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GEOLOGY AND THERMAL FEATURES OF EL RAMAL AREA, JUJUY PROVINCE, ARGENTINA

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ABSTRACT

The region of "El Ramal Jujeño" in the eastern part of Jujuy Province, northwestern Argentina, presents several areas with thermal manifestations, mainly warm springs. Reconnaissance studies were able to delimit three locations with surface spring temperatures ranging between 37° and 58°C; they are: Aguas Calientes de Caimancito, Laguna La Quinta and Termas El Palmar. Detailed geological and geochemical surveys were carried out to evaluate their individual characteristics, as well as to develop a conceptual model of the area. The thermal system occurs in a Cretaceous-Recent sedimentary basin, more than 5 kilometers thick. A main structural system striking NNE characterizes the region, and is responsible for spring occurrences parallel to the western foothills of the Santa Bárbara range. Geochemical surveys showed that each location has its own water type, related to its circulation depth. Isotopic determinations indicate that thermal waters are of meteoric origin, with recharge occurring west of the areas of interest, where the permeable strata hosting the aquifers crop out. On the basis of chemical geothermometers, the water subsurface temperatures are estimated to range between 80° and 125°C, resulting from deep groundwater circulation under a normal geothermal gradient. As shown by old exploration oil wells, high temperatures might be found at shallower depths by drilling in the foothill areas of the western Santa Bárbara range.

1. INTRODUCTION

The approximately 9,000 km^2 area known as "Ramal Jujeño" in the Santa Bárbara Department of Jujuy Province, northwestern Argentina (Fig. 1), presents several thermal areas, mainly of warm springs (Moreno Espelta, 1981).

Reconnaissance surveys delimited three areas that extend over some 1,300 km^2. They are: Aguas Calientes de Caimancito (23° 45´ lat. S/ 64° 31´ long. W), Laguna La Quinta (23° 53´ lat. S/ 64° 28´ long. W) and Termas El Palmar (24° 05´ lat. S/ 64° 33´ long. W). Their temperatures range between 37º and 58ºC; being interesting prospects for direct use geothermal projects (Pesce *et al.*, 1995). Detailed geological and geochemical surveys were carried out in each of the areas to evaluate their geothermal potential. On the basis of these surveys and data from over 600 km of seismic lines and gravimetric surveys, and 12 oil wells drilled by YPF S.A., a conceptual model of the area was developed.

2. GEOLOGICAL BACKGROUND

At a regional scale, the area of El Ramal belongs to a fold and thrust belt in the eastern border of the Andean range. The oldest outcropping units are Paleozoic sedimentary rocks at the western flank of the Santa Bárbara range. There is an unconformity between these rocks and the overlying Cretaceous to Recent sedimentary units that extend along the top and eastern flank of the range. About 5,000 m thick sediment columns were found in wells drilled in the San Francisco River Valley, while in the ranges their thickness vary depending on the amount of erosion (Fig. 1).

Paleozoic rocks in the area are quartzites, quartzitic and micaceous sandstones, with some shales. The boundary between these and Cretaceous to lower Tertiary limestones and marls is a regional unconformity (representing a long hiatus), followed by shales and clays with anhydrite and minor sandstones. During the Upper Tertiary and Quaternary, synorogenic conglomerates, sandstones and shales, with interbedded tuffs and gypsum were deposited. The presence of travertine layers close to the western Santa Bárbara foothills suggests long-term hydrothermal activity.

Two main faults limit the study area. The Zapla-Valle Grande thrust to the west, and the Santa Bárbara thrust to the east (Fig. 1). Both belong to a NNE-striking structural system related to the Andean orogeny. Transverse ENE and NW structures locally dislocate the Andean thrusts.

The thermal springs are located close to the main NNE thrusts faults, where local transverse and antithetic faults create structural closures. The El Palmar, Caimancito and Laguna de La Quinta areas are aligned following a reverse fault (N 25° E , dip 57° ESE) that limits the eastern flank of the Santa Bárbara range (Fig. 1).

3. THERMAL MANIFESTATIONS

The Aguas Calientes de Caimancito hot springs are located in Tertiary outcrops of well-sorted and poorly consolidated fine sandstones. The temperature of the springs ranges from 46º to 58ºC. According to their location in the field, two groups of springs were identified, a western one (with a total flow rate of 1,000 L/min) and an eastern one (with flow rates between 2 and 75 L/min**).** Both groups are controlled by parallel faults striking N 25º E.

Laguna La Quinta constitutes a semicircular pond partially covered by brackish mud deposits. The pond is fed by several internal as well as nearby hot springs, all controlled by a fault at the foothills of the Santa Bárbara range. A significant gas (mainly H_2S) emission is evident by the odor. Hot (37º to 53º C) waters come to the surface through calcareous marls. A flow rate of 190 L/min was measured on the main spring located at the fault scarp.

Hot springs at the Termas El Palmar emerge from pink quartzites and very cohesive, medium-grained quartzitic sandstones belonging to the Paleozoic sequence (Lower

Ordovician). The springs are numerous with temperatures from 42º to 51ºC and generally have a low-to-medium flow rate (from 5 to 240 L/min). This area is characterized by abundant travertine deposits found around the springs, as well as in the little river into which the thermal waters flow.

4. HOT WATER CHEMISTRY

Water samples for chemical and isotopic ($^{3+}$H, D and ^{18}O) analyses were collected from 22 warm springs in the three thermal areas. Geochemical data showed different types of waters in the three areas (Fig. 2). SO_4 type fluids occur in Aguas Calientes de Caimancito, with total dissolved solids (TDS) between 751 and 1561 mg/L, and pH of 8.3 to 8.9; ClNa-type fluids in Laguna de La Quinta with the highest TDS (reaching up to 14700 mg/L) and pH values between 6.5 and 7.6; and Na-type fluids in Termas El Palmar with TDS from 2480 to 3360 mg/L and an average pH of 6.8.

Stiff diagrams for both the Aguas Calientes de Caimancito and Termas El Palmar springs show diluted and undiluted waters (Fig. 3). These differences in ionic proportions are related to mixing with younger or shallower waters, as evidenced by the Tritium content (> 0 T.U.) in diluted waters. In the δD vs. δ^{18}O diagram (both δ referred to VSMOW (Vienna-Standard Mean Ocean Water) all warm springs match the MWL (Meteoric Water Line), showing that these springs originate from infiltration of meteoric water under similar precipitation conditions (Fig. 4). Regardless of their common origin, the chemical composition for each particular area reflects the different circulation pathways (i.e., strata), from the moment the waters enter the hydrological system of the basin. Tritium data indicate that the circulation-residence time for these waters exceeds 50 years.

4.1 Geothermometry

Subsurface temperatures were calculated selecting samples that do not show traces of mixing with younger waters (springs with T.U. = 0). Since a single silica geothermometer applied to natural springs could lead to ambiguous results we used different ones to estimate possible temperature ranges for each of the selected areas (i.e., the quartz geothermometer described by Fournier and Rowe, 1966, and Fournier and Potter, 1982, and the chalcedony geothermometer of Fournier, 1973).

The same argument can be applied to cation geothermometers. The Na-K-Ca ratio (Fournier and Truesdell, 1973) with the ß = 1/3 factor for the Laguna La Quinta area, and ß = 4/3 for the Termas El Palmar and Aguas Calientes de Caimancito areas were used. Because of high Mg contents (> 30 mg/L), the magnesium correction (Fournier and Potter, 1979) was applied to the first two areas. It was also considered to be proper to use in all three areas the K^2/Mg (Giggenbach, 1988) and Li/$\sqrt{}$Mg ratios (Kharaka and Mariner, 1989), to indicate the temperature of the last water-rock equilibrium. Temperatures obtained from these geothermometers are summarized in Table 1.

At the Aguas Calientes de Caimancito area, geothermometer data show slight variations. This could indicate that the water-rock equilibrium could have reached the estimated 70º-80º C temperature, and that the water-rock reactions on the way to surface were minimum or none.

The values obtained for the Laguna La Quinta area range from 97° to 139°C. However, one should take into account that, first, cation geothermometers applied under the best possible conditions have an uncertainty of at least ± 5-10°C (Fournier, 1991) and, second, the fact that in relatively deep sedimentary basins where the water is in contact with rock at a given temperature for extended periods of time, quartz may be present as the controlling phase of the dissolved silica, even at temperatures under 100ºC (Fournier, 1991). Also, the significant amount of travertine deposits present in the area and the silica contents (43-49 mg/**L**) of the waters are indicative of temperatures below 150ºC and above 100ºC. Considering all this, estimated subsurface temperatures between 100º and 120°**C** could be more realistic for the Laguna La Quinta area.

In the Termas El Palmar area, the resemblance between K^2/Mg and Li/$\sqrt{}$Mg ratios which give temperatures significantly lower to those obtained using the quartz and Na-K-Ca (β=4/3) geothermometers, would indicate that the waters might have stayed in a secondary reservoir at intermediate depths and temperatures for a relatively short time, where water-rock re-equilibration only occurs for the most reactive phases (Fournier, 1991). Given the limitations of the methods used, this hypothesis should be confirmed by future studies. Nevertheless, taking into account the same considerations as in case of the Laguna La Quinta area, it is possible to estimate a subsurface temperature ranging between 100 and 125° C.

5. CONCEPTUAL MODEL

The main recharge area for El Ramal is located on the western foothills of the Zapla and Valle Grande ranges, where there are outcrops of permeable strata. Its large (1,500 km^2) area and dip towards the center of the basin favors meteoric water infiltration. Subsurface water samples with low mineral content (slightly calcium bicarbonated), are consistently found in this area. Some fifteen aquifers at different depths were reported for the basin where El Ramal is located; the data is from exploration oil wells.

From west to east, the general attitude of the permeable strata shows a monoclinal deepening towards the center of the basin (at 64° 45´ W longitude); from there, the strata are subhorizontal down to 5,000 m depth. The aquifers become shallower towards the east. At the western foothills of the Santa Bárbara range, there is a major thrust fault that caused it to rise. This fault conducts the groundwaters towards the thermal springs (Fig. 1).

Seismic lines reveal no significant faults between the recharge and discharge areas. Nevertheless, despite the data available from exploration oil wells, no correlation between aquifers could be made due to facies changes within the basin.

Following the geochemical signatures of 140 water samples taken from thermal springs, and shallow and deep wells (Hagermann, 1933; Aquater, 1979; Pesce *et al.,* 1995), three main depth intervals that include many of the aquifers, were defined. These are, Quaternary and Upper Tertiary, with low-salinity waters, such as meteoric recharge and Aguas Calientes de Caimancito waters; Upper Cretaceous and Lower Tertiary, with brines resulting from the dissolution of interbedded evaporites, which are a component of La Quinta's mixture; and

Middle Cretaceous, bicarbonated sodium waters, such as those at Termas El Palmar and the main component of Laguna La Quinta's mixture.

The heat for the thermal waters in the El Ramal area is related to the normal geothermal gradient. The regional gradient was established on the basis of borehole temperatures, water and oil temperatures, mineral geothermometer data from cores, and oil maturity assays. The regional gradient ranges between 2.6 °C/100 m and 3.5 °C/100 m. The deeper aquifers in the basin are at depths of about 5,000 m**,** which indicates that water temperatures in the order of 150°C in equilibrium with the host rock, are possible. It could be said that the proposed stratigraphy, the data on geothermometry, geothermal gradients and, heat source, and the cooling and mixing as the groundwaters rise toward the east are consistent.

6. CONCLUSIONS

The area of El Ramal constitutes a low-temperature geothermal system hosted in a sedimentary basin, heated by the normal geothermal gradient. According to the studies carried out in the area, water temperatures of 120°C, to up to 150°C, could be found at about 4,500 m depth. The western foothills of Santa Bárbara range, where a main thrust fault allows the upflow of hot waters, is the preferential drilling area since high temperatures might be encountered at shallower depths. Old exploration oil wells drilled in the area intersected **a** 80°C aquifer, with flow rates of about 100,000 L/h, between 500 and 1,000 m depth. In the proposed areas, similar flow rates could be obtained by drilling relatively shallow wells intersecting faults carrying ascending geothermal waters.

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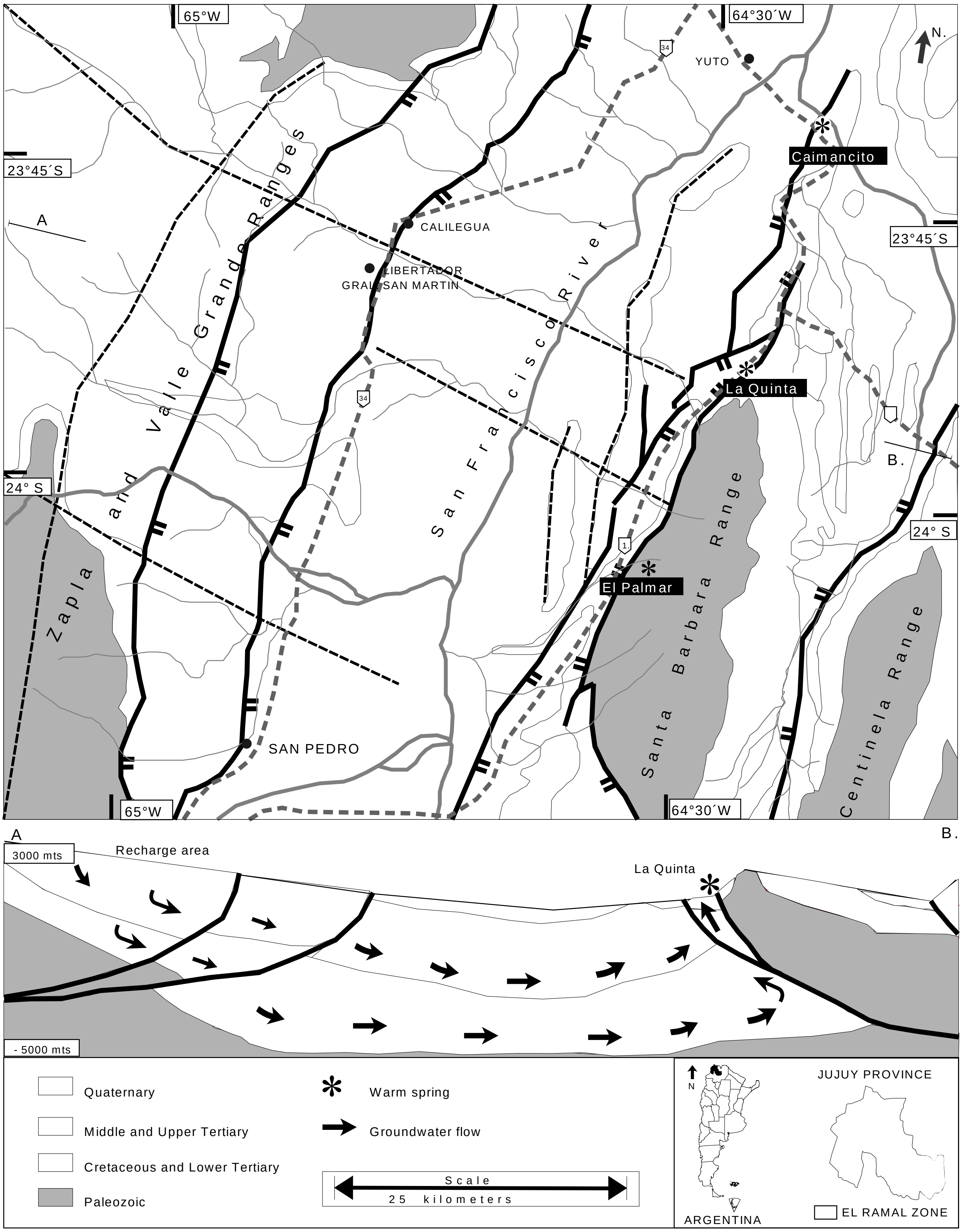

Figure 1. El Ramal zone: Location, geology, structure, springs location and transversal section.

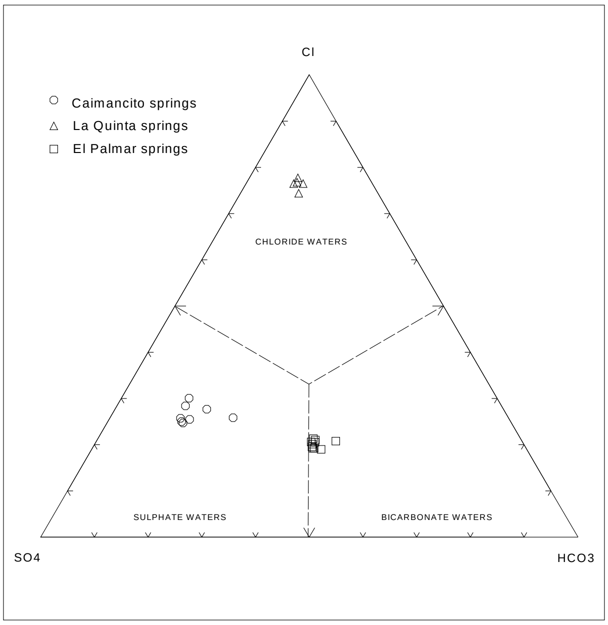

Figure 2. Water types at each of the three locations.

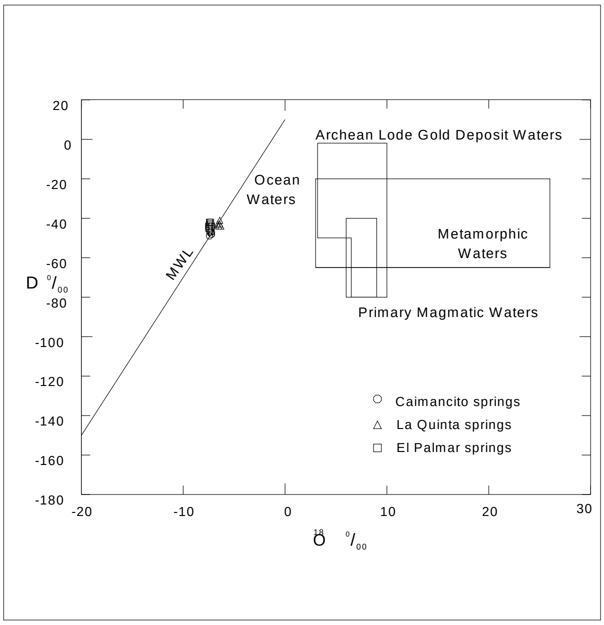

Figure 4. Oxygen 18 and Deuterium diagram.

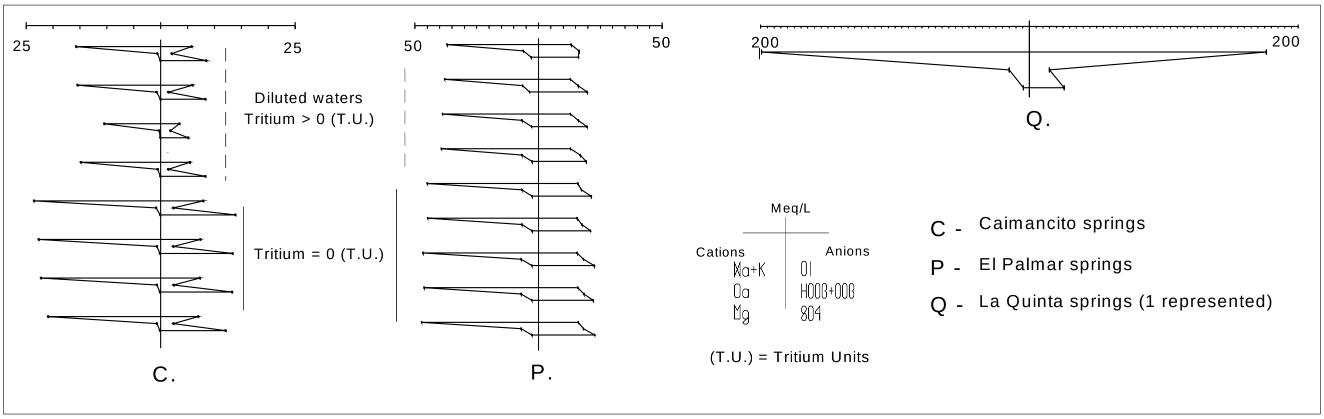

Figure 3. Stiff diagrams for the Aguas Calientes de Caimancito, Termas El Palmar and Laguna La Quinta areas (units in meq/L). Diluted (Tritium >0) and undiluted waters (Tritium= 0) are shown for Caimancito and El Palmar areas. For Laguna La Quinta, only one spring (Tritium=0) is shown.

Table 1. Geothermometer temperatures. TQC (conductive quartz), TQA (adiabatic quartz), TQ (Fournier and Potter, 1982), TCH (Chalcedony). The rest geothermometers are detailed in text. * Mg corrected.

Geothermometer	Caimancito	La Quinta	Palmar
TQC (Fournier and Rowe, 1966).	75-77°C	97°C	120-130°C
TQA (Fournier and Rowe, 1966).	79-81°C	98°C	118-128°C
TQ (Fournier and Potter, 1982).	76-77°C	97°C	120-132°C
TCH (Fournier,1973).	44-45°C	67°C	91-104°C
Na-K-Ca (ß=1/3) Fournier and Potter (1979)	---	121°C*	---
Na-K-Ca (ß=4/3) Fournier and Potter (1979)	71-75°C	---	119-126°C*
K-Mg (Gigembach, 1988).	53-60°C	139°C	94-102°C
Li-Mg (Kharaka and Mariner, 1989)	69-79°C	127°C	105-112°C