VITRINITE REFLECTANCE GEOTHERMOMETRY IN THE CERRO PRIETO GEOTHERMAL FIELD BAJA CALIFORNIA, MEXICO

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ABSTRACT

Measurements of vitrinite reflectance in oil (Ro) on phytoclasts extracted from hydrothermally altered mudstones in Well M84 at Cerro Prieto exhibit an increase in Ro from 0.12% (peat) at 0.24 km depth to 4.1% (anthracite) at 1.7 km depth. Temperatures increase from about 60" to 340°C over this interval. Three other wells sampled in the field show similar relationships. The median values of Ro plotted against temperature fall along a smooth exponential curve with a correlation coefficient greater than 0.9. The correlation between the reflectance profiles and temperature logs, together with consistent temperature estimates from fluid inclusion and oxygen isotope geothermometry, both indicate that changes in Ro are an accurate and sensitive recorder of the maximum temperature attained. Therefore, vitrinite reflectance can be used to predict the undisturbed temperature in a geothermal well during drilling before it regains thermal equilibrium. Although existing theoretical models which relate Ro values to temperature and duration of heating are inadequate, empirical Ro/temperature curves are still useful for geothermometry.

INTRODUCTION

The purpose of this paper is to illustrate the usefulness of a geothermometer based on temperature-induced changes in organic matter, termed phytoclasts, which are minute coaly particles found ubiquitously dispersed in fine-grained sedimentary rocks (Bostick, 1979). We extracted phytoclasts from chip samples derived during drilling of Wells M84, M93, M94, and M105 in the Cerro Prieto geothermal field (Fig. 1).

Thermal maturation of phytoclasts is considered to be largely independent of pressure and fluid chemistry, and is superior to inorganic geothermometers in these respects. Phytoclast-based geothermometers, of course, are restricted to geothermal systems in which organic matter is present, normally those with sedimentary rocks. An additional restriction is that because phytoclast thermal alteration is an irreversible process, it records the maximum temperatures reached in the history of the sediment. This may be higher than the present temperatures in the geothermal system. Studies of phytoclasts have shown that thermal

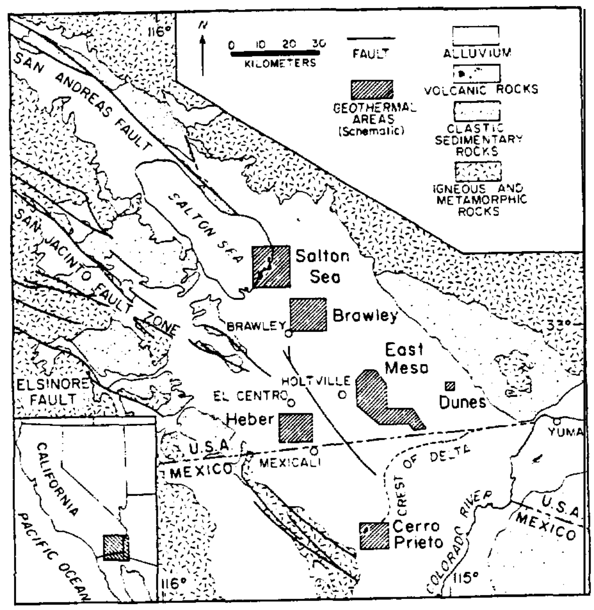

Figure 1. Geothermal fields of the Salton Trough. From Hoagland and Elders (1978).

degradation of organic matter is also dependent on the duration of heating as well as on temperature (Bostick, 1979). The degree of phytoclast alteration, termed rank, could, in principle, be used as a dating method by utilizing a time-temperature-rank function, such as that of Huck and Karweil (1955), if empirical curves are derived from rank-temperature measurements. The physical measure of rank we utilized here was vitrinite reflectance in oil (Ro), which is defined as the ratio of the intensity of reflected light to incident light, acting on polished surfaces of the vitrinite maceral component of phytoclasts (Piller, 1977).

VITRINITE REFLECTANCE GEOTHERMOMETRY

The basis for vitrinite reflectance geothermometry lies in the changes of optical properties resulting from devolatization and condensation of the maceral in response to temperature and duration of heating (Stach et *al.*, 1975). This process, termed catagenesis, involves a progressive evolution of H_2O, CO_2, and hydrocarbons, resulting in a relative increase in carbon content and greater crystallinity. Pressure is now thought to have little influence on catagenesis (Bostick, 1979; Tissot and Welte, 1978; Stach et at., 1975).

Time is considered important for temperatures exceedinq 50°C when siqnificant reactions occur. The duration of effective heating is then taken to be the interval that the phytoclasts are above 50°C in most time-temperature-rank functions (Bostick, 1973). Temperature can be estimated from vitrinite reflectance using theoretical time-temperature-rank functions only if the duration of effective heating is known or geologically delimited. However, if an empirical relationship between an equilibrium temperature log and a vitrinite reflectance profile for one well in a system is determined, this empirical temperature-rank function can then be used to estimate temperatures in subsequent wells. We can then estimate heating time by comparison to the theoretical functions. The effects of time and temperature on phytoclasts are irreversible due to the loss of volative components, which are then not available for retrograde reactions. Consequently, the present temperatures measured in the geothermal system must be the maximum it has experienced, if we are to use theoretical time-temperature-rank functions for geothermcmetry, or develop empirical curves.

Methods

Sample material (preferable fine-grained) was taken from well cuttings at about 50 m intervals. Core samples were taken where available. After grinding this material to pass a 2 mm mesh sieve, the sample was treated with 20% HCl and repeatedly washed to remove the dissolved reactants (Bostick and Alpern, 1977). This was followed by treatment with 48% HF and a second thorough washing. The remaining sample was ultrasonically dispersed in zinc bromide ($ZnBr_2$) dissolved in 10% HCl to make a solution of 2.1 specific gravity. The phytoclasts were present in the supernatant fraction after centrifuging the mixture to settle the heavy fraction. The supernatant liquid was poured off, washed thoroushlv in water and freeze dried. The powder remaining-from this process was then mixed in epoxide to form a thick slurry and allowed to harden on a frosted glass slide (Barker, 1979). The slide was then ground in three steps using ZOO, 400, 600 grit silicon carbide, applied long enough to provide a flat surface parallel to the frosted slide and to remove the scratches from the prior step. Polishing the phytoclast mount involved three steps: 0.5 micron aluminum oxide on canvas cloth, 0.3 micron aluminum oxide on nylon cloth, and 0.3 micron cerium oxide on silk.

Vitrinite reflectance was measured on a Zeiss photomicroscope fitted with a microphotometric system '(Model MPM 01). The phytoclast was vertically illuminated with a stabilized Xenon light source and routed to the photometer through an interference line filter of 546±2 nm. A 40 power/O.85 n.a. achromat oil immersion lens and an optovar setting of 1.25 were used for a total magnification of 500x. At this magnification, the photometer was adjusted to read a 3 micron spot on the polished slide. The photometer was also standardized before and after each sample run by using a glass prism with a calculated reflectance of 1.414% Ro in an immersion oil of N_e = 1.518 (Cargille Laboratories, Type A). Vitrinites were selected by the operator at the microscope and the measured reflectance values were automatically sorted in a Hewlett-Packard HP-9825A computer, interfaced with the photometer system. Normally 75 vitrinite grains per polished mount were measured to describe the Ro distribution adequately and to produce reliable statistics. After scanning a polished mount, a computer program was used to compute and print out reflectance distribution statistics from the stored reflectance data.

Results

As the duration of effective heating of Cerro Prieto is not well known, we will discuss the empirical rank-temperature relationships before consideration of the effects of time. Our empirical curve utilizes equilibrium temperature data from one well in the reservoir to predict temperatures in others. The data should cover the full temperature range possible in the system to minimize extrapolation. Of four boreholes studied, the data from Wells M84 and M105 best fit this criterion. In these wells, the temperature gradients are confirmed by repeated logging with little change in the temperature profile in time. Furthermore, the measured temperatures are corroborated by prograde mineral assemblages, fluid inclusion homogenization temperatures,-and oxygen isotope geothermometry (Elders *et al.*. 19781. The agreement of these independent temperature estimates suggests that the measured temperatures in the deeper portion of these wells are equilibrium reservoir temperatures. Furthermore, we believe these temperatures are the maximum yet experienced by the reservoir, as we have seen no evidence of falling temperatures, such as retrograde mineral zones.

For temperature prediction in this study we used the Ro-temperature measurements from Well M105. The M105 data were selected because they are more frequent and more evenly equally spaced down the well compared to M84, and their regression curve had the higher correlation coefficient (0.98 versus 0.92) of the two data sets. Using all available reflectance data from Well M105 and corresponding near-equilibrium temperature data (Barker, 1979), the following regression equation was derived:

$$Ro(\text{in }\%) = 0.261\, e^{0.000793\ T(\text{in }°C)}$$

This regression curve gives a good fit for data points deep in Well M105, but the fit is poorer below values of 2.5% Ro where the data are sparser. The data points (crosses) and the regression curve for Well M105 (line marked Cerro Prieto) are shown in Figure 2, superimposed on the time-temperature-rank function of Huck and Karweil (1955) which is further discussed below.

To test this empirical vitrinite reflectance geothermometer, the Ro data were used to estimate temperatures which were then compared to the measured temperatures in Well M84 (Fig. 3).

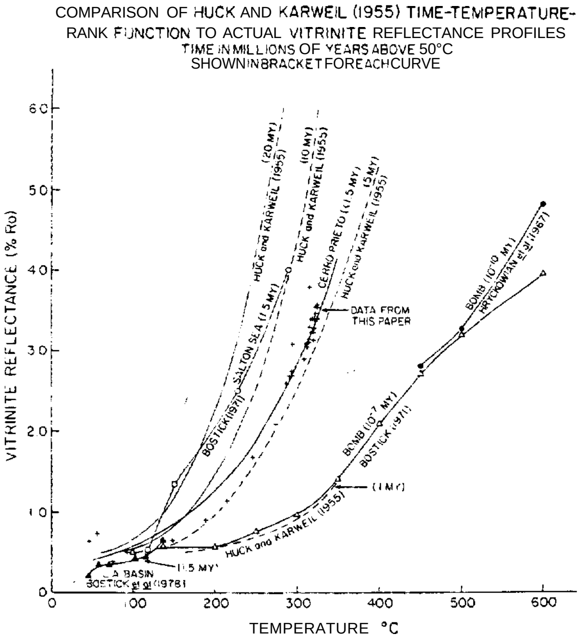

Figure 2. Regression curve and data from Well M105 compared to Huck and Karweil (1955) model. Modified from Bostick (1973).

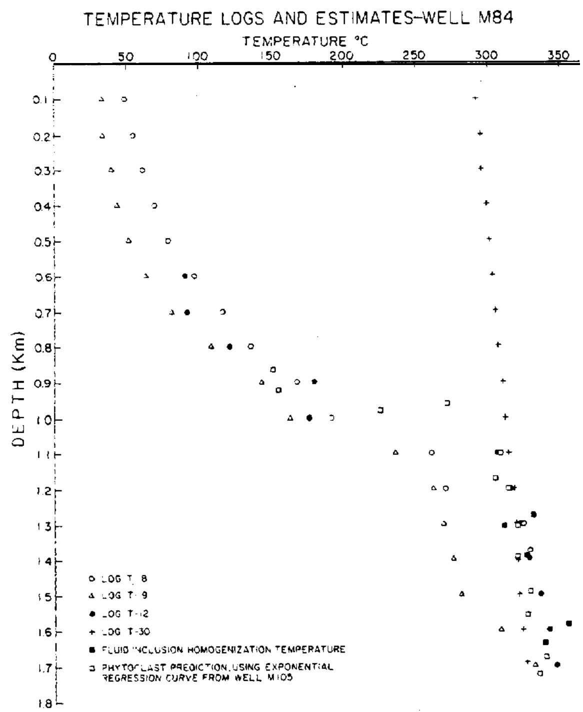

Figure 3. Measured temperature data from Well M84 compared to temperature predictions from Ro data. The well was flowing when log T30 was run. Fluid inclusion data from Elders et al. (1978).

The equilibrium temperatures logs correlate with the predicted temperatures at almost all points and also correlate with the fluid inclusion temperatures. The correspondence of these results confirms which temperature logs are equilibrium profiles and also suggests that the temperatures observed in the well are now at a maximum. Temperature profiles of two other wells studied in the field were also successfully predicted by this method (Barker, 1979). We therefore conclude that vitrinite reflectance appears to be an accurate geothermometer in this system.

TIME-TEMPERATURE-RANK

Huck and Karweil (1955) proposed a time-temperature-rank model for describing the approximate rate of catagenesis. They assumed that the devolatilization of organic matter is a first order homogeneous reaction, which can be described by the Arrhenius equation. Figure 2 depicts this relationship as a family of curves describing vitrinite reflectance as a function of temperature with various effective heating times. Bostick (1973) studied thermal alteration of phytoclasts both in experimental and in young natural systems. The results indicated differences due to the effects of the longer times available in natural systems. His data for the Salton Sea geothermal field (Fig. 1) plot over the theoretical curves of Huck and Karweil for 10 to 20 million years (my). However, Bostick (1971) regards this field to be no more than 1.5 my old.

Reed (1975) correlated the Cerro Prieto reservoir rocks with the Pleistocene Brawley Formation of the Salton Trough, based on environmental and age information from freshwater ostracodes in Well M3. Vertebrate fossils found in the Imperial Valley suggest an age of less than 0.6 my BP for the Brawley Formation (M. O. Woodburne, pers. comm.). The actual age of the geothermal system must be less than the age of the reservoir rocks. Confinement and convection of large volumes of hot fluids and widespread heating of the reservoir rock probably did not occur until an adequate seal developed above the permeable reservoir. The correspondence of vitrinite rank and temperature data in the four wells in the Cerro Prieto field indicates that a single thermal event occurred across the field. A reasonable hypothesis for the thermal history would be the rapid accumulation of the water-saturated reservoir rocks overlain by an impermeable seal, and then the subsequent intrusion of a magma body associated with the Cerro Prieto volcano, providing a heat source in the underlying basement. Comparison of the data from the Cerro Prieto field (Well M105) to the Huck and Karweil model suggests a heating age of about 5 my. However, the geological evidence, referred to above, suggests that it is younger than 1 my. Although the model appears to give unrealistic ages for both the Cerro Prieto and Salton Sea fields, the relative age of the heating events appears to be correctly predicted, with the Salton Sea field older. This relative chronology is substantiated by differences in the isotopic ratios of brines in these two fields (Crosby et *al.*, 1972). We also suggest that the greater textural changes seen in the Salton Sea reservoir rocks relative to those observed at Cerro Prieto indicate that the former is older.

It appears to us that the Huck and Karweil model overestimates the heating age, but predicts the form of the rank-temperature curve closely. This suggests that if the theoretical basis for the model is valid, the reaction rates used in the model are too low to represent those in geothermal systems. Because the ages suggested by the model are inconsistent with the apparent effective heating times in these young systems, equilibrium temperatures cannot be estimated from Ro measurements using the theory. It is necessary to determine empirical relationships for Ro and temperature. If adequate time-temperature relationships can be determined independently, they should serve to refine the theory in the future.

CONCLUSIONS

Application of the vitrinite reflectance geothermometer to four widely-spaced wells at Cerro Prieto, together with other data on the geothermal system, indicates: (1) while the method is not firmly based on theory, it is an accurate empirical estimator of reservoir temperatures; (2) temperatures in the system are now at a maximum in its thermal history; (3) the heating event is younger than 0.6 my old and is apparently contemporaneous across the field; and (4) this event is younger than that at the Salton Sea geothermal field.

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