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# Geothermal reservoir potential of volcaniclastic settings: The Valley of Mexico, Central Mexico

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ABSTRACT

The geothermal potential of the Valley of Mexico has not been addressed in the past, although volcaniclastic settings in other parts of the world contain promising target reservoir formations. An outcrop analogue study of the thermophysical rock properties of the Neogene rocks within the Valley of Mexico was conducted to assess the geothermal potential of this area. Permeability and thermal conductivity are key parameters in geothermal reservoir characterization and the values gained from outcrop samples serve as a sufficient database for further assessment. The mainly low permeable lithofacies types may be operated as stimulated systems, depending on the fracture porosity in the deeper subsurface. In some areas also auto-convective thermal water circulation might be expected and direct heat use without artificial stimulation becomes reasonable. Thermophysical properties of tuffs and siliciclastic rocks qualify them as target horizons for future utilization of deep geothermal reservoirs.



## 1. Introduction

In recent years the efficient use of energy resources and energy storage has gained great importance. For the future, increasing global energy demand strongly relies on renewable energy development that may reduce the dependence on fossil fuels and its related negative effects for the environment. Right now, Mexico is still mainly based on fossil-fuelled (hydrocarbons and coal, 68%) power plants, and more than one fifth (22%) on hydroelectric plants. Geothermal electric capacity represents 2% and wind only 0.1% [1]. The rest (1.9%) is represented by nuclear power plants. The solar potential for electricity is largely untapped, leaving room for great improvements in the future [2]. Furthermore, the development of so-called hybrid systems combining solar/wind, geothermal and biomass energy may be very promising in countries like Mexico but have not been implemented, yet.

According to the Global Energy Network Institute [3] Mexico has an estimated geothermal electricity potential of at least 8000 MWe, second in the world only to Indonesia. In reality, Mexico is not that far, yet, in harvesting this geothermal potential to the maximum. Nevertheless, with 980 MW [4] (887 MW according to the World Energy Council [5]), the country is ranked fourth in terms of global installed geothermal capacity (after the U.S. (3098 MW), the Philippines (1904 MW), and Indonesia (1197 MW); values according to Bertani [6]).

The currently four operating geothermal fields in Mexico are Cerro Prieto (a geothermally active area intersecting the southern end of the Imperial Fault and the northern end of the Cerro Prieto Fault in the Baja California), Las Tres Vírgenes (related to a complex of volcanoes located in the Mulegé Municipality in the Baja California Sur), Los Azufres, and Los Humeros. The project Cerritos Colorados, formerly known as La Primavera, has been scheduled for 2014 [7]. The three latter geothermal fields are all part of the Transmexican Volcanic Belt and are associated to large calderas [8], which could, in the future, be the source for a lot more energy for Mexico and also the U.S., considering that in 2012 already 1,285,959 MWh had been exported to the northern neighbour [9].

In Mexico, geothermal energy is almost entirely used to produce electricity. The direct use of Mexican geothermal energy is still under development and currently remains restricted to bathing and swimming facilities. The use of geothermal heat pumps is minimal, and underdeveloped with no information available [10]. Furthermore, to date, no useful information is available on the geothermal gradients of the Mexican deep sedimentary basins or graben settings, such as the Valley of Mexico [11–13], and its possible potential for a direct use of geothermal energy. Nevertheless, according to the geothermal map of North America [14], the

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area of the Valley of Mexico shows an intermediate terrestrial heat flow of 80–84 mW/m$^2$ in comparison to areas such as Cerro Prieto (~100 mW/m$^2$) [15] and Las Tres Vírgenes (117 mW/m$^2$) [16], located at thermal anomalies. Additionally, the heat flow values of Los Azufres (84 mW/m$^2$) [17] and Los Humeros (85 mW/m$^2$) [17], show that the values of the Valley of Mexico are within a useable range.

In addition to the direct use of the Mexican deep sedimentary basins for geothermal energy, they could be used to overcome another problem of renewable energy sources. One of the biggest problems holding back renewable energy is that energy sources such as wind and the sun, are not constant, and therefore do not allow a steady output. The best way of overcoming this problem is by developing energy storage systems that can store excess energy produced during times of high output, and release it again when it is needed during times of low output. Energy from both sources, wind and sun, can be stored in porous rocks deep underground for later use. Wind energy – which is often produced at night when winds are strong and energy demand is low – can be stored by compressed air energy storage (CAES) [18,19].

Underground thermal energy storage (UTES) [20–23] is a system that uses inter-seasonal heat storage, storing excess heat (e.g. from solar collectors) for use in winter heating, and the cooling potential from winter for cooling in summer [24]. UTES could contribute significantly to meeting society's need for heating and cooling and may be implemented in rocks or soil via a series of vertical borehole heat exchangers or in deep aquifers [25].

This paper deals specifically with the potential of the deep sedimentary basin which is the Valley of Mexico with regards to geothermal energy and possible energy storage and should be seen as an impulse for future research.

## 2. Geothermal energy from deep sedimentary basins

Using deep geothermal energy either involves natural hot water resources (hydrothermal plants) or the heat stored in the rock (petrothermal plants). Both can be used to supply heat (at temperatures above ca. 60 °C) and for power generation – usually at temperatures >100 °C [26], with >150 °C for dry steam power plants and >180 °C for flash steam power plants [27–29]. Nevertheless, especially in low-to-medium temperature (~60–170 °C), water-dominated geothermal fields, the binary-cycle method [28,30,31] has made considerable progress for electricity production [32–35]. Compared to other international terrestrial heat flow and temperature data of sedimentary basins where deep geothermal energy is already harvested, the potential of the Valley of Mexico is obvious. In Germany, for instance, areas such as the Molasse Basin in the South, the Upper Rhine Graben and the North German Basin are already used for geothermal energy. According to BINE [26], in the Molasse Basin, groundwater with temperatures of 70–140 °C at 800–4500 m depth (heat flow of 80 mW/m$^2$ [36] and very similar to the conditions in the Valley of Mexico) is already used to produce electricity. The same applies for the Upper Rhine Graben were temperatures of 135–160 °C are measured at depths of 2500–3300 m (heat flow of >100 mW/m$^2$) [36], and northern Germany with groundwater temperatures of 55–170 °C at depths of 1300–3800 m.

The geothermal energy that is already harvested in China is mostly exploited from sedimentary geothermal systems (e.g. North China and Wei River Basins) with low–medium temperature resources (groundwater temperatures of 40–120 °C at 1500–4100 m and heat flow values of 55–80 mW/m$^2$) [37–40]. This is because the population and economic activities are mainly distributed in the eastern part of China where low–medium resources are abundant, similar to the Valley of Mexico.

Finally, in Rumania and Hungary, where the geothermal potential is currently assessed [41], groundwater temperatures of 60–120 °C at 800–3500 m [42] (heat flow 37–83 mW/m$^2$ [43]), and 150–200 °C at a depth of 3000–4000 m [44] (heat flow 90–100 mW/m$^2$ [45]) are measured, respectively.

The Valley of Mexico contains most of the Mexico City Metropolitan Area, as well as parts of the State of Mexico, Hidalgo, Tlaxcala and Puebla, and can be subdivided into four sub-basins [46,47].

Below a 30 to >200 m thick cover of Quaternary to recent volcanic and lake deposits [11,48,49] that outcrop extensively on the plain, Neogene volcanic rocks intercalated with siliciclastic and volcaniclastic rocks attain a thickness of up to 4000 m [11,12,50] on top of the basement. These units are extensively fractured and crossed by fault (graben) systems that resulted from tensional regional forces [51]. They partially cover an excess thickness of 1000 m of limestone strata of Cretaceous age.

A reasonable amount of data is available only on the hydraulic properties of the Pliocene–Quaternary and Quaternary–Recent deposits. The properties of the deeper aquifer units, however, are not known [11]. However, several hundreds of litres of water per second that are continuously extracted from the Mid Tertiary volcanics for the dewatering of a mine [52] in a mine district in the northern part of the Basin of Mexico, i.e. in Pachuca (Hidalgo State), are evidence for an effective reservoir and aquifer [53]. Furthermore, Carrillo-Rivera et al. [54] interpreted the hydraulic conductivity of the deeper aquifer from shallow boreholes (~300 m depth) in the northern part of the catchment.

Due to the lack of detailed well logs and physical data of this area, a pilot study on the thermophysical rock properties of the Tepoztlán Formation was conducted in outcrops, following detailed studies on the geological history [53,55–58].

The aim of this study is to provide thermophysical rock properties of the different lithofacies types to be added as important attributes into 3D reservoir models, identifying target formations for geothermal reservoir utilization.

## 3. Geological setting

The Valley of Mexico refers to the lower part of the Basin of Mexico (Fig. 1) which is one of the largest of a series of closed catchments located in the Transmexican Volcanic Belt [59,60]. Groundwater recharge occurs in the volcanic rocks of the mountains that surround the valley to form the Basin of Mexico [61]. The groundwater temperature towards the west of Mexico City is 19 ± 1 °C and increases to a fairly uniform 23 ± 1 °C near the centre of the basin [11]. After an increase in groundwater extraction in the 1950's, the thermal water is tapped solely by boreholes with a distinct discharge temperature of 45 °C [12]. Direct temperature logging in a nearby borehole showed a temperature of 87 °C at a depth of 1800 m [62,63]. According to Huizar-Alvarez et al. [12], the observed temperature of the sampled water is in agreement with the natural geothermal gradient of ca. 3.16 °C/100 m as the closest active volcanic area is located ca. 40 km to the southeast. By means of a silica geothermometer, Fournier [64] calculated an equilibrium temperature of 163 °C in a depth of at least 2500 m (at an assumed geothermal gradient of 3.16 °C/100 m).

Seismic studies and deep wells (drilled by PEMEX, Petróleos Mexicanos) in the Basin of Mexico reaching 4000 m, give evidence that the volcaniclastic succession in the lower unit of the basin is correlative with the Miocene Tepoztlán Formation [65,66] (Fig. 2).

## 4. Materials and methods

This study is based on an integrated analysis of petrographical and petrophysical data from the Tepoztlán Formation. 125 core