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MINIMUM AGE OF THE ALUTO GEOTHERMAL SYSTEM (ETHIOPIA) FROM FOSSIL TEMPERATURES BENEATH A DEEP LATERAL OUTFLOW

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ABSTRACT

Fossil temperatures of about 260°C, obtained from a study of alteration minerals, are indicated for a deep layer of acidic rocks (1.05 km depth) in an exploratory well outside the Aluto geothermal system. The layer is underlain by impermeable, dense basalts. The present-day temperature of the layer is only 90°C. The fossil and present-day temperature profiles can be explained in terms of a heating-cooling cycle associated with the build-up and decay of a deep sheet flow of hot water. A model is presented which reproduces the ancient temperature profile and which shows that the heating-cooling cycle at the bottom of the well lasted about 140,000 yr. Since the thermal, outflow originated from the Aluto geothermal system, this period indicates a minimum age for this system.

INTRODUCTION

The age of geothermal systems can be estimated by using radiometric dates of altered reservoir rocks or surface deposits and by modelling time variant heat transfer patterns. An example for the first approach is the study by Browne (1979) and, for the second one, the work by Norton and Knight (1977). In each case, ages of the order of more than 100,000 yr are indicated for hot water systems, and it is now accepted that some, still active systems may be as old as 500,000 yr (Browne, 1979).

In the case of concealed, lateral thermal outflows originating from such a system, and which rest upon an impermeable substratum, the temperature inversion beneath an outflow can be analysed by finding solutions of the time variant heat conduction equation which match the observed temperature profile. This approach can be further developed for an ancient thermal outflow for which a fossil temperature profile can be constructed from equilibrium temperatures of stable, thermal alteration minerals using criteria as summarized by Browne (1978). The application of this method is discussed in this paper using the fossil temperature profile of the deep exploratory well LA-2 as an example. The well was recently completed in the Aluto geothermal prospect (Ethiopia).

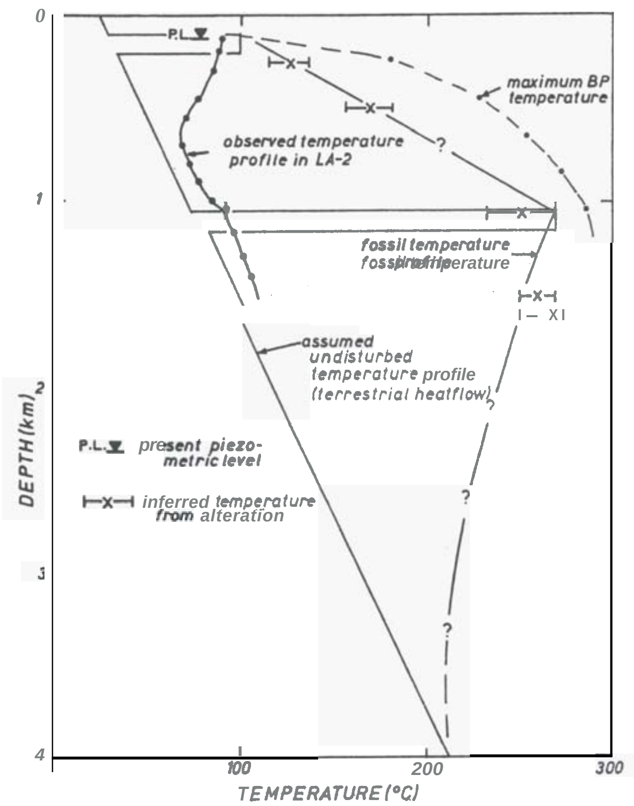

Fig. 1: Observed and fossil alteration temperatures in LA-2 (Aluto geothermal project); shown are also an undisturbed temperature profile and a boiling point (BP) temperature curve for the upper part of the well.

Fossil and present-day temperatures in LA-2

Alteration minerals in cores and cuttings of well LA-2 were studied by Kifle (1983); for the location of this well see Hochstein et al., 1983. The inferred fossil temperature profile is shown in Fig. 1 together with the stable, present-day temperature profile. The ancient temperature profile represents maximum temperatures which were attained during an earlier heating episode. These indicate an almost linear temperature profile between 0.1 km depth, where temperatures of about 90°C prevail, which are still maintained today by a near surface outflow, and about 1.1 km depth where fossil temperatures of 250 – 20°C are indicated (first occurrence of epidote); the fossil temperatures remain about constant (i.e. about 250 to 260°C) between 1.1 km depth and the bottom of the well (1.6 km). The ancient temperatures never reached boiling point (B.P.) temperatures at depth – see B.P. profile in Fig. 1 based on present-day piezopetric level.

The fossil temperature profile can be explained if one considers the lithology and permeability of the rocks in LA-2 and the setting of the Aluto geothermal reservoir. Geological logging, analysis of alteration minerals, and water injection tests have shown that the well encountered practically impermeable rocks, apart from the permeable near-surface layer (0.1 to 0.2 km depth) and about a 200m thick layer of acidic rocks (ignimbrites?) at 1.05 to 1.25 km depth, where some minor permeability occurs as indicated by the intensity of alteration. The rocks above this layer consist of a sequence of tight lake sediments and rhyolites, whereas dense basalts form the deeper, impermeable substratum.

This setting is similar to that of the first deep well (LA-1), where a permeable surface layer occurs which acts as a channel for a separate thermal outflow and where a 130m thick layer of acidic rocks, probably with some permeability, lies on top of practically impermeable basalts at 1.2 km depth (Hochstein, 1983). A temperature gradient of 0.045°C/m was observed in these basalts with a surface intercept temperature (25°C) which is almost the same as the mean annual temperature (22°C). It was therefore assumed that this gradient reflects the normal temperature field beneath the Rift Valley in the absence of thermal flows (see Fig. 1). The rank of thermal alteration in LA-1 is significantly lower than that in LA-2 (Kifle, 1982).

The first two wells were drilled in the S and W foothill region of Aluto Volcano respectively. The Aluto geothermal reservoir was recently discovered by the third deep well (LA-3), drilled on top of the volcano in the E part of the Aluto caldera (Hochstein et al., 1983). At LA-3 a productive layer (>350m) of acidic rocks (ignimbrites?) was encountered at 1.75 km depth with temperatures greater than 290°C (H. Hole, pers. comm.). This well lies about 7 km to the E of LA-2 and about 7 km NNE of LA-1.

Considering the hydrogeological setting of the Aluto system, it is reasonable to infer that at an early stage a deep lateral flow of hot water occurred in a coherent layer of permeable rocks, together with shallow, near-surface outflows beneath the flanks. These flows heated up rocks by conduction producing, for example, the linear fossil temperature profile in LA-2 (Fig. 1). After this heating up process, subsidence of Aluto Volcano might have occurred which stopped the deeper outflow but not the shallow flows. The temperatures in LA-2 decreased until the present-day temperature profile was reached. If theoretical temperatures can be calculated which reproduce the conductive heating and cooling process in the substratum, a time estimate for the whole cycle can be obtained.

Computation of theoretical temperatures of ancient deep thermal outflow of LA-2

A finite difference method was used to obtain a set of theoretical temperature profiles which satisfy the one-dimensional, time-dependent conductive heat flow equation (see Kappelmeyer and Haenel, 1974, p 67). A thermal diffusivity of 0.86 x 10^{-6} m^2 s^{-1}, based on laboratory data, was used for the basalts forming the substratum in LA-2; it was also assumed that the diffusivity of the volcanics lying between the surface and 1.2 km depth is the same as that of the substratum.

The initial temperature profile is shown in Fig. 1 with a constant gradient of 0.045°C/m and a surface intercept temperature of 25°C. Two isothermal layers were superimposed which represent a shallow and a deep outflow of hot water with temperatures of 90°C and 270°C respectively. The problem is therefore reduced to two independent boundary condition problems. The upper zone is bounded by constant temperatures of 90°C at 100m and 270°C at 1100m, the lower zone was bounded by 270°C at 1200 and 272.5°C at 5500m. The lower boundary of the lower zone is determined by the requirement that its temperature has to be greater than 270°C and lies upon the undisturbed temperature profile.

The computed temperature profiles for the heating cycle were obtained by using a time step of 100 yr and a depth increment of 100m. The temperature profiles shown in Fig. 2 represent theoretical temperatures at intervals of 10,000 yr. It was found that a minimum period of 70,000 yr is required before the inferred fossil temperature of 260°C is reached at 1.6 km depth. It is unlikely that this heating period was shortened significantly by convective transfer because of the negative temperature gradients below 1.2 km depth. In the upper zone, stable temperatures are reached by conduction after 10,000 yr (see Fig. 2), although this period could be shorter if convective transfer had occurred; the linear fossil temperature profile in this zone, however, is difficult to explain in terms of convection. The calculated profile with a 70,000 yr heating period matches the observed fossil temperature curve shown in Fig. 1.

Using the same procedure, a set of theoretical temperatures was calculated for the cooling cycle. It was assumed that, after 70,000 yr, the deep outflow of hot water stopped and that fluids with the present-day temperature of 90°C enter the layer; the surface outflow was kept unchanged. The resulting temperature curves at intervals of 10,000 yr are shown in Fig. 3. It was found that a minimum period of 80,000 yr is required to obtain a temperature of 114°C at 1.6 km depth, which is still slightly greater than the present-

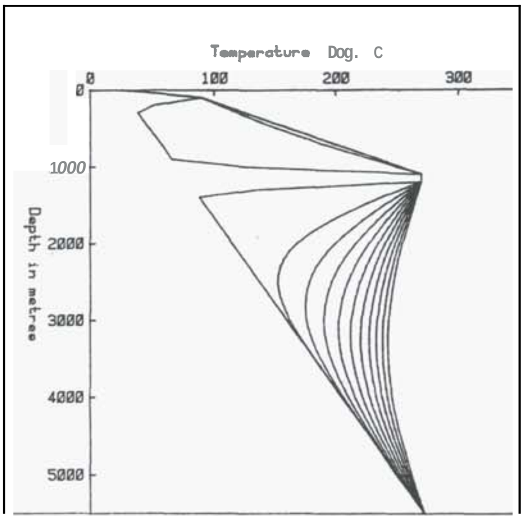

Fig. 2: Theoretical temperatures in LA-2 assuming conductive heating. The first curve to the left is the initial temperature profile, each of the following curves is separated by a time interval of 10,000 pr, total heating period shown is 100,000 yr.

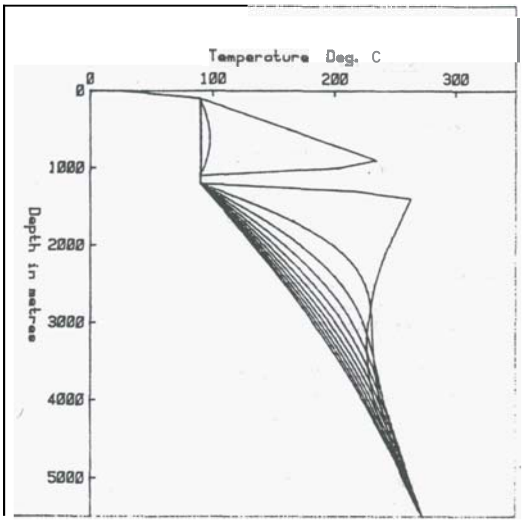

Fig. 3: Theoretical temperatures in LA-2 assuming conductive cooling. The curve on the right hand side represents the initial temperature profile. For explanation of the curves, see Fig. 2. Total cooling period shown is 100,000 yr.

day temperature of 110°C at this depth. The assumption of a purely conductive heat transfer for the whole cooling cycle, however, is not justified since a strong positive gradient occurs in the substratum during the first 10,000 to 20,000 yr, after which convective transfer becomes less likely. It therefore appears that the period of the cooling cycle is similar to that of the heating cycle. Cooling of the upper zone is by conduction only with stable, constant temperatures occurring after 10,000 yr. The constant temperatures in the upper zone, however, do not agree with the present-day temperature profile. The difference can be explained by a minor, colder inflow at about 700m depth (see Fig. 1).

CONCLUSION

Observed present-day and fossil temperatures in the deep well LA-2 can be explained by assuming that a deep, lateral outflow of hot water with temperatures of about 270°C took place in a layer at 1.05 km depth during an earlier episode of the Aluto geothermal system. Since the substratum below this layer is almost impermeable, the heating and cooling history of this event can be modelled by numerical solutions of the conductive heat flow equation, which indicate a minimum period of heating and cooling of about 70,000 yr for each cycle. The computed temperature profile after 70,000 yr matches the observed fossil temperature profile. The cooling cycle might have been shortened if convection occurred during the first 10,000 yr of cooling.

A minimum age of about 140,000 yr is therefore indicated by the heating and cooling cycle of the rocks at the bottom of this well. This age is of the same order of magnitude as inferred by different methods (Browne, 1979, Norton and Knight, 1977) for active hot water systems in other parts of the world.

ACKNOWLEDGEMENT

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