APPROXIMATION OF GEOTHERMAL RESERVOIR CHARACTERISTICS BASED ON GRAVIMETRY

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Key words: Residual gravity, reservoir engineering, geophysics, convcction rate. East Mesa.

Abstract

A close correspondence between heat flow anomalies and residual gravity anomalies has been observed in several geothermal fields. particularly in the Imperial Valley of California. This correspondence provides evidence that the residual gravity anomaly is due to densification of the supra-basement sediments as a result of mineral deposition by convecting geothermal fluids. Based on this correlation, the total amount of fluid that has circulated in the geothermal system can be determined. Dissolved minerals from the geothermal fluid are precipitated as the tluid convects from deeper, high-temperature. high-pressure zones within the reservoir to shallower, low-temperature, low-pressure zones.

Analysis of the residual gravity anomaly associated with the convecting system is used to provide the total mass of hydrothermally precipitated minerals. By utilizing the estimate of mass loss per unit volume of fluid with the total excess mass calculated from gravimetry, the total fluid and thermal energy throughput of the geothermal system over its active lifetime is calculated. Alternatively, the convection rate of the hydrothermial system can be calculated using heat flow and reservoir engineering methods. The excess mass derived from gravimetry is then used together with the calculated convection rate to determine the age of the hydrothermal system.

Introduction

The question of convection rates in geothermal systems and the age of geothermal systems has been the subject of several studies in the past. Goyal and Kassoy (1977, 1981) approached the problem from the purely reservoir engineering approach. They speculated at a value for the characteristic permeability of the reservoir, thickness of the reservoir. and the reduction in temperature of the upward convecting fluids from the base of the reservoir to its top, just below the cap layer. Utilizing natural convection theory (Kassoy and Zebib, 1975) and the estimated reservoir parameters plus the conductive heat flow data for the East Mesa geothermal field. they were able to estimate the convective heat flow rate per unit area. They calculated that for the East Mesa field convective heat flow was approximately three orders of magnitude greater than the conductive heat flow rate (Goyal and Kassoy, 1977).

Working at the problem of conduction versus convection from the purely geophysical point of view, we have concluded (Meidav. James and Sanyal, 1977). that the convective heat flow was substantially greater than the conductive heat flow at East Mesa, if we assume the age of the geothermal system to be 50,000 years. A higher convection rate results from assuming an age younger than 50,000 years. The two totally independent methods, one relying on reservoir engineering considerations and the other on purely gravimetric data are within less than an order of magnitude difference, suggesting that both methodologies reasonably estimate the convection rate in the system.

This paper is a refinement of the previous paper on that topic (Meidav et al, 1977). It describes a method for estimating total fluid and thermal energy throughput of a geothermal system based on analysis of residual gravity anomalies. Alternatively, an estimate of the age of the geothermal system is made by combining the reservoir engineering approach of Goyal and Kassoy with the residual gravity analysis approach. That is. if we fix the convection rate, as estimated by reservoir engineering methodology. we can calculate the age of the geothermal system.

Residual Gravity and Hydrothermal Convection

The existence of densified rocks in the central areas of geothermal systems has been previously reported by various investigators (White. 1965: Facca and Tonani, 1967). It was explained as being the result of precipitation of minerals in a water-convective system when the water cools down and decompresses as it rises vertically in the geothermal reservoir.

Similar observations were made by industry geophysicists who noted the close correlation between residual gravity anomalies and the conductive heat flow anomalies associated with the same hydrothermal system. All of the known geothermal systems in the Imperial Valley are associated with residual gravity anomalies. except for the South Brawley field. That exception is explainable by the rapidly subsiding extensional basin and extreme depth of the convecting system (>3 km). The large negative gravity expression of the ongoing tensional tectonics overwhelms the much smaller and very deep positive residual gravity anomaly which may occur in that reservoir.

Likewise, several geothermal systems in northern Nevada are characterized by residual positive gravity anomalies that coincide with actively convecting geothermal systems, as corroborated by subsequent drilling.

The evidence for the existence of hydrothermal convection in geothermal systems is clearly manifested by the changes in the temperature gradient at the cap layer of the reservoir, which seals the reservoir and prevents upward fluid flow. Whereas the thermal gradient above the cap layer tends to be steep and nearly linear, indicating conductive heat flow, the gradient becomes isothermal or nearly so within the reservoir, due to the homogenizing effect of the hydrothermal convection.

It should be noted that although many well-developed geothermal systems are characterized by residual gravity anomalies, the reverse is not necessarily true. The existence of a residual gravity anomaly does not necessarily indicate the existence of an active geothermal system. Most epithermal mineral deposits and their associated gravity anomalies are a product of hydrothermal convection which took place millions of years ago, but have long since ceased activity. The mineral deposit remains behind as cold testimony to a long-extinct geothermal system (Miller and Flynn, 1992).

Computation of Excess Mass from Residual Gravity

It is possible in gravimetry to determine uniquely the total excess mass causing a residual positive gravity anomaly, regardless of the geometry of the excess mass. Hammer (1945) has proven, by invoking Gauss' flux theorem, that the volume distribution of the

mass causing a gravity anomaly is defined by the integral of the gravity anomaly per unit area multiplied by the area element,

$$\iint dg\,dS = 2\pi GM$$

where dg is the gravity anomaly, G is the gravitational constant and M is the mass. If dg is expressed in milligals and the areal element dS is in square meters, the above equation reduces to

$$M \text{ (metric tons)} = 23.9 \sum dg\,dS$$

To determine the excess mass in metric tons, one measures the surface area within each contour of the residual gravity anomaly and sums up the areas, multiplied by the unit gravity selected (e.g. one milligal) for the entire anomaly, then multiplied by the constant, to come up with the total excess mass. If the separation of the residual anomaly from the total Bouguer gravity is correctly conducted over an area where the hydrothermal convection took place, the excess mass calculation will yield the total mass deposited out of the geothermal fluid. **As** an example, Table 1 contains the tabulation for the entire computation of the excess mass for the East Mesa geothermal field.

Excess Mass, Chemistry and Water Circulation in the East Mesa Field

The mass excess in the East Mesa field has been determined to be about 8×10^9 metric tons, by utilizing Hammer's technique (see Table 1). This excess mass of about 8 billion tons is believed to be due to the combination of replacement of low density minerals with higher density ones and of authigenic mineral deposition in the pore space of the detrital sediments which are characteristic for the area. The excellent correlation between the residual gravity map (Figure 1) and the isothermal map at a depth of 6,000 feet (1.828 km, Figure 2), provides corroboration of the above assertion.

Without exception, all temperature gradient graphs for wells that are deeper than 1 km drilled in the East Mesa field show a flattening of the gradient at a depth of about 600-1000 m. Hoagland (1976) determined from mineralogical analysis that at approximately that depth authigenic (post-depositional) mineralogy prevails, and that rock density increases from about 1.9 gm/cm^3 to about 2.3 gm/cm^3 below about 900 m.

Hydrothermal Convection Computation and Age of the East Mesa Hydrothermal System

The amount of water that has circulated through the East Mesa hydrothermal system can be estimated from the excess mass computed from gravimetry, by estimating the amount of water that had to convect in order to deposit the excess mass. First, **an** estimate is made of the fraction of minerals that precipitated out of solution as the temperature of the convecting fluid decreased in its sojourn from the base of the geothermal system to its top. If 7 gm/liter precipitated from the convecting hydrothermal system results in **8** x 10^9 metric tons of excess mass. then the amount of water that circulated to create the excess mass is 1.143 x 10^{12} metric tons.

Goyal and Kassoy (1977) estimated the rate of vertical convection to be about one cm per day. Since the density of water at near-surface is about one gram per cm^3, then about one gram per cm^2 of water would migrate upward per day across the entire fractured area. By dividing the total mass of water that crossed a unit surface area per day by the rate of movement, we come up with the age of the convecting system, which in this case is about 78,000 years.

The age calculated above for the East Mesa geothermal system is inversely proportional to the areal size of the fractured rock. Hence, it can be considered as an order of magnitude only.

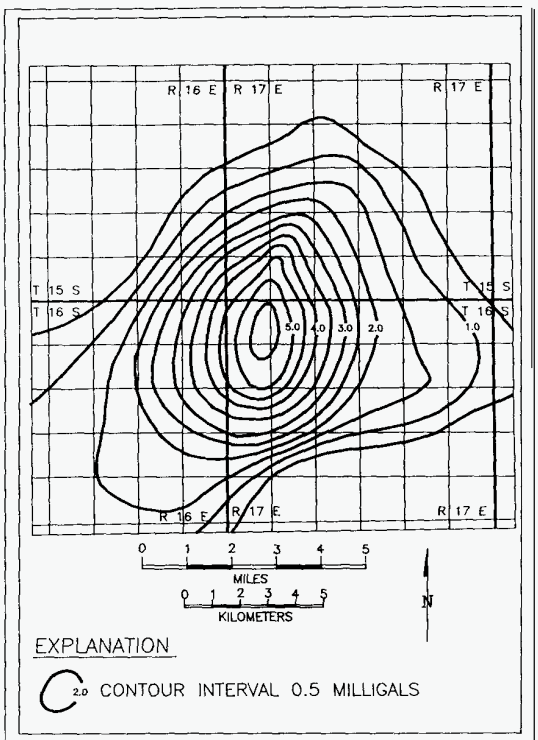


FIGURE 1. RESIDUAL GRAVITY MAP *OF* THE EAST MESA FIELD (BIEHLER, 1971)

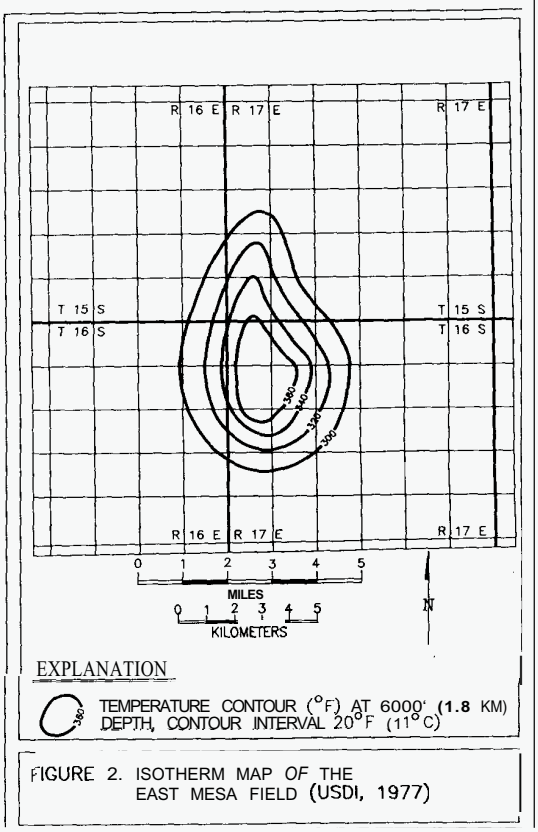


FIGURE 2. ISOTHERM MAP *OF* THE EAST MESA FIELD (USDI, 1977)

We can take the inverse approach of fixing the age of the system and ask the question regarding the convection rate within the system. Previous investigators (White, 1965; Ellis, 1970) suggested that the life of **a** typical geothermal system is in the range of 10,000 to 50,000 years. Taking **a** mean value of 30,000 years, we

calculate that the hydrothermal convection rate over the East Mesa field had to be in the range of about 1.2 tons per second.

We can also estimate the ratio of convection to conduction in the East Mesa field. If we estimate the calorific energy convected upward to be about 100 calories per gram. we find that the heat convected by the above water flow, H_v amounted to about 1.2×10^8 calories per second over the entire East Mesa field. Combs (in Rex, 1971) calculated that 4.88×10^6 cal/sec cross about 110 km^2 of the East Mesa anomaly, being transmitted conductively upward. through the cap layer.

The ratio of convective to conductive heat flow in the East Mesa field, assuming a 30,000 year old system, is

$$H_v / H_d = 1.2 \times 10^8 / 4.88 \times 10^6 = 24.7$$

where H_v = convective heat flow, H_d = conductive heat flow. Hence, the convective heat flow is approximately 25 times greater than the conductive heat flow rate at the East Mesa field. That ratio will vary inversely with the estimated age of the geothermal system. Assuming that our calculated age above (73.000 years) gives the more correct age of the East Mesa system, then the ratio of convection to conduction decreases to about 10. The above example suggests that convective heat transfer is more than 10 times greater than conductive heat transfer.

TABLE 1

EAST MESA GRAVITY ANOMALY EXCESS MASS CALCULATION

ANOMALY (MILLIGALS)	AREA (A) (Millions of Sq. Meters)	GRAVITY ANOMALY (A)(dg) in millions	EXCESS MASS (METRIC TONS) in millions
0.5	232.0	116.0	2,770.0
1.0	152.0	759.0	1,820.0
1.5	92.7	46.4	1,110.0
2.0	61.4	30.7	734.0
2.5	46.7	23.4	558.0
3.0	35.7	17.9	427.0
3.5	25.5	12.7	305.0
4.0	15.8	7.90	189.0
4.5	11.5	5.77	138.0
5.0	6.12	3.06	73.0
5.5	1.59	0.73	19.0
	Total Excess Mass (millions of metric tons)		8,130.0

The excess mass for each contour interval is determined by multiplying the area within a contour by the contour interval (0.5 mgal) and by a constant (see text). Summing the mass of all the contour intervals gives the total excess mass of the anomaly.

Conclusions

Analysis of gravimetric data from geothermal fields with positive residual gravity anomalies can be used to determine the total mass deposited from geothermal tluid due to cooling and decompression in a convective system. By utilizing the vertical convection rate which may be provided from reservoir engineering data (i.e. the Kassoy and Zebib's approach), we can calculate the age of the system.

Conversely, by restricting the age of the system, based upon general hydrogeothermal considerations, we can determine the convection rate within the system.

Acknowledgments

Thanks to William J. Tcplow and to the anonymous reviewer

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