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The fracture patterns of the Tin Tin anticline: Fracturing process during the foreland evolution in the Calchaquí Valley, northwestern Argentina

Mariano Hernández*, Juan R. Franzese

Centro de Investigaciones Geológicas (UNLP-CONICET), diagonal 113 n° 275, B1904DPK, La Plata, Buenos Aires, Argentina

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ABSTRACT

We present a field-based work which illustrates the fracture patterns of the carbonate-siliciclastic Yacoraite Formation in the Tin Tin anticline, a basement fault-related fold located in southern part of the Eastern Cordillera, northwestern Argentina. The fracture patterns include small-scale strike-slip faults (vertical shear fractures and *en echelon* arrays), thrust faults, extension fractures (joints, veins and normal faults) and stylolites. Extensional mesostructures were formed by along-foreland stretching, prior to the contractional ones that were formed by the layer-parallel shortening mechanism. Furthermore, all fractures are interpreted to be formed before or at the early stages of folding and thrusting during the Andean contraction, all of them belonging to the Eocene thrust belt-foreland system at the Calchaquí Valley of northwestern Argentina.

1. Introduction

The study of small-scale structures (i.e. observable at outcrop scale, also known as mesofractures), and particularly those related to folds, has become increasingly important for the management of naturally fractured reservoirs of fold and thrust belts all around the world (Antonellini and Mollema, 2000; Hennings et al., 2000; Nelson, 2001). In northwestern Argentina, as well as along the Andes, much of the hydrocarbon is trapped in naturally fractured rocks, as is the Yacoraite Formation of the Cretaceous-Paleogene Salta Group (Mon and Salfity, 1995; Disalvo et al., 2002; Marquillas et al., 2005). This formation is a well-known carbonate fractured reservoir in the Subandean Ranges (e.g. Grosso et al., 2013) and it is exposed along the Eastern Cordillera (Fig. 1a). Despite its economic relevance, only few studies dealing with the fracture pattern of the Yacoraite carbonates have been published (e.g. Massaferro et al., 2003; Likerman et al., 2011; Grosso et al., 2013). More generally, studies linking mesoscale fractures and stress evolution in foreland thrust belts (e.g. Tavani et al., 2015) are not abundant in Argentina (e.g. Di Marco, 2005; Branellec et al., 2015).

In this work we illustrate the fracture patterns of the Yacoraite Formation in the Tin Tin anticline, a basement-cored fold located in the southern Eastern Cordillera of northwestern Argentina (Fig. 1a and b), representing an analogue for fractured reservoirs. Our aim is to contribute to the understanding of the structural setting during fracture formation and folding processes in naturally fractured reservoirs in northwestern Argentina.

2. Field area: Calchaquí Valley of NW Argentina

The Calchaquí Valley area is one of a series of N-S-oriented valleys that extends between the Puna and the Eastern Cordillera and further south into the Pampean ranges (Fig. 1a). Structurally, the area is characterized by broadly N-S-striking and west-vergent fault-related folds (such as the Tin Tin anticline) surrounded by large basement blocks (Fig. 1b). This structural framework is extensively assigned to the tectonic inversion of the Salta Group Basin resulted from Cenozoic Andean contraction (Grier et al., 1991; Mon and Salfity, 1995; Carrera et al., 2006; Carrera and Muñoz, 2008, 2013). The rift-related Salta Group Basin (Fig. 1d) developed during an extensional phase that took place during the Lower

* Corresponding author.
E-mail addresses: mhernandez@cig.museo.unlp.edu.ar (M. Hernández), franzese@cig.museo.unlp.edu.ar (J.R. Franzese).

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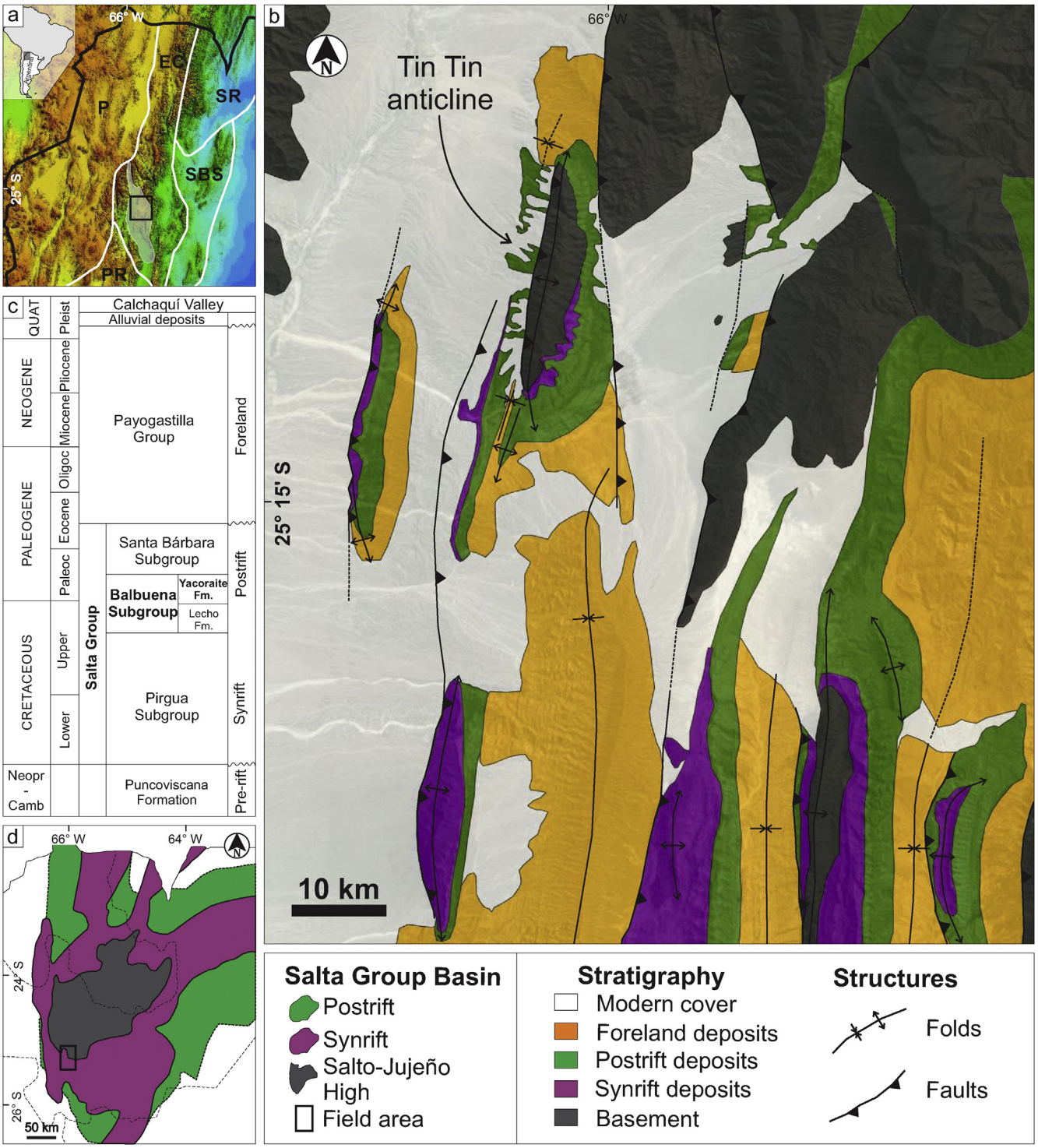

Fig. 1. a) Geological provinces of northwestern Argentina. P: Puna; EC: Eastern Cordillera; SR: Subandean Ranges; SBS; Santa Barbara System; PR; Pampean Ranges. Grey shade indicates the Calchaquí Valley. Black rectangle marks the study area showed in Fig. 1b. b) Geologic map of the study area showing the main structures and units. Dotted lines are inferred or unknown structures. c) Stratigraphic chart of the study area. d) Salta Group Basin deposit distribution. Black rectangle marks the Valle Calchaquí area showed in Fig. 1b.

Cretaceous and the Paleogene in NW Argentina. Isolated grabens characterized the early synrift stage. These sub-basins were placed around a structural basement high (Salto-Jujeño High) and were characterized by different orientations (Fig. 1d). The synrift deposits of the Pirgua Subgroup (Fig. 1c) were later overlaid by the early postrift deposits of the Balbuena Subgroup (Fig. 1c) when the decrease in tectonic subsidence and a relative sea-level rise allowed a shallow Atlantic marine ingression, in coincidence with humid conditions (Marquillas et al., 2005). The late postrift stage of the Salta Basin (Santa Bárbara Subgroup; Fig. 1c) is also characterized by thermal subsidence but different (drier) environmental conditions prevailed (Marquillas et al., 2005). Afterward, the onset of Andean contraction during the Paleogene led to the development of a foreland basin, filled by the Payogastilla Group in the Calchaquí