NOTICE CONCERNING COPYRIGHT RESTRICTIONS

This document may contain copyrighted materials. These materials have been made available for use in research, teaching, and private study, but may not be used for any commercial purpose. Users may not otherwise copy, reproduce, retransmit, distribute, publish, commercially exploit or otherwise transfer any material.

The copyright law of the United States (Title 17, United States Code) governs the making of photocopies or other reproductions of copyrighted material.

Under certain conditions specified in the law, libraries and archives are authorized to furnish a photocopy or other reproduction. One of these specific conditions is that the photocopy or reproduction is not to be "used for any purpose other than private study, scholarship, or research." If a user makes a request for, or later uses, a photocopy or reproduction for purposes in excess of "fair use," that user may be liable for copyright infringement.

This institution reserves the right to refuse to accept a copying order if, in its judgment, fulfillment of the order would involve violation of copyright law.
Exploration of the La Torta Geothermal Prospect, Northern Chile

William B. Cumming', Hugo Vieytes2, Carlos F. Ramírez2, and David Sussman3

1Cumming Geoscience, Santa Rosa, California, USA
2Empresa Nacional del Petróleo (ENAP), Santiago, Chile
3Geotérmica Limitada, S.A., Santiago, Chile

Keywords
Geothermal, exploration, MT, TDEM, magnetotellurics, resistivity, geochemistry

ABSTRACT

Geochemical and geophysical surveys completed in 2002 at the La Torta geothermal prospect by Geotérmica del Norte (GDN) have identified drilling targets for a high temperature resource extending 5 to 10 km southeast of the El Tatio geothermal field. Temperature and geochemistry data from El Tatio indicated that, although several of the 13 bore holes drilled between 1968 and 1974 to depths of up to 1800 m were completed in a shallow <225°C outflow, several encountered a higher temperature outflow from a >260°C geothermal resource. Because the prospective areas near El Tatio extended over more than 150 km² with limited access at elevations of 4300 to 5300 m, few geothermal exploration results were reported for the adjacent La Torta area. Based on regional geology and the extrapolation of trends detected in a 1996 El Tatio MT-TDEM survey, a previously unreported hot spring and gas seep were discovered in 1998 north of the La Torta dacite dome, about 10 km southeast of the El Tatio wells. Following GDN's acquisition of the La Torta geothermal concession in 2002, geochemistry and geophysics studies including a 52 station MT-TDEM survey, were completed. A low resistivity hydrothermal smectite clay zone was found to extend more than 15 km southeast of El Tatio, continuing beneath the La Torta dome and covering more than 50 km². Cross-sections showed an apex in the base of this clay “cap” on the La Torta Concession, about 2 km north of the La Torta dome. Similar features have been correlated with permeable shallow, high temperature zones in many geothermal fields. GDN has begun preparations to drill a deep well targeting this area in late 2002 in order to prove a commercial resource.

Introduction

The La Torta Geothermal Concession acquired by Geotérmica del Norte (GDN) in December 2000 is in Northern Chile (Figure 1) about 1400 km north of Santiago and 70 km east of the city of Calama. GDN, a joint venture between CODELCO, the national mining company of Chile, and ENAP,

![Figure 1. Location map of the La Torta Prospect in northern Chile.](image-url)
the national oil company, was formed in 2001 to exploit geothermal business opportunities in northern Chile created by the enactment of Chilean laws and regulations governing geothermal development. In late 2001, GDN began following up preliminary exploration work conducted by ENAP in an earlier 1995-99 partnership with Unocal Corporation.

The interest of ENAP and its partners was first drawn to the La Torta prospect while exploring for a >250°C geothermal reservoir near the El Tatio geothermal field (Figure 2). Although all of the 13 wells drilled at El Tatio between 1968 and 1974 appeared to be on an outflow margin, several wells achieved geothermal production from a ~250°C aquifer than had chemistry compatible with a >260°C neutral chloride reservoir. In the search for this reservoir, a series of geoscience surveys were completed by ENAP and its partners from 1995 to 2002 that successively directed attention further southeast in the direction of La Torta dome. Although it was close to El Tatio, no earlier geothermal exploration work in the La Torta area had been reported. A ENAP/Unocal team confirmed the existence of thermal features in 1998, leading to the current exploration campaign.

To illustrate how the exploration program in this area led to the current plan to target wells at La Torta, we briefly outline earlier exploration results at El Tatio, summarize the more recent La Torta and El Tatio geochemistry, and review the resistivity imaging provided by the 2002 magnetotellurics survey with co-located time-domain-electromagnetics (MT-TDEM). The integration of these data into a geothermal resource conceptual model supports the targeting of a deep geothermal exploration well at La Torta.

**Geothermal Exploration at El Tatio and La Torta Before 2001**

Starting in 1968, CORFO, a Chilean government development corporation, drilled 13 wells at El Tatio with United Nations support, labeled 1 to 13 in Figure 2. Of the first six slim holes drilled 571 to 733 m deep near the most prominent thermal manifestations, Well 3 encountered the highest temperature of 252°C. Wells 7 to 13 were drilled from 873 to 1816 m deep in an area of less than one km² near Well 3. Maximum temperatures were 230 to 256°C and, although most of the wells produced some steam, shallow casing and well damage complicated testing. Production capacity in 1981 based on short tests was about 15 MWe. Geochemical and downhole temperature interpretations suggested that the wells encountered several discrete aquifers. Two hot outflow aquifers shallower than 600 m had temperatures <170°C and showed evidence of mixing with cold meteoric water. Well 2 and perhaps several other wells encountered hypersaline fluids below 600 m depth, possibly related to evaporite deposits common in this area. Much of the production came from a neutral chloride brine at temperatures from 225 to 250°C. Most wells showed temperature reversals, indicating that they had encountered a tabular outflow flowing to the west and north from an area to the east or south of Wells 7 to 13.

Although the pattern of the more easily accessed hot springs and fumaroles was the most important factor used in targeting the first six wells at El Tatio, surface geochemistry and resistivity surveys were also considered. Schlumberger sounding and profiling surveys with relatively shallow depth of investigation (<600 m) were conducted (Hochstein, 1971). Macdonald (1974) reviewed all of the resistivity data in light of the drilling results and identified an area to the east of the existing deep bore field as the most prospective for a deep high temperature resource. Lahsen and Trujillo (1976a and b) integrated the geochemistry and shallow alteration studies of Armbrust, et. al., (1974) and Cusicanqui et al. (1976) and came to a similar conclusion. Subsequent studies were also influenced by the interpretation of isotope data in Giggenbach (1978) which implied that El Tatio reservoir fluids were derived from meteoric water from the east. Several proprietary reservoir studies were conducted in the early 1980's before economic reorganization and the lack of a legal basis for geothermal development in Chile halted further assessment work.

In anticipation of a new geothermal resource law, from 1995 to 1999 ENAP worked in partnership with Unocal Corporation to review the existing well, geophysics and geochemistry data and conduct new surveys. Additional thermal manifestations were discovered and sampled at high elevation to the east and southeast, new samples were taken for gas geochemistry analyses, remote sensing imaging analyses were completed and, in
1996, an MT-TDEM survey was completed to evaluate the probable extent of the postulated deep resource at El Tatio. The 23 MT-TDEM sites recorded in 1996 shown in Figure 2 were interpreted in conjunction with gas geochemistry as being consistent with a 250 to 300°C resource extending to the east and southeast of the existing El Tatio deep bore field. Geophysical trends and regional geological studies led to a search for thermal manifestations near the La Torta dacite dome, 10 km to the southeast of the main El Tatio borefield. In 1998, an ENAP/Unocal team discovered hot springs and gas seeps near 4800 m elevation at La Torta. After Unocal withdrew from geothermal exploration in Chile in 1999, ENAP continued the exploration of this area and created the GDN partnership with CODELCO in 2001 to accelerate the project.

Geology and Geochemistry of the La Torta Region

The geology of the La Torta area is assumed to be similar to the section drilled at El Tatio (Lahsen and Trujillo, 1976b; Hauser, 1997). The lithology is dominated by thick Tertiary ignimbrite flows, of which two, the permeable Puripicar and Salado units, host the >225°C tabular outflow at El Tatio (Figure 3). The stratigraphy from the El Tatio wells suggests a thickening of these and similar units to the southeast. Most of the El Tatio cores in these units had relatively high porosity of over 15%. The oldest rocks at the surface in the area, Mesozoic sediments exposed along a north-south structural trend to the west, are unlikely to be encountered in a well at La Torta since they were not found in the deep wells at El Tatio and La Torta is over 500 m higher in elevation.

The tabular Pleistocene La Torta dacite dome (Figure 2) is part of a series of similar domes extending along a large-scale southeast structural trend that is prominent in satellite imagery. The presence of altered ground between La Torta and the Sol de Mañana geothermal field 20 km to the southeast in Bolivia further suggests a large scale alignment of hydrothermal manifestations along regional trends in magmatic intrusion that has created an extensional structural environment along its crest. The most recent local structures at El Tatio appear to trend northeast and southeast. These are evidenced by the pattern of hot springs at El Tatio and the geometry of the low resistivity clay cap detected using MT-TDEM.

The pattern of thermal manifestations at La Torta-El Tatio is characteristic of high relief volcanic areas. Chloride springs from water derived from a geothermal reservoir are found in outflow areas outside the exploitable margins of the reservoir. Acid-sulfate thermal manifestations created by gases rising through a vadose zone are found over the high temperature reservoir itself. Although cation geothermometry of chloride springs may provide a more reliable estimate of the minimum temperature of equilibration for a parent geothermal fluid located within

![Figure 3. Conceptual cross-section A-A' of the La Torta Geothermal Prospect showing its relationship to the El Tatio Geothermal Field. The well temperatures found at El Tatio are contoured with an irregular interval designed to highlight likely flow directions. The resistivity contours from 2D inversions of MT-TDEM data illustrate the "dome" in the base of the smectite clay cap centered between La Torta and the Cerros del Tatio summit.](image-url)
1 to 20 km, experience from other fields suggests that qualitative trends in the gas analyses of acid-sulfate manifestations are more likely to reflect trends in properties of an underlying reservoir (Powell, 2000). Therefore, they tend to be more relevant to targeting specific exploration wells.

The cation geothermometry of water from the El Tatio chloride springs northeast of Wells 7 to 13 and from water produced from the wells themselves is consistent with the isotherms from the well logs in Figure 3. A 250°C tabular aquifer outflows to the northwest along the Puripicar and Salado ignimbrites at about 600 m depth, cooling to <225°C. Mixing from 170°C and cooler shallower aquifers is also apparent in the cation spring chemistry. The isotherm model suggests that a new exploration well should be targeted to the east or southeast of El Tatio but does not indicate a specific location. Gas geochemistry at La Torta-El Tatio does qualitatively suggest a likely upflow area for the resource. Consistent N2/Ar and He isotopes and scattered but generally consistent geothermometry of 250 to 280°C suggest that the gas seep at La Torta originates from the same hydrothermal system as the gases from the El Tatio fumaroles. The trend in gas concentrations between the gas seep at La Torta and the fumaroles near El Tatio Wells 6 and 7 suggest progressive southeast to northwest depletion of less water-soluble gases relative to CO2, consistent with an upflow near the La Torta gas seep.

La Torta Geophysics

The geophysical program completed in 2002 extends the 1996 MT-TDEM coverage of El Tatio further to the south onto GDN’s La Torta geothermal concession (Figure 2). As illustrated in cross-section A-A’ in Figure 3, the overall MT-TDEM resistivity pattern resolved by the combined La Torta-El Tatio surveys is typical of areas hosting geothermal reservoirs (Cumming, et al., 2000). A relatively resistive 50 to 200 ohm-m zone of unaltered surface rocks overlies a 1 to 10 ohm-m low resistivity smectite clay alteration zone that is domed over the apex of an underlying, relatively resistive 10 to 100 ohm-m high temperature geothermal reservoir. The geometry of the base of the smectite cap at La Torta is illustrated in the Figure 2 contours showing the elevation of the base of the <10 ohm-m zone derived from 2D smooth inversions supplemented by a 3D smooth inversion. The base of the smectite zone forms a dome centered south and to the east of the Cerros del Tatio ridge (Figure 3), covering an area greater than 10 km². Much of the smectite alteration in this domed area is apparently associated with aquifers perched in the vadose zone above the water table at about 4300 m elevation. From the apex in the smectite alteration zone at La Torta, conductive clay alteration dips down to the northwest and southwest, capping tabular >250°C high permeability outflow paths like the one associated with the El Tatio hot springs and fumaroles. Structural highs in the base of the clay cap resolved by MT at other geothermal prospects correlate with structurally high, productive zones in underlying high temperature reservoirs (Anderson, et al., 2002).

Although the conventional scheme for interpreting geothermal resistivity is consistent with most of the La Torta MT-TDEM observations, some aspects of the data set are unusual. The most serious interpretation issue is that, in comparison to most geothermal fields of comparable apparent size and environment, the smectite alteration zone at La Torta has a relatively high average resistivity, generally 3 to 20 ohm-m rather than 1 to 10 ohm-m. The Sol de Mañana field, at over 5000 m elevation 20 km to the southeast in Bolivia, has a thick, low resistivity clay cap despite a similarly dry climate and deep water table. An unusually high proportion of difficult to alter, low porosity lavas increases resistivity over parts of several geothermal reservoirs (Cumming, et al., 2000) but this is not expected at La Torta. The relatively high resistivity of the La Torta clay cap is more likely to be related to water chemistry, temperature and alteration rather than to lithology or aquifer elevation.

A variety of water chemistry and temperature related mechanisms could account for the high resistivity of the La Torta clay cap. Meteoric water circulating through the massive sulfur deposit on Cerros del Tatio produces acid-sulfate surface water that is often associated with types of clay alteration more resistant than smectite. Sulfate water in perched aquifers would be incompatible with chloride water in the reservoir, causing anhydrite precipitation in permeable paths where they mixed, consistent with both the relatively resistive cap and the lack of vigorous surface thermal manifestations near the apparent La Torta reservoir apex. The inactive Tatio sulfur deposit suggests that at least part of the La Torta prospect underwent a high temperature, high-sulfadation stage that has waned, probably resulting in relict, relatively high resistivity alteration in the smectite zone. It also implies an increased chance of encountering an isolated low volume acid aquifer and a localized low permeability zone around it, a pattern observed in several geothermal fields (Reyes, et al., 1993). To target the high permeability upflow at La Torta that is the source of the very vigorous high temperature outflow evidenced in the El Tatio wells and springs, wells will be directed at the most promising structural targets while avoiding relict high-sulfadation zones.

An unusual aspect of the correlation of the MT-TDEM with the El Tatio well data is that the extremely thick conductive zone adjacent to El Tatio is only partly due to smectite alteration in basinal volcanoclastics as is common on geothermal field margins. Figure 3 shows that the high temperature sections of the El Tatio wells correlate with resistivity in the low range for reservoirs, 3 to 15 ohm-m. Measurements of smectite in El Tatio well cuttings samples using the methylene-blue (MeB) method (Gunderson, et al., 2000) indicate that smectite clay alteration can account for low resistivity only in the top 300 m of these wells. The deeper low resistivity has been partly attributed to 15,000 ppm chloride water at >220°C saturating the unusually porous ignimbrites found in well cores. However, the detection of hypersaline fluids below 600 m depth in the northern El Tatio wells suggests that buried evaporites may be the principal cause of this resistivity pattern. The very thick low resistivity on the northwest end of cross-section A-A’ is consistent with a saline basin bordering the northwest margin of El Tatio. Other sections
show a similar feature on the southwest margin of La Torta. Fault control is suggested by the apparent abruptness of the resistivity boundaries. However, the higher than 10 ohm-m resistivities below the smectite zone throughout the expected resource area suggests that hypersaline brines are not a serious concern within the reservoir.

Conclusions

The focus of the geothermal exploration activity that started at El Tatio in 1968 progressively shifted southeastward and, in 2002, identified a large geothermal prospect on GDN’s La Torta geothermal concession area. The current conceptual model in Figure 3, based on integrated geochemistry, geology and MT-TDEM data, shows a resource centered near the Cerros del Tatio and the La Torta dome. This is the primary target for the 2002-03 drilling program.

The exploration work conducted in 2002 addressed a variety of risk issues including resource size, quality and well targeting. Some earlier concerns were mitigated; for example, the MT-TDEM resistivity images suggest that potentially corrosive hypersaline water detected in the northern El Tatio wells is unlikely to impact production in a La Torta resource development. Although large inactive sulfur deposits and a clay cap with only moderately low resistivity might imply higher risk of encountering zones of low permeability in a high temperature reservoir at La Torta, this can be mitigated by targeting structurally suitable areas while avoiding suspected high-sulfidation zones. The pattern of the resistivity is consistent with a relatively shallow resource and the expected lithology and structural environment based on patterns extrapolated from El Tatio and regional data are favorable. The first La Torta wells are being designed to quickly discover a large, economically viable resource.

Acknowledgements

Thanks are due to Marc van Gerven (then with Unocal) who assisted ENAP teams in the discovery of the La Torta thermal manifestations and advised on safely exploring the prospect.

References


