A Neogene giant landslide in Tarapacá, northern Chile: A signal of instability of the westernmost Altiplano and palaeoseismicity effects

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ABSTRACT

Giant landslides, which usually have volumes up to several tens of km^3, tend to be related to mountainous reliefs such as fault scarps or thrust fronts. The western flank of the Precordillera in southern Peru and northern Chile is characterized by the presence of such mega-landslides. A good example is the Latagualla Landslide (19°15′S), composed of ~5.4 km^3 of Miocene ignimbritic rock blocks located next to the Moquella Flexure, a structure resulting from the propagation of a west-vergent thrust blind fault that borders the Precordillera of the Central Depression. The landslide mass is very well preserved, allowing reconstitution of its movement and evolution in three main stages. The geomorphology of the landslide indicates that it preceded the incision of the present-day valleys during the late Miocene. Given the local geomorphological conditions 8–9 Ma ago (morphology, slopes and probably a high water table), large-magnitude earthquakes could have provided destabilization forces enough to cause the landslide. On the other hand, present seismic forces would not be sufficient to trigger such landslides; therefore the hazard related to them in the region is low.

1. Introduction

In mountain ranges, landslides in general and mega-landslides in particular are important erosion processes and elements in the evolution of topographic relief. Landslides are some of the largest suppliers of sediments to rivers (e.g. Burbank et al., 1996; Hovius et al., 1997). The majority of landslides are associated with the slope evolution of fluvial and glacial valleys, and consequently form part of the dissection of landforms. Less frequent are landslides related to the elements of relief formation such as fault scarps and thrust fronts, but they can reach volumes of tens of km^3. The analysis of such mega-landslides located in main orogenic structures yields information on palaeoseismicity, the latest activity of these structures, and the geodynamic evolution of orogens. As for their social impacts, it is very important to know the triggers and conditions of this type of landsliding.

There are several examples of giant landslides around the world, of volumes from hundreds of millions of m^3 to tens of km^3, such as the mega-landslide of Bogd in Mongolia (Philip and Ritz, 1999), the Tsao-Ling rock slides in Taiwan (Hung et al., 2002), and the Flims mega-landslide in the Swiss Alps (Abele, 1974; Von Poschinger, 2002). In South America, the western flank of the Precordillera in southern Peru and northern Chile between ~16°S and ~21 S is also characterized by the presence of mega-landslides. One of these is the Lluta mega-landslide in Chile, which has been well described (Uhlig et al., 1996;

Naranjo, 1997; Parraguez et al., 1997; Strasser and Schlunegger, 2005). Landslides of comparable size also exist in Peru, for example the Caquilluco Landslide. In Chile, south of Lluta, between the Camarones and Camiña Valleys (Fig. 1), two giant landslides can be identified: the Latagualla and Miñimiñi (Pinto et al., 2004). These mega-landslides are not associated with valley slopes but with main tectonic features; for the Lluta Landslide, the western flank of the Oxaya Anticline (García and Hérail, 2005), and for the Caquilluco Landslide, the relief produced by the activity of the Incapuquio fault system (Audin et al., 2006). Activity of the Moquella Flexure played an important role in triggering the Latagualla and Miñimiñi Landslides (Pinto et al., 2004).

In this paper we investigate the Latagualla Landslide as a typical example of mega-landslides of the Andes of northern Chile located along the western side of the Precordillera of the Tarapacá region (Figs. 2 and 3). We describe its morphological and structural characteristics, discuss the possible mechanisms of emplacement, and consider the significance of the landslide in the geodynamic evolution of the western side of the Andes of southern Peru and northern Chile, as well as the risk implications for the region's inhabitants.

2. Geological, geomorphological and seismological background

2.1. Tectonic setting

On the western flank of the Andes of southern Peru and northern Chile, tectonic deformation is concentrated along a set of parallel flexures between the Precordillera and the Central Depression, which
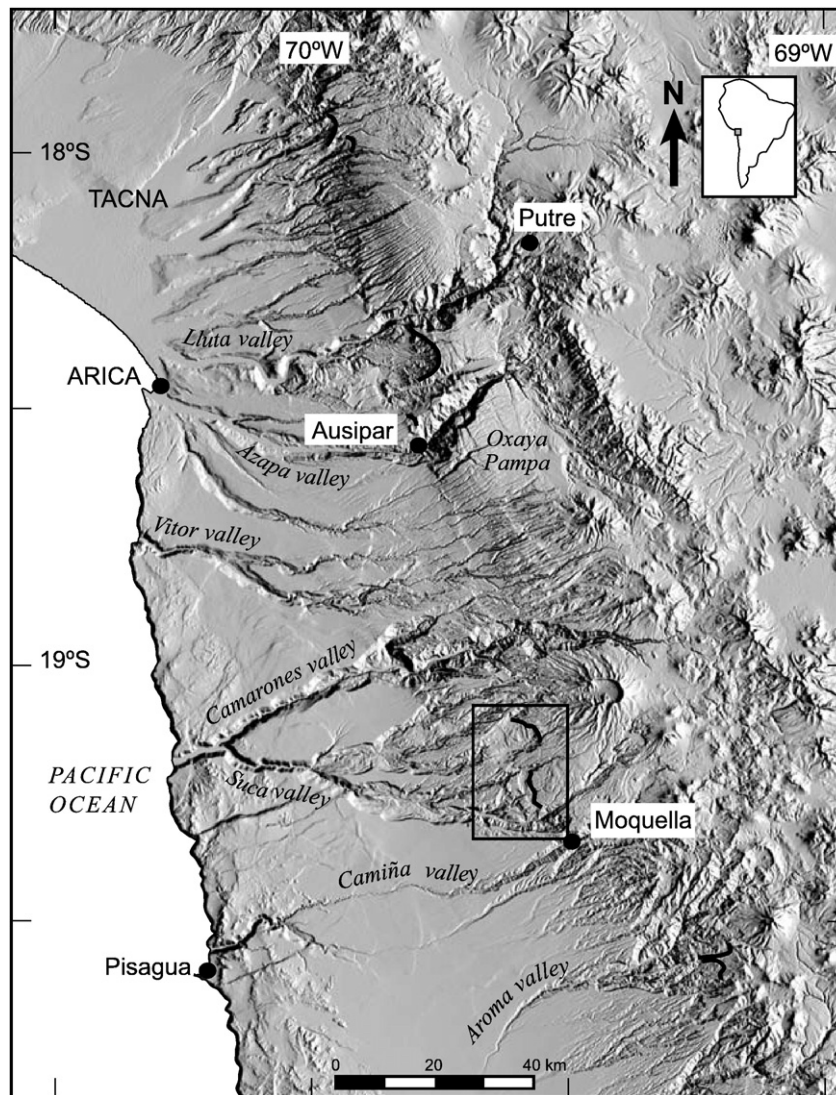
Fig. 1. Shaded relief map from a digital terrain model of the Tarapacá region, northern Chile (SRTM). Black lines indicate major landslide scars in the region (west of Tacna; Lluta Valley; north of Ausipar; north of Moquella and Aroma Valleys); black box indicates the study area shown in Figs. 3 and 4.

explains the significant uplift along the western edge of the Precordillera (García and Hérail, 2005; Farías et al., 2005; Riquelme et al., 2007). The altitude of these flexures changes from roughly 1200 m a.s.l. in the Central Depression to around 4000 m a.s.l. in the Precordillera in less than 50 km (Fig. 2). These flexures correspond to the westernmost expression of the N10°–20°W-trending thrust fault and fold belt developed during the Neogene uplift of the western edge of the Andes (Muñoz and Charrier, 1996; García et al., 1996, 2004; Charrier and Muñoz, 1997; Parraguez et al., 1997; Victor and Oncken, 1999; García, 2002; Pinto et al., 2004; Victor et al., 2004; Farías et al., 2005). The main structure of this system is composed of the Ausipar Fault, the Oxaya Anticline, the Moquella Flexure, the flexure of Aroma and the flexure of Altos de Pica from north to south (Galli and Dingman, 1962; Salas et al., 1966; Parraguez et al., 1997; García et al., 1999; Wörner et al., 2001, 2002; Pinto et al., 2004; Victor et al., 2004; García and Hérail, 2005) (Fig. 2). Several authors discuss the role of these flexures in the uplift of the Andes (e.g. Isacks, 1988; Lamb and Hoke, 1997; Riquelme et al., 2007). The flexures are located along the western side of the Precordillera, in a sector of slope increase, and locally cause a marked increase in the dip of the strata, from about 10° to 30°–70°.

The Moquella, Aroma and Altos de Pica flexures have been active since the early Miocene. They have mainly affected Neogene ignimbritic and sedimentary facies. In the Moquella area, around 19.5°S, the Moquella Flexure corresponds to one of the westernmost indications of this structural system (Fig. 2). The flexure, which defines a major topographic rupture striking N20°W, is well exposed in the Suca (Fig. 2) and Camiña Valleys (Pinto et al., 2004). The activity of this flexure is shown by the syntectonic deformation of the Mesozoic substrate and pyroclastic, sedimentary and volcanic rocks, the age of which lies between 21 and 16 Ma and probably up to 8 Ma (Pinto et al., 2004). The Cenozoic succession is characterized along the Moquella Flexure by progressive unconformities, similarly to other flexures that separate the Precordillera and Central Depression in the area of Tarapacá (Pinto et al., 2004; Farías et al., 2005), which show continuous tectonic activity throughout this period. The Moquella Flexure results from the propagation of a west-vergent thrust blind fault that corresponds to the southward continuation of the Ausipar Fault recognized in the Arica area (Pinto et al., 2004; García et al., 2004).

2.2. Geomorphological framework

In the Tarapacá region, two major geomorphological units are in contact: the western side of the Precordillera and the Central Depression. Both are notched by east–west valleys (steeply incised
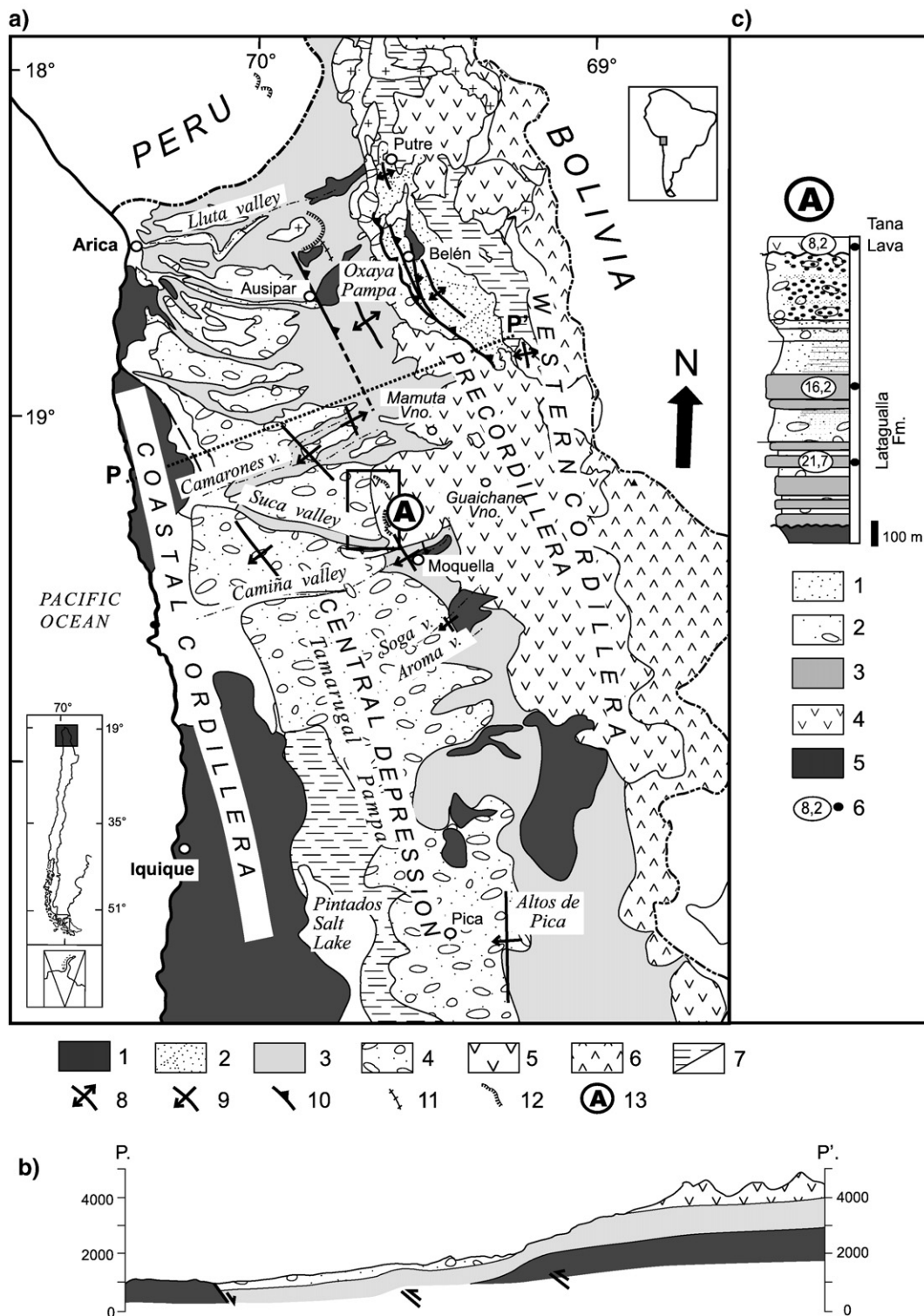
Fig. 2. Geological setting of the Tarapacá region (based on Salas et al., 1966; Naranjo and Paskoff, 1985; Seguel et al., 1991; García et al., 1996, 2004; Victor and Oncken, 1999; Pinto et al., 2004; Farías et al., 2005). a) Geological map of the region. The box indicates the study area in Figs. 3 and 4. 1 - Lower Paleozoic and Mesozoic basement; 2 - Azapa, Lupica and Chucal Formations (late Oligocene to early Miocene); 3 - Oxaya and Altos de Pica Formations (late Oligocene to early Miocene); 4 - Joracane, Huaylas and El Diablo Formations (middle Miocene to Pliocene); 5 - andesitic volcanic chain (middle to late Miocene); 6 - present volcanic arc; 7 - Holocene sedimentary deposit including lacustrine, alluvial and saline sediment; 8 - anticline; 9 - flexure; 10 - thrust fault; 11 - tensional fracture; 12 - scar position of the landslide; 13 - location of stratigraphic column in (c). b) Generalized geological profile of the Tarapacá region. Blind thrust faults associated with flexures and normal fault are indicated. Legend is common to (a). c) Generalized stratigraphic column in the area between Moquella and Suca. 1 - sandstone; 2 - limestone; sandstone and conglomerate; 3 - ignimbrite; 4 - andesitic lava; 5 - substratum of Mesozoic rock; 6 - radiometric age in million years.

ravines) that arise in the Cordillera and the Precordillera. The topographic surface of the Precordillera corresponds to the top of the Nama Ignimbrite strata (Figs. 3 and 4), and escarpments of the normal faults associated with the folding of the Moquella Flexure can be clearly observed. In the Central Depression, interfluves correspond to the pediment located at the top of the sedimentary infill. This surface on the southern bank of the Suca Valley (Fig. 4) is covered by a lava flow of basaltic andesite dated at 8.2±0.5 Ma (Muñoz and
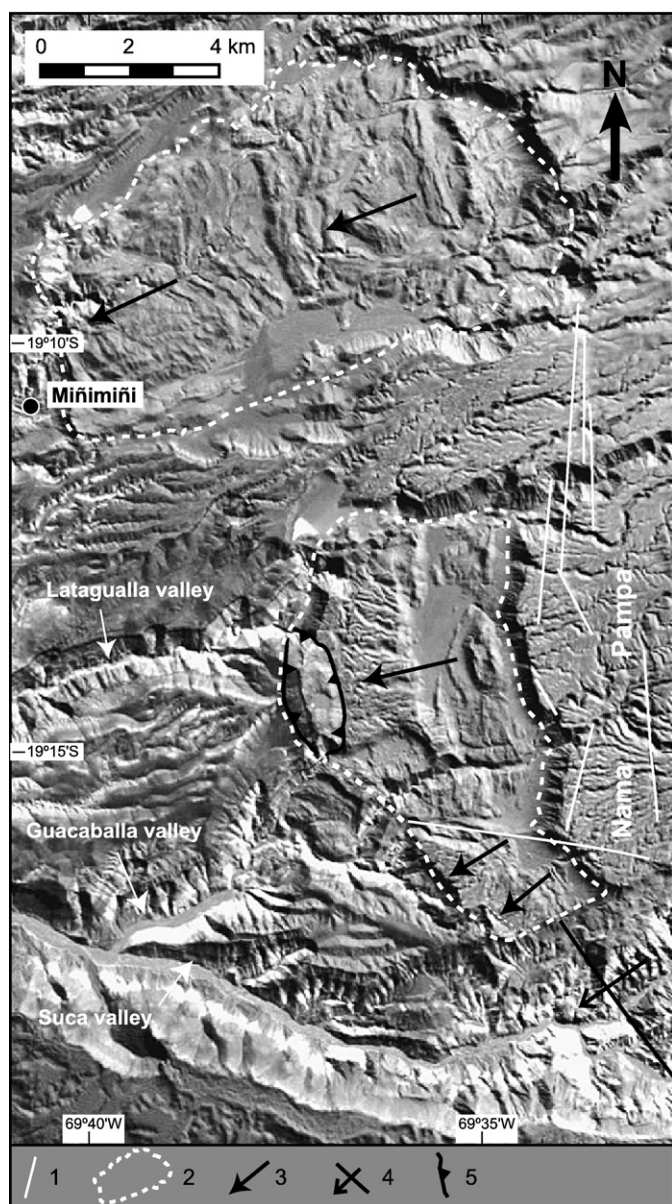
Fig. 3. Shaded relief image of the area of Miñimiñi and Moquella (modified from Pinto et al., 2004). The location of the area is shown in Figs. 1 and 2. On the Nama Pampa the lineament of tensional fractures (narrow grabens) associated with the Moquella Flexure are exposed. The landslides are aligned on the prolongation towards the north of the Moquella Flexure. 1 - tensional fracture; 2 - limit of the area affected by landslides; 3 - direction of propagation of a landslide; 4 - flexure; 5 – thrust fault.

Sepúlveda, 1992). Given the position of this lava flow, it can be concluded that the incision of the Suca Valley is posterior to this date.

It is known that throughout the piedmont of the Precordillera in northern Chile, the incision of the valleys began approximately 8–9 Ma ago (García and Hérail, 2005; Von Rotz et al., 2005). The evolution of the incision had a direct impact on the ground water table; thus we can assume that up to 8–9 Ma the ground water table along the Precordillera and Central Depression contact was very close to the surface, and that this level fell as the valleys were incised. The incision rate of the valleys can be estimated at approximately 60 m per million years (García and Hérail, 2005). Given the extreme aridity of the climate, the interfluves, on the contrary, are eroded very slowly; their rate of denudation is about 0.1 to 1 m per million years (Kober et al., 2007). This explains the perfect preservation in the interfluve morphologies associated with the deformation, even if they are rather old (García and Hérail, 2005). The valley incision in the Precordillera

and the relief formation related with the Moquella Flexure started after about 9 Ma (Muñoz and Sepúlveda, 1992; Pinto et al., 2004), whereas in the Central Depression, which is the local base level, the valleys were not incised, but deposition of silt and formation of palaeo-salt lakes, such as the Tamarugal Pampa and Pintados Salt Lake, were taking place. In these conditions of drainage and dissection, the water table must have been very close to the topographic surface.

2.3. Seismic activity

The region has historical records of the three main types of earthquakes: large magnitude ($M > 8$) interplate earthquakes, with hypocentres along the contact of the Nazca and South American plates; intermediate-depth intraplate earthquakes, with epicentres on the continent and foci in the subducted plate, and shallow crustal earthquakes along active faults. The tectonic history of the area suggests that these types of earthquakes have all been present during the Neogene. The last large earthquakes that affected the area are the 2005 Tarapacá earthquake (intermediate-depth intraplate, M 7.7; Peyrat et al., 2006), the 2001 Aroma–Chusmiza earthquake (shallow crustal, M 6.3; Legrand et al., 2007) and the 1877 northern Chile earthquake (interplate, $M \sim 9$; Chlieh et al., 2004). The absence of a large interplate earthquake for more than a century defines a seismic gap and suggests that an earthquake of this type may occur in the near future (Comte and Pardo, 1991). This prediction is supported by elastic deformation measurements in the region (Chlieh et al., 2004). Furthermore, the area of this study is also affected by interplate earthquakes in southern Peru such as the 1868 and 2001 ones.

3. The Latagualla Landslide area

3.1. Geology of the landslide area

On the western edge of the Precordillera, between Arica and Moquella (Fig. 2), the substrate corresponds to marine and continental Mesozoic sedimentary deposits, deformed into small synclines and anticlines and intruded by plutons of granodiorites and rhyolitic rocks (Galli, 1957; Cecioni and García, 1960; Salas et al., 1966; Camus and Fam, 1971; Muñoz et al., 1988; Muñoz and Charrier, 1993) (Fig. 2).

In the Precordillera, the substrate is covered by Neogene deposits constituted by layers of ignimbrites of 300–600 m thick: the Oxaya Formation in the Arica area and the Latagualla Formation in the Moquella area. These volcanics represent the facies formed near the volcanic centres as well as at the leading edge of tectonic deformation. The volcanogenic series is partially covered, mainly in the Precordillera, by a series of basaltic andesites, basalts and andesites of middle to late Miocene (Fig. 2).

Towards the west, the volcanic deposits are interstratified with sedimentary beds which fill the Central Depression and correspond to a continental series deposited in an NW–SE elongated basin (Fig. 2) (Montecinos, 1963; Salas et al., 1966; Pinto et al., 2004). The strata of this basin are gently tilted towards the west and are very little deformed. The basal units of this sedimentary succession are composed of conglomerates and sandstones deposited in a fluvial environment and the upper units are composed of conglomerates deposited in an alluvial environment.

In the Moquella area, the Neogene succession is represented by the Latagualla Formation, which corresponds to a syntectonic unit showing intercalations of 20 to 100 m thick ignimbrites at its base. The sedimentary part of the Latagualla Formation corresponds to beds of coarse conglomerate, sandstone and mudflows, with poorly defined stratification towards the top. These deposits are preserved mainly in the Central Depression to the west of the Moquella Flexure (Fig. 4). A remarkable abundance of ashy matrix throughout the sedimentary succession is observed. The top of the Latagualla Formation corresponds to the erosion surface of the "pampas" (extense plains, Fig. 3);
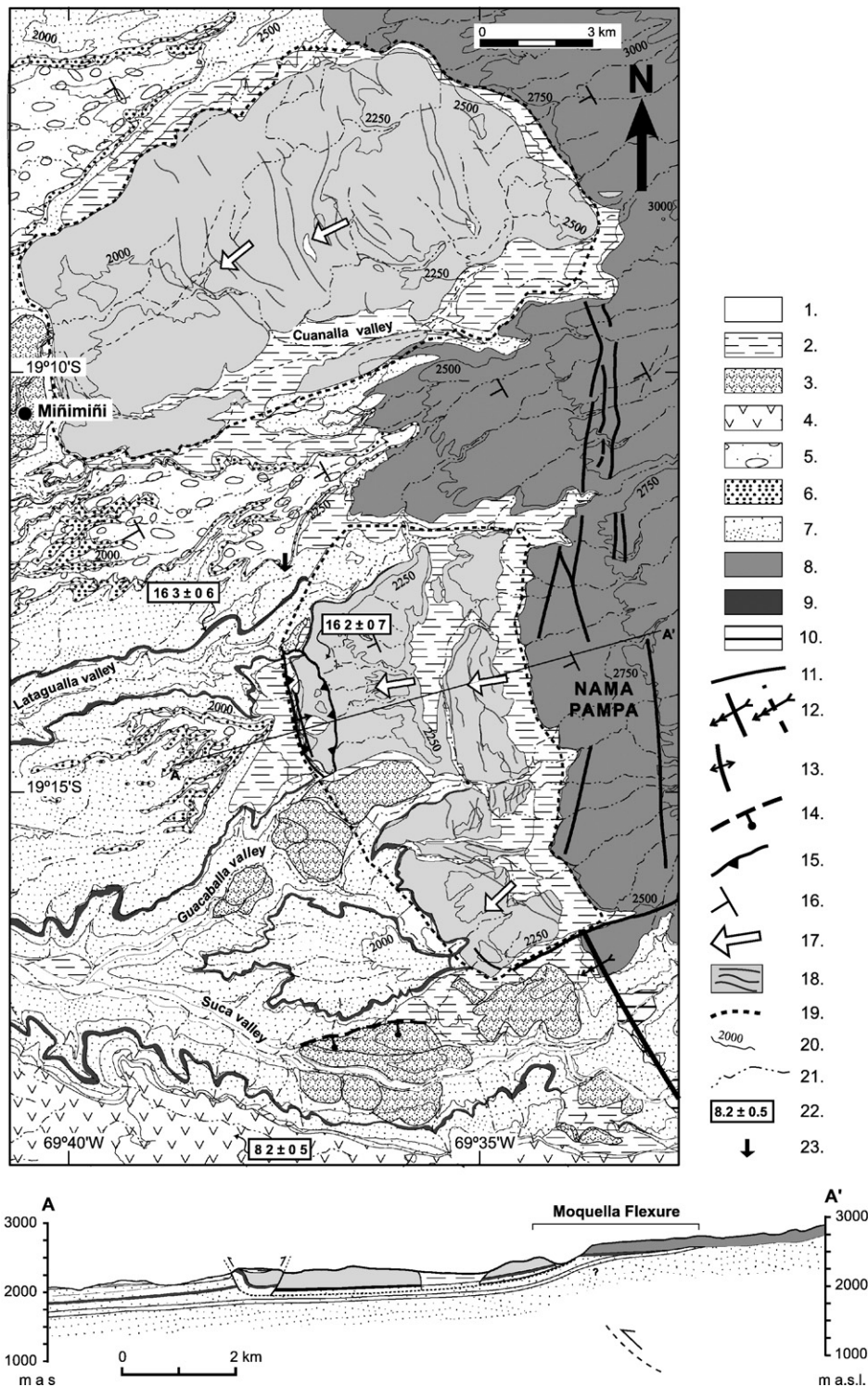
Fig. 4. Geological map showing the units and structures implied in the mega-sliding of Lataguala (based on Pinto et al., 2004). The location of the area is shown in Figs. 1 and 2. 1 - alluvial sediment in valley; 2 - sediment in plain and colluvium; 3 - block slid into gorge slope; 4 - andesitic lava in Tana Pampa, pertaining to late Miocene volcanic complex; 5 to 9 - Lataguala Formation: 5 - Gravelly sandstone and sandy conglomerate with shale interbed; 6 - pumaceous medium-grained gravel; 7 - conglomerate, sandstone and mudstone, and intercalation of acid tuff concentrated at the lowest levels of the Lataguala Formation; 8 - Nama Ignimbrite; 9 - Tarapacá Ignimbrite; 10 - stratified Mesozoic substratum formed by conglomerate, sandstone and shale of various volcanic components, and andesite; 11 - fracture, minor fault and lineament; 12 - observed and inferred flexure; 13 - anticline fold associated with the superficial sliding; 14 - inferred normal fault; 15 - thrust fault; 16 - orientation and dip of layer; 17 - sliding direction; 18 - landslide block with superficial folding; 19 - approximate limit of landslide; 20 - height contour, 250 m interval; 21 - ravine; 22 - date (age in Ma) (Muñoz and Sepúlveda, 1992); 23 - Location and direction of the photo in Fig. 5. In profile A-A' thrust faults in the landslide front, and the probable location of a thrust fault related to the Moquella Flexure are indicated.

and in the Tana Pampa, it is locally covered by the Tana Lava (Figs. 2 and 4). Two volcanic levels are interstratified in the Lataguala Formation: the Tarapacá and the Nama ignimbrites. The Nama ignimbrite, 150 m thick, crops out in the north of the Suca Valley

mainly in the Precordillera and is bevelled towards the west above the Moquella Flexure. There, the ignimbrite overlies the Tarapacá Ignimbrite, which is 40 m thick. The latter extends from the flexure towards the west, where it is intercalated with sedimentary strata of

the Latagualla Formation (Fig. 4). Its thickness decreases rapidly towards the west over a distance of 8 km, where it clinches out. The Nama and Tarapacá Ignimbrites result from the same eruptive process in which the second is a vitrophire of the first (Pinto et al., 2004). The dark brown colour of the Nama Ignimbrite and the black colour of the Tarapacá Ignimbrite contrast with the colour of the sedimentary deposits and of the other ignimbrites, which makes these ignimbrites an excellent marker unit in studying the deformation that affected the Neogene succession. These ignimbrites have an approximate age of 16.3 Ma (Fig. 4) (Muñoz and Sepúlveda, 1992; Pinto et al., 2004).

The basal units of the Latagualla Formation were deposited in an alluvial and fluvial environment and the upper units represent a system of alluvial fans in which many well-defined channels can be observed (Pinto et al., 2004). The apices of the cones are located mainly along the axis of the Moquella Flexure, and during the last episode of sedimentation they migrated towards the east (Pinto et al., 2004). This and the presence of synsedimentary progressive unconformities clearly indicate the syntectonic character of the sedimentation generated by activity of the Moquella Flexure.

3.2. The Latagualla Landslide

West to Miñimiñi Village and between the Latagualla and Suca Valleys, there are many landslides that affect the Latagualla Formation and the Nama Ignimbrite (Figs. 3 and 4). It is possible to recognize, on the one hand, landslides due to the displacement of the valley slopes. On the other hand, there are two landslides of great extension that affect the upper part of the Latagualla Formation; they are NNW–SSE trending along the side of the Moquella Flexure (Figs. 3 and 4). These giant landslides, that we refer to as the Miñimiñi and Latagualla Landslides (from north to south, Figs. 3 and 4), are cut by the main valleys, thus they were formed prior to the incision of the valleys. Therefore, they owe their origin to a mechanism different from collapse of the valley slopes.

The landslide located east of the village of Miñimiñi affects an area of 57 km^2 (Figs. 3 and 4). It is 11 km long and 5.5 km wide. The landslide scarp is 350 m high whereas the front of the landslide lobe is 200 m high. The landslide is bound to the north by an escarpment covered with debris and to the south by a zone of abundant sediment accumulation in Quebrada Cuanalla (Figs. 3 and 4), which is associated with the edges of the slipped blocks. The transported rock blocks present several deformation features and associated deposits: zones with trapped sediments; normal and thrust small-scale (0.1–1 km) faults, which adapted the westward landslide; breccia zones mainly along the edges of the slipped blocks; and vertical strata in the frontal part of the landslide lobe. The landslide was accommodated by the movement of many blocks, which are very deformed. Vertical folds were produced by the displacement of these slipped blocks, which show a direction of propagation towards S74°W (Figs. 3 and 4).

The Latagualla Landslide (Figs. 3–6), located south-east of Miñimiñi between the Latagualla and Suca Valleys, affects an area of about 36 km^2 and its total volume is approximately of 5.4 km^3 (Figs. 3 and 4). It extends from the Nama Pampa towards the west, with a width of about 9 km NNW to SE, and a length of around 4 km WSW, which corresponds to the direction of displacement (Figs. 3 and 4). The displaced blocks are formed mainly by the Tarapacá and Nama Ignimbrites and are preserved almost intact (Figs. 4 and 6). The displacement produced a depression behind the moved blocks, oriented NNW–SSE, the edges of which correspond to two parallel and very craggy escarpments that coincide with tension faults, N5°E and N10°W oriented, towards the Nama Pampa. The western escarpment is 70 m high, whereas the eastern escarpment reaches 300 m (Figs. 4 and 6), the latter corresponding to the main landslide scarp.

In the deformation front the larger block folds were formed by propagation of a thrust fault, the geometry of which is defined by the Tarapacá Ignimbrite bedding in the area of the Moquella Flexure (Figs. 4–6). Its axis is subhorizontal, N14°W-trending with a WSW vergence. It is limited by two high-angle thrust faults with opposite vergencies, which have the same orientation as the fold axis (Fig. 4). These faults raised a small block of 1600×700 m in length and width, and 300 m in height. The uplifted block has a pop-up morphology and a small dry pond is preserved on its summit. This pop-up was formed in the toe of the landslide, producing a front escarpment of 200 m high. The fold is preserved between the Latagualla and Guacaballa Valleys (Fig. 6).

The rupture surface of the landslide is relatively flat (gradient of 5° to 10°) and it was developed on top of the sedimentary level of the Latagualla Formation (Fig. 4). Here, a thin, poorly lithified clayey layer along the contact between the Tarapacá Ignimbrite and clastic strata of the Latagualla Formation is found (Fig. 7). The clay layer was possibly originated by alteration during the emplacement of the ignimbrites over the sedimentary beds. We hypothesize that this clay layer may have acted as the shear surface of the landslide, due to its differential strength in comparison with the ignimbrites and clastic sedimentary strata. Deposition centres of sediments associated with erosion of the landslide are preserved (Fig. 4). A smaller sized block is recognized between the main landslide mass and the main scarp. This block corresponds to a second episode of landsliding after the first event, as discussed later. Both masses are separated by an alluvial plain (Figs. 4 and 6).
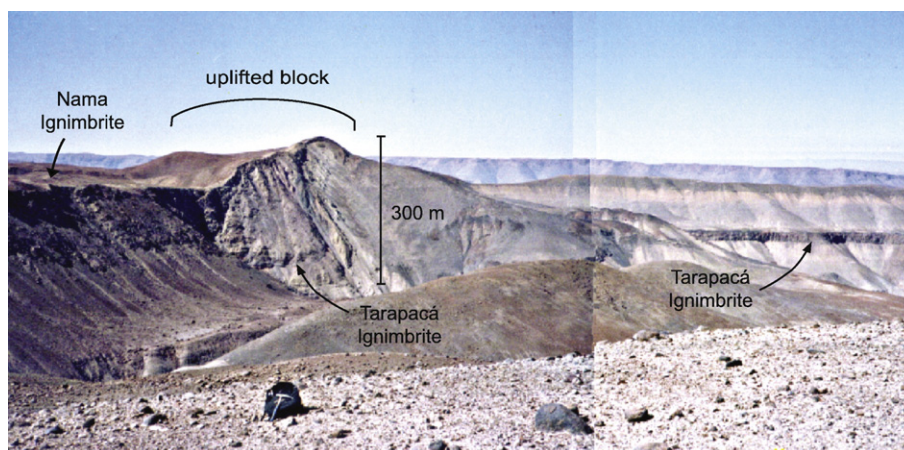

Fig. 5. Panoramic view towards south of the landslide front, showing the thrust-propagated anticline fold generated in front of the slide between the Latagualla and the Guacaballa Valleys. Note that ahead of and behind the fold the Tarapacá Ignimbrite is subhorizontal.
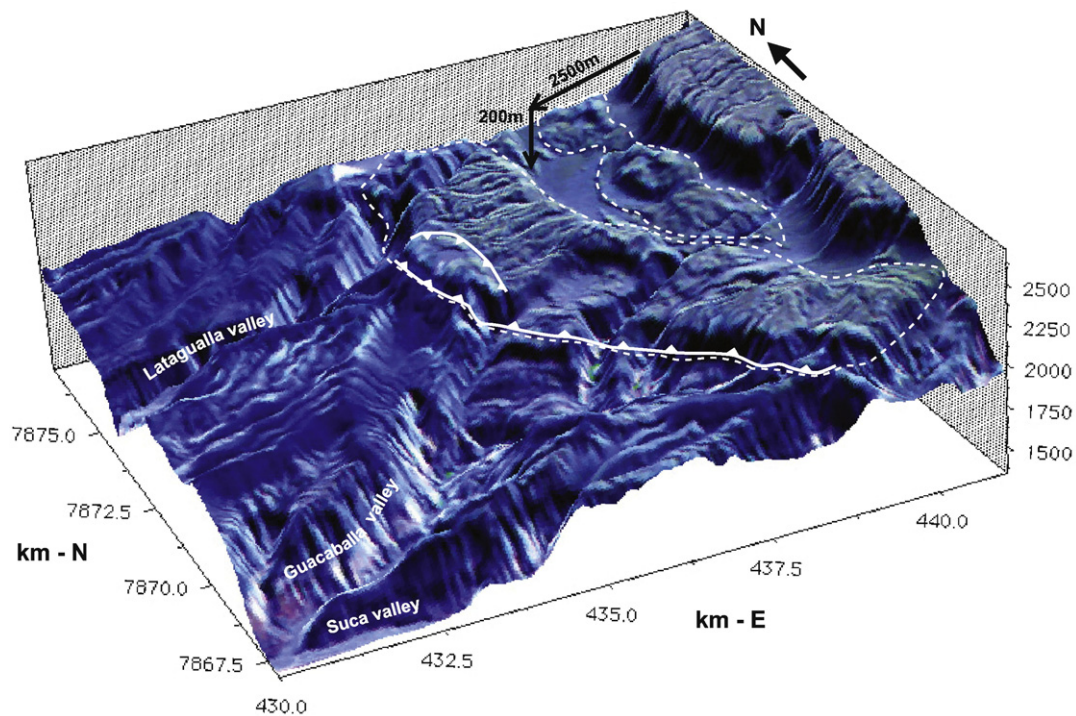
Fig. 6. Digital terrain model, NE view, showing the mega-landslide of Latagualla, between the Latagualla and Suca Valleys. The white dashed lines outline the displaced blocks of the landslide; the arrows indicate the vectors of horizontal and vertical displacements of the front block; and the white solid line with triangles indicates the location of the thrust faults at its front. The small blocks behind the main front block are those involved in the re-equilibrium of the landslide scarp.

3.3. Emplacement of the Latagualla Landslide

The rock mass moved by the Latagualla Landslide is so well preserved that it is possible to reconstitute its emplacement. The relationships between the topographic forms and the tectonic structures allow the process to be separated into three stages (Fig. 8):

Stage 1: Transfer to the west of block number 1. The preservation on its surface of gully morphologies, which can be linked with similar morphologies preserved on the surface of the Nama Pampa, allows the direction of displacement to be determined and the amount of this displacement to be estimated at ca. 2.3 km.

Stage 2: Deformation by compression of the front of the moved mass and the heightening of block number 2 by pop-up between two faults of opposed vergence accompanied by folding. Consequently, the fold (Fig. 5) and thrust faults, recognized south-east of Miñimiñi and interpreted as the result of regional tectonics (Muñoz and Sepúlveda, 1992), are actually structures due to deformation of the landslide front. Stage 2 is thus almost synchronous with stage 1.

Stage 3: Emplacement of block number 3, characterized by a chaotic internal structure, preserved at the foot of the main landslide scarp. We interpret this event as the gravitational readjustment of the scarp after the movement of block number 1.
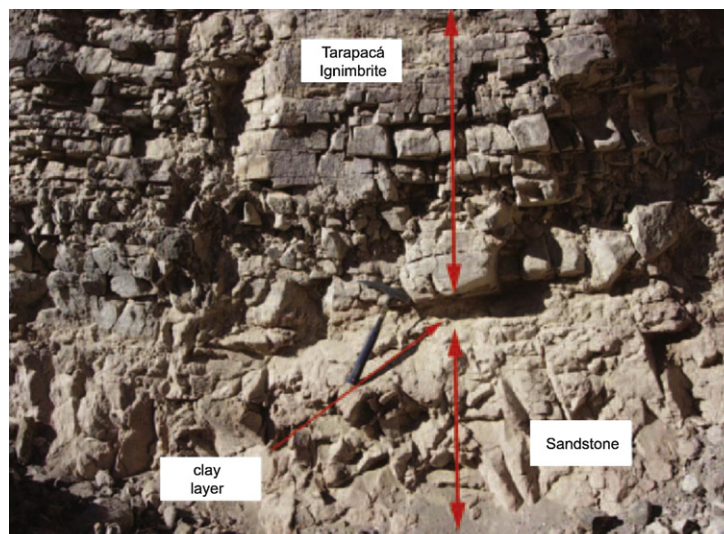

Fig. 7. Detail of the clay layer between the Tarapacá Ignimbrite and the sedimentary deposits.
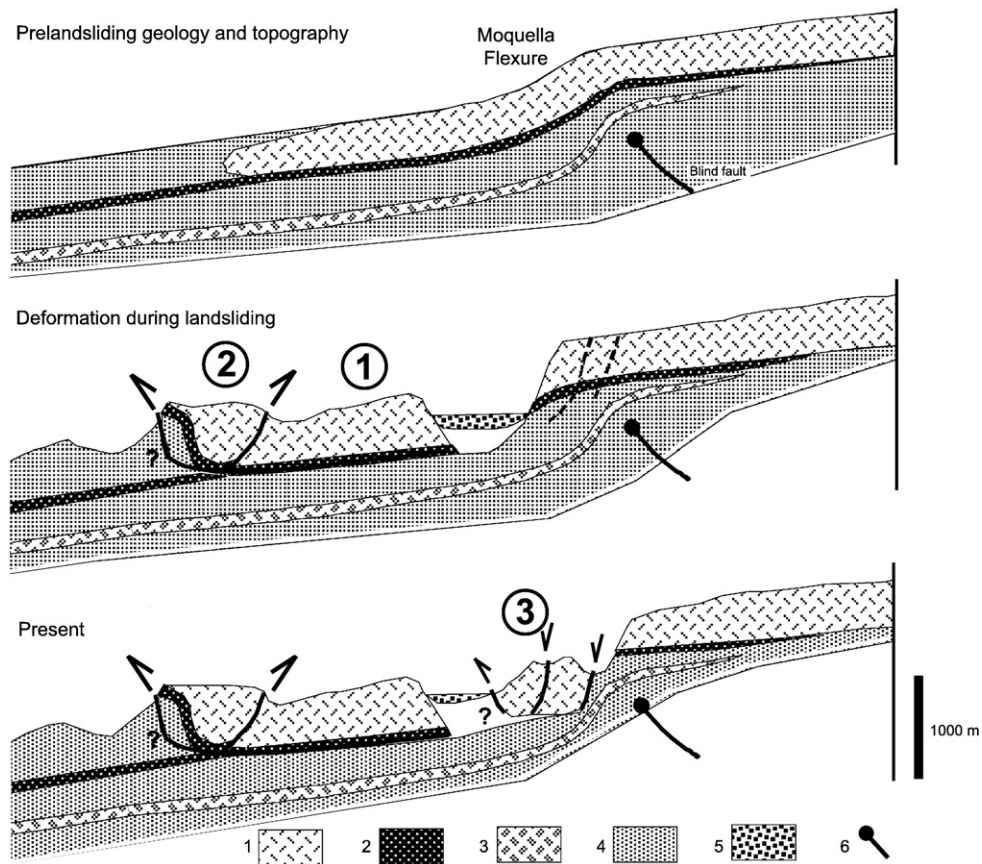
Fig. 8. Three stages of the emplacement of the Latagualla Landslide. 1 - Nama Ignimbrite; 2 - Tarapacá Ignimbrite; 3 - Suca Ignimbrite (see Pinto et al., 2004); 4 - Sediment of the Latagualla Formation; 5 - Quaternary deposit; 6 - Blind fault associated with the Moquella Flexure.

The age of the landslide has not been determined directly, but is prior to the incision of the present-day valleys. At that time, the erosion of the ravines was much shallower and the water table would have been much higher than at present, as already discussed.

4. Discussion

A giant, prehistoric landslide like the Latagualla Landslide is generally interpreted as having been induced by earthquakes (e.g. Keefer, 1984; Philip and Ritz, 1999; Schuster and Highland, 2007). Conditions that support the assumption of a seismic trigger for large palaeo-landslides include strong seismicity in the area, proximity to active faults, and the need for extra forces to induce landsliding obtained from geotechnical analyses (Solonenko, 1977; Crozier, 1992; Philip and Ritz, 1999). All these conditions apply to the Latagualla Landslide. The Tarapacá region has been seismically active, associated with the subduction tectonic setting. Hence, given the large landslide volume, slide structure and morphology, the seismicity of the Tarapacá region and the proximity of an active fault, we propose a seismic trigger for the Latagualla Landslide.

According to the classification of earthquake-induced landslides by Keefer (1984), the Latagualla Landslide can be considered as a coherent rock slide. Statistically, these types of landslides can be generated by earthquakes of magnitude over M_L 6.5 or M_S 5.9, and earthquake intensities (MMI) of VI or higher (Rodríguez et al., 1999). Preliminary geotechnical and stability analyses by Pinto et al. (2007) and Darrozes et al. (2007) show that the rock mass may have failed during an earthquake in the Moquella flexure of magnitude about M 7.0 and peak horizontal accelerations around 1.0 g. The factor of safety reduces considerably when a high water table is considered (Darrozes et al., 2007), while the landslide is largely stable without a seismic

trigger. Alternatively, a very large earthquake (M over 9.0) in the subduction zone may also have triggered the landslide given a medium to high water table position (Darrozes et al., 2007).

Inactive drainage patterns on the surface of the landslide mass suggest that the local water table may have been quite shallow prior to landsliding. Although high earthquake intensities (up to around IX) and accelerations close to 1.0 g may be reached in epicentral areas with the different earthquake types that occur in the region (Campos et al., 2005; Astroza et al., 2005; Sepúlveda et al., 2008), the presence of a flexure immediately next to the landslide suggests that this fault is the most likely seismic source. The area has records of recent shallow earthquakes, such as the 2001 Aroma–Chusmiza earthquake, triggered within the Aroma Flexure about 50 km south of the study area (Farías et al., 2005; Legrand et al., 2007). Acceleration values in Chilean earthquakes are typically high (Ruiz and Saragoni, 2004; Campos et al., 2005), and there are cases of peak accelerations close to or over 1.0 g near to the epicentre in shallow crustal earthquakes in Chile (Sepúlveda et al., 2008). According to intensity records of the 2001 Aroma–Chusmiza earthquake (M 6.3) in the Tarapacá region and the 1958 Las Melosas earthquake (M 6.9) in Central Chile, intensity values exceeding VI for Chilean shallow earthquakes are registered within an epicentral distance of about 40 km; whereas, to reach peak accelerations close to 1.0 g, the focal distance has to be less than about 20 km (Campos et al., 2005; Sepúlveda et al., 2008). These limits suggest that the landslide would have been induced by a very proximal, shallow earthquake. Therefore, an ancient strong earthquake in the Moquella flexure, given favourable geomorphological conditions, may have induced the mega-landslide.

The water table at the time of the landslide triggering would have been much higher than now, given the minor dissection of the valleys at this time. These conditions were more favourable to landslide

susceptibility than today, where the water table is below the landslide shear surface. This fact implies that under the current climatic and water table conditions, the low slope angle and the short space in front of the landslide mass, a reactivation of the landslide or the generation of new, similar instabilities is less likely, requiring a very strong earthquake to reach the necessary peak horizontal accelerations to trigger the movement. Furthermore, structural boundary conditions that allow sliding have to be present. Hence, the hazard of giant landslides in the area can be considered as low, but not necessarily negligible.

5. Conclusions

Along the Western Cordillera of southern Peru and northern Chile, landslides of several km^3, with a very well preserved morphology given the extreme aridity of the climate, are observable from 14°S to 23°S. Many of these landslides did not come from the destabilization of the slopes of the valleys but resulted from the failure of the western slope of the Precordillera directly associated with tectonic activity. The landslide of Latagualla, in the Andes of northern Chile, was caused by the failure of the western side of a flexure that marks the contact between the Precordillera and the Central Depression, and that resulted from the activity of a blind fault. The nearby landslide of Miñimiñi probably has the same origin. These landslides have not yet been able to be dated precisely, but are prior to the incision of the principal valleys that started after 8–9 Ma. The Latagualla Landslide mass is very well preserved, allowing reconstitution of its movement and evolution in three main stages: main landslide movement; compression and deformation of the landslide front; and gravitational readjustment of the landslide scarp by a second, minor landslide. By estimating the condition of the materials which compose the Latagualla Landslide before their displacement, and the probable position of the ground water table, we conclude that an acceleration provided by a seismic shock was necessary to start the landslide. Given the local conditions of 8-9 Ma (morphology, slopes and probable position of the ground water table), a large-magnitude earthquake, most possibly with a source in a local blind fault, whose surficial expression is the nearby Moquella Flexure, could have provided enough destabilization forces to cause these landslides. On the other hand, presently these seismic forces would not be sufficient to trigger such landslides. Indeed, the drastic incision of valleys in the Precordillera and the Central Depression caused the phreatic level to fall and, consequently, produced an important reduction in the water contents of the rocks close to the surface. Therefore, the acceleration necessary to start such slides could only be provided by very large earthquakes, the occurrence of which is unlikely. On the other hand, the valley-side slopes formed by dissection since 8-9 Ma can be destabilized by smaller earthquakes.

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