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Igneous Related Geothermal Resource in the Chilean Andes

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ABSTRACT

The Andean volcanic arc includes over 200 active stratovolcanoes and at least 12 giant caldera systems. Nevertheless, there is not a standard procedure for estimating geothermal resources associated with unexplored volcanic systems. A GIS-based method is used for estimating the volume of the volcanic edifice of major volcanic complexes in the zone. This value is used to infer the volume of magma emplaced under each volcano, and applied as a certainty parameter in a igneous related geothermal resource assessment. The method of magmatic heat transfer was applied in the main volcanic complexes of the Chilean Andes. Using principles of conductive heat transfer and volcanology to calculate temperature distribution in time and space following an instantaneous magma emplacement, then calculates potentially recoverable geothermal energy resources. The analysis of resources obtained for volcanoes in the area includes a variety of factors, such as age, temperature and depth of magma emplacement, and establishes a correlation between the resources and the volume of magma emplaced in the upper crust.

1. INTRODUCTION

The Andean volcanic arc occurs in four separate segments referred to as the Northern (NVZ; 2ºN-5ºS), Central (CVZ; 14-28ºS), Southern (SVZ; 33-46ºS) and Austral (AVZ; 49-55ºS) Volcanic Zones. Volcanism results from subduction of the Nazca and Antarctic oceanic plates below South America (Stern, 2004). This arc in comprises over 200 active Quaternary volcanoes with a tremendous natural geothermal potential, but still represents one of the largest undeveloped geothermal provinces of the world (Lahsen 2005, 2010). The country presents more than 300 geothermal areas located along the Chilean Andes and associated with Quaternary volcanism. The main geothermal areas take place in the extreme north (17°-28°S) and central-southern part (33°-46°S). In areas where the Quaternary volcanism is absent, such as along the volcanic gaps of 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).

Early resource assessments by Aldrich et al (1981) considered a gradient of 45ºC/km in the Chilean Plio-Quaternary volcanic belt, yielding 1.85×10^{22} J of thermal energy stored in water above 150 ºC. 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 3,000m. Updated estimates of potential in northern Chile yield values between 400 and 1,300 MWe. In southern Chile results vary between 600 and 1400 MWe (eg; Lahsen et al., 2010; Aravena & Lahsen, 2012 and references therein; Procesi, 2014). In this work, an estimated potential for all the recently active-volcanoes in the Chilean Andes is computed.

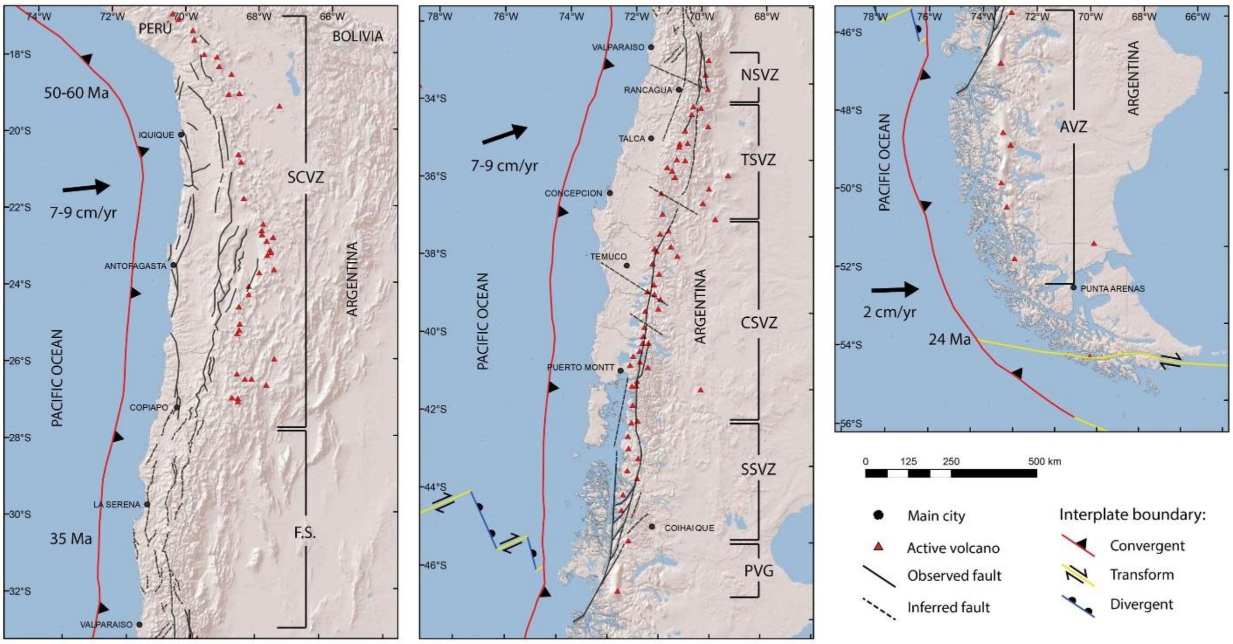

Figure 1: Tectonic setting, regional scale faults and active volcanoes of the Chilean Andes. Main fault systems of the SCVZ modified from Cembrano., et al., 2007. Flat Slab structures modified from SERNAGEOMIN (2003). Regional structures in the SVZ modified from (Servicio Nacional de geología y Minería, 2003); Cembrano and Lara, 2009 and references therein.

2. METHODS

2.1 Volcano selection and volume estimation

Active volcanoes in the Chilean Andes (table 5) are selected from the SERNAGEOMIN active volcanoes database (Gabriel Orozco, Perss.Comm) as well as from the Smithsonian Global Volcanism Program (Holocene Volcanoes). Volcanoes with a morphology that does not allow a proper measuring of the edifice volume were not included (eg: Sierra Nevada, Nevado Ojos del Salado). As well as parasitic and monogenetic cones whose composition evidence a deep source (eg: Carran Los-Venados, Pali-Aike volcanic field).

Typically, the amount of material extruded as lava or pyroclastic material is balanced by a similar amount of magma located in shallow areas of the upper crust (Sanyal et al., 2002). Therefore, the volume of the magmatic complex located beneath the volcano can be roughly estimated by determining the volume of extruded material. For many volcanoes, most of the extruded material may be stored as part of the volcano today. This is particularly true for conical well shaped stratovolcanoes, where the eruptive activity is dominated by lava flows and moderately explosive pyroclastic eruptions. In these cases, the volume of the volcano is related to the emplaced volume in a 3:1 ratio, representing a good estimate of the minimum volume of the igneous complex that is available to act as a geothermal heat source. This approximation corresponds to a lower limit for the heat source size, as Crisp (1984) suggests that the ratio of intrusive to eruptive volumes (I:E) for silicic volcanic centers in the Andes is ~6:1, close to the most repeated and average values of 3:1 and 5:1 yielded by White et al. (2006) for volcanoes ranging on a worldwide scale.

To estimate the volume of each volcanic complex, we use the tool *Surface volume* from the *3D analyst* extension in ArcGIS. From a digital elevation model (DEM) and estimating a horizontal plane (baseline; Bo) as the base of the complex, this software provides the volume between the horizontal plane and the topography determined by the DEM. Estimating the proper plane, from which the volume is measured for each edifice, is performed by analyzing the geometry of the volcano. For well-shaped stratovolcanoes, the baseline (Bo) is selected according to available literature and the elevation with the highest slope change. For more complex morphologies, the baselines lower limit is constrained by the highest altitude of the basement.

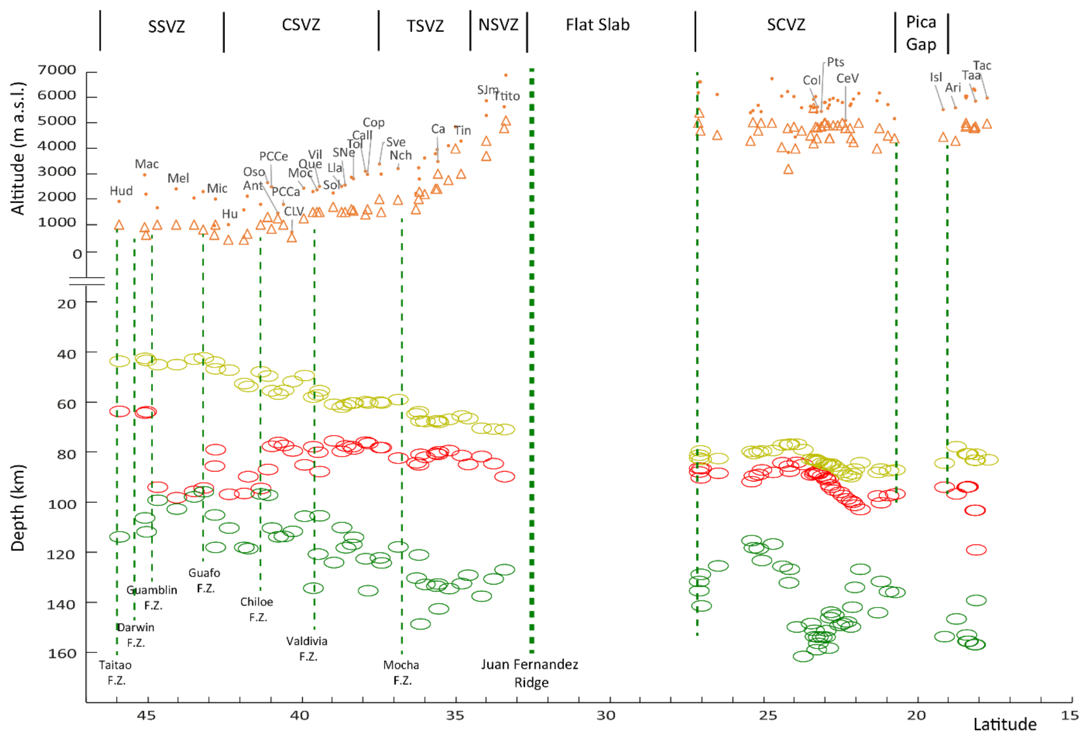

Figure 2: Selected volcanoes base (Bo; orange triangles), peak (orange dots). Projected distance directly below the volcano into i) the MOHO (Yellow circles), ii) Lithosphere-Asthenosphere Boundary (LAB; red circles) and iii) subducting SLAB (green circles) calculated from Tassara et al.,2012. Subducting SLAB discontinuities projected bellow the arc (green segmented lines) and main active arc segmentation (Muñoz B. & Stern 1988; Worner et al., 1992). Volcanoes related to thermal feature above 60º C, are displayed with labels: Tac: Tacora; Taa: Taapaca; Ari: Arintica; Isl: Isluga; CeV: Cerro Volcán; Pts: Putas; Col: Colachi; Ttito: Tupungatito; SJm: San José de Maipo; Tin: Tinguiririca; Ca: Calabozos; Nch: Nevados de Chillán; Sve: Sierra Velluda; Cop: Copahue; Call: Callaqui; Tol: Tolhuaca; SNe: Sierra Nevada; LLa: LLaima; Sol: Sollipulli; Vil: Villarica; Que: Quetrupillan; Moc: Mocho-Choshuenco; CLV: Carran-Los Venados; PCCa: Puyehue- Cordon Caulle; Oso: Osorno; Hu: Huequi; Mic: Michinmahuida; Mel: Melimoyu; Mac: Maca; Hud:Hudson.

2.2 Resource assessment

In a volcanic geothermal system the ultimate heat source is the magma emplaced at relatively shallow levels beneath the ground surface as part of the process of volcanic activity. We calculate the geometric volume of the volcanic edifices using a geographic information system (GIS) method. Then, we use the solution for an instantaneous source, as described in Sanyal et al. (2002) where instead of a cubic chamber, we assumed a magma body corresponding to that of a cylinder with the chamber's volume, which has a diameter:height ratio of 4:1, aiming to simulate a sill like emplacement as stated in Cembrano et al., 2009. Volume variations due to a larger eruptive history are not taken into account since this is a first order approximation and the time window used for each volcanic complex is relatively small (<500 ka). This estimation considers the volume as a fixed parameter (instead of an uncertainty parameter) in a Monte Carlo simulation. The Monte Carlo simulation is a quantitative technique that uses statistics and computers to imitate, using mathematical models, the random behavior of real systems. This technique combines statistical concepts (random sampling) with the ability of computers to generate pseudo-random numbers and automate calculations. We implemented the Monte Carlo method using MATLAB R2013a. This program is used both to simulate the temperature distribution around a magmatic body and to compute the geothermal resources associated with this temperature distribution. The use of this simulation is considered necessary since there are three first order parameters presenting different levels of uncertainty in performing the estimate: depth, temperature and age of magma emplacement. Using principles of conductive heat transfer and volcanology, we can approximate the temperature at any depth under a surface location, at any distance from the magma chamber, at any time after magma emplacement. Then, it is possible to calculate potentially recoverable geothermal energy resources associated with a single volcano or volcanic complex. Conductive heat transfer from a magma body to the surrounding rock can be calculated if one can estimate the following basic parameters of the magma: volume, depth of burial, age and initial temperature (Sanyal et al., 2002). The fixed and uncertain parameters used in the estimate can be observed in Tables 2 and 3. They were selected based on the geodynamic context that characterizes the Andean volcanism and some values are extracted from previous works involving specific studies for each volcano (e.g., Lopez and Munizaga, 1983; Hildreth et al., 1984; Grunder and Mahood, 1988; Grunder et al., 1987; Naranjo and Haller, 2002; Sellés et al., 2004).

Latent heat, contributes a great deal of energy to the system. Incorporating this parameter into calculations can more than double the solidification times of intrusions (Nabelek et al.,2012 and references within). However, we expect to overcome this heat underestimation, along with other unconsidered mechanisms and heat sources (e.g. advection, fault strain, permeability variations, temperature dependence of rock thermal properties), by relating the regional scale of the volcanic assessment with the more detailed reservoir approach from literature.

Table 1: Uncertainty and fixed parameters used as input for the resource assessment. Min, M.l. and Max values are the lower, most likely and upper limits for the parameter distribution of values in the Monte-Carlo simulation. For each selected volcano, Min, m.l. and Max values range between the ones displayed below and are individually selected.

	Monte Carlo		
Uncertain parameters:	min	m.l.	max
Age (ky)	0		500
Temperature (ºC)	700		1200
Depth (km)	3	4	5
Fixed parameters:			
Temperature Gradient	30	ºC/km	
Maximum reachable depth	3	Km	
Density of rock	2700	Kg/m^3	
Thermal conductivity	0.0025	kJ/m/s/ºC	
Rejection temperature	30	ºC	
Cut-off temperature	200	ºC	
Specific Heat of rock	1	kJ/kg/ºC	
Specific heat of fluid	2.08	kJ/kg/ºC	
Power plant life	30	y	
Utilization factor	0.45		
Plant factor	0.9		

3. RESULTS AND DISCUSSION

3.1 Volcanic edifice volume

We use a classification scheme for the volcanic edifices, based on their morphology (Table 1) that ranges from 1 (“individual conical stratovolcanoes, morphologically well defined”, our ideal case) to 4 (“heavily eroded volcanic central structures”, generally not considered here). The classification largely coincides with morphometric definitions given by Grosse et al. (2009) and Volker et al. (2011) and relates to volcano type categories of Siebert and Simkin (2002), but there are some differences as it reflects the applicability of our method to the edifice rather than trying to define strict morphometric or genetic criteria.

In the CVZ, the highest volume of a modern individual volcano is, by far, that of the Sierra Nevada volcano. Although, the massif morphology of this eruptive center induces a high error associated with variations with the chosen baseline and volcano delimitation. The only volcano with a volume higher than 60 km^3 and a well-shaped morphology (cat 1 or 2) is, naturally, the Ojos Del Salado volcano (highest volcano in the world). The rest of the most volumetric edifices (Sierra Nevada, Cordon de Puntas Negras, Incahuasi and Nevado Tres Cruces) have a massif like nature and therefore are not completely reliable for the magmatic chamber simulation. A similar result is observed in the SVZ where only 2 out of the 8 more massive volcanoes (volume over 60 km^3) could be classified in categories 1 or 2. Fig. 4 shows the frequency distribution of volumes for Chile (green), the CVZ (red) and SVC (blue). The total extruded volume is higher in the CVZ, yielding a total value of ca. 1000 km^3 and 500 km^3 distributed along 20 and 28 volcanoes corresponding to categories 1-2 and 3-4 respectively. The SVZ has a total extruded volume of ca. 400 and 1100 distributed along 12 and 33 volcanoes corresponding to categories 1-2 and 3-4 respectively.

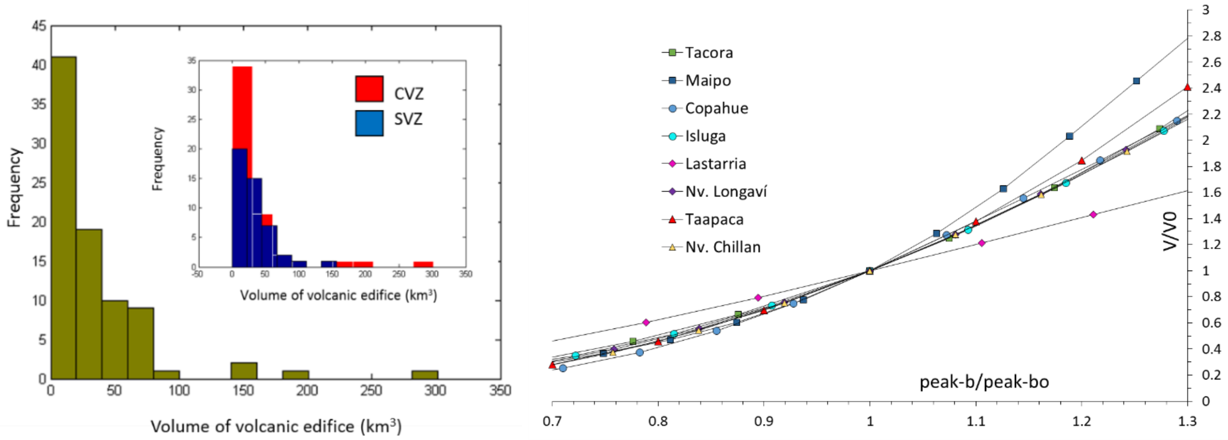

Figure 3: Left: Histogram of measured volcanic edifice volume. Green bars are the results for the entire country. Small inner figure shows same histogram for the CVZ and SVZ. Right: Sensitivity test for 8 volcanoes in the CVZ and SVZ. Selected volcanoes are symbolized acording to their morphostructural category. Squares: cat 1; circles: cat 2; diamonds: cat 3; triangles: cat 4.

This method presents several sources of error that have to be considered, but ambiguities in defining the volcanic edifice base is by far the largest source of uncertainty. Figure 4 present a test of the sensitivity of the volume calculation to uncertainties of the baseline following Volker et al (2011) and references within. A careful field study is needed for each volcanic complex in order to understand the sensitivity of the estimation to uncertainties of local parameters, such as structural or stratigraphic data. The relative volume variations (v/v0, with v0 being the volume for our best estimate) when the volcanos height (peak-b) is varied in relation to the baseline minimum of our preferred estimate (peak-b0). Lowering the baseline minimum by 30%, translates into a volume increase of 60–180%, depending on the shape of the volcano. For most volcanoes, uppering the baseline by 10% translates into a 75-85% volume decrease. Lastarria volcano represents a good example of a massif type volcano (category 3) while Maipo volcano has a well formed conical shape (category 1).

3.2 Resource assessment

It was possible to characterize the magmatic heat methods sensitivity with each of the uncertainty parameters and its correlation with the volume of magma emplaced. For determined configurations of the uncertain parameters, there is a lower volume from which resources are not high enough for electricity generation, this can be observed for several volumetrically small volcanoes. The most influential uncertain parameter is, by far, the depth of emplacement for the magmatic chamber (chambers roof in Figure 4, left). Special care must be taken in order to establish a more detailed study for each individual system. Parameters like temperature and age of emplacement have a relatively lower influence than the depth of emplacement but they still have to be established with a high level of certainty since they relate to the rocks thermal conductivity, affecting also the age-volume relation in which greater resources are expected (Figure 4, right). The notion that the volume-age relationship determines the possible geothermal potential is consistent with the analysis of Smith and Shaw (1975), whereby an igneous system can reach a post-magmatic stage of cooling, which is achieved earlier for small volumes.

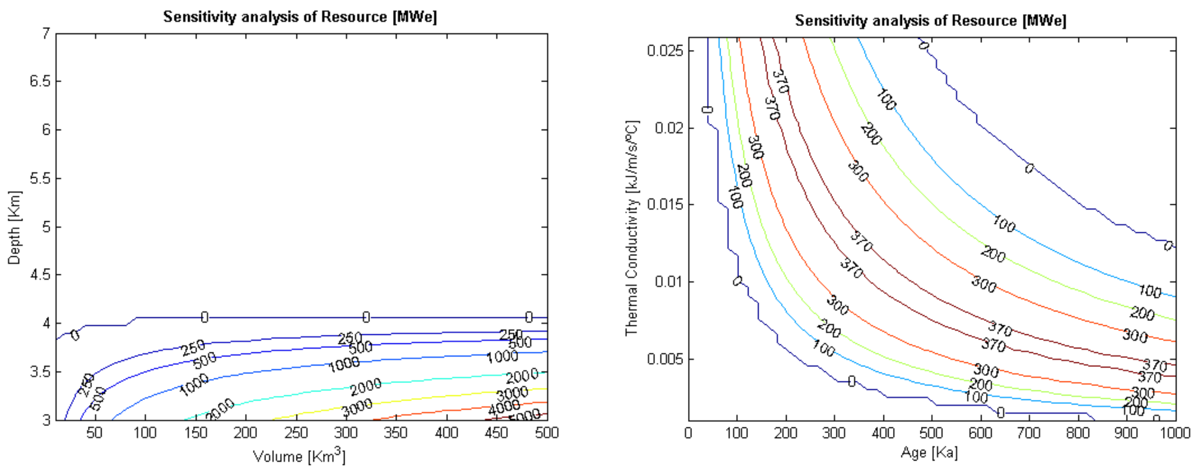

Figure 4: Power potential isolines (MWe) relating to Magma Volume/Depth (left), and Age/ Thermal Conductivity of rock (right) for a 50 km^3 chamber of magma emplaced at 4 km depth with an initial temperature of 800ºC.

Table 2 and Table 3 show a summary of the calculated volume and MWe for the CVZ and SVZ respectively. For assessment purposes we differentiate between morphological categories which we consider have a high (1 and 2) and low (3 and 4) reliability for the volume assessment. Given the high influence of the volcanic edifice's morphology in the volume assessment, we consider than the volume of the volcanoes on categories 3 and 4 should be estimated by a different method. Taking into account volcanoes in categories 1 and 2, we estimate a P90 inferred resource of ca.15.440 and 23.398 MWe for the SCVZ and SVZ respectively.

A simple exercise is to use a common value of production per km^2 (5 to 10 MWe/km^2) and apply it to the total high (1,163 km^2) and part of the medium (23,647 km^2) favorability areas yielded by Aravena & Lahsen 2013. If at least 10% of the medium favorability surface is susceptible to become resource. Then the total resource is:

$$\textit{High Fav. Surface} * 10\ MWe/km^2 + \textit{Medium Fav. Surface} * 1\ MWe/km^2 = 35{,}000\ MWe$$

This value is consistent with the resource inferred by the instantaneous heat source approach for well-shaped Chilean volcanoes. Standard deviation for the results of each volcano are highly variable, in many cases comparable with the calculated MWe on a 1:1 relation, this accounts for the high variability applied to the uncertainty parameters which in the end corresponds to the biggest limitation of this method due to its regional approach.

CONCLUSIONS

The methodology for estimating volume of volcanic edifices by geographic information systems (GIS) is presented as an objective tool to estimate the minimum volume of the volcanic edifice. This value can be related to the volume of magma emplaced under a volcanic complex and used as a regional approach for a comparative mass balance of volcanic edifices.

Based on available geological data, and using the magmatic heat transfer method, we calculated an igneous related geothermal resource, associated with well-shaped active volcanoes in the Chilean Andes. This assessment is based on inferred resource estimations and yields a total P90 value of ca. 39,000 MWe. 15,440 and 23,398 MWe for the CVZ and SVZ respectively.

Table 2: Selected volcanoes in the SCVZ, Latitude (lat), Longitude (lon), calculated volume and estimated P10, P50 and P90 values (MWe) with standard deviations of Monte-Carlo results.

	Volcano	N	E	Volume (km3)	P10	P50	P90	Std
1	Tacora	-17.7	-69.8	27	397	290	178	21%
2	Taapaca	-18.1	-69.5	38	706	566	400	17%
3	Pomerape	-18.1	-69.1	30	536	403	258	20%
4	Parinacota	-18.2	-69.1	56	818	623	406	19%
5	Acotango-Humarata	-18.4	-69.0	51	952	750	515	18%
6	Capurata	-18.4	-69.0	19	385	320	239	15%
7	Guallatiri	-18.4	-69.1	50	973	764	523	18%
8	Arintica	-18.7	-69.0	165	1876	1443	956	19%
9	Isluga	-19.2	-68.8	113	1586	1214	799	19%
10	Irruputuncu	-20.7	-68.6	12	205	159	106	19%
11	Aucanquilcha	-21.2	-68.5	95	1516	1163	768	19%
12	Ollahue	-21.3	-68.2	181	2190	1669	1091	19%
13	San Pedro	-21.9	-68.4	56	963	755	516	18%
14	Paniri	-22.1	-68.2	111	1657	1221	757	21%
15	Cerro del Leon	-22.1	-68.1	75	934	694	435	21%
16	Cerro Volcan	-22.3	-68.0	25	341	250	153	21%
17	Tocorpuri	-22.4	-67.9	19	433	355	261	15%
18	Licancabur	-22.8	-67.9	39	731	583	409	17%
19	Juriques	-22.9	-67.8	61	1030	807	551	18%
20	Purico Complex1	-23.0	-67.7	22	434	360	268	15%
21	Laguna Verde	-23.3	-67.7	16	358	298	224	15%
22	Lascar	-23.4	-67.7	81	965	710	439	21%
23	Tumisa	-23.5	-67.8	34	644	519	370	16%
24	Llullaillaco	-24.0	-68.5	144	1864	1425	935	19%
25	Socompa	-24.4	-68.3	179	2289	1756	1159	19%
26	Lastarria	-25.1	-68.5	30	231	162	93	23%
27	Incahuasi	-26.5	-68.3	231	2485	1905	1255	19%
28	Nevados Tres Cruces	-27.0	-68.8	225	2441	1867	1225	19%
29	El Solo	-27.1	-68.7	11	245	203	152	15%
	Total CVZ			2195	30185	23236	15440	

Table 3: Selected volcanoes in the SVZ, Latitude (lat), Longitude (lon), calculated volume and estimated P10, P50 and P90 values (MWe) with standard deviations of Monte-Carlo results.

	Volcano	N	E	Volume (km3)	P10	P50	P90	SD
30	Tupungato	-33.4	-69.8	36	800	639	449	17%
31	Tupungatito	-33.4	-69.8	96	859	614	363	22%
32	Maipo	-34.0	-69.8	70	595	419	242	23%
33	San Jose-Marmolejo	-34.0	-69.9	234	1153	819	479	22%
34	Tinguiririca	-34.8	-70.4	188	1770	1312	820	21%
35	Planchon-Peteroa	-35.2	-70.6	111	1923	1467	959	19%
36	Descabezado Grande	-35.6	-70.8	189	2255	1658	1023	21%
37	Cerro Azul	-35.7	-70.8	51	841	637	411	20%
38	San Pedro-Pellado	-36.0	-70.9	129	1498	1088	659	21%
39	Laguna del Maule	-36.2	-70.5	191	2598	1981	1295	19%
40	Nevado de Longavi	-36.2	-71.2	33	480	349	212	21%
41	Lomas Blancas	-36.3	-71.0	23	358	266	167	20%
42	Nevados de Chillan	-36.9	-71.4	25	2534	1935	1267	19%
43	Antuco	-37.4	-71.4	78	886	631	370	22%
44	Sierra Velluda	-37.5	-71.4	70	1405	1084	722	19%
45	Copahue	-37.9	-71.2	289	3479	2654	1736	19%
46	Callaqui	-37.9	-71.4	189	1462	1043	613	22%
47	Tolguaca	-38.3	-71.6	70	1141	847	531	21%
48	Lonquimay	-38.4	-71.6	46	567	413	250	21%
49	Sierra Nevada(b)	-38.6	-71.6	47	1067	835	568	18%
50	Llaima	-38.7	-71.7	129	1170	826	479	23%
51	Sollipulli	-39.0	-71.5	51	1086	850	579	18%
52	Villarica	-39.4	-71.9	79	1503	1151	758	19%
53	Quetrupillan1	-39.5	-71.7	76	914	651	383	22%
54	Lanin	-39.6	-71.5	155	1690	1221	732	22%
55	Mocho-Choshuenco	-39.9	-72.0	93	1678	1244	777	21%
56	Puyehue-Cordon Caulle	-40.6	-72.1	469	4740	3655	2430	19%
57	Antillanca Group	-40.8	-72.2	37	847	675	472	17%
58	Puntiagudo-Cordon Cenizos	-41.0	-72.3	132	1193	843	489	23%
59	Osorno	-41.1	-72.5	28	489	370	238	20%
60	Calbuco	-41.3	-72.6	27	599	468	316	18%
61	Yate	-41.8	-72.4	114	673	488	295	22%
62	Hornopiren	-41.9	-72.4	34	794	633	444	17%
63	Michimahuida	-42.8	-72.4	176	2477	1878	1217	20%
64	Yanteles	-43.5	-72.8	63	1327	1023	680	19%
65	Melimoyu	-44.1	-72.9	102	1025	726	422	23%
	Total SVZ			3894	49078	36752	23398	

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