A Geothermal Favorability Map of Chile, Preliminary Results

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ABSTRACT

The Andean volcanic arc includes over 200 active stratovolcanoes and at least 12 giant caldera systems. The tectonic context of this volcanic arc favors the occurrence of volcanic associated geothermal systems, due to the presence of shallow magmatic chambers and active structures that allows the development of geothermal systems in the upper crust.

In order to identify areas with a high probability of geothermal system development, and using a GIS based superposition method, a geothermal favorability map was created. This favorability map involves using geological, geophysical and geochemical data. The map is then analyzed in the light of known geothermal systems in the region.

Introduction

Geothermal exploration in Chile is currently very active and is driven by the need for energy security and stability. The country contains more than 300 geothermal areas located along the Chilean Andes and associated with Quaternary volcanism. The main geothermal areas lie in the extreme north (17°-28°S) and central-southern part (33°-46°S).In areas where Quaternary volcanism is absent, such as along the volcanic gaps of the Andean Cordillera (28°-33° 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).

Preliminary assessment of the geothermal potential of the north and central-southern volcanic-geothermal zones gives a value on the order of 16,000 MW for at least 50 years from geothermal fluids with temperatures exceeding 150°C, and located at a depth of less than 3,000 m (Lahsen A., 1986). Slim holes have been drilled Tinguiririca, Calabozos, Laguna del Maule, Chillán, Tolhuaca, Sierra Nevada and Puyehue Cordón Caulle. Preliminary estimates of the potential for power generation from these areas vary between 600 MWe and 950 MWe. (Lahsen et al. 2010).

Nevertheless, there is currently not a long term plan to identify and characterize geothermal prospects and, even tough, the Andean volcanic arc represents one the largest yet undeveloped geothermal provinces in the world. This work focus on the first part of an ongoing project, aiming to develop a national geothermal resource assessment.

Geologic Framework

The Andean volcanic arc includes over 200 potentially active Quaternary volcanoes, and at least 12 giant caldera/ignimbrite systems, occurring in four separate segments referred to as the

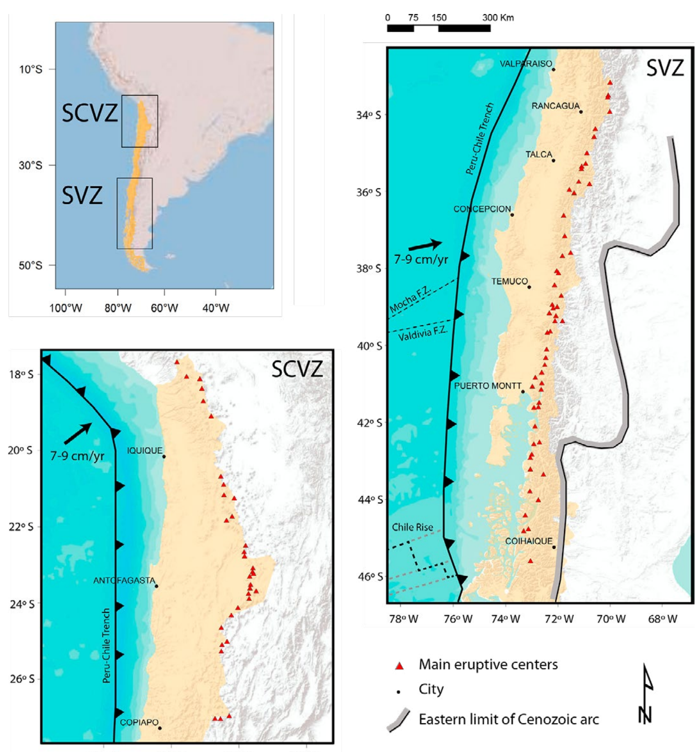

Figure 1. Location of main eruptive centers and tectonic context for the Southern Central Volcanic Zone (SCVZ) and Southern Volcanic Zone (SVZ). Modified from Stern, 2004; Charrier et al, 2007.

Northern (ZVN; 2ºN-5ºS), Central (ZVC; 14-28ºS), Southern (ZVS; 33-46ºS) and Austral (ZVA; 49-55ºS) Volcanic Zones. The volcanic activity is related to subduction of the Nazca and Antarctic oceanic plates below South America (Stern, 2004).

Below the Southern Central Volcanic Zone (SCVZ) the <60 Ma Nazca plate lithosphere is being subducted at 7-9 cm/yr, in an orthogonal angle with the trench direction. The volcanic front is located in the western Cordillera Occidental, 120 km above the subducted slab and 240-300 km east of the trench, which reaches a maximum depth of 8,055 m below sea level at 23°S (Stern, 2004). Basement ages range from as old as ~2000 Ma below northernmost Chile and Bolivia, to late Precambrian and Paleozoic below the southern part of this segment in northern Chile and Argentina. The active volcanoes in the CVZ overlie volcanic rocks of Late Oligocene to Quaternary age, including large ignimbrite sheets, stratovolcanoes and caldera systems (De Silva, 1989; Charrier et al, 2007). This zone (Figure 1; SCVZ) contains about 90 thermal areas, and there has been exploration of at least 6 geothermal prospects, all done by geothermal and copper mining related companies.

The SVZ includes, at least, 60 historically and potentially active volcanic edifices in Chile and Argentina In contrast to the CVZ, the calderas in the SVZ have all formed in the last <1.1 Ma (Stern, 2004). Quaternary volcanism in Central-South Chile is restricted to the Andean Cordillera. This volcanic activity has given rise to stratovolcanoes, pyroclastic cones and calderas, with associated lavas and pyroclastic flows. Lahar`s flows from these volcanoes usually cover extensive areas of the Central Depression. From 33° to 34°S, most of the thermal areas are associated with the Pocuro fault system, where upper Cretaceous and Tertiary volcaniclastic rocks are dominant (Hauser, 1997). Between 39° and 46°S, the geothermal activity is partially controlled by the 1,000 km long, NNE Liquiñe-Ofqui Fault Zone (LOFZ; Hervé 1984), an intra-arc dextral strike-slip fault system (Cembrano et al., 2000). There are more than 200 geothermal areas, where sulphate, bicarbonate and chloride waters are found. In this zone, 6 geothermal prospect have been explored by ENG, the University of Chile and private companies (Lahsen et al, 2010).

Favorability Model

The favorability model method involves using geological, geophysical, and geochemical data to identify areas that are likely to have geothermal potential. Favorable and unfavorable geothermal terrains were defined using a weighted overlay superposition model and a multi-class favorability ranking (Table 1), presenting 5 separate layers of evidence; young volcanic rocks, proximity to eruptive centers, young fault density, proximity to hot springs and upper crust earthquake density.

These 5 evidence layers were chosen because they can be easily shaped into evidence maps in raster format and they can be obtained from public available sources. Several studies support the association of the evidence layers with the presence of geothermal systems (e.g.,Koenig, 1983; Hanano, 2000; Blewitt et al., 2003; Julian, 2004; Coolbaugh et al., 2006; Noorollahi et al., 2007; Kratt, et al., 2010). These studies were used to assign a set of suitability and weighting factors for each layer (Table 1).

Table 1. Multi-class favorability ranking for the five separate layers of evidence.

Data	%	Layer	%	Class	Value
Geological	60	Volcanic Rocks	40	Absent	1
				Mixed	5
				Present	9
		Fault Density (m/Km2)	20	< 35	1
				35–100	5
				> 100	9
		Proximity to Volcano (Km)	40	> 15	1
				7–15	5
				< 7	9
Geochemical	30	Proximity to hot springs (Km)	40	> 10	1
				5–10	5
				< 5	9
Geophysical	10	Earthquake Density (Eq./Km2)	100	< 0,002	1
				0,002–0,02	5
				> 0,02	9

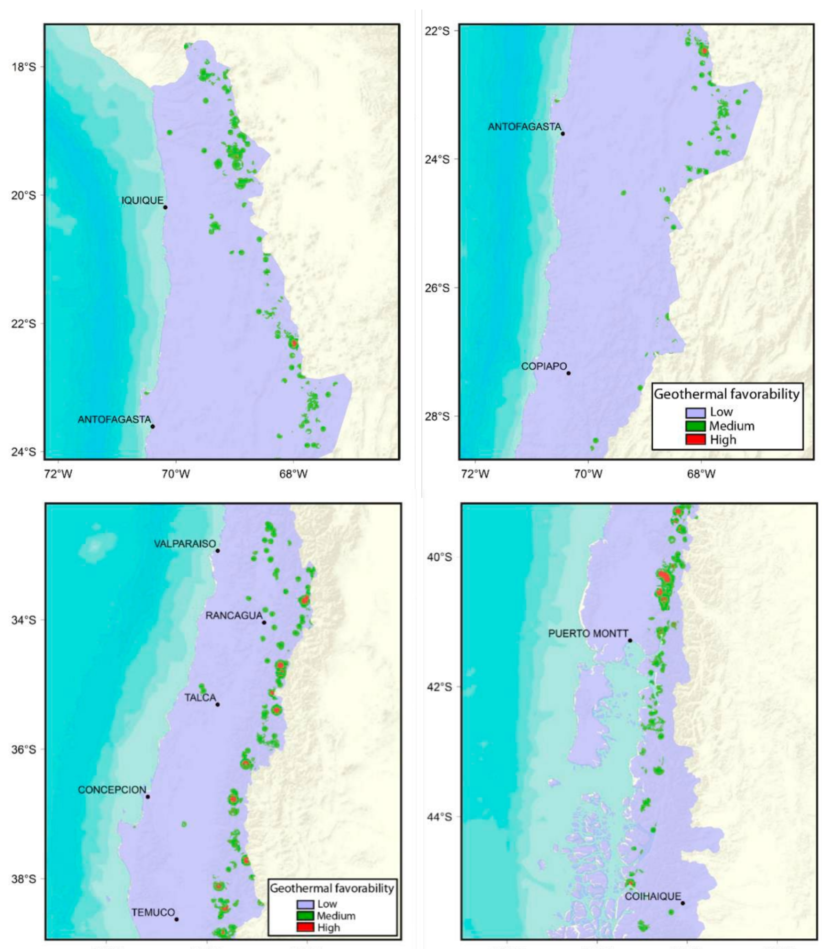

Figure 2. Geothermal favorability map for the SCVZ (upper) and SVZ (lower).

The favorability model was developed using the raster calculator tool within Arc Map. This tool reclassifies the pixel values in the input rasters onto a common evaluation scale of suitability. Then each input rasteris weighted according to its importance and added to produce the output raster. The weight is expressed as a relative percentage, and the sum of the percent influence weights must be equal to 100% (Noorollahi et al., 2007). Finally, we classified the study area into different levels of favorability based on exploration data and the final value obtained for each pixel.

Results

Through the analysis of geological, geochemical and geophysical evidence, and using the weighted overlay superposition method, it was possible to generate a map of geothermal favorability in the study area (Fig. 2).

As expected, there is a clear correlation with eruptive centers, showing areas of high and medium geothermal favorability following the volcanic arc trend. Naturally, approximately 0.2% of the country would be classified as highly favorable, 3.2% as moderately favorable and the remaining 96% as unfavorable.

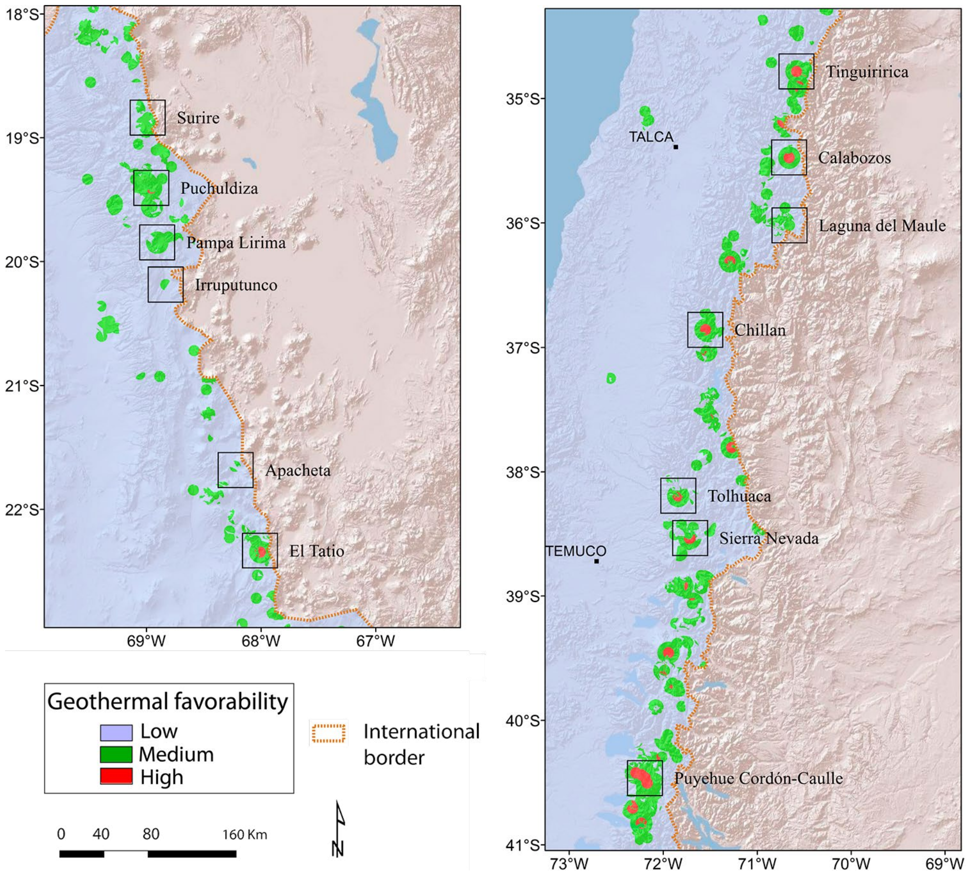

Figure 3. Geothermal favorability map and explored geothermal areas in the SCVZ & SVZ.

Discussion

Figure 3 shows the geothermal favorability map for the SCVZ and SVZ, compared with a number of explored geothermal systems. The areas where exploration programmes were carried out in the SCVZ are; Surire, Puchuldiza, Lirima, Apacheta and El Tatio. At the Apacheta and El Tatio geothermal areas, 4 holes have been drilled up to depth of 1,700 meters. Preliminary estimates of potential of these areas is between 400 MWe to 1,000 MWe, and preliminary results of the drilled holes indicate a potential of 5-10 MW per well (Lahsen et al, 2010). In the SVZ, 7 geothermal prospect have been explored by ENG, the University of Chile and private companies (Lahsen et al, 2010), they are; Tinguiririca, Calabozos, Laguna del Maule, Chillán, Tolhuaca, Sierra Nevada and Puyehue-Cordón Caulle; while exploration slim holes have been drilled at Calabozos, Laguna del Maule, Chillán and Tolhuaca, with a potential estimated of 3-10 MW per well. Preliminary estimates of the potential for power generation from these areas vary between 600 MWe and 950 MWe (Lahsen et al; 2010).

The favorable zones indicated in figure 3 show a strong correlation with the distribution of existing geothermal wells and known high-temperature fields. As is illustrated in the map, 8 out of the 13 areas are located within or adjacent the first priority area (most favorable), with the remaining 5 areas located in the second priority area, and none located in the third priority area. Other parts of the country show a scarce amount of territory associated with medium and high favorability systems. Mainly associated with the low number of hot springs that have been explored in this areas, and it is considered that a more detailed sampling of these sectors could increase the degree of favorability associated with these areas.

The results demonstrate that the vast majority of wells and explored geothermal areas are located within the first priority area. The model developed in this study shows that there are numerous other areas that have a high potential for geothermal development. The resulting map is a powerful tool that will allow a better understanding and territory planning for geothermal development.

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