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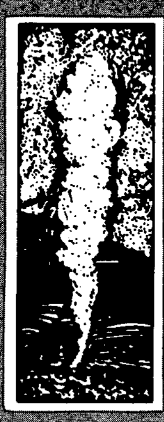

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A FAULT-ZONE CONTROLLED MODEL OF THE MESA ANOMALY†

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1. Introduction

Recent studies of liquid-dominated systems like Wairakei (Grindley, 1965), Broadlands (Grindley, 1970), Cerro Prieto (Mercado, 1969), Long Valley (Rinehart and Ross, 1964, Bailey, et al. 1976), Ahuachapan (Ward and Jacob, 1971) suggest that geothermal anomalies are intimately associated with specific patterns of faulting.

In the Imperial Valley, California, there are several geothermal anomalies which are close to or intersected by active faults (Elders, et al. (1972)). The basic field data for these systems are described by Babcock, Combs and Biehler in Rex (1971), Helgeson (1968), Meidav and Furgerson (1972), Goforth, et al. (1972), Douze and Sorrells (1972), Combs and Swanberg (1977), Combs and Hadley (1975, 1977), Loeltz, et al. (1975), Dutcher, et al. (1972), Elders, et al. (1972), Swanberg (1974, 1976), Elders and Bird (1974), Coplen, et al. (1975) and Coplen (1976). Some of the information is surveyed in Kruger and Otte (1973) and in a series of Bureau of Reclamation Reports (1974). Black (1975) and Bailey (1977) have summarized a large spectrum of the available geological, geophysical, geochemical, hydrological and heat flux data for the purpose of synthesizing a composite conceptual model of the Mesa system. In addition they used primary bore hole logging data to provide additional input.

One may infer from these studies that the East Mesa anomaly is intersected by a seismically active fault which acts as a conduit of heated water from depth. The fault appears to extend through the sediments and into the basement rock beneath. It is almost certainly closed off in the first 0.6-0.7 km by shaley deposits, and no surface expression exists.

The fault itself is hypothesized to be a vertically oriented region of heavily fractured material of finite width. The vertical extent of the fault, and the second horizontal dimension are large compared to the width. The fault has probably been active for an extensive period because the region exhibits tectonic activity (Elders, et al. (1972)). The continual microearthquake activity (Combs

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and Hadley (1977)) suggests that there are mechanical processes available for fracturing of the rock. This is necessary to counteract the mineral deposition associated with a rising, cooling column of saline geothermal fluid which tends to close up the system by reducing the permeability (Ellis (1975)).

It is surmised that water, derived basically from the Colorado River (Coplen, 1976), percolates gradually into sediments and/or fractured basement rock over an area considerably larger than the anomaly itself. Heated at depth by an unknown source the liquid can rise in the high permeability fractured fault zone convecting energy toward the surface. The artesian over-pressure, between 50 psi and 120 psi, associated with the convection process leads to aquifer charging whenever the fault intersects a horizontal layer of relatively large permeability. Extensive fracture systems are presumed to provide the basic permeability in the aquifers. The deposition of calcite and silica over extended periods has probably closed up the intergranular spaces in the sandy sediments.

Heat flux measured near the surface of the clay cap, enhanced by the upflow of hot liquid water beneath, is as much as 7.9 HFU compared to a background level of 1.5 HFU. Temperatures to 200°C at 2.4 km have been measured in Mesa 6-1 and Combs (1977) has suggested a sediment-basement interface temperature between 325°C and 365°C at 4.15km.

Semi-quantitative estimates of heat and mass transfer can be obtained by considering key parameters. The Rayleigh number (R) is a measure of convective effects in the system. Here R is defined by

$$R = \frac{gk\alpha\ell_R\Delta T}{\nu^2} Pr_m$$

where g is the gravity constant, k is a characteristic permeability, α is a characteristic thermal expansion coefficient for water, ℓ_R is the reservoir depth, ΔT is the characteristic temperature difference through the reservoir, ν is the characteristic kinematic viscosity of water and Pr_m is the Prandtl number for water based on the thermal conductivity of the saturated porous medium. For typical high temperature thermodynamic values, a permeability $k = 10^{-9}$ cm^2 and minimal reservoir values $\ell_R = 1.5$ km and $\Delta T = 50°C$, then $R \approx 940$. Of course sensitivity to the value of k, which is a bit speculative, is noted. If Combs' (1977) prediction of depth to the basement interface is correct, then $\ell_R = 3$ km and $\Delta T \approx 200°C$. This gives R = 6000. Even if the value of k is reduced considerably it is clear that Rayleigh numbers of 500 should be viable (Kassoy and Zebib (1975)).

Natural convection theory (Kassoy and Zebib (1975)) can be used to show that the vertical convection velocity in the fault zone is characterized by

$$v_V = g\ k\alpha\Delta T/\nu$$

For the first set of values used above $v_V \approx 1$ cm/day. Assuming an average temperature of about 175°C in the convection-active section of the fault, one finds that 1.75×10^7 cal/s km^2 is convected upward. This is about 3 orders of magnitude larger than the purely conductive flux.* If 10% of this energy is lost to the claycap and conducted to the surface where Combs (in Rex (1971)) measured 4.88×10^6 cal/s crossing about 110 km^2, then the horizontal area of the fault zone is about 2.9 km^2. Since thermal activity of the Mesa extends along the primary fault for about 16 kms., a fault (fracture-zone) width h $\approx$ 180m is suggested. One should recognize that this is an order of magnitude estimate. Given the variable nature of the input a range 100m $\leq$ h $\leq$ 300m might be appropriate. If k were far smaller than 10^{-9} cm^2 the fault zone area estimate would be far larger, and thus not representative of the relatively localized anomalous properties at the Mesa field.

Convection theory (Kassoy and Zebib (1975)) can also be used to show that the artesian over-pressure magnitude is given by

$$\Delta P_A = \rho g \ell_R\ \alpha\ \Delta T$$

where ρ is the characteristic liquid density. ΔP_A is of the magnitude of 10 bars for the parameters given above. Coplen (1976) has noted that shut-in-pressures for Mesa 6-2 have ranged from 3.5 to 8.2 bars, which indicates that there is reasonable agreement between field data and theoretical assessment for the selected parameter values.

2. Modelling

The conceptual model of the system is based on a fracture zone (the fault) of finite width h' which extends downward nearly vertically through a clay-rich region (the cap) of thickness ℓ_c', through the interbedded sediments of the reservoir for a distance ℓ_R' and finally into the basement rock for a length ℓ_B'. It is postulated that the fault is charged at depth by liquid which has been heated in an extensive basement fracture system. The rate of charge cannot be speculated *a priori* without a global analysis of the convection process. Liquid rises in the reservoir section of the fault. The presence of clays in the cap suppresses vertical transport there. Water pushed out of the fault by artesian overpressure is assumed to flow horizontally in the reservoir aquifer. Vertical transport should be less important in-the-large because of the presence of shaley-layers associated with interbedding.

For mathematical purposes the fracture zone is idealized as a vertical slab of porous media. The adjacent reservoir aquifer is

*The value is based on the temperature difference between well-bores 5-1 and 6-2 in the convective zone.

represented as a porous medium of lateral halfwidth y_R' with horizontal permeability only. Finally the overlying clay cap is assumed to be impermeable.

Spatially uniform temperature boundary conditions are imposed on the cold cap surface and at the hot bottom boundary of the reservoir. On the lateral boundary far from the fault ($y_R' \gg \ell_R' \gg h'$) the temperature distribution is controlled by vertical conduction, the pressure distribution is hydrostatic and mass flux is permitted to conserve matter.

A quasi-analytic theory is developed for high Rayleigh number convection of a liquid in a rigid porous medium. In this approximation liquid rises up the fault and spreads into the near-region of the reservoir adiabatically. The cooling effect of the cap in the reservoir is confined to a thin layer adjacent to the interface. The layer grows with distance from the fault. In the far field of the aquifer the full depth of the reservoir is cooled by the surface. Predicted temperature distributions with depth in the near field are quite like that for Mesa borehole 8-1, and qualitatively similar to those in 6-1 and 6-2. Far field profiles can be related to those in 5-1 and 31-1. Although the flow field is purely horizontal in the aquifer one finds steep temperature gradients in the cap and reduced variations at depth. The heat flux calculated at the cap top compares favorably with Mesa field data.

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