Assessment of High Enthalpy Geothermal Resources and Promising Areas of Chile

Diego Aravena^{a,b,*}, Mauricio Muñoz^{a,b}, Diego Morata^{a,b}, Alfredo Lahsen^{a,b}, Miguel Ángel Parada^{a,b}, Patrick Dobson^c

^a*Centro de Excelencia en Geotermia de los Andes (CEGA), Facultad de Ciencias Físicas y Matemáticas, Universidad de Chile, Santiago, Chile.*

^b*Departamento de Geología, Facultad de Ciencias Físicas y Matemáticas, Universidad de Chile, Santiago, Chile.*

^c*Earth Sciences Division, Lawrence Berkeley National Laboratory, Berkeley, California, USA.*

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

*Corresponding author

Email addresses: daravena@ing.uchile.cl (Diego Aravena), maumunoz@ing.uchile.cl (Mauricio Muñoz)

potential geothermal resources.

Keywords: Geothermal power potential, high enthalpy, Chilean Andes, USGS Heat in Place, Monte Carlo.

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; Pérez, 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 Universidad de Chile, aimed to improve geothermal knowledge and promote 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 & 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 1,300 MWe (Procesi, 2014). In southern Chile estimates vary between 600 and 1,400 MWe (Lahsen et al., 2010; Aravena & 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 establishing 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; $2^{\circ}\text{N} - 5^{\circ}\text{S}$), Central (CVZ; $14 - 28^{\circ}\text{S}$), Southern (SVZ; $33 - 46^{\circ}\text{S}$), and Austral (AVZ; $49 - 55^{\circ}\text{S}$) Volcanic Zones (Fig. 1). Volcanism results from subduction of the Nazca and Antarctic oceanic plates below South America (Muñoz & 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 ($17 - 28^{\circ}\text{S}$) and central-southern part ($33 - 46^{\circ}\text{S}$) of Chile. In areas where Quaternary volcanism is absent, such as along the Andean volcanic gaps ($28 - 33^{\circ}\text{S}$ and $46 - 48^{\circ}\text{S}$), 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.

Figure 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 & Lara (2009), and references therein. Age of oceanic plate after Tebbens et al. (1997).

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 byMuffler

68 & Cataldi (1978) for the subdivision of the geothermal resource base. Geother-
69 mal resources are subdivided according to increasing geological confidence into
70 Inferred, Indicated, and Measured categories. Areas where reservoir features
71 have been constrained indirectly by geophysics (dimensions) and fluid geochem-
72 istry (reservoir temperature), but whose reservoir has not been reached by wells
73 are ranked as Inferred. Areas where the reservoir has been confirmed by ex-
74 ploratory wells are ranked as Indicated. If the geothermal play has wells with a
75 proven deliverability, it is ranked as Measured.

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

88 *3.2. USGS Heat in Place method for reservoir constrained assessment*

89 To assess the geothermal resources of Chile, a reformulation of the USGS
90 Heat in Place method is applied (Garg & Combs, 2015). This model involves
91 estimating the thermal energy available in a liquid dominated reservoir to cal-
92 culate recoverable electric power (Williams et al., 2008, and references therein).
93 A Monte Carlo approach is used to quantify variability of boundary conditions.
94 After 100,000 iterations, the resulting power output is fitted to a probability
95 distribution to assess the 10%, 50% and 90% confidence intervals, referred to as
96 P90, P50 and P10, respectively. Fig. 3 shows the fit of results to a Birnbaum-
97 Saunders distribution for the Tolhuaca geothermal system.

Figure 2: Main geothermal areas in Chile. Indicated and Inferred resources are displayed with name and assessment results. Highly probable and interest areas are depicted in Table 3 and 4, respectively. Regional structures as in Fig. 1.

98 The USGS Heat in Place volumetric method was used in early geothermal
99 resource estimations in the 1970's (Nathenson, 1975; White & Williams, 1975;
100 Muffler & Cataldi, 1978; Muffler, 1979), and later improved based on updated
101 empirical factors, and specific power cycles (e.g. Lovekin, 2004; Williams et al.,
102 2008; Zarrouk & Moon, 2014; Garg & Combs, 2015). This method states that
103 the electric power potential for an identified geothermal system can be deter-
104 mined by the reservoir thermal energy, the amount of thermal energy that can
105 be extracted from the reservoir at the wellhead, the specific power cycle, and
106 the efficiency for the electric power conversion of the wellhead thermal energy
107 (Garg & Combs, 2015, and references therein). Once mass flux and its thermal
108 properties at the wellhead are determined, the thermodynamic and economic

Figure 3: Results after 100,000 Monte-Carlo iterations for the Tolhuaca geothermal System. Left, power output results (bins) and fit (red line) to a Birnbaum-Saunders probability distribution function (PDF); right, cumulative distribution function (CDF) showing P10, P50 and P90 intervals of confidence.

constraints for conversion to electric power can be calculated (e.g. DiPippo, 2012b; Zarrouk & Moon, 2014).

The reservoir thermal energy, q_R [J], is calculated as follows:

$$q_R = \bar{\rho c} V (T_R - T_r) \quad (1)$$

Here, $\bar{\rho c}$ is the volumetric heat capacity in the reservoir [$\text{J}/\text{m}^3\text{K}$], V is the reservoir volume [m^3], T_R is the reservoir temperature, and T_r is a reference or abandonment temperature (Garg & Combs, 2015). Regarding the reservoirs temperatures, we assessed single flash cycles, for all geothermal plays. Therefore, for a single flash power plant, the abandonment temperature is given by the saturation temperature corresponding to the separator pressure (5 bar, 151.831 °C). The geothermal recovery factor R_g is defined as the ratio of the heat recovered at the wellhead q_w , to the heat stored in the reservoir q_R .

$$R_g = \frac{q_w}{q_R} \quad (2)$$

In the above equation R_g is the geothermal recovery factor [dimensionless]. Updated values of the geothermal recovery factors include 0 to 0.2, the latter value is believed to be the maximum reliable value based on global experience

123 with production from liquid dominated reservoirs (Garg & Combs, 2010). If
 124 the well drilling and testing has shown adequate well productivity, it is justified
 125 to assume a non-zero minimum value (say 0.05) for the geothermal recovery
 126 factor (Garg & Combs, 2015). In addition, we carry out a sensitivity test for
 127 the power output as a function of the geothermal recovery factor, encompassing
 128 values from the published literature.

129 Combining Eqs. (1) and (2), the heat recovered at the wellhead q_w , can be
 130 expressed by the following expression:

$$q_w = \alpha(T_R - T_r) \quad (3)$$

131 Here:

$$\alpha = R_g V \overline{\rho c} \quad (4)$$

132 Assuming isenthalpic flow in the wellbore and neglecting the work required
 133 to raise the water, the enthalpy of produced fluid at the well head h_w , is equal
 134 to that of liquid water at reservoir temperature.

$$h_w = h_w(T_R) \quad (5)$$

135 The amount of fluid produced at the wellhead m_w , is given by:

$$m_w = \frac{q_w}{(h_w - h_r)} \quad (6)$$

136 Here, h_r is the enthalpy of liquid water at the reference temperature T_r .
 137 Substituting from Eq. (3) into Eq. (6), there follows:

$$m_w = \alpha \frac{(T_R - T_r)}{(h_w - h_r)} \quad (7)$$

138 Neglecting kinetic or potential effects, the maximum energy output per unit
 139 mass of the substance e is given by (DiPippo, 2008):

$$e = h - h_{ex} - T_{ex}K(s - s_{ex}) \quad (8)$$

Here, h and s denote the enthalpy and entropy of the substance (*e.g.*, steam) at turbine inlet conditions with temperature T , T_{exK} is the absolute exit temperature (Kelvin), and s_{ex} is the entropy of the liquid phase (water), at the exit temperature. For mass m of substance the available work is therefore given by:

$$W_A = me = m(h - h_{ex} - T_{exK}(s - s_{ex})) \quad (9)$$

In the case of single flash power plant, it is assumed that the produced fluid with reservoir temperature at the wellhead is separated at the separator temperature T_{sep} . The separated brine is reinjected into the reservoir, and the steam is used to generate power. The mass of the fluid produced at the wellhead is given by Eq. 7 with $T_r = T_{sep}$. The steam fraction of the produced fluid is:

$$m_{stm} = m_w \frac{(h_w(T_R) - h_w(T_{sep}))}{h_{gl}(T_{sep})} \quad (10)$$

Here, $h_{gl}(T_{sep})$ denotes the heat of vaporization. Combining Eqs. 7 and 10, there follows:

$$m_{stm} = \alpha \frac{(T_R - T_{sep})}{h_{gl}(T_{sep})} \quad (11)$$

Substituting m_{stm} for m in Eq. 9, the available work for the single slash case is given by:

$$W_{Aflash} = \alpha \frac{(T_R - T_{sep})}{h_{gl}(T_{sep})} (h_{stm}(T_{sep}) - h_w(T_c) - T_{cK}(s_{stm}(T_{sep}) - s_w(T_c))) \quad (12)$$

In the above equation, T_c denotes the condenser temperature (assumed to be 40 °C; (Garg & Combs, 2015)), and T_{cK} is the absolute condenser temperature.

A conservative value for the electrical conversion efficiency η_u of 70% to 80% is proposed by Garg & Combs (2015), thus we used 75% for calculations. In addition, a load factor f_{load} of 0.95 is considered. Therefore, the electric power for a given period of years is determined as follows:

$$W_e = \frac{W_{Aflash} \eta_u}{Y f_{load}} \quad (13)$$

159 Finally, for calculation simplicity, the years (Y) in Eq. 13 are expressed in
160 seconds [s].

161 4. Results

162 4.1. *Inferred and Indicated resources*

163 4.1.1. *Boundary conditions*

164 Parameters required for the calculation are summarized in Tab. 1. Reservoir
165 specific parameters must be established individually for each geothermal system
166 since they constrain the geometry and temperature/enthalpy of the Indicated
167 or Inferred reservoir. Common parameters remain constant for all systems. For
168 instance, for the Tolhuaca geothermal prospect, reservoir specific parameters
169 were extracted from the geological setting and geothermal surveys performed in
170 the area (Tab. 1).

171 Variability in the estimates is accommodated through a Monte Carlo sim-
172 ulation approach. For each system, we determine most likely (m.l.), minimum
173 (min) and maximum (max) values for reservoir temperature, thickness, and
174 area. Those values are used to generate triangular (min, m.l. and max) and
175 uniform (min, max) probability distributions. Parameters with only a most
176 likely value (m.l.) remain constant for each Monte Carlo iteration (Tab. 1).

177 4.1.2. *Geological, geochemical and geophysical constraints*

178 We considered 9 geothermal prospects that have enough information to esti-
179 mate their power potential. The first three systems presented below are ranked
180 as Indicated (Apacheta, El Tatio and Tolhuaca). The remaining 6 systems are
181 ranked as Inferred (Puchuldiza, La Torta, Tinguiririca, Mariposa, Nevados de
182 Chillán, and Cordon Caulle). El Tatio/La Torta is considered as two separated
183 systems even though they probably share a deep reservoir (see details in text).

184 Apacheta/Cerro Pabellón geothermal system

185 The Cerro Pabellón geothermal power generation project, located in the
186 Apacheta geothermal concession in Antofagasta region, Chile, is owned by a

Reservoir specific parameters	min	m.l.	max
Area (km^2)	4	-	8
Thickness (km)	1	-	1.4
Temperature ($^{\circ}C$)	250	280	300
USGS Heat in Place parameters			
Volumetric Heat Capacity (kJ/m^3K)	-	2700	-
Abandonment Temperature ($^{\circ}C$)	-	151.831	-
¹ Geothermal Recovery Factor (%)	0	-	20
Condenser Temperature ($^{\circ}C$)	-	40	-
Electric Conversion Efficiency (%)	-	75	-
Plant Load Factor (%)	-	95	-
Plant or Project Life (years)	-	30	-

Table 1: Parameters required for the calculation of the electric generation capacity using the USGS volumetric Heat in Place method for the Tolhuaca geothermal system. Constraints are shown as Minimum (min), most likely (m.l.) and maximum (max) values for reservoir specific and common parameters. ¹In case well drilling and testing, that confirm geothermal resource, the minimum value of geothermal recovery factor is 5%.

joint project between Enel Latin-American (Chile) Ltd., and the National Oil Company (ENAP). The project, already approved by the environmental authorities and currently under development, involves the construction and operation of a geothermal power plant with installed capacity of 48 MWe (ENEL, 2012). This graben-hosted system has four deep wells, placing it into the Indicated Resource category. The thickness of the reservoir is constrained by the convective regime in wells CPE-1 (880 m) and CPE-2 (1120 m), starting at 900 and 820 m depth, respectively. Wells CPE-4 and CPE-3 show a conductive regime (ENEL, 2012). Horizontal extension of the reservoir will be assessed as parallel and perpendicular to the graben, following the conceptual model proposed by Urzua et al. (2002), Fig. 4. The minimum horizontal extension of the reservoir is given by the distance between wells ($4 km^2$). Maximum extension in the NE-SW orientation is given by the projected distance between the graben main

faults at the depth of the reservoir. In the NW-SE direction, maximum extension will be considered as the linear projection of thickness vs distance for wells CPE-1 and CPE-2 ($\sim 5 \times 5 \text{ km}^2$). Minimum and maximum temperatures of the reservoir are reached in wells CPE-2 (212°C) and CPE-1 (256°C), consistent with gas geothermometry estimates of around 250°C reported by Urzua et al. (2002).

El Tatio/La Torta geothermal system

The El Tatio geothermal prospect is one of the largest geothermal fields of South America (Fig. 5). This geothermal system comprises 85 fumaroles, 62 hot springs, 40 geysers, 5 mud volcanoes and extensive sinter terraces, scattered over an area of 30 km^2 (Tassi et al., 2005). The La Torta geothermal field is located at the southern extension of the eastern edge of the El Tatio graben. Geophysical evidence suggests that El Tatio and La Torta share the same deep reservoir. According to the interpreted resistivity structure, the El Tatio geothermal system must be at the edge (out-flow) of the main geothermal reservoir located in the La Torta prospect, which contains the main up-flow zone (Cumming et al., 2002). We use a conservative approach, assessing the areas as separate reservoirs with different constraints and resource categories.

The geometry of the El Tatio reservoir is constrained by exploratory and exploitation wells, and therefore qualifies as an Indicated system. The minimum and maximum reservoir thickness is 150 m and 600 m, respectively, as constrained by well data (Lahsen & Trujillo, 1976; Sarmiento et al., 2010). The average thickness of the Puripicar and Río Salado ignimbrite is 430 m, considered as the most likely value (Lahsen & Trujillo, 1976). The minimum resource area is constrained by wells where convective heat transfer zones are observed 11.5 km^2 , and the maximum areal extent is constrained by early geophysical surveys, where 30 km^2 was estimated through vertical electrical sounding interpretation (Lahsen & Trujillo, 1976). A minimum temperature of 213°C was measured in well 8 and the maximum temperature of 260°C was encountered in well 7 (Lahsen & Trujillo, 1976); these values are selected as the minimum and maximum reservoir temperatures, respectively. A most likely value of 250°C

Figure 4: Geological map of the Apacheta area. Geology modified from Ramírez & Huete (1981). Bottom; schematic cross section with geothermal features and well location. Projected faults, MT and temperature interpretation modified from Urzua et al. (2002).

231 was selected for calculations.

232 The main reservoir at the La Torta prospect was constrained by geochem-
233 ical and geophysical evidence. Cumming et al. (2002) delineates a 20km^2 low
234 resistivity anomaly ($<10\ \Omega\text{m}$) under the El Tatio volcanic chain. This value
235 will be considered as the most likely, with a variability of $5\ \text{km}^2$, therefore a
236 minimum areal extent of $15\ \text{km}^2$ and a maximum of $25\ \text{km}^2$ were considered.
237 Minimum thickness is 650 m, based on well data (Sarmiento et al., 2010). Max-
238 imum thickness can reach 2,000 m based on stratigraphic data and MT survey
239 results (Cumming et al., 2002). The minimum temperature is $240\ ^\circ\text{C}$, based
240 on temperatures reached by wells located on the southern edge of the El Tatio
241 prospect. The maximum temperature is constrained by gas geothermometry
242 wch suggests that the temperatures in the El Tatio-La Torta deep geothermal
243 reservoir reaches up to $270\ ^\circ\text{C}$ (Tassi et al., 2010).

244 **Tolhuaca geothermal system**

245 The Tolhuaca geothermal system was confirmed by a flow test of one of
246 the deep wells, and thus can be considered as an Indicated resource. As pro-
247 posed by Melosh et al. (2012), we consider a two level reservoir with steam and
248 steam-heated waters at shallow depths, and a deep liquid reservoir below. For
249 simplicity, they will be treated as individual reservoirs in closed systems. Be-
250 tween 200 and 600 m depth, temperatures in Tol-2 are above the hydrostatic
251 $1.1\ \text{wt}\%$ gas boiling point for depth (BPD) curve, suggesting steam-dominated
252 conditions nearby; similar conditions were encountered in Tol-1 between 200
253 and 400 m depth, consistent with a convective thermal regime (Melosh et al.,
254 2012). Most wells reach $150\text{-}200\ ^\circ\text{C}$ at 500 m depth (considered as min. and
255 max. respectively). The results for the shallow reservoir show power produc-
256 tion values of less than 1 MWe, and therefore are not considered as commercial
257 when compared to the deep reservoir. The deep well, Tol-3, encountered a
258 liquid-dominated reservoir from 1,100 to 2,500 m depth at $300\ ^\circ\text{C}$, consistent
259 with the high temperature propylitic alteration zone ($> 250\ ^\circ\text{C}$) observed in
260 the other wells (Iriarte, 2013, Fig. 6). These values will be used as the max-
261 imum thickness and temperature respectively. Minimum horizontal extent of

Figure 5: Geological map of El Tatio area. Borehole data from Lahsen & Trujillo (1976); Sarmiento et al. (2010). Bottom; geological cross section with geothermal features and well location.

262 the reservoir is constrained by a low resistivity conductive anomaly associated
263 with a 7-8 km^2 clay cap, identified by Melosh et al. (2012).

264 **Puchuldiza geothermal system**

265 The Puchuldiza geothermal prospect is characterized by extensive superficial
266 geothermal features such as thermal springs, fumaroles and mineral alteration
267 (Tassi et al., 2010). The minimum areal extent is 10 km^2 which is delineated by
268 shallow exploratory wells (< 600 m deep, reaching $170^\circ C$). Vertical electrical
269 soundings indicate a potential maximum areal extent of 28 km^2 (JICA, 1979;
270 Lahsen et al., 2010). Geological and geophysical surveys indicate a reservoir
271 thickness range between 600–1000 m (Ortiz et al., 2008, and references therein).
272 A minimum reservoir temperature of $200^\circ C$ was measured in a 1000 m deep
273 exploratory well, whereas the most likely and maximum reservoir temperature is
274 expected to reach $250^\circ C$ and $270^\circ C$, respectively, based on Na-K and Na-K-Ca
275 geothermometry (Ortiz et al., 2008).

276 **Tinguiririca geothermal system**

277 The tinguiririca geothermal project is located ~ 150 km SW from Santiago
278 within the main Andean Range, on the western flank of the Tinguiririca Volcanic
279 Complex. The Tinguiririca reservoir volume is constrained by the potential up-
280 flow zone identified by Clavero et al. (2011), a subtle concave shaped conductive
281 anomaly at 2,500 m.a.s.l interpreted by Lira (2011) as a deep geothermal reser-
282 voir, although this preliminary conclusion is subject to further exploration. This
283 surface covers between 5 and 25 km^2 ; the minimum and maximum thickness
284 of the reservoir are 500 m and 1,000 m, respectively, accounting for the dis-
285 tance between the 10-75 and 10-120 (Ωm) intervals respectively ($< 10 \Omega m$ is
286 interpreted to be a low resistivity clay altered cap). The lower temperature of
287 the reservoir is given by the temperature reached in well Pte-1, $210^\circ C$. The
288 maximum temperature is estimated to be $300^\circ C$, based on geothermometry by
289 Clavero et al. (2011); Vázquez et al. (2014).

290 **Mariposa geothermal system**

291 The Mariposa Geothermal System (MGS) is located ~ 300 km south of San-
292 tiago in the TSVZ. It lies within an area characterized by extensive Quaternary

Figure 6: Geological map of Tolhuaca area (modified from Emparán et al., 1997; SERNA-GEOMIN, 2003; Rojas et al., 2014) including, quaternary volcanic vents (modified from Moreno & Gardeweg, 1989) and main structures (Rosenau et al., 2006; Pérez et al., and references within); Geographic coordinates WGS84, zone 19 °S. Bottom; Schematic cross section with geothermal features, wells and temperature interpretation after Iriarte (2013). LOFZ, Lique Ofqui Fault Zone.

volcanism associated with the Maule Volcanic Complex and the Tatara-San Pedro-Pellado volcanic complex. A volumetric resource assessment performed by SKM yielded 320 MWe for a plant life of 30 years. In this assessment, the reservoir area was constrained by a 23 to 27 km^2 conductive anomaly obtained during the 2009 and 2010 MT surveys (Hickson et al., 2011). In this case we consider a minimum value of 9 km^2 , accounting for the two principal upflow areas inferred by Hickson et al. (2011), this value can be extended to a less conservative 23 km^2 as interpreted from data presented by Hickson et al. (2011). Reservoir thickness is taken from the base of the conductor (600-1,000 m depth) to a depth that can be readily accessed by drilling, and up to the thickness of the Oligocene-Miocene units that host the reservoir, yielding values ranging from 1 to 2 km thick. The minimum reservoir temperature is constrained by the well MP-1 (210 °C), maximum temperature (300 °C) is based on gas geothermometry by Hickson et al. (2011).

Nevados de Chillán geothermal system

The Nevados de Chillán geothermal area is associated with a 13 km long NW trending volcanic chain comprising calderas, polygenetic volcanoes and flank volcanoes. Hot springs discharge over 500 l/s of sulfate-bicarbonate waters with temperatures of up to 70 °C, equal to a heat loss of about 100 MWt (Sepúlveda & Lahsen, 2003). The reservoir volume is constrained by a concave shaped resistivity anomaly interpreted from an MT survey performed by the National Geothermal Company (Empresa Nacional de Geotermia, ENG) (ENG, 2007). The size of the anomaly ranges from 6 to 15 km^2 . The reservoir has an estimated thickness varying from 500 to 1,000 m, with minimum and maximum temperatures of 220 °C and 260 °C, based on temperatures reached by well Nieblas-1 and gas geothermometry respectively (ENG, 2007). The shallow reservoir reached by NCh-1 is considered too small for electric generation and therefore will not be included in the assessment.

Cordón Caulle geothermal system

The Cordón Caulle geothermal area is located in a 15 km long, 5 km wide, flat-topped volcano-tectonic depression, bounded to the northwest by the 8.5 km

wide caldera of the Cordillera Nevada, and to the southeast by the 2,240 m high Puyehue volcano (Sepúlveda et al., 2007, and references therein). The minimum reservoir area is inferred from the distribution of thermal springs, $\sim 8 \text{ km}^2$, on the other hand the maximum area may be expanded to 20 km^2 , as suggested by gravity and MT data (Sepúlveda, 2005; Rojas, 2013). Based on stratigraphic relationships, gravity, MT, and seismic data, the thickness for the potential reservoir was estimated between 500 to 2,000 m (Sepúlveda, 2005; Rojas, 2013). Gas geothermometry yields temperatures from 240 to 300 °C (Sepúlveda et al., 2007).

4.1.3. *Inferred and Indicated resource*

Results for the Heat in Place method are summarized in Table 2, along with the standard deviation, and probability confidence intervals of 10, 50 and 90%. The Heat in Place method yields a total mean estimate of 659 MWe distributed among the 9 geothermal systems, with a mean standard deviation of 49 MWe. The three Indicated systems yield a total value of 119 MWe with a standard deviation of 154 MWe. Of this systems, Apacheta and Tolhuaca are estimated to reach 99 and 70 MWe respectively. On the other hand, El Tatio yields only 56 MWe, because of its low reservoir thickness. La Torta, and Cordón Caulle have the highest estimated power output with Inferred category, reaching 128, and 97 MWe, respectively. The remaining systems, Puchuldiza, Tinguiririca, Mariposa (Laguna Del Maule), and Nevados de Chillán, yield intermediate values of 63, 54, 58, and 32 MWe, respectively (Table 2).

4.2. *Highly Probable Resource Areas*

Geothermal plays where geophysical surveys indicate the existence of a geothermal reservoir, or geothermometry suggests high temperature associated with a deep reservoir are ranked as highly probable resource areas (Table 3). Each geothermal play is described below.

Tacora

System	Location		Area	Thickness	Temperature	Results [MWe]		Fit to distribution [MWe]		
Name	Lat.	Long.	Km^2	m	$^{\circ}C$	Mean	Std	P10	P50	P90
¹ Apacheta	21.84	68.15	4–25	880–1120	212–250–256	99	58	185	81	72
¹ El Tatio	22.33	68.01	11.5–30	150–430–650	213–250–260	59	32	105	51	25
¹ Tolhuaca	38.31	71.66	4–8	1000–1400	250–280–300	70	30	110	69	33
² Puchuldiza	19.41	68.98	10–28	600–1000	200–250–270	63	44	127	52	13
² La Torta	22.42	67.97	15–25	650–2000	240–270	128	89	256	107	27
² Tinguiririca	34.85	70.38	5–25	500–1000	210–300	54	45	117	42	9
² Mariposa	36.06	70.53	9–23	500–1000	210–300	58	43	120	47	11
² Nv. de Chillán	36.90	71.40	6–15	500–1000	220–260	32	23	66	27	7
² Cordón Caulle	40.49	72.16	8–20	500–2000	240–300	97	76	203	77	17
Total						659	439	1290	548	180

Table 2: Geothermal systems selected for the assessment of Indicated and Inferred Resource. Categories: ¹Indicated; ²Inferred. Minimum, most likely and maximum values for the area, thickness and temperature of the reservoir are included. Mean electrical power output (MWe), standard deviation after 100,000 Monte Carlo iterations and 10-50-90% confidence interval after fitting the results to Birnbaum Saunders (Indicated) and Weibull (Inferred) probability distribution. Geographic coordinates WGS84, zone 18 – 19°S.

352 The Tacora geothermal prospect is associated with the 5,980 m high vol-
353 cano with the same name close to the Chile-Peru international boundary. This
354 geothermal prospect is characterized by intense fumarolic activity and with ex-
355 tensive, white colored, superficial alteration areas along the NW and W flanks
356 of the volcanic structure. Chemical and isotopic compositions of the main car-
357 bon species are interpreted to indicate the presence a deep geothermal reservoir
358 with temperatures of 270 – 310 °C (Capaccioni et al., 2011).

359 Colpitas

360 The Colpitas geothermal prospect is located in the northernmost part of
361 Chile in the Arica and Parinacota region. The area is characterized by volcano-
362 sedimentary sequences ranging in age from Miocene to Holocene, with at least
363 3 nearby active volcanoes. Thermal springs are located at the bottom of a wide
364 basin, with spring water temperatures ranging from 28 to 55 °C and a total
365 discharge of 10 l/s. Na/K geothermometry suggests equilibration temperatures
366 higher than 200 °C. A 3-D MT study shows a conductive area (3-8 Ωm) of
367 several tens of km^2 interpreted as the clay cap of an inferred geothermal reservoir

Name	Lat	Lon	Survey	Ref.
Tacora	17.70	69.80	Chemical and isotopic assessment of gas emissions.	1
Colpitas	17.95	69.45	3-D MT geophysical survey; Chemical assessment of hot water discharges.	5
Surire	18.92	68.06	Chemical and isotopic assessment of gas emissions and water discharges.	1, 4, 10
Pampa Lirima	19.85	68.90	Geophysical survey; water and gas geothermometry; Exploratory wells.	4, 6, 12
Irruputuncu	20.71	68.59	MT,TDEM and ZTEM geophysical surveys; Chemical and isotopic assessment of gas emissions and water discharges.	9, 11
Olca	20.95	68.48	Geophysical survey; Chemical and isotopic assessment of gas emissions and water discharges.	1, 2, 3, 11
Juncalito	26.51	68.82	Geophysical survey; gas geothermometry; exploratory wells.	10, 13
Sierra Nevada	38.57	71.62	Geophysical survey; shallow exploratory wells.	8

Table 3: Highly probable resource areas and geothermal related surveys in the Chilean Andes. Geographic coordinates WGS84 zones 18 – 19 °S. 1 Cusicanqui (1979); 2 De Silva & Francis (1991); 3 González-Ferrán (1995); 4 Tassi et al. (2010); 5 Aguirre et al. (2011); 6 Arcos et al. (2011); 7 Capaccioni et al. (2011); 8 Muñoz et al. (2011); 9 Reyes et al. (2011); 10 Risacher et al. (2011); 11 Tassi et al. (2011); 12 Legault et al. (2012); 13 Garcia (2014)

(Aguirre et al., 2011).

Surire

The Surire geothermal prospect is located south of the Surire salt deposits near the Polloquere volcano. Conventional aqueous geothermometers cannot be used because of the salt deposits (Risacher et al., 2011). Nevertheless, silica geothermometry indicates equilibrium temperatures ranging from 150 – 180 °C (Cusicanqui, 1979). The gas composition indicates medium to high equilibrium temperatures (> 200 °C), suggesting interactions of deeply circulating and shallow water (Tassi et al., 2010).

Pampa Lirima

The Pampa Lirima geothermal project is located in the Altiplano of northern Chile, within the Central Andes Volcanic chain. The geochemical features of thermal water and gas discharges at Pampa Lirima are typical of fluids that have evolved within shallow aquifers; therefore low temperature aquifers may mask any signal of deep fluids (Tassi et al., 2010; Achurra, 2011). An MT/TDEM geophysical survey was carried out at Pampa Lirima, revealing a large conductive anomaly interpreted as a deep geothermal reservoir (Arcos et al., 2011), although this preliminary conclusion is subject to further exploration. In addition, ZTEM inversion images appear to agree very well with the MT data, including the presence of a conductive layer at >500 m below the Pampa Lirima valley (Legault et al., 2012).

Irruputuncu

Irruputuncu is a geothermal prospect located near the southeastern edge of the Tarapacá region, in northern Chile, east of the Doña Ines de Collahuasi copper mine, the owner of the geothermal exploration concession. Acid sulphate hot springs discharge at the base of the Irruputuncu dacitic stratovolcano (Reyes et al., 2011). A 3-D inversion of TEM-MT data indicates two conductive layers separated by a resistive zone. Beneath the conductive layers lies a resistive structure, interpreted as a high temperature geothermal reservoir, (Reyes et al., 2011). Two slim holes drilled west of the Irruputuncu volcano (800 and 1,430 m depth) encountered bottom hole temperatures of 150 °C and 195 °C (at 3,350 and 3,000 m.a.s.l., respectively) and record an argillic alteration assemblage. Temperature profiles were conductive and TEM-MT data suggests a potential deep reservoir temperature up to 220 °C (Reyes et al., 2011).

Olca

Olca stratovolcano forms part of a 20 km long, EW-oriented volcanic chain that includes Paruma and Michincha volcanoes (De Silva & Francis, 1991; González-Ferrán, 1995). The Olca geothermal prospect is characterized by a scarcity of superficial manifestations, as fumaroles are only found at the volcano crater, and a single warm spring is located at the base of the volcano.

Groundwater exploration wells (<700 m) drilled at the base of the Olca volcano revealed an extensive clay-cap and temperatures up to 70 °C. Beneath this clay-cap, there is a high resistivity zone interpreted to result from high temperature alteration in the geothermal reservoir (Reyes et al., 2011). He, $\delta^{18}\text{O}$ and δD isotopic signature of the fumaroles suggests a mixing process between magmatic and hydrothermal sources. Gas geothermometry suggests equilibrium temperatures of 280 to 400 °C (Tassi et al., 2011).

Juncalito geothermal area

The Juncalito geothermal prospect is located in the Claudio Gay Cordillera, at the southern end of the CVZ, between Miocene eroded volcanic centers to the west, and Pliocene to Holocene volcanic centers to the east. An MT survey performed in 2012 shows a 2 km thick low resistivity anomaly, interpreted as the clay cap ($>16\ \Omega\text{m}$) above an inferred geothermal reservoir ($\sim 100\ \Omega\text{m}$). The geology and structural setting points to a N-S elongated shape for the reservoir (Garcia, 2014). Geothermometers must be used with extreme caution due to probable salt contamination (Risacher et al., 2011).

Sierra Nevada geothermal area

The Sierra Nevada geothermal system is associated with the similarly named Pleistocene-Holocene volcano in the Araucanía region of Chile. There are surface manifestations extending on the N and NW flanks of the volcano. Gas compositions of fumaroles suggest a high enthalpy, liquid dominated reservoir with an equilibrium temperature of $\sim 215\ ^\circ\text{C}$ (Muñoz et al., 2011). Further geophysical studies are essential to constrain the depth and dimensions of the inferred geothermal reservoir.

4.3. Interest areas

Based on geothermal exploration at a regional scale (Días, 1983; Hauser, 1989, 1997; Pérez, 1999; Risacher et al., 2011) and surface geothermal features, the interest areas are summarized in Tab. 4.

Name	Lat	Long	Geothermal feature	Ref.
------	-----	------	--------------------	------

Jurase	18.20	69.53	Hot springs temperature 65 °C; hydrothermal alteration; and silica sinters.	1, 3, 5
Berenguela	19.25	69.18	Hot springs temperature 58 °C.	1, 3
Quitatiri	19.34	69.50	Hot springs temperature 87 °C.	1, 3
Chimisa	19.38	69.29	Hot springs temperature 90 °C.	1, 3, 5
Laguna Churicollo	19.55	68.95	Hot springs temperature 90 °C.	1, 3
Mamiña	20.07	69.21	Hot springs temperature 52 °C.	1, 3, 5
Aguas Calientes	23.13	67.43	Hot springs temperature 50 °C.	1, 3, 5
El Toro	29.91	70.05	Hot springs temperature 60 °C.	1, 3
Colina	33.83	69.98	Hot springs temperature 50 °C.	3
Termas del Flaco	34.95	70.43	Hot springs temperature 77 °C.	3
El Azufre	35.32	70.54	Hot springs temperature 70 °C.	3
El Llolli	35.37	70.58	Hot springs temperature 95 °C.	3
El Colorado	35.41	70.52	Hot springs temperature 75 °C.	3
Tigre Naciente	35.47	70.51	Hot springs temperature 65 °C.	3
Estero El Volcán	35.50	70.76	Hot springs temperature 95 °C.	3
Descabezado Chico	35.53	70.54	Hot springs temperature 80 °C.	3
Baños de la Turbia	36.29	71.17	Hot springs temperature 50 °C.	3
Baños de Longaví	36.35	71.14	Hot springs temperature 81 °C.	3
San Lorenzo	36.76	71.40	Hot springs temperature 60 °C.	3
Aillin	37.54	71.38	Hot springs temperature 93 °C; extensive hydrothermal alteration.	3
Quilaquín	37.60	71.40	Hot springs temperature 75 °C.	3
Emanuel	37.60	71.28	Hot springs temperature 54 °C.	3
Copahue	37.82	71.16	Hot springs temperature 93 °C.	3
Avellano	37.99	71.53	Hot springs temperature 81 °C.	3, 5
Manzanar	38.46	71.71	Hot springs temperature 52 °C.	3, 5
Balboa	38.96	71.71	Hot springs temperature 67 °C.	3, 5
Huife	39.22	71.66	Hot springs temperature 60 °C.	3
Panqui	39.25	71.53	Hot springs temperature 50 °C.	3
Geométricas	39.50	71.87	Hot springs temperature 72 °C.	3, 4, 5
Coñaripe	39.63	71.92	Hot springs temperature 62 °C.	3, 4
Liquiñe	39.74	71.84	Hot springs temperature 82 °C.	3, 4
Hipólito Muñoz	39.76	71.79	Hot springs temperature 85 °C.	3, 4
Oporto	40.14	71.99	Hot springs temperature 60 °C.	3, 4
Cupido	40.15	71.91	Hot springs temperature 80 °C.	3, 4
Chihuio	40.19	71.93	Hot springs temperature 82 °C.	3, 4, 5

La Esperanza	40.34	71.82	Hot springs temperature 60 °C.	3, 4
Puyehue	40.71	72.32	Hot springs temperature 75 °C.	3, 4, 5
Rupanco	40.86	72.22	Hot springs temperature 63 °C.	3, 4, 5
El Callao	40.98	72.16	Hot springs temperature 59 °C.	3, 4
Las Juntas	41.25	72.04	Hot springs temperature 73 °C.	3, 4
Cayetué	41.30	72.20	Hot springs temperature 65 °C.	3, 4
Cochamó	41.36	72.32	Hot springs temperature 70 °C.	3
Llancahue	42.07	72.51	Hot springs temperature 52 °C.	3
Cahuelmó	42.26	72.38	Hot springs temperature 84 °C.	2, 3
Michinmahuida	42.96	72.39	Hot springs temperature 65 °C.	2, 3
Río Frío	43.47	72.47	Hot springs temperature 70 °C.	2, 3
Puerto Bonito	43.95	72.73	Hot springs temperature 70 °C.	2, 3
Puyuhapi	44.41	72.64	Hot springs temperature 80 °C.	2, 3
Puerto Pérez	45.24	70.21	Hot springs temperature 90 °C.	2, 3
Aguas Calientes	45.42	73.03	Hot springs temperature 65 °C.	2, 3, 5
Contreras	45.44	73.11	Hot springs temperature 68 °C.	2, 3
Quitrusco	45.58	73.38	Hot springs temperature 65 °C.	2, 3
Estero Negro	45.69	72.33	Hot springs temperature 60 °C.	3
Huemules	45.87	73.29	Hot springs temperature 60 °C.	3
Cupquellán	45.96	73.39	Hot springs temperature 60 °C.	3
Huina	46.31	72.81	Hot springs temperature 55 °C.	3
Caleta Román	46.06	75.51	Hot springs temperature 65 °C.	3

Table 4: Interest Area locations and geothermal features in the Chilean Andes. References in right column. Geographic coordinates WGS84 zones 18 – 19 °S. 1 Días (1983); 2 Hauser (1989); 3 Hauser (1997); 4 Pérez (1999); 5 Risacher et al. (2011)

5. Discussion

The experience of recent decades, has shown that the Heat in Place method is usually biased high. The tendency to overestimate the potential of geothermal prospects, in particular, has led to the reduced credibility of the method (Grant, 2015). Much of the problem lies in the estimation of the recovery factor, the proportion of the resource that can actually be exploited. This factor cannot be determined without further evaluation of the reservoirs structural control and permeability heterogeneity (López & Smith, 1996; Rowland & Sibson, 2004).

444 For low permeability systems (such as EGS), this recovery factor may be less
 445 than 0.02 (Grant & Garg, 2012; Grant, 2015). Wilmarth & Stimac (2015) esti-
 446 mated the power densities of 66 geothermal fields above 10 MWnet with more
 447 than 5 years of production history. Their work suggests that volcanic arc sys-
 448 tems tend to be moderate to high-temperature and have moderate to high power
 449 densities (5–15 MWe/ km^2). Wilmarth & Stimac (2015), and references therein,
 450 state that the fraction of the geothermal anomaly determined from low resis-
 451 tivity and thermal area that may eventually be developed is typically on the
 452 order of 0.5, but may range from 0 to more than 1. In this work we apply the
 453 power density method to an areal extent corresponding to half of the conduc-
 454 tive anomaly. Fig. 7 (Left) depicts a comparison with results after applying the
 455 power density method to each system. Values obtained in Apacheta, La Torta,
 456 Tolhuaca, and Cordon Caulle correlate with a power density equivalent of ~ 8
 457 to 15 MWe/ km^2 , the remaining systems correlate nicely within a range of 4 to 5
 458 MWe/ km^2 suggesting that Andean systems might hold a much higher power po-
 459 tential if a best case scenario is achieved. Although the volume method provides
 460 a means of estimating the heat content of a geothermal reservoir, it does not ex-
 461 plicitly predict the reservoir permeability (Williams et al., 2008). The structural
 462 setting in the Chilean volcanic arc is dominantly compressive (Fig. 1), but with
 463 varying complexities regarding each system local context. This variability is a
 464 source of uncertainty that must be taken into account. Puchuldiza, Apacheta,
 465 El Tatio/La Torta and Cordon Caulle are graben-related geothermal areas near
 466 an active volcanic arc. These systems show extensive superficial features, sug-
 467 gesting the occurrence of medium to high permeability. On the other hand,
 468 volcanic related systems like Tinguiririca, Mariposa, Nevados de Chillán and
 469 Tolhuaca are highly influenced by episodic re-shearing events. The nature of
 470 permeability in these areas is still a matter of debate. Further studies regarding
 471 permeability in Andean systems is highly recommended in order to understand
 472 its influence on the recovery factor.

473 Published data from 94 geothermal plants (Zarrouk & Moon, 2014) helps to
 474 constrain single flash plants efficiency, and new models for the recovery of heat

Figure 7: Left: Tornado diagram comparing results of this work with the power density method applied to the half of the areal extend of conductive anomaly. Right: Recovery factor sensitivity test for each system.

from heterogeneous, fractured reservoirs (Williams et al., 2008) provide a physically realistic basis for evaluating the production potential of natural geothermal reservoirs. Calculations are based upon recovery and conversion factors from single flash and dry steam power plants (Zarrouk & Moon, 2014), since this is the type of power plant installed at a newly developed high temperature geothermal fields (>200). Once the single flash steam power plant is running, DiPippo (2012a) recommends the installation of a double flash steam power plant in order to produce 15-25% more power output for the same geothermal fluid conditions. Many plants often include both flash and binary systems to maximize electrical power generation. Nevertheless, an economic analysis is required for each individual system in order to properly address this issue.

Apacheta, La Torta, Tinguiririca, and Mariposa encompass extensive superficial features, suggesting the presence of large systems. Estimated volume and temperature of these areas show a high variability. For large geothermal systems, variation of temperature causes a great uncertainty in available energy. As a result, estimated power output for large systems show a higher standard deviation (Table 2).

The electrical anomaly, recorded by MT or TEM surveys, is usually interpreted as a result of successive alteration processes, which are part of the

geothermal system evolution. Those processes can migrate over time. Therefore, the areal extent of the geothermal system inferred from the dimension of the clay cap may be overestimated, because there are no guarantees of geothermal fluid below the clay cap (*e.g.*, the clay cap could correspond to a fossil system).

Temperature estimation can be a major source of uncertainty issues. If the up-flow zone has not been reached by exploratory wells, there is a chance temperatures can be underestimated. On the other hand, the application of geothermometers can lead to gross overestimation if they are not interpreted with caution.

Indicated and Inferred systems can be grossly classified into high and medium potential power-producing systems. Apacheta, La Torta and Cordón Caulle yield values of 99, 128 and 97 MWe respectively. The remaining systems (Nv. De Chillán, Tinguiririca, Mariposa, El Tatio and Tolhuaca in increasing order) range from 32 to 70 MWe, consistent with mean production values for volcanic-hosted geothermal systems (*e.g.* Zarrouk & Moon, 2014, and references therein).

The heat source in El Tatio/La Torta and Puchuldiza remains unclear. It is necessary to consider the combined influence of volcanic convection dominated systems (Moeck, 2014), yet with a high influence of a regional heat flow anomaly. Geophysical surveys in El Tatio and La Torta suggests both systems share the same deep geothermal reservoir (Cumming et al., 2002), and are the largest Inferred system in the Chilean Andes, yielding 187 MWe with a standard deviation of 121 MWe. Additionally, the Sol de la Mañana geothermal field lies just 20 km east, on the east edge of the Pre-Altiplanic Cordillera, supporting the hypothesis of deep, high temperature reservoirs emplaced along this segment of the arc. Deep drilling and an EGS approach can be assessed as an alternative for several mining projects located along the CVZ whose energetic needs are consistent with geothermal high plant factors.

Many Andean systems present fluids of an acid nature which can be problematic due to the impact in costs and maintenance. Nevertheless, the resource can be exploited by binary plants (DiPippo, 2008). Therefore, despite there

525 is no consideration about geothermal fluid composition, the geothermal power
526 potential is still valid even in the case of problematic geothermal fluids.

527 **6. Conclusion**

528 We gathered and ranked geothermal exploration data available in the liter-
529 ature, establishing categories of Measured, Indicated, and Inferred geothermal
530 resource. We then applied, numerical methods to 9 high enthalpy reservoirs
531 ($> 200^{\circ}\text{C}$) in the Chilean Andes. In addition, 8 areas are highlighted as highly
532 favorable, based on geological, geochemical and/or geophysical surveys. Fur-
533 thermore, 57 geothermal areas are considered as potential high enthalpy geother-
534 mal resources, suggesting there are many undiscovered geothermal systems in
535 the Chilean Andes.

536 Based on available published geological, geochemical and geophysical evi-
537 dence, the total Indicated resource is 228 MWe with a Standard deviation of
538 119 MWe. Inferred resources reach 431 MWe with a Standard deviation of 321
539 MWe, adding up to 659 MWe among medium (6) and large systems (3) in the
540 Chilean Andes. This total estimated power potential is equivalent to $\sim 4.4\%$ of
541 the total installed electric capacity in Chile.

542 Although volumetric methods provide a means of estimating the heat content
543 of a geothermal reservoir, it does not explicitly predict the power potential. It
544 does allow for a gross estimate and a comparative evaluation of the different
545 geothermal prospects. Comparison with values obtained through the power
546 density method leads to a better understanding of the full uncertainty of resource
547 capacities.

548 Despite the high degree of geologic uncertainty, finite element modeling is
549 highly recommended for Indicated and Inferred systems (Tab.2). This approach
550 provides a more rigorous way to evaluate and understand conceptual models and
551 system thermodynamics.

552 7. Acknowledgments

553 This work has been supported by the FONDAP/CONICYT Project number
554 15090013 (Centro de Excelencia en Geotermia de los Andes, CEGA) and Depar-
555 tamento de Geología, FCFM, Universidad de Chile. P. Dobson was supported
556 by Lawrence Berkeley National Laboratory under U.S. Department of Energy,
557 Assistant Secretary for Energy Efficiency and Renewable Energy, Geothermal
558 Technologies Office, under the U.S. Department of Energy Contract no. DE-
559 AC02-05CH11231. The authors would especially like to thank to Dra. Jennifer
560 Blank and two anonymous reviewers for their valuable comments.

561 References

- 562 Achurra, L. (2011). *Estudio hidrogeoquímico sobre la interacción de aguas sub-*
563 *terráneas profundas y someras en Pampa Lirima, Norte de Chile*. Master
564 thesis Universitat Politècnica de Catalunya Barcelona.
- 565 Aguirre, I., Clavero, J., Simmons, S., Giavelli, A., Mayorga, C., & Soffia, J.
566 (2011). Colpitas—a new geothermal project in Chile. In *Geothermal Resources*
567 *Council Transactions* (pp. 1141–1145). California: Geothermal Resources
568 Council volume 35.
- 569 Aldrich, M., Laughlin, A., & Gambill, D. (1981). *Geothermal Resource Base of*
570 *the World: A revision of the Electrical Power Research Institute's estimate*.
571 Technical Report Electrical Power Research Institute.
- 572 Aravena, D., & Lahsen, A. (2012). Assessment of exploitable geothermal
573 resources using magmatic heat transfer method, Maule Region, Southern
574 Volcanic Zone, Chile. In *Geothermal Resources Council Transactions* (pp.
575 1307–1313). California: Geothermal Resources Council volume 36.
- 576 Aravena, D., & Lahsen, A. (2013). A geothermal favorability map of Chile, pre-
577 liminary results. In *Geothermal Resources Council Transactions*. California:
578 Geothermal Resources Council volume 37.

- 579 Arcos, R., Clavero, J., Giavelli, A., Simmons, S., Aguirre, I., Martini, S.,
580 Mayorga, C., Pineda, G., Parra, J., & Soffia, J. (2011). Surface explo-
581 ration at Pampa Lirima geothermal project, central Andes of northern Chile.
582 In *Geothermal Resources Council Transactions* (pp. 689–693). California:
583 Geothermal Resources Council volume 35.
- 584 Capaccioni, B., Aguilera, F., Tassi, F., Darrah, T., Poreda, R., &
585 Vaselli, O. (2011). Geochemical and isotopic evidences of mag-
586 matic inputs in the hydrothermal reservoir feeding the fumarolic dis-
587 charges of tacora volcano (northern Chile). *Journal of Volcanology*
588 *and Geothermal Research*, 208, 77–85. URL: <http://www.sciencedirect.com/science/article/pii/S0377027311002587>. doi:<http://dx.doi.org/10.1016/j.jvolgeores.2011.09.015>.
- 591 Cembrano, J., & Lara, L. (2009). The link between volcanism and tec-
592 tonics in the southern volcanic zone of the Chilean Andes: A re-
593 view. *Tectonophysics*, 471, 96–113. URL: <http://www.sciencedirect.com/science/article/pii/S0040195109001310>. doi:<http://dx.doi.org/10.1016/j.tecto.2009.02.038>. Understanding stress and deformation in
595 active volcanoes.
- 597 Cembrano, J., Lavenue, A., nez, G. Y., Riquelme, R., García, M., Hérail, G., &
598 González, G. (2007). Neotectonics. In T. Moreno, & W. Gibbons (Eds.), *The*
599 *Geology of Chile*. London: The Geological Society of London.
- 600 Clavero, J., Pineda, G., Mayorga, C., Giavelli, A., Aguirre, I., Simmons, S.,
601 Martini, S., Soffia, J., Arriaza, R., Polanco, E., & Achurra, L. (2011). Ge-
602 ological, geochemical, geophysical and first drilling data from Tinguiririca
603 geothermal area, central Chile. In *Geothermal Resources Council Transac-*
604 *tions* (pp. 731–734). California: Geothermal Resources Council volume 35.
- 605 Cumming, W., Vieytes, H., Ramirez, C., & Sussman, D. (2002). Exploration of
606 the La Torta geothermal prospect, northern Chile. In *Geothermal Resources*

607 *Council Transactions* (pp. 3–7). California: Geothermal Resources Council
608 volume 26.

609 Cusicanqui, H. (1979). *Estudio geoquímico del área termal de Surire - provincia*
610 *de Arica - I Región*. Technical Report Comité Geotérmico CORFO Santiago.

611 De Silva, S., & Francis, P. (1991). *Volcanoes of the Central Andes*. Berlin:
612 Springer-Verlag.

613 Días, F. (1983). *Present state of geothermal research and development in Chile*.
614 Technical Report Servicio Naciona de Geología y Minería Santiago.

615 DiPippo, R. (2008). Binary cycle power plants. In R. DiPippo (Ed.),
616 *Geothermal Power Plants (Second Edition)* chapter 8. (pp. 157 – 189).
617 Oxford: Butterworth-Heinemann. (Second edition ed.). URL: [http://](http://www.sciencedirect.com/science/article/pii/B9780750686204500137)
618 www.sciencedirect.com/science/article/pii/B9780750686204500137.
619 doi:<http://dx.doi.org/10.1016/B978-075068620-4.50013-7>.

620 DiPippo, R. (2012a). Geothermal power generating systems. In R. DiP-
621 ippo (Ed.), *Geothermal Power Plants* chapter 2. (pp. 79–80). Boston:
622 Butterworth-Heinemann. (Third edition ed.). URL: [http://www.](http://www.sciencedirect.com/science/article/pii/B9780080982069000324)
623 [sciencedirect.com/science/article/pii/B9780080982069000324](http://www.sciencedirect.com/science/article/pii/B9780080982069000324).
624 doi:<http://dx.doi.org/10.1016/B978-0-08-098206-9.00032-4>.

625 DiPippo, R. (2012b). Reservoir engineering. In R. DiPippo
626 (Ed.), *Geothermal Power Plants* chapter 4. (pp. 49–77). Boston:
627 Butterworth-Heinemann. (Third edition ed.). URL: [http://www.](http://www.sciencedirect.com/science/article/pii/B978008098206900004X)
628 [sciencedirect.com/science/article/pii/B978008098206900004X](http://www.sciencedirect.com/science/article/pii/B978008098206900004X).
629 doi:<http://dx.doi.org/10.1016/B978-0-08-098206-9.00004-X>.

630 Emparán, C., Suárez, M., & Muñoz, J. (1997). *Hoja Curacautín: Regiones de*
631 *la Araucanía y del Biobio*. Number 71 in Carta Geológica de Chile. Santiago:
632 Servicio Nacional de Geología y Minería. 105p – 1 map.

633 ENEL (2012). *Cerro Pabellon Geothermal Project (Apacheta)*. Technical Re-
634 port Enel, Latinoamérica (Chile) Ltda.

635 ENG (2007). *Estudio de impacto ambiental: Exploración geotérmica profunda*
636 *Nevados de Chillán sector Valle de las Nieblas*. Technical Report Empresa
637 Nacional de Geotermia S.A.

638 Garcia, K. (2014). *Aplicación del método magnetotelúrico en la exploración*
639 *de un sistema geotermal, en la región de Atacama, Chile*. Master's thesis
640 Universidad de Chile Santiago. URL: [http://tesis.uchile.cl/handle/](http://tesis.uchile.cl/handle/2250/116320)
641 [2250/116320](http://tesis.uchile.cl/handle/2250/116320).

642 Garg, S. K., & Combs, J. (2010). Appropriate use of usgs volumetric heat
643 in place method and monte carlo calculations. In *Workshop on Geothermal*
644 *Reservoir Engineering* Stanford University (p. 7). Stanford, CA volume 34.

645 Garg, S. K., & Combs, J. (2015). A reformulation of usgs volumetric "heat in
646 place" resource estimation method. *Geothermics*, 55, 150 – 158. URL: [http:](http://www.sciencedirect.com/science/article/pii/S0375650515000280)
647 [//www.sciencedirect.com/science/article/pii/S0375650515000280](http://www.sciencedirect.com/science/article/pii/S0375650515000280).
648 doi:<http://dx.doi.org/10.1016/j.geothermics.2015.02.004>.

649 González-Ferrán, O. (1995). *Volcanes de Chile*. (First edition ed.). Santiago:
650 Instituto Geográfico Militar.

651 Grant, M. (2015). Resource assessment, a review, with reference to the
652 Australian Code. In *Proceedings World Geothermal Congress*. Melbourne.

653 Grant, M., & Garg, S. (2012). Recovery factor for EGS. In *Workshop on*
654 *Geothermal Reservoir Engineering* 37. Stanford University.

655 Hauser, A. (1989). Fuentes termales y minerales en torno a la Carretera Austral,
656 regiones X–XI, Chile. *Andean Geology*, 16, 229–239.

657 Hauser, A. (1997). *Catastro y catacterización de las fuentes de aguas minerales*
658 *y termales de Chile*. 50. Santiago: Servicio Nacional de Geología y Minería.

659 Hickson, C., Ferraris, F., Rodriquez, C., Sielfeld, G., Henriquez, R., Gislason,
660 T., Selters, J., Benoit, D., White, P., Southon, J., Ussher, G., Charroy, J.,
661 Smith, A., Lovelock, B., Lawless, J., Quinliven, P., Smith, L., & Yehia, R.

- (2011). The Mariposa geothermal system, Chile. In *Geothermal Resources Council Transactions* (pp. 817–825). California: Geothermal Resources Council volume 35.
- Iriarte, S. (2013). Exploración geotérmica proyecto Tolhuaca.
- JICA (1979). *Informe preliminar segunda fase JICA - Proyecto de desarrollo del campo geotérmico de Puchuldiza*. Technical Report Comité Geotérmico CORFO Santiago.
- Lahsen, A. (1976). Geothermal exploration in Northern Chile - Summary. In *Circum-Pacific Energy and Mineral Resources* (pp. 169–175). The American Association of petroleum Geologists.
- Lahsen, A. (1978). *Evaluación de los resultados de la exploración del campo geotérmico de Puchuldiza I Región Tarapacá*. Technical Report Comité Geotérmico CORFO Santiago.
- Lahsen, A. (1986). *Origen y potencial de energía geotérmica en los Andes de Chile*. Technical Report Geología y Recursos Minerales de Chile, Universidad de Concepción Concepción.
- Lahsen, A. (1988). Chilean geothermal resources and their possible utilization. *Geothermics*, 17, 401 – 410. URL: <http://www.sciencedirect.com/science/article/pii/0375650588900685>. doi:[http://dx.doi.org/10.1016/0375-6505\(88\)90068-5](http://dx.doi.org/10.1016/0375-6505(88)90068-5).
- Lahsen, A., Muñoz, N., & Parada, M. A. (2010). Geothermal Development in Chile. In *World Geothermal Congress* (pp. 25–29). Bali.
- Lahsen, A., & Trujillo, P. (1976). *El campo geotermico de El Tatio, Chile. Proyecto Geotermico CORFO-ONU*. Technical Report Corporación de Fomento de la Producción (CORFO) Santiago.
- Lee, S., Simkin, T., & Kimberly, P. (2010). *Volcanoes of the World*. (3rd ed.). Berkeley and Los Angeles, California: University of California Press.

- 689 Legault, J., Lombardo, S., Zhao, S., Clavero, J., Aguirre, I., Arcos, R., & Lira,
690 E. (2012). ZTEM airborne AFMAG EM and ground geophysical survey
691 comparisons over the pampa lirima geothermal field in northern Chile – a
692) Z-axis tipper electromagnetic system. In *Geothermal Resources Council*
693 *Transactions* (pp. 1001–1008). California: Geothermal Resources Council
694 volume 36.
- 695 Letelier, M. (1981). *Geoquímica de las manifestaciones termales de Puchulduza*
696 *y sus alrededores*. Technical Report Comité Geotérmico CORFO Santiago.
- 697 Lira, E. (2011). *Estudio de sismicidad, tomografía sísmica y modelo de física de*
698 *rocas: Potencial sistema geotermal asociado al complejo volcánico Tinguirir-*
699 *ica*. Master's thesis Universidad de Chile Santiago.
- 700 López, D. L., & Smith, L. (1996). Fluid flow in fault zones: influence of hydraulic
701 anisotropy and heterogeneity on the fluid flow and heat transfer regime. *Wa-*
702 *ter Resources Research*, 32, 3227–3235. doi:[http://dx.doi.org/10.1029/](http://dx.doi.org/10.1029/96WR02101)
703 96WR02101.
- 704 Lovekin, J. (2004). Geothermal inventory. *Bulletin Geothermal Resources Coun-*
705 *cil*, 33, 242–244.
- 706 Melosh, G., Moore, J., & Stacey, R. (2012). Natural reservoir evolution in
707 the Tolhuaca geothermal field, southern Chile. In *Workshop on Geothermal*
708 *Reservoir Engineering*. California volume 36 of *SGP-TR-194*.
- 709 Moeck, I. S. (2014). Catalog of geothermal play types based
710 on geologic controls. *Renewable and Sustainable Energy Reviews*,
711 37, 867–882. URL: [http://www.sciencedirect.com/science/article/](http://www.sciencedirect.com/science/article/pii/S1364032114003578)
712 [pii/S1364032114003578](http://www.sciencedirect.com/science/article/pii/S1364032114003578). doi:[http://dx.doi.org/10.1016/j.rser.2014.](http://dx.doi.org/10.1016/j.rser.2014.05.032)
713 05.032.
- 714 Moreno, H., & Gardeweg, M. (1989). La erupción reciente en el Complejo
715 Volcánico Lonquimay (diciembre 1988), Andes del Sur. *Andean Geology*, 16,
716 93–117.

- 717 Muffler, L. (1979). *Assessment of geothermal resources of the United States–*
718 *1978*. Circular 790 U.S. Geological Survey.
- 719 Muffler, L., & Cataldi, M. (1978). Assessment of geothermal resources of the
720 United States – 1978. In L. Muffler (Ed.), *Geological Survey Circular 790*
721 (pp. 1–7). Arlington: U.S. Geological Survey.
- 722 Muñoz, J., & Stern, C. (1988). The quaternary volcanic belt of the south-
723 ern continental margin of south america: Transverse structural and petro-
724 chemical variations across the segment between 38 °S and 39 °S. *Jour-*
725 *nal of South American Earth Sciences*, 1, 147–161. URL: [http://www.](http://www.sciencedirect.com/science/article/pii/0895981188900326)
726 [sciencedirect.com/science/article/pii/0895981188900326](http://www.sciencedirect.com/science/article/pii/0895981188900326). doi:[http:](http://dx.doi.org/10.1016/0895-9811(88)90032-6)
727 [//dx.doi.org/10.1016/0895-9811\(88\)90032-6](http://dx.doi.org/10.1016/0895-9811(88)90032-6).
- 728 Muñoz, M., Alam, A., Parada, M., & Lahsen, A. (2011). Geothermal system as-
729 sociated with the Sierra Nevada volcano, Araucanía region, Chile. In *Geother-*
730 *mal Resources Council Transactions* (pp. 935–941). California: Geothermal
731 Resources Council volume 35.
- 732 Nathenson, M. (1975). *Physical factors determining the fraction of stored energy*
733 *recoverable from hydrothermal convection systems and conduction-dominated*
734 *areas*. Open-File Report 75-525 U.S. Geological Survey.
- 735 Ortiz, M., Achurra, L., Cortés, R., Fonseca, A., Silva, C., & Vivallos, J. (2008).
736 *Estudio geológico, geofísico e hidroquímico del sector Puchuldiza sur*. Unpub-
737 lished report Servicio Nacional de Geología y Minería Santiago. 1 map.
- 738 Pérez, P., Sánchez, P., Arancibia, G., Cembrano, J., Veloso, E., Lohmar, S.,
739 Stimac, J., Reich, M., & Rubilar, J. (). Sampling and detailed structural
740 mapping of veins, fault-veins and faults from Tolhuaca Geothermal System,
741 southern Chile. In *Congreso Geológico Chileno*. Antofagasta volume 13.
- 742 Pérez, Y. (1999). *Fuente de aguas termales de la Cordillera Andina del centro-*
743 *sur de Chile (39–42 °S)*. 54. Santiago: Servicio Nacional de Geología y
744 Minería. 1 map 1:500,000.

- 745 Procesi, M. (2014). Geothermal potential evaluation for northern Chile and
746 suggestions for new energy plans. *Energies*, 7, 5444–5459. URL: <http://www.mdpi.com/1996-1073/7/8/5444>. doi:[http://dx.doi.org/10.3390/](http://dx.doi.org/10.3390/en7085444)
747 [en7085444](http://dx.doi.org/10.3390/en7085444).
748
- 749 Ramírez, C., & Huete, C. (1981). *Hoja Ollague, escala 1:250,000*. Carta
750 Geológica de Chile,. Santiago: Servicio Nacional de Geología y Minería. 47p
751 – 1 map.
- 752 Reyes, N., Vidal, A., Ramirez, E., Arnason, K., Richter, B., Steingrimsen, B.,
753 Acosta, O., & Camacho, J. (2011). Geothermal exploration at Irruputuncu
754 and Olca volcanoes: Pursuing a sustainable mining development in Chile.
755 In *Geothermal Resources Council Transactions* (pp. 983–986). California:
756 Geothermal Resources Council volume 35.
- 757 Risacher, F., Fritz, B., & Hauser, A. (2011). Origin of components in
758 chilean thermal waters. *Journal of South American Earth Sciences*, 31,
759 153–170. URL: [http://www.sciencedirect.com/science/article/pii/](http://www.sciencedirect.com/science/article/pii/S0895981110000349)
760 [S0895981110000349](http://www.sciencedirect.com/science/article/pii/S0895981110000349). doi:[http://dx.doi.org/10.1016/j.jsames.2010.](http://dx.doi.org/10.1016/j.jsames.2010.07.002)
761 [07.002](http://dx.doi.org/10.1016/j.jsames.2010.07.002).
- 762 Rojas, E., Folguera, A., Zamora, G., Bottesi, G., & Ramos, V. (2014).
763 Structure and development of the andean system between 36°S and 39°S.
764 *Journal of Geodynamics*, 73, 34–52. URL: [http://www.sciencedirect.](http://www.sciencedirect.com/science/article/pii/S0264370713001336)
765 [com/science/article/pii/S0264370713001336](http://www.sciencedirect.com/science/article/pii/S0264370713001336). doi:[http://dx.doi.org/](http://dx.doi.org/10.1016/j.jog.2013.09.001)
766 [10.1016/j.jog.2013.09.001](http://dx.doi.org/10.1016/j.jog.2013.09.001).
- 767 Rojas, G. (2013). *Magnetotélúrica en el Complejo Volcánico Cordón Caulle*.
768 Bachelor thesis Universidad de Concepción.
- 769 Rosenau, M., Melnick, D., & Echtler, H. (2006). Kinematic constraints
770 on intra-arc shear and strain partitioning in the southern Andes between
771 38°S and 42°S latitude. *Tectonics*, 25. doi:[http://dx.doi.org/10.1029/](http://dx.doi.org/10.1029/2005TC001943)
772 [2005TC001943](http://dx.doi.org/10.1029/2005TC001943).

- 773 Rowland, J., & Sibson, R. (2004). Structural controls on hydrothermal flow in
774 a segmented rift system, Taupo Volcanic Zone, New Zealand. *Geofluids*, 4,
775 259–283. doi:<http://dx.doi.org/10.1111/j.1468-8123.2004.00091.x>.
- 776 Sánchez, P., Morata, D., Lahsen, A., Aravena, D., & Parada, M. A. (2011).
777 Current status of Geothermal Exploration in Chile and the role of the New
778 Andean Geothermal Center of Excellence (CEGA). In *Geothermal Resources*
779 *Council Transactions* (pp. 1215–1218). California: Geothermal Resources
780 Council volume 35.
- 781 Sarmiento, Z., Ármannsson, H., Abanes, R., Marangunic, C., Ingimundarson,
782 A., & O’Ryan, R. (2010). *Revisión de la ejecución del proyecto Perforación*
783 *Geotérmica Profunda El Tatio, Fase I, Informe Final*. Technical Report
784 Comisión Nacional de Energía Chile.
- 785 Sepúlveda, F. (2005). *El sistema Geotermico de Cordón Caulle: caracterización*
786 *geológica y geoquímica*. Ph.D. thesis Universidad de Chile.
- 787 Sepúlveda, F., & Lahsen, A. (2003). Geothermal exploration in central-southern
788 Chile (33–42°S). In *Geothermal Resources Council Transactions* (pp. 635–
789 638). Geothermal Resources Council volume 27.
- 790 Sepúlveda, F., Lahsen, A., & Powell, T. (2007). Gas geochemistry of
791 the cordón caulle geothermal system, southern Chile. *Geothermics*, 36,
792 389–420. URL: <http://www.sciencedirect.com/science/article/pii/S0375650507000533>.
793 doi:[http://dx.doi.org/10.1016/j.geothermics.](http://dx.doi.org/10.1016/j.geothermics.2007.05.001)
794 2007.05.001.
- 795 SERNAGEOMIN (2003). Mapa geológico de Chile: versión digital. Digital
796 Geological Publishing, No. 4 (CD-ROM, version 1.0, 2003).
- 797 Tassi, F., Aguilera, F., Darrah, T., Vaselli, O., Capaccioni, B., Poreda, R.,
798 & Huertas, A. D. (2010). Fluid geochemistry of hydrothermal systems in
799 the Arica–Parinacota, Tarapacá and Antofagasta regions (northern Chile).
800 *Journal of Volcanology and Geothermal Research*, 192, 1–15. URL: [http:](http://)

801 [//www.sciencedirect.com/science/article/pii/S0377027310000405](http://www.sciencedirect.com/science/article/pii/S0377027310000405).
802 doi:<http://dx.doi.org/10.1016/j.jvolgeores.2010.02.006>.

803 Tassi, F., Aguilera, F., Vaselli, O., Darrah, T., & Medina, E. (2011). Gas
804 discharges from four remote volcanoes in northern Chile (Putana, Olca,
805 Irruputuncu and Alitar): a geochemical survey. *Annals of Geophysics*, 54.
806 URL: [http://www.annalsofgeophysics.eu/index.php/annals/article/](http://www.annalsofgeophysics.eu/index.php/annals/article/view/5173)
807 [view/5173](http://www.annalsofgeophysics.eu/index.php/annals/article/view/5173). doi:<http://dx.doi.org/10.4401/ag-5173>.

808 Tassi, F., Martinez, C., Vaselli, O., Capaccioni, B., & Viramonte, J.
809 (2005). Light hydrocarbons as redox and temperature indicators in the
810 geothermal field of El Tatio (northern Chile). *Applied Geochemistry*,
811 20, 2049–2062. URL: [http://www.sciencedirect.com/science/article/](http://www.sciencedirect.com/science/article/pii/S0883292705001599)
812 [pii/S0883292705001599](http://www.sciencedirect.com/science/article/pii/S0883292705001599). doi:[http://dx.doi.org/10.1016/j.apgeochem.](http://dx.doi.org/10.1016/j.apgeochem.2005.07.013)
813 2005.07.013.

814 Tebbens, S., Cande, S., Kovacs, L., Parra, J., LaBrecque, J., & Vergara, H.
815 (1997). The Chile Ridge: A tectonic framework. *Journal of Geophysical*
816 *Research: Solid Earth (1978–2012)*, 102, 12035–12059. doi:[http://dx.doi.](http://dx.doi.org/10.1029/96JB02581)
817 [org/10.1029/96JB02581](http://dx.doi.org/10.1029/96JB02581).

818 Tocchi, E. (1923). Il Tatio, ufficio geológico Larderello SpA. Unpublished
819 Report.

820 Urzua, L., Powell, T., Cumming, W., & Dobson, P. (2002). Apacheta, a new
821 geothermal prospect in northern Chile. In *Geothermal Resources Council*
822 *Transactions* (pp. 65–69). Geothermal Resources Council volume 26.

823 Vázquez, M., Nieto, F., Morata, D., Droguett, B., Carrillo-Rosua,
824 F., & Morales, S. (2014). Evolution of clay mineral assemblages
825 in the Tinguiririca geothermal field, Andean Cordillera of central
826 Chile: an {XRD} and hrtem-aem study. *Journal of Volcanology and*
827 *Geothermal Research*, 282, 43–59. URL: [http://www.sciencedirect.](http://www.sciencedirect.com/science/article/pii/S0377027314001760)
828 [com/science/article/pii/S0377027314001760](http://www.sciencedirect.com/science/article/pii/S0377027314001760). doi:[http://dx.doi.org/](http://dx.doi.org/10.1016/j.jvolgeores.2014.05.022)
829 [10.1016/j.jvolgeores.2014.05.022](http://dx.doi.org/10.1016/j.jvolgeores.2014.05.022).

- 830 White, D., & Williams, D. (1975). *Assessment of geothermal resources of the*
831 *United States-1975*. Circular 726 U.S. Geological Survey.
- 832 Williams, C., Reed, M., & Mariner, R. (2008). *A review of methods applied by*
833 *the US Geological Survey in the assessment of identified geothermal resources*.
834 Open-File Report U.S. Geological Survey.
- 835 Wilmarth, M., & Stimac, J. (2015). Power density in geothermal fields. In *World*
836 *Geothermal Congress* (p. 7). Melbourne: Proceedings World Geothermal
837 Congress.
- 838 Zarrouk, S. J., & Moon, H. (2014). Efficiency of geothermal power
839 plants: A worldwide review. *Geothermics*, 51, 142–153. URL: [http:](http://www.sciencedirect.com/science/article/pii/S0375650513001120)
840 [//www.sciencedirect.com/science/article/pii/S0375650513001120](http://www.sciencedirect.com/science/article/pii/S0375650513001120).
841 doi:<http://dx.doi.org/10.1016/j.geothermics.2013.11.001>.