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ACTIVE METASOMATISM IN THE
CERRO PRIETO GEOTHERMAL SYSTEM, BAJA CALIFORNIA, MEXICO:
A TELESCOPED LOW PRESSURE/TEMPERATURE METAMORPHIC FACIES SERIES

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ABSTRACT

In the Cerro Prieto geothermal field, carbonate-cemented, quartzo-feldspathic sediments of the Colorado River delta are being actively metasomatized into calc-silicate metamorphic rocks by reaction with alkali chloride brines between 200° and 370°C, low fluid and lithostatic pressures, and low oxygen fugacities. Our petrologic investigations of drill cores and cuttings from over 50 wells in this field identified a prograde series of calc-silicate mineral zones which include as index minerals: wairakite, epidote, prehnite, and clinopyroxene. Associated divariant mineral assemblages are indicative of a very low pressure/ temperature metamorphic facies series which encompasses the clay-carbonate, zeolite, greenschist, and amphibolite facies. This hydrothermal metamorphic facies series, which is becoming increasingly recognized in other active geothermal systems, is characterized by temperature-telescoped dehydration and decarbonation mineral equilibria. Its equivalent should now be sought in fossil hydrothermal systems.

INTRODUCTION

The processes of metamorphism and metasomatism are normally inaccessible to direct observation, except on the laboratory scale. Therefore for many geologists, ourselves included, these processes tend to remain a challenging enigma. However, in recent years, exploration of active geothermal systems by deep drilling is affording an opportunity to study metasomatism in action. To witness geothermal wells discharging hundreds of tonnes of hot water and steam an hour tends to make metasomatism seem more credible. Furthermore, in a geothermal well we can measure directly in situ pressure, temperature, permeability and porosity, and can obtain samples of fluid and rock for analysis. Such measurements can then provide insight into understanding fossil hydrothermal systems.

The few comprehensive studies available on metasomatism in active geothermal systems all observed systematic zonation of temperature-dependent hydrothermal minerals (see Browne, 1978, for a recent review). Many workers (e.g., Muffler and White, 1969; McDowell and Elders, 1980) have noted correlations between this kind of mineral zonation and that produced by progressive low-grade metamorphism (from the zeolite or clay-carbonate to greenschist facies) observed in fossil analogues. In addition, mineral parageneses in active geothermal systems correlate well with experimentally (e.g., Zen and Thompson, 1974) and theoretically (e.g., Helgeson, 1967; Bird and Norton, 1981) deduced phase relations for low grade metamorphism.

Petrologic studies on samples from the highest temperature (i.e., 300-360°C) portions of some active geothermal systems such as Larderello, (Cavarretta et al., 1982), Krafla (Kristmannsdottir, 1981), Salton Sea (McDowell and Elders, 1980) found authigenic calc-silicate minerals such as wollastonite, garnet, and clinopyroxene which were previously not recognized to be stable phases under the ambient pressure and temperature conditions of these systems. In some cases, crystallization of these so-called "high-temperature" minerals was attributed to thermal anomalies due to dike intrusions (Kristmannsdottir, 1981) or earlier local higher temperature events (Cavarretta et al., 1982).

In this paper, we will describe authigenic mineral zonation in the Cerro Prieto geothermal field as an example and suggest that this paragenesis of calc-silicates crystallizing at temperatures less than 370°C represents an extremely low pressure metamorphic facies series which spans the zeolite to amphibolite facies.

Geologic Setting of the Cerro Prieto Geothermal System

The Cerro Prieto geothermal field of Baja California (Figure 1) is part of the large thermal anomaly associated with the structural province of the

Salton Trough (see Elders et al., 1972, for a review of the regional geology). Deltaic sediments of the Colorado River deposited within this basin since latest Miocene time (Van de Kamp, 1973) apparently approach a stratigraphic thickness of 10-16 km (Fuis et al., 1982). These quartzo-feldspathic sandstones, siltstones, and mudstones have compositions similar to modern Colorado River deltaic sediments (Muffler and Doe, 1968). Deep drillholes in several of the geothermal fields of the Salton Trough intersect widespread mafic to silicic dikes or sills possibly related to surficial Quaternary volcanic activity (Robinson et al., 1976). These dikes may be part of the larger intrusions within pull-apart basins associated with a leaky transform fault system believed to be the heat sources for the geothermal fields of the Salton Trough (Elders et al., 1983).

The Cerro Prieto field, with currently an installed generating capacity of 180 MWe, is the most developed commercial geothermal system in the Salton Trough; more than 110 wells have been drilled there to date. Since 1977, in collaboration with the Comisión Federal de Electricidad of Mexico and the Lawrence Berkeley Laboratory of the U.S.A., we have carried out a comprehensive petrologic/geochemical study of this geothermal field. We have obtained petrographic, XRD, electron microprobe, fluid inclusion and light stable isotopic data on cuttings and cores from more than half of the geothermal wells in the field (Elders et al., 1981).

PHYSICAL-CHEMICAL CONSTRAINTS ON METASOMATISM AT CERRO PRIETO

Pressure

The deepest geothermal wells drilled to date approach 3.6 km and have lithostatic pressures of about 900 bars, assuming an average bulk density of 2.5 gm/cm³ for the reservoir. Measured downhole fluid pressures within the producing (usually deepest) intervals of the geothermal wells generally range

between 100 and 200 bars (Bermejo et al., 1979). These measured hydrostatic pressures together with both measured temperatures and geothermometry indicate that the fluids in the reservoir are close to boiling.

Temperature

Temperatures within the Cerro Prieto geothermal system have been determined by a variety of techniques: downhole measurements (Bermejo et al., 1979), solute geothermometry (Truesdell et al., 1981), stable isotope geothermometry (Olson, 1979; Williams and Elders, 1983), fluid inclusion geothermometry (Elders et al., 1978), and vitrinite reflectance geothermometry (Barker and Elders, 1981). Apart from the inherent limitations of measuring downhole temperatures by the customary method using mechanical recorders, both direct measurements and solute geothermometers are subject to the effects of drilling and flowing geothermal wells (see Figure 2). Solute geothermometry is also limited because the fluids come from an interval several hundred meters thick. This temperature information is averaged over the production interval and is not obtained outside it. Thus, solute methods cannot provide continuous temperature-depth profiles for the wells. For our purpose, the most useful estimates of the temperature of the reservoir in its pre-exploitation state are based upon the partitioning of oxygen isotopes between calcite in the rock and the reservoir fluid (Williams and Elders, 1983).

Fluid Composition

The geothermal fluid at Cerro Prieto is a mixture of Colorado River water and connate water which has subsequently reacted with the deltaic sediments during hydrothermal alteration (Truesdell et al., 1981). This alkali chloride brine has total dissolved solids of about 15,000 ppm. The approximate ranges of the concentrations of major components are: Cl = 6000-11,000 ppm, SiO₂ = 550-700 ppm, Na = 3000-5500 ppm, K = 500-1000 ppm, Ca = 100-400 ppm, total CO₂ = 10-75 ppm (Fausto et al., 1981). In high temperature reservoir fluids,

CO₂ is the dominant gas species (Nehring and D'Amore, 1981) with pCO₂ on the order of 5-10 bars (e.g., 7 bars in fluids from well M-5 at approximately 1285 m and 340°C; Ellis and Mahon, 1977) and XCO₂ in the fluid phase is about .05 (assuming ideal solution behavior).

Oxygen Fugacity

Nehring and D'Amore (1981) suggested that f_{O₂} in the geothermal fluids is buffered by equilibrium between CO₂ and free carbon (in the form of lignite as described by Barker and Elders, 1981). For high temperature (i.e., 300-350°C) reservoir fluids, their calculations indicate f_{O₂} near 10⁻³⁵. Similarly, we have calculated f_{O₂} assuming that oxygen is buffered by a reaction relationship between epidote and calcium clinopyroxene at temperatures of 320-360°C. The resulting f_{O₂} is on the order of 10⁻³³ to 10⁻³⁷, slightly more reducing than the quartz-fayalite-magnetite buffer curve.

Fluid/Rock Ratios

Oxygen isotopic compositions of both reacted and unreacted fluids have been determined in the Cerro Prieto geothermal system (Truesdell et al., 1981). Mass balance calculations by Williams and Elders (1983) indicate a minimum integrated fluid:rock volume ratio of approximately 3:1 was necessary to produce the oxygen isotope exchanges observed in the altered sediments.

MINERAL ZONATIONS AND CALC-SILICATES AT CERRO PRIETO

Elders et al. (1981) recognized that various hydrothermal mineral zones within the field exhibit an obvious correlation with isotherms. These mineral zones were defined by changes of modal abundances, and by disappearance, or first appearance of key authigenic phyllosilicates and calc-silicate minerals.

Below the surficial layer of sediments (generally less than 1 km thick), there is a self-sealed "cap rock" over the geothermal reservoir which is typi-

cally a carbonate-cemented sandstone. The carbonate (predominantly dolomite with subordinate calcite) precipitates in the pores of the unconsolidated sediments by the heating of descending, cold CO₂-rich surface waters (Elders et al., 1981). In contrast, in the less widespread zones where discharge of hot fluids occur, the cap rocks consist of quartz or potassium feldspar-cemented sandstones.

Within the carbonate cap, at approximately 150°-230°C, mineral reactions transform the diagenetic carbonate cement and phyllosilicate matrix. With increasing temperature, calcite becomes the dominant cementing agent and detrital/authigenic illite, kaolinite, and expandable interlayered illite/smectite are progressively replaced by authigenic chlorite and sericite. Here we use "sericite" to refer to all the complex dioctahedral layer silicates including illite and muscovite. These transitions in authigenic phyllosilicates are a higher grade continuation of similar transformations in clay minerals observed in the burial diagenesis of clastic sediments in the Gulf Coast of the U.S.A. (Perry and Hower, 1970). However, the phyllosilicate reactions at Cerro Prieto are occurring in response to a much higher ambient geothermal gradient active over a much shorter time period. Above 320°C authigenic biotite is the dominant phyllosilicate. This sequence of layer silicate minerals at Cerro Prieto is similar to that in the related Salton Sea geothermal field in the northern part of the Salton Trough (McDowell and Elders, 1980).

Sediments in the highest temperature (i.e., 230°-370°C) portions of the geothermal system recrystallize to form predominantly calc-silicate bearing mineral assemblages causing pronounced textural changes. Decarbonation reactions tend to produce secondary porosity as the first formed calc-silicates, wairakite and epidote replace the carbonate cement. These calc-silicates rarely replace the framework grains of quartz and feldspar but generally exhi-

bit sharp crystal boundaries against them. In sandstones from the highest temperature portion of the calc-silicate zone (>330°C), grain boundaries between pore-filling epidote, prehnite, and clinopyroxene and between recrystallized framework grains may approach a hornfelsic fabric.

The approximate temperature ranges of crystallization for the calc-silicate minerals in the Cerro Prieto system are shown in Figure 3. The temperatures indicated are based on oxygen isotopic ratios of coexisting matrix calcite (Williams and Elders, 1983). Matrix calcite is progressively destroyed by decarbonation reactions at increasing temperatures, however, trace amounts are present at temperatures above 300°C, sufficient for geothermometry.

Figure 4 showing authigenic mineral distributions within sandstones, based on our X-ray and petrographic criteria, for a representative cross-section through the field exemplifies the very close relationship between isograds and isotherms. Between 200° and 250°C, the calcite content decreases abruptly from greater than 15 to about 5 wt %. Concomitantly, a series of calc-silicate phases appears; wairakite appears at about 200°C, epidote at about 230°C, prehnite and actinolite near 275°C, and clinopyroxene near 320°C. Although wairakite disappears at temperatures above 300°C, all of the other calc-silicate minerals in sandstones persist at temperatures up to 370°C.

Compositional variations of authigenic silicate minerals in the Cerro Prieto geothermal field reflect equilibration with hydrothermal fluids under low pressure and low f_{O_2} conditions. $Fe/Fe+Al^{VI}$ ratios in epidotes range from 0.11 to 0.31 and in prehnite from 0.01 to 0.28. Both epidotes and prehnites exhibit variable compositional zoning at all scales, although weak compositional variations with temperature and depth are noted. Actinolites exhibit molar $Mg/Mg+Fe+Mn$ between 0.67 and 0.82 with very low Al^{IV} (<0.20 $Al^{IV}/15$ cations). Hydrothermal clinopyroxenes are calcic augites with molar

Mg/Mg+Fe+Mn between 0.23 and 0.90. The hydrothermal biotite has low Al^{VI} (<0.23 Al^{VI}/7 cations minus Na, K, and Ca), low interlayer site occupancy (<0.80 Na+K/formula unit), and molar Mg/Mg+Fe+Mn between 0.58 and 0.87. These biotites are similar in composition to those observed at similar temperatures in the Salton Sea geothermal system (McDowell and Elders, 1980). Conversely, tectosilicates show limited compositional variations. Wairakites have a nearly constant ratio of Ca/(Na+K+Ca), averaging near 0.97. Microcline (adularia), which is ubiquitous throughout the calc-silicate zone, has a composition of OR₉₆₋₁₀₀. Albite has been identified by X-ray diffraction only.

DISCUSSION

In our opinion, the sequence of minerals in the calcic sandstones at Cerro Prieto, which are being metamorphosed at temperatures between 150° and 370°C, constitutes a low P/T facies series which encompasses the clay-carbonate, zeolite, greenschist, and amphibolite facies. Tie lines in Figure 5 denote the two and three phase calc-silicate and phyllosilicate assemblages observed. All assemblages also contain variable amounts of quartz, microcline, albite, sphene, pyrite, and magnetite.

Within the carbonate cap at temperatures below 200°C, the authigenic mineral assemblage consists of carbonate + sericite ± chlorite. This clay-carbonate facies (Zen, 1961) is stabilized by high X_{CO₂} in the intergranular fluid phase of relatively impermeable carbonate-cemented sandstones. At temperatures near 200°C, the first calc-silicate, wairakite, forms through decarbonation reactions; aluminum and silicon are probably supplied through dissolution of phyllosilicates or feldspars. Epidote, first appearing at temperatures near 230°C, forms predominantly through reaction from calcite + wairakite. Wairakite or wairakite + epidote assemblages represent the lowest P_{fluid} form of the zeolite facies (Frost, 1980). At Cerro Prieto, P_{CO₂} is

buffered by the epidote + wairakite + calcite assemblage to values in excess of 15 bars (Elders et al., 1981) at depths in the system where total fluid pressures do not generally exceed 75 bars (Bermejo et al., 1979), thus X_{CO_2} may exceed 0.2 at these temperatures. Prehnite and actinolite, which first appear at temperatures near 300°C, form in part through decomposition of calcite + chlorite via a reaction which is also operative at relatively high X_{CO_2} (Glassely, 1974). These minerals may also form through complex ionic reactions in which iron and magnesium is supplied through dissolution of matrix sericite. Clinopyroxenes, first appearing near 320°C, may form through the generalized dehydration reaction: actinolite + prehnite = clinopyroxene + epidote + H_2O , or through the mixed volatile reaction: actinolite + calcite = clinopyroxene + CO_2 + H_2O . The latter reaction has been experimentally delineated by Slaughter et al. (1975) for the Fe-free system; crystallization of clinopyroxene by this reaction at $P_{fluid} = 100$ bars and temperatures near 325°C will buffer X_{CO_2} to very low values (i.e., 0.05). Thus, increasing metamorphic grade in the Cerro Prieto geothermal system is related to both increasing temperature and a concomitant decrease in X_{CO_2} at very low lithostatic pressures.

CONCLUSIONS

Certain of the observed prograde mineral assemblages at Cerro Prieto are generally similar to sequences reported in both other geothermal systems and in low grade burial/regional metamorphism. In particular, the layer silicate assemblages follow a regular "pelitic" prograde sequence from clay-carbonate facies to chlorite, actinolite, and biotite-bearing rocks of the greenschist facies. Accompanying these changes are the series of calc-silicate assemblages which overlap assemblages observed in the zeolite to pumpellyite/prehnite to greenschist to amphibolite facies series common in

"mafic" to "intermediate" rocks. For instance, similar greenschist and amphibolite facies mineral assemblages in mafic rocks have been noted in fossil low P/T contact metamorphism (e.g., Melson, 1966). The epidote + prehnite + actinolite assemblage observed near 300°C (Figure 5) is almost identical to the lower grade greenschist facies in metamorphosed ophiolitic metabasites (Schiffman and Liou, 1980).

However, some minerals and mineral assemblages appear to be unique to geothermal systems; wairakite is characteristic of low P_{fluid} geothermal systems. The distinctive assemblage clinopyroxene + epidote + prehnite (350°C, Figure 5) has thus far been observed only in active geothermal systems (e.g., at Larderello, by Cavarretta et al., 1982; and at The Geysers by Sternfeld and Elders, 1982).

This assemblage, which is not characteristic of any commonly accepted metamorphic facies, can exist only in equilibrium with low- f_{O_2} fluids (e.g., values between the quartz-fayalite-magnetite and magnetite-wustite buffers; Cavarretta et al., 1982). Note that this distinctive geothermal assemblage occurs in a wide range of bulk rock compositions in different geothermal systems including calcareous sandstones, limestones, greywackes and volcanic rocks, suggesting that the overriding control on its stabilization is a combination of high geothermal gradients (>100°C/km), extremely low fluid pressures, relatively low X_{CO_2} , and low f_{O_2} . These conditions markedly displace mixed volatile metamorphic reactions from the P-T conditions of typical skarn assemblages (Einaudi et al., 1981), and allow the appearance of high temperature calc-silicates (e.g., clinopyroxene, and also calcic garnets and wollastonite in other geothermal systems) at temperatures as low as 300°C. We suggest therefore that these mineral associations constitute a distinct wairakite to pyroxene + epidote + prehnite metamorphic mineral facies series

appropriate to geothermal conditions. We anticipate that this facies series will in the future become increasingly recognized in the geologic record.

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FIGURE CAPTIONS

Figure 1. Sketch map of the Cerro Prieto geothermal field, Baja California, Mexico, showing the surface trace of the cross-section presented in Figure 3. P = power plant, Cerro Prieto I. Circles indicate existing geothermal wells. Identifying numbers are shown for the wells shown in Figure 3 (solid circles).

Figure 2. Twenty different logs of temperature vs. depth measured under different conditions in the well M-11 at Cerro Prieto. The black circles are temperatures estimated using the calcite-water oxygen isotope geothermometer.

Figure 4. North-south cross section through the Cerro Prieto geothermal field depicting (a) isotherms from oxygen isotope geothermometry and (b) metamorphic mineral zones in sandstones. Numbers along the top of each cross-section indicate investigated geothermal wells. Abbreviations: TS = mineral identified in thin section; XRD = mineral identified by X-ray diffraction; + = mineral in; - = mineral out.

Figure 3. Approximate temperature intervals for the occurrence of key calc-silicate minerals in the Cerro Prieto geothermal field. Temperatures were determined by calcite-fluid oxygen isotope geothermometers (see text).

Figure 5. A ($Al_2O_3 + Fe_2O_3$) - C (CaO) - F (FeO+MgO+MnO) diagrams which schematically depict the changes in mineral assemblages observed in calcareous sandstones from the Cerro Prieto geothermal field metamorphosed over the temperature interval of 150°-350°C. Bulk composition of calcareous sediments has been estimated on the basis of unpublished whole rock analyses. Note sericite refers to all dioctahedral white micas (e.g., illites, phengites, muscovites).

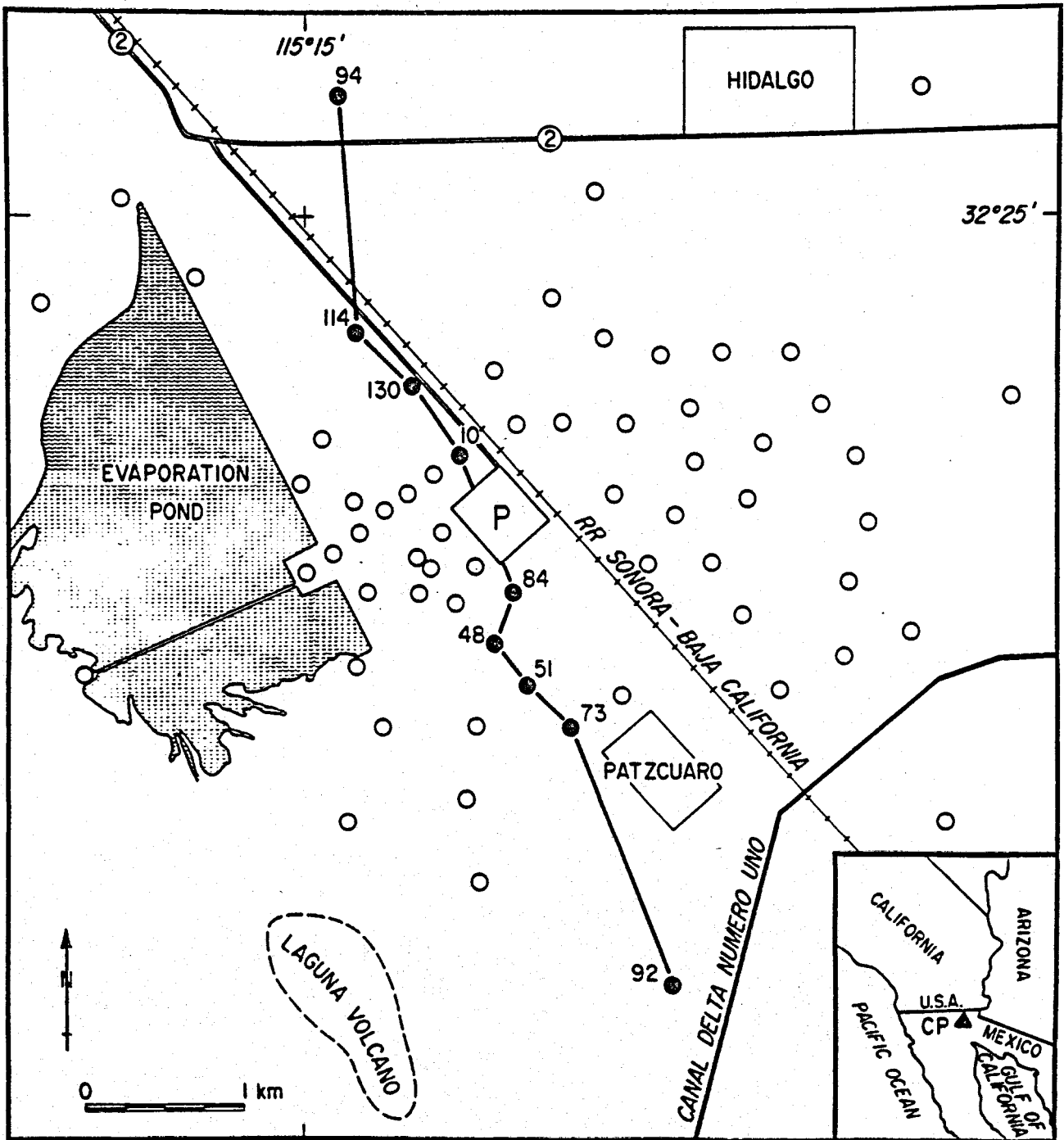


Figure 1.

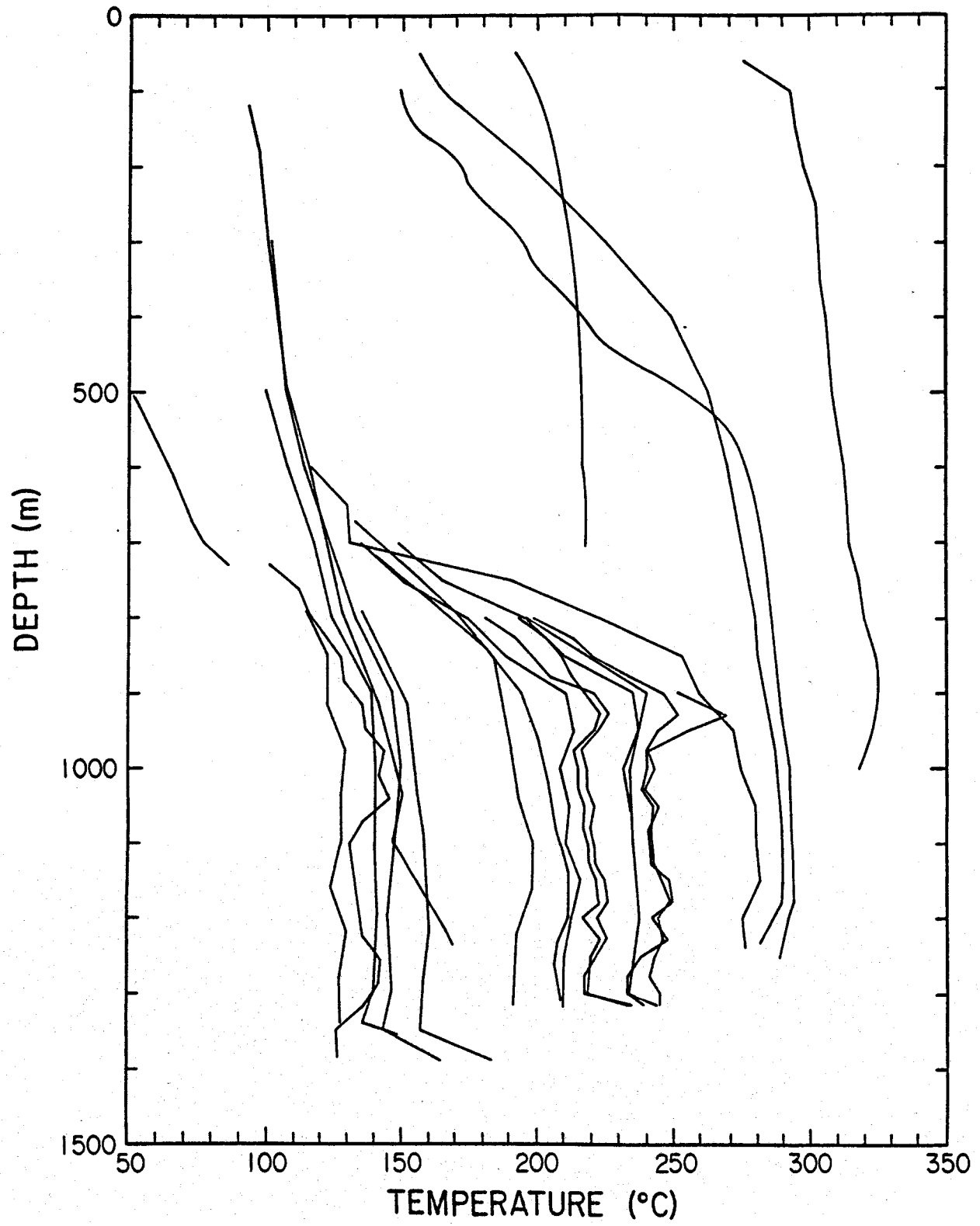


Figure 2.

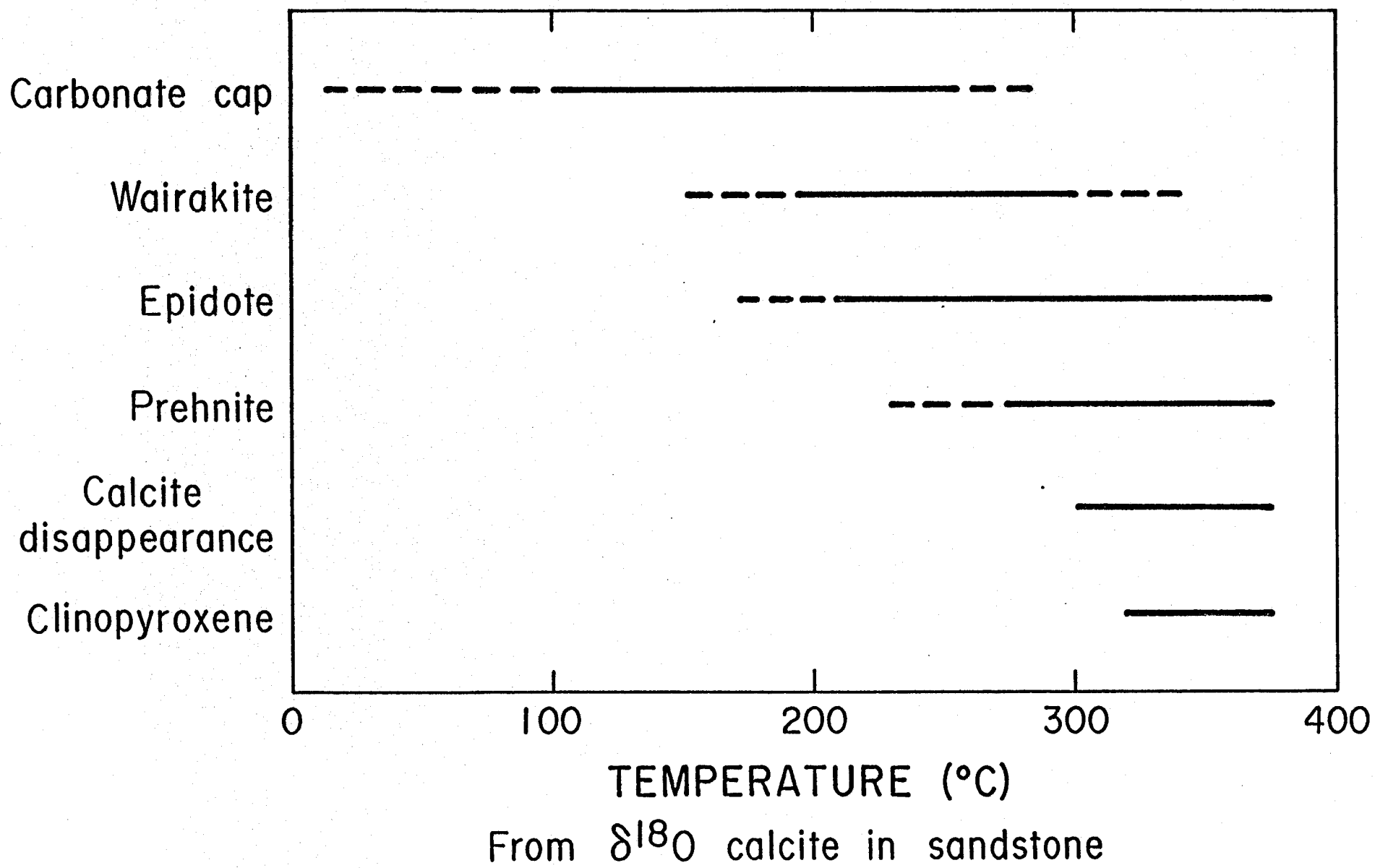


Figure 3.

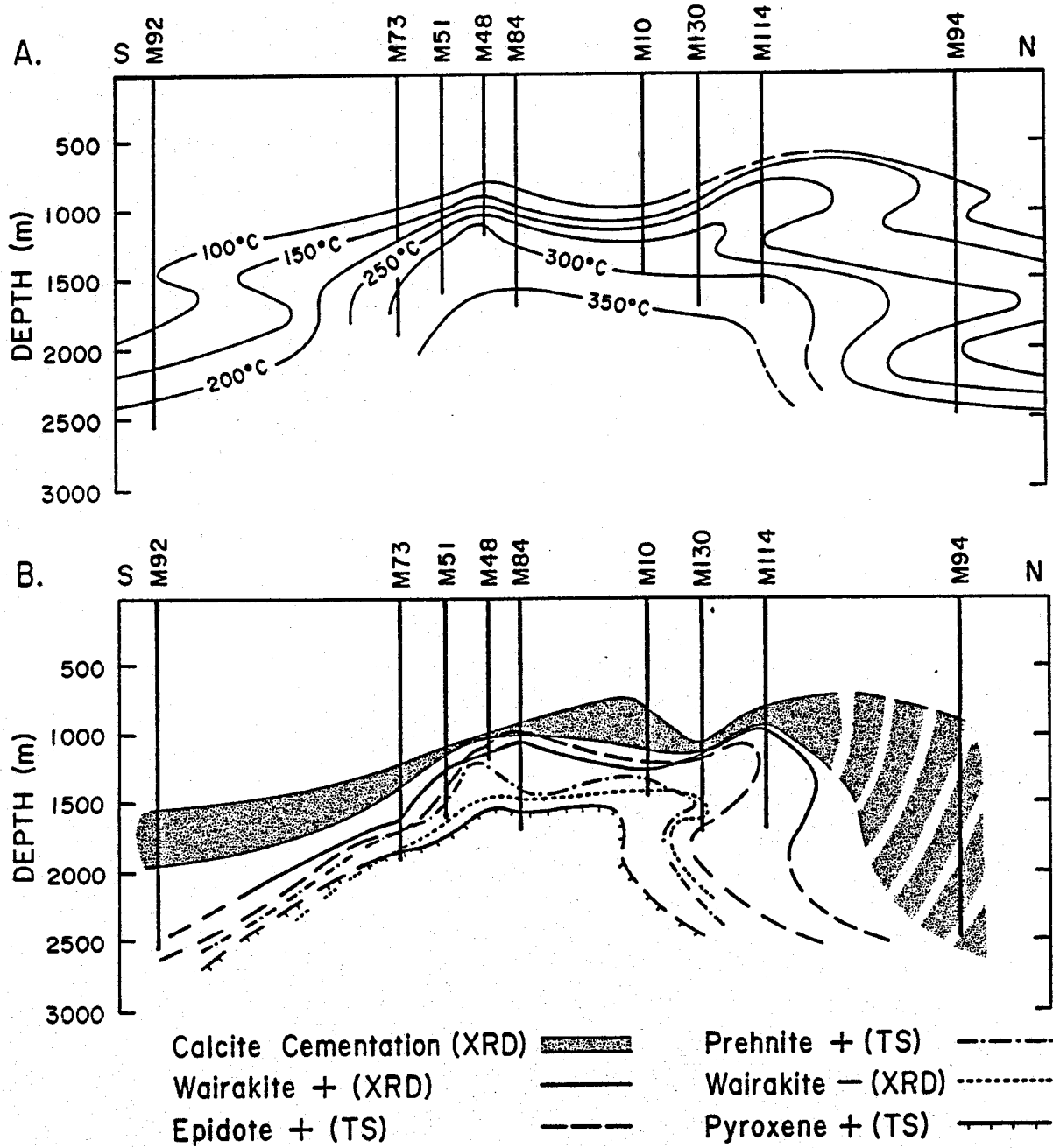


Figure 4.

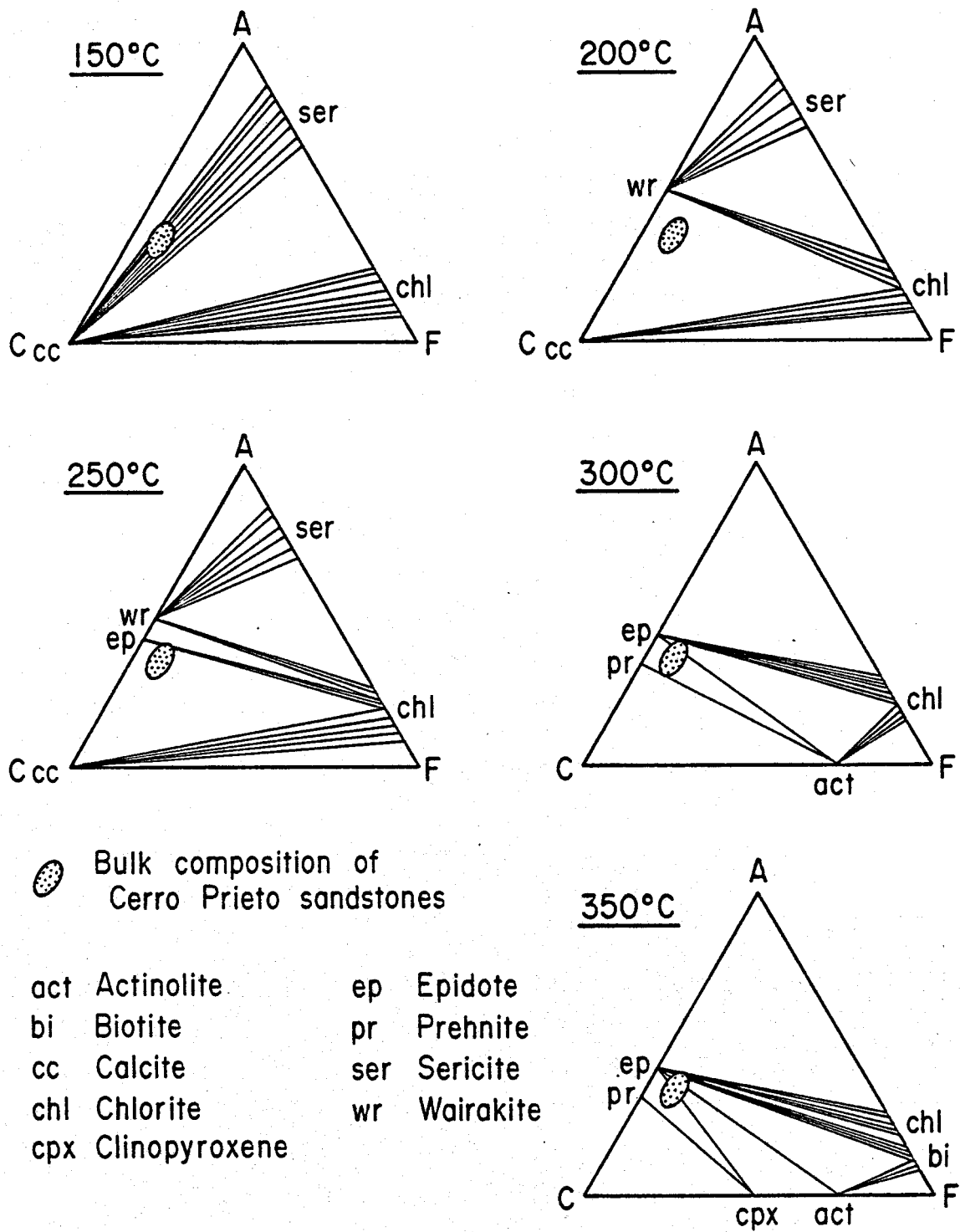


Figure 5.