Reverse fault geometry of the Chuculay system, northern Chilean outer forearc, using morphotectonical and numerical approach

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INTRODUCTION

The nature of reverse faults scarps morphology is controlled by a complex relation between amount of slip, sense of slip, fault geometry, properties of deformed layer and topography (Phillip et al., 1992). When the fault plane is covered or buried, the morphotectonic features are the most relevant source of data to constrain the geometry and kinematics of faults. Accurate fault geometry determination is extremely relevant to formulate geodynamic and tectonic implications (shortening magnitude and deformation nature). Thus, the study of morphotectonic features (scarp profile, flexural bending, tension fractures, secondary faults, displaced geomorphic surfaces and slope structures) and its relations (i.e. tension fracture frequency along the slope profile and magnitude of tension fracture opening along the slope profile) make possible to constrain, with relative accuracy, the fault geometry in depth. In this contribution we present the first results of morphotectonic study of a reverse fault system developed in the inner part of Bolivian Orocline, northern Chilean Coastal Cordillera. This study was based on field observations and geodetic measurements, detailed analysis of 1 m – resolution IKONOS images and FEM models.

In the outer forearc of northern Chile (19°-21.6°), trench-parallel shortening has been documented by trench orthogonal reverse faults expressed as a prominent scarps (450 m of high), whose age has been constrained to post-Miocene times (Allmendinger et al., 2005). In the study area, located east-south of Salar Grande (Figure 1), shortening is accommodated by a number of faults labeled as Chuculay Fault System (Allmendinger et al., 2005). The kinematics of these faults is predominantly pure dip-slip as evidenced by slickenslides from secondary faults, displaced channels and ridges. These data indicate no significant lateral components of slip. The principal fault planes are buried by colluvial wedge deposits (debris slope), but the hyperaridity of the Atacama Desert since the Miocene (Hartley and Chong, 2002) has allowed the extraordinary well-preservation of morphotectonic features related to scarps.

MORPHOTECTONICS ANALISYS OF CHUCULAY FAULT SYSTEM

The Chuculay Fault system is formed by a group of subparallel reverse faults that strike EW-N70°E. Morphological analysis reveals that faults deform a gentle slope surface (~2° S) producing a well-defined tilted-block (5°- 6° S) morphology. These blocks show geometry similar to an asymmetrical antiform whose back limb has a 5°-6°, south-dipping slope (Figure 1b). The faults are represented by 40 - 350 m high scarps which show tension fracturing and secondary faults.

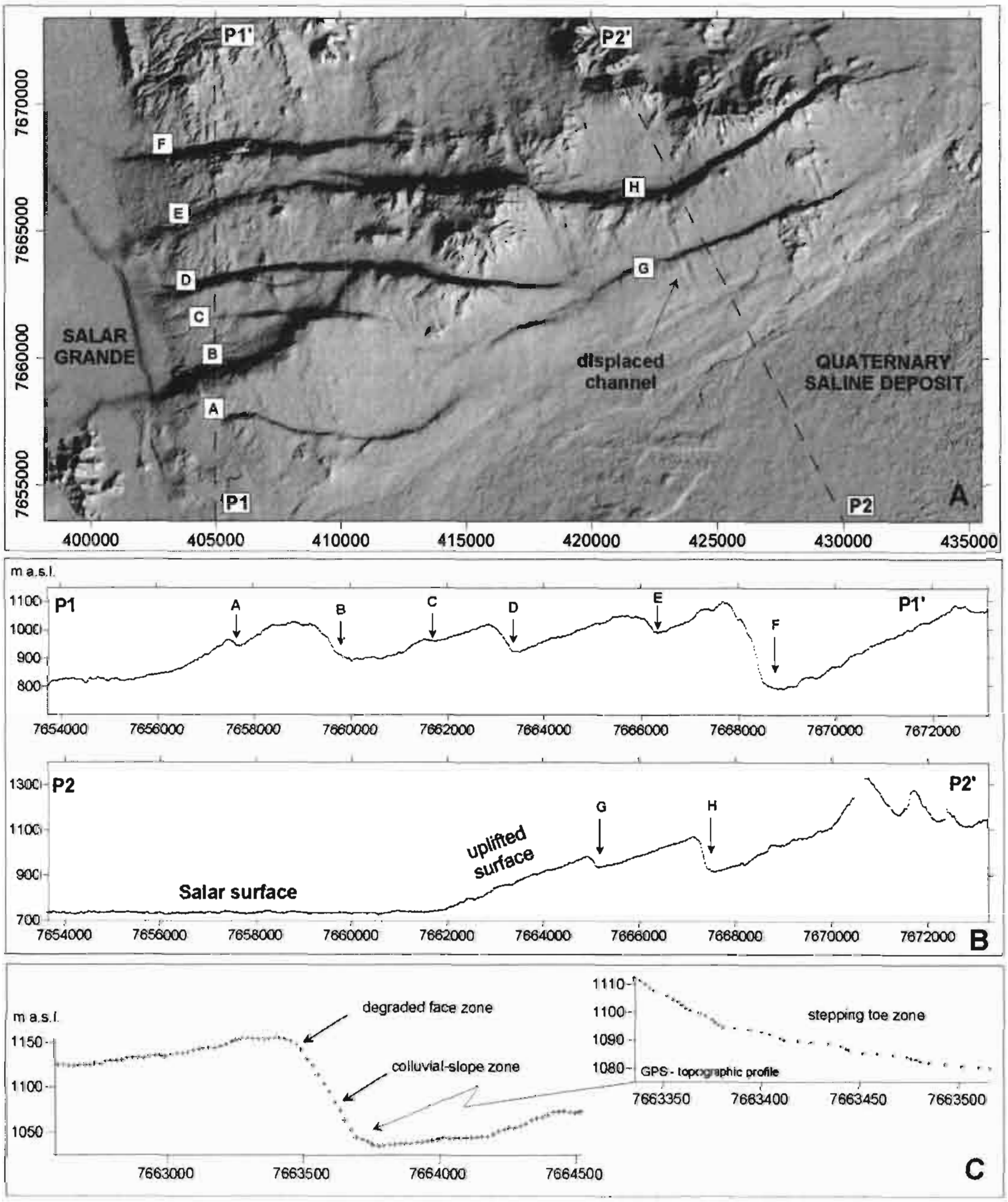
Original surface morphology: Ne^{21} exposures age determinations in progress indicate that the fault- displaced surface is at least Miocene in age. Morphological measurements of undeformed areas and isolated pre-faulting drainages indicate that the original surface was characterized by a general gentle south-slope gradient (2°) related to isolated ranges.

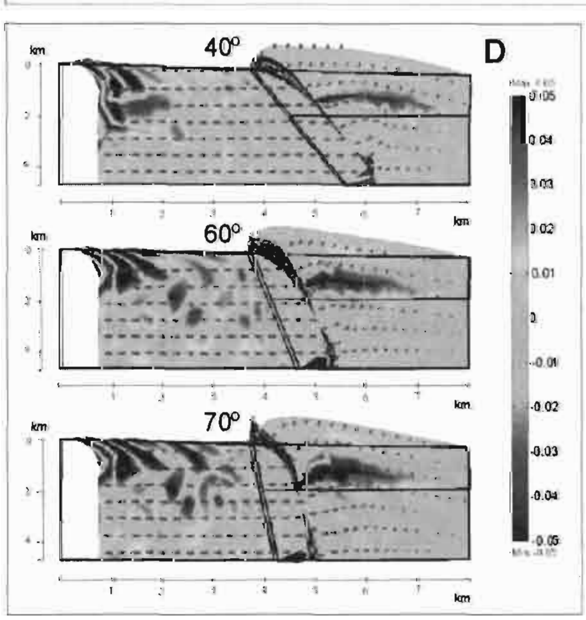
Scarp profiles: The reverse faults form abrupt multiple northward-stepping scarps with 200 – 350 m of accumulated vertical separation (scarp height). Scarp morphology is strongly controlled by diffusion processes and does not show evidence of relevant back-cutting processes related to rain events. The scarp profile shape is formed by three main zones: a) degraded-face zone; b) colluvial-slope zone and c) stepping toe zone. The degraded-face zone corresponds to the upper part of profile and it is formed by eroded crystalline rocks with numerous subparallel shallow incisions and collapse morphologies. The colluvial-slope zone is made up of gravitational deposits generated by scarp degradation processes, containing cobbles, boulders and 1 – 3 m^3 of rock blocks. This zone has a slope of ca. 25° – 35° and represents the 60 – 70% of the total scarp profile. The stepping toe zone consists of a series of terraces located in the scarp toe and are limited by small scarps (0.5 – 3 m in height, Figure 1e) that strikes parallel to the main scarp forming sinuous and irregular traces. The terrace surfaces are subhorizontal, but in some cases stratigraphic markers shows south-tilting (opposite to the main scarp face). The general curvature of main scarp profile revels a gentle bending of the upper block closely restricted to the scarp crest and spatially related to a tension fracture zone (see *details in González et al., this issue*).

Scarp-related secondary structures: Pervasive tension fractures zones are located in the hanging wall. These strike subparallel to the scarp trend, increasing their frequency close to the scarp crest. The distribution and longitude of fractures are not lithology-controlled and in some cases the fractures local orientations are slope-controlled, forming curved geometries parallel to topographic contours (*details González et al., this issue*). Vertical hybrid faults were observed related to tension fractures. These structures show 0.5 – 6 m of vertical separations and 3 -10 cm of opening and the scarp faces are consistently oriented to the south forming an up-slope facing profile. Tectonic depressions formed by two subparallel faults are common. Isolated reverse faults were observed in the upper block and the fault trace terminations, oriented parallel to the main scarp, with dip angles that range from 55° to 77° S and vertical separations that range from 0.3 to 2.5 m.

NUMERICAL MODELING

We performed 2-D viscous flow numerical modeling to test the dip angle effect in the morphotectonic related to reverse fault propagation. Taking into account the field geometrical data of secondary faults, we used 40°, 60° and 70° dip values for the fault modeling. The problem is solved using the PDE2D6.0 package for finite element partial differential equations. The topographic changes on upper block surface induced by slip faulting was considering as our first order discriminator of fault geometry. Our preliminary results show that the 40°-dip model has a profile characterized by a notorious topographic perturbation in the upper block, producing a strong bending close to the scarp crest, a flat zone behind the bending zone and ending with a tilted surface marked by an abrupt slope change. The 60° - 70°-dip model





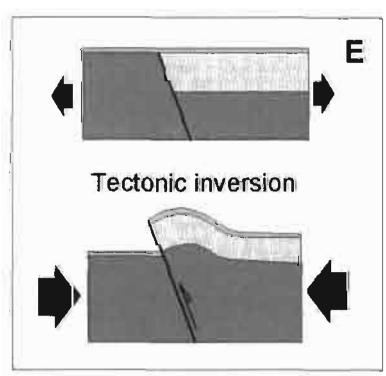


Figure 1. A) Shaded relief map of the Chuculay System. Are indicated the faults and profiles localization. **B)** Topographic profiles of Chuculay System showing the tectonic steps morphology. (Vertical exaggerations 4X) **C)** Detail profiles showing the typical morphology. **D)** Numeric Models. **E)** Tectonic inversion cartoon.

shows an asymmetrical bending morphology of the upper block with a relative homogeneous gentle slope. The topographic changes are restricted to the scarp crest zone and the final topography is characterized by gently tilting of the initial surface. These results suggest that 60° - 70° dip angle models have a good fit with the topography and field observations (Figure 1d). The 70°-slope model shows diffuse extensional zones close to the scarp crest as we observed in the field and the IKONOS images (*details González et al., this issue*).

DISCUSION AND CONCLUSION

The results of the numerical models suggest that the Chuculay System is formed by reverse fault zone that has a 60°-70° dip angle. Considering these dip angles, the faults accommodate approximately 378 - 238 m of horizontal shortening in a 15 km straight line across the fault system. That means about 2.4% shortening (60° of dip) to 1.4% shortening (70° of dip) and the faults allow for 36 to 280 m of local uplift.

In mechanical terms, high dip angle reverse faults (>45°) are unlikely to be generated in natural conditions; our hypothesis argues that these reverse structures could have an inherited geometry, and its current expression is the result of tectonic inversion of preexistent (Cretaceous?) normal faults (under high fluid pressures?). The origin of NS-shortening in the Chilean outer forearc has been discussed by Allmendinger et al. (2005) relating this structures with processes associated of plate coupling and oroclinal bending geometry. Alternatively, buttressing processes in the forearc related to strain partitioning in a curved margin can explain trench-parallel shortening. On the other hand, NS-contraction in the inner part of the Bolivian Oroclinal related to less than 5° of clock wise rotation is consistent with the low magnitude of the obtained horizontal shortening. These ideas are being explored for a better understanding of the Chilean outer forearc complex deformation.

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REFERENCES

Allmendinger, R., González, G., Yu J., Hoke, G. & Isacks, B.. 2005. Trench-Parallel Shortening in the Northern Chilean Forearc: Tectonic & Climatic Implications. *GSA Bulleting*, v.117, n° 1/2, 84-104.

Hartley, A. and Chong, G. 2002. Late Pliocene age for the Atacama Desert: Implications for the desertification of Western South America, Geology, V 30, N°1, 43-46.

Phillip, H., Rogozhin, E., Cisternas, A., Bousquet, J. C., Borisov, B., Karakhanian, A. 1992. The Armenian earthquake of 1988 December 7; faulting and folding, neotectonics and paleoseismicity. *Geophys. J. Inst.* 110, 141-158.