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Thermometric Study of Copahue Geothermal Field; Argentina

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ABSTRACT

The objective of this work is to carry out the application of different geothermometers on samples of two wells of the Copahue Geothermal Field and to compare the results obtained with all of them and with the present day measurements and the stabilized temperatures.

Hydrothermal alteration of the rock depends upon several factors such as temperature, pressure, lithology and subsurface structure of the rocks and a close correlation between the temperature and the type of secondary minerals is found in most geothermal systems of the world.

The secondary minerals in Copahue can be divided in clay minerals: smectites, C/S, chlorites and illite; zeolitic minerals: stilbite, laumontite and wairakite; and Ca-Al silicate minerals: epidote, prehnite, actinolite and garnet; besides quartz and calcite.

Fluid inclusions in quartz and calcite contain low salinity waters and have homogenization temperatures of up to 300ºC in the deepest samples.

1. INTRODUCTION

The Copahue Geothermal Field is a volcanic complex of Tertiary-Quaternary age, formed by a great caldera of about 15x20 km, which would have originated from a big stratovolcano, in which several extrusive centers have developed associated to the major structures related to the former caldera. Some of these centers would have evolved into explosion craters.

It is located at latitude 37°50'S and longitude 71°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 localities. This geothermal field is on 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.

The magmatism shows characteristics of a calcoalkaline series with predominance of pyroclastics and lava flows from dacitic to andesitic compositions. The present day thermal anomaly of Copahue is centered on an area delimited by interconnected active faults. Three exploration wells have been drilled in this field, in a sector about 6 km northeast of the Copahue volcano. The three wells form a triangle with 1 km side length, placed over a predominant fault WNW-ESE. They confirm the occurrence of a vapor-dominated reservoir below a depth of 800 m.

2. METHODS

Cutting samples of the well COP-2 and cutting and core samples of COP-3 were studied in thin sections to determine rock type and the distribution and paragenetic relationships among the secondary minerals. X-ray diffraction techniques were used to characterize the alteration minerals and to determine the ratio of mineral phases in the rock.

Fluid inclusions analysis were made, located over the trend of the highest values of heat flow of the field. Most of the thermometric measurements were made on quartz fragments, and a total of 275 fluid inclusions were measured.

Heating and freezing data were obtained for fluid inclusions from polished wafers of hydrothermal quartz and calcite from 13 samples of cutting and core from the exploration well COP-3. The phase change temperatures on heating experiences were studied by means of a heating/freezing Linkan MDS 600 stage. The thermometric studies were centered mainly in the primary and pseudosecondary inclusions selected according to their general characteristics of distribution. Since primary inclusions are considered cogenetic with the hosting mineral, it is possible to assume that the homogenization temperatures is a registry of the evolution of the temperature of the fluid during the growth of crystals.

Fluid inclusions analysis of vein material yielded the homogenization temperatures and apparent salinities of the fluids that produced the alteration minerals.

Mineral geothermometers are compared with the inclusion temperatures and down hole thermal measurements to assess the evolutionary changes that have occurred since the secondary minerals were formed.

3. ALTERATION MINERALOGY

All the volcanic formations drilled in the geothermal field have been subject to strong hydrothermal alteration. A detailed study of the alteration petrography evidenced a vertical zoning of alteration that results from time-space super-impositions of at least three hydrothermal stages (Mas et al, 2003). The first stage of hydrothermal alteration affected the totality of the geothermal zone and led to a zoned distribution of mineralogical facies ranging from clay-zeolite to propylitic facies with increasing depth and temperature. Alteration paragenesis suggests that temperatures grades from less than 100ºC at surface to 250º/300ºC at 1200m depth (chlorite-epidote-prehnite assemblage). This stage represents a thermal event typical of the external part of aureoles during which zoned pervasive alteration developed in response to mainly conductive thermal gradient (Mas, 1993).

The second stage of hydrothermal alteration was initiated by a hydraulic fracturation of part of the system (between

800 m and 1200 m depth). Infiltration of the permeable newly fractured horizons by aqueous fluids of meteoric origin promoted the intense alteration of the wall rocks. Fluid inclusions data evidence boiling during this alteration stage. Quartz, wairakite, prehnite, epidote and even garnet, precipitated mainly in open fractures at temperatures of about 240º-280ºC. Clay minerals formed also in open fractures and replaced preexisting igneous and hydrothermal minerals of the early stage in surrounding wall rocks. Clays are essentially non-expandable chlorites or chlorite rich C/S mixed layers. These newly formed clay minerals occur along the fractures of the permeable horizons.

Nowadays, active circulation of hydrothermal fluids is channeled by active vertical faults. In permeable horizons, coating of very fine grain material overprint the coarser grain chlorite and C/S formed during the previous stage.

3.1 Clay Mineralogy

Smectite minerals are common in the upper 200m of the wells, but they are also present immediately below the intensively fractured and altered zone of reservoir between 800m and 1200m depth. Swelling chlorites are the most common phyllosilicates in drill hole cores at depth greater than 150 m, with abundance only comparable with that of the chlorites.

Chlorite with non-expandable d_{001} spacing is also common in Copahue although it is less abundant than the swelling one and it is restricted to the higher degree and more intensive alteration levels. With the increase of depth the percentage of chlorite layers in C/S mixed layer minerals increases and they change to chlorite rich clay. Figure 1 shows a photomicrography of a vesicle filled up with chlorite. It occurs in the inferior middle of the wells, approximately between 650m and 1000m and it is considered stable at temperatures over 250° C, associated to epidote, prehnite, wairakite, garnet and amphibole.

The XR diffractogram of well-crystallized chlorite gives additional chemical and structural information (Brindley & Brown, 1984). For example, the b_o parameter of the unit cell varies between 9,294 Å and 9,252 Å, with a tendency to decrease with increasing depth. The main variable that can be estimated from this measurement is the substitution of Mg by Fe^{2+}. The ratio Fe/Fe+Mg changes in the chlorites of Copahue from 0,45 to 0,32. On the other hand, the Al^{IV} proportion is relatively constant, varying between 1,0 and 1,2 without an apparent relationship with depth. All the non-expandable chlorites analyzed are trioctahedrical IIb and Ib polytype with IIb type dominant.

3.2 Zeolite mineralogy

The most common zeolites in Copahue are stilbite, laumontite and wairakite. In addition to these common zeolites, mordenite, clinoptilolite, heulandite and others were also identified.

Stilbite occurs at shallow depths of the drill core, presumably formed from the recrystallization of the glassy siliceous matrix of the tuffaceous rocks. It is found at depths up to 300m, and most commonly between depth of 70-210m. Figures 2 and 3 show two SEM images of stilbite.

Laumontite is the least common of the three main zeolites. It is characteristically found at depths greater than 200m and shallower than nearly 650m, commonly between 400 and 650m. It occurs overlapping the stilbite zone above and the wairakite zone below, and commonly appears as sub – parallel lath aggregates as a filling of small fractures and amygdales or replacing plagioclase phenocrysts and glassy groundmass.

Wairakite is the most abundant zeolitic mineral in the Copahue drill-cores. It has been identified in samples beginning at depths of 600m, and extending to the bottom of the holes, though it is more abundant in the reservoir zones with cracks, fissures and open spaces. In the upper levels it appears as a fine filling of pores and amygdales and to a lesser extent replacing plagioclase and fine grain matrix. Microscopically it appears as irregular masses and anhedral grains. It is colorless, with low relieve, refraction index about 1.5 and very low birefringence. The more conspicuous optic features of this mineral is the cross-hatched twinning. Figure 4 shows a photomicrography of a twin wairakite. At greater depth the crystals are bigger, commonly up to 0.8 to 1mm of diameter, and they are found filling the cores, of veins. Figure 5 shows the SEM image of a druses of wairakite crystals lining a vein from the COP3 well at 1015 m of depth.

3.3 Ca-silicates mineralogy

The calcium silicates of the CaO-MgO-FeO-Al_2O_3 -TiO_2-SiO_2-HO_2 system constitute an important rock forming mineral group, widespread in well samples of geothermal areas. A given sequence of calcium silicates reflects a progressive dehydration with the increase of the temperature. Taking into account that the genesis of these calcic minerals depends strongly on the temperature, their identification is a useful guide in the analysis of the temperatures of formation. Besides the group of zeolites that occurs at low temperature (<110ºC) and are common in the low temperature geothermal field of Iceland (Kristmannsdottir and Tomasson, 1978) or in the peripheral and/or the superficial levels of higher temperatures fields, there also a group of minerals that occurs at higher temperatures. Among them epidote seems to be one of the most reliably and consistent temperature guide, for its occurrence is common in geothermal fields at temperatures higher than 250ºC, no matter the lithology nature. Another interesting mineral guide is prehnite, although there are discrepancies about the lowest formation temperature (from >220ºC to >300ºC) probably due to pH differences, calcium content in fluids and the iron rate in solid solution in the mineral. Wairakite, the high temperature calcium zeolite that occurs generally at the same temperatures as prehnite, and the calcic garnet, also indicate temperatures about -or higher- than 270°C or 300°C.

In Copahue epidote occurs as tabular or prismatic euhedrals crystals, as spongy aggregates replacing matrix and plagioclase, or as fan shaped coarse-grained aggregates. Two different varieties of epidote have been identified by their optical properties in the reservoir zone. One had been identified as clinozoicite, in anhedral masses of pale green to ligh yellow pleochroism, and moderate birefringence and relieve, and epidote in subhedral to euhedral crystals, with high relieve and birefringence -which suggests a higher Fe^{3+}ratio- and strong pistachio green to yellow pleochroism. This mineral is related to the plagioclase, pyroxene and amphibole replacement. Figure 6 shows a photo micrography of plagioclase partially replaced by epidote.

Miyashiro and Seki (in Deer et al., 1965) suggest that epidotes formed at lower temperatures would have a composition near 33% molar of the extreme member of Fe^{3+}, while those that crystallize at greater temperatures will show a greater amount of Fe^{3+} substitution. A systematic variation of epidote with depth has not been

determined in the Copahue Geothermal Field, though it has been noticed that epidote associated to chlorite and pyrite seems to have greater iron content than the one of the epidote – prehnite - wairakite association. Photomicrographies of figures 7 and 8 (level 816 of COP-3) show a mass of epidote with an external edge of green, pleochroic variety, with high relief and second order interference color and the core occupied by an almost colorless clinozoicite, less pleochroic and with lower relieve and birefringence.

The orthorhombic calcium silicate prehnite $CaAl_2[(H0)_2 SiO_{10}]$ is common in cores from approximately 600m of depth and specially in the reservoir zone. It occurs with epidote, wairakite, chlorite, quartz, albite and sporadic actinolite and garnet, as fine grained aggregates after plagioclase, discrete patches in matrix and vesicles, or as veins of variable thickness. Prehnite is colorless to pale green in color and displays second-order yellow birefringence. Bow-tie and parquet structures are common due to the presence of subindividuals. Figures 9 and 10 shows photomicrographies of prehnite with these structures.

Prehnite formed by replacement is fine grained, and appears commonly in a prehnite-wairakite-epidote-quartz-albite-chlorite association sometimes with actinolite and garnet. On the other hand prehnite that occurs filling up veinlets is large, euhedral, and occurs with wairakite and quartz, and subordinate epidote. Figures 11 and 12 show SEM images of euhedral aggregates of prehnite, the photomicrography of figure 13 shows an aggregate of pinacoidal crystal of prehnite with prismatic epidote and quartz from a veinlet of level 1015 of COP-3, and figure 14 shows an aggregate of prehnite and wairakite.

Liou (1985) attributes variations of this type in the mineral association of the Onikobe Geothermal Field, coincident as well with a diminution in Fe_2O_3 ratio in the prehnite of the veinlets, and assigns this fact to slight differences in fO_2 (and/or temperature). Prehnite of the matrix may have crystallized under conditions of fO_2 controlled by highly oxidized rocks whereas the one of the veinlets would have formed under conditions of minor fO_2 and greater CO_2 in a later stage.

Garnet, although not very abundant, is frequent in the samples of the deepest levels. It occurs as aggregates of small, euhedrals, poikilitics crystals, colorless and with high relieve. With crossed nicols they show a very slight anisotropy, common in grandites. Bigger crystals are tenuously zoned, constituted by an external, thin and colorless band and a greater, slightly colored nucleus, of higher relieve. It is frequently associate to prehnite, epidote, quartz and actinolite.

Garnet crystals of up to 1 mm of diameter occurs in quartz veinlets of the reservoir level. They are of pink to pale salmon color and have developed good dodecahedral habit. SEM image of figure 15 shows one of these crystals, with the effect of oscillating growth on the dodecahedral faces. In spite of its relatively scarcity, its single presence is a fact of interest in the analysis of the temperature formation of a geothermal field, since it implies a temperature over 300°C.

Albite occurs as plagioclases replacement in the volcanic rocks at temperatures between 120-180°C. In the upper levels plagioclase crystals with typical chessboard structure are common while at deeper levels, where the rock has been altered to a high degree, plagioclase phenocrystals are completely replaced by masses of albite, wairakite, adularia, chlorite, etc. In the reservoir zone albite is closely associate to epidote.

Actinolite is common but in small amounts. It is usually associated with chlorite and often occurs as small inclusions in quartz. Association with prehnite and epidote is also frequent. Figure 16 shows a microphotography of epidote and quartz, with fibers of actinolite.

4. FLUID – INCLUSIONS DATA

The quartz crystals shows primary, secondary and pseudosecondary inclusions. Primary inclusions are more common in the limpid ends of euhedral crystals and the secondary ones, smaller and more abundant, appear preferably in the base of them, conferring to the mineral a milky aspect. The pseudosecondary inclusions on the other hand are widely distributed forming small clusters or short trails all over the crystals.

The fluid inclusions in calcite were studied in samples from levels 528, 801 and 882m, since they were the only ones where the mineral occurs with a suitable diaphaneity and the inclusions had enough size to be analyzed. The calcite crystals shows a predominance of pseudosecondary and secondary inclusions. Some euhedrals crystals of wairakite from a veinlet of the reservoir level (1009m) were also analyzed, but with negative results, since although the crystals are extraordinarily diaphanous, they do not show visible inclusions.

According to the number and type of phases in the inclusions, they can be classified in three types:

1. Aqueous inclusions: two fluid phases, the volume of the liquid phase is greater than the steam one (L>V);
2. Gaseous inclusions : two fluid phases, of which V>L;
3. Three-phase inclusions (G type): with three immiscible fluid phases. Three different classes can be distinguished as well within these:

3a. Three-phase inclusions at room temperature: they are formed by a dominant aqueous phase, a subordinated water steam phase, and a third immiscible fluid phase that formed a elongated and apparently denser bubble of similar volume to the steam one. These bubbles show a continues and slow movement and suffer deformations when moving. These inclusions were observed in samples of levels 801, 806 and 813 m.

3b. Three-phase inclusions by heating: some inclusions, that look as two-phase type at room temperature, separate a third fluid phase at a temperature slightly inferior to 100°C. It is a small, perfectly circular bubble, very moving with fast movements. The two aqueous phases, liquid and steam, homogenized between 250 and 280° C, but the third bubble continues present, and at 300°C approximately an intense effervescence phenomenon takes place inside the inclusion. These inclusions have been detected in the peripheral growth zone of quartz crystals from veinlets of levels 1009 and 1013 and presumably they are constituted by liquid H_2O, water steam, and H_2S.

These inclusions also showed a distinguishing behavior on cooling. They became darker and the steam bubble contracted slightly and became deformed during the cooling, but they only seemed to be completely frozen at -130°C approximately. On reheating, the liquid clarified between –85º and -80°C and a very tenuous oval bubble is formed. The ice dissolution began at –38ºC, and it finished at –5,5ºC. At this temperature both aqueous phases –liquid and steam- seem to have recovered the initial aspect and the water steam bubble is perfectly rounded. Nevertheless the second bubble this still present, though constitute by an

aggregate of tiny spheres links one to each other like a small transparent cluster of low relieve. The inclusions maintain this aspect even though is warmed up to 30°C, and after several days at room temperature the spheres gradually dissolve and the inclusions return to their initial aspect.
The bubble nucleation temperature of -85°C would confirm the presumption that the non condensable phase is SH_2. This compound has its triple point at -85.5°C and its critical temperature is +100.4°C. (Burruss, 1981).

3c. Three-phase inclusions by freezing: they are two-phase aqueous fluid inclusions at room temperature, that nucleated a third gaseous phase at low temperatures. Some inclusions in quartz from level 801 nucleated a small bubble of steam on cooling at temperatures between -52 and -60°C. This gaseous phase still did no freeze until -140°C, possibly because of its low density, and it dissolved in the aqueous phase at -20°C. Owing to its characteristics and behavior on cooling it seems to be CO_2 steam of very low density.

The difference between the behavior of a particular system, for example H_2O-NaCl, and the observations during the freezing experiences yield to some interesting deductions about the natural system in study. The first fusion temperature or eutectic point (Me) is important to determine the composition of the system. This temperature is -20.8°C in the system HO_2-NaCl, but in this case the first fusion of the ice takes place between Me=-30.0° and -35.0°C, suggesting the presence of additional components in the solution, probably $CaCl_2$. The temperature of last ice melting, (Tf) was in average of -3.5°C -with very low dispersion of the values- giving a salinity of 5.62w% NaCl eq., (about 1,02M).

Figure 17 and 18 shows the Th histograms of the fluid inclusions in quartz and calcite respectively. The histograms of the superior zone correspond to the samples from 120, 180 and 210 m and from 320 m respectively. The homogenization temperatures are very dispersed over an ample rank of temperature that extends towards the highest ones, consequently with an important standard deviation. Besides, all the registered temperatures are higher that the boiling point of the pure water for these depths. This fact suggest that fluid was not homogeneous at the trapping moment, because of the effect of a deeper boiling process, and so the inclusions trapped heterogeneous fluids formed by two phases (liquid and steam) mixed in different proportions. A similar phenomenon of increase of the dispersion with the diminution of the depth is mentioned by Moore (1990), in its study on the fluid inclusions of the active geothermal system of Zumil, Guatemala.

In the zone about 800m (samples from 801, 806, 813 and 852 m) and 1000 m (from 1009 and 1013m), which are considered productive, the homogenization temperatures are concentrated in a close rank, with a much smaller standard deviation, although there are also inclusions that homogenize to liquid and steam in a same sample. The average temperature of these inclusions is very close, almost coincident with the boiling point curve for these depths. This suggest that here the boiling produced the net separation of both fluid phases which were trapped separately.

Histograms of calcite correspond to three samples from 528, 801 and 882m. In the deeper zone homogenization temperatures are similar to that display by the quartz from these depths. In the upper zone however, the temperatures are lower (they are the lowest registered in all the field) but continue accompanying the trajectory of the curve.

5. DISCUSSION

When the distribution of clay minerals is examined as a function of depth in drill holes of Copahue geothermal area, three zones with distinctive characteristics can been distinguished:

- an upper zone, approximately up to 700 m of depth, in which the intense and low graded alteration has pervasive character and replacement minerals predominate. Smectite is common near the surface, besides very subordinate illite and zeolites. From 80m and up to 620m S/C and C/S mixed layer clays occur, with a progressive increase of chlorite. In Cop 3 well, there is some subordinate illite between 450 m and 660 m of depth.

- a deeper zone, from about 700m and up to 1020m, in which minerals show evidences of higher temperatures of formation. Secondary minerals formed by precipitation in vesicles and along fractures coexist with replacement mixed clays. Non expandable chlorite is the dominant clay mineral. This is a zone of total drilling mud losses, and corresponds to a fracture controlled permeable horizon submitted to active flow regime, i.e. a reservoir.

- Below 1022m a conspicuous change takes place, since the chlorite diminishes again and it is substituted gradually by swelling chlorite and smectite.

Smectite occurs in the upper 100m of depth, at relatively low temperatures, 120º-130ºC. C/S mixed layer clays occur mainly between 50 and 650 m, at a temperature of about 200ºC. Non expandable chlorite occurs in deeper levels, between 650 m and 1000 m depth, at temperatures of 250ºC and higher. It is associated with epidote, prehnite, wairakite, garnet and amphibole. Al^{IV} ratio (1,0-1,2) in chlorites corresponds to temperatures between 240º and 300ºC, according to the graphic proposed by Cathelineu and Nievas (1985).

The thickness of crystallites increases with depth, indicating a better crystallization degree. The presence of IIb and Ib polytypes confirms this tendency. Hayes (in Bailey, 1988) pointed out that it is necessary a temperature higher of 200ºC to get the transition Ib to IIb, for the structural changes are very sensitive to temperature changes and relatively insensitive to changes in composition. Walker (1989), on the other hand, said that the chlorite IIb is the end product of thermal metamorphism and the transition would take place to a temperature between 150º and 250ºC.

The secondary minerals associated to clays, which vary between cristobalite and calcic zeolites near the surface to calcic secondary minerals, in deeper levels, confirm the zoning. The most common zeolites, stilbite, laumontite and wairakite show a depth zonation. The two former occur at temperatures below 200ºC, whereas the latter, accompanied by epidote, prehnite, chlorite, actinolite, and garnet, occurs within a range of temperatures from 200ºC to at least 300ºC. The occurrence of wairakite in the reservoir zone coexisting with Ca-Al silicates, indicates that thermal waters at depth are hot and neutral to slightly alkaline and that X CO_2 is rather low. It also strongly suggest a good path for the vapor. This association has been formed by the circulation of hot fluids through fractures.

Kristmannsdottir (in Browne, 1990) describes a similar tendency in Reykjanes, Island, where smectite is present as a discreet phase where the temperature is lower than 200ºC, it becomes erratically interbedded with chlorite at

temperatures between 200º and 270ºC. Above 270ºC chlorite is the only clay mineral present. Fujishima and Fan (1977) pointed out that in Keolu Hills the increment of temperature and pressure with the increasement of depth reduces the incidence of the expandable layers of chlorite.

The sporadic presence of illite in certain levels, and the even scarcer pyrophyllite, seems to be more related with changes in pH of solutions that with temperature, probably because of boiling episodes.

The occurrence of smectite and C/S mixed layer clays in the deepest level of the wells, below the mineral assemblages of high temperature, suggests that they are consequence of a inverse zonation below the area of circulation.

The abundance of gaseous inclusions that display some samples of quartz from the reservoir level, i.e. 801, 806, 813 and 1013 m, suggests that these fluids were trapped under boiling conditions that divided the initially homogeneous fluid in two different fluids, one liquid relatively more salty and another gaseous enriched in volatile and with lower pH due to the increase in CO_2 and SH_2 concentration. In other levels, for example 852 m, the samples of quartz display fewer gaseous inclusions, but peculiarly they have greater homogenization temperatures average and greater dispersions towards the highest temperatures.

This would indicated that inclusions were also entrapped in a boiling system, but in a medium where the phases were not net separated, and so the aqueous solution had carried small steam bubbles at the moment of being trapped, which yield to a greater homogenization temperature. Roedder (1984) indicates that the boiling phenomenon can be expressed in both ways, although in this last case it must be also evaluate the possibility of attributing the dispersion to necking down, leakage, etc.

The existence of effervescence phenomena, characterized because the fluid of low density is compositionally different from the aqueous phase of the inclusion was observed in quartz crystals of the productive levels. This fluid of low density, also denominated "primary gas" (Roedder, 1984) was identified as SH_2 on the basis of his behavior during the experiences of heating and cooling. According to Roedder (op.cit.) the entrapping of primary gas is a very rare phenomenon in most of hydrothermal environment, but it can be relatively common in geothermal systems. The presence of S in a C-O-H system yield to the formation of SO_2 or H_2S. Both species are mutually incompatible, being SO_2 dominant where fO2 is high. In Copahue the regular pyrite presence in many of the studied samples indicates that the fluid is in the field of the SH_2.

Figure N° 19 is the resume of all the thermometry aspects considered just now. In this graphic it have been plotted the sequence of secondary mineral, with the occurrence depth and the temperature of formation proposed. It have been plotted also the curve of boiling for the pure water, the profile of temperature of the well COP-3 (JICA-EPEN, 1992), and the partial Th histograms of quartz and calcite samples. It is possible to observed that these histograms fall over or to the right of the nowadays boiling curve.

By comparing these curves it is clear that undisturbed present day temperature in the formation is lower than the secondary mineral temperature curve which implies cooling in the geothermal system at the depth range studied. However the minimum secondary *mineral* temperature are all within the limits set by the boiling point curve except perhaps actinolite and garnet which surpasses it.

In the temperature profile two differentiated zones can be distinguished: one from the surface to about 760m, that shows a constant increase of temperature, which indicates a transmission of the heat by conduction, and another one below this depth in which the temperature remains constant or shows to irregular increases or slight diminutions, product of the transmission of the heat by convection.

Besides, between the 1000 and 1050 m a negative acute variation is observed, that corresponds to a zone of loss of perforation mud injection, that is a level with high permeability by fractures. The greater amount of injection that penetrated in the rock in this level, produced a greater cooling of it, with the consequent retardation to reach the recovery temperature.

Panarello (2002) based in a ^{2}H and ^{18}O study of the vapor, water and associated gases of Copahue proposed the existence of at least two productive levels, connected by faults and with good vertical zonation, with isotopic temperatures around 200ºC and 250ºC for the upper and deeper level respectively.

6. CONCLUSIONS

Assemblages in the boreholes reflect the temperatures within the rock formations both present and in the past. The borehole studies are made to understand the evolution of geothermal system by correlation of present day subsurface temperature with the temperature indicated by secondary minerals and fluid inclusions. Comparison of the present day temperature estimated by alteration minerals with the boiling point curve gives trend of heating/cooling of the geothermal reservoir as shown in Figure 19.

The homogenization temperatures are slightly higher than the present measured temperatures, ranging from 230°C to 270°C. Melting-point temperature measurements suggest a salinity of 3.5% en peso NaCl eq. for the liquid phase. The coexistence of liquid- and vapor-dominated fluid inclusions, and the presence of non-condensate gases suggest that the liquid -vapor separation have occurred at depth because of boiling and effervescence processes.

The lithology and distribution of hydrothermal minerals in wells COP-2 y COP-3 in the Copahue area were studied through the drillcuttings combined with the data obtained from the well testing. The study supports the idea that the wells were located in a major fault controlled hydrothermal upflow zone. The hydrothermal rock alteration is grouped into hydrothermal index mineral zones which are temperature dependent in order of the increasing temperature. Smectite-zeolite zone is low temperature (up to 200º C), mix layer clay zone (200-230º), Chlorite zone (230-250ºC) and chlorite-epidote zone (250-280ºC). Comparison of the measured formation temperature in the hydrothermal system during the drilling with fossil temperatures in the rock formation as suggested by secondary mineral study and with the hydrothermal boiling point curve which implies that the hydrothermal system cooled in recent times.

Hydrothermal clay minerals, among other geothermal minerals, may be used as thermo indicators in geothermal fields because their structure and chemical composition are sensitive to thermal changes. Temperatures based on the proportion of clay minerals are in good agreement with those proposed for other geothermal systems as Reykjanes,

Iceland or Los Azufres, Mexico. In the two well studied here microthermometric measurements on fluid inclusions are equivalent to the clay minerals temperatures, but yielded slightly higher temperatures than the measured values. Possibly hotter fluids occurred at the moment of hydrothermal mineral deposition. The difference among temperatures could indicate that a cooling has occurred in the reservoir.

The temperature up to 200º C is characteristic of upper zone while the lower zone is signified by higher temperature approaching the boiling point curve. Hot fluid is moving upward from the lower zone to the upper zone i.e. the wells are located in the upflow zone. A total circulation loss is experienced from 800 m down to 1000 m depth. The subsequent downhole temperature log done shortly after drilling, is suggestive of a fracture controlled permeability and secondary mineral evolution in the well.

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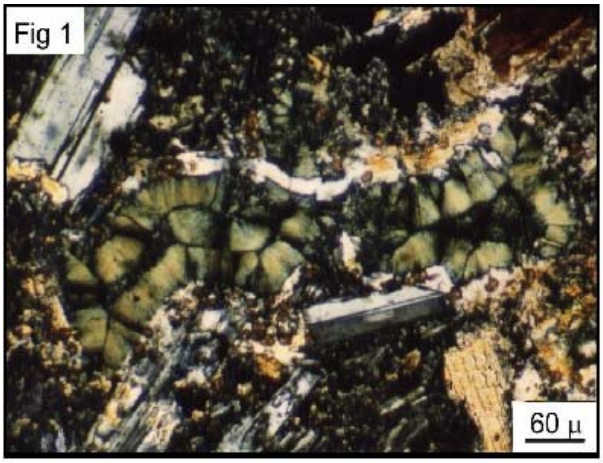
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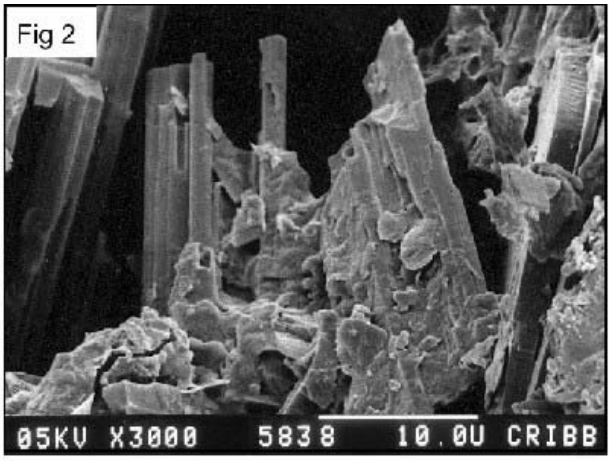
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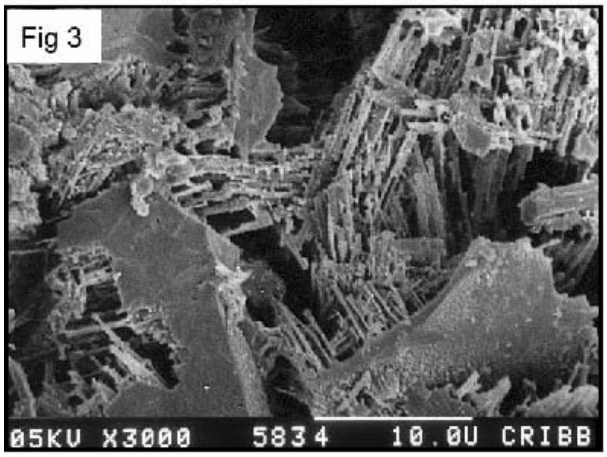
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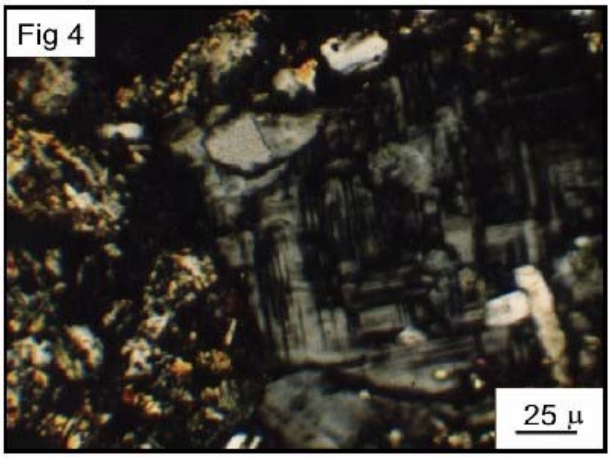
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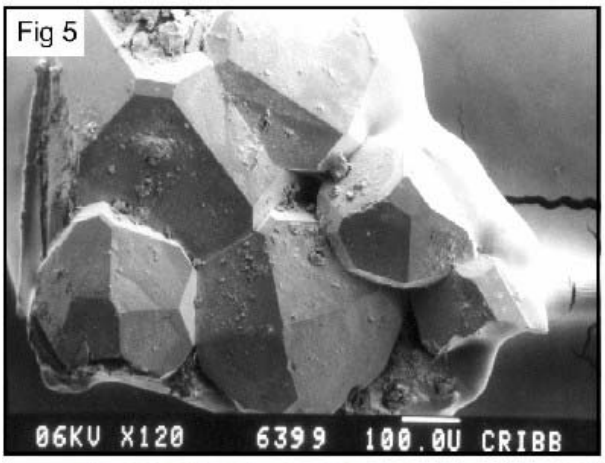
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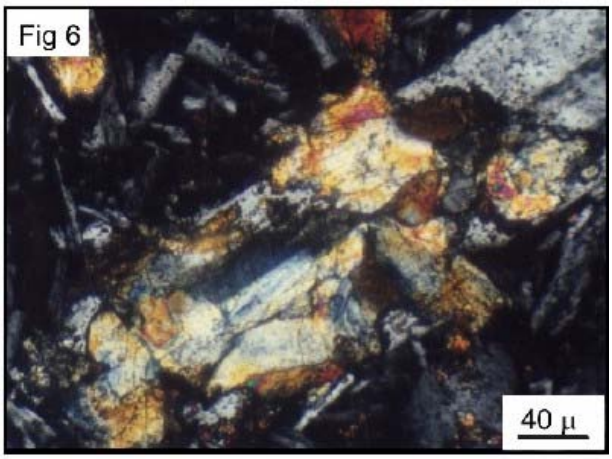

Fig 1
60 µ

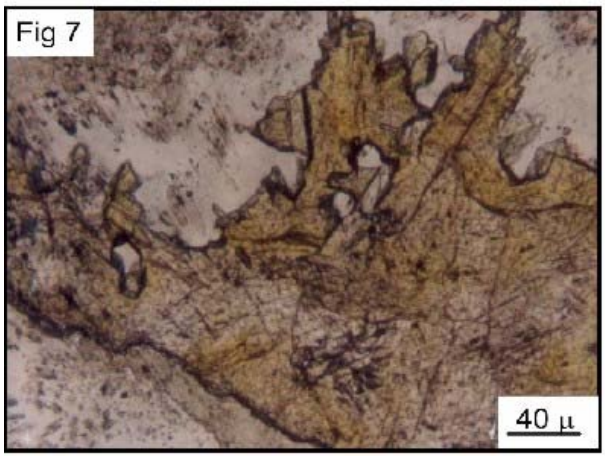

Fig 2
05KV X3000 5838 10.0U CRIBB

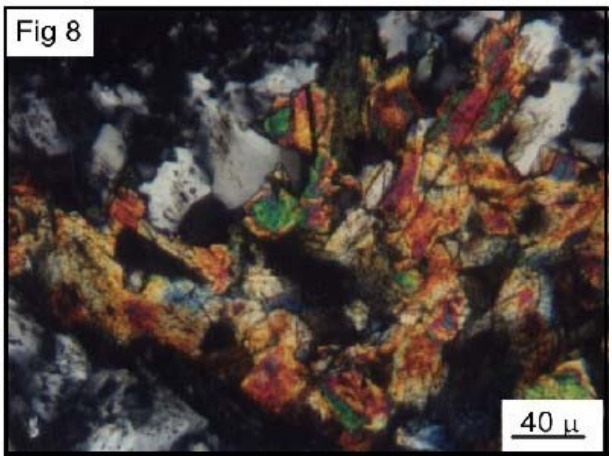

Fig 3
05KV X3000 5834 10.0U CRIBB

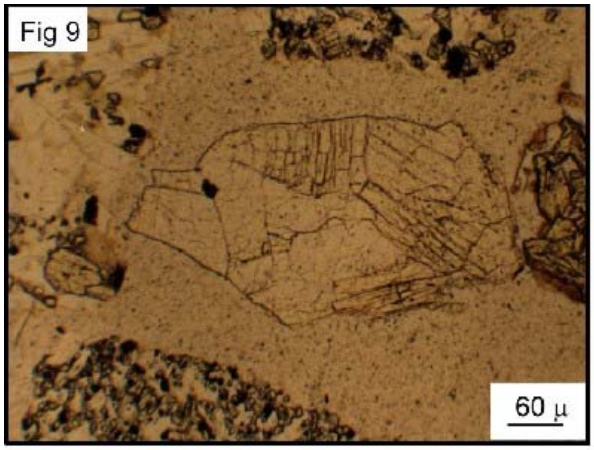

Fig 4
25 µ

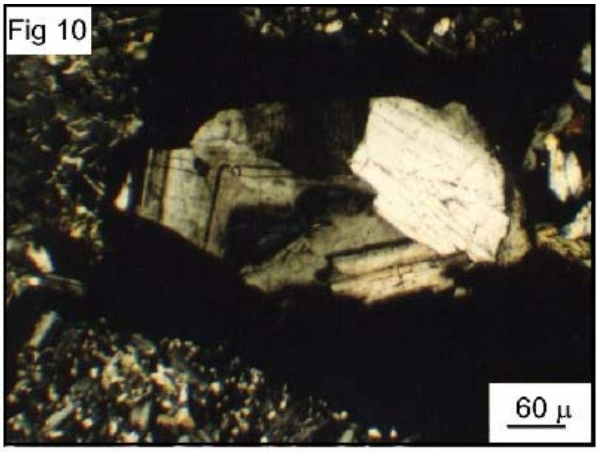

Fig 5
06KV X120 6399 100.0U CRIBB

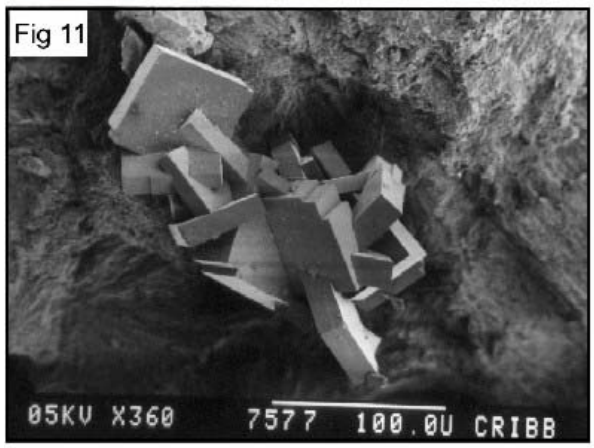

Fig 6
40 µ

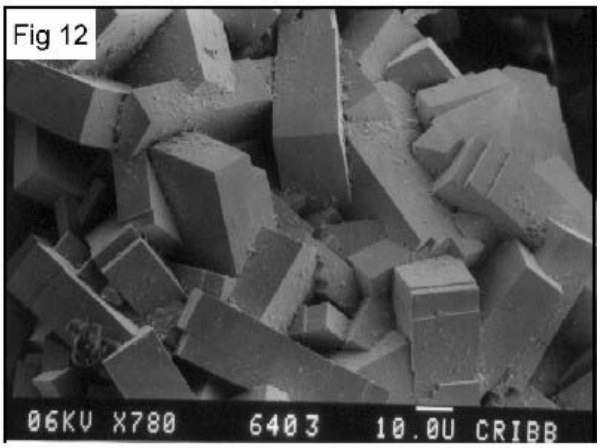

Fig 7
40 µ

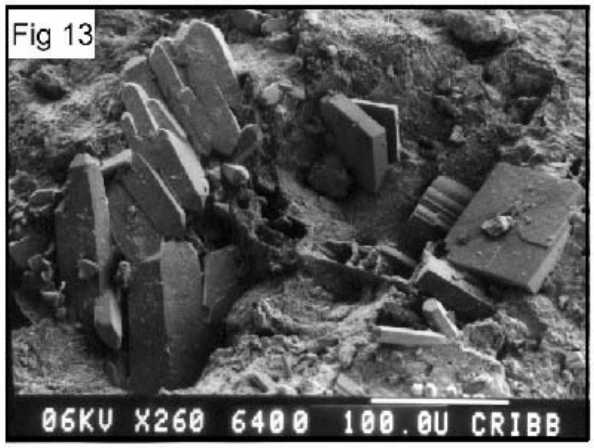

Fig 8
40 µ

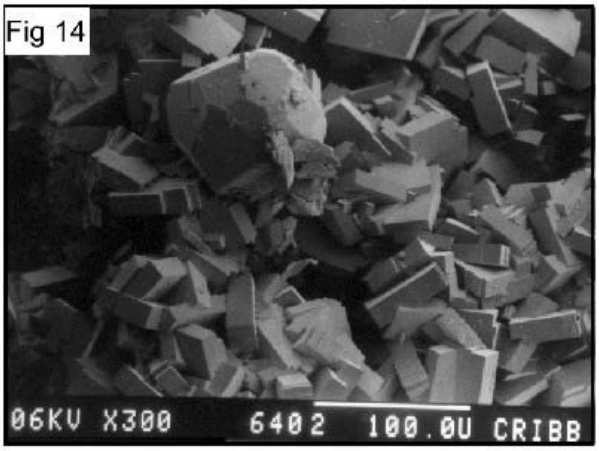

Fig 9
60 µ

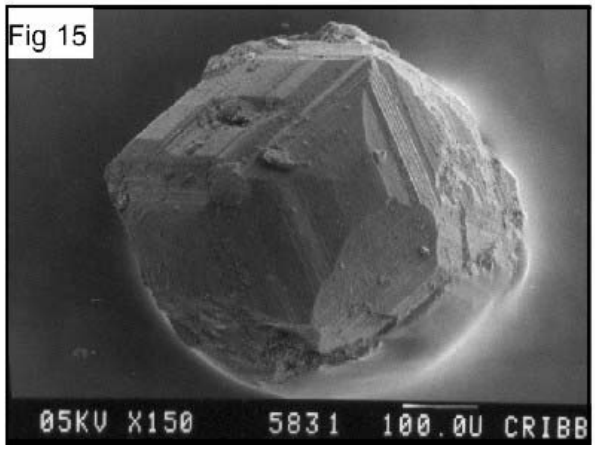

Fig 10
60 µ


Fig 11
05KV X360 7577 100.0U CRIBB


Fig 12
06KV X780 6403 10.0U CRIBB


Fig 13
06KV X260 6400 100.0U CRIBB


Fig 14
06KV X300 6402 100.0U CRIBB


Fig 15
05KV X150 5831 100.0U CRIBB

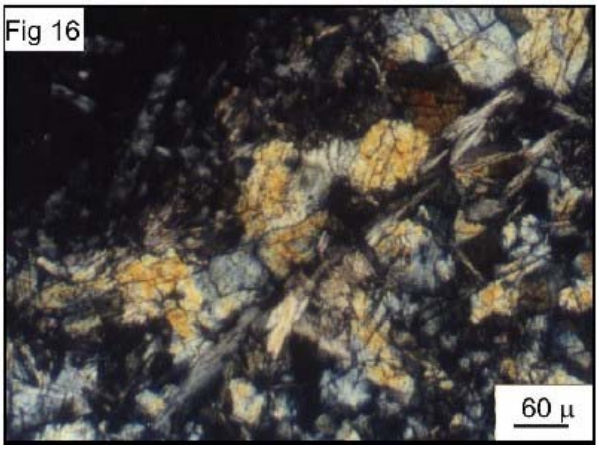
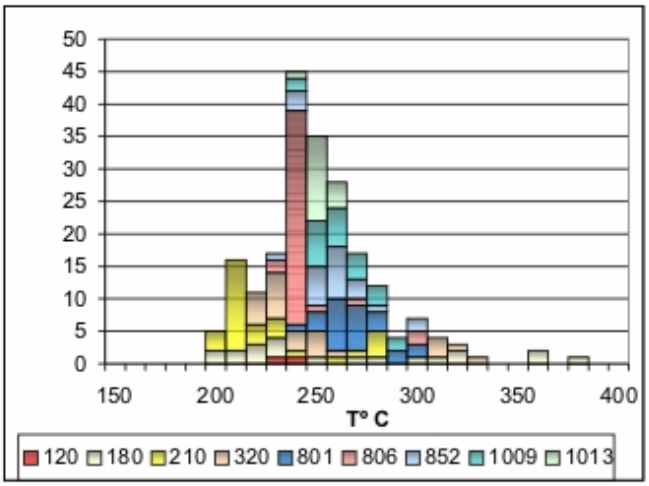
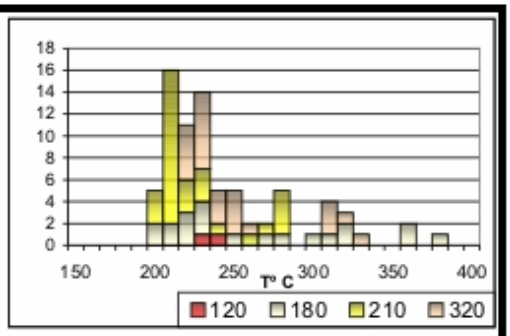
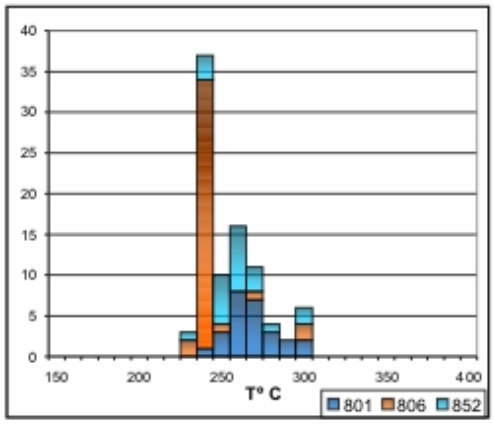

Fig 16
60 µ

Fig 17 Th Histograms in Quartz

General Histogram (below)
Partial Histograms at different depths







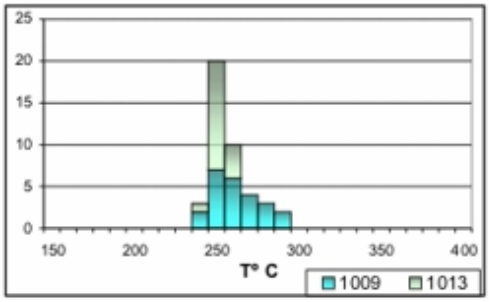
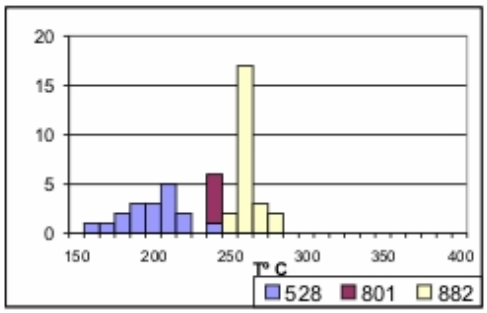
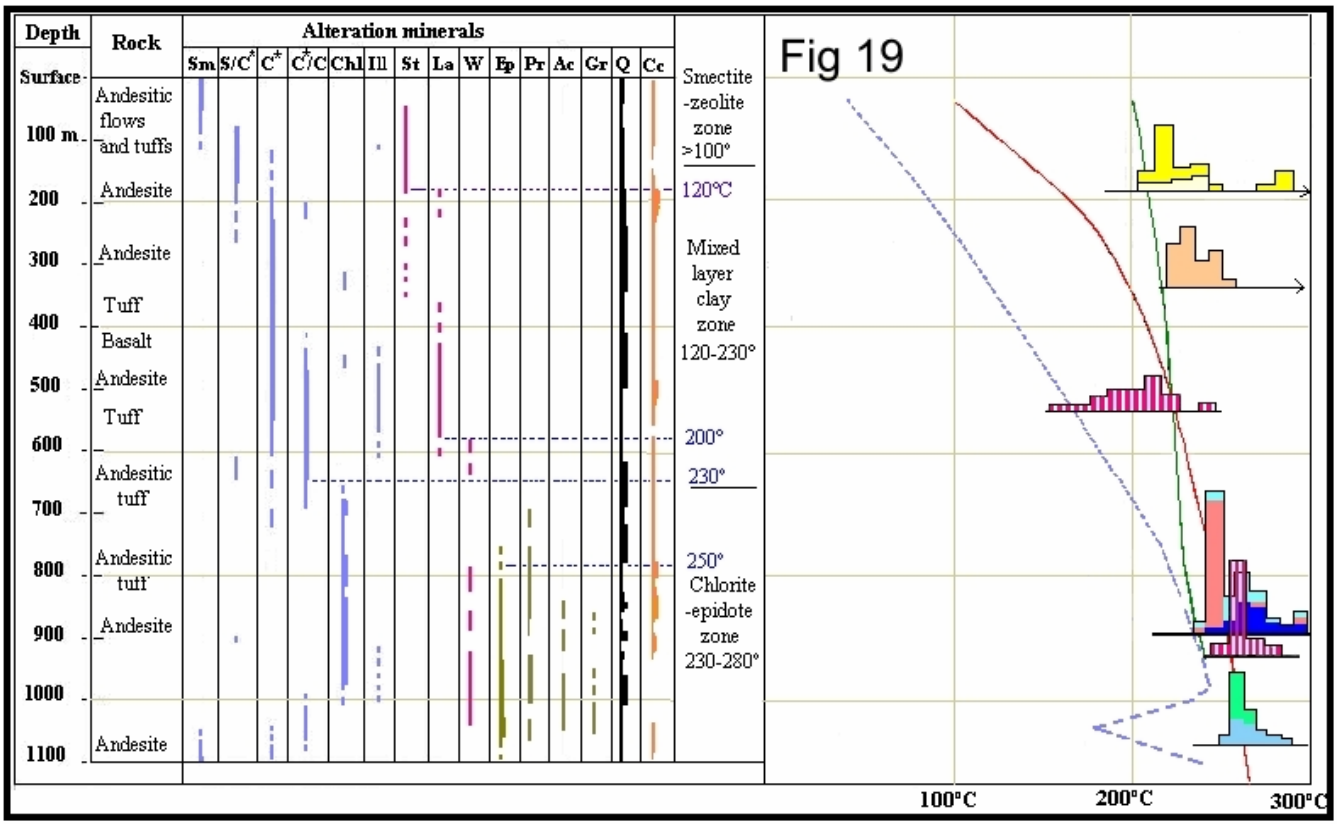


Fig 18 Th Histogram in Calcite




Fig 19
Depth
Rock
Alteration minerals
Sm
S/C*
C*
C*/C
Chl
Ill
St
La
W
Ep
Pr
Ac
Gr
Q
Cc
Surface
100 m
200
300
400
500
600
700
800
900
1000
1100
Andesitic flows and tuffs
Andesite
Andesite
Tuff
Basalt
Andesite
Tuff
Andesitic tuff
Andesitic tuff
Andesite
Andesite
Smectite -zeolite zone >100°
120°C
Mixed layer clay zone 120-230°
200°
230°
250°
Chlorite -epidote zone 230-280°
100°C
200°C
300°C