THE EAST-WEST FAULT SCARPS OF NORTHERN CHILE: TECTONIC SIGNIFICANCE & CLIMATIC CLUES

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INTRODUCTION

In the forearc of the Central Andes in northern Chile, the Coastal Cordillera is the only part of the South American continent actually in contact with the subducting Nazca Plate. As such, the structures of the forearc ought to reflect the first order processes that operate at the interface between two tectonic plates. Most forearcs are characterized by structures that strike parallel to the margin, yet in the region between 19° and 21.5°S latitude, the Coastal Cordillera contains a suite of well defined fault scarps that trend EW to ENE, intersecting the margin at high angles. These morphologic features are particularly well displayed on a new, 20 m resolution digital elevation model (DEM) of northern Chile produced using radar interferometry (InSAR) (Yu and Isacks, 1999). The key questions concerning these scarps are: (1) what is their kinematic significance? (2) when did they begin to form? (3) why are they restricted to the region between the Río Loa and the Quebrada Camarones? and, (4) what is their tectonic significance?

Due to extremely poor exposure in most of the northern Chilean Coastal Cordillera, previous authors have interpreted these features on the basis of their morphology as normal fault scarps (González et al., 1997; Reijs and McClay, 1998). However, we show here that they are produced by reverse fault scarps that began to uplift in the latest Miocene and may still be active today. We relate the scarps to north-south compression developed on the inner arc of the Bolivian Orocline. Although, not the main purpose of our work, the interaction of the scarps with other geomorphic...
features of the Coastal Cordillera record clues to the climatic evolution of northern Chile since the late Miocene.

**Regional Setting**

The Coastal Cordillera of northern Chile is formed mainly by Jurassic-Early Cretaceous dioritic to granodioritic plutons and Jurassic volcanic rocks. These units form the remnants of a Mesozoic magmatic arc formed at the birth of the modern Andes (Coira et al., 1982; Mpodozis and Ramos, 1990; Rutland, 1971). The magmatic arc was emplaced into an ensialic crust formed by Paleozoic sedimentary rocks and Precambrian metamorphics. The most important structure of the Coastal Cordillera is the Atacama Fault System (Arabasz, 1971) that extends for more than 1000 km between 21 and 26°S latitude. The Atacama Fault System is trench parallel orientated and its formation is related to the end stages of the Mesozoic magmatic arc (Scheuber and González, 1999). The Neogene to Quaternary sedimentary cover of the Coastal Cordillera records predominantly arid to hyperarid climatic conditions during deposition (Hartley and Chong, 2002; Hartley and Jolley, 1995; Hartley et al., 2000). Several internal basins in the Coastal Cordillera are integrated by Oligocene-Miocene alluvial deposits covered locally by Mio-Pliocene evaporite deposits (Chong D. et al., 1999). The most spectacular evaporite basins are the Salar Grande and Salar the Llamara basin.

More than a decade of intense geophysical study, spurred in part by the 1995 Mw=8.1 Antofagasta earthquake, has made the northern Chilean Coastal Cordillera one of the Geophysically best known forearcs on earth. Combined active and passive source, off-shore and on-shore, seismic studies show that the interplate seismic zone extends from about 20 to 50 km depth (Buske et al.,

![Figure 1. Simplified structure map of the Coastal Cordillera of northern Chile between 18°30' and 22°S latitude, showing the distribution of the EW fault scarps and the localities described in the text. The dashed line just south of Iquique is Gephart’s (1994) best-fit symmetry plane. QC – Quebrada Camarones, QT – Quebrada Tiliviche](image-url)
2002; Husen et al., 2000; Husen et al., 1999; Pritchard et al., 2002; von Huene et al., 1999). Geodetic studies of global positioning system (GPS) station data document both interseismic and coseismic deformation (Bevis et al., 2001; Klotz et al., 1999).

Initial studies of digital elevation models (DEMs) of the Central Andes renewed long standing interest in the nature and origin of the Bolivian orocline (Gephart, 1994; Isacks, 1988). In this study, we have taken advantage of the just-released Shuttle Radar Topographic Mission 90 m DEM, as well as an unpublished 20 m DEM produced by interferometric synthetic aperture radar (InSAR).

KINEMATICS OF THE EAST-WEST SCARPS

The fault scarps that form the focus of this study are spectacularly displayed in the 20 m DEM from the Coastal Cordillera (e.g., Fig. 2), but outcrops of the fault planes are very scarce. We were able to locate outcrops along the Coastal Escarpment, in the deep canyons of the Quebrada Tiliviche and the Quebrada Suca (Chiza), as well as in a few man-made excavations and one natural exposure in the interior of the Coastal Cordillera. In all cases, the fault that produced the scarp is a moderately dipping reverse fault. The P and T axes (Marrett and Allmendinger, 1990)

![Figure 2.](image)

Figure 2. Shaded relief image of the InSAR 20 m DEM from the Salar Grande area showing (A) the Salar Grande fault, (B) the Cerro Chuculay system of EW reverse faults, and (C) the NNW-striking strike slip fault that offsets the trace of the Chuculay fault. At (D), a small paleodrainage is incised into two uplifted blocks but is not offset laterally, indicating no strike-slip component on the EW faults.

from all of the field measurements define a composite fault plane solution showing that the average fault dip is approximately 45°, and the average shortening (“P”) axis is nearly horizontal with an azimuth of 170° (Fig. 3). The fault plane solution is almost a perfect thrust mechanism confirming field relations of offset geomorphic features showing no strike-slip component (Fig. 2,
The shortening axis is nearly exactly parallel to the regional trend of the Coastal Cordillera.

In the northern part of the region, both the Pisagua and Atajaña scarps change along strike from fault scarps to fold scarps as the tip line of the fault plunges beneath the surface and become blind. The fault-propagation folds are well exposed in the Quebrada Tiliviche and the Quebrada Chiza. Thus, at the eastern edge of the Coastal Cordillera, the faults die out: there is no evidence that they cross the Central Valley or reappear in the Precordillera.

Because there is so little erosion, the scarp heights can be used as proxies for the vertical throw on the faults and this, in combination with the observation of an average dip of 45° can be used to determine the amount of horizontal shortening. In the 300 km between the Quebrada Camarones in the north and Río Loa in the South, there has been about 3 km or 1% horizontal shortening. The region south of Iquique has slightly more shortening than the area to the north, although the fault scarps tend to be larger in the north.

**TIMING**

In this segment of the Coastal Cordillera, the dominant Neogene structures are ~NS normal faults, NNW-striking strike-slip faults, and the EW reverse faults (González et al., 2003a; González et al., 2003b; González et al., 1997). Cross-cutting relations at Cerro Chuculay just east of Salar Grande (Fig. 2) show that the EW reverse faults are cut by the strike-slip faults (Skarmeta and Marinovic, 1981). At Pisagua, the ENE-striking reverse fault is probably cut and offset by the north-striking normal fault, although the relationship shown on the map of the region is just the opposite of the interpretation given here.

**Figure 3.** Equal area lower hemisphere projection showing the “P” (solid dots) and “T” (open boxes) kinematic axes calculated for all of the reverse faults measured in the area of Figure 1. The black triangles show the average kinematic axes: 1 = infinitesimal principal extension axis, and 3 = principal shortening axis. Shown also is the best fit fault plane solution, which demonstrates that the faults have no significant strike-slip component and that the average fault dip is 45°.
At Barranco Alto south of Iquique (Figs. 1, 4), an extraordinary exposure of growth strata with intercalated tuffs provides excellent absolute age control on the EW reverse faults (Fig. 4). Strata in a small evaporite basin in the footwall of the thrust onlap the fault scarp. Whereas the unconformity at the base of the basin strata is offset by ~60 m, a tuff within the part of the basin strata that onlap the scarp is offset across the fault by just 2 m. Single crystal laser dating of feldspars yields a statistically valid isochron of 5.6 Ma for the tuff. Thus, the Barranco Alto structure probably began growing in the latest Miocene and was probably mostly finished growing by early Pliocene. Preliminary geochronology from the fold scarp at the east end of the Pisagua...
structure shows that the folding was synchronous with, or younger than, a tuff yielding an Ar total gas age of 6.36±0.03 Ma, putting it in the same age range as the Barranco Alto structure. Because of geomorphic relations described below, we suggest that most of the EW scarps formed at about the same time. However, as described elsewhere in this volume (González et al., 2003a), the existence of Pleistocene wave cut platforms locally uplifted along strike of the prominent EW faults (Atajaña, Pisagua, Iquique, Barranco Alto) suggests that continued, or reactivated, north-south shortening is warping these surfaces.

GEOMORPHIC RELATIONS AND CLIMATIC IMPLICATIONS
At several localities (from south to north: Río Loa, Chuculay, Barranco Alto, Pisagua among other areas), the uplifted blocks of the EW scarps are incised by small fossil drainages that no longer carry any water. They were cut at a time prior to the development of the current hyperarid conditions of the Coastal Cordillera. The Barranco Alto site (Fig. 4, B) provides a beautifully detailed record of how and when this happened: Prior to reverse faulting, paleodrainage was to the NW towards the ocean shoreline that must have been located several kilometers farther west. When faulting began, there was initially enough water to keep pace with uplift and the hanging wall block was incised. Eventually, however, the fault scarp dammed the drainage and created an internally draining evaporite basin that covered the upstream part of the drainage located in the footwall. Strata accumulated in the basin include the dated 5.6 Ma tuff. The onset of hyperaridity here post dates 5.6 Ma, a scenario in agreement with interpretations based on more regional data (Chong D. et al., 1999; Hartley and Chong, 2002). The paleodrainage is not incised into the current Coastal Escarpment at all and the evaporite basin is abruptly truncated at the escarpment, indicating the escarpment retreated from west to east to its current position after 5.6 Ma.

TECTONIC INTERPRETATION OF THE NS SHORTENING
Any tectonic explanation of the north-south shortening of the northern Chilean forearc must account for two basic observations: (1) In east-west extent, the structures are limited exclusively to the Coastal Cordillera and do not extend across the Central Valley. Instead some of the faults have been documented to die out at the eastern limit of the Coastal Cordillera. Thus, the structures are uniquely related to the processes of the interplate zone. (2) In north-south extent, the fault scarps are limited to the region between the Quebrada Camarones (19°S) and just south of the Río Loa (21.6°S). Although north-south shortening has been observed elsewhere in the forearc of the Central Andes (e.g., Lavenu and Cembrano, 1999), only in this range has the shortening been sufficient to form scarps up to 500 m high.

McCaffrey (McCaffrey, 1996) has shown that the kinematics of the forearc of subduction zones can be predicted from the relation between the obliquity of plate convergence (relative to the plate boundary) and the obliquity of interplate earthquake slip vectors. When looked at in this way, most forearcs experience arc-parallel extension. Northern Chile, however, is one of only two forearcs surveyed by McCaffrey that displays arc-parallel shortening. McCaffrey’s model is strictly observational and kinematic; it does not explain why the shortening occurs there.

Gephart (1994) showed that the topography of the Central Andes is remarkably symmetric with a best-fit symmetry plane whose pole coincides with the pole of rotation between Nazca and South America during the birth of the modern Andes in the early Miocene. This symmetry plane does not coincide with the bend in the coastline at Arica but crosses the shoreline nearly 2° of latitude farther south at 20.5°S, close to the city of Iquique (Fig. 1). The EW fault scarps are distributed
symmetrically to the north and south of the symmetry plane, indicating that they are related to formation or the modern shape of the Bolivian orocline.

Bevis and others (2001), have shown that orthogonal convergence across a locked plate boundary that is concave towards the subducting plate will produce an elastic deformation field with a strong component of shortening parallel to the plate boundary across the symmetry plane of the curvature. This appears to be exactly the situation in northern Chile forearc. In fact, the triangle of GPS stations that straddles Gephart’s symmetry plane displays a component of north-south shortening (Allmendinger et al., in prep.).

CONCLUSIONS
The east-west scarps of the northern Chilean Coastal Cordillera are produced by pure dip slip reverse faults that resulted in about 3 km or 1% horizontal shortening along an azimuth of 350° parallel to the trench, the contours on the Wadati Benioff Zone, and the trend of the Cordillera itself. Preliminary dating shows that the faults formed in the latest Miocene and early Pliocene, although Pleistocene wave-cut platforms are locally deformed suggesting more recent reactivation. The faults formed when the region of the Coastal Cordillera was less arid than today; they dammed paleodrainages and formed the small evaporite basins common to this part of the Coastal Cordillera. Significant Coastal Escarpment eastward retreat has occurred since the scarps formed and the drainages were dammed. Subsequent onset of hyperaridity (Hartley and Chong, 2002) has resulted in a region totally devoid of surface water today. The region of trench parallel shortening straddles symmetrically the symmetry plane of the Central Andes defined by Gephart (1994). Thus we conclude that the deformation is related to the shape of the Bolivian orocline, a concept borne out by GPS data and elastic modeling (Bevis et al., 2001).

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