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Morphometric characterization of a large scale rockslide, and probable seismogenic origin of landslides on the western flank of Central Precordillera, Argentina

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ABSTRACT

The distribution of late Pleistocene to Holocene rockslides in the western flank of the eastern mountain ranges of Central Precordillera (30° 40′–31° S), has been analyzed to determine the triggering mechanisms. The mode of failure was determined to be translational sliding. This paper presents the results of research on one of the Holocene rockslides located in the western flank of Sierra de La Dehesa, which is composed of stratified limestones of early Paleozoic age. In order to characterize this slide, high resolution satellite imagery interpretation was carried out, along with the recognition of the landslide detachment zones and landslide bodies with the aim of reconstructing the pre-slide topography. The model proposed for this slide is a translational or planar slide, as the mode of failure was along a broadly planar surface accompanied by shear or tensile fractures and joints. The estimated rock volume involved is 1.24 Mm^3. We compared rockslide occurrence patterns to slope, topography, lithology, geological structures, and seismicity records. After analysis of the spatial relationships among all the slides and the distribution of seismic epicenters, historical earthquakes and neighboring Quaternary faults as seismogenic sources, we hypothesize that these Quaternary rockslides in the Central Precordillera have been triggered by shallow seismicity associated with active faults.

1. Introduction

Cruden and Varnes (1996) defined the term ‘landslide’ as the gravitational mass downslope motions of rock, debris or soil, or as a translational movement of rock which occurs along a more or less planar or gently undulating surface (Varnes, 1978). The presence of these slides is frequent in mountain slopes or rock exposures where the slope angle is close or parallel to the dip of the rock. The movement is controlled by planar structural discontinuities, such as faults, joints and bedding. Rockslides are characterized by well-defined head scarps and flanks, a pronounced scar generally left with little or no debris, and usually a mass of debris that accumulates in the track or at the base. In general, the triggering mechanisms of this kind of slide are undercutting of the toe support by erosion, and earthquakes. Study of these features is important, as they may cause loss of life and property, damage natural resources, and hamper development projects such as road and communication lines.

Keefer (1984) studied 40 historical earthquakes worldwide and several hundred earthquakes from the United States to determine the characteristics, geologic environments, and hazards of landslides caused by seismic events. His study indicated that earthquakes as small as 4.0 in local magnitude (ML) can dislodge landslides from susceptible slopes, and those with large magnitude can generate many slope failures across wider areas. Sepúlveda et al. (2004, 2005a,b) has studied several topographical factors which can generate faults in rock slopes, one of the most important being seismic wave amplification. He found relationships between the slope size and shape with the dominant wavelength favoring topographical amplification and landslide generation.

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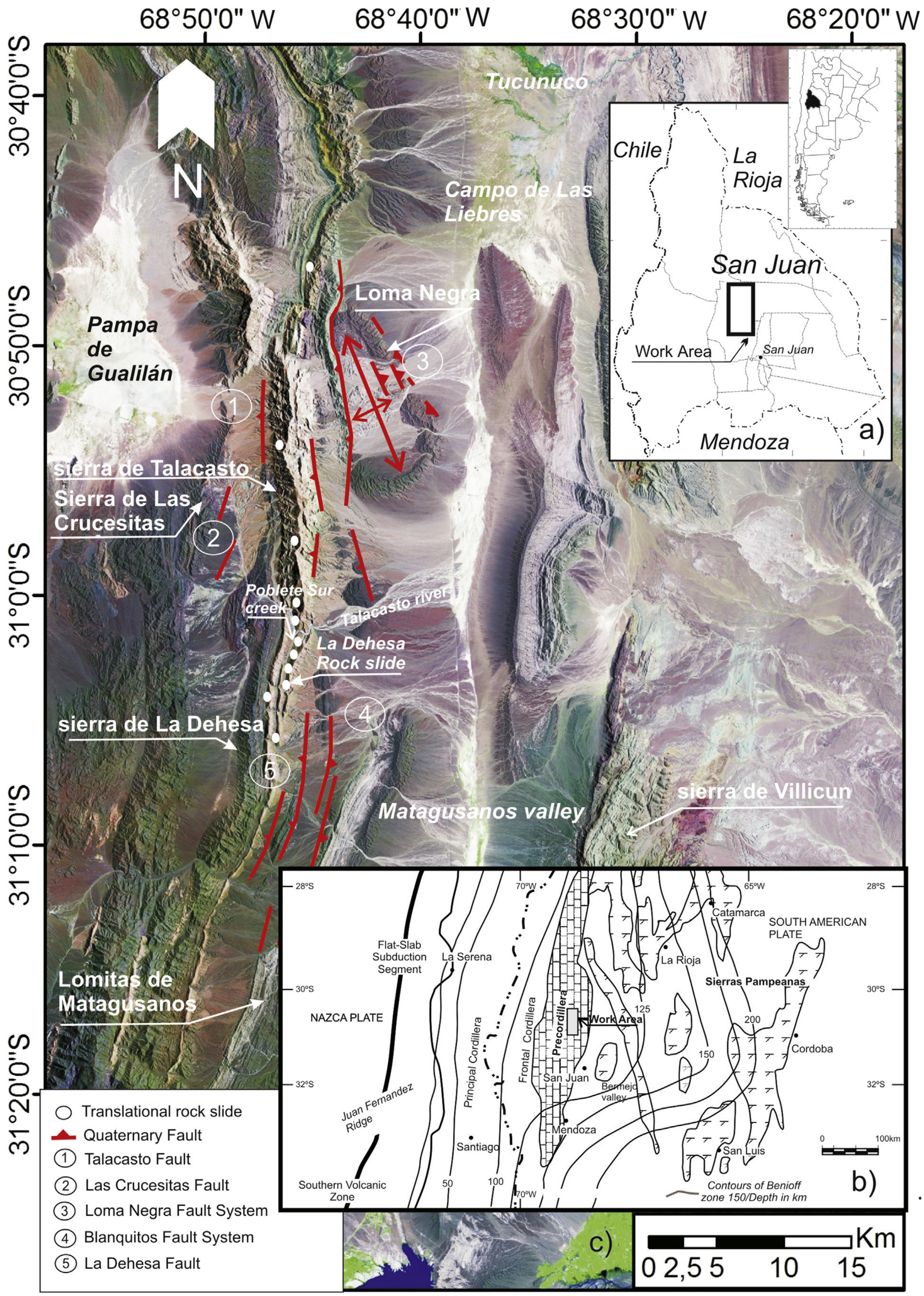

Fig. 1. a) San Juan Province and study area, b) Location of the Pampean flat-slab segment between 28° and 32° S with depth-contours of the oceanic slab (Modified from Ramos et al., 2002), c) Spatial distribution of rockslides inside the study area (white dots) and main neotectonic structures recognized in the study area.

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Fig. 2. La Dehesa rock slide. (a) General view of the rock slide area. (b) View to the south showing the hummocky texture of the rock slide deposits, covered with vegetation. The lateral limits of the slide are drawn with a dotted line. White circle indicates a person for scale (c) down-dip and laterally stepped morphology of the failure surface, (d) View of the main rock slide, e) low persistence discontinuities.

Several authors have studied landslides in Argentina (Fauqué et al., 2000; Fernández, 2005; Moreiras, 2006; Perucca and Esper Angillieri, 2008, 2009a,b; González Díaz, 2009; Esper Angillieri, 2011, 2012; Esper Angillieri and Perucca, 2013) and in the Central Andes of Chile (Moreiras and Sepúlveda, 2009; Welkner et al., 2010; Sepúlveda et al., 2012), associating them with earthquakes.

Between 28° and 32° S, an extended zone of crustal seismicity in central-northern Argentina highlights a well-known flat-slab region of this subduction zone, where the Nazca plate moves horizontally for several hundred kilometers before continuing its descent (Fig. 1a,b). This intra-plate setting had high levels of seismic shaking, and it was here the most important destructive earthquakes have taken place during the last century in Argentina, such as the earthquakes of 1894 (Ms 7.5), 1944 (Ms 7.4) and 1977 (Ms 7.4). Throughout the entire western slope of the Sierra de Talacasto and la Dehesa, overlying the flat slab of the Nazca plate, secondary structures have been interpreted as being of gravitational origin, such as slides and rock falls, cascade folds shapes, and knee folds, affecting Ordovician limestones and dolomites. These units constitute a monocline structure with dips between 30° and 60°W. This geographic concentration of rockslides hints at a common triggering mechanism, e.g. one or more earthquakes. However, although it is likely that some large rockslides correspond to weather-induced failures, the distribution of all the rockslides in the area do not follow any known climate patterns, past or present. Shallow seismicity is consistent with ongoing tectonic activity in the area, and the occurrence of the rockslides close to Quaternary faults (Fig. 1c) points direct triggering of rockslides through strong ground acceleration, possibly enhanced by topographic amplification. This relationship is supported by the observation that for more than 90% of the rockslides, the detachment surface is in the upper third of the western flank of Sierra de Talacasto and La Dehesa in Central Precordillera. The main aim of this work is to describe and characterize one of the well preserved existing Holocene rockslides, located in the western flank of the La Dehesa range, in order to better understand the emplacement and triggering mechanisms.

2. Regional setting

The sierras de Talacasto (2528 m asl) and La Dehesa (1682 m asl) are located in central-western Argentina 60 km northwest of San Juan City, 31°S, 68°47'W, Central Precordillera (Fig. 1a). The regional landscape is mountainous, with open valleys and intra-mountain basins, with elevation ranging from 800 to 2500m asl. San Juan province is characterized by semi-arid conditions with dry climates, short-lived summers and rigorous winters with very low temperatures (−18 °C–0 °C), little precipitation (below 100 mm/year), and strong winds. In the sierras de Talacasto and La Dehesa the temperature ranges from 35 °C in summer (with highs up to 40 °C) to 16 °C during the dry winters, with lows of −8 °C (18 °F). During the December–March period, heavy rainfalls of short duration commonly feed torrential freshets and floods, with a flora characterized by xerophytes. Provincial highway 436 is the main road that supports the regional economy (gold mining) and tourism in San Juan Province.

2.1. Geological and tectonic setting

Between 29° and 33°S, and with a convergence azimuth near 78° (Vigny et al., 2009), the Nazca plate is being subducted at a rate of 6.3 cm/y beneath the South American plate to depths of up to 100 km (Ramos, 1988; Kendrick et al., 2003). The flat geometry of the subducted slab is attributed to the oblique subduction of the Juan Fernández ridge beneath the South American plate (Pilger, 1981; Anderson et al., 2007; Alvarado et al., 2009; Martinod et al., 2010; Rosenbaum and Mo, 2011) (Fig. 1b).

The rockslides are located in the Central Precordillera Geological Province, which is characterized by several elongated mountainous ranges with a regional north-south trend (Fig. 1c). The main rock constituents are limestones, dolomites, and marine clastic sediments of Early Paleozoic age, continental Carboniferous, Paleogene, and Neogene rocks, and Quaternary deposits. The structure is a characteristic thin-skinned thrust-and-fold belt due to Neogene crustal shortening on west-dipping imbricate structures rooted to a 10–15 km deep main decollement.

The Sierras de Talacasto and la Dehesa trend N–S and constitute a tectonic block, affected on its eastern flank by a reverse fault with eastern vergence showing a markedly asymmetrical profile, abrupt in the east and slightly extended in the west. In addition to N–S thrusts, E–W fractures are recognized. Controlled by one of these E–W fractures, the antecedent Talacasto River crosses the ranges. Its northern and southern tributaries follow the direction of the main structures, faults, and strata.

The fault affecting the eastern slope of the sierras de Talacasto and La Dehesa has a high angle on the surface and decreasing at depth, placing Paleozoic rocks over Neogene and Quaternary strata. The calcareous strata, approximately 100 m thick, dip with angles ranging between 60° and 30°W. They are light gray to medium gray, medium grained, medium to finely stratified and with amalgamated layers up to 1 m thick. In the lower section, compact gray limestone and dolomites with thick stratification occur. At the top of the sequence there are black limestones and shales with thin stratification and local pelitic interbeds. In some sectors, sandstones and mudstones of Silurian age are present.

3. Material and method

In this study, GIS technology and satellite imagery (acquired in August 2002) from Google Earth™, along with field reconnaissance using a Differential Global Positioning System, were used to conduct the mapping and to characterize one of the slides, the La Dehesa rock slide, selected for size and state of preservation. In the field, the lateral sections and toe of the deposit were determined, and the crown was examined for cracks, slickensides, faults, and lithological contacts which could provide evidence for triggering mechanisms. Hand-held GPS-altimeter measurements were used to delineate boundaries and estimate present and eroded rockslide volumes on the selected rockslide. A digital elevation model (DEM), at 30 m resolution, was constructed using GIS software and information obtained from ASTER GDEM V2 (NASA, 2011). Records of seismic activity were collected from USGS-NEIC (2013), including data from 1923 to 2012 and within a 100 km radius from the rockslide. A total of 1150 records were collected, which were separated considering magnitude and depths: 1040 had magnitudes between 4 and 5, 9 had magnitudes of 5–6, and 4 had magnitudes of 7–7.4. The earthquakes are considered on the basis of their depth as shallow (<70 km) and intermediate (70–350 km).

For the geometric interpretation of the rock-slide, the following parameters were used (modified data from Dikau et al., 1996):

- Altitude (H): maximum (H_{max}), minimum (H_{min}) altitude contour level.
- Slope (S)
- Total length (L): minimum distance comprised between the tip and the top of the slide.
- Length of the displaced mass (L_d): minimum distance between the tip and the top.
- Depth of the displaced material (D_d): the maximum depth of the slide deposit, measured at 90° to the plane formed by W_d and L_d.
- Width of the rupture zone (W_r): maximum width of the displaced rock mass.
- Width of the displaced material (W_d): maximum width of the displaced rock mass measured at 90° to the L_d direction.
- Perimeter length of the displaced material (P): total contour length of the displaced material accumulation.
- Area (At): total area, including the rupture zone and the area of the displaced material (Ad)
- Estimated volume (V): probable volume of the rockslide deposit.

Slide volume was determined by comparing estimated elevation data of the pre-slide and post-slide topography. The main criterion is that the paleo-surface is well preserved in the vicinity. In other words, the adjacent topography would be very similar to that existing prior to the event that gave rise to the disturbance. Basically, the method consists in creating new elevation values for a disturbed area, and performs an interpolation of these new data points and the points of the undisturbed area. In this way, a new grid of the "restored" surface is created, and the differential volume between the original surface and the restored surface is calculated (Fig. 3). Finally, a digital 3D model of elevations was constructed that allowed visualizing the actual morphology of the slide (Fig. 4). The "restored" surface created was estimated from a DEM of low resolution (30 m), which subsequently limits the accuracy of the rock slide volume estimate.

One of hypotheses of this investigation is that distance from the earthquake rupture source (active fault), provides a good measure of predicting the area of landsliding. A map of the locations of main Quaternary faults and fault systems in the neighboring area of rockslides was constructed, with fault names based on published maps and previous research (Perucca et al., 2013a,b) (Fig. 1c).

4. Results and discussion

On the sierras de Talacasto and La Dehesa, the large accumulation of debris, lithological characteristics, absence of vegetation, and occurrence of triggering events, such as historical and/or prehistorical earthquakes, have all favored landslides. A number of mass removal processes have been recognized in the study area, including colluvial cones, rock and debris slides, and rock falls (Fig. 2a).

Perrin and Hancox (1992) indicated that slides that form as a result of intense rainfall are more fluid and tend to spread out more across a depositional area, whereas seismically induced landslides may have a blockier appearance and a more limited depositional extent. Even though none of these criteria are definitive, the types and characteristics of the studied landslides in the western flank of sierras de Talacasto and La Dehesa suggest seismic triggering and can be used as corroborative evidence. In areas where large landslides have been documented to occur only during earthquakes in historical times (Perucca and Moreiras 2006), the large size of prehistoric landslides may suggest seismic origin.

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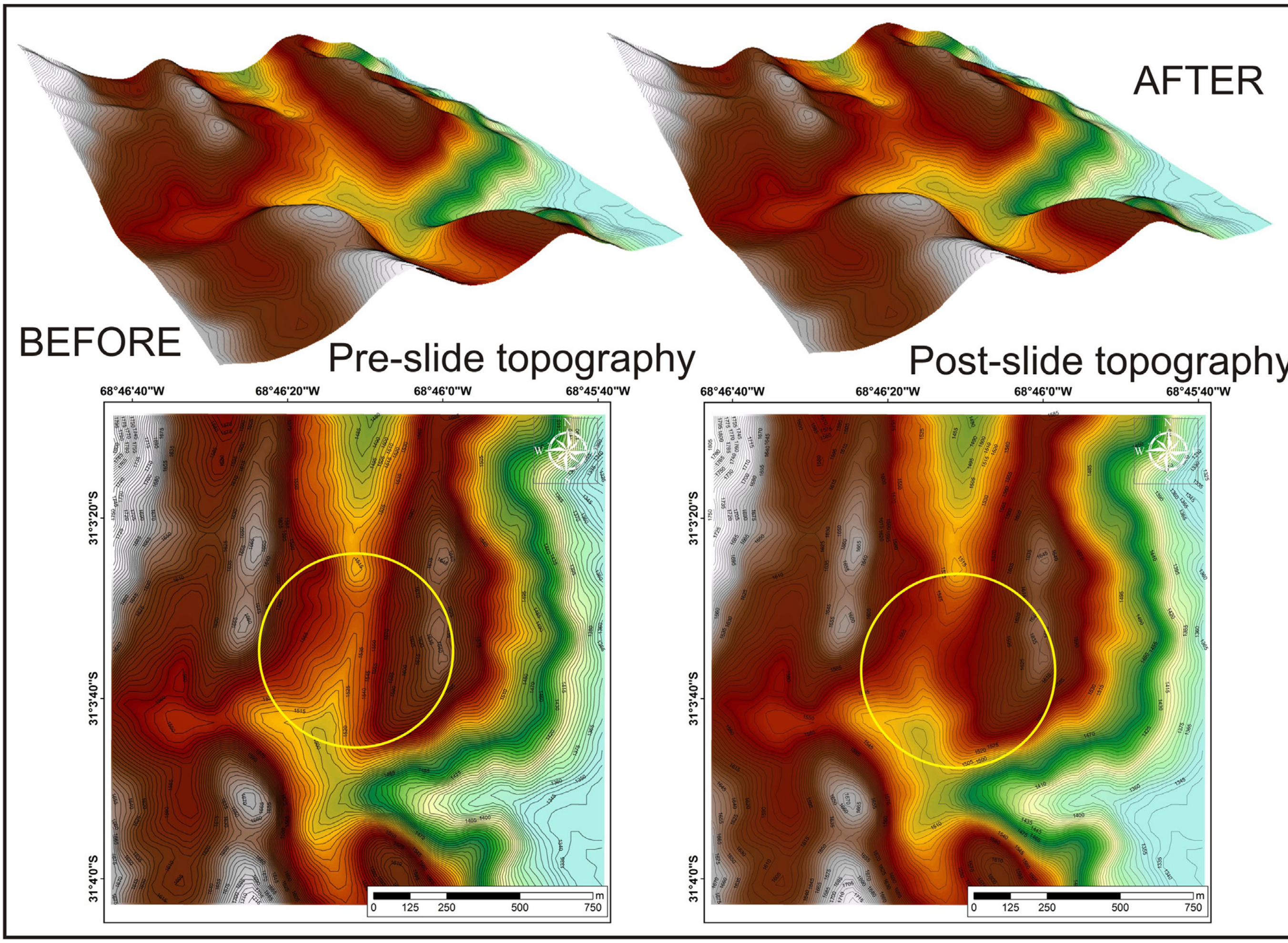

Fig. 3. Estimated DEM data of the pre-slide and post-slide topography.

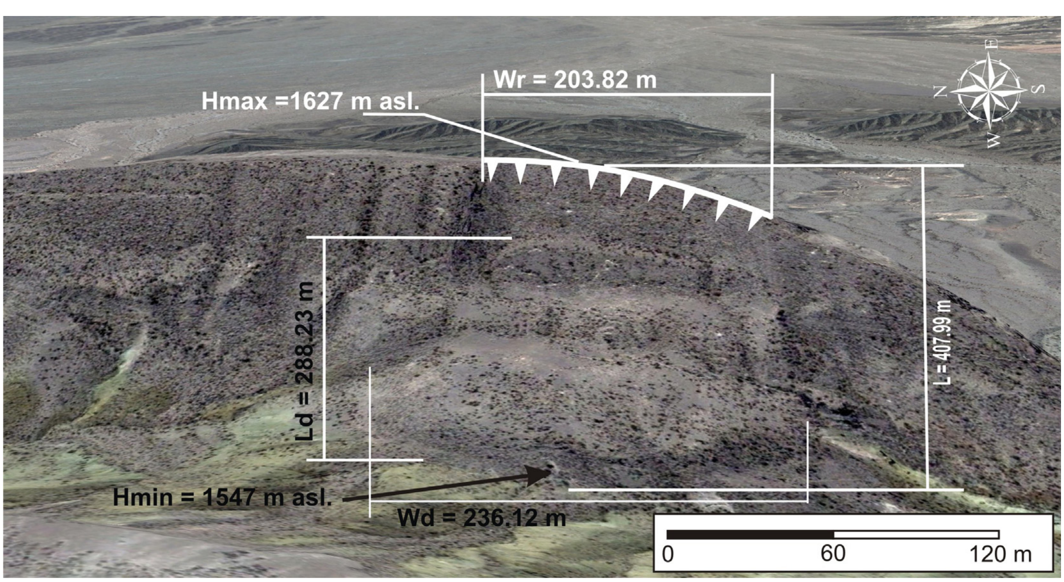

Fig. 4. 3D View (Google Earth™), and geometric analysis of the La Dehesa rock slide.

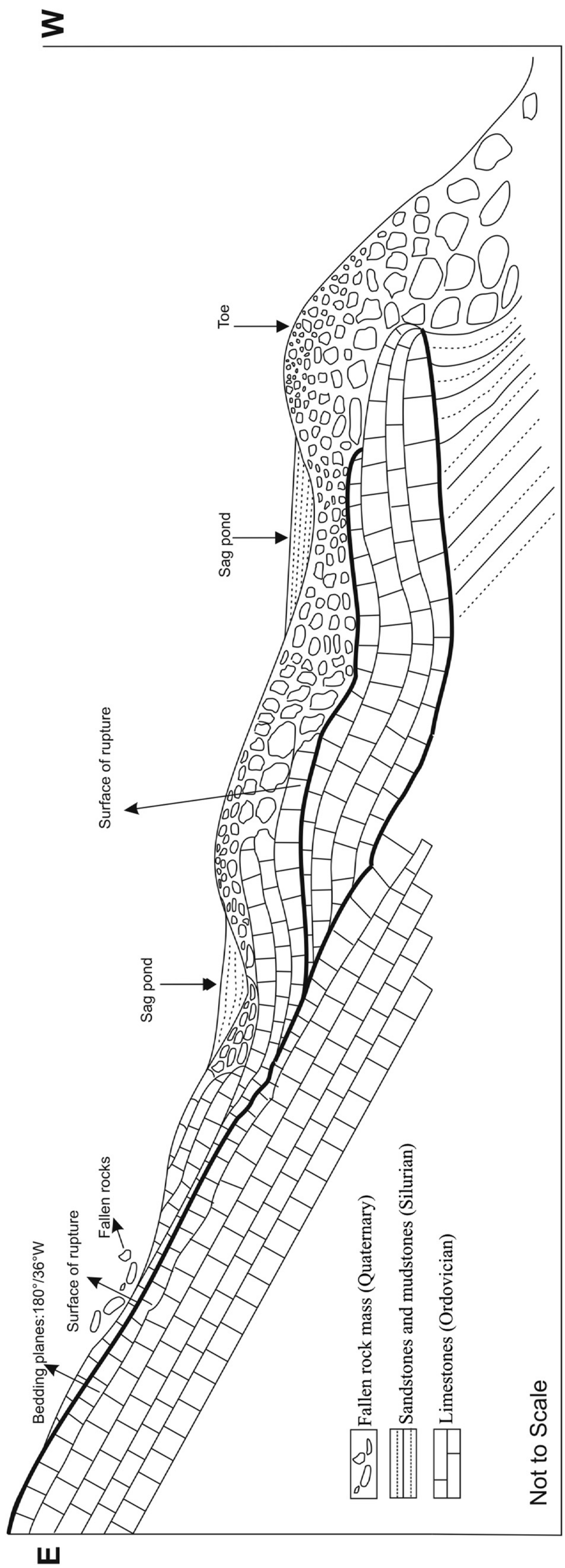

Fig. 5. Diagrammatic sketch of the La Dehesa translational rockslide.

4.1. The La Dehesa rockslide

The rockslide is located on the western slope of the sierra de La Dehesa, in the Poblete sur creek. The basic bedrock geology of this part of the sierra de La Dehesa was mapped as early Ordovician limestone trending 200° and dipping 30° to the W. All these rocks are strongly folded and faulted (Fig. 2). The bedding angle parallels the ground surface and can therefore be classified as cataclinal (Cruden, 2000, 2003).

The main escarpment extends N–S for about 450 m. The summit of the crown and the tip are 1638 and 1547 m asl, respectively, giving a height difference of 91 m. The vertical cliff is 79 m high in the center. The depletion zone of the rockslide covered an area of approximately 0.04 km^2, with an average scarp depth of 21 m. The accumulation zone occupied an area of 0.03 km^2, and the slide deposits, with an average debris diameter of 50 cm, occupied a volume of more than 1 Mm^3 and covered 0.06 km^2. More details about geometry of the slide are presented in Table 1. In general, the slide deposits have an irregular topography with a hummocky surface and inter-hummock depressions or sag ponds, composed of limestone angular gravel supported by a matrix of limestone origin (Figs. 2 and 4). The rockslide was initiated with large rock blocks at the top, breaking as they slide towards to the bottom. Physical disruption and mixing of footwall strata are present. The footwall deformation can be interpreted as an interference effect between the moving slide sheet and positive topographic irregularities. Immediately after the first failure (main slide body), or a short time after (seconds or minutes, very probably), the second main slope rupture took place, mobilizing the main block (length of about 280 m) that slid down, and was superimposed on the previously fallen block.

Table 1
Morphological parameters of the La Dehesa rock slide.

Parameters		Value
Altitude (H)	($H_{máx}$)	4481 m asl.
	(H_{min})	2950 m asl.
Central–point coordinates	Latitude	31° 03′ 36″
	Longitude	68° 46′ 07″
Surface of rupture		Plana
Total Length (L)		407.99 m
Displaced material Length (Ld)		288.23 m
Length of the rupture surface (Lr)		119.76 m
Depth of displaced material depth (Dd)		15 m
Width of the surface of rupture (Wr)		203.82 m
Width of the displaced material (Wd)		236.12 m
Perimeter length of the displaced material (P)		1003.49 m
Area (A)	Total (At)	0.08 km^2
	Displaced material (Ad)	0.06 km^2
Estimated Volume (V)		1013658.2 m^3

4.2. Seismic data

Earthquakes are one of the main triggers that cause landslides. Earthquake induced landslides have been documented in Central-western Argentina (Perucca and Moreiras, 2006; Perucca and Esper Angillieri, 2008; Esper Angillieri and Perucca, 2013; among others). San Juan Province experiences around 20–30 earthquakes daily, although the majority of these earthquakes are not felt due to low magnitude. Fig. 6 shows the distribution of earthquakes over magnitude 4.0 and how they relate to the studied area. Fig. 5

4.3. Neotectonics

Reverse faults with Quaternary tectonic activity are found in the eastern piedmont of Sierras de Talacasto and La Dehesa (Perucca et al., 2013a, b). These structures are N–S trending, with east and west facing scarps affecting alluvial fans. All the faults recognized in this area are located between 1.8 and 21 km from the rockslides area. The landslides are located along the major active faults (Fig. 1c). This distribution is consistent with the presence of active tectonic motion.

Las Crucesitas fault, verging to the east, has a 210° azimuth and dips 30° W. It displaces Neogene rocks over Pleistocene alluvial deposits and is located 18 km NNW of La Dehesa rockslide (Fig. 1c).

Talacasto fault is located in the western piedmont of sierra de Talacasto. It is 10 km long and strikes 180°, with a counterslope scarp to the east. The fault affects Neogene rocks and alluvial deposits tentatively assigned to the Pleistocene, and is located 14 km north of the rockslide (Fig. 1c).

Several Quaternary deformations were recognized in the eastern piedmont of sierra de Talacasto affecting early Pleistocene sediments and terrace deposits of probable late Pleistocene to lower Holocene age. The Western Loma Negra fault (Perucca et al., 2013b), 7 km NE of the rockslide, strikes N20W and dips 70° W (Fig. 1c). At the surface, this structure affects Miocene rocks, which have been thrust onto Pleistocene deposits. The Loma Negra anticline is formed above a west-vergent fault.

The Eastern Loma Negra thrust (Perucca et al., 2013b) is located in the eastern piedmont of the Loma Negra anticline affecting a Holocene terrace. It is a 125° striking fault that dips 28° W and is situated 24 km NE of the rockslide (Fig. 1c).

La Dehesa Fault is located in the eastern piedmont of sierra de La Dehesa, and is west verging (Fig. 1c). The fault affects Miocene rocks, which have been trusted onto Late Pleistocene–Holocene fanglomerates, trends 28°, dips 60°W, and is located 11 km southeast of the rockslide.

According to Moreiras and Coronato (2010), most of the large landslides recognized along the Argentine Andes were triggered by earthquakes affecting seismic areas, as was also reported by González Díaz et al. (2001, 2006), Fauqué et al. (2000), Fauqué and Tchilinguirian (2002), Hermanns et al. (2001), Perucca and Esper Angillieri (2008), and Esper Angillieri and Perucca (2013). Hermanns et al. (2001) noted that, given the proximity of rockslides to faults with significant Upper Pleistocene–Holocene activity, most of the landslides of central western Argentina were seismically triggered.

Therefore, seismic activity is proposed as the triggering factor of landslides in the area. This mechanism is validated by the existence of several slides along the western slope of the main N–S mountains of the area, in addition to the presence of Quaternary faults.

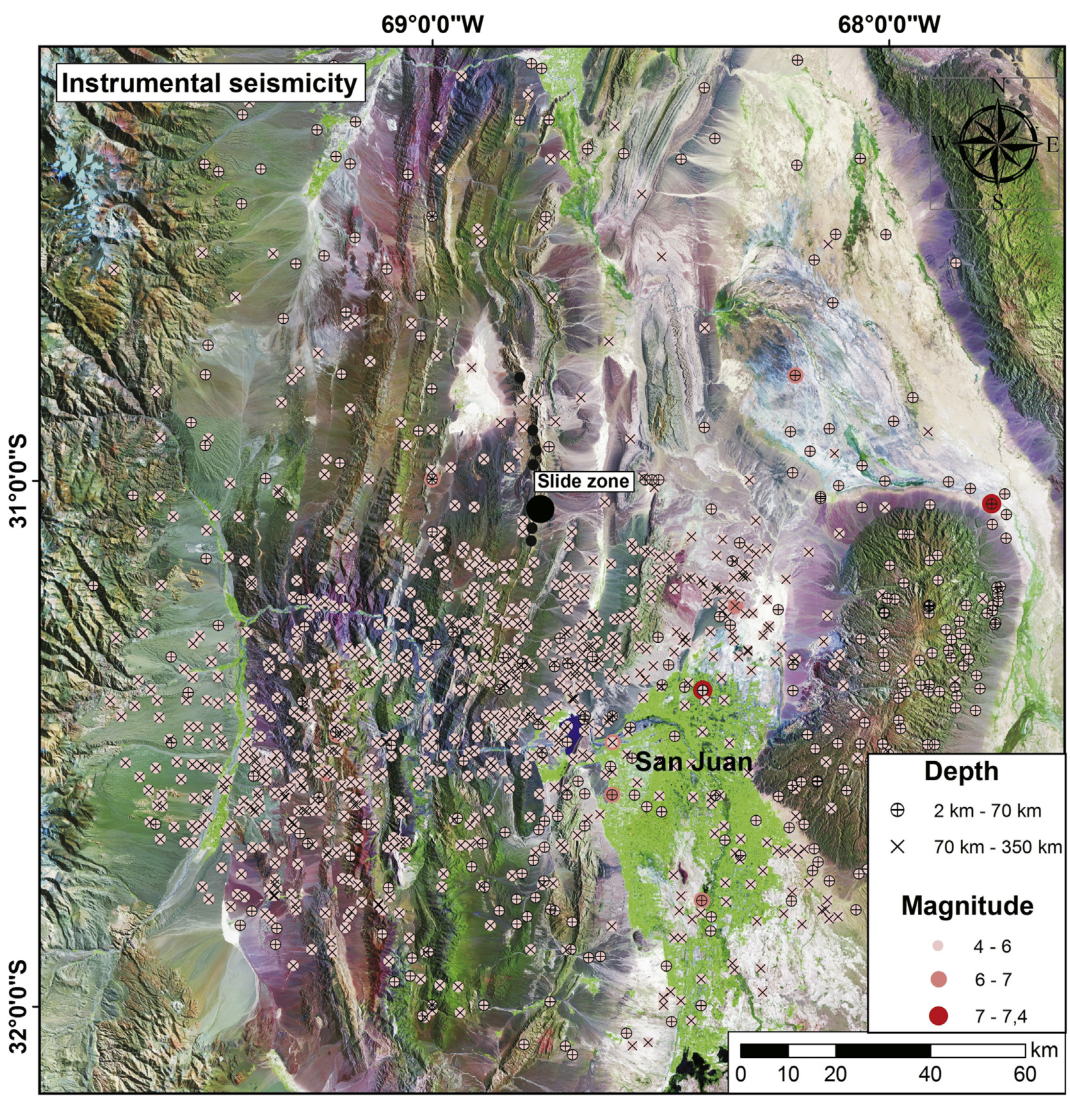

Fig. 6. Map showing the epicenters of historical earthquakes ($M > 4.0$) within a 100 km radius from the study area. The location of the main rock slide is indicated by black dots.

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5. Conclusions

A seismic origin related to Quaternary faults is proposed as the triggering factor of landslides in the area, in the absence of sufficient historical records and strong evidence which can allow correlation of the slides with prehistoric earthquakes. Quaternary faults located along the neighboring valleys increase susceptibility. Most of these structures trend north to south, dip to the west or east, and have clear evidence of Late Pleistocene–Holocene activity.

The mountain slopes facing W show the highest concentration of landslides along the N–S mountain ranges (sierras de Talacasto and La Dehesa). Comparison of this distribution with the dominant N–S active faulting could be a good topic for further seismic analyses. Through high resolution satellite imagery interpretation, a large rockslide was identified (volume > 1 Mm^3): lithology and structures act as the main controlling factors.

Our initial landslide reconnaissance mapping has shown some interesting relationships between landslide development and slope aspect and steepness, with preferential failure on west facing slopes clearly indicated. Further analysis using GIS is recommended to explore the relationships of landsliding to slope aspect and slope angle in more detail. Analysis and dating of the landslides to determine their palaeoseismic significance is also advisable. Finally, the research presented in this paper may be considered as a valuable tool for land-use in planning, design and management of roads in a seismic area.

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