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Seismic activity and stress tensor inversion at Las Tres Vírgenes Volcanic and Geothermal Field (México)

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ABSTRACT

We analyze local earthquakes occurring between 2003 and 2012 at the Las Tres Vírgenes Volcanic and Geothermal Field (TVVGF) to establish their temporal and spatial distribution, and relationships with local and regional fault systems, water injection, acid stimulation and steam production tests. We obtained focal mechanisms and inverted data for the stress tensor to understand the local and regional stress fields. We analyzed 423 local earthquakes with magnitudes between 0.1 and 2.9 Mc and hypocentral depths from 0.2 to 7.4 km b.s.l. The cutoff depth at ~7.4 km possibly delineates the brittle–ductile transition zone. We identified seven swarms (from 1 to 7). Swarms 1 (December 2009), 2 (May 2010), 3 (June–July 2010) and 7 (December 2012) are strongly correlated with injection processes; whereas swarms 5 (April 2012) and 6 (September 2012) are correlated with local tectonic faults. Stress inversion showed NW–SE, E–W and NE–SW extensional orientations (S_{hmin}), in agreement with the local tectonic stress field; while NE–SW compressional orientations (S_{Hmax}) are correlated with the regional tectonic stress field.

1. Introduction

Seismic monitoring allows one to study local seismicity distribution and to characterize their source mechanisms. Worldwide, earlier seismic studies in different volcanic and geothermal zones revealed that seismic activity and seismic swarm are associated with magmatic processes, high tectonic activity (local and regional), steam production, acid stimulation and fluids injection. Many studies have demonstrated that the local earthquakes are correlated with fluid injection, rather than production (Sminchak and Gupta, 2003; Baisch et al., 2006; Suckale, 2009; Kwiatek et al., 2010; Nicol et al., 2011). According to Majer et al. (2007), fluids injection helps to maintain reservoir pressures and flow rates at production wells, but induces local seismicity. Fluid injection not only perturbs stress regime and creates new fractures, but also potentially introduces pressurized fluids into pre-existing fault zones, causing slip to occur earlier than it would otherwise occur naturally (Scholz, 1990). Moreover, Šílený et al. (2014) state that the injection of fluid into firmly consolidated sedimentary rocks, may cause a shear slip on existing faults and fractures, inducing microseismic events.

In geothermal fields, depths of local earthquake inferred to be induced by injection–production operations are generally less than 10 km and in many cases are most commonly located above 5 km (Sminchak and Gupta, 2003; Suckale, 2009; Nicol et al., 2011) generally clustered within or immediately around the well bottoms. Clusters have typically circular or elongated shapes attributed to reactivation of pre-existing faults, they can migrate toward and away from the injection site (Baisch et al., 2006; Kwiatek et al., 2010). On the other hand, the deeper limit of local earthquake hypocenters is interpreted as an indicator of the transition between brittle and ductile zones (Meissner and Strehlau, 1982), due to the high temperature at depth. This factor could determine the maximum depth of local earthquakes (Chen and Molnar, 1983).

Thus the source mechanisms of induced local earthquakes can be used to determinate whether or not events occurred on pre-existing faults, or at new cracks (Cuenot et al., 2006). Because faults are the primary control on geothermal activity, it is important to understand their geometry and kinematics to establish fault patterns or fault segments most favorable for geothermal activity. Fault opening by *shear slip* or by *tensile cracks* is particularly important at geothermal sites because shear displacement might act on existing fractures or originating new ones, resulting in permeability enhancement within the reservoir (Evans et al., 2005).

On the other hand, knowledge of the stress field at a geothermal site can assist the development of deep geothermal projects because their full characterization requires a global perspective of the geothermal system and associated faults, information provided by the stress regime. Orientation of the pre-existing fractures and faults and stress regime

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are key parameters that largely define the response of the medium to massive fluid injections direction of fracture (Zang et al., 2014)

Seismic activity studies of local and regional stress field at the Las Tres Vírgenes Volcanic and Geothermal Field (TVVGF) initiated in 1993 by Comisión Federal de Electricidad (CFE) (Ballina, 1985; Macías, 1996; Romo et al., 2000; Wong et al., 2001; Wong and Munguía, 2006; Lermo et al., 2011) indicate that the TVVGF is seismically active between 1.0 and 8.0 km depth with magnitudes ranging from 1.0 to 3.0 Mc. Accordingly, seismicity occurs as swarms. However, the correlation of local earthquakes with injection–production rates was not clearly established because seismicity was not located immediately bellow wells like in other geothermal fields such as Los Humeros (Lermo et al., 2008), Cerro Prieto (Fabriol and Munguía, 1997), Rotokawa (Bannister et al., 2008) and Northwest Geysers (Viegas and Hutchings, 2011).

In this study, we analyzed local earthquake activity at the Las Tres Vírgenes Volcanic and Geothermal Field (TVVGF) recorded from 2003 to 2012 to establish the source of local earthquakes, their relationship with the amount of the water injection, acid stimulation and steam production tests in well LV6 and water injection in well LV8. We also inverted the data for the stress tensor to understand the local and regional stress fields and to identify changes of the stress during the injection processes.

The TVVGF is one of the important geothermal fields in Mexico whose monitoring began many years ago and provides a valuable seismological database enabling us to a reliable stress field determination. This study certainly represents a basic contribution to the characterization of faulting at the TVVGF.

2. Geological and tectonic setting

The Las Tres Vírgenes Volcanic and Geothermal Field (TVVGF) is located in the Baja California Peninsula, to the north of the state of Baja California Sur State, and near the Gulf of California coast 34 km north-west of Santa Rosalía City (Fig. 1). This field rests on a crystalline basement (99.1 ± 0.8 Ma) which has been cut by the geothermal wells, and observed in xenoliths in several younger rocks. This basement is covered by the miocenic Comondú Group igneous rocks (Santa Lucia andesite), La Esperanza basalt (7.64 ± 1.16 Ma) and volcanic and epiclastic rocks of the late Pliocene to Pleistocene Reforma (1.34–1.09 Ma) and Aguajito (0.5–0.76 Ma) calderas. The Las Tres Vírgenes Volcanic Complex (TVVC) comprises three volcanoes: El Viejo (198 ± 42 ka), El Azufre (>44 ka), and La Virgen (~36 ka), which are emplaced along a NE–SW alignment (Fig. 2a) and gets progressively younger southwestward (López et al., 1994; Capra et al., 1998).

The high density fault systems present three orientations: NW–SE (Bonfil, El Mezquital, La Virgen, El Volcán, El Viejo 1, El Viejo 2, El Partido and El Azufre), NE–SW (Los Volcanes alignment, El Álamo) and N–S (Las Víboras, El Colapso, El Cimarrón) associated with the tectonic interaction between the Pacific, Farallon and North American plates (García and Gonzáles, 1998; López, 1998; Rocha and Romero, 2009; Macías and Jiménez, 2012, 2013). According to Stock and Hodges (1989) and Atwater and Stock (1998), the limits between the Pacific and North America plates experienced a dramatic accommodation at about ~10 Ma, when the subduction of Guadalupe and Magdalena microplates beneath the North America plate ceased. Between 8 and 6 Ma the North American plate boundary moved inland from the former Farallon subduction arc or back-arc zone, transferring the Baja California Peninsula to the Pacific plate around 1 Ma and opening the present day Gulf of California.

Geothermal research at the TVVGF was initiated in 1982, with geological (López et al., 1994; Capra et al., 1998; López, 1998) geophysical (Ballina, 1985; Campos-Enríquez, 1992; Macías, 1996; Romo et al., 2000; Wong, 2000; Romo et al, 2006; Wong and Munguía, 2006) and

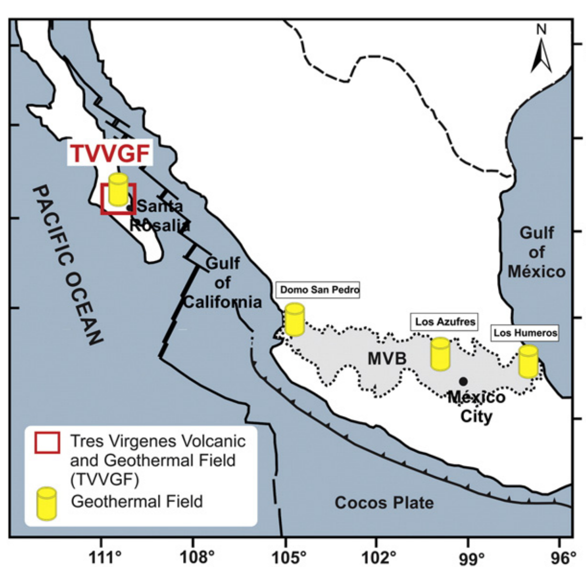

Fig. 1. Study area location and regional tectonic setting. The red square represents the Las Tres Vírgenes Volcanic and Geothermal Field (TVVGF) located 34 km NW of Santa Rosalía City (black circle). MVB: Mexican Volcanic Belt.

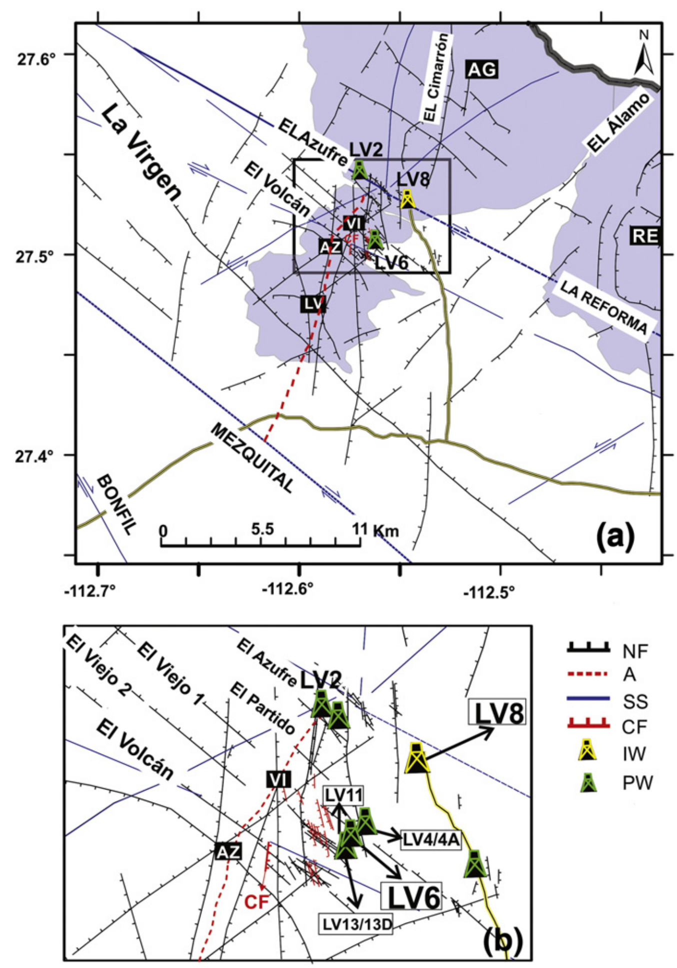

Fig. 2. (a) Map of the Las Tres Vírgenes Geothermal Field showing local and regional structural features. NF: normal fault; A: Los Volcanes alignment; SS: strike–slip fault; CF: conjugate fault; IW: injection wells; PW: production wells; LV: La Virgen volcano; AZ: El Azufre volcano; VI: El Viejo volcano; AG: El Aguajito caldera; RE: La Reforma caldera. (b) Detail of the Las Tres Vírgenes Geothermal Field showing the local structural features and injector–productor wells.