CERRO TUZGLE GEOTHERMAL PROSPECT, JUJUY, ARGENTINA

Beatriz Coira

UNIVERSIDAD NACIONAL DE JUJUY-CONICET
casilla de Correo N° 258 (4600) S.S. de Jujuy-Argentina

Key words: heat flow, magnetotelluric survey, geothermometry, Cerro Tuzgle field, Argentina

ABSTRACT

Cerro Tuzgle geothermal prospect (24°S, 66°05'W) is located on the east central Puna plateau, Argentina, ~275 km east of the main front of the central volcanic zone. The geothermal potential is connected to quaternary back-arc volcanism represented by the Tuzgle center (high-K rhyodacites to mafic andesites), the result of complex mixing processes in the mantle and thickened crust (>50 km), during *0.5* Ma and Recent.

Heat anomalies are exposed at the surface as hot *Springs* with temperatures of 40°-56°C. Geochemical water studies indicate mixtures between deep and shallow waters and geothermal reservoir temperatures of 132°-142°C (according to geothermometers).

MT measurements gave two conductive layers: one (superficial reservoir) between 100 and 200 m depth (permeable Upper Miocene ignimbrites) and another at 2 km depth which could *represent* a deep geothermal reservoir. A magmatic body may also be inferred, by MT and Gravity studies, beneath the Tuzgle volcano at 5-11 km depth

Based on the investigation a ~28 km² area in the SW-W margin of Tuzgle volcano has been selected to develop a future deep drilling exploration plan.

1. INTRODUCTION

Cerro Tuzgle geothermal prospect is located at 24°S-66°30'W *on* the east Central Puna plateau, Argentina. The geothermal field is connected to Tuzgle volcano, one of the easthernmost Quaternary centers *(0.5* ME-Recent) of the Central Volcanic Zone, ~275 km *east* of the main front.

As the result of a geothermal reconnaissance *study* by Aquater SPA (ENI Group, Italy) during 1978-79 in the Puna zone, the Cerro Tuzgle area (900 km²) was chosen to *carry* out a high enthalpy geothermal prefeasibility *study*. It was initiated in 1980 by Aquater SPA, Jujuy Mining Direction and Mining *secretary* and consist of geovolcanological, hydrogeological and geochemical *studies*.

The second phase of the prefeasibility-study performed by Hydroproyectos SA-Setec SRL-Cepic SC, during 1983 and 1984, was aimed at providing *geophysical* and tectonic information and completing volcanological and hydrochemical data. The third phase, focuses on geoelectric profiles, chemical and isotopic hydrogeology and tectono-volcanic studies, was carried out in 1987/88 by Jujuy Goverment, CREGEN and Universidad Nacional de Jujuy.

Finally a drilling program of temperature gradient wells has been performed in a selected area of 85 km² during the 1989 and 1990 summers.

The purpose ofthis paper is to analyze and interpret the subsurface results obtained on C° Tuzgle field to propose a geothermal model and to define a future feasibility *study.*

2. GEOLOGICAL SETTING

The Tuzgle volcano area occurs near the northern end of the tectonic transition zone in the Puna (24° to 28°S) under which the *subducting* plate gradually shallows from the more steeply dipping segment, north of 249, to the shallowly dipping volcanically inactive segment (flat slab), between -28° and 33°S. The High-Potassium Tuzgle center as several small shoshonitic *centers*(San Gerónimo and Chorrillos) developed along extensional Quaternary faults of the OLACAPATO - EL TORO lineament (Fig.1). Volcanic activity in the *study* area postdate extensive Miocene to early Pliocene andesitic and dacitic eruptions from large centers like Queva (Fig. 2 B). These older eruptions are associated with plateau uplift (Coira and Knox, 1989; De Silva, 1989) which resulted primarily from crustal thickening and shortening over a shallower subduction zone than exists today (Isacks, 1988). Subsequent steepening of the subduction zone caused Pliocene and younger magmatic activity to be concentrated further west. Renewed back-arc volcanism in the Tuzgle region followed a reorientation of the regional stress pattern in the Puna back-arc. This change can be observed south of the El Toro lineament, where a late Tertiary pattern of WNW-ESE compression and vertical extension was replaced by a late Pliocene to Recent pattern of predominantly east-wed compression and horizontal north-south extension (Allmendinguer et al, 1989). Mafic volcanic flows with intraplate-like or back-arc calc-alkaline chemical signatures (Knox et al, 1989; Kay et al, 1990) and well-defined young normal and strike-slip faults are common in this region. North of the Olacapato-El Toro lineament, evidence for n o d and strike-slip faulting is less obvious and small young back arc flows have shoshonitic signatures.

The Tuzgle volcano is placed in the central part of a tectonic depression N-S elongated, delimited by normal faults and separated southward from Tocomar-Olacapato depression by a WNW-ESE horst of lower Paleozoic rocks (Mon, 1987). The volcanic products rest *on* a thick complex basement constituted by clastic and volcanic upper tertiary sequences (Trinchera Formation and Pastos Chicos Formation, Schwab, 1973), upper cretaceous *sedimentary* rocks, marine Ordovician shales and sandstones interbedded with dacitic volcanic rocks and Late Precambrian-Upper Cambrian shales and slates of the Puncoviscana Formation (Coira and Paris, 1981).

Heat anomalies are represented in the depression by hot *Springs* as Tuzgle *Agua* Caliente, in Qda. *Agua* Caliente, (Fig. 2 A) with 40°-56°C and at Planta Mina Betty with 21°.

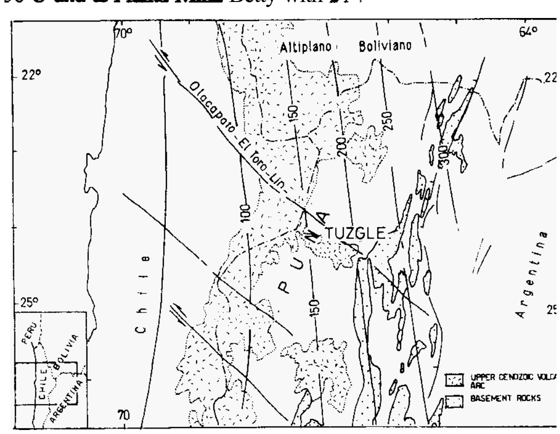
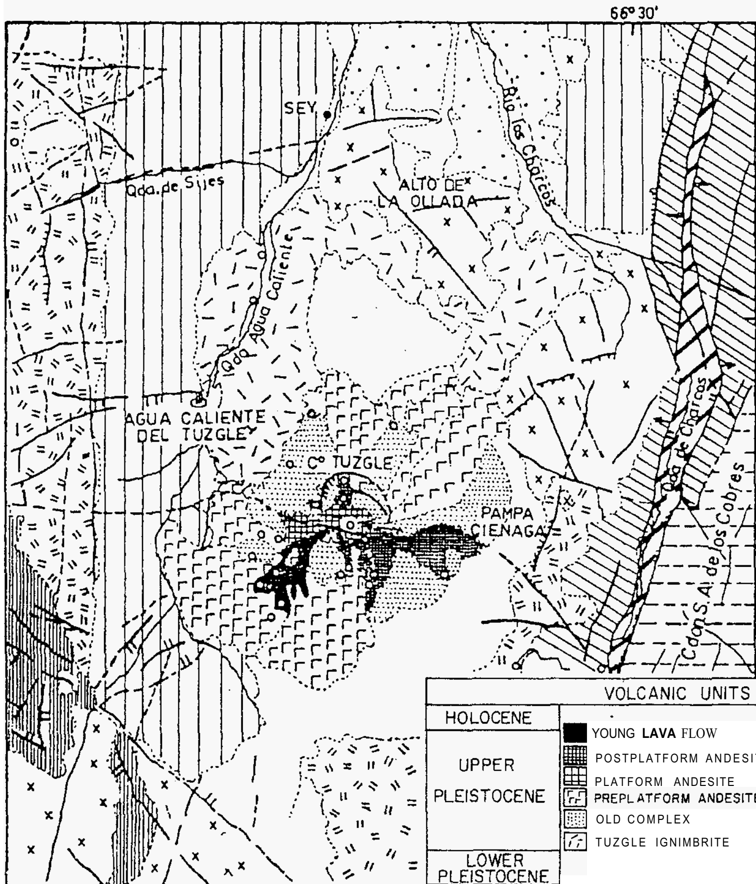


Fig. 1 Mapa of the Andes between 21' and 27°S showing location of Tuzgle geothermal area on the eastern margin of the Puna plateau, relative to 50 km contours to the Benioff zone.

3. VOLCANOLOGY

3.1 Eruptive history of Tuzgle

Tuzgle volcanic activity began at 0.5 ma with the eruption of ~0.5 km³ of dacitic ignimbrite (TUZGLE IGNIMBRITE) which *created*



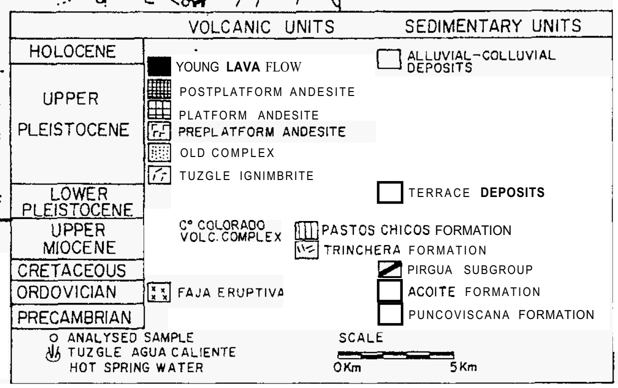


Fig. 2A Map of Tuzgle volcano showing distribution of principal units.

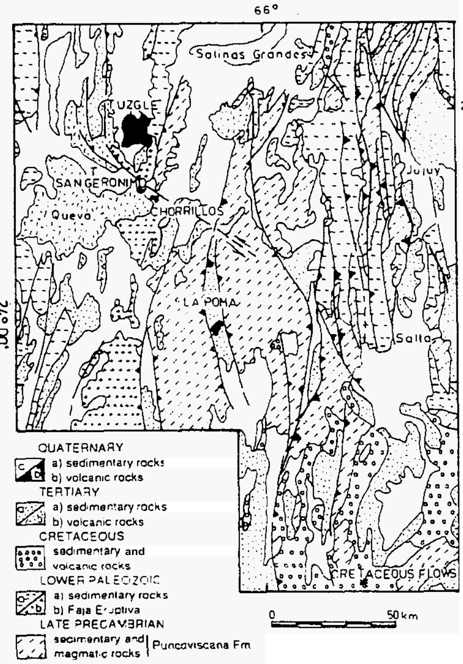


Fig. 2B Geologic *map* of **east-central Puna showing locations of Tuzgle** volcano, **shoshonitic** centers (San Geronimo-**Chorrillos and Miocene Queva volcanic center.** Thrust faults (with **tringles,** El Toro-Olacapato-El Toro **lineament fault** (with **arrows**).

a plateau of **60** km^2 and **2-80 m** thick. This **unit** flowed over Ordovician *sedimentary* and magmatic rocks and also covered **Miocene** clastic and volcanic secuences (Trincheras **Fm.** and Pastos Chicos Fm).

This event was followed at 0.3 Ma by the formation of a dacitic lava **dome (Old** complex) with a **total erupted** volume of about 3.5 km3. **Subsequently** andesitic lavas of the **Pre-platform** unit flowed down from the crater **rim** in a **NNE** and SSW direction **Next, the** crater **(1.4 km** in diameter) **was partially filled** by the mafic andesitic flow which forms the prominent Platform *unit.*

Tectonic reactivation, **indicated** by a W-E and **NW-SE** faulting, affected the **previous** volcanic **units** and controlled the **eruption** of the **Post-platform** and the **Recent young flow units** (Coira and Paris, 1981). Together the Pre-platform, Platform, Post-platform and Young Flow units total a volume of about *0.5* km3.

3.2 Petrography-temperature and pressure constraints of the Tuzgle volemic rocks

Tuzgle Ignimbrite. This unit, dacitic to rhyolitic in composition is relatively crystal rich *(20* to 25%), pomez moderate and shows **small** to **moderate** welding. In *order* of **abundance, phenocrysts** are normally zoned plagioclase **(An_{45-32})**, quartz, biotite and **alkali** feldspar. **Groundmass** phases are **plagioclase (An_{28-33})** *quark* and **titanomagnetite**.

Compositional **similarities between** these **phenocrysts** and xenocrysts were derived from a **host** like the ***ignimbrite.*** Isotopic **data** support **this** conclusion (Coira and Kay, 1993).

Andesitic and dacitic lavas. **The** Tuzgle **lavas** are crystal-rich **andesite and dacite. Their most striking feature is the contrast** between **their** large feldspar and *quartz* xenocrysts (up to 3 **to 6 cm across)** and their biotite grains, *small* mafic phenocrysts and hyalopilitic to **pilotaxic groundmass.**

Groundmass phases include **plagioclase (An57-An78), olivine, clinopyroxene,** ortopyroxene, **opaque oxides** and apatite. Other notable characteristics are: 1)absence of plagioclase **phenocrysts 2)generally regular** variation **of** mafic **phenocryst types** (forsteritic olivine, phlogopite, **salitic** to augitic clinopyroxene, ortopyroxene, opaque **oxides** and apatite) with whole **rock** composition.

The **most** common xenocrysts **are plagioclase** (An33 to **An38)** and quartz. Disequilibrium with **the** host magma is indicated by sieved **textured,** calcic **rims** (to **An 76)** on **plagioclase** and embayed **brown glass rim** and clinopyroxene **(Fs14-16 En44-46 Wo38-46)** on *quark.* The xenocrystic nature of **all** of these grains **has** been confirmed by isotopic *analyses.* The preservation of reaction rims suggets **that** the xenocrysts were incorporated shortly before **eruption**

Temperature **and pressure geothermometers. Tuzgle mineral** assemblages suggest fractionating mafic *magmas* **mixed** with a component like **the Tuzgle** ignimbrite. **The** presence of **olivine** and pyroxene, **but** no plagioclase phenocrysts in mafic andesite **suggests that these mafic magmas began crystallizing at dephs >~25 to 30 km.**

Constraints on crystallization **temperatures** of **the** mafic magma come from pyroxene and oxide assemblages in andesite using **the two pyroxene geothermometer (Lindsley,** 1983) and the **Andersen and Lindsley** (**1988) oxide thermometer.** These data *suggest* **initial**

crystallization of mafic magmas at ≥1075°C and *quenching* of **groundmass** oxides at ~**800°C**.
The **experimental** data suggest for **the** Tuzgle **ignimbrite** a **pre-eruption temperature >760°C and a pressure >**2.5 **to 3 kbar ,if the** P_{H2O} was 4.5. The data permit the Tuzgle **Ignimbrite** to be from a mid-crustal magma chamber.

3.3 Chemical characteristics and petrologic model for the Tuzgle suite

Tuzgle volcanic rocks follow **a high** K-andesite to **rhyolite trend** *on* a K_2O versus SiO_2 **diagram** and have a calc-alkaline arc-like **Al_2O_3 concentrations** (1 5 to **17%)** and **FeO/MgO** ratios (1 to 2.5). **They** are more **K and** Ti **rich (1.2** to **1.6%** TiO_2 in andesite) **than** underlying **Mio-Pliocene** high-K volcanic rocks and less K-rich **than** nearby shoshonitic **series rocks** (San **Geronimo** and **Chorrillos** *centers).*
Trends of generally compatible mayor elements with *increasing* SiO_2 *can* be approximated by closed **system** fractional crystallization **models** involving hornblende, plagioclase and magnetite. However, **a paucety** of amphibole **and a** lack of plagioclase *phenocrysts* in andesitic samples indicate that these **models** are unrealistic. Trace element **and** isotopic data confirm that **the processes** involved *mixing* of several **components**, as wells as crystal fractionation.
Trace element **data**, particulary REE **data**, *can* be used to separate the Tuzgle suite **into** an older **and a younger group. The** older, low La/Yb *group* consits of the Tuzgle **ignimbrite, the** Old complex **and the Pre-Platform, Platform** and some of the **Post-Platform units. Theme** samples have **moderate** to *steep* REE patterns **(La/Yb** ratios=20 to 28) that **tend** to steepen **as** SiO_2 concentrations increase **fiom 56** to **70.**
The younger high La/Yb *group* **consits** of the other **part** of **post-Platform** unit **and the young** Flow. **These samples** have **58** to **61%** SiO_2 **and** *steep* REE **patterns** (La/Yb ratios>35).
Neither, **the** *steepness* of Tuzgle **REE patterns, nor the differences between the patterns** of malic low **and high La/Yb** group lavas, *can* be explained **by** fractionation of modal *phenocryst* **phases,** instead *can* be **attributed** to variable **REE** retention **by** garnet **during** separate melting events producing discrete precursor magmas. The low La/Yb lavas require **higher mantle** melt percentages than **the high La/Yb ones.**
Another feature of Tuzgle **REE patterns is** that negative **Eu** anomalies **(Eu/Eu*=0.78** to **0.56) occur** in **all** samples, whether or not **they contain** feldspar phenocrysts. **These** anomalies are **attributed** to mixing of feldspar -free mafic magmas with silicic *magmas* that have **fractionated** feldspar. **A** silicic magma related to **the** Tuzgle **ignimbrite,** in which the xenocrysts would have **been** *phenocrysts*, is an **obvious** choice.
Intraplate like sources are **suggested** for Tuzgle samples **by Ba/Ta** (120 to 260) **and La/Ta (13** to **22)** ratios **that** fall in **the OIB** range and by **high TiO_2** concentrations.
In **detail** incompatible trace elements in **the** Tuzgle suite behave in a non-systematic fashion that **cannot** be **related** to formation of accesory **phases** and multiple source components are required.
Substantial upper crustal type contamination in Tuzgle lavas is **indicated by decreasing ΣNd (-2.5** to -6.7) with **increasing** $^{87}Sr/^{86}Sr$ **(0.7063** to 0.7099) ratios **and** SiO_2 **concentrations.** Trace element arguments indicate that **the bulk** *contaminant* was **more** silicic **than** the **Tuzgle ignimbrite** and left a residue with a **high pressure mineralogy.**
In summary petrologic **and** geochemical **data show** that **Tuzgle** volcano **represents** a *complex* mixture of **crustal and** mantle derived **components.** It was postulated *on* this basis, by **Coira and** Kay (1993), that **Tuzgle mantle derived magmas** were modified at deep *crustal* levels **by** crystal fractionation **and** mixing with upper crustal **components.** In that case *crustal* shortening **processes** provided **mechanisms** for transporting upper crustal rocks to depth **where they** *can* be **mixed** with lower *crustal* rocks and **metamorphosed** at high pressure. **These** upper crustal ***components*** were **preferentially** incorporated into ascending magmas, that **rise and accumulated** at **mid** to upper crustal **depths** possibly at **crustal** scale decollements (20-25 **km, Cahill,** 1990).
When mantle melting rates were **high the** flux of malic melts **ponding** in the **crust was** also **high** and silicic magmas accumulated *rapidly* and erupted as the ignimbritic unit. Instead when the flux was low, silicic melts **accumulated** more **slowly** and **the ascending** mafic melts ***mixed*** with *this* before erupting **and incorporated their phenocrysts as xenocrysts.**

4. Geochemical Hydrogeology and Hydrology

Water samples from hot **springs** and rivers have **been** collected over different phases of the studies. Temperatures, **pH,** ***alkalinity*, electrical** conductivity, NH_3, SiO_2 and **gas/water** ratios were **measured** in situ. Quantitative ***analysis*** for **Na,** K, Li, Ca, Mg, **Mn, Fe,** *Al*, CO_3H^-, $CO_3^=$, NO, Cl, **F,** $SO_4^=$, **B,** $S^=$, **SiO_2** *were* **done** *on* each water samples. **Oxygen** 18, deuterium **and** tritium stable **isotope analysis were also realized.**
Gas ***analysis*** for CO_2, H_2S, SO_2 **and H_2O** were **performed** in situ and He, H_2, O, N_2, CH_4, CO, H_2S contents were **analysed** in **gaschromatography laboratory.**
Physical-chemical characteristics of **thermal** Tuzgle **waters were** *analysed on* **Stiff diagrams.** They belong to **alkaline-chloride** waters and *can* be **subdivided** considering **their** conductivity in **two** subgroups: a) conductivity **5000** to **6710 µ s/cm -** PH 6-6,2; b) **1920** to **3950 µ s/cm -** PH **6.4 - 7.99.**
Temperatures of 3 9 T to **56°C were determined** at **Tuzgle Aguas calientes** hot spring. Mina *Betty* **spring waters, with temperatures** of **20°C,** are also **alkaline-chloride** type with **6.7 PH and a conductivity** of **1307 µ s/cm.**
Another **group** earth alkaline-bicarbonate **was pointed out for** cold

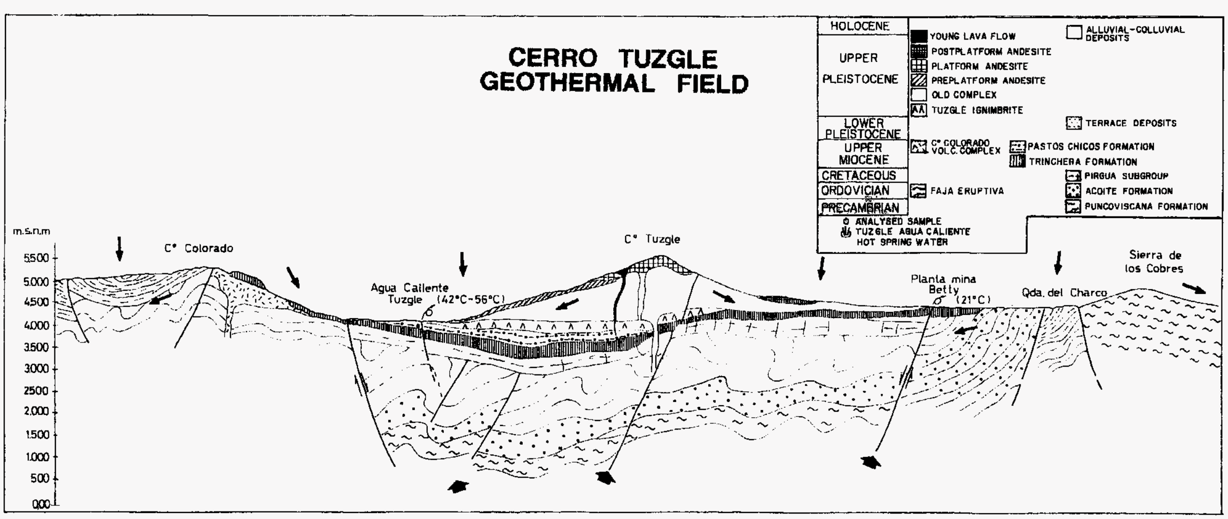


Fig. 3 Geothermal **Fluid** circulation scheme ▲ flow of deep geothermal **waters** → local recharge-flow of **superfitial aquifers.**

waters with 6.1-7.6 PH and low conductivities (122-590 μ s/cm). Stable isotope data were applied to analyze mixing of waters. Plots of chloride versus $\delta^{18}O$ of Tuzgle hot waters determine mixing between deep geothermal fluid and superficial cold waters.
In the geothermometric study of the Tuzgle waters K-Mg and silice (chalcedony) geothermometers were selected to estimate temperatures considering it best fit the system condition.
The reservoir temperatures calculated were (K-Mg)=134°C, silicic (chalcedony)= 143°C. Outside of the Tuzgle area geothermometers indicate low temperatures (<66°C).
Geochemical parameters as CO_2, NH_3 and H_3BO_3 were used as leakage indicators. Belts of anomalous values of these elements, one located east of Tuzgle volcano with NNE-SSW trend, and another coincident with Olacapato lineament, point out two main leakage structures.
A geothermal fluid circulation scheme (see Fig. 3) was suggested from the geochemical data. West of Cerro Tuzgle, thermal and cold waters were separated by an impermeable cover whereas in the east leakage anomalies and mixing between deep and shallow waters can occur. Southward a topographic high parallel to Olacapato lineament interrupts, the Tuzgle geothermal field as denoted the hydrochemical differences among the two areas.
The hydrogeological investigations defined recharge areas by the iafiitration of the snow fields situated in the southern, eastern and western sectors. A recharge altitude of 4400 m. and 4500 m. was identificd using correlation diagrams: recharge altitude versus δD% and $\delta^{18}O$% respectively.
Volume calculations of the of infiltrated water for Tuzgle area give values of 3,2 m³/seg.

5. Geophysical survey

The geoelectric studies in the Tuzgle area began with a hundred of AUDIO-MT (10 to 2,000 HZ) and vertical electric (AB/2 up to 3000 m) soundings performed by Hydroproyectos SA, Setec SRL and CEPIC S.C.(1984).
The geoelectric methods used gave a definition of the subjacent *structure* up to 700-900 m deep. The geoelectric data obtained point out a superficial *reservoir* (2 ohm-m) 100 to 600 m thick at SO to 300 m depth. Also was detected a second conductive unit (1 ohm-m), although puntualy at 620 depth. This could correspond to a deep reservoir represented by Ordovician sequences (CREGEN, 1988).
A regional gravimetric *study* for the area has been done by Götze et al (1988). They obtained the residual gravity field of a large area between 20° and 26°S. From that *study* negative gravity values (up to-30mgal) and an local E-W symmetry axis in the distribution of the residual gravity isolines were observed in the Tuzgle area.
A regional magnetotelluric (MT) study across the Puna, at 25 km tothe south of Tuzgle area was *carried* out by Schwarz et al, 1990. Their results indicate a deep conductive layer at −35 km east of Tuzgle volcano at about *20* km depth.
Ten deep soundings (0.0001 to 10 HZ) were carried out in *the* Tuzgle area by Sainato et al (1993). The MT results interpretation from the 1-D inversion modeling at each MT station have put in evidence three main conductive *layers* with average tops at 1 km, 7km and 31 km of depth and a W o w conductive *structure* at depth between 100 m and 200 m approximately. The superficial layer could be associated with the upper geothermal reservoir proposed by Aquater (1980), as the permeable ignimbritic unit of the Trinchera Formation, sealed by the Pastos Chicos Fm. (*see* Fig. 3).
A 2-D magnetotelluric model of resistivity distribution and a 2-D gravimetric model of the area has been proposed by Sainato and Pomposiello (1994) as a second interpretation. From these models three main bodies *may* be out lined. The deep conductive regional layer detected at approximately 31-34 km depth associated to deep release of *energy* related to subduction processes between Nazca and South American plates.
The second body, characterized by a resistivity of 0.1 ohm-m and a density contrast of 0.07 g/cm³, *seems* to be a magmatic chamber located in the crust beneath the Tuzgle volcano with its top at 5 km depth.
The conductive and low density layer hundreds of meters thick, detected at approximately 2 km deep, could be related with the layer of shales and volcanic ordovician rocks proposed by Mon (1987) as a possible deep geothermal reservoir sealed by the Pirgua Formation.

A more superficial reservoir detected at 50-300 depth was assigned to Trinchera Formation.

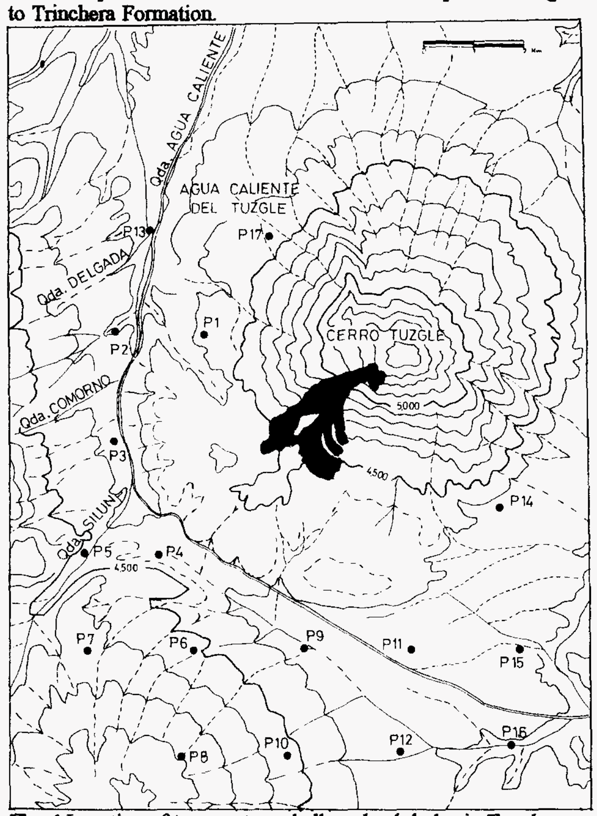


Fig. 4 Location of temperature shallow depth holes in Tuzgle area

6. Thermal gradient drilling program

Thermal measurements were obtained *during* 1989/90 in 18 shallow (60-100 mts) depth holes located along the western and southern margin of the Tuzgle volcano in a area of 85 km² (see Fig. 4). The holes were drilled up to 100 m, only one to 172 m, with hole diameters ranging from *9* to 6 pulgadas.
Temperatures were logged in each hole inmediately after complition the drill (To *initial* temperature) and each hour *during* 5 hours. After that, temperature measures were run at 8, 16, 32 and 64 hs; 5, 10, 20 y 28 *days*.
Temperatures recorded in the shallow drilling program took longer to equilibrate. The temperature disturbance in the holes was corrected using a dense mud injection and a hole diameter of 6 inches.
The formation equilibruim temperature at each depth was calculated to infinite time. Temperatures measured in the lower and upper 10 m of the bore holes were not regarded in the calculations. The mean thermal gradient values obtained fluctuated between 0,14°C/m (hole P15) to 0,37°C/m (hole P=9).
Isotherms across holes were plotted to evaluate variations in thermal gradients. Thermal data show two zones of high thermal gradients: one located south of Tuzgle young lava flow between holes P6 and P11 and another placed in the northwestern margin of the volcano nearby hole P1.
Thermal *conductivity* measurements were made on five cores representing the hole P15 at 84m, 123m and 172m and the hole P4 at 27m and 49,5m, where they cut ignimbritic and clastic rocks tentative assigned to Trincheras Formation. The values range from 0,6 W/m°C to 1,22 W/m°C.
Heat flow values from the holes were calculated applying an average value of the thermal conductivities measured. The highest heat flow 0,263 W/m², 0,220 W/m² and 0,188 W/m² were determined in holes P9, P11 and P1 respectively.
The Tuzgle area belongs to the higher heat flow belt of the Bolivian Cordillera and *Altiplano*, situated inmediatly to the east of the *Quaternary* back arc volcanoes. The heat flow values determined in the Tuzgle zone are anomalous with regard to the mean heat flow of 0,084 W/m² reported for that belt in Bolivia (Henry and Pollack, 1988).
Studies of cutting and core samples of the *drilling* program

corroborated the superficial geoelectric stratigraphy. The holes penetrated in the most cases the shallow conductive layer (Trincheras Fm.)

7. Geothermal model

Cerro Tuzgle geothermal system is located in a N-S elongated tectonic depression, delimited by normal faults and separated southward from the Tocomar-Olacapato graben by a WNW-ESE horst of Ordovician rocks.

Recharge areas were defined in the southern, eastern and western sectors the Tuzgle depression at 4400 to 4500m of altitude.

Heat anomalies are represented at surface by hot springs with temperatures of 40°-56°C, (Tuzgle Agua Caliente) and 21°C (Planta Mina Betty).

Geochemical water studies indicate mixtures between deep and shallow waters and geothermal reservoir temperatures of 1329: to 142' C (according to K-Mg and chalcedony geothermometers).

A shallow reservoir 100 to 600m thick, at 50 to 300m depth, was pointed out by geoelectric soundings, as the permeable, mainly ignimbrite unit, Trincheras Formation. The cap rock, in this case, is represented by the low conductive (20-1000ohm-m) Pastos Chicos Formation which is probably missing in the eastern margin of the volcano, where was determined a leakage anomaly area (see Fig. 3).

A deep geothermal reservoir represented by the conductive and low density layer, hundred of meters thick, detected at aproximately 2 km deep, could be related with the shales and volcanic Ordovician rocks (Faja Eruptiva and sediments) intensely fractured and sealed by Pirgua Subgroup. (cap rock).

A body characterized by resistivity of 0,1ohm-m and a density contrast of -0,07 g/cm³, result of a 2D magnetoteluric and gravimetric model, probably corresponds with a magmatic chamber placed in the crust beneath the Tuzgle volcano, with its top at 5 km depth.

Structural profiles interpreted from the geoelectric soundings permit analysis of reservoir structure. Thus it is possible to determine how basement blocks, that outcrop nearby Sey, fall down northward and southward that locality, probably controlled by WNW-ESE fracturation. Whereas, in the southwestern area, NE-SW echelon block system is developed ,with P6 and P9 as P3 and P5 holes located in the uplifted blocks and separated by a graben. Northward and southward, of that uplifted blocks, take place a regional sinking of the superficial resistive unit and a thickening of the shallow reservoir. The deep reservoir is detected in the uplift block of the holes P6 and P9 at a 620 depth

Taking in account the analyzed structural controls, geoelectric stratigraphy, discharge areas, underground temperature distribution and heat flow values determined in the drilling program, it is possible to select a potential area of approximately 28 km², along the southwest and west edge of Tuzgle volcano (4 km thick and 7 km long from hole P9 to P1), to develop a future deep drilling exploration plan.

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