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UTILIZATION OF GRAVIMETRIC DATA FOR ESTIMATION OF HYDROTHERMAL RESERVOIR CHARACTERISTICS IN THE EAST MESA FIELD, IMPERIAL VALLEY, CALIFORNIA

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Introduction

This paper presents an attempt at correlating the observed phenomena of small positive gravity anomalies and self-sealing in some geothermal systems with possible geochemical, thermal and flow properties of such systems. In particular, the East Mesa geothermal area in the Imperial Valley, California shows up to 6 milligal positive residual gravity anomaly. Calculations show that the maximum depth to the center of gravity of the anomalous mass is a few kilometers, which is less than the depth to the basement in the area. We hypothesize that the presence of this gravity anomaly in the midst of a reasonably regular alluvial basin is due to deposition of minerals in pore spaces of sediments by upward rising plumes of geothermal water over geological time.

Facca and Tonani (1967) have explained the origin of hard, impervious caps in some geothermal systems, as being the result of precipitation of minerals in a water-convective system. Briefly restated, thermal water at depth has a certain dissolving power which is dependent upon temperature, pressure, pH and the nature of the rock. Because of the reduced density of the hot water which forces it to flow up, a convection system is created. The term "convection" is used loosely here, to signify heat transfer by this movement and not necessarily motion around a loop. Gravity data considerations favor either a once-through flow or a convective flow which has very large horizontal components (Figure 1). As the water flows up through progressively colder and lower-pressure strata, it precipitates part of the ions which are carried in solutions. Such precipitates consist primarily of silica and calcite. Detailed investigations of the Dunes Anomaly (Elders, 1973) in the same geological basin, show that a series of quarzite layers occurs in the central part of the Dunes geothermal anomaly. No significant silica deposition has been reported in the East Mesa area, the subject of this study. However, the lithologic data gathered in the holes indicate increased calcite precipitation in the pore space (R. Fournier, personal communication).

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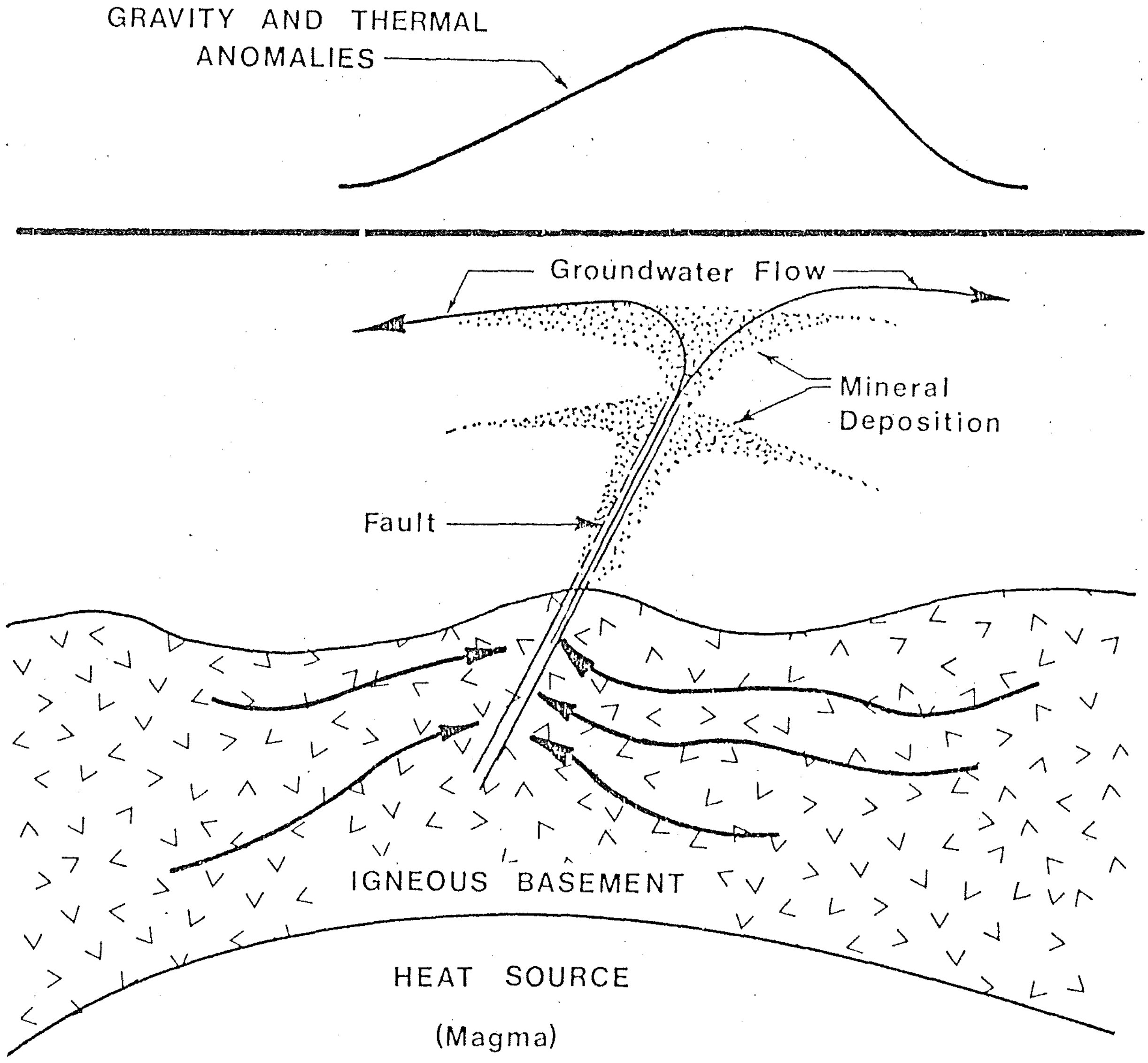


Figure 1. Conceivable flow model for a self-sealing hydrothermal system, with the associated gravity and thermal gradient anomalies.

Clear evidence for hydrothermal convection in the East Mesa Field is seen in any of the temperature -depth plots obtained by the U.S. Bureau of Reclamation in the various holes which were drilled in the East Mesa Field (Figure 2). The temperature gradient graphs show a sudden flattening at a depth of about 700 m. This may be interpreted as indicating the existence of a cap layer into that depth. Above the cap, the dominant heat transfer mechanism is conductive heat flow. Below this depth, convection predominates. This situation is in concordance with the models of Facca and Tonani (1967), or White (1965).

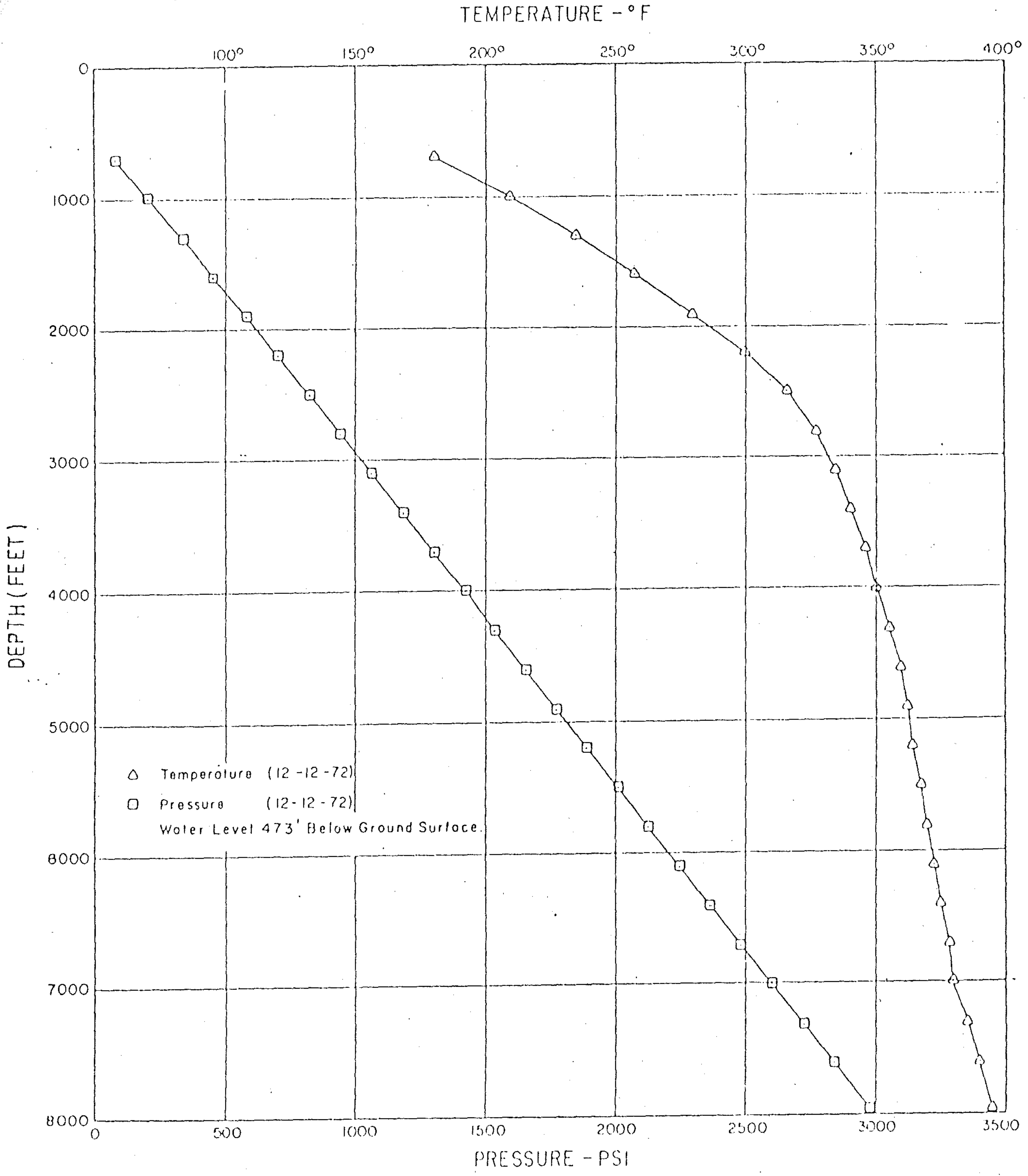
A detailed gravity survey of the East Mesa Anomaly has been carried out by Biehler (1971) from which a residual gravity map (Figure 3) has been prepared. The gravity high corresponds to the temperature gradient high in the same area (Figure 4).

Mass-excess Calculations From Gravity Data

Hammer (1945) has shown that it is possible to calculate from gravity data the total anomalous mass giving rise to the gravity anomaly, without regard to the geometry or depth of the anomalous body, by performing a surface integration over the gravity anomaly area.

Performing that calculation with regard to the residual gravity anomaly at East Mesa, we estimate a net excess mass of about $(10 \pm 2) \times 10^9$ metric tons. This excess mass of about 10 billion tons of matter is believed to have been deposited in the alluvial strata directly as a result of the cooling effect of the shallower alluvium on the rising hot plumes of water. The basis for this assertion comes from the gravity data itself: trial half-width depth determinations show that the center of gravity of the anomalous mass must be within the sedimentary column. These determinations do not preclude however, that at least part of the gravity anomaly is due to basement uplift or due to density changes within the upper part of the basement rocks. Visual comparison with an unpublished aeromagnetic map of the area shows the absence of a magnetic anomaly at East Mesa. Such an anomaly would have been expected had the cause for the gravity anomaly been a basement uplift. One can attribute the absence of a magnetic anomaly to hyper-Curie-point temperature in the basement. We consider such a possibility as unlikely. Thus, we conclude that the gravity anomaly is largely due to hydrothermal mineral deposition within the sedimentary column, due to hydrothermal convection.

Assuming typical numbers for average porosity (20%) in the sedimentary column and rock matrix density (2.65 gms/c.c), we calculate that the excess mass has been deposited within a total volume of 19 km^3 of sediments. The East Mesa anomaly has an areal extent of 200 sq. km. Thus, over this area, the total thickness of the densified layers is estimated to be 95 meters or 311 ft., which is geologically reasonable.



TEMPERATURE & PRESSURE IN WATER COLUMN
MESA 6-1, IMPERIAL VALLEY, CALIFORNIA

Figure 2.

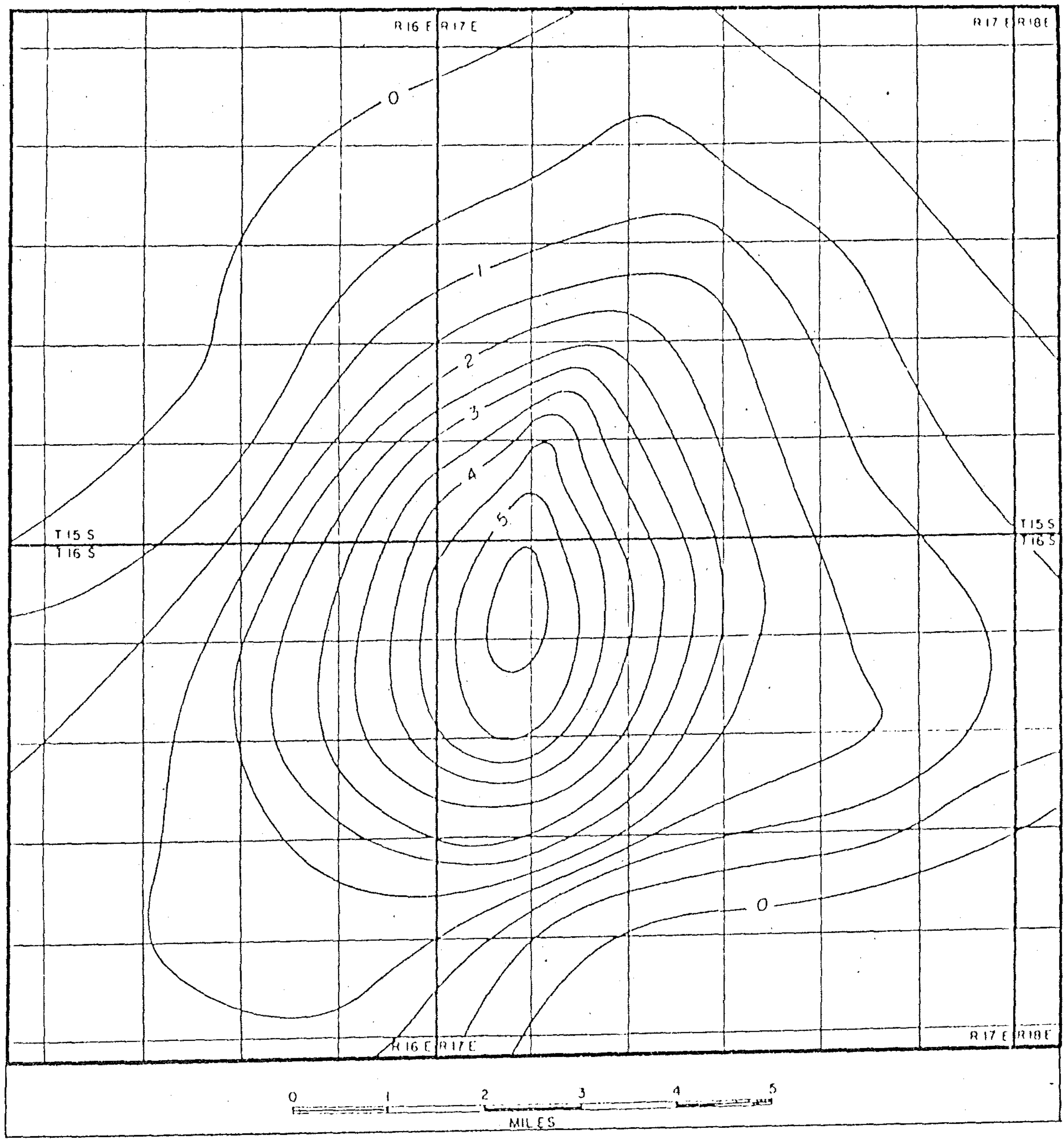


Figure 3. Residual gravity map of the Mesa area (Biehler, 1971). Contour Interval 0.5 mgal.

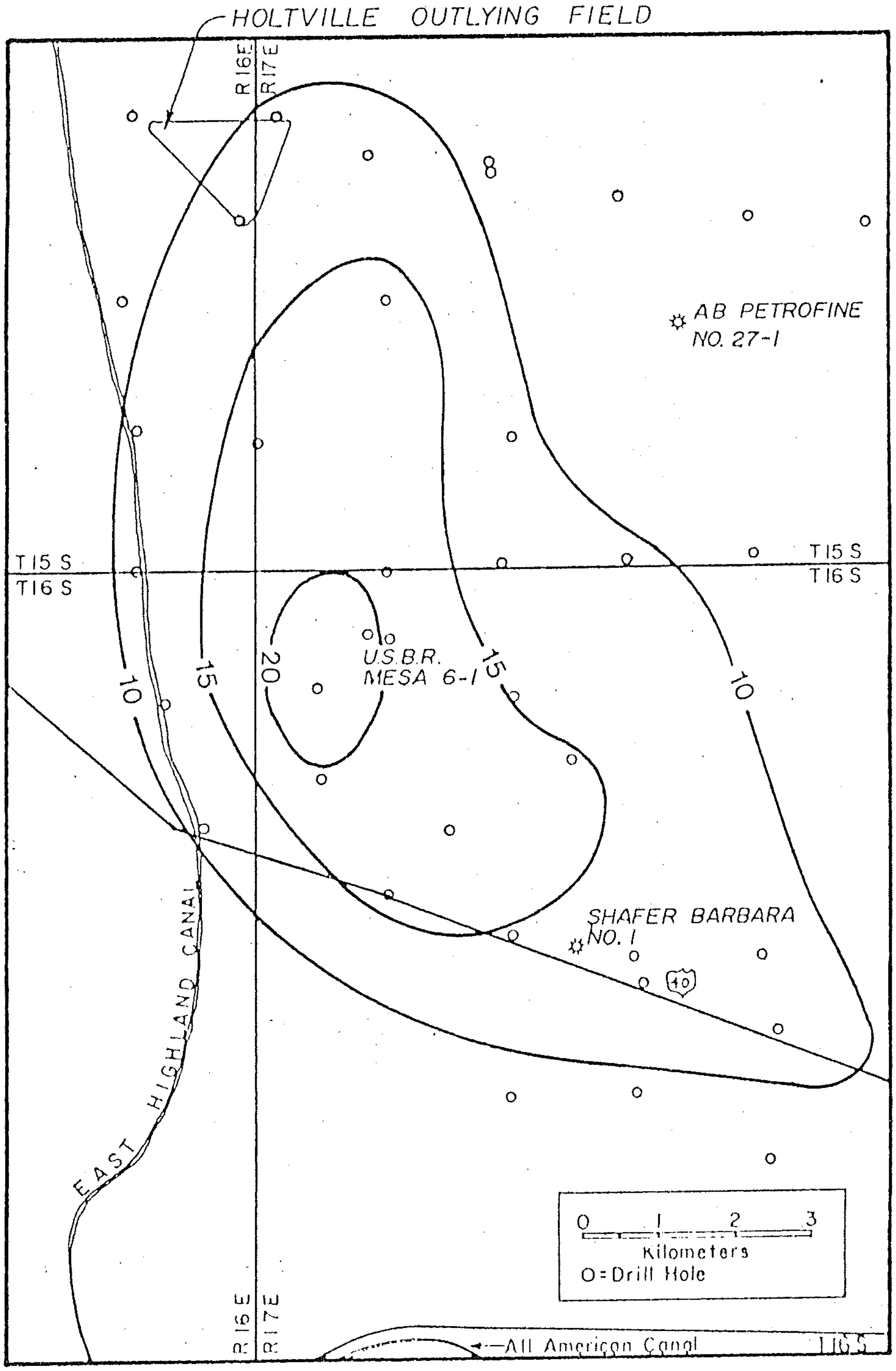


Figure 4. Temperature gradient map of the East Mesa anomaly (Combs, 1971; based partially on data by Rex, 1970). Contour Interval = °C/km.

Mass Convection of Water

Quartz solubility data indicate that up to 0.44 grams per liter of silica could precipitate out of solution when an originally silica-saturated solution precipitates the excess silica as it cools down from 250° to 100°C. Likewise, a significant amount of carbonate could precipitate out of a bicarbonate-rich solution as it decompresses. Assuming a mean of .4 gm/liter precipitation, a mass excess of 10 billion tons of precipitate would have required about 25 trillion tons of thermal water to have circulated through the system. The water flow must be primarily vertical, to account for the observed residual gravity anomaly. As the rising plume of water encounters an impermeable boundary, it is deflected laterally in all directions. The upward flow of the geothermal water results in deposition of minerals, either due to cooling (silica) or to decrease in pressure (calcite). The zero contour on the residual gravity anomaly is an expression of the outermost possible limit of the lateral extent of precipitation. The actual limits might be closer to the center of the rising plume.

A flow model of "once-through" is preferred to a model of toroidal circulation. The "once-through" model is based upon the assumption that hot water, mobilized in the igneous basement or in the deeper part of the sedimentary strata, moves through fractures and shear zones upward above the hot spot, in a heat-pump-like process. Having reached its apex, the water flow is dissipated laterally in all directions. The toroidal circulation model, on the other hand, may pose the problem of mass balance, which theoretically at least would minimize the size of any residual gravity anomaly. This is because in such a model, the dissolved matter at the base of the convecting cell is deposited above it, hence no mass is gained or lost. Of course, the shallow excess mass would give rise to a higher gravitational attraction, but Gauss' theorem shows that if the integration of the surface integral is carried over the area of the source and the sink, the mass loss and deficiency would balance out. On the other hand, if the source of the mass is from a very large area, it would not affect Hammer's surface integral which is carried out over a smaller area.

Figure 5 shows the rate of water convection over the entire East Mesa Anomaly for different assumed ages of the system. The minimum upward flow is about 0.8 m^3/sec. for a one-million year old system, to 80m^3/sec. for a 10,000 year old geothermal system. Investigations of other geothermal systems suggest that the life of a geothermal system lies typically in the range of 10,000-50,000 years (White, 1965; Ellis, 1970). For a 50,000 year old system the vertical convection rate had to be of the order of 8,600,000 barrels/day (1,400,000 tons /day). Even if we assumed that there is an order of magnitude error in overestimating the contribution of the sediments to the total gravity anomaly, these numbers remain quite impressive. These numbers indicate that vertical permeability is a major factor in the flow regime of a geothermal system.

If this vertical flow had taken place over 50,000 years across the entire horizontal extent (200 square km) of the East Mesa anomaly, average macroscopic velocity should have been 0.8×10^{-5} cm/sec. An average value of the vertical permeability can then be calculated from Darcy's law as:

$$k = -\frac{v\mu}{\frac{dp}{dz}}$$ (in Darcy units), where

k = vertical permeability (Darcy)

v = macroscopic velocity = 0.8×10^{-5} cm/sec.

= viscosity = 0.2 centipoise (a value typical for the salinity, temperature and pressure of the East Mesa formation water)

$\frac{dp}{dz}$ = vertical pressure gradient due to buoyancy of hot water surrounded by cold water = -0.0002 atm/cm (gradient caused by the maximum temperature difference of 150°C between hot and cold water).

This gives a value k = 8 millidarcy. However, convective flow must have taken place across a far smaller cross-section than the entire 200 sq. km. Assuming that only one percent of the cross-section was involved in convective flow, the average vertical permeability is calculated to be 800 millidarcy. A vertical permeability of this magnitude through a faulted or fractured conduit is not inconceivable. If the estimated flow rate (Q) of $16.0\,m^3$/sec takes place through a vertical fault of lateral extent L, then the required fracture width (h) along the fault is given by:

$$h^3 = \frac{12\mu Q}{L\,dp/dz}$$

For L = 1 kilometer, using consistent units, we calculate h = 2.6 mm. Thus, a one kilometer long vertical fault along which an average fracture width of 2.6 millimeters could have been an adequate flow conduit.

No hot springs or other geothermal surface manifestations exist at the East Mesa Anomaly. It is possible, however, that hot springs have flowed to the surface in the geologic past. We conclude from the foregoing discussion that although geysers, hot springs and fumaroles may perhaps be a spectacular demonstration of the great heat reservoirs which are located at a shallow depth below the earth's surface, the absence of these geothermal manifestations need not be taken as a sign of absence of tappable geothermal energy at an economic

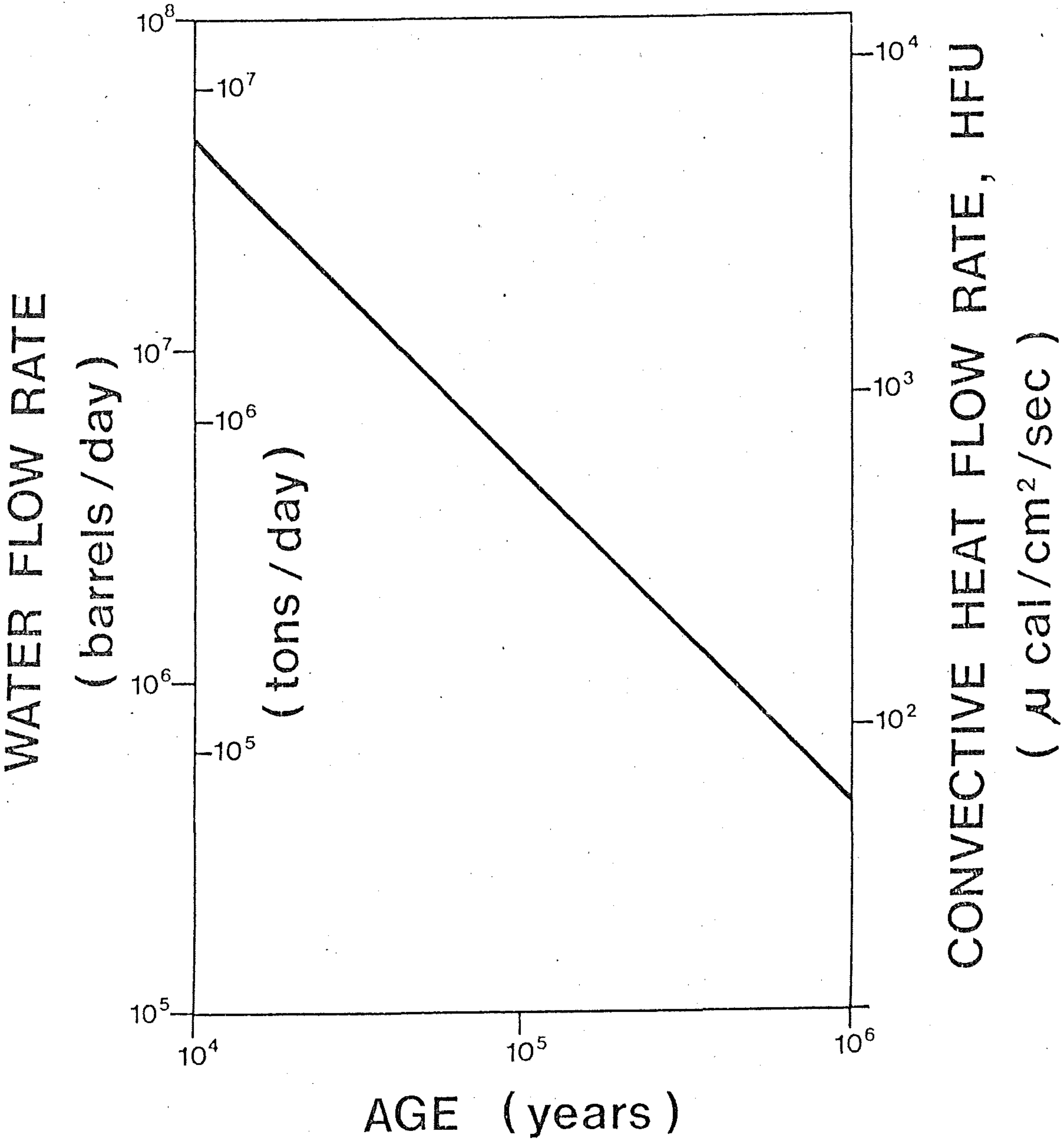


Figure 5. Estimated Water and Convective Heat Flow Rates of East Mesa Hydrogeothermal System.

depth of exploration. Very large thermal water flows, of the same order of magnitude as the more spectacular geysers, may be circulating at shallow depths below the earth's surface, when hydrogeological conditions do not favor outflow to the surface.

Convective Heat Transfer

We can calculate the amount of heat convectively transferred by the above system. Assuming that the temperature drop required for precipitation of the excess mass at the East Mesa Anomaly is 150°C, the total heat transferred convectively with the water since the birth of the East Mesa geothermal system is about 3.8×10^{21} calories, taking the mass flow of water as 25×10^{12} tons. This is much greater than the value given by White (1965) for the heat stored to a depth of 3 km in some typical hot spring systems, which he calculates to be of the order of 2×10^{20} calories.

The area of the East Mesa geothermal anomaly is about 200 sq. km. Hence, the convective heat transfer of the geothermal anomaly has been about 1.9×10^9 cal/cm^2 from the birth of the East Mesa geothermal system to the present.

Figure 5 contains also a plot of heat flow (μ cal/cm^2/sec) versus possible age for the East Mesa Anomaly. It is noted from this figure that for an assumed age of 50,000 years for the East Mesa system, the convective heat flow would be 1200 heat flow units (HFU). This is about 200 times the estimated present conductive heat flow for the anomaly.

The reported conductive heat flows for the geothermal anomalies in the Imperial Valley vary between 7-17 HFU (Rex, 1966; Helgeson, 1968). For the East Mesa anomaly, the conductive heat flow is estimated to be 4-6 HFU (Combs, 1971). The difference between the lower observed heat flow and the estimated high convective heat flow rate may be due to the possibility that as selfsealing progresses, the vertical component of convective water flow becomes minor, while lateral dissipation of heat becomes more important. Eventually heat may be totally dissipated laterally into large aquifers at great depth without substantially increasing observed heat flow rate at the ground surface.

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