Earth and Planetary Science Letters 388 (2014) 249–256

Contents lists available at ScienceDirect

Earth and Planetary Science Letters

www.elsevier.com/locate/epsl

The giant coastal landslides of Northern Chile: Tectonic and climate interactions on a classic convergent plate margin

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ARTICLE INFO

Article history:
Received 14 October 2012
Received in revised form 8 October 2013
Accepted 9 October 2013
Available online 30 December 2013
Editor: P. Shearer

Keywords:
giant landslides
Andean forearc
tectonics
geomorphology
geohazard
Atacama

ABSTRACT

Documented for the first time are an extensive suite of late Neogene giant terrestrial coastal landslides along the classic convergent margin of western South America (18° to 24° south). These are remarkable in terms of their unusual abundance and atypical setting, such failures previously being linked with oceanic volcanic edifices or over-steepened glaciated coastlines. Located within the hyper-arid Coastal Cordillera of the Atacama Desert of Northern Chile we report the presence of more than 60 individual large-scale landslides with individual volumes up to 9 km^3 developed over a horizontal coastline distance of some 650 km. These landslides were emplaced as a combination of rock avalanches and multiple rotational failures. The majority terminated directly into the Pacific – likely generating significant tsunami hazard to the Chilean and south Peruvian coastline in a region which is today considered to be part of a notorious seismic gap. The proliferation and scale of these Late Neogene giant landslides in this actively uplifting, hyperarid terrain suggests they are the main geomorphic agent for relief reduction, probably triggered by megathrust earthquakes and potentially providing a unique palaeoseismic archive. The temporal and spatial distribution of these giant landslides corresponds with a period of surface steepening of the forearc wedge in the Central Andes and south to north differential uplift associated with factors such as aseismic ridge subduction. The resulting surface gradient increases, combined with the persistent climatic aridity of the region, have served to limit effective relief-reducing geomorphic processes in this oversteepened terrain to large-scale landsliding. The phenomena documented here geospatially link previously recognised large-scale slope failures from the off-shore environment and higher altitude areas of the Andean forearc, suggesting that large-scale landsliding is capable of transferring sediment on a regional scale to the off-shore Peru–Chile trench. This has implications for the friction of the subducting Nazca plate and associated seismicity and uplift.

1. Introduction

The lateral collapse through large-scale landsliding of mid-oceanic volcanic islands formed over mantle hot spots is well-documented (Keating and Mcguire, 2000; Masson et al., 2002). It is also believed that these failures have been responsible for mega-tsunamis affecting coastlines in Australia and the eastern seaboard of North America (Ward, 2001; Whelan and Kelletat, 2003). However, there appears to have been less investigative work on the potential landslide and commensurate tsunami hazard associated with subduction zone boundaries, despite the obvious similarity of rapid uplift creating highly over-steepened slopes. Indeed the increased seismic hazard in a subduction zone compared to mid-oceanic volcanic islands would suggest that the occurrence and magnitude of geohazards in these areas would be greater. In this study remote sensing and field investigations of the seaward scarp of the Coastal Cordillera in Northern Chile has revealed previously unreported large terrestrial landslides and features indicative of giant landslide backscars. The scale of landsliding represented by these features is comparable in size to the failures reported from Hawaii (Moore et al., 1994; Clague and Moore, 2002) and the Canary Isles (Masson et al., 2002) suggesting a significant but presently unrecognised natural hazard to development in this and other regions of comparable geological setting. We document for the first time the presence of giant terrestrial landslides (volumes of $> 10^8$ m^3 and areas of 10^0 to 10^3 km^2; Korup et al., 2007) along the coastal margin (Coastal Cordillera) of the Central Andean forearc of western South America (18° to 24° south, some 650 km). The Central Andes is often cited as the type example of a convergent continental margin wherein the forearc is an important element that directly reflects the interaction between the subducting and overriding plates. Thus within this context an understanding of the dominant terrain shaping geomorphic processes can provide insights into the nature of the regional deformation

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http://dx.doi.org/10.1016/j.epsl.2013.10.019

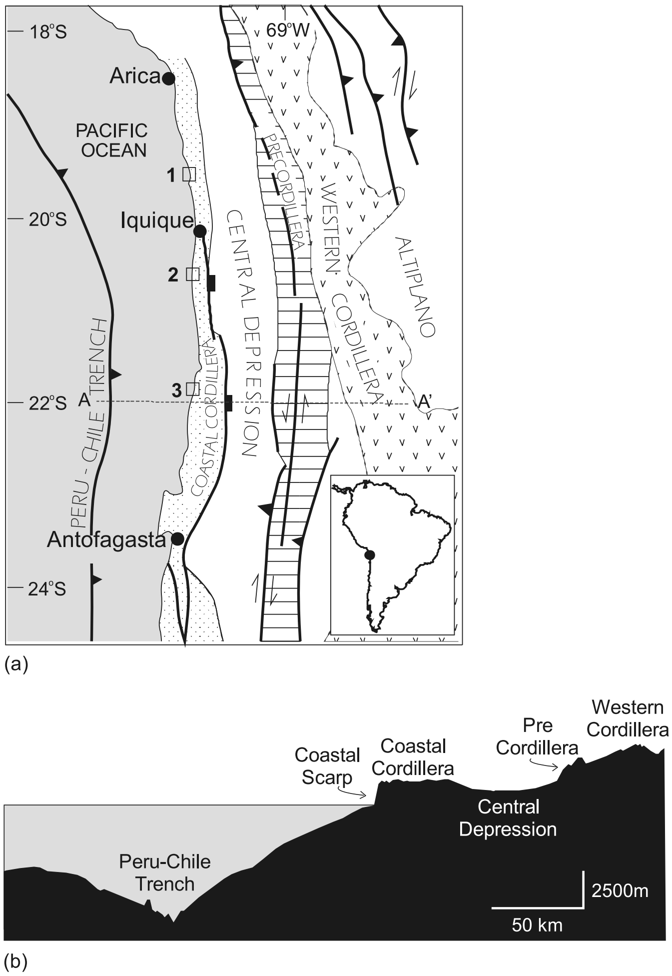

Fig. 1. (a) Main terrain units and structures of the study area. A–A′ shows line of section depicted in (b). Bold lines with triangles indicate thrusts; bold lines with solid rectangles indicate normal faults; half arrows indicate lateral movement along faults. Main type sections used in this study are located by (1) Caleta Buena; (2) El Magnifico and (3) Rocas Tortuga. (b) Topographic transect A–A′ showing the onshore to offshore topography of the study area and key terrain units.

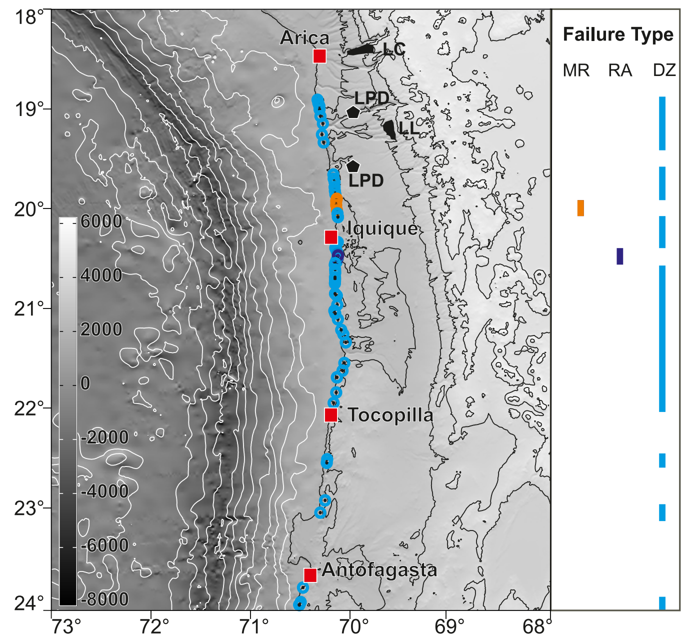

Fig. 2. Topography and landslide location in the Northern Chile study area. Bathymetry and elevation of the study area (source GEBCO 30' Arc 2008 data). Contours are at 1 km intervals. Black circles indicate locations of giant coastal landsides (this study). Inland black areas represent the Lluta Collapse (LC) of Strasser and Schlunegger, 2005; Lataguala landslide (LL) of Pinto et al., 2008 and large-scale landslide prone drainages (LPD) identified by the authors but not discussed here. The preserved failure types are Multiple Rotational (MR); Rock Avalanche (RA) and Depletion Zone (DZ) as discussed in the text. These data are recorded in the supplementary information for this paper.

affecting this important landscape element whilst a hyper-arid climate presents an environment which can conserve that evidence over suitably long timescales. With this in mind, we aim to document for the first time the regional scale of coastal giant landslides in the western Atacama Desert and explore their wider tectonic and climatic significance within this classic terrain setting.

2. Study area

The study area (Fig. 1) is located within the Central Andes which is often cited as the type example of a convergent continental margin, yet it is unusual in maintaining shear stresses across the subduction zone that are some three times higher (∼37 MPa) than other convergent continental margins (Lamb, 2006). The stress build up is considered to be related to increased friction at the plate interface because of a lack of lubricating trench fill sediment (Von Huene and Ranero, 2003; Lamb and Davis, 2003). The relative lack of sediment offshore is related to the climatic aridity that has prevailed along this continental margin for much of the Neogene (e.g. Dunai et al., 2005). The response to the shear stress build up and lack of lubricating sediments has been to steepen the surface of the forearc wedge towards the trench through underplating beneath the Coastal Cordillera (Clift and Hartley, 2007). This has helped develop a relief of some 2 km above sea level and an additional 7 km below sea level (Fig. 1) within a hyper-arid climate setting. Recent cosmogenic radionuclide (CRN) exposure dating using ^{21}Ne on quartz pebbles from alluvium in the Coastal Cordillera has highlighted negligible erosion rates over the last ∼9 Ma (Dunai et al., 2005) suggesting, along with other data (e.g. nitrate and gypsum soils) that an arid/hyper-arid climate has prevailed across much of Northern Chile during this period (Hartley, 2003; Dunai et al., 2005; Evenstar et al., 2009) punctuated with low frequency, high magnitude rainstorm events, particularly in the south of the study area (e.g. Vargas et al., 2006; Placzek et al., 2010). The region is located within a seismically active terrain (Delouis et al., 1997; Spence et al., 1999) but historically is part of a well known seismic gap (Chlieh et al., 2004; Baker et al., 2013; Béjar-Pzarro et al., 2013; 450 km of coastline from 18°–23° south) with recurrence intervals in the order of 111 yr (Comte and Pardo, 1991). Recent research suggests that some 2000–9000 individual large plate boundary earthquakes have occurred in this region in the past 0.8 to 1 million yr (Baker et al., 2013). Although recent large earthquakes have been recorded close to the north and south of this gap (June 23rd 2001; southern Peru $M\text{w} = 8.4$; July 30th 1995; Antofagasta $M\text{w} = 8.1$, Chlieh et al., 2004) the last major event within the gap was in 1877. This generated a 25 m runup tsunami in Arica (Kulikov et al., 2005) and it is generally accepted that the region is now overdue its next megathrust event (Béjar-Pzarro et al., 2013).

Within the study area the Coastal Cordillera is up to 2.2 km high and 20 to 50 km wide (Fig. 1). It largely comprises basaltic andesites and granodiorites cut by N-S to NE-SW trending, landward-dipping, normal faults that bound a series of half-graben (Paskoff, 1978). The western margin of the Coastal Cordillera is represented by a coastal scarp – a prominent break in slope 600 to 1500 m high that runs for 700 km along the coastline of Northern Chile. Where the scarp is separated from the active coastal erosion by the narrow (<6 km wide) coastal plain it is considered