The Mariposa Geothermal System, Chile

C. J. Hickson[1], F. Ferraris[2], C. Rodriquez[2], G. Sielfeld[2], R. Henriquez[2], T. Gislason[3], J. Selters[2], D. Benoit[4], P. White[5], J. Southon[5], G. Ussher[5], J. Charroy[5], A. Smith[5], B. Lovelock[5], J. Lawless[5], P. Quinlivan[5], L. Smith[6], and R. Yehia[1]

[1]Alterra Power Corp. (formally Magma Energy Corp, Vancouver, British Columbia Canada
[2]Magma Energía Chile (ENERCO), Providencia, Santiago, Chile
[3]HS Orka hf, Reykjanesbæ, Iceland
[4]Magma Energy (US) Corp, Reno NV, USA
[5]Sinclair Knight Merz, Auckland, New Zealand
[6]Sinclair Knight Merz Minmetal Limitada, Santiago, Chile

ABSTRACT

The Mariposa Geothermal System (MGS) is located 300 km south of Santiago, Chile, and has an inferred resource of 320 MWe. The field is outlined by a low resistivity MT anomaly with two lobes (or wings) that appear to relate to a clay cap associated to two principal upflow areas. The resource depth varies approximately 700 m to over 1000 m depending on terrain. The reservoir is likely contained within non-deformed volcanic rocks of the Campanario formation (Miocene-Pliocene) and folded and faulted volcaniclastic rocks of Curamallin formation (Eocene to Miocene). Structural analysis indicates locally a main control by east-northeast vertical structures with perpendicular extension, which intersect regional major NS lineaments.

Geothermal manifestations (steaming ground and fumaroles) occur at four locations surrounding the MT anomaly, where the steep terrain cuts the margins of the clay cap. Gas geochemistry from these sources indicates a liquid-dominated reservoir with temperatures of > 250°C in the western part of the reservoir and lower temperatures (200 - 250°C) in the eastern lobe. There are no indications in the gas chemistry of acidic magmatic conditions.

Drilling the MGS has proven to be challenging and of the three slim holes drilled to date, none have penetrated the deeper parts of the reservoir. Two wells measured temperatures over 200°C in the shallowest part of the reservoir. The wells were cored and have provided high quality geological information of the capping rocks of the reservoir. Plans for additional slim-hole drilling and large-diameter drilling into the deep reservoir, are well advanced as Magma progresses on developing this large, high quality resource.

Introduction

Chile represents one of the largest undeveloped geothermal provinces of the world. Geothermal areas in Chile are closely related to Quaternary volcanism. The volcanic-geothermal activity is primarily controlled by the convergence of the Nazca and South-American plates. Detailed geothermal investigations in Chile, including drilling and feasibility studies, date back to the mid 1970's. At that time, a CORFO-UNDP geothermal program explored northern Chile leading to the identification of several geothermal prospects such as El Tatio, Surire and Puchuldiza. By the mid 90's, geothermal exploration was resumed by ENAP (Chile National Oil Company) both in northern and southern Chile. Farther south, investigations were focused on the geothermal prospects of Calabozos and Nevados de Chillán. Later on, a compilation of geochemical data from all the thermal areas of Chile was conducted by the National Geological Survey of Chile (SERNAGEOMIN) (see for example Hauser 1997).

Magma acquired from the University of Chile the Laguna del Maule (LDM, 40,000 ha) exploration concession in September 2008. Immediately following the acquisition, an accelerated exploration program began in January 2009. Six month later, based on the favourable results obtained by the program, a development

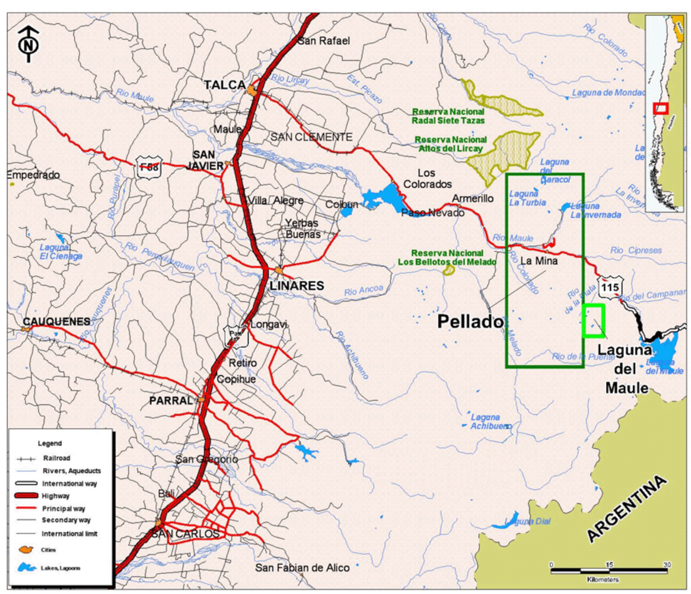

Figure 1. Location map showing Laguna del Maule exploitation concession (light green) and Pellado exploration concession (dark green).

plan to convert the LDM into an exploitation lease (4,000 ha), was submitted to the Ministry of Mining (Chile), and the granting decree was published in May 2010. In parallel, during January 2010 the exploration concession Pellado (100,000 ha), located to the west of LDM area was granted to Magma.

Previous geological work on the LDM concession area were restricted to regional mapping and research projects carried on the Laguna del Maule and San Pedro-Tatara volcanic complexes by universities and government researchers (eg. Singer et al, 1997). Magma exploration program begun by doing a geological compilation, local mapping, sampling of geothermal manifestations, and a MT study covering the 40,000 ha lease area by initially placing stations to provide regional coverage (the MT survey was completed by Schulmberger Chile under the supervision of Sinclair Knight Merz -SKM).

The favourable results obtained during the first stage of the exploration program were followed by a slimhole (MP 01) drilling campaign in May 2009. The positive results reported by MP01, were confirmed further by two additional slimholes (MP 02 & MP 03) during the 2010 drilling season.

Location

The Mariposa Geothermal System is located 300 km south of the capital city Santiago, 5.5 hours driving to the heart of the project, and 1.5 hours from the city of Talca (Figure 1). From Talca paved National highway #115 (*Paso Pehuenche* International route) leads to Magma's two adjoining concessions: Laguna del Maule and Pellado exploration concessions.

Tectonic Context

The Chilean Andes are the result of the subduction of the oceanic Nazca Plate beneath the South American Plate (Figure 2), at the Chile (or Atacama) Trench at a rapid rate of about 80 mm/year with a N78º convergence angle (De Mets, et al. 1994; Tamaki, 1999). This subduction is responsible for the volcanic activity within the Andes, and the production of numerous potential magmatic heat sources for geothermal fields. The Andean volcanic arc includes over 200 potentially active Quaternary volcanoes occurring in four separate segments referred to as the Northern (NVZ), Central (CVZ), Southern (SVZ) and Austral (AVZ) Volcanic Zones (e.g. Thorpe and Francis, 1979; Thorpe, 1984; Stern and Kilian, 1996; Stern 2004). Many geothermal systems have been identified in the SVZ, although none have yet been developed for power production.

The SVZ (33-34.5°S) has been divided into four segments: Northern (NSVZ), Transitional (TSVZ), Central (CSVZ) and Southern (SSVZ) (López –Escobar et al, 1995). The MGS project area is located in the Transitional (TSVZ) which is an up to >200 km wide belt. Quaternary volcanism within the belt, occur on uplifted basement blocks separated by inter-arc extensional basins containing numerous stratovolcanoes, monogenetic cones, domes and lava flows in a complex transition from calc-alkaline to alkaline back-arc volcanism. The TSVZ volcanoes overlie Eocene to Pliocene volcanic and volcaniclastic continental sequences deposited on Paleozoic and Mesozoic basement.

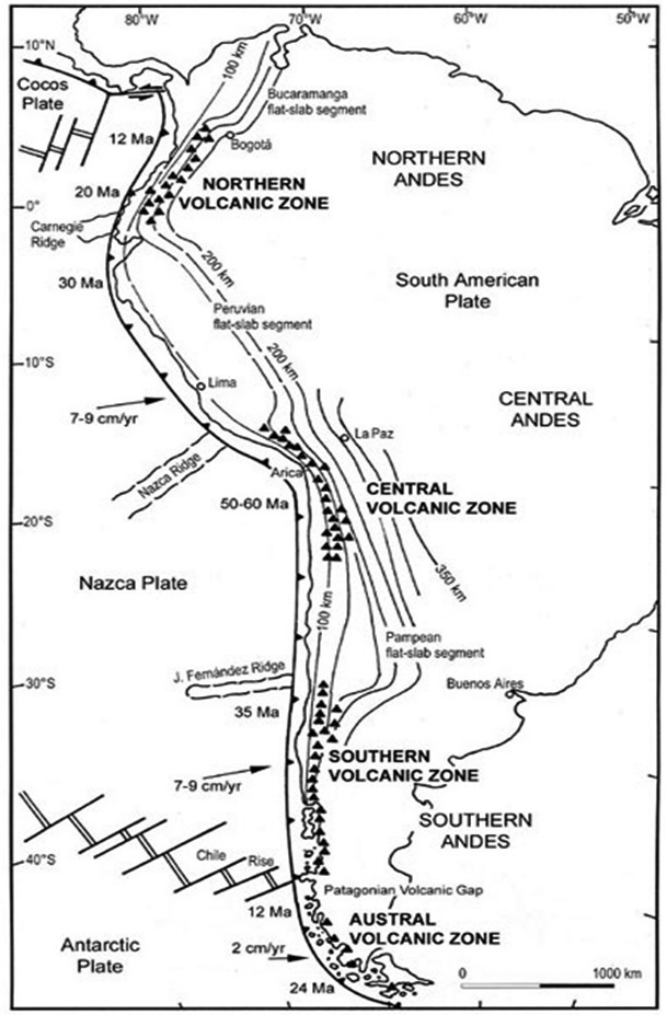

Figure 2 . Regional tectonic setting (adapted from Stern, 2004).

Geology

The exploration program conducted by Magma in the concession areas LDM and Pellado resulted in a geological map based on the compilation of regional and more detailed works (e.g. Muñoz and Niemeyer, 1984; Singer et al, 1997) along with detailed local mapping carried out by Magma.

The main geologic units found in the project area are the following:

Recent sedimentary deposits. Debris flows, glacial, alluvial and fluvial material forming diamictites including matrix-supported and poorly sorted breccias up to 25 m thick. These deposits are widely distributed, particularly within deep glaciated and fluvial valleys.

Laguna del Maule volcanic complex (LDMC, ca. 1.5 Ma-Late Holocene). This complex is located on the border with Argentina, between 35 ° 55'S and 36 ° 10'S. It includes lava flows and tuffs that extend over 35 km from the border towards the NNW, covering a surface area of approximately 750 km^2. It is characterized by numerous small post glacial volcanic centers and a few older stratovolcanoes. The complex includes ~107 volcanic centers, which have emitted more than 350 km^3 of magma between

1.4 Ma to recent times. The LDMC includes the Bobadilla Caldera, 6 ignimbrites, 9 remnants of mafic stratovolcanoes, 30 cinder cones, 28 postglacial lavas and silicic domes and subordinated distinguished stacks of dacitic and andesitic lavas (e.g. Hildreth et al., 2004; Frey et al. 1984; Munizaga, 1979).

Tatara-San Pedro-Pellado volcanic complex (TSPPC, ca. 930 ka-Late Holocene). This complex is located to the east of the Laguna del Maule volcanic complex (~36° S) in front of the Quaternary volcanic arc. Extensive and detailed, petrological, geochemical, paleomagnetic, stratigraphic and geochronological studies (e.g. Davidson et al., 1988, Dungan et al., 2001, Singer et. al, 1997 and references therein) have been carried out. The TSPPC comprises 8 or more volcanic sequences generated during the last ~930 ka. The sequences are bounded by unconformities, some of which represent periods of significant erosion. The construction of the complex began with the eruption (~930 ka ago) of a large volume of dacitic magma, followed by the eruption of a rhyolite ~100 ka after. From 780 ka, over 89% of preserved lavas correspond to basaltic andesites (52-57% SiO_2) with sporadic events of dacitic magma (63-69% SiO_2). The younger sequences (less than 230 ka), are formed by basaltic lavas (49-52% SiO_2). The isotopic variation found in the volcanic rocks of the TSPPC have been interpreted as the result of multistage, open system, multi-component and polybaric evolution (Dungan et al, 2001). The TSPPC rests unconformably above the Campanario Formation and older units, including the Trapa-Trapa and Cura-Mallin formations.

Campanario Formation (Upper Pliocene): Comprises non-deformed volcanic rocks, including lithic tuffs, intermediate lavas and minor epiclastic rocks (Drake, 1976; Muñoz & Niemayer 1984). In the project area, this formation is affected by argillic alteration (smectite, illite, calcite, quartz, Fe-oxides, etc) whose intensity and mineralogy varies with location and depth.

Trapa-Trapa Formation (Middle to Upper Miocene). Volcanic sequence formed by folded and faulted andesitic lavas, epiclastic and minor sedimentary rocks (Muñoz & Niemayer 1984). The sequence is locally affected by weak to moderated alteration (chlorite, calcite, quartz, clays, etc).

Cura-Mallin Formation (Eoceno – Mioceno inferior (40 – 16 Ma). Volcanic and sedimentary continental rocks. In the project area this unit is formed mainly by basic to intermediate lavas and volcaniclastic rocks, displaying strong deformation. Locally this formation show moderate alteration done by chlorite, epidote, calcite, Fe-oxides, etc. Curamallin Formation is unconformable lying over older sedimentary rocks from Río Damas (Upper Jurasic) and Baños del Flaco (Upper Jurassic - low Cretacic) formations (Muñoz & Niemayer 1984), well exposed to the north of TSPPC (Figure 3).

Intrusive rocks. A number of intrusive bodies from Cretaceous to Upper Miocene have been identified in the project area. The youngest intrusives are Upper Miocene in age (6.2-6.4 Ma; Nelson, et al. 1999; Singer, et al. 1997) and correspond to the *Risco Bayo* Pluton (gabbro to granite) and *Huemul* Pluton (leucogranite). The *La Plata* Stock correspond to a dioritic intrusive discovered by the Magma team at the headquarters of La Plata valley. It has been dated in 12.17±0.1 Ma. Finally, *El Indio* Pluton is a large granitic to tonalitic Upper Cretaceous intrusive (two ages:79.8 ±0.4 and 79.4±0.3 Ma; Nelson *et. al.*, 1999). MT geophysical surveys suggest that these intrusive rocks do not occur within the conjectured Mariposa geothermal reservoir area (see section below).

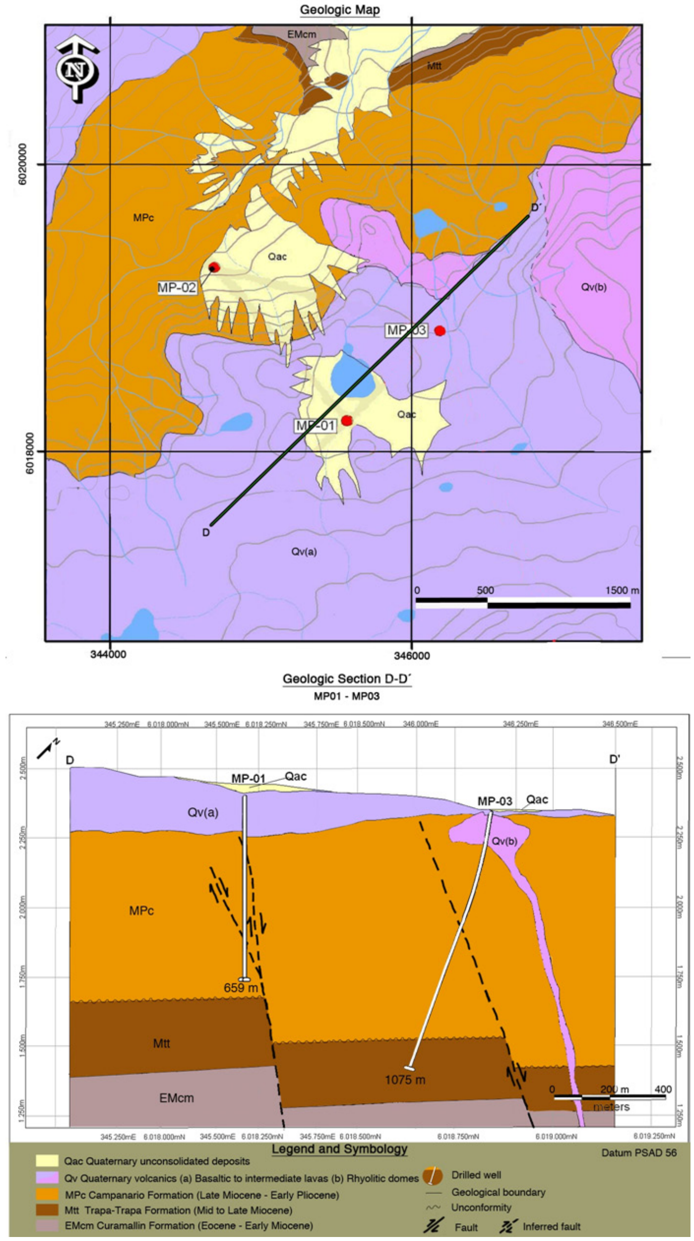

Figure 3. Geologic Map of the headwater La Plata valley, showing geological units and location of the three slimholes: MP 01, MP 02 and MP 03. D-D´: detailed section showing geological units found by MP 01 and MP 03.

Structural Geology

Tectonic of the Chilean central Andes is controlled by the oblique convergence of the Nazca Plate below the Southamerican plate producing a transpressional stress field. This stress condition has operated since late Cretaceous (Mpodozis & Ramos, 1989, and references therein) with minor extensional and compressional episodes. Complex and variable deformation styles are observed in the basement units found in the project area.

Pre Pliocene Tectonic

Rocks of Curamallin (Eocene-Miocene) and Trapa-Trapa (Middle to Upper Miocene) formations record the effects of a compressional deformation. These rocks display asymmetrical folding with NS to N10ºE axes, characterized by west dipping (10-20°) long limbs and east dipping (30-40º) short limbs. The wave length of these folds is variable in the order of: 1 km, 100 - 80 m, and 10-20 m. Inverse faults have been identified associated to the synclinal fold axes, consistent with the compressional tectonic.

Pliocene – Late Pleistocene Tectonic

Deformation in Pliocene-Pleistocene rocks are observed as NE – ENE dikes, faults, fractures, and lineaments that cross cut the TSPPC, LDMC and basement in the project area (Figure 4).

The TSPPC and proximal basement is affected by intermediate to basaltic dikes (0.5-6 m thick), with no evidences of shearing. Most of dikes in the project area form swarms having N70ºE-EW trends, dipping 60-90º. Less abundant NNE and NW subvertical dikes with intermediate to basaltic compositions are also found in the project area.

Four Pleistocene dike swarms were studied in detail to identify the main attitudes. At La Plata headwaters a mafic dike swarm trend mainly N70ºE, but rare NW dikes are also present. Two dikes swarms were studies at the northern flank of TSPPC, in both the predominant orientations are NE to NNE. At the south-eastern flank of TSPPC dikes trend ENE and WNW.

Sub-vertical ENE normal faults have been identified in the northern flank of TSPPC. These structures extends horizontally by hundred of meters and display indications of up to 15 m normal separation. Some authors interpret these structures as part of a graben (Singer et al. 1997), affecting volcanic rocks from Pellado volcano. At La Plata headwaters similar faults are found, cutting rocks from LDMC. In the same locality co-seismic NE – ENE open fractures were measured after the Feb 27, 2010 earthquake.

Finally, regional NE and E-NE lineaments are commonly found at the Andes of the Maule region. The most important in the project area are those controlling rivers such: La Plata, La Puente, Saso and Bahamondes.

Based on the structural analysis of data collected from dikes, the Recent (Quaternary) general strain field in the project area has ENE main compressive strain direction (σ_1), sub-vertical secondary stress (σ_2), and NNW to NS extensional strain direction (σ_3).

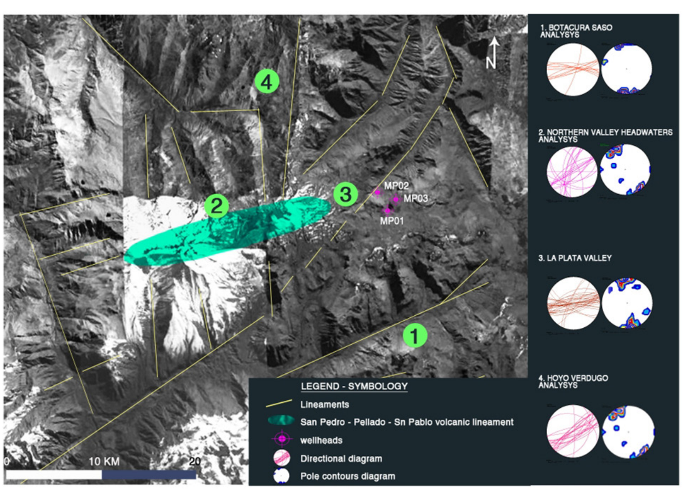

Figure 4. Satellital image showing the the MGS project area, the location of three slimholes (MP 01, MP 02 and MP 03), and the pole contour diagrams based on four dike swarm locations.

Gas Geochemistry

Geothermal manifestations at the MGS occur in the borders of the MT anomaly. Gas geochemical survey has been carried on in April 2009 and March 2010, sampling three fumaroles areas: Los Hoyos, La Plata and Pellado (Figure 5). The existence of fumaroles is evidence of a high enthalpy geothermal system at depth, due to the fact that such manifestations do not occur in association with low enthalpy reservoirs. The relative proportions of gases in the MGS fumaroles samples are typical of neutral high temperature geothermal reservoirs, no indications of acidic fluids have been found. The gas geothermometry indications are positive. (Table No.1) The hydrogen-argon geothermometer (Giggenbach, et al. 1991) which usually presents good correlation with the measured temperatures compared to other geothermometers, gives temperatures of 247-292°C, close to those obtained by using D'Amore and Panichi (1980), in the range 230-296°C. On the H_2/Ar versus CO_2/Ar plot (Figure 4), used to assess phase conditions, the samples plot slightly above the liquid equilibrium line, suggesting a two-phase or vapour-dominated deep reservoir with temperatures in the range of 200-250°C. Isotopic compositions support a local recharge of the reservoir, as expected. (Magma Energy Corp - ENERCO, 2011)

Table 1. Gas thermometry data for MGS fumaroles samples.

Date	Locality	T ºC H2/Ar, Giggenbach 1991	T ºC Dámore & Panichi, 1980
7-Mar-09	Los-Hoyos	272,2	270,0
7-Mar-09	Los-Hoyos	255,8	230,5
7-Mar-09	La-Plata	291,6	296,4
7-Mar-09	Pellado	284,4	285,7
8-Mar-09	Pellado	287,6	250,4
13-Mar-10	Pellado	284,7	242,7
13-Mar-10	Pellado	284,2	242,2
13-Mar-10	Pellado	283,8	239,8
12-Mar-10	La-Plata	282,2	291,0
14-Mar-10	La-Plata	290,1	291,3

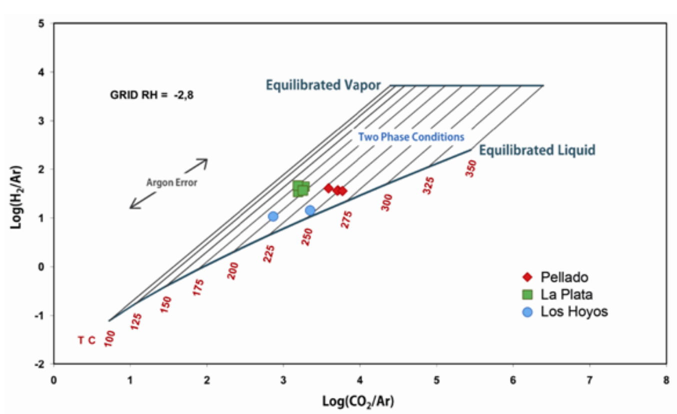

Figure 5. H_2/Ar-CO_2/Ar gas geothermometer showing gas samples from Pellado, La Plata and Los Hoyos fumaroles.

Geophysical Surveys

As part of the comprehensive geoscientific study of MGS, three types of geophysical surveys – magnetotelluric (MT), gravity and ground magnetic –were carried out in two stages – 2009 and 2010.

A large scale magnetotelluric (MT) survey took place in 2009 which successfully outlined the extent of the MGS. Results of the MT soundings were analysed as the survey progressed and as interesting low resistively features were imaged. This technique allowed Magma to rapidly focus it exploration efforts on a resistivity anomaly area on the extreme western border of the Laguna del Maule concession and to site the first exploration slimhole (MP 01), drilled in 2009. During 2010, additional geophysical surveys were commissioned comprising fill-in MT stations, plus gravity and magnetic surveys.

Magnetotelluric (MT) Survey

A 73 station MT survey was designed, supervised and interpreted over the Laguna del Maule area in early 2009 (Figure 8). Schlumberger (Geosystem) conducted the field data acquisition, data processing and 3D inversion modelling of the results. The survey extended across the entire Laguna del Maule exploration concession, with a denser coverage in the NW sector of the concession, were a low resistivity anomaly was identified.

The objectives of the MT survey were as follows:

1. 3-dimensional shape of all conductive zones in order to locate potential areas of reservoir and any preferential outflow directions
2. assessment of the geothermal resource in terms of lateral and vertical extent (area and volume)
3. Insights into the connection between shallow surface outflows producing the geothermal manifestations (Pellado, La Plata, Los Hoyos, Estero del Valle) and the deep geothermal reservoir
4. Sufficient data to designate exploration well targets

In 2010, another MT survey was undertaken including 19 extra soundings over the Mariposa prospect to increase the resolution of the geophysical picture and better constrain its extents (Figure 6).The general quality level was good, with only a few sites showing poor data quality. More importantly, data quality was very good in the central part of the geothermal system, where it matters most.

The modelling presented a clear picture of resistivity across the Mariposa geothermal system. A strong horizontal conductive layer extends from south of the Los Hoyos thermal area to near the Pellado fumarole, covering an area of about 27 km^2. This conductive layer lies at about 500 m depth beneath most of this area and is overlain by high resistivity which is indicative of cool and unaltered volcanic rocks. The extent of this conductive layer is assumed to be indicative of the extent of the subsurface geothermal system.

The low resistivity layer is of the order of 300-400 m thick, and is overlain by very high resistivity material which corresponds to the unaltered Quaternary volcanics at the surface. The elevation of the base of the low resistivity layer (contoured on Figure 8) varies between about 1700 and 2200 masl, and hence between about 250 m (near La Plata) and 1100 m below the surface (in the western lobe, approximately 3 km NNE of Pellado fumarole). It approximately coincides with the elevation of the smectite-rich zones that were observed in the three slimholes that have been drilled into the anomaly.

This conductor is typical of the clay alteration cap which forms over active geothermal systems. The shape of this feature highlights two main low resistivity centres joined by a narrow neck. It is possible that these may be caused by the presence of two upflow zones which may or may not be hydrologically linked. The clay cap interpretation was reinforced by temperature measurements from the three slimholes, indicating that the conductive cap corresponds to a zone in which temperatures increase with depth from about 50 or 100°C at the top of the conductor to about 200°C at its base, though admittedly the three slimholes cover only a small part of the area of the resistivity anomaly.

The four thermal areas that have been identified (Pellado, La Plata, Los Hoyos and Estero del Valle) all occur at the edges of this conductive feature, which supports the interpretation of it acting as an impermeable cap such that steam can only escape from the reservoir around the edges of the cap.

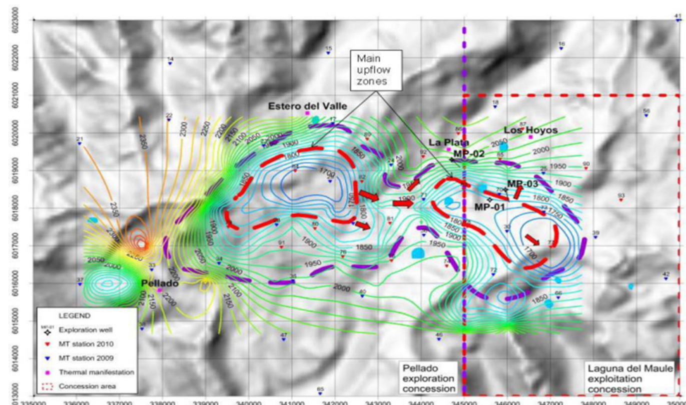

Figure 6. Combined 2009 & 2010 MT survey results.

The results of the ground magnetic survey indicate a complex pattern of highs and lows, and a predominantly ENE-trending magnetic fabric. The complete Bouguer gravity anomaly map indicates a gravity low that corresponds quite closely with the outline of the conductive zone indicated by MT surveys. The key finding from this study is that there is no evidence of intrusives within the geothermal field itself. Or if there are, that they are small, and/or of low density.

Well Data

Three cored exploration slimholes have been drilled in MGS (Figure 3, 4 & 6). The first of these, MP 01, was a helicopter assisted slimhole drilled May – June, 2009. In September 2009, construction of an access road began and in March 2010 Well MP 02 was spudded, followed by MP 03 in July (Figure 7). These wells provided detailed information of the subsurface lithology and contributed to the understanding of the geothermal characteristics of the MGS.

The geology encountered in MP 01 was largely as expected from an assessment of the local surface geology. The vertical hole drilled unconsolidated alluvial material (0-13 mMD), then through Quaternary volcanic rocks from LDMC (13 to 305 mMD) including: fresh basalts followed by tuffs interlayered with dacitic to andesitic lavas. Campanario Formation was encountered below (350-659 mMD) formed by dacites, lapilli tuffs, and pyroclastic breccias.

Within well MP 01, very little alteration was observed in the upper 200 mMD, with just minor calcite, smectite and iron oxides identified. Below 200 mMD, the alteration intensity gradually increased, and the mineralogy changed from interlayered illite-smectite, chlorite-smectite, tridymite and cristobalite above 500 mMD to illite, chlorite, quartz, calcite and adularia below 500 mMD. The argillic alteration is consistent with temperature logs. Epidote and prehnite are found in the lower portion of the well (below 540 mMD), but they are not in agreement with measured temperatures, hence do not represent current conditions.

Drilling difficulties forced the hole to BQ diameter in the last meters. Then a major snow storm in late June 2009, forced drilling termination. Despite the restricted diameter, a good PT run, using a Kuster K10 instrument was achieved by inserting the instrument inside the BQ pipe and running the log. A temperature of 202°C at 650m was achieved after 7 days (Figure 10).

Figure 7. Slimhole MP 03 drilled under winter conditions where seasonal snow fall exceeded 5 m.

MP 02 core inclined hole was drilled through unconsolidated alluvial material (0-6.8 mMD) and then through the Campanario Formation (6.8 to 551mMD) formed by dacitic lavas capping a thick sequence of coarse ash and lapilli tuffs, pyroclastic breccias and intermediate lavas. The Trapa-Trapa Formation was found below (551-862 mMD) formed by andesitic lavas interbedded with strongly altered pyroclastic breccias, tuffs and minor rhyolites. La Plata stock appeared in the final section of the well (862 -897 mMD).

Argillic alteration observed at MP 02 increases in intensity with depth. The secondary mineralogy is dominated by chlorite, interlayered chlorite-smectite and illite-smectite, with lesser calcite and quartz. Locally, veining and hydrothermal brecciation events are found, including quartz, calcite, chlorite, epidote, prehnite, Kfeldspar, garnet and amphibole. Epidote, prehnite, garnet and secondary amphibole occur as replacement and vein minerals, but they represent retrogressed mineral assemblages inconsistent with measured temperatures. The diorite is moderately altered to adularia, chlorite, calcite, prehnite, and epidote. Clay mineralogy is consistent with increasing temperatures and depth (Figure 10), although the high temperature secondary minerals (epidote, prehnite, amphibole and garnet) do not reflect current temperatures. The mineral assemblages are indicative of near-neutral pH fluids throughout the well.

The temperature-pressure logging using kuster K10 instrument were run in this well, both during drilling and afterwards (Figure 10). The maximum temperature recorded was 192.83°C in late December 2010, during this measurement the well flowed unassisted. After 10 hours it was closed in. In January 2011 the well was reopened and flowed for more than 20 days. The last temperature-pressure log was made March 2011 and the well flowed again while the measurement was run. Unfortunately, contamination from drilling fluid additives have not allowed for a definitive chemical analysis of the fluid.

Well MP 03 was drilled in July to November 2010 as an inclined exploration slimhole oriented to the southeast (Figure 6). After unconsolidated alluvial material (0-8.2 mMD), the core hole drilled through volcanics from LDMC (8-63 mMD) including fresh basalts, lapilli tuff, and dacitic to riolitic lavas. Below that, the Campanario Fm extends down (63- 823 mMD), including lapilli tuffs interlayered with minor pyroclastic breccias and dacites. Trapa-Trapa Fm is found in the lower portion of the well (823-1074 mMD), formed by andesitic lavas interlayered with minor lapilli and ash tuffs.

Detailed log by rig site geologist and petrographic analysis indicate argillic alteration assemblages increasing in intensity with depth, similar to those described for MP 02. This alteration is consistent with temperature logs. Retrogressive disequilibrium minerals are also found in some portions of MP 03 showing strong brecciation and veining. These assemblages include epidote, prehnite, garnet, secondary amphibole and platy calcite. These minerals are likely to reflect past rather than current reservoir conditions.

Several downhole Kuster temperature-pressure surveys were run at MP 03, both during and following drilling. A maximum temperature of 205.6ºC was recorded at 892.6 TVD (Figure 8), on November 8, 2010 during the early stage of the waterloss survey.

Permeability

Within the geological context where the Mariposa geothermal system is installed, secondary permeability is the main geomechanical characteristic that permits flow circulation. Secondary permeability of rocks should be controlled in first order by tectonic fracturing and subjected hydrothermal fluid circulation, resulting for pyroclastic rocks, in progressive dissolution of glass and the growth of secondary minerals (Wohletz and Heiken, 1992).

Along the drilled MP 01-MP 02 and MP 03 geothermal exploration slim wells, recorded loss circulation zones seem to be spatially associated with intense fractured zones and defined fault zones. In spite of that, several high fracture index levels, open cracks and fault zones do not show any circulation losses.

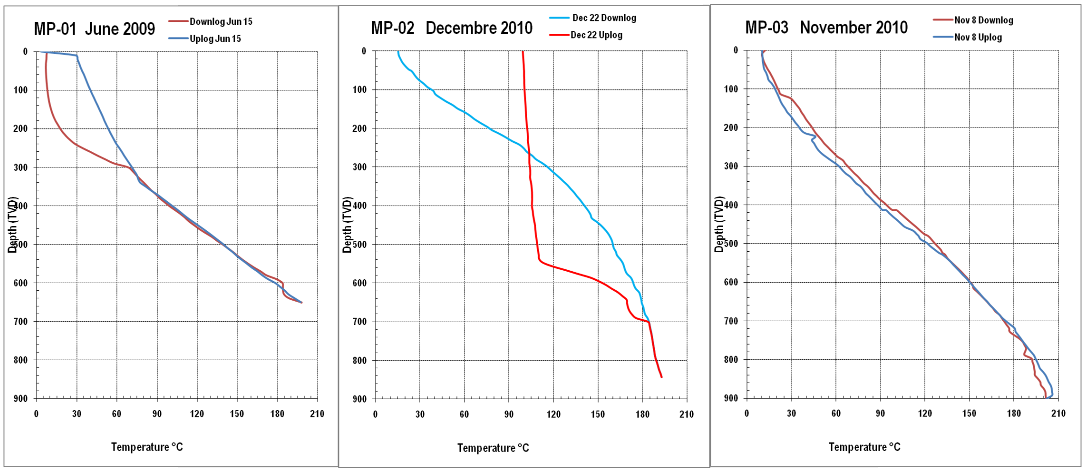

Figure 8. Temperature vs. depth logs for MP 01, MP 02 and MP 03 slimholes.

In a hydrostratigraphic sense, the upper volcanic cover (Quaternary basaltic to andesitic lavas), recorded high value of loss circulation, including levels with total loss circulation. For this portion, the recorded loss would be explained by connectivity between clean open fractures, becoming a unit of aquifer behaviours.

Bellow the Quaternary volcanic cover, lavas and pyroclastic rocks from the Campanario and Trapa-Trapa Formations, show a more random distribution of permeability. This is expected to be controlled by minor faulting and spatially related fracturing. Within this level, all the zone with loss circulation range from 55% to 100%, where detected associated to structures (minor faults and fractures).

Conceptual Model

The magnetotelluric (MT) survey results, in combination with geological mapping, geochemistry and distribution of thermal activity, originally defined an area of about 23 km^2 for the Mariposa geothermal system was used as the basis for inferred estimate of 320 MWe. The Canadian code compliant Resource Assessment Report issued by Magma in June 2010 (SKM 2010) is available on SEDAR through Alterra's corporate website. When the additional 2010 MT survey points were included, the revised 3D model indicated that the system covered a larger area of 27 km^2 (Figure 9). The inferred resource of 320 MWe has not been updated to reflect the larger area.

The MT data indicate that the top of the reservoir is sub-horizontal beneath terrain that generally slopes up to the south (Figure 6 & 9). This means that the geothermal resource is considered to occur as close as 250 m below the land surface near Los Hoyos fumarole, decreasing to about 1150m below surface to the west. These depths mean that the reservoir is easily accessible by drilling. Part of the area in the west will be difficult to access at the surface, but with deviated wells, most of the conjectured resource can be tapped.

The fluid chemistry appears to be benign with no indication of acidity or high gas content. Gas geothermometry from the fumaroles indicates deep reservoir temperatures in the range of 200-250°C, which is sufficiently high for a conventional condensing steam turbine plant, possibly supplemented by a binary plant, depending on the enthalpy actually encountered.

Gas chemistry indicates that the fumaroles emanate from localised steam zone(s) above a liquid reservoir, which together with the absence of any liquid outflows from the system (no warm springs in the valleys, and the MT resistivity shows no conductive zones surrounding the main resource area) implies that the system could be vapour dominated, with a deep water level. This will be resolved by deep drilling.

Summary

- The Mariposa Geothermal system is located in the Chilean Andes (36°S), inside an area characterized by extensive Quaternary volcanism associated with the Maule volcanic Complex and the Tatara-San Pedro-Pellado volcanic complex.
- Geology of the MGS project is characterized by thick and widely distributed Quaternary volcanic sequences from the Laguna del Maule and the Tatara-San Pedro-Pellado volcanic complexes. These rocks range from basalt to rhyolites, including lavas, domes, and pyroclastic deposits. They cover unconformably the Campanario Formation (Miocene),

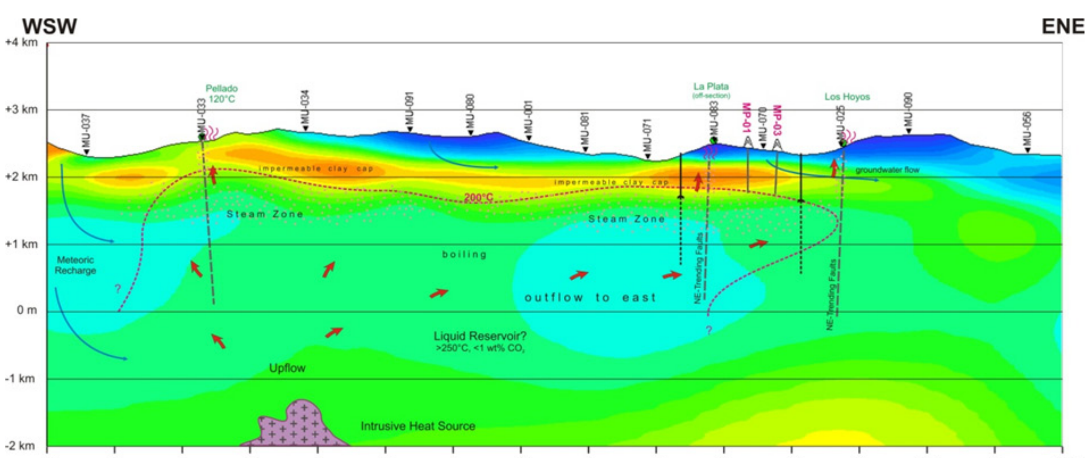

Figure 9. MGS Conceptual model shown as a WSW-ENE MT cross section through the resistivity anomaly. Location of fumaroles, slimhole wells, and inferred temperatures and fluid flow paths are indicated.

mostly formed of intermediate tuffs and minor andesitic to dacitic lavas. The Curamallin Formation (Eocene-Miocene) is found below Campanario. The contact between both formations is an angular unconformity. The Curamallin Formation, formed by basaltic to andesitic volcanic and volcaniclastic with minor sedimentary rocks, is folded and faulted, contrasting with the undeformed Campanario Formation. Finally, Cretaceous to Miocene intrusives rocks are found along with dykes which cut all the basement sequences up to Pleistocene volcanic.

- The tectonic regime in the MGS project area is mainly controlled by ENE subvertical, extensive structures that have controlled the emplacement of the Quaternary volcanic centers and extended dike swarms.
- The result of two MT campaigns in the project area, confirmed an extended (23 km^2) low resistivity anomaly distributed between the LDM and Pellado concessions, both granted to Magma Energy Chile Ltda, and operated by the subsidiary ENERCO.
- Geothermal manifestations located around the border of the MT anomaly, have reported favourable gas chemistry data, consistent with the presence of a steam–dominated reservoir at depth. Geothermometers applied to samples from different years report stable conditions and reservoir temperatures in the range 247-290 °C. There are no evidences of acidic conditions.
- Three wells have been drilled in the eastern sector of the MGS. Drilling difficulties have affected the drilling under the rigorous winter conditions of the Chilean Andes. The wells have reached the upper part of the reservoir only, recording temperatures over 200°C.

Acknowledgments

The companies and consultants who worked with Magma on this project are thanked for their dedication and professionalism. Much of the data referred to in the paper comes from internal Magma documents. Magma staff, Dr. Carlos Arevalo contributed significantly to the structural interpretation of the MGS and several figures were drafted by cartographer Rodrigo Acha. Both individuals no longer work for Magma, but are thanked for their contributions.

References

Charrier, R., Baeza, O., Elgueta, S., Flynn, J.J., Gans, P., Kay, S.M., Muñoz, N., Wyss, A.R., Zurita, E. 2002. Evidences for cenozoic extensional basin development and tectonic inversion south of the flan-slab segment, southern Central Andes, Chile, 33°36°S.L.). *Journal of South American Earth Sciences*, v. 15, p. 117-139.

Costa, F., Singer B. 2002. Evolution of Holocene dacite and compositionally zoned magma, Volcán San Pedro, Southern Volcanic Zone, Chile. *Journal of Petrology,* v. 43, No. 8, p.1571-1593

D'Amore, F., and C. Panichi, C. 1980. Evaluation of deep temperatures of hydrothermal systems by a new gas geothermometer. *Geochimica et Cosmochimica Acta*, v. 44, p. 549–556

Davidson, J.P., Ferguson, K.M., Colucci, M.T., Dungan, M.A. 1988. The origin and evolution of magmas from the San Pedro-Pellado volcanic complex, S. Chile: multi-component sources and open system evolution. Contrib. Mineral. Petrol., v. 100, p. 429-445.

DeMets, C.; Gordon, R.; Argus, D.; Stein, S. 1994. Effect of recent revisions to the geomagnetic reversal time-scale on estimates of current plate motions. *Geophysical Research Letters,* Vol. 21, No. 20, p. 2191-2194.

Drake, R.E., 1976. Chronology of Cenozoic Igneous and Tectonic Events in the Central Chilean Andes. Latitudes 35°30'to 36°S. *Journal of Volcanology and Geothermal Research*, v.1, p. 265-284.

Dungan M.A., Wulff A, Thomson R. 2001. Eruptive stratigraphy of the Tatara-San Pedro Complex, 36°S, Southern Volcanic Zone, Chilean Andes: Reconstruction method and implications for magma evolution at long-lived arc volcanic centers. *Journal of Petrology,* v 42, No. 3, p. 555-626.

Frey, F.A., D.C. Gerlach, R.L. Hickey, L. Lopez-Escobar, and F. Munizaga-Villavicencio. 1984. Petrogenesis of the Laguna del Maule volcanic complex, Chile (36°S). *Contributions to Mineralogy and Petrology*, v 88, p. 133-149.

Giggenbach, W.F. 1992, Isotopic shifts in waters from geothermal and volcanic systems along convergent plate boundaries and their origin. *Earth and Planetary Science Letters***,** v. 113, p. 495-510.

Giggenbach, W.F. and Goguel, R.L. 1989, Collection and analysis of geothermal and volcanic water and gas discharges, DSIR report CD 2401, 4th ed., Pentone, New Zealand.

Giggenbach, W. F. 1991. Chemical techniques in geothermal exploration. In: Applications of geochemistry in geothermal reservoir development. Edited by Franco D'Amore. Unitar. Rome-Italy. Pp 119-144.

Giggenbach, W.F. and Stewart, M.K. 1982. Processes controlling the isotopic composition of steam and water discharges from steam vents and steam-heated pools in geothermal areas. *Geothermics*, v.11, No. 2, p. 71-80.

Gonzalez-Ferrán, O. & Mario Vergara M. 1962. Reconocimiento Geológico de la Cordillera de Los Andes entre los paralelos 35° y 38° Latitud Sur. Universidad de Chile, Facultad de Ciencias Físicas y Matemáticas, Instituto de Geología. Ed. Universitaria S.A.

Hauser, A. 1997. Catastro y Caracterización de Fuentes Termales y Minerales de Chile. Boletín Nº 50, Subdirección Nacional de Geología, SERNAGEOMIN**.**

Hildreth, W., J. Fierstein, E. Godoy, R.E. Drake & B. Singer. 1999**.** The Puelche Volcanic Field: extensive Pleistocene rhyolite lava flows in the Andes of central Chile. *Revista Geológica de Chile*, v.26, No.2, p 275-309.

Hildreth, W., Godoy, E., Fierstein, J., and Singer, B. 2004. Quaternary eruptive history of the Laguna del Maule volcanic field, Chilean Andes (36°S), Proceedings IAVCEI General assembly, Pucón, Chile.

López-Escobar, L.; Cembrano, J.; Moreno, H. 1995. Geochemistry and tectonics of the Chilean Southern Andes basaltic Quaternary volcanism (37-46°S). *Revista Geológica de Chile*, v. 22, No. 2, p. 219-234.

Magma Energy Corp - ENERCO, 2011. Development Plan for the Laguna del Maule Project, Chile. Unpublished internal document, 233 pgs.

Mpodozis C, Ramos VA. 1989. The Andes of Chile and Argentina. In: Ericksen GE, Cañas MT, Reinemund JA (eds) Geology of the Andes and its relation to hydrocarbon and mineral resources, vol. Circum Pacific Council for energy and mineral resources, Earth Sciences Series, Houston, Texas, v. 11, p. 59-90.

Munizaga, F. 1979. Geología del Complejo Volcánico Laguna Del Maule. Memoria Universidad de Ciencias Físicas y Matemáticas Universidad de Chile, Departamento de Geología.

Muñoz, J y Niemeyer, H. 1984. Hoja Laguna Del Maule. Carta Geológica de Chile, 1:250.000., no. 64. Servicio Nacional de Geología y Minería.

Naranjo J, Haller M. 2002. Erupciones holocenas principalmente explosivas del volcán Planchón, Andes del sur (35°15'S). *Revista Geológica de Chile*, v. 29, No.1, p. 93-113

Nelson, S.T., J.P. Davidson, M.T. Heizler & B.J. Kowallis. 1999. Tertiary tectonic history of the southern Andes: The sub-volcanic sequence to the

Tatara–San Pedro volcanic complex, lat 36°S. *GSA Bulletin*; Sept.1999; v.111; No.9; p.1387–1404.

Powell, T. 2000, A Review of Exploration Gas Geothermometry, Proceedings, 25th Workshop on Geothermal Reservoir Engineering, Stanford University, Stanford, CA, SGP-TR-165.

Singer B.S., R.A. Thompson, M.A. Dungan, T.C. Feeley, S.T. Nelson, J.C. Pickens, L.L. Brown, A.W. Wulff, J.P. Davidson, & J. Metzger. 1997. Volcanism and erosion during the past 930 k.y. at the Tatara–San Pedro complex, Chilean Andes. *GSA Bulletin*; v. 109; No. 2; p. 127–142.

Stern, C.R. 2004: Active Andean volcanism: its geologic and tectonic setting. Revista geológica de Chile, Vol. 31, No. 2, pp. 161-206.

Stern, C. and Kilian, R. 1996. Role of the subducted slab, mantle wedge and continental crust in the generation of adakites from the Andean Austral Volcanic Zone. *Contributions to Mineralogy and Petrology*, v. 123, p.263-281.

SKM, 2010a: Mariposa Geothermal Resource, Laguna del Maule and Pellado Concessions, Chile. Resource Estimate. Unpublished report for Compañía de Energía Limitada (ENERCO). (Available on SEDAR) http://www.alterrapower.ca/corporate-profile/Company-SEDAR-Links/default.aspx

Tamaki, K. 1999. Nuvel-1A calculation results. Ocean Research Institute, University of Tokyo. http://manbow.ori.u-tokyo.ac.jp/tamaki-bin/post-nuvella.

Thiele, R. 1980. Hoja Santiago Carta Geológica de Chile, No. 39, escala 1:250.000. Servicio Nacional de Geología y Minería.

Thorpe, R.S. 1984, The tectonic setting of active Andean volcanism, *in* Harmon, R.S. and Barreiro, B.A., eds, Andean Magmatism, Cheshire, Shiva Pub. Ltd., p. 4-8.

Thorpe, R.S. and Francis, P.W. 1979, Variations in Andean andesite compositions and their petrogenetic significance: *Tectonophysics*, v. 57, p. 53-70.

Wohletz, K. and Heiken, G. 1992. Volcanology and Geothermal Energy. University of California. Pag340-342