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Hydrology, hydrochemistry and geothermal potential of El Chichón volcano-hydrothermal system, Mexico

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ABSTRACT

Fluid and heat discharge rates of thermal springs of El Chichón volcano were measured using the chloride inventory method. Four of the five known groups of hot springs discharge near-neutral Na–Ca–Cl–SO_4 waters with a similar composition (Cl ~ 1500–2000 mg kg^{-1} and Cl/SO_4 ~ 3) and temperatures in the 50–74 °C range. The other group discharges acidic (pH 2.2–2.7) Na–Cl water of high salinity (>15 g/L). All five groups are located on the volcano slopes, 2–3 km in a straight line from the bottom of the volcano crater. They are in the upper parts of canyons where thermal waters mix with surface meteoric waters and form thermal streams. All these streams flow into the Río Magdalena, which is the only drainage of all thermal waters coming from the volcano. The total Cl and SO_4 discharges measured in the Río Magdalena downstream from its junction with all the thermal streams are very close to the sum of the transported Cl and SO_4 by each of these streams, indicating that the infiltration through the river bed is low. The net discharge rate of hydrothermal Cl measured for all thermal springs is about 468 g s^{-1}, which corresponds to 234 kg s^{-1} of hot water with Cl = 2000 mg kg^{-1}. Together with earlier calculations of the hydrothermal steam output from the volcano crater, the total natural heat output from El Chichón is estimated to be about 160 MWt. Such a high and concentrated discharge of thermal waters from a hydrothermal system is not common and may indicate the high geothermal potential of the system. For the deep water temperatures in the 200–250 °C range (based on geothermometry), and a mass flow rate of 234 kg s^{-1}, the total heat being discharged by the upflowing hot waters may be 175–210 MWt.

1. Introduction

Fluid discharge rates of major thermal areas, worldwide, range from a few liters to several cubic meters of hot water per second. For example, the total thermal waters discharge from the Yellowstone Caldera, USA, was estimated from chloride flux measurements to be 3200 L s^{-1} (Fournier, 1989). At the Mutnovsky geothermal field in Kamchatka, Russia, where a 60 MWe power plant is now operational, the total hot water discharge rate before drilling was estimated to be about 80 L s^{-1} (Vakin and Pilipenko, 1986). Pre-exploitation discharge at Wairakei, New Zealand (190 MWe power plant in operation), was about 100 L s^{-1} (Ellis and Wilson, 1955). About 340 L s^{-1} was measured by Mariner et al. (1990) for the thermal water discharge along about 1000 km of the Cascade Range, in NW USA. A hot spring area associated with the Lassen Peak, USA, hydrothermal system is characterized by about 20 L s^{-1} of measured thermal water flow (Sorey, 1986). Heat output associated with the hot water discharge (i.e. the advective heat flow) may be used as a preliminary indicator of the thermal power of a given hydrothermal system (Ellis and Mahon, 1977; Hedenquist et al., 1988; Pilipenko, 1989; Hochstein and Browne, 2000).

Prior to this study the amount of thermal water discharging from the volcano-hydrothermal system of El Chichón volcano in the state of Chiapas, Mexico, was poorly known. Taran et al. (1998) and Rouwet et al. (2004) reported a very preliminary flow rate of about 100 L s^{-1} for the Agua Caliente hot springs at El Chichón. Taran and Rouwet (2008) and Mazot and Taran (2009) estimated the heat output from the volcano crater, where the main convective heat flow is provided by the steam vents, to be about 120 ± 30 MWt.

The purpose of the work reported herein was to determine the fluid and heat output rates from hot springs on the slopes of El Chichón. The mass and heat output associated with the discharge of steam from the crater and thermal water from the slopes of volcano and its distribution over the area may be further used to quantitatively model and characterize the El Chichón volcano-hydrothermal system.

2. El Chichón volcano and its hydrothermal manifestations

El Chichón is a small, complex volcanic edifice composed of domes and a pyroclastic cover of trachyandesitic composition. Its maximum elevation is about 1100 m above sea level (m asl). Max-

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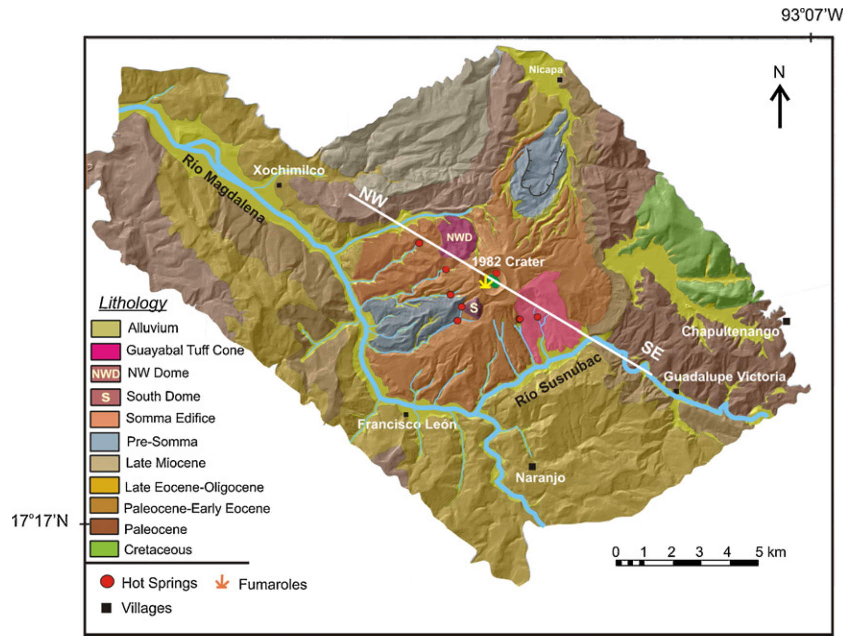

Fig. 1. Simplified geologic map of El Chichón area based on the Digital Elevation Model showing the main hydrographic network (modified after Layer et al., 2009). Red dots: hot springs (see Fig. 2). Also shown is the location of the NW–SE cross-section given in Fig. 9. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of the article.)

imum relief on the southwestern side of the volcano is 800 m, whereas to the ENE it is only 400–500 m. This seems to indicate that the pre-volcanic basement beneath El Chichón is generally dipping to the SSW.

The basement is represented by Neogene–Paleogene sandstones and siltstones, and Cretaceous to Jurassic limestones and evaporites (Macías et al., 2003; García-Palomo et al., 2004). The oldest exposed volcanic structure is the southern extrusive dome with a $^{40}Ar/^{39}Ar$ age of about 200 Ka (Layer et al., 2009). The age of a younger NW dome structure was estimated to be around 90 Ka. A schematic geologic map of the El Chichón area is given in Fig. 1.

Geothermal surface manifestations existed at the same general locations as today before the 1982 catastrophic eruption of El Chichón (Molina-Berbeyer, 1974; Templos et al., 1981). Thermal springs on the southern slopes of the volcano and steam vents at the base of the former central lava dome provided evidence for a boiling hydrothermal system beneath the volcanic edifice. The Comisión Federal de Electricidad of Mexico (CFE) completed an initial geological and geothermal investigation of the area and issued several internal reports with a limited set of very preliminary data on the chemical composition of the summit fumaroles and thermal waters of the Agua Caliente hot springs (Molina-Berbeyer, 1974; Templos et al., 1981).

After the 1982 eruption a one km wide, 160 m deep crater was formed that exposed the El Chichón hydrothermal system. The elevation of the crater floor is ~870 m asl. The total thermal output of the crater fumaroles, steam-heated pools, boiling springs and a warm, large and shallow crater lake with bubbling gas was estimated to be about 120 ± 30 MWt (about 45 ± 10 kg s^{-1} of steam; Taran and Rouwet, 2008; Mazot and Taran, 2009). A chain of hot springs off the crater extends along the southern slope from SE to NW at about 600 m asl, 2–3 km from the crater floor (Fig. 1). All springs are located at the upper parts of canyons whose mouths end at the Río Magdalena, the only drainage of all thermal waters discharging from the volcano slopes. The geochemistry of the spring waters, including trace elements, water isotopes and geothermometry, was reported by Taran et al. (2008).

The study area is in a wet tropical zone with an average yearly rainfall of about 4000 mm (Taran and Rouwet, 2008). The volcanic edifice is covered by thick vegetation that grew after the 1982 eruption.

3. Methodology

3.1. Flow rate measurements

All thermal springs on El Chichón slopes discharge hot water from multiple orifices or as seepages from walls of altered rocks or thermal swamps; some vents are located in inaccessible parts of deep canyons covered by thick vegetation. All these springs drain into cold water streams whose flow rates vary during the wet and dry seasons. However, the hot spring discharge rates vary insignificantly, as indicated by a near constant Cl content of the hottest vents, independent of the season (Tassi et al., 2003; Rouwet, 2006; Taran et al., 2008). All cold (i.e. non-thermal) streams at El Chichón are relatively high in Cl, (7–9 mg L^{-1}) and high in SO_4 (up to 300 mg L^{-1}) due to leaching of the anhydrite-rich pyroclastics deposited by the 1982 eruption (Luhr et al., 1984).

The discharge rate of each group of hot water springs was determined based on measurements made where streams merge into the Río Magdalena, the only drainage for all El Chichón thermal springs. We utilized the chloride inventory method of Ellis and Wilson (1955), that has been used subsequently by several authors (e.g. Fournier et al., 1976; Fournier, 1989; Pilipenko, 1989; Mariner et al., 1990; Ingebritsen et al., 2001; Taran, 2009).

The basis of the Cl-inventory method is the simultaneous measurement of flow rate and chemical composition of streams and rivers at specific sampling locations. We used a standard FP101 flow probe (Global Water) for determining flow rates in the Río Magdalena and all streams entering it from the southern slopes of the volcano. We measured and calculated flow rates following the methodology of Rantz et al. (1982). This was facilitated because near El Chichón the Río Magdalena can be waded across in many places. The five-point method was used with measurements at 0, 0.2, 0.5, 0.7, 1.0 of the total water depth, with 6–8 vertical profiles