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Quality assessment of reservoirs by means of outcrop data and “discrete fracture network” models: The case history of *Rosario de La Frontera* (NW Argentina) geothermal system

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ABSTRACT

We report the results of a systematic study carried out on the fracture systems exposed in the *Sierra de La Candelaria* anticline, in the central Andean retrowedge of northwestern Argentina. The aim was to elaborate a kinematic model of the anticline and to assess the dimensional and spatial properties of the fracture network characterizing the Cretaceous sandstone reservoir of the geothermal system of *Rosario de La Frontera*. Special regard was devoted to explore how tectonics may affect fluid circulation at depth and control fluids' natural upwelling at surface. With this aim we performed a Discrete Fracture Network model in order to evaluate the potential of the reservoir of the studied geothermal system. The results show that the *Sierra de La Candelaria* regional anticline developed according to a kinematic model of transpressional inversion compatible with the latest Andean regional WNW–ESE shortening, acting on a pre-orogenic N–S normal fault. A push-up geometry developed during positive inversion controlling the development of two minor anticlines: *Termas* and *Balboa*, separated by further NNW–SSE oblique-slip fault in the northern sector of the regional anticline. Brittle deformation recorded at the outcrop scale is robustly consistent with the extensional and transpressional events recognized at regional scale. In terms of fluid circulation, the NNW–SSE and NE–SW fault planes, associated to the late stage of the positive inversion, are considered the main structures controlling the migration paths of hot fluids from the reservoir to the surface. The results of the fracture modeling performed show that fractures related to the same deformation stage, are characterized by the highest values of secondary permeability. Moreover, the DFN models performed in the reservoir volume indicates that fracture network enhances its permeability: its secondary permeability is of about 49 mD and its fractured portion represents the 0.03% of the total volume.

1. Introduction

The characterization of naturally fractured reservoirs continues to challenge geoscientists due to their complexity and unpredictable nature (Nelson, 1998; Jafari and Babadagli, 2011). Furthermore, naturally occurring fractures have significant effects on reservoir fluid flow (Evans and Hobbs, 2003; Roure et al., 2005, 2010; Fischer et al., 2009; Bjørlykke, 2010; Faulkner et al., 2010; Beaudoin et al., 2011; Barbier et al., 2012; Evans and Fischer, 2012; Bigi et al., 2013). As a matter of fact not only they could increase or decrease the permeability of many reservoirs worldwide, but also may induce significant permeability anisotropy due to their geometry and type (Aydin, 2000). For this reason, a correct evaluation of reservoirs means to obtain the best understanding of its fracture network in order to analyze the effects on fluid flow (Guerriero et al., 2010, 2011, 2013, and references therein). As a consequence, this is also a key target for the exploitation of water dominated geothermal reserves (Grant et al., 1982; Brogi et al., 2003; Vignaroli et al., 2013; Giordano et al., 2014).

The classification of naturally fractured reservoirs based on the relationship between primary and secondary porosity and permeability proposed by Nelson (1992) is generally accepted. Particular attention must be paid in the evaluation of those reservoirs where fractures produce significant reservoir anisotropy (barriers) creating compartmentalization instead of providing additional porosity and/or permeability (Odling et al., 1999; Aydin, 2000; Jolley et al., 2010; Manzocchi et al., 2010). Having granular material the potential to develop particularly low porosity deformation zones (Antonellini and Aydin, 1994; Aydin, 2000), their occurrence in sandstone reservoir can reduce permeability of some orders of magnitude when compared

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to that of the undeformed hosting rock (Matthai et al., 1998; Fossen and Bale, 2007; Sternlof et al., 2004). Therefore, an accurate classification of fractures and a quantitative evaluation of the fracture network have a direct impact on the development planning of geothermal fields, because production may strongly depend on the permeability anisotropy created by fractures.

Discrete Fracture Network (DFN) modeling (Dershowitz and Einstein, 1988; Cacas et al., 1990; Watanabe and Takahashi, 1995) represents an important tool during exploration and exploitation phases of fractured reservoirs. It is widely accepted that it provides an accurate prediction of the fracture network since it accepts as input data, statistical and probabilistic information on fracture properties, obtained by means of systematic fracture field mapping.

In this framework, the reliability of fracture system characterization highly depends on the quality of mapping and of outcrop conditions, especially in the case of limited extension of rock exposures and/or limited depths of boreholes. For this reason, a variety of methodologies for both data acquisition and analysis have been developed, from outcrop/well scale to regional/seismic scale, in order to provide the best criteria for predicting fracture networks (Van Dijk, 1998). Some acquisition techniques are based on the characterization of outcropping structures as analogues for subsurface portions of the reservoirs (Hennings et al., 2000; Belayneh et al., 2006; Laubach and Ward, 2006; Barr et al., 2007). These techniques comprise the acquisition of fracture data along scan-lines (e.g. Priest and Hudson, 1981; Zeeb et al., 2013; Bisdom et al., 2014 among many others), and on scan-areas (e.g. Pahl, 1981; Marchegiani et al., 2006), at outcrop scale, in order to elaborate a probabilistic model representing fracture distribution at reservoir scale and some tools that are more modern such as the light detection and ranging technique (LiDAR, or laserscan) and new, effective developments in phogrammetry (Tavani et al., 2014).

In this work, we have applied scan-line acquisition technique in order to collect structural data to assess the quality of the geothermal reservoir of *Rosario de La Frontera* system, belonging to the *Sierra de La Candelaria* anticline, one of the positively inverted structures cropping out between the provinces of Salta and Tucuman (NW Argentina). The purpose of this approach is to compute its secondary permeability in order to predict the reservoir behavior in prospect evaluation and reservoir management.

The Cretaceous deposits of the *Salta* Group (*Pirgua* Subgroup), provide the reservoir of this active geothermal system (Moreno Espelta et al., 1975; Seggiaro et al., 1995; Seggiaro et al., 1997; Maffucci et al., 2012b, 2013; Invernizzi et al., 2014). It consists of continental deposits, mainly represented by sandstones and conglomerates, related to the syn-rift stage (Late Neocomian–Early Maastrichtian) (Salfity and Marquillas, 1994; Marquillas et al., 2005). In the area, they are deformed in a N–S trending hangingwall anticline (*Sierra de La Candelaria*) and dissected by subsequently strike-slip and normal faults.

The anticline and the associated deformative structures (faults and fractures) represent the structural backbone of the studied geothermal system.

2. Geological setting

Sierra de La Candelaria ridge is located in the foothills of the Central Andean retro-wedge, in the Salta province (NW Argentina) between the Eastern Cordillera to the west and the southern segment of the Santa Bárbara System to the east (Fig. 1).

These units are characterized by a basement-involved thrust system (Baldis et al., 1976; Rolleri, 1976; Allmendiger et al., 1983; Jordan et al., 1983; Cahill et al., 1992; Kley and Monaldi, 1998; Seggiaro and Hongn, 1999), resulting from an eastward migrating shortening that occurred during Miocene–Quaternary times (Grier et al., 1991; Salfity et al., 1993; Kress, 1995; Cristallini et al., 1997; Kely and Monaldi, 2002; Allmendiger and Gubbels, 1996; Kley and Monaldi, 1999; Reynolds et al., 2000; Kley and Monaldi, 2002).

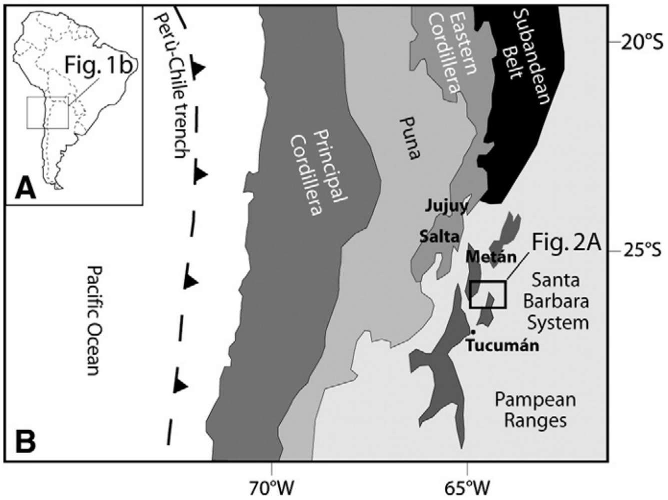

Fig. 1. Map illustrating the geological provinces of northwest Argentina, modified from Carrera and Muñoz (2008).

As a result, the Andean structure in this area is dominated by broad, low-amplitude folds, generated in the hangingwall of east-verging high-angle thrust faults (Kley and Monaldi, 2002; Mon and Gutierréz, 2007; Norini et al., 2013) mainly due to the Andean inversion of pre-existing normal faults generated during the Cretaceous rifting event (Bianucci et al., 1982; Grier et al., 1991; Carrera et al., 2006).

Sierra de La Candelaria ridge represents one of these broad anticlines that is elongated in N–S direction for about 55 km and with a maximum elevation of about 2600 m a.s.l. (Fig. 2A; González et al., 2000; Salfity and Monaldi, 2006). The main structural feature responsible of its uplift is a high-angle reverse fault plane dipping to the west with top-to-the-east sense of transport that borders the anticline along its eastern margin (Moreno Espelta et al., 1975; Seggiaro et al., 1997). It is interpreted as an inverted normal fault inherited from the rifting stage (Iaffa et al., 2013).

The stratigraphy of the geothermal system covers a wide time span: from pre-Cambrian to Pliocene–Quaternary times (Fig. 2B). The older stratigraphic unit crops out in the core of the anticline. It is the Precambrian basement made up of low grade metasedimentary rocks (*Medina* Formation) that, in the northern portion and along the western limb of the anticline, is unconformably overlain by a thick succession of continental Cretaceous to Paleogene strata (*Salta* Group) related to the Cretaceous rift stage (Turner, 1959; Salfity, 1982; Galliski and Viramonte, 1988; Salfity and Marquillas, 1994; Viramonte et al., 1999; Marquillas et al., 2005). The Early to Late Cretaceous *Pirgua* subgroup, marks the syn-rift fill stage (Salfity and Marquillas, 1994), whereas the *Balbuen*a and *Santa Bárbara* subgroups represent the post-rift thermal subsidence stage (Bianucci et al., 1981; Salfity and Marquillas, 1994; Comnínguez and Ramos, 1995). Post-rift deposits are in turn overlain by a thick continental foreland basin fill, related to the Andean mountain uplift and erosion, that was deposited from Middle Miocene to Pliocene–Quaternary times (Gebhard et al., 1974). The retrowedge basin fill includes two subgroups (*Metán* and *Jujuy*, according to Gebhard et al., 1974) belonging to the *Orán* Group. The main outcrops of these subgroups cover the northern portion of *Sierra de La Candelaria* ridge at the lowest elevations.

The stratigraphic succession cropping out along the *Sierra de La Candelaria* ridge forms an anticline whose general trend is N–S (Fig. 2A). In detail, this trend is characterized by a NNE to NNW change of the longitudinal axis moving from south to north as a result of the two regional E–W and WNW–ESE shortening directions occurred during the Andean compression (Marrett et al., 1994; Iaffa et al., 2011). In addition, the northern portion of the anticline is offset by several minor faults. The most important is a NNW–SSE trending high angle fault that divides the structure in two anticlines: *Termas* and *Balboa* (Moreno Espelta et al.,