Huge Slope Collapses Flashing the Andean Active Orogenic Front (Argentinean Precordillera 31–33°S)

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Abstract

The study area is located along the Andean active orogenic front comprising the most seismically active region of Argentina. Main Quaternary deformation is concentrated in this Western central part of the country associated with active faults linked to an intense shallow seismic activity (<35 km depth). During the last 150 years, the region has suffered at least six major earthquakes with a magnitude greater than Ms $\geq$ 7.0. The focus of this research is to analyse the landslide behaviour along this Andean active orogenic front. To that end, we carried out a landslide inventory along Precordillera (31°–33°S). We analysed type, size, activity grade and other morphological parameters of these landslides. We found huge collapses coincide with traces of active Quaternary faults in this region. However, landslides are clustered being denser splayed in the centre of study area. Furthermore, activity grade of such landslides is higher in this central zone decreasing gradually towards the north and the south. This central area is affected by the Juan Fernandez Ridge which is likely related to higher deformation rate.

Keywords

Quaternary • Neotectonics • Active fault • Earthquakes

Introduction

Distribution of landslides along active tectonic fronts is not a new finding among paleoseismologists and geomorphologists (Keefer 1987, 1994, 2000; Jibson and Keefer 1993; Jibson 1996; Jibson et al. 2006). This has been also achieved along the main ranges of the Andes (Fauqué et al. 2000; Moreiras 2006; Perucca and Angillieri 2008, 2009a, b; Moreiras and Sepúlveda 2009; Moreiras and Coronato 2010; Esper Angillieri 2011, 2012; Esper Angillieri and Perucca 2013; Esper Angillieri et al. 2014 among others). However, correlation between landslide behavior with characteristics of the active front has been rarely reached.

A seismic genesis is commonly suggested for main landslides in the Andes because of their relation with neotectonic activity, given the proximity of the failures to faults and statistical correlation of the landslide distribution with faults and shallow crustal seismic activity (Abele 1984; Antinao and Gosse 2009). Nonetheless, Quaternary activity of regional faults has been rarely proved by the lack of seismotectonic and palaeoseismological studies and the low frequency of large magnitude crustal earthquakes during the last century in the region (Moreiras and Sepúlveda 2015). Neotectonic studies focused on this dilemma are beginning in Argentina. Seismicity is extended

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to the Holocene in the Precordillera (Perucca and Moreiras 2008) based on preservation of seismites in palaeo-lakes dammed by two rock avalanches in the Acequión River (San Juan province, 32°SL). Rock avalanches clustered in the northern extreme of the Cordon del Plata (Cordillera Frontal) linked to evidences of Quaternary activity of the Carrera fault system prove the occurrence of $M > 6$ palaeo-earthquakes at least until the Late Pleistocene (Moreiras 2006; Moreiras et al. 2015).

In this research correlation between neotectonic activity and landslide spatial distribution is encouraged with the aim of understanding this relationship in the Andean Orogenic front.

Study Area

The study area corresponds to the Precordillera morphostructural unit being a north-south fold-and-thrust belt (Jordan et al. 1993) (Fig. 1). It is divided in four sectors: Eastern, Central, Western and Southern Precordillera (Cortés et al. 2005). The differences between these are based on their stratigraphic composition and structural nature. Stratigraphically, Eastern and Central Precordillera are composed of a thick sequence of Silurian, Devonian and Carboniferous rocks overlying Cambrian platform limestones. Western Precordillera is mainly composed of Cambrian and Ordovician ocean-floor sediments interbedded with basic and basaltic rocks. Southern Precordillera is composed of Lower Paleozoic rocks. West vergence characterized Eastern Precordillera; whereas Western, Central and Southern Precordillera show an east vergence in their structures.

Most of the Quaternary tectonic deformation in Argentina is gathered in the backarc region of the Andes. This fact is attributed to the flat-slab segment of the Nazca Plate produced due to the oblique subduction of the Juan Fernández ridge beneath the South American plate (Barazangi and Isacks 1976; Cahill and Isacks 1992; Anderson et al. 2007). This effect generates a shallow seismic activity (<35 km depth) (Smalley et al. 1993; Alvarado et al. 2009) that is evidently related to Quaternary faults. This highest seismic hazard region of the country recorded the most significant historical and instrumental seismicity. The largest Argentinean historical earthquake with an epicenter in the north of San Juan province (Ms: 7.5) occurred in this region. Quaternary deformation already known in Argentina is concentrated within this sector where several surface ruptures were reported during historical earthquake events such the case of the 1944 La Laja earthquake (Ms: 7.4) and the 1977 Caucete earthquake (Ms: 7.4).

Methodology

Initially, geological information was collected from Geological sheets published by SEGEMAR (Argentinean Mining Geological Service) at 1:100.000 and 1:250.000 scale. These geological sheets are Cerro Aconcagua 3369-I, Mendoza 3369-II, Potrerillos 3369-15 and San Juan 3169-IV. There is not published geological sheet of the Calingasta and Barreal region. Indeed, we included geological data collected by Quartino et al. (1971). This active tectonic segment of the Central Andes is strongly affected by Neotectonic activity. Data about Quaternary regional faults was collected to evaluate the relation between distribution of landslides and neotectonic activity in the study area (Costa et al. 2000, Casa et al. 2014).

A landslide inventory map was produced out using images from Google EarthTM for easy visualization. Manual digitalization of the identified landslides was released using QGIS software. We included in our inventory those landslides identified in previous works (Angillieri 2015; Pantano Zuñiga 2014). Landslide parameters were measured. Altitude data were obtained from ASTER Global Digital Elevation Model V002 (USGS 2015). The following parameters were estimated from the inventory:

- Area (At): total area that includes the ruptured zone and the area of the displaced mass (Ad).
- Perimeter (Pt): contour length of the lanslide.
- Perimeter of the displaced mass (Pd): contour length of the displaced material.
- Elevation (H): highest altitude is represented as maximum (Hmax). Lowest altitude is represented as minimum (Hmin).
- Height of the rupture zone (Hr): is calculated by the difference between Hmax and Hmin. It is the vertical distance between the crown and the foot.
- Total length (L): minimum distance from crown to landslide toe.
- Length of displaced mass (Ld): minimum distance from toe to top.
- Width of surface of rupture (Wr): maximum width between flanks of landslide perpendicular to the length of surface of rupture.
- Width of displaced material (Wd): maximum brendth of displaced mass perpendicular to length (Ld).
- Slope (S)
- Aspect (A): orientation with respect to geographic North.

Identified landslides were classified according to type of moment (Varnes 1978), depth of deformation (superficial or deep) and grade of activity (Crozier 1984) considering three categories: active, inactive, and dormant. An active landslide shows a main fresh scarp or reactivations are visible. Inactive

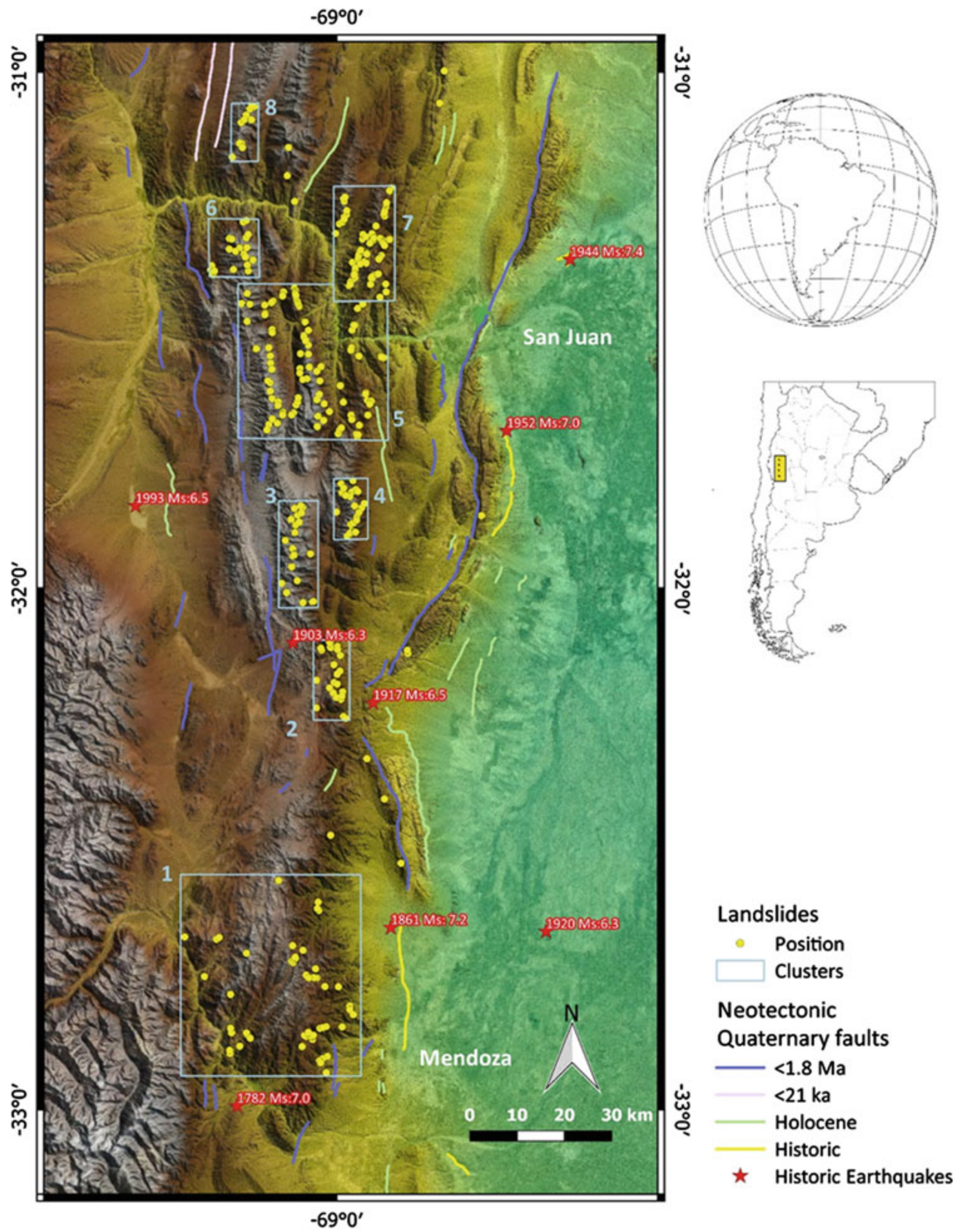

Fig. 1 Location map of the study area showing the landslide inventory and Quaternary faults between San Juan and Mendoza rivers in the Precordillera range

landslide does not show any evidence of activity. Whereas, landslides were classified as dormant when relicted reactivities are visible. The number of reactivations of each landslide was considered according to the grade of activity (Table 1).

Landslide Inventory

A total of 348 were identified in the study area including different types of movements. We distinguished 175 (=50%) rock slides, 78 (22%) debris slides, 72 (21%) debris-rock slides, and 23 (7%) complex events (Table 1). These landslides show very deep movements.

The primary lithology where more than 80% of landslides failured was detritic and sedimentary rocks such as sandstones, pelites, graywackes and shales and, to a lesser extent, metamorphic and volcanic rocks such as andesites, phyllites, schists, tuffs and volcanic breccias.

A total of 199 landslides are smaller than 0.25 km^2, which is a 57% of the total. A total of 114 landslides were identified with areas between 0.25 and 1 km^2. The 34 landslides remaining are greater than 1 km^2 reaching areas of 7.6 km^2. It is important to note that 25 of 34 landslides greater than 1 km^2 are actives.

The most common range of slope degree for 145 landslides is between 40° and 45° followed by 79 landslides

Table 1 Classification and parameters of each landslide clusters expressed in percentage

Cluster	1	2	3	4	5	6	7	8
N	55	26	23	27	103	21	70	11
Type								
Debris slide	27	23	22	11	19	38	17	55
D-Rock slid	18	23	39	7	20	24	23	18
Rock slide	44	50	35	81	53	38	54	0
Complex	11	4	4	0	7	0	6	27
Lithology								
(1) Fm CR	5							
(2) Fm LC	24							
(3) Fm Potre	7							
(4) Fm SMx	9							
(5) Fm VV	25							
(6) Gr Bon	4							
(7) Gr CHO	18							
(8) Gr USP	7	19						
(9) Cg SM		4						
(10) Fm CPA		15	74		29	76		100
(11) Fm Leon		4						
(12) Fm Mñ		12						
(13) Gr VV		46						
(14) Bl-O			26					
(15) Fm PN				100	57		57	
(16) Fm Alb					1			
(17) Fm LD					10		1	
(18) Fm SJ					3		30	
(19) Fm DP						24		
(20) Fm TC							10	
(21) Fm TMB							1	
Activity								
Active	2	35	57	74	37	33	21	18
Inactive	69	58	30	15	51	48	56	73
Dormant	29	8	13	11	12	19	23	9
Reactivities								
Yes	31	35	65	56	40	43	44	27
No	69	65	35	44	60	57	56	73
Depth								
Deep	53	38	61	56	51	33	37	18
Shallow	47	62	39	44	49	67	63	82

(1): Fm Cerro Redondo (andesites), (2): Fm Las Cabras (sandstones, pelites), (3): Fm Potrerillos (sandstones, conglomeratic sands), (4): Fm Santa Máxima (feldspathic sandstones, arkoses, pelites), (5): Fm Villavicencio (sandstones, pelites, shales), (6): Bonilla Group (carbonatic shales, phyllites, schists), (7): Choiyoi Group (lava, fenoandesitic tuffs, volcanic breccias), (8): Uspallata Group (conglomerates, sandstones, claystones, siltstones, tuffs), (9): Santa María Conglomerate (conglomerates), (10): Fm Cortaderas, Peñasco, Alojamiento (metasandstones, phyllites, marbles, sandstones, pelites), (11): Fm Leoncito (diamictites, siltstones, sandstones), (12): Fm Mariño (conglomerates, sandstones, clays, sandy tuffaceous clay), (13): Villavicencio Group (graywackes, shales, conglomerates), (14): Olistolitic blocks (olistolitic calcareous blocks), (15): Fm Punta Negra (graywackes, shales), (16): Fm Albarracín (sandstones, siltstones, conglomerates, pyroclastic flow deposits), (17): Fm La Dehesa (sandstones, siltstones, conglomerates), (18): Fm San Juan (limestones, marls), (19): Fm Don Polo (wackes, shales), (20): Fm Talacasto (sandstones, shales), (21): Fm Tambolar (sandstones, shales, marls, graywackes) between 45° and 50°. Only one slide collapsed on a slope greater than 60°.

Concerning topography the lowest and the highest altitude in the study area are 889 and 4380 m asl, respectively. The range of elevation where landslides failured is fairly wide. The most common altitude range was 2500–2750 m asl where 77 landslides collapsed. 54 landslides occurred in elevations between 2250–2500 m asl and 49 landslides between 2750–3000 m asl. Only 7 landslides collapsed at higher altitudes above 4000 m asl.

Slope aspect shows a remarkable failure orientation. The highest percentage (75%) of landslides show a NE-SE orientation. The rest are widely distributed at other orientations except the North that corresponds to warmest slope exposition.

Grade of Activity

Analysing the activity grade of identified landslides we found that 31% of them is active and 16% is dormant type. However, many of these landslides have been reactivated showing multiple movements, or at least they correspond to a successive style. Most of them show retrograde movement distribution. General aspect, preservation of primary geoforms and degree of degradation of landslide features suggest a Pleistocene age for initial collapses of these events. Otherwise, the lack of rock varnish development on the top of blocks, that in some cases should reach 6 m in size, could confirm this assumption. Furthermore, activity grade of landslides decreases gradually towards the north and the south from the centre of the study area.

Spatial Distribution of Landslides

Landslides are not randomly distributed in the study area. They are gathered in at least eight clusters in this segment of Precordillera (31–33°S). Only 12 landslides are located far away from any concentration falling out of any cluster (Fig. 1). We analysed the main features of each cluster (Table 1):

Cluster 1 is located in Precordillera of Mendoza. Apparently, landslides in this sector do not follow any pattern of distribution but seem to be more concentrated in the eastern part. This sector shows the lowest activity with only one active landslide representing 2%. The predominant type of landslide is rock slide and more than half of them were failed on sandstones and pelites.

The degree of activity increases by up to 35% in cluster 2. Landslides are shallower than sector 1. Conglomerates, shales, graywackes and sandstones are the main lithology where landslides failed. The predominant type is rock slide.

Cluster 3 shows a 57% activity rate. The main types of landslides are debris-rock slide and rock slide. Here, the percentage of deep slides and reactivities are the highest of the study area with 61% and 65%, respectively. The predominant lithologies of failures are sandstones, pelites and phyllites. This high sector has altitude of 4369 m asl., then 65% of the landslides were triggered higher than 3500 m asl.

Cluster 4 is located in Las Osamentas Range. The highest rate of activity is registered in this cluster with 74% of active landslides. Most of them are rock slides in graywackes and shales.

The greatest number of gathered landslides corresponds to cluster 5. The degree of activity decreases comparing with

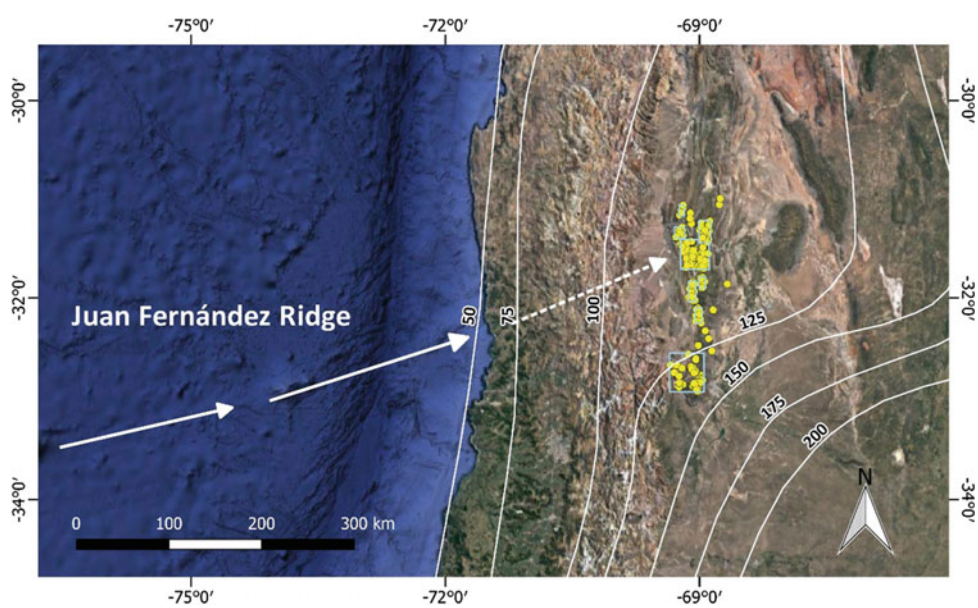

Fig. 2 Juan Fernandez Ridge overlapping more active landslide cluster

sector 4. The main type of landslide is rock slide; whereas there is the same percentage of shallow and deep slides. It is important to note that the biggest landslides are grouped in this sector with areas from 2 km^2 to 7 km^2.

In cluster 6 the grade of activity is a bit lower than sector 5 and the percentage of shallow landslides increases to 67%. The number of debris slides and rock slides is the same being the predominant type of landslide. 76% of the slides failed on sandstones, pelites and phyllites.

At the same latitude, we found the cluster 7 being the second sector with the most landslides. The grade of activity is low in this cluster with a 21% of active landslides. The main type of landslide is shallow rock slide. Failure associated lithologies are graywackes, shales, limestones and marls.

Cluster 8 is the second group with the lowest grade of activity after cluster 1. In turn, this sector contains just 11 landslides. The predominant type of landslide is debris slide and most of them are shallow. All of them failed on sandstones, pelites and phyllites in high altitudes.

Discussion and Conclusions

Despite that the spatial distribution of huge collapses coincides with traces of active Quaternary faults, our findings show that landslides are not randomly distributed along the study area. At least 8 landslide clusters were distinguished along the Precordillera region. However, landslide density is concentrated in the central region of study area coinciding with higher elevations of the Central Precordillera. Moreover, rate of activity is clearly evidenced in this central area where cluster 3 and 4 are identified. Landslide grade activity decreases gradually towards the north and south.

The most affected area in the Precordillera overlaps the alignment of Juan Fernandez Ridge (Fig. 2) associated with a greater regional deformation and likely linked to more active neotectonics. This fact could explain the concentration of huge collapses in this area. In particular, a seismic triggering is postulated for this landslides which seem to have been reactivated several times evidencing paleoseismic activity. Besides, this segment coincides with higher elevations of Central Precordillera justifying a greater acceleration as consequent of topographic effect.

Even though spatial distribution of landslides could be clearly conditioned by lithology, steeper slope and elevations; analyses of these parameters distribution is not enough to explain landslide clusters in the study area.

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