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Tectonic activity revealed by morphostructural analysis: Development of the Sierra de la Candelaria range, northwestern Argentina

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ABSTRACT

The tectonically active broken foreland of NW Argentina is a recent analog of the eastern margin of the Puna plateau during Mio-Pliocene times and likely of other broken forelands worldwide. In order to evaluate active tectonism in the broken foreland of the NW Argentine Andes, we examined the complex geomorphology in the vicinity of the basement-cored Sierra de la Candelaria range at ~26°S and deciphered multiple episodes of crustal deformation spanning the Pliocene to the Quaternary. Digital elevation models, satellite images and geological data within a GIS environment allowed us to analyze the terrain, drainage networks, river dynamics and structure, as well as to obtain detailed geomorphological mapping, active tectonic indices, longitudinal river profiles and structural sections. Three morphostructural segments were defined based on the structural features, the differential vertical dissection pattern over the basement, the faulted Pliocene to recent deposits, the stepwise propagation of anticlines and the distortion over the fluvial system. By combining the several lines of evidence, we concluded that the Sierra de la Candelaria range was subjected to a multi-stage development. The first stage uplifted the central segment concomitant with the formation of the surrounding ranges and with the main partition phase of the foreland. After a significant time lapse, the mountain range was subjected to southward thick-skinned growth and northward growth via stepwise thin-skinned deformation and exerted control over the dynamics of the Río Rosario. Taking into account the surrounding basins and ranges of the Sierra de la Candelaria, the southern Santa Bárbara System is characterized by partially isolated intramontane basins (Choromoro and Rosario) limited by shielded ranges that caused moisture block and shows continuous deformation. These features were related to early stages of a broken foreland evolution model and modern analogs were found at the northern Santa Bárbara System, in the vicinity of the Siancas/Güemes Valley or at the more evolved stage represented by the Lerma Valley. In addition, ancient analogs were defined for the Humahuaca basin conditions at 4–3 Ma ago or for the Toro basin at 6–3 Ma, among others.

1. Introduction

Flexural subsidence, which determines the space for the sedimentary fills in response to the progressive vertical and lateral growth of fold and thrust belts, controls the sediment accumulation within continuous foreland basins (Flemings and Jordan, 1989; DeCelles and Giles, 1996). The resulting foreland structural style could be favored by the existence of deep sedimentary basins combined with rheological weak zones that behave as *detachment* horizons (Allmendinger et al., 1983). In contrast, broken foreland basins may develop by shortening accommodated along reactivated basement anisotropies and inversion of high angle structures (Jordan and Allmendinger, 1986; Jordan and Alonso, 1987). The broken foreland model comprises diachronous reactivation of structures and spatially disparate patterns of range uplifts that lead to the formation of highly localized depocenters. If the ranges establish a laterally continuous topographic barrier, able to block moisture-bearing winds, the accreted basins remain within an arid environment (Jordan and Allmendinger, 1986; Strecker et al., 2007, 2011; Pingel et al., 2014). Also, the accommodation of deformation within basement ranges and the broken foreland configuration are likely to occur well inboard of the primary topographic margin of the orogen (e.g. Ramos et al., 2002; Strecker et al., 2009; Iaffa et al., 2011, 2013).

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Modern examples of such broken foreland basins include the Santa Bárbara System, the northern Sierras Pampeanas and the foreland side of the Eastern Cordillera in NW Argentina (González Bonorino, 1950; Allmendinger et al., 1983; Jordan and Allmendinger, 1986; Ramos et al., 2002), the Eastern Cordillera of the Colombian Andes (e.g. Mora et al., 2006; Parra et al., 2009), the Qilian Shan of the Tibetan Plateau (Tapponnier et al., 1990; Métivier et al., 1998; Sobel et al., 2003) and the Tien Shan of Kyrgyztan and China (e.g. Sobel and Dumitru, 1997; Sobel et al., 2003). The ancient analog of such basin system may be the Laramide foreland of the western United States (Dickinson and Snyder, 1978; Steidtman et al., 1983; Jordan and Allmendinger, 1986) and the paleozoic Alice Springs broken foreland in Australia (Haines et al., 2001).

The evolution of a broken foreland determines a concomitant complex dynamic landscape. The uplift of local barriers modifies the relief and the drainage systems that control the sedimentary, exhumation and erosion patterns in the area (e.g. Hain et al., 2011; del Papa et al., 2013; Pingel et al., 2014). Tectonic fragmentation of the drainage system may be enhanced by orographic shielding, river transport capability, and river incision rates in the hinterland (Hain et al., 2011). In addition, aggradation and excavation within intermontane basins may act as an oscillatory filling process because of the dynamics of the fluvial system that connects the intramontane basin to the foreland (Hilley and Strecker, 2005). The analysis of the current morphology of the ranges and the surrounding relief together with the description of the alluvial deposits and the fluvial network adjustment may allow analyzing the evolution of the uplift and clarifying its current stage.

Relief and drainage analyses have been extensively applied to study deformation sequences, in local and regional areas, through uplift rates, fold propagation and active tectonic studies in Cenozoic to recent time scales (Holbrook and Schumm, 1999; Azor et al., 2002; Font et al., 2010; Mrinalinee Devi et al., 2011; Kirby and Whipple, 2012; Molin et al., 2012; Castillo et al., 2014). Terrain and water channel parameters are useful to define geological and structural controls over the landscape, and may be combined with active tectonic indices to obtain a better temporal constraint of the features (Whipple, 2004; Duffy et al., 2014). Several studies have revealed that active folding produces a notable change in fluvial network, relief and geomorphic settings (e.g., Melosh and Keller, 2013; Montero et al., 2013). Because of the sensitivity of drainage patterns to active tectonics, such as faulting or folding growth, rivers respond by producing changes in their channel geometry, deflections, incisions and asymmetry of their channel basins that are suitable for modern and ancient landscape setting recognition (e.g., Holbrook and Schumm, 1999; Whipple, 2004; Jain and Sinha, 2005; Amos et al., 2010; Pérez-Peña et al., 2010; Gong et al., 2014).

In the present study, we focused on the Sierra de la Candelaria mountain range, which is the southeastern expression of the Santa Bárbara System in NW Argentina (Fig. 1a), and is recognized because of its geothermal sites and the numerous populations surrounding it. An integrated analysis combining geomorphology and morphostructural characterization, including standard parameters and tectonic active indices, as well as the application of structural sections, was performed to elucidate the uplift evolution, growth and recent tectonic activity of this mountain range. Also, the current features of this range and the surrounding ranges were highlighted to define the implications of the current evolution of this range as well to correlate it with the ancient stage of more evolved broken foreland stages in the region. From this point of view, the present work attempts to show a snapshot over the processes and evolution of the landscape over the early stages of the broken foreland formation.

2. Geological settings

Our study area is located in the morphostructural province Santa Bárbara System, in the broken foreland of NW Argentina,

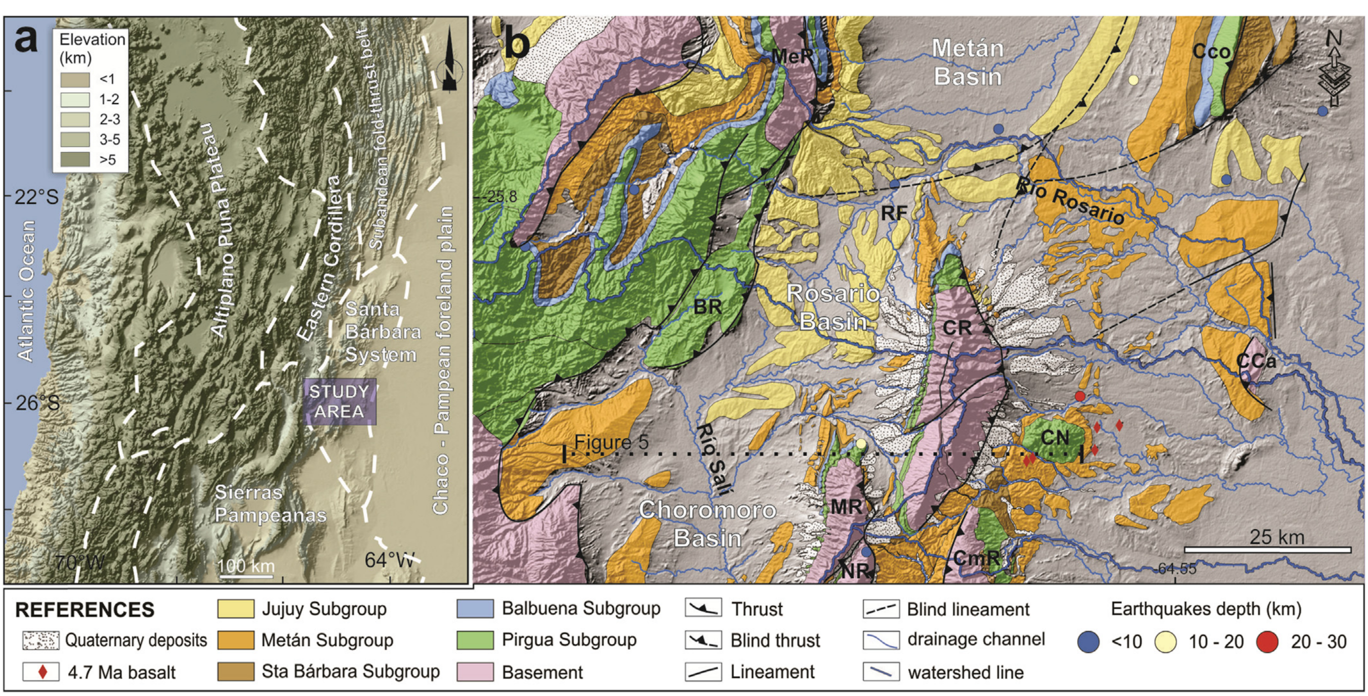

Fig. 1. a) Digital elevation model with the morphostructural provinces and the location of the study area. b) Simplified geologic map based on González (2000), Salfity and Monaldi (2006), Gioncada et al. (2010) and Iaffa et al. (2011). CR – Sierra de la Candelaria range; MR – Medina range; NR – Nogalito range; CmR – Campos range; CN – Cerro Negro hill; CCa – Cerro Cantero hill; CCO – Cerro Colorado; MeR – Metán range; BR – Brete range; RF – Rosario de la Frontera town. The trace of the structural cross section of Fig. 5 (black dot line) was included. Earthquakes database from International Seismological Center-Global Instrumental Earthquake Catalogue (2014).