Schwartz, 1988; Macharé et al., 2003, 2009a; 2009b; Siame et al., 2006b; Margirier et al., 2017). Vertical slip rates range from 5.1 ± 0.8 to 0.6 ± 0.2 mm/a (Schwartz, 1988; Siame et al., 2006b; Margirier et al., 2017).

Another earthquake-related hazard became explicit in this high-

relief area when an Mw 7.9 subduction earthquake in 1970 triggered a deadly landslide, taking the life of near 10,000 people in (Plafker and Ericksen, 1978).

Historical surface ruptures, such as the Quiches fault related to the Ms 7.2 1946 Ancash earthquake (Doser, 1987; Bellier et al., 1991; Audin et al., 2009d) and suspected historical ruptures associated to the Chaquibamba fault (Bellier et al., 1989; Macharé et al., 2003, 2009c), both of extensional nature, are located in this domain.

In some areas of the Western Cordillera, the occurrence of Quaternary normal faults is related to deeply incised canyons and active volcanoes (i.e. the Colca Canyon and the Huambo-Cabanaconde volcanic complex) (Fig. 3). A dynamic interplay in these settings among mountain uplift, high incision rates, and the flank collapse of active volcanic edifices, might enhance the geomorphic expression of surface faulting through deep-seated gravitational phenomena (Benavente et al., 2013; Wimpenny et al., 2020; García et al.,).

The high-relief areas of the Altiplano plateau are also characterized by Quaternary normal faulting, although the occurrence of neotectonic structures has not been yet properly surveyed (Sévrier et al., 1985; Lavenu et al., 2000; Macharé et al., 2003; Agurto et al., 2012; Aguirre et al., 2016; <https://www.ingemmet.gob.pe/mapa-neotectonico>; <http://neotec-opendata.com/>; https://sara.openquake.org/hazard_rt2). This high-altitude region (~3800 m on average) is characterized by endorheic basins and continues to the south into the Puna plateau in Argentina.

The majority of Quaternary faulting inventoried throughout the Altiplano is located around the Lake Titicaca area. Surface ruptures related to the 2016 Mw 6.1 earthquake has been reported for the Parina normal fault (Wimpenny et al., 2018, 2020; Aguirre et al., 2016). Wimpenny et al., (2020) reported a general ~ NNE-SSW Late Quaternary extension in the Peruvian Altiplano with fault slip rates in the range of 1–4 mm/a.

Little is known about the Quaternary faulting affecting the Puna plateau. The preliminary descriptions and general studies account for faults with different slip regimes, but lacking detailed parametric data (Costa et al., 2000a; Casa et al., 2014; García et al., 2017; <https://sigam.segemar.gov.ar/visor/>; https://sara.openquake.org/hazard_rt2).

3.5. The Eastern Cordillera and the Inter Andean zone of the Central Andes

This domain flanks the eastern Peruvian and the Bolivian Andes through the Bolivian orocline down to ~26° S in northern Argentina (Figs. 3 and 4). It extends above both flat-slab and normal subduction segments and Quaternary deformation is represented by different kinematic regimes, prevailing oblique-slip compressive and extensional structures, (Philip and Megard, 1977; Sévrier et al., 1985; Cabrera et al., 1987; Audin et al., 2009e; Macharé et al., 2009d; Benavente et al., 2013; García et al., 2017; Wimpenny et al., 2020).

The reverse-sinistral Huaytapallana fault (Fig. 3), which bounds the homonymous cordillera, was reactivated during the 1969 Ms 6.2 Pariahuanca earthquakes. It ruptured through scarps up to 2m high and sub metric sinistral component (Philip and Megard, 1977; Dorbath et al., 1991; Macharé et al., 2009d), testifying on the seismogenic capability of these faults. Interestingly, some rupture segments resemble single event scarps (like other surface ruptures, such as the Quiches fault), rather than long-evolved landforms.

Close to the subandean belt (Inter Andean zone), reverse faulting usually basement-cored are dominant (García et al., 2017; Rojas Vera et al., 2018).

3.6. The Pampean Ranges

The Pampean Ranges (Sierras Pampeanas) of Argentina constitutes the broken foreland of the southern Central Andes above the Pampean-Chilean flat-slab segment (27°–33°S, Fig. 5). Neogene mountain building in these former flat-lands was triggered by the subduction of the

aseismic Juan Fernández ridge, which started ~8 Ma in northern Chile and progressively moved south (e.g. Jordan et al., 1983; Jordan and Allmendinger, 1986; Gutscher et al., 2000; Yáñez et al., 2001; Ramos et al., 2002; Davila and Carter, 2013). These mountain blocks, bounded by reverse faults exhibit a notorious topographic asymmetry, being the Quaternary-active thrusts usually located at the foothills of the steep western slopes (e.g. Massabie, 1987; Fauqué and Strecker, 1987; Costa and Vita-Finzi, 1996; Costa, 1999, 2019; Costa et al., 2000a, 2001; 2014b, 2018, this volume; Casa, 2009; Casa et al., 2010; Costa, 2019; Rother et al., 2019). The youngest activity of fault systems bounding most Pampean Ranges seems to have migrated basin-wards during the Neogene block uplift (Costa, 2019).

Although ongoing deformation across the Pampean Ranges has not yet been suitably captured through satellite geodesy, some of these thrusts account for Holocene slip rates ~1 mm/a (Costa et al., 2018) and pose a seismic threat for urban areas and infrastructure (Costa et al.,). Paleoseismic studies suggest that Pampean faults can generate earthquake magnitudes similar to those structures in the Andean region, although with a longer recurrence interval (Costa et al., 2018, this volume).

3.7. The South America-Scotia plates transform boundary

This domain is exposed onshore at the southern tip of South America, in Tierra del Fuego island (Fig. 7). Sinistral-normal slip characterizes this deformation zone, concentrated throughout the Magallanes-Fagnano Fault System (MFFS), as indicated by seismicity, geophysical studies, GPS and field observations (Dalziel et al., 1975; Klepeis, 1994; Lodolo et al., 2003; Smalley et al., 2003, among others).

Despite difficult accesses and very scarce exposures, neotectonic evidence along this transform boundary has been described or suspected in the Chilean side (Winslow, 1982; Winslow and Prieto, 1991; Perucca and Bastías, 2008; Sandoval and De Pascale, 2020) and east of the Lake Fagnano in Argentina (Winslow, 1982; Costa et al., 2006b; Costa and Lara, 2009 and references below). In the latter area, trench studies highlighted prehistoric ruptures related to 3 or 4 earthquakes during the last ~8 ka, including the ruptures related to the two Mw 7.5 1949 events, with 1 m of coseismic vertical slip (Costa et al., 2006b). The prevalence of the vertical component recorded in the Lake Fagnano area is consistent with this fault segment being a transtensional zone of the transform boundary (Lodolo et al., 2003; Esteban et al., 2014, 2018; Roy et al., 2018, 2019).

Onorato et al. (2016, 2018, 2019, this volume) and Roy et al. (2019) reported Quaternary deformation related to the MFFS further to the east. The latter contribution estimated a 6.4 ± 0.9 mm/a left-lateral slip rate based on offsets of post-glacial morphologies, which are lined-up with GPS velocity models across the MFFS (Smalley et al., 2003). Sandoval and De Pascale (2020) suggested rates ranging from 10.5 ± 1.5 mm/a in Chile and 7.8 ± 1.3 mm/a east of Lake Fagnano, based on the interpretation of aerial images.

3.8. Slowly deforming regions

In intraplate South America, structures with Quaternary activity are located either on pre-existing Precambrian shear zones and metamorphic foliation or are newly formed structures that cut across the pre-existing Precambrian fabric. Several studies have highlighted their capability of producing surface ruptures and related phenomena (Bezerra and Vita Finzi, 2000; Bezerra et al., 2001, 2006, 2007, 2011; Ramos et al., this volume, among others). These intraplate regions comprise a much larger area than the entire Andean chain, but neotectonic data are patchy and most faults lack of slip-rate constrains. Estimated Quaternary rates are <0.1 mm/a and recurrence intervals presumably encompass 5–100 ka or more. For example, alluvial infill dating in the deformation zone of the Jundiaí fault (Fig. 9a) has led to estimate a mean recurrence period of 15.8 ka (Nogueira et al., 2010).

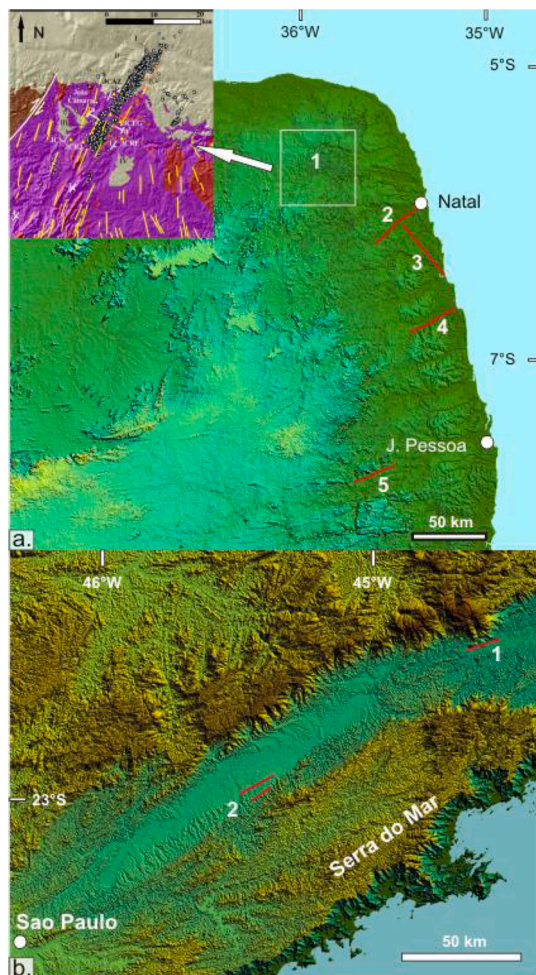


Fig. 9. a. Main faults compiled in northeast Brazil. 1. Samambaia (highlighted by shallow seismicity, modified after Bezerra et al., 2011), 2. Jundiá, 3. Boa Cica, 4., Canguaretama, 5. Cariata faults. b. Quaternary faults compiled in the Serra do Mar region, southeast Brazil., 1. Resende, 2. Taubate faults. See the location of both areas in Fig. 1.

Challenges for mapping neotectonic structures under common standards in cratonic-pericratonic regions, as for those applied for Andean settings, usually deal with the critical judgment of the preserved fault-related morphologies. Macroscale continuous linear features may result from old tectonic structures with inherited escarpments, being enhanced by fluvial systems. Whether or not these features have undergone Quaternary activity is often a matter of controversy, due to the lack of diagnostic data.

In the Brazilian platform, two main areas with Quaternary deformation have been documented with field support. In northeastern Brazil, the Samambaia fault shows prominent shallow seismicity illuminating the fault zone (Takeya et al., 1989; Bezerra et al., 2007; Ramos et al., this volume) (Fig. 9a). The Jundiá and Boa Cica faults are among the most important structures recording Holocene displacements, the former having a cumulated vertical slip of approximately 260 m on Miocene deposits (Bezerra and Vita Finzi, 2000; Bezerra et al., 2001, 2006) (Fig. 9a). Other important seismogenic faults in the region are the Pernambuco Lineament (Coelho et al., this volume) and the Riacho Fundo fault (Oliveira et al., 2015; Ramos et al., this volume). These structures, such as the Samambaia fault, reactivate Precambrian or early Cambrian fabrics and are underlined by recent seismic activity.

At the Serra do Mar (Fig. 9b), Quaternary faults reactivating Mesozoic rift structures have been described (Riccomini et al., 1989; Riccomini and Assumpção, 1999; Gontijo-Pascutti et al., 2010). They all

reactivated Mesozoic rift faults, which in turn have over imposed Precambrian shear zones of the Ribeira belt.

Quaternary deformations have been reported east of the Pampean Ranges in the Pampean plain (Fig. 10), related to propagating faults and usually interpreted through anomalous drainage pattern (Mon et al., 2005; Rossello et al., 2005; Brunetto and Iriondo, 2007; Mon and Gutiérrez, 2009; Brunetto et al., 2010, 2019; Peri and Rossello, 2010). The geometries, kinematics, and rates of activity of these subsurface structures are poorly known to date.

4. Strategies and methods for compiling hazardous faults

4.1. Definitions and criteria adopted

Hazardous structure and fault activity assessment. A Hazardous structure is a fault or fault-related-fold either outcropping or blind, capable of producing earthquakes of social/engineering concern in the future, and considered relevant as for seismic hazard implications. There is no consensus about a discrete timeline for defining whether a structure is potentially hazardous or not. For areas with medium to low strain rates, this means to include structures with activity during the Quaternary (~2.6 Ma). However, the Pliocene-Pleistocene boundary is poorly known in vast regions of South America. Besides, in key areas such as the Andean Thrust Front, this time window is represented by contemporaneous deformation and sedimentation, turning not very practical to define a time baseline. Therefore, it has been intended to also include in the inventory those structures affecting layers whose chronostratigraphy

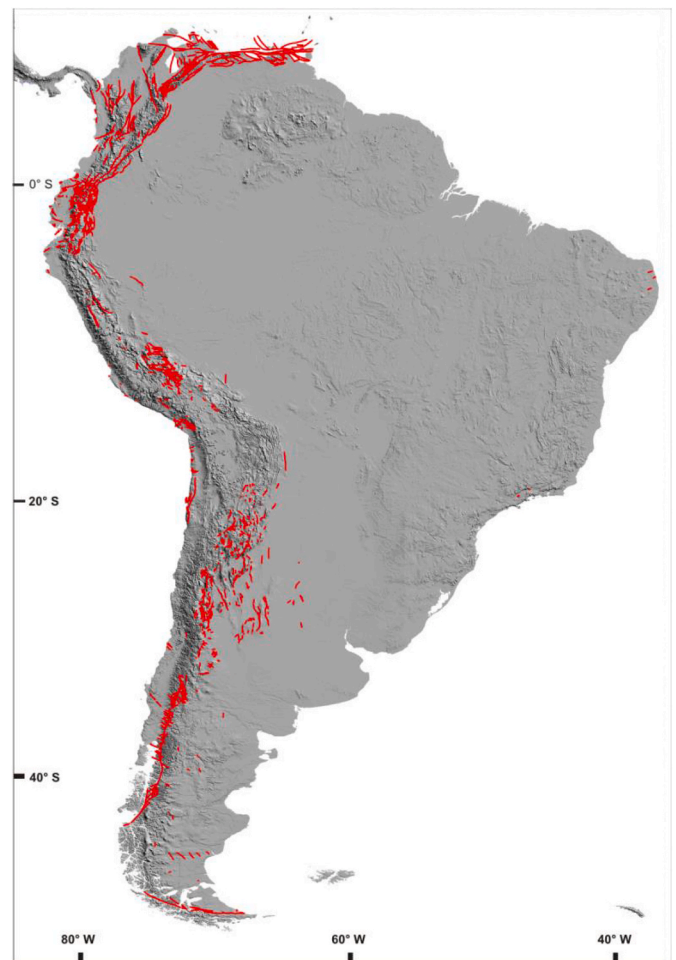


Fig. 10. Cartographic representation of the compiled structures under the activities of the SARA T2 project. See the text for details.

is doubtful, those affecting Miocene-Pliocene stratigraphic units, or those where young activity is suspected and Quaternary deformation markers are absent.

A hazardous structure is here considered as a synonym of neotectonic structures or Quaternary deformation *s.l.* SARA compilation has used a conservative approach, taking into account that fault maps for SHA should encompass a time interval that includes several earthquake cycles (Machette, 2000). Then, it is considered that the Quaternary period meets this standard even for long-recurrence interval faults. Overall, it has been intended to populate the database with information to be useful for different purposes and users in the future (territorial planning, critical facilities, geotechnical issues, etc.).

Fault activity assessment is here approached according to parameters related to the structure dynamics during the Quaternary (i.e. slip rate, age of the last movement). Aiming to favor homogeneous compilation criteria, it has not been relied on the heterogeneous criteria for systematizing fault activity. Common definitions of 'active fault' available in the scientific literature and promoted by regulatory agencies, usually constrain a specific timeline of interest for fault activity, such as the Holocene (11,7ka), the Late Pleistocene (125ka) or the Quaternary (~2.6 Ma) (e.g. Slemmons and de Polo, 1986; WSSPC, 1997; Machette, 2000; Haller et al., 1993; IAEA, 2010). Rating the hazard associated with a structure based on the age of the last movement may not be appropriate, particularly for regions of low to medium strain rates and long recurrence intervals (which represent most parts of continental South America). In these settings, the most active structure (in terms of the elapsed time since the last movement), might not be the most hazardous in terms of threat for rupture or ground shaking probabilities. Thus, adopting any particular definition for the term 'active fault', might not be suitable to characterize fault hazard throughout different seismotectonic settings.

Fault source. Fault surface with an assigned three-dimensional representation given by a generalized geometry, kinematics, area, and spatial coordinates within the seismogenic crust or at interplate boundaries. It is conceived to represent the surface where the earthquake slip and most of the released seismic energy is concentrated (Basili et al., 2008; Haller and Basili, 2011, among others).

Seismic-Hazard Source Model (SHSM). Computational engine for the description of the magnitude, location, and timing of expected earthquakes, based on a probabilistic approach and usually limited to those events that pose a significant threat. The SARA project relied on the OpenQuake platform for the calculation of hazard and risk, as well as for the generation of Probabilistic Seismic Hazard Assessment (PSHA) maps (i.e. Pagani et al., 2014, 2015).

4.2. Previous studies and data availability

The pre-existing neotectonic information in South America is very heterogeneous not only in terms of reliability and geographic coverage but also regarding the criteria applied for mapping Quaternary deformation. In wide areas, the compiled data are of a reconnaissance nature, largely based on remote sensing interpretation and general fieldwork.

The first regional cartographic attempt for compiling regional neotectonic information was under the framework of the SISRA Project (González-Ferrán, 1985), although the few Quaternary faults depicted were mostly derived from previous regional maps, without a relational database.

Venezuela, through the work of FUNVISIS, has been the pioneer country in developing regional neotectonic maps for supporting SHA since the 80s (e.g. Soulas, 1986; Beltrán, 1993, 1994; Audemard and Singer, 1996; Audemard, 2001, 2006). As a result, nationwide maps of Quaternary deformation and the seismogenic characterization of faults have been incorporated in the national seismo-resistant building code for Venezuela.

Systematic regional neotectonic compilations in South America started in the early 90s with the International Lithosphere Program

(World Map of Major Active Faults-ILP-II2) (Trifonov and Machette, 1993). This decade-long effort led to the development of country maps and inventories of Quaternary deformation, being the first experience attempting to inventory regional Quaternary deformation under common criteria (Audemard et al., 2000; Costa et al., 2000a, 2000b; Lavenu et al., 2000; París et al., 2000; Saadi et al., 2002; Egüez et al., 2003; Macharé et al., 2003). More than 300 Quaternary-active structures were compiled for South America and some countries of Central America (Cowan et al., 1998; Montero et al., 1998). The resulted database was updated and improved during the Multi Andean Project (MAP-GAC) (2005–2007), which contributed to the compilation of ~600 structures in Andean countries (PMA, 2009). Both projects relied on a GIS-based georeferenced mapping, linked to files depicting attributes for each mapped structure.

The end-products of ILP II2 and MAP projects were released as reports and maps with the structure surface characteristics and available knowledge on the fault trace and related data. These efforts focused on the terrain imprint of Quaternary fault traces, rather than on fault source geometry. Thus, some key data as for the SHA requirements, such as slip rate and the 3D structure geometry of faults were not available for a significant number of them. After these experiences, many initiatives have updated and expanded the information on Quaternary deformation under diverse digital platforms with a countrywide or regional scope (<https://sigam.segemar.gov.ar/visor/>; <https://www.ingemmet.gob.pe/mapa-neotectonico>; <http://neotec-opendata.com/>; <https://documents.ku.edu/ORGS/Academics/>).

4.3. Compilation strategies

The SARA Topic 2 project was conceived as a community-based effort involving local expertise and relying on regional networking. Data gathering relied on a responsible person with collaborators for each participating country (Argentina, Bolivia, Brazil, Chile, Colombia, Ecuador, Perú, and Venezuela). The first stage of the compilation involved a systematic inventory aimed to capture all available information on structures with evidence of Quaternary activity. However, as a conservative approach, the inventory also took into account presumably older structures in the following situations;

- Where regional low strain rates turned advisable to include structures with older activity (i.e. Late Pliocene) of potential significance for a wide range of possible applications (nuclear siting, territorial planning, etc.),
- When evidence for Quaternary activity was not conclusive, barely known or suspected to fall within the timeframe of interest,
- When the Pliocene-Pleistocene boundary was not properly established,

The inventoried structures were hierarchized at a second stage, by selecting those structures with available mandatory data for the characterization of fault sources (Table 1) as required by the SARA SHSM. Structures meeting at least one of the following criteria were included;

- Faults with slip rates >0.1 mm/a. This information applies to rates already available or estimated by compilers through quantitative-semi-quantitative data. Although rates derived from geological data were preferred, GPS-derived rates were also considered. For those structures with a wide rate range (i.e. 0.001–0,1mm/a), the higher value (or the preferred one if existing) was considered.
- Structures with Late Pleistocene activity or younger. Both confirmed and suspected.
- Structures confirmed or suspected to be the source for historical/instrumental seismicity with magnitude >5.5.

Structures have been inventoried as single or sectioned faults. Single faults are structures with a simple and essentially continuous trace

Table 1
Attribute table for data upload of the faults selected for feeding the SHSM. See text for explanation. The complete set of parametric data considered for compiling all structures is displayed in table S1 (supplementary data).

| Attribute name | Object ID | Name | Strike | Slip type | Slip type (R) | Dip direction | Dip direction (R) | Dip angle | Dip angle (R) | Slip rate | Slip rate (R) | Age of last movement | Age of last movement (R) |
|----------------|-----------|-----------|----------------|-----------|---------------|----------------|-------------------|-----------|---------------|----------------|---------------|----------------------|--------------------------|
| Query name | ID_STR | STR_F_NAM | STR_F_SC | STR_F_ST | CF_F_ST | STR_F_DD | CF_F_DD | STR_F_DC | CF_F_DC | STR_F_SRC | CF_F_SRC | STR_F_ALM | CF_F_ALM |
| Attribute type | String | String | String-Integer | String | Integer | String-Integer | Integer | Integer | Integer | String-Integer | Integer | String | Integer |

(observed or inferred), a concept that could be applied for a set of folds as well. Sectioned faults or faults systems with sections may correspond to km-scale gaps, step-overs, major changes in geometry (strike, dip, dip direction, rake) different fault splays or fault systems, or differences in key activity parameters (slip rate, recurrence interval, last event, etc.). Therefore, certain mapping attributes (i.e. age of last movement, trace characteristics) or parameters may vary for the different sections of a structure. For compilation purposes, the term “section” was here also applied to each trace of a fault assemblage grouped in plan view, such as flexural-slip faults or secondary splays of the main thrust. Key parameters of the selected structures were also displayed in complementary summary attribute tables (Table 1). A fault section essentially depicts geometric or kinematic characteristics of a structure, but it should not be regarded as fault segments or earthquake rupture segments (e. g. Schwartz and Sibson, 1989; McCalpin, 2009; DuRoss et al., 2016), because unitary surface rupture lengths remain unknown for most compiled structures.

Structure attributes were also designed to fault-related folds, although very few neotectonic folds have been incorporated into the database.

Compilers were requested to include structures regardless of data reliability, although a reliability rate (R) was assigned to the uploaded data (See Table 1).

4.4. Database structure

A relational database was designed to link the cartographic georeferenced representation of fault traces with the structure parameters (geometry, kinematic, geomorphology, paleoseismology, seismicity, and complementary information whenever available) (see supplementary information). The attribute table used for data upload included the key parameters for fault source characterization, such as fault strike and dip direction, slip sense, slip rate, and age of the last movement. The database was populated by both direct observations and measurements in the field (i.e. geometry and kinematics of faults and folds such as strike, dip, rake) and derivative parameters (slip rate, recurrence interval, age of last movement, 3D geometry, etc.). It is worth to note that most critical data as for fault source definition rely on derivative data.

Because of the continental scale representation, no direct differentiation of cartographic attributes (line styles, colors) has been included for the data visualization to distinguish parameters such as fault reliability, slip rate, and age of the last movement. But this differentiation is possible through informatic tools. To favor a straight-forward data entry for feeding the SHSM, the upload format of the structures selected was oriented to basic parameters for source characterization. Some general data (tectonic setting, geomorphic expression, etc.) were not taken into consideration at this stage.

The relational database allows to retrieve different fault parameters through a structured query language (SQL). Compilation relied on the upload of ESRI-shapefiles through a freeware software (QuantumGis) to enter/import the data for each structure in an attribute table.

5. Results

The compiled information for the SARA Topic 2 project, is the first open-source experience in South America in which fault data were considered as an input layer for feeding an SHSM. Moreover, it constitutes the first comprehensive state-of-the-art on neotectonic knowledge to date at a continental scale. The main efforts have been concentrated in database harmonization and population whenever possible with activity rates and 3D sources geometry.

During this 2-years long effort, 1523 structures and 3586 fault traces considered hazardous as for SHA purposes, have been compiled according to common criteria (Fig. 10). The project did not contemplate the generation of new field data, except for visits to specific sites. Thus, a significant part of the information was imported from existing databases

and bibliography. Not all the structures inventoried were considered as entry data for the SARA Open Quake engine, given that a significant number of inventoried structures did not meet the selected standards as for SHA or lack specific information for fault source characterization. Only 497 structures (~30% of the total population) met these criteria (Fig. 11). In many cases, the quantitative data for the key parameters were derived from qualitative estimates or expert judgment, assigning thus a low-reliability rate for these cases.

Almost all the structures inventoried are concentrated along the Andean chain, depicting at a synoptic view the major neotectonic framework of the Andes. Structures in the Northern Andes show an integrated arrangement of major faults, outlining the distribution of major hazardous faults with a dominance of strike-slip motion (Figs. 2 and 12). In contrast, most hazardous faults mapped in the Central Andes exhibit short individual lengths and a more distributed pattern in space, where

even major faults do not evidence regional continuity or integration into regional fault systems as in the Northern Andes. The different geometries of the subducting Nazca plate can be roughly recognized, highlighted for example by the propagation of Quaternary deformation into foreland areas at the Pampean-Chilean flat-slab in Argentina (Fig. 5). Here, the general arrangement in a plan view of the compiled data results in a triangular shape. The exception to these characteristics corresponds to the Atacama and Liquiñe-Ofqui fault systems in northern and southern Chile, respectively. Although integrated by many fault sections, these fault systems display a master deformation belt recognized along ~1000 km (Figs. 6 and 8).

Knowledge of the occurrence and characteristics of hazardous faults in the Southern Andes is still very incomplete (Figs. 6 and 7). The Magallanes-Fagnano Fault System, which represents the onshore transform boundary between the South American and Scotia plates (Fig. 7), is

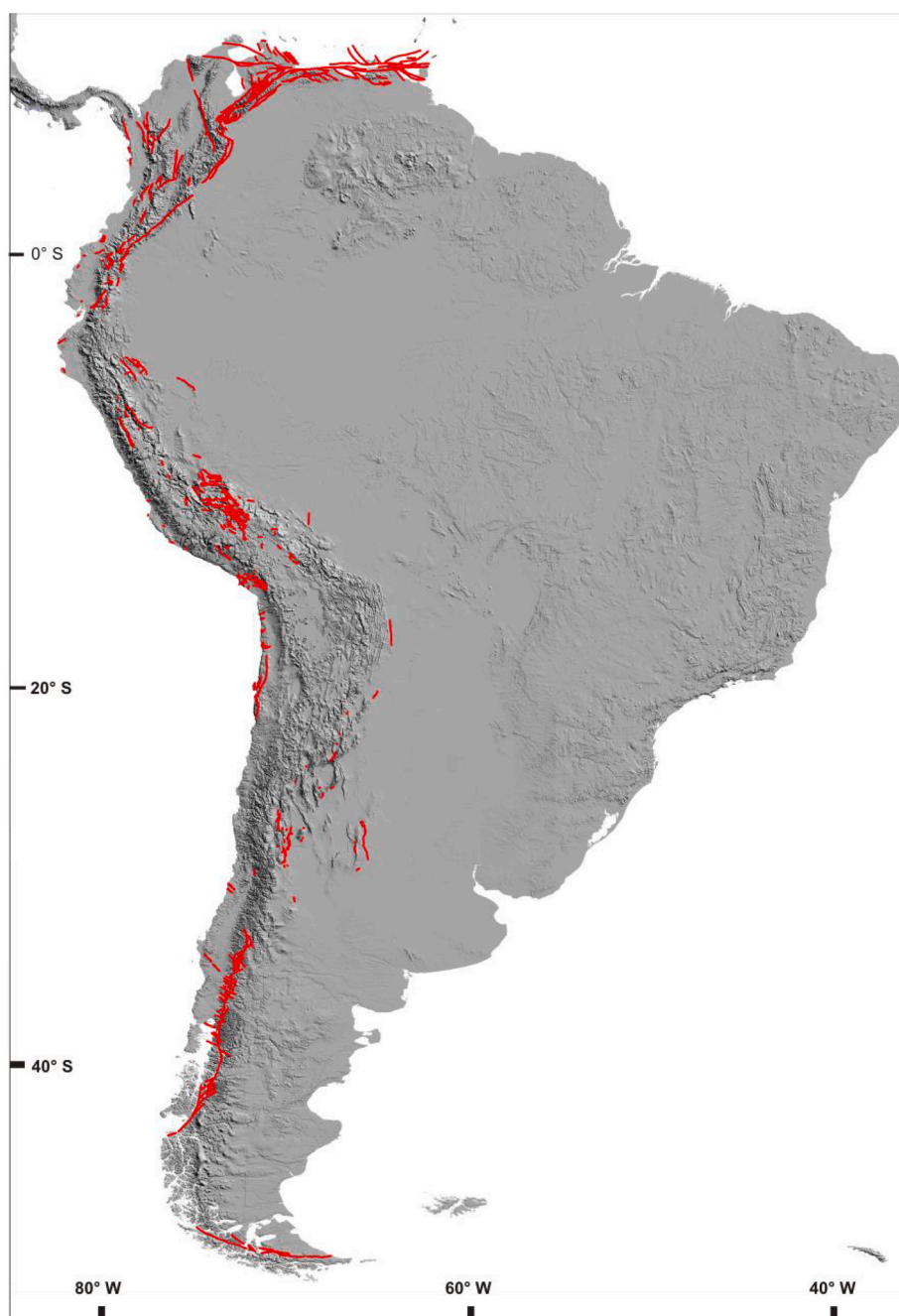


Fig. 11. Faults selected for incorporation to the SARA SHSM.



Fig. 12. Slip types of hazardous faults in Northern South America.

one of the very few places where punctual neotectonic studies have been conducted to date. This fault system has been the source of large historic earthquakes.

Neotectonic faults inventoried in cratonic regions constitute a much smaller population concerning the Andean region. However, some of these structures have generated surface deformation during the Quaternary.

Because estimation of slip rates has been addressed through derivative data and in some cases by expert judgment, these metadata might reflect either kinematic heterogeneities and/or data provider preferences. In any case, the filtering of the compiled faults according to their slip rate values also highlights the concentration of the structures with the higher rates along the NAS east boundary. (Fig. 13). Spatial variations of individual parameters may help to stand out heterogeneities in tectonic settings, as well as to point out that data harmonization is still required.

The main outcome of the data sets has been their integration as a data layer of the probabilistic seismic hazard assessment (PSHA) for South America generated through the OpenQuake engine for the SARA project (Fig. 14a). This map results from the integration of data layers provided by both historical and instrumental shallow seismicity, aside with hazardous faults information, and using a ground motion model considering the different regional tectonic regimes. Subduction and deep seismicity sources (e.g. Bucaramanga Nest) were not considered, with the aim of emphasizing the contribution of shallow sources to the seismic hazard computed along the Pacific coast. Details on the methodology behind the generation PSHA input model for South America can

be found at https://sara.openquake.org/hazard_rt7. The SARA T2 database can be accessed in electronic format at https://sara.openquake.org/hazard_rt2. Disaggregation of individual data layers allows identifying the contribution of crustal hazardous faults (Fig. 14b) to the estimated hazard, expressed as mean PGA (Peak Ground Acceleration) with 2% probability of exceedance in 50 years (a return period of 2.475 years). These results highlight the input of recognized hazardous faults for more realistic SHA, particularly for recurrence intervals >1ka, which characterize the vast majority of areas in South America. Fig. 14b also underscores that punctual data reporting high slip-rate faults (e.g. the Mandeyapecuá Thrust System), strongly influences SHA calculations (Fig. 14a).

The SARA T2 database can be accessed in electronic format at https://sara.openquake.org/hazard_rt2.

6. Concluding remarks

6.1. Data harmonization and completeness

Significant efforts were directed to elaborate and homogenize data sets compiled in different countries by different compilers. Although significant improvements have been achieved in comparison with pre-existing databases, many remaining issues still require further discussion and complementary data to homogenize parametric and cartographic information. Among these, the fault slip rate is a key parameter for SHA which conveys significant epistemic uncertainties to the compiled data.



Fig. 13. Slip rates of main inventoried faults.

Aside from remaining inconsistencies in data harmonization, the representation of hazardous faults is very heterogeneous particularly in terms of geographic coverage, availability, and/or data reliability. As the NAS east boundary in the Northern Andes, satellite geodesy indicates that transient strain is being concentrated nowadays at the Andean Thrust Front (Norabuena et al., 1998; Kendrick et al., 1999, 2006; Brooks et al., 2003, 2011; Weiss et al., 2015; Mora-Páez et al., 2019a). Accordingly, local studies conducted in the Subandean zone have unveiled very hazardous structures regarding their capabilities for producing large crustal earthquakes (Brooks et al., 2011; Weiss et al., 2015) (Fig. 4). However, the cartographic representation of this key area for SHA purposes is underrepresented by the regional neotectonic knowledge acquired to date.

Cartographic results also convey an unbalanced representation of hazardous faults when contrasting with specific areas where systematic neotectonic mapping has been carried out. For example, the detailed mapping of Quaternary faults around the Cusco region (Benavente et al., 2013) gave rise to a concentration of hazardous faults in this area at a regional scale (Figs. 3 and 11). This led to a biased view when contrasting with the much less populated surrounding areas (the compilation of neotectonic faults for the Arequipa region by Benavente et al., 2017a, was not yet available during the SARA project lifetime).

In summary, the compilation conducted provides a good representation of the current knowledge on the occurrence and characteristics of hazardous faults in continental South America. However, it does not necessarily provide an objective picture or balanced representation of the hazardous crustal structures existing in the region.

6.2. From neotectonic faults compilation to seismogenic sources characterization

The geological community has contributed particularly during the last 30 years to a better knowledge of the seismic hazard in South America through the identification of Quaternary deformation as potential fault sources. The neotectonic data accrued, from detailed scale surveys to regional scale cartography, constitute a significant input for applied earth sciences and engineering purposes. Many existing maps and parametric data of hazardous structures carry information on structure-activity through fault-related morphologies, but with few data depicting the characterization of fault sources. Thus, many SHA analyses have not considered hazardous faults as entry data or did so sparingly, partly because key fault data are absent or not available in an adequate format for SHA. Besides, the information of many faults lacks an appropriate uncertainty analysis of data, and the 3D source geometry (length and area) is poorly depicted or difficult to characterize. This turns many neotectonic data of limited application in PSHA and deterministic approaches.

Venezuela has conducted a nation-wide systematic effort since the 80s for translating neotectonic data into fault sources, and recent progress has been made in Ecuador and Colombia. The results achieved highlight the significance of setting institutionally-based and time-sustainable programs for the successful incorporation of fault source data in SHA models.

Approximately 30% of the total fault population inventoried has been incorporated into the generation of PSHA maps. A similar

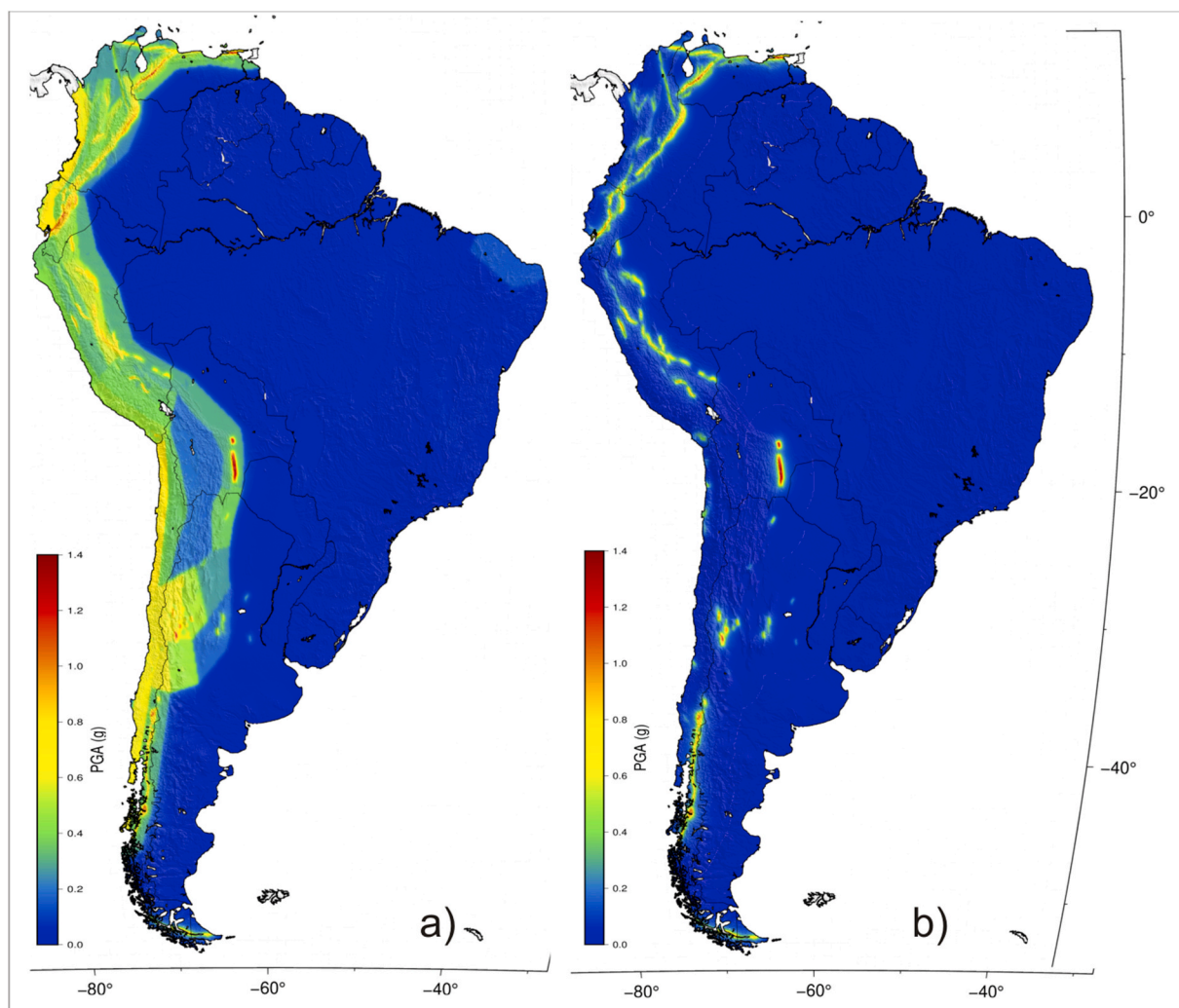


Fig. 14. Probabilistic Seismic Hazard Assessment maps resulting from the SARA project database obtained through the SARA SHSM. They depict expected PGA (Peak Ground Acceleration) on rock for 2% probabilities of exceedance in 50 years or equals to a 2.475 years return period, computing; a) seismicity and hazardous faults, b) hazardous faults.

percentage has resulted from the Quaternary deformation compiled in the United States incorporated into the USGS seismogenic source model (Haller and Basili, 1993). Aiming to increase the percentage of hazardous fault participation in SHSM, might help to organize future research paths and would be of relevance to SHA in South America.

6.3. Seismic hazard and risk in South America through the lens of a hazardous faults database

Subduction and interplate earthquakes are the most significant seismic threat for the region. However, historic destructive earthquakes related to shallow crustal sources ($\geq M 6.5$) have occurred onshore and the here compiled data underpin the seismogenic capability of many faults, even in low strain rate intraplate regions. The knowledge acquired also suggests that there is not necessarily a direct correlation between the fault activity rate and the threat that the fault implies. Many seismogenic capable fault zones may be characterized by current low or even no specific or localized seismicity and long recurrence intervals. Thus, they are probably barely noticeable in the landscape or even not studied yet.

Likewise, many of South America's capital cities are established nearby crustal fault sources, whose seismogenic capability is known or suspected, such as Caracas (Audemard et al., 2000; Rodríguez et al., 2016), Bogotá (Paris et al., 2000), Quito (Egüez et al., 2003; Alvarado

et al., 2014; Beauval et al., 2014; Yepes et al., 2016; Marinière et al., 2020), La Paz (Lavenu et al., 2000; Ramírez et al., 2009), and Santiago (Lavenu et al., 2000; Rauld et al., 2006; Rauld, 2009; Armijo et al., 2010; Vargas et al., 2014; Estay et al., 2016). Other hazardous faults occur near many large fast-growing cities, touristic places, or critical infrastructures, such as dams, pipelines, and even nuclear facilities (Costa et al., this volume). The estimated recurrence interval for most of these faults is much longer than the ~ 500 years spanning the historical period. This means that the last seismic event with surface deformation that these fault sources hosted, only affected at most a few dwellings. But the next one would probably hit urban areas with several million inhabitants, in most cases with inappropriate or inexistent building codes and/or poor observance of seismic safety procedures.

Studies in many of the here compiled hazardous faults have testified for their capability in generating large shallow crustal earthquakes with surface ruptures and related phenomena of social and engineering concern. This regional compilation spotlights that further studies are mandatory in many of them.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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