Journal of Structural Geology 30 (2008) 791–808

Contents lists available at ScienceDirect

Journal of Structural Geology

journal homepage: www.elsevier.com/locate/jsg

Crack formation on top of propagating reverse faults of the Chuculay Fault System, northern Chile: Insights from field data and numerical modelling

Gabriel González[a,*], Muriel Gerbault[b], Joseph Martinod[c], José Cembrano[a], Daniel Carrizo[a], Richard Allmendinger[d], Jacob Espina[a]

[a] Departamento de Ciencias Geológicas, Universidad Católica del Norte, Avenida Angamos 0610, Antofagasta, Chile
[b] IRD, Departamento de Geología, Universidad de Chile, Plaza Ercilla 803, Santiago, Chile
[c] Laboratoire des Mécanismes de Transfert en Géologie (LMTG), Université de Toulouse, France
[d] Department of Earth and Atmospheric Sciences, Cornell University, Ithaca, NY 91125, USA

ARTICLE INFO

Article history:
Received 29 March 2007
Received in revised form 25 January 2008
Accepted 4 February 2008
Available online 4 March 2008

Keywords:
Reverse faults
Fractures
Fault scarps
Numerical modelling
Northern Chile

ABSTRACT

Reverse faults in northern Chile have formed 20–300 m high scarps that contain open fractures which occur in a zone of 20–1600 m wide. Two-dimensional numerical models were used to explore the geometrical and mechanical parameters needed to produce extension within a bulk contractional regime. All of the mechanical models show the same structure as the field: a concentration of cracks predominantly at the top, rather than on the forelimbs of the scarps. In the field case extension begins as soon as a discrete scarp forms; with progressive shortening the scarp height increases producing a broadening of the zone in extension. The numerical models show that this broadening stabilizes when a maximum in the scarp height is reached. To produce concentration of the extension on top of the scarps, the reverse fault needs to be weak ($\phi \sim 10°$). The models suggest that distribution of this extensional zone depends on the cross-sectional geometry of the fault and on the location of the detachment at depth. The main mechanism that produces extension on the top of the reverse scarp is stretching of the topographic surface by folding of the hanging wall at the tip of the fault zone.

1. Introduction

Cracks related to fault propagation have been widely reported in the literature. Their most common occurrence is in strike-slip faults where en-echelon cracks are characteristic at releasing bends, at extensional step-overs or ahead of tip lines of propagating strike-slip faults (Tchalenko, 1970; Klinger et al., 2005). Crack occurrence related to propagation of dip-slip faults has also been documented (Yielding et al., 1981; Hilley et al., 2001; Rajendran et al., 2001; Martel and Langley, 2006). For example, blind normal faults frequently form monoclines with secondary tensional structures on the crest. These structures, including cracks and secondary normal faults, are parallel to the strike of normal faults. Similarly oriented extensional structures have been observed to form coseismically during large historical thrust-fault earthquakes. King and Vita-Finzi (1980) documented open cracks and normal faults that formed during the 1980 El Asnam, Algeria reverse-fault earthquake. In this case, extensional structures formed on top of uplifted blocks (Philip and Meghraoui, 1983).

Numerous analogue and numerical models based on rock mechanics have simulated fault structures developing in a crustal layer under compression (e.g. Hafner, 1951; Jaeger and Cook, 1979; Malavieille, 1984; Sassi and Faure, 1997). These models help to understand the first-order relationship between fault-propagation fold geometries and the amount of slip on master faults (Allmendinger, 1998; Cardozo et al., 2003; Mitra and Islam, 1994; Finch et al., 2003), but the relationship between secondary tensional structures (cracks and normal faults) and reverse-fault propagation remains poorly understood. Healy et al. (2004) performed elastic models to predict the mode and distribution of subseismic fractures around large reverse earthquakes, using as natural setting the El Asnam, Algeria earthquake. Comparison between models and the natural examples helps to understand critical geometrical parameters of a scarp able to produce extensional structures on top of propagating reverse faults. Furthermore, numerical models allow unravelling the mechanical properties of faults and their mechanical contrast with deforming rocks at the scale of hundreds of meters.

Near the Salar Grande in northern Chile (21°05′–21°15′), a conspicuous network of open cracks pervades the topographic surface. These cracks occur at the top of, and strike parallel to, 20–300 m high reverse-fault scarps, suggesting that their origin is causally

* Corresponding author. Tel.: +56 55 355952; fax: +56 55 355977.
E-mail address: ggonzale@ucn.cl (G. González).

0191-8141/$ – see front matter © 2008 Elsevier Ltd. All rights reserved.
doi:10.1016/j.jsg.2008.02.008

connected with either fault propagation or collapse of these fault scarps. Due to the hyper-arid conditions of the Atacama Desert, these open fractures are extremely well preserved and constitute a superb example of secondary structures related to reverse faulting. Using 1 m spatial resolution IKONOS satellite imagery, we mapped 16,358 fractures over a 250 km^2 area. Integrating the IKONOS data with 90 and 20 m resolution DEMs, we describe the general geometry of the fractures and their spatial relationship with the fault scarp. Geological observations help to characterize some attributes of the fractures in the field. In the second part of this paper we use numerical models to reproduce extensional zones on top of developing reverse faults. By comparing data and models, we constrain the origin of the fractures and delineate some geometrical parameters and mechanical properties of the deforming rocks and the fault zone.

2. Tectonic setting and topography of the Central Andes forearc

The tectonic setting of the study area is dominated by the subduction of the Nazca Plate beneath the South American Plate (Fig. 1). The interplate seismogenic zone (Tichelaar and Ruff, 1991) extends offshore and below the coastal line of Peru and Chile. Several thrusting earthquakes, 40 and 50 km below the Coastal Cordillera, define the seismic coupling zone of the Andean subduction zone (Delouis et al., 1996; Comte et al., 1999).

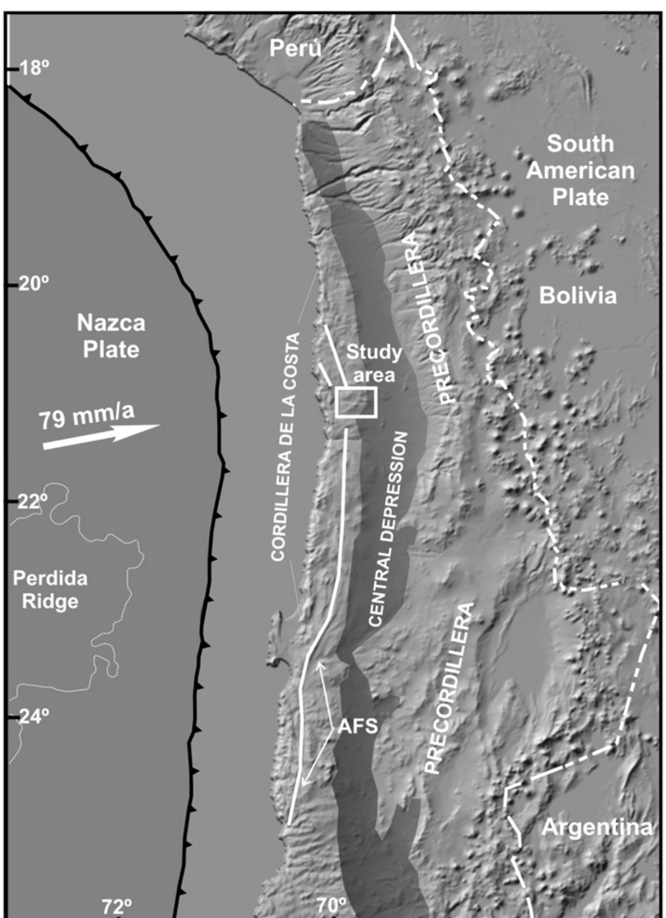

Fig. 1. Tectonics and morphology of the western border the Central Andes, showing the main morpho-structural units of the Coastal Cordillera, Central Depression and Precordillera. The polygon shows the location of the study area. Onshore digital topography from the USGS 30″ DEM.

The topography of the Central Andes forearc is composed of three morpho-structural units, the Coastal Cordillera, the Central Depression and the Precordillera (Fig. 1). The Coastal Cordillera is a structural height, located 1000–2000 m above sea level; the western margin is formed by ∼1000 m of a high sea cliff which dominates the topography of the coastline (Fig. 2). The eastern side of the Coastal Cordillera is a smooth and gradual boundary with the Central Depression. The top of the Coastal Cordillera is a 20 Ma old pediplain surface (Dunai et al., 2005; Carrizo et al., 2008). The preservation of this surface testifies to the long-term dominance of the hyper-arid climate in the Atacama Desert.

3. Structural framework of the area

The study area is located within the Coastal Cordillera, between 21°05′S and 21°15′S. The structural framework is highlighted by spectacular morphological expression of NW and ENE to E–W striking faults (Fig. 2). The most important NW-striking fault is the Salar Grande Fault which produces a 30–40 m high scarp on the halite surface of the Salar Grande. Along the northernmost part of the Salar Grande Fault several valleys crossing the trace show dextral offsets documenting a strike-slip component for the fault (González et al., 2003; Carrizo et al., 2008). Another important NW-striking fault is the Chomache Fault, located west of the Salar Grande. Several stream channels flowing across the fault also show dextral offsets. E–W structures are regionally visible across the Coastal Cordillera, between 22° and 20°S. They are displayed in the 90 m DEM as several scarps that extend from the coastal line to the eastern side of the Coastal Cordillera (Fig. 2). The scarps end at the boundary between the Coastal Cordillera and the Central Depression, terminating in fault-propagation folds that affect the Tertiary infill of the Central Depression (Allmendinger et al., 2005). The lack of horizontal offset of paleovalleys crossing the scarps documents predominantly dip-slip displacement.

Exposures of the fault plane of the E–W faults are very scarce, the few documented cases show consistently that the fault planes dip beneath the uplifts (Allmendinger et al., 2005), confirming that the scarps were formed by displacement of the topographic surface by slip along reverse faults. On closer inspection, it is clear that some scarps are associated with emergent reverse faults that offset the topographic surface, whereas other scarps result from folding of the surface above blind reverse faults. Regionally, the youngest known motion for these faults is documented by vertical offset of the Late Pleistocene (younger than 125 ka) coastal terrace exposed at the base of the Coastal Escarpment (Fig. 4a, Caleta Chica 19°20′, Iquique 20°17′ and Barranco Alto 20°38′). In general, fault planes dip to the north or south, with dip angle being steeper (∼68°) in the higher parts of the Coastal Cordillera and gentler at sea level (∼30°). Combined with the 1–4° rotation of the paleosurface, this suggests that the fault planes are listric. Furthermore, some of the E–W thrust-faults are reactivated Mesozoic normal faults. In fact, close to Caleta Chica, an E–W reverse fault places Early Cretaceous conglomerate over Jurassic volcanic rocks of La Negra Formation. This geometry clearly suggests inversion of a Mesozoic rift basin. Other field evidence, in the form of small scarps localized at the foot of the highest scarps (Fig. 3c), indicates that the E–W fault scarps were formed by successive discrete slip events.

4. The Chuculay Fault System

East of the Salar Grande, the most relevant structures are ENE to E–W striking reverse faults, which are collectively known as the Chuculay Fault System (Allmendinger et al., 2005). These faults control the topography, forming five 20–300 m high north-facing scarps (Figs. 3 and 4). The scarps extend from the eastern margin