

PROCEEDINGS
TWENTY-FIRST WORKSHOP
GEOTHERMAL RESERVOIR
ENGINEERING

January 22-24, 1996



**Stanford Geothermal Program
Workshop Report SGP-TR-151**

DISCLAIMER

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency Thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

DISCLAIMER

Portions of this document may be illegible in electronic image products. Images are produced from the best available original document.

HYDROTHERMAL SURFACE ALTERATION IN THE COPAHUE GEOTHERMAL FIELD (ARGENTINA)

Graciela R. Mas¹
Luis C. Mas²
Leandro Bengochea¹

¹ CONICET-Universidad Nacional del Sur
San Juan 670, 8000 Bahía Blanca, Argentina

² Ente Provincial de Energía del Neuquén.
Rioja 385, 8300 Neuquén, Argentina

ABSTRACT

In the area of the Copahue Geothermal Field, there are five active geothermal manifestations, which mainly consist of fumaroles, hot springs and mud pots. Four of these manifestations are located in Argentina: Las Máquinas, Termas de Copahue, Las Maquinitas and El Anfiteatro, and the fifth on the Chilean side: Chanco Co. All of them present a strong acid sulfate country rock alteration, characterized by the assemblage alunite + kaolinite + quartz + cristobalite + pyrite + sulfur + jarosite, as the result of the base leaching by fluids concentrated in H_2SO_4 , by atmospheric oxidation at the water table in a steam heated environment of H_2S released by deeper boiling fluids. Another alteration zone in this area, called COP-2, is a fossil geothermal mani-

festation which shows characteristics of neutral to alkaline alteration represented mainly by the siliceous sinter superimposed over the acid alteration.

The mineralogy and zoning of these alteration zones, and their relation with the hydrothermal solutions and the major structures of the area are analyzed.

INTRODUCTION

The Copahue Geothermal field is located at latitude $37^{\circ}50'S$ and longitude $71^{\circ}05'W$, some 1170 km WSW of Buenos Aires City, and adjoining the border with Chile. The area is connected with the city of Neuquén by national and provincial routes, covering nearly 360 km through Zapala, Las Lajas and Loncopue (figure 1). This geothermal field is on

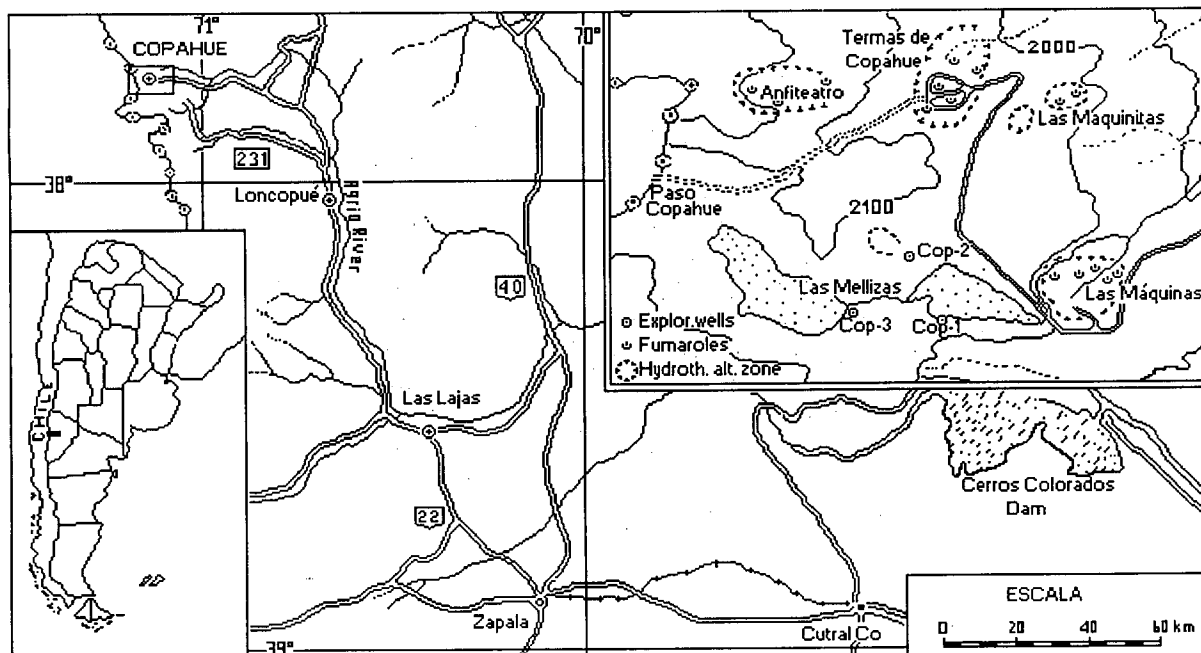


Figure 1: Location Map.

the east side of Los Andes, in the ridge which forms the watershed separating the river basins of the Pacific and Atlantic sides, as typified by Volcan Copahue and Paso Copahue in the western part of the area. This area rises to about 2000 m above sea level.

Three exploration wells had been drilled in this field: COP-1 (1414 m); COP-2 (1241) and COP-3 (1065). A demonstrative geothermal power plant of binary cycle has been installed in COP-1, which produces 670Kw.

In the studied zone there are five active geothermal manifestations areas, one of them being located on the Chilean side. All of them are on the horst northeast of Vn. Copahue, and the overall area comprises approximately 20 km². The four geothermal manifestations areas located on the Argentine side are Termas de Copahue, Las Maquinas, Las Maquinitas and El Anfiteatro (figure 1, inset). These geothermal manifestation areas are characterized by horseshoe-shape depressions and form acidic alteration zones, where a surface acid sulfate alteration is strongly developed. At present, a rather intense fumarolic activity affects the four areas, with fumaroles and mud pods. The single geothermal manifestation area on the Chilean side is located at Chanco Co, which is beyond Paso Copahue, across the national border near Termas de Copahue.

Many fractures, mainly in NE-SW and WNW-ESE directions, have developed in these geothermal manifestation areas, suggesting that these areas are closely related to the fractures. In the local depressions, there are many fumaroles, mud pots and hot springs. The main discharges are of vapor type, and there are few of flowing hot water.

Three exploration wells (COP-1, COP-2 y COP-3) had been drilled here, in a sector NW of the circular basin and about 6 km northeast of Vn. Copahue. (Figure 1, inset). The latter was drilled in the course of the "Northern Neuquén Geothermal Development Project" carried out by EPEN (Ente Provincial de Energía del Neuquén) and JICA (Japan International Cooperation Agency). These exploration wells confirm the occurrence of a vapor dominated reservoir below a depth of 800 m. The three wells form a triangle with 1 km side length, placed over a predominant fault WNW-ESE which links the Chanco Co and Las Máquinas manifestations.

There is one more area near the COP-2 well zone, currently without any geothermal activity and over

the same fault system than Las Máquinas, where an important level of siliceous sinter, besides montmorillonite and kaolinite, has developed.

The purpose of this paper is to describe the mineralogical characteristics of the surface alteration in the areas of geothermal manifestations, and discuss the relation between these areas and the structure of the region.

The study of the alteration minerals was performed using optical microscopy, Xray Diffractometry and Scanning Electronic Microscopy Analysis.

STUDIED AREAS

Termas de Copahue

Termas de Copahue is the largest geothermal area in this geothermal field, and there are medical facilities for balneotherapy, including hot water pools and steam baths.

The alteration zone of Termas de Copahue mainly consists of white and yellowish clays and is distributed from the center through the northeast of the depression and the south wall.

The extension, zoning and mineralogy of this alteration zone cannot be analyzed in detail due to the fact that it is partially covered by the houses and streets of the town which was built precisely over it. Its original condition has been deeply altered by the presence of dams and cutwaters built to make use of the thermal manifestations in bath houses, this resulting in the formation of small lagoons known by the names of El Chanco, Sulfurosa, Verde, Baño N°9, etc. The pools called "El Chanco" and "Sulfurosa" are cloudy due to colloidal sulfur and gas which spring at some places, clearly noticed by the bubbling at the water surface.

It is at the area named Agua del Limón, at the eastern end of the Termas area, where natural conditions are less disturbed. Here alteration minerals appear as very fine and relatively plastic argillaceous textured assemblage whose color ranges from whitish to yellow and orange yellow. The presence of fine veins and irregular crusts of a very hard, porcelain-like siliceous material can also be observed.

By means of XR diffractometry it has been determined that the fine, white to whitish dusty material is basically composed of alunite and kaolinite in different ratios, ranging from sulphate to

practically pure kaolinite. Both minerals appear accompanied by subordinate quantities of quartz, cristobalite and cryptocrystalline silica.

In the yellow coloured areas the predominant mineral is jarosite. This appears well crystallized and correspond to the potassic variety. It is accompanied by quartz and cristobalite as subordinate species, and variable quantities of alunogen are often detected. This material of variable and uncertain composition is formed by the evaporation of solutions containing sulphate ions in the presence of cations such as K^+ , Na^+ , NO_2^+ , etc.

On the spring centers, cristobalite is predominant together with alunite and quartz, while fine crystals line cracks and free surfaces, as a result of gas sublimation.

In the currently inactive springs the same mineralogical association has developed and also cristobalite is the main component of the colloform crusts and porcelaneous veins which are present in the zones of alunite and kaolinite.

At the southern end of the alteration zone, on the slope of the valley where the small town of Termas is located, there is observed a very well crystallized kaolinite, accompanied by cristobalite, quartz and alunite interspersed with porcelaneous zones made up of very poorly crystalline kaolinite, amorphous silica and anatase. The presence of this TiO_2 often has been determined in Termas de Copahue and El Anfiteatro, always accompanied by cryptocrystalline silica or cristobalite. Above this area of dominant kaolinite, there is another in which alunite prevails, accompanied by kaolinite, cristobalite, quartz and anatase.

In the small veins and vitreous crusts of this section, essentially consisting of cryptocrystalline SiO_2 , the incipient presence of a zeolite of the clinoptilolite group is observed. This mineral is later than the acid-sulphatic alteration that originated the described association and is a product of silica decomposition.

Las Máquinas

Las Máquinas is a large geothermal area elongated in N75W direction, where the alteration is best exposed. The area of active manifestation covers a surface of about 180,000 m^2 , and the overall altered zone comprises a surface of 560,000 m^2 . There are fumaroles surrounding the large hot water pond. The pond is turbid due to the colloidal sulfur and gas

springing at some places. The rocks around the fumaroles have been severely altered, and sublimation and mud pots are seen. The fumaroles in this depression are also arranged in WNW-ESE direction.

A Sanatorium operated by the Clínica Militar is located at Las Máquinas, and used by the public.

At Las Máquinas, two reverse faults were observed downstream the Arroyo Blanco, and no alteration is observed on the east side of the faults. It is considered that these faults have acted as an impervious barrier for the hydrothermal fluids.

The prevailing mineral in the area of highest activity is a well crystallized and relatively pure alunite, only accompanied by subordinate quantities of other argillaceous and siliceous materials. The abundant presence of alunite is considered of interest, as it is an indicator of the low pH of the fluids that produced the alteration. It appears as earthy to powdery, whitish to white greyish, granular masses. The surface of the alunitized zone presents a rather high temperature because of the escape of hot gases. It is evident in winter, when this alunitized nucleus is the only place free of snow.

Using the graphs proposed by Maiza and Mas, (1980) which related unit cell size with the K:Na ratio, a relation was determined for this alunite of about 98:2, what means that it can be considered a practically pure potassic term.

At the upper part of this alteration zone, the material appears more compact and silicified. The XRD analysis showed that it is composed of amorphous silica, cristobalite and alunite as main minerals, subordinate quartz and variable quantities of kaolinite.

At the borderline of the altered area of Las Máquinas, an important increment of kaolinite and quartz is observed as compared with cristobalite. The surface of these sections is oftenly covered by a gossan, essentially composed of jarosite accompanied by montmorillonite, kaolinite, gypsum and hematite.

On the walls of the thermal springs and fumaroles, small sulphur and pyrite crystals are forming.

Las Maquinitas

Las Maquinitas is the smallest geothermal

manifestation area in the Copahue Field. It consists of two small depressions, located at different heights along the NE-SW faults. At present, only the lower depression is active. The temperature of this fluid discharge does not generally exceed 93°C (this is the boiling temperature at this height above sea level) but superheated steam, with temperatures of up to 132°C has been measured in this area.

Amorphous silica (siliceous residue) is the most abundant material among the alteration minerals. It is present as partially recrystallized tridimite and/or cristobalite. There is also some quartz and variable quantities of kaolinite and alunite. There are greyish masses of pyrite and sublimated sulphur around fumaroles and mud pots.

El Anfiteatro

El Anfiteatro is located at the far west end of the horst. This area is not so active as the others, but mud pots and fumaroles are observed. The shape of the depression resembles that of an explosion crater of about 540,000 m².

Each one of these springs precipitates sulphur on their surfaces and is surrounded by a halo of pyrite, from some centimeters to one meter wide. The rocks surrounding these manifestations are quite altered and silicified with quartz, tridimite and cristobalite. It presents subordinate kaolinite and alunite, and the amorphous silica is very scarce or inexistent. On the rock surfaces surrounding the hot springs and fumaroles small sulphur crystals formed from sublimation of the gaseous phase are deposited.

Over and outside the most intense silicification area, the rock is totally kaolinized with subordinate alunite and quartz. Finally, and always on the upper part, topping the small white kaolinized mounds, are the hard, porous, brownish-reddish to orange-yellowish gossans, which are composed of jarosite, hematite, goethite and quartz.

By comparing this mineralogy with that of the Las Máquinas area it can be seen that the most striking difference is the abrupt decrease of alunite, which only is present as a subordinate mineral, and the increase of goethite. This indicates that the solutions that produced the alteration of the Anfiteatro has a less acidic pH.

COP-2

Close to well Cop-2 area, 300 m to the NW, there is

a zone where though thermal manifestations are not currently produced, the presence of an alteration mineralogical association is registered. The lower section is represented by a level of hard and porous siliceous material, white in color, in part with a spongy appearance. At the upper part of the outcropping the siliceous material presents a fibrous, subparallel to radiated structure, with fibers of several centimeters in length.

By means of XRD this material presents a very simple mineralogy, essentially composed of amorphous silica with very small reflections of cristobalite and quartz. The study of the samples by optical and binocular stereoscopic microscopy enabled to assess that the fibers correspond to a relic organic structure produced by the silicification of vegetal residues of superior order. The assessment of this type of residues of vegetal tissue is a strong evidence that the material is siliceous sinter, formed at surface from solutions of almost neutral pH.

At approximately 100 m from the sinter outcropping, to the NW (in the direction of Copahue town) a gossan formed by goethite with subordinate jarosite is observed. In the same direction, at approximately 100 m from the previous point, there is another gossan, this time surrounded by a wide zone of argillaceous minerals. The bottom section of this mound is composed of a light green, very fine and plastic textured montmorillonitic material, with subordinate quantities of kaolinite and amorphous silica and very scarce quartz.

Above this area there is another one, also made up by a very fine material, white to very white in color, formed by kaolinite with subordinated alunite and quartz.

DISCUSSION

The thermal manifestations of Termas de Copahue, Las Máquinas and El Anfiteatro, and partially Las Máquinas, are associated with a group of parallel faults in the N55°E direction, and the thermal area Las Máquinas and the altered zone close to Cop-2 well, are also related with the WNW-ESE fault system. These faults are in turn associated with a regional structural system oriented in the bearing N55°W. (JICA-EPEN 1992; Mas 1993).

The fluids (fumarolic gases and solutions) that produce the alteration, are discharged through these two fissure systems, i.e. there exists a strong structural control of the field shape.

The close relationship that links fluid composition and hydrothermal mineralogy can be clearly observed in the surface alteration. The four zones of active manifestations thus studied show features that in principle may be characterized as products of acid alteration. However, they exhibit particular characteristics that enable to establish some differences among them.

Considering that acid-sulphate alteration is produced by the extreme leaching of bases by fluids with a relative H_2SO_4 concentration, at temperatures below 400°C , its presence indicates the existence of very low pH and oxidant redox conditions. Sulphuric acid is produced through oxidation of H_2S distilled from the underlying hydrothermal system, on (or close to) the water table.

The mineralogy associated with this type of alteration of the surface, or very close to the surface, is represented by the presence of opal, cristobalite, tridimite and alunite. This constitutes an area very rich in silica where all the other components have dissolved ($\text{pH} \approx 2.5$). Besides this mineral, at the alunite section, kaolinite, cristobalite and opal are formed from fluids with a pH between 2.5 and 3.0. Henneberger y Browne (1988) have established that the presence of alunite in the most altered rocks of the Ohakuri hydrothermal system requires that a minimum molality of $10^{-3} \text{H}_2\text{SO}_4$ is locally reached.

The Las Máquinas area presents a practically monomineral alteration center, surrounded by zones of siliceous minerals (opal, tridimite and cristobalite) and kaolinite.

Also at Las Maquinitas and El Anfiteatro areas there is this association of minerals without a clear predominance of any one of them. Alunite is less abundant and even subordinate to kaolinite, thus indicating a slightly higher pH. The abundance ratios are variable in both areas, being the Las Maquinitas association slightly more acidic than that of El Anfiteatro. In the case of Termas de Copahue, the existing mineralogy indicates a similar pH to that of Las Máquinas, but the artificial modifications that affect this area preclude to assess it with certitude.

In turn, the alteration area adjacent to Cop-2 well presents minerals such as montmorillonite and siliceous sinter related with neutral to alkaline fluids.

The presence of siliceous sinter together with minerals such as kaolinite, alunite, sulphur and

sulphates may indicate that this was formed after disappearing the conditions that led to the formation of the acidic association, for example by the substitution of an alkali-chloride solution instead of acid steam. According to Rye *et al.* (1992) this is a common characteristic, though not necessarily always existing, in environments with overheated steam, such as that of Copahue.

The acidity of the alteration fluids decrease gradually from the alunite zone through the kaolin zone to the montmorillonite zone.

The presence of H_2S in the reservoir level fluids, as well as the existence of effervescence and boiling processes in depth, has also been confirmed by the study of fluid inclusions made on core samples taken from wells Cop-2 and Cop-3 (Mas *et al.* 1993).

CONCLUSIONS

The four studied zones of active manifestations, of acid-sulphate characteristics, are the result of the action of fluids (fumarolic gases and aqueous solutions) on the volcanic rocks of the area. Mineralogically this alteration is represented by sulphur and cristobalite accompanied by alunite, kaolinite, quartz, jarosite and iron oxides and hydroxides. This association of low pH alteration is produced by the release and subsequent recondensation of acid gases, mainly CO_2 and H_2S resulting from the boiling and effervescence of the fluids in the deeper levels.

Conditions of higher acidity of solutions, according to the mineralogical association, are registered in Las Máquinas area, with alunite and cryptocrystalline silica predominance. El Anfiteatro and Las Maquinitas evidence similar acidity conditions each other, though slightly more acid in the second one, according with the relative abundance of the minerals. The Termas de Copahue area appears to present a similar association to that of Las Maquinitas, but the artificial modifications that affect it make impossible to establish an unquestionable alteration zoning.

The strong dynamism suffered by this field has generated a secondary permeability which is limited to the areas in which high temperature fluids ascend to the higher levels.

The axis with higher heat flow value (WNW-ESE) and the main structural alignments exhibit a

correlation that confirms the strong structural domination of the field (Mas 1993).

There seems to be a link between fluid composition, alteration mineralogy and heat flow in the Copahue geothermal field. Termas de Copahue, Las Maquinitas and El Anfiteatro are related to the NE faults. On the other hand, Las Máquinas is the only one not directly linked to the N55°E fault system, but it is in a crossing between these and the WNW-ESE faults. This bearing also coincides with the axis of higher geothermal values, which implies a more direct and greater magmatic supply.

Finally, in the alteration area named Cop-2, an overlap of two different mineralogical associations is observed, thus indicating an evolution in the acidity of the solutions, which is characterized by the association of alunite, kaolinite and cryptocrystalline silica, with a stage of alkaline-chloride, almost neutral, solutions, with the formation of montmorillonite and siliceous sinter. An acidity change, as this may be due to a decrease in the supply of magmatic gases or to an interruption of the in depth boiling of the fluids.

ACKNOWLEDGEMENTS

The authors wish to thank the Ente Provincial de Energía del Neuquén (Neuquén Energy Entity) for making available to them all the existing information and field facilities; to the CONICET for the grant with which this project was funded and to the Universidad Nacional del Sur for making available their laboratories and equipment.

REFERENCES

- Henneberger, R.G. & Browne, P.R.L. (1988), "Hydrothermal Alteration and Evolution of the Ohakuri Hydrothermal System, Taupo Volcanic Zone, New Zealand". *Journal of Volcanology and Geothermal Research*; 34: 211-231. Elsevier Publishers B.V., Amsterdam.
- JICA-EPEN (1992), "The Feasibility Study on the Northern Neuquén Geothermal Development Project". Final Report. Ente Provincial de Energía del Neuquén (inédito). Japan International Cooperation Agency.
- Maiza, P.J. & Mas, G.R. (1980), "Estudio de los Sulfatos Alunita-Natroalunita". *Síntesis de la Serie. Revista de la Asociación de Mineralogía, Petrología y Sedimentología*. 11(1-2): 32-41.
- Mas, L.C. (1993), "El Campo Geotérmico Copahue: Los Minerales de Alteración y las Inclusiones Fluidas como Indicadores de los Parámetros Físico-Químicos del Sistema". Tesis Doctoral Departamento de Geología Universidad Nacional del Sur. Biblioteca Central Universidad Nacional del Sur. Bahía Blanca. 199 pp.
- Mas, G.R.; Mas L.C. & Bengochea, L. (1993), "Inclusiones fluidas en el pozo exploratorio COP-3; Campo Geotérmico Copahue; Provincia de Neuquén, Argentina". 12° Congreso Geológico Argentino. Mendoza. V: 92-98.
- Rye, R.O.; Bethke, P.M. & Wasserman, M.A. (1992), "The stable isotope geochemistry of acid sulfate alteration". *Economic Geology*; 87: 225-262.