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Assessment of high enthalpy geothermal resources and promising areas of Chile

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ABSTRACT

This work aims to assess geothermal power potential in identified high enthalpy geothermal areas in the Chilean Andes, based on reservoir temperature and volume. In addition, we present a set of highly favorable geothermal areas, but without enough data in order to quantify the resource. Information regarding geothermal systems was gathered and ranked to assess Indicated or Inferred resources, depending on the degree of confidence that a resource may exist as indicated by the geoscientific information available to review. Resources were estimated through the USGS Heat in Place method. A Monte Carlo approach is used to quantify variability in boundary conditions. Estimates of total Indicated resource are confined to 3 geothermal systems; Apacheta, El Tatio and Tolhuaca, yielding a total value of 228 ± 154 MWe. The estimates of the total Inferred resources for Chile include 6 geothermal systems and yield a total value of 431 ± 321 MWe. Standard deviation reflects the high variability of reservoir specific parameters for each system. A set of 65 favorable geothermal areas are proposed as the most likely future development targets. Eight of them have initial exploration results that suggest they are highly favorable targets as potential geothermal resources.

1. Introduction

Early geothermal exploration in Chile began in 1921, when an Italian technical group from Larderello drilled two wells of about 70–80 m depth at El Tatio geothermal field (Tocchi, 1923). Systematic exploration resumed in 1968 as a result of a joint project by the Chilean Development Corporation (Corporación de Fomento de la Producción, CORFO) and the United Nations Development Program (UNDP) (Lahsen, 1976). In addition, geothermal exploration was carried out by the Japan International Cooperation Agency (JICA) in Puchuldiza (Lahsen, 1978; JICA, 1979; Letelier, 1981) and Surire (Cusicanqui, 1979). Since then, basic exploration, drilling and feasibility studies have been conducted sporadically, mainly by Universidad de Chile (Lahsen, 1976, 1988), the National Geological Survey (Servicio Nacional de Geología y Minería, SERNAGEOMIN) (Hauser, 1997; Peréz, 1999), and the National Oil Company (Empresa Nacional del Petróleo, ENAP). By early 2000, a geothermal law was enacted providing the framework for the exploration and development of geothermal energy in Chile. Henceforth, comprehensive efforts to assess geothermal potential have been made by public entities and private companies (e.g. Lahsen et al., 2010 and references therein). During the first half of 2011, the Chilean Government founded the Andean Geothermal Center of Excellence (Centro de Excelencia en Geotermia de Los Andes, CEGA), a Fondap-Conicyt project hosted at the Universidad de Chile, aimed at improving geothermal knowledge and promoting its use in the Andean countries. This work is part of a nationwide geothermal evaluation carried on since then (e.g. Sánchez et al., 2011; Aravena and Lahsen, 2012, 2013).

Early resource assessments considered a gradient of 45 °C/km in the Chilean Plio-Quaternary volcanic belt, yielding 1.85×10^{22} J of thermal energy stored in water above 150 °C for depths less than 5 km (Aldrich et al., 1981). Later on, Lahsen (1986) calculated values on the order of 16,000 MWe for 50 years contained in fluids with a temperature over 150 °C, and at a depth less than 3 km. Updated estimates of the geothermal potential in northern Chile yield values between 400 and 1300 MWe (Procesi, 2014). In southern Chile

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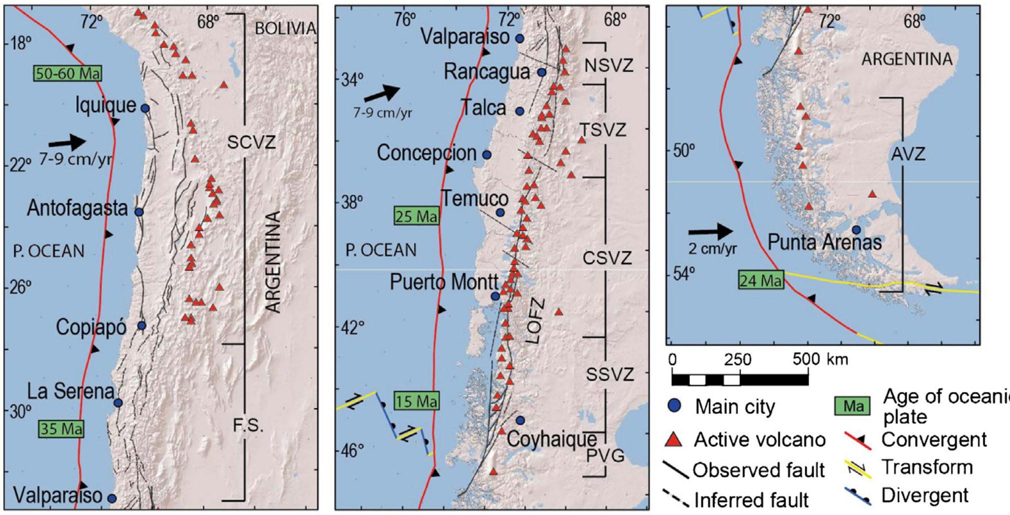

Fig. 1. Tectonic setting, regional scale faults and active volcanoes of the Chilean Andes. SCVZ, Southern Central Volcanic Zone; F.S., Flat Slab; NSVZ, Northernmost SVZ; TSVZ, Transitional SVZ; CSVZ, Central SVZ; SSVZ, Southern SVZ; PVG, Patagonian Volcanic Gap; AVZ, Austral Volcanic Zone. Main fault systems of the SCVZ modified from Cembrano et al. (2007). Flat Slab structures modified from SERNAGEOMIN (2003). Regional structures in the SVZ modified from SERNAGEOMIN (2003), Rosenau et al. (2006), Cembrano and Lara (2009), and references therein. Age of oceanic plate after Tebbens et al. (1997).

estimates vary between 600 and 1400 MWe (Lahsen et al., 2010; Aravena and Lahsen, 2012).

This work was initiated to provide a realistic estimate of accessible geothermal resources associated with high enthalpy (>200 °C) reservoirs in the Chilean Andes, with emphasis on geological, geophysical and geochemical evidence constraining each geothermal system. To do this, we gathered and ranked published information regarding available geothermal exploration and Quaternary volcanic features to establish a hierarchy of Measured, Indicated and Inferred geothermal resources. To assess the geothermal resources of Chile, the USGS Heat in Place method is applied. Although this study does not produce absolute values of power potential, it does provide a systematic manner with which to compare prospects based on the available/published information. In addition, we present a set of areas with a favorable geothermal setting whose published information is still considered deficient.

2. Volcanic and geothermal setting

The Andean volcanic arc includes over 200 potentially active volcanoes, and at least 12 giant caldera/ignimbrite systems (Lee et al., 2010), occurring in four separate segments referred to as the Northern (NVZ; 2°N – 5 °S), Central (CVZ; 14–28 °S), Southern (SVZ; 33–46 °S), and Austral (AVZ; 49–55 °S) Volcanic Zones (Fig. 1). Volcanism results from subduction of the Nazca and Antarctic oceanic plates below South America (Muñoz and Stern, 1988; Cembrano et al., 2007). The country contains more than 300 geothermal areas located along the Chilean Andes, associated with Quaternary volcanism. The main geothermal systems occur in the extreme northern (17–28 °S) and central-southern part (33–46 °S) of Chile. In areas where Quaternary volcanism is absent, such as along the Andean volcanic gaps (28–33 °S and 46–48 °S), as well as in the Coastal Range, thermal springs are scarce and their temperatures are usually lower than 30 °C (Lahsen et al., 2010). The Andean volcanic arc still represents one of the largest undeveloped geothermal provinces of the world. There are currently 3 geothermal systems in the country with available measured wellhead resource values: (i) Apacheta (2 wells, 9 MWe); (ii) El Tatio (4 wells, 23 MWe); and (iii) Tolhuaca (1 well, 13 MWe). These wells yield a total confirmed power potential of 45 MWe.

3. Methodology

3.1. Selection and ranking of geothermal areas

A major challenge in geothermal resource assessment lies in quantifying the size and thermal energy of a reservoir. This work follows other Heat in Place geothermal resource studies in using the terminology adopted by Muffler et al. (1978) for the subdivision of the geothermal resource base. Geothermal resources are subdivided according to increasing geological confidence into Inferred, Indicated, and Measured categories. Areas where reservoir features have been constrained indirectly by geophysics (dimensions) and fluid geochemistry (reservoir temperature), but whose reservoir has not been reached by wells are ranked as Inferred. Areas where the reservoir has been confirmed by exploratory wells are ranked as Indicated. If the geothermal play has wells with a proven deliverability, it is ranked as Measured.

Through the analysis of geological, geochemical and geophysical data, and using a GIS weighted overlay superposition method, Aravena and Lahsen (2013) generated a nationwide map of geothermal favorability. This map, along with data gathered in this work, was used to establish two additional categories of geothermal plays: (i) highly probable resource areas for regions where geophysical surveys indicate the existence of a geothermal reservoir or fluid geothermometry suggest high temperatures associated with a deep reservoir; and (ii) interest areas for regions with extensive surface geothermal features and high temperature discharges. Interest areas include zones with discharges of lower temperature, yet whose context has a research concern, such as an unknown heat source in areas with no active volcanism (Fig. 2). Most of these areas lack available data needed to properly quantify the resource.

3.2. USGS Heat in Place method for reservoir constrained assessment

To assess the geothermal resources of Chile, a reformulation of the USGS Heat in Place method is applied (Garg and Combs, 2015). This model involves estimating the thermal energy available in a liquid-dominated reservoir to calculate recoverable electric power (Williams et al., 2008 and references therein). A Monte Carlo approach is used to quantify variability of boundary conditions.