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Determination of heat flow anomaly in Agbor, delta state

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ABSTRACT

Heat flow values were obtained from four boreholes located at Agbor, Delta State, Nigeria. The values obtained from the four wells, A, B, C and D was respectively 75, 68, 60 and 56mWm^{-2}. However, the average value of 64.75mWm^{-2} is very close to the estimated value of 65mWm^{-2} from the semi-empirical law of heat flow versus lithospheric age. The platinum resistance thermometer and the thermistor were used for the measurement of borehole temperature. From the measured temperature distribution, the temperature gradient was computed. The formation heat flow was obtained by multiplying the gradient by the mean thermal conductivity of the rocks. The interpretation of high and low values of heat flow in wells A and D respectively were explained. However anomalous high heat flow values have been observed in well A. The result reveals that a hot plate mobility of heat carrier through some structural boundary and chemical reactions of some organic matters are some specific causes of high heat flow anomaly in the area of the research.

Introduction

The measurement of variations in the earth's temperature which are not attributed to daily variations in solar heating is regarded as geothermal prospecting. The objective may be to locate sources of geothermal energy, geological features which affect heat flow such as salt domes, dikes, faults, etc or ground water variations.

Diunal variations due to solar heating penetrate to about 1m and annual temperature varies up to 20m. Therefore, measurements made of 0.5m to 2m over a relatively short time period reflect variations of heat flow.

The mean heat flow of the earth in heat flow unit is 1.2 – 1.5hfu. Heat flow ranges from about 0.9 in shield areas to over 2hfu in Cenozoic volcanic areas while mid ocean ridge values reach 8hfu.

There exist certain factors which affect heat flow. These are effects of topography in the region, local variations in radioactive content, past seasonal variations, mode of sedimentation, perturbation of gradient by variations of thermal conductivity or local injection of material and variation in flux from deep interior.

When a radioactive isotope decays, it emits energetic particles and $\gamma - rays$. The two particles that are important in radioactive heat production are $\alpha -$particles and $\beta -$particles. The energy of the decay must be fully converted to heat, and the isotope must be sufficiently abundant. The main isotopes that fulfill these conditions are Uranium, ^{238}U, ^{235}U, Theorium, ^{232}Th and Potassium, ^{40}K. ^{235}U has a shorter half-life than ^{238}U and releases more energy in its decay. The amounts of heat generated per second by these elements in (μWkg^{-1}) are ^{238}U=95.2, ^{232}Th=25.6 and ^{40}K=0.0034 Rybach 1976, Rybach 1988).

Heat flow distribution, however, shows unexpected high values along the deepest part of a borehole constructed along Okoh Street in Well A, close to the river in the town and Well B along Imudia Street drilled to about 100m deep.

The heat values of 50 – 80mWm^{-2} were predicted for the area around the holes from the distribution pattern compiled by Egbai 2000).

Temperature usually varies with depth and this variation can be measured using temperature logging. On the average, it is about 3^{o}C/100m. The product of temperature gradient and thermal conductivity is equal to the rate of flow of heat upwards from the interior of the earth. In formations less than 15m deep, temperature gradients due to heat flow from below are usually masked by those due to daily and annual temperature variations surface, but long term surface effects are observable below this depth. (Egbai and Asokhai 1998).

Variations in sea-floor depth and heat flow with age provide the main constraints on the thermal structure and evolution of the oceanic lithosphere. Joint fitting of heat flow and bathymetry yields a model with a hotter, thinner lithosphere than in previous models (Carol and Seth 1992).

Various mechanisms including radiogenic heat, shear heating, small scale convection; and mantle plumes are the sources of the additional heat at the subsurface. In most of these formulations, the asymptotic thickness to which the lithosphere evolves corresponds to the depth at which the additional heat is supplied, the plate model in a standard for comparing the predicted temperature within the lithosphere to data including seismic wave velocities, flexure due to applied loads and the depths of intriplate earthquakes

Conduction heat flow values derived from measurement in drill holes of the temperature gradient below the ground surface, and the thermal conductivity of the adjacent country rock, can provide insight to the past thermal history of the crust, and constrain tectonic models of lithospheric evolution (Allis et al 1995). The drill holes typically have to be at least several hundred meters' deep to remove most of the thermal effects of surface temperature fluctuations due to past climate variation, and special case is needed when interpreting the thermal regime in regions with high permeability and high topography to distinguish the effects of ground water movement.

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Stretching is ascribed to regional stress field related to the plate boundary forces, dragging and erosion to underplate movements of the hotter asthenospheric material. The thinning of the lithosphere causes the subsidence of the basin and the passive upwelling of the asthonospheric material.

Conductive thermal modeling shows that either magmatic underplatic intrusions into the crust, or magmatic underplating at the base of the crust, ate capable of explaining the increased surface heat flow anomaly (Allis et al 1995).

Theory

Heat flows when there is a difference of temperature in a material body. The rate of flow is proportional to the difference in temperature.

$$w = -k\frac{\partial T}{\partial n}$$

where $w =$ heat flux, $k =$ thermal conductivity of the material.

The heat flux is the heat flow per unit time per unit cross-sectional area normal to the coordinate, n which is measured in the direction of heat flow.

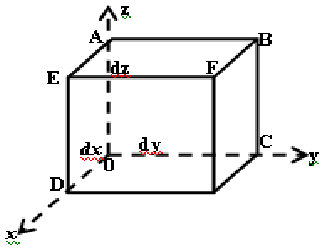


Fig. 1: Heat flow across volume of earth

Heat is flowing in and out of the small volume as shown in figure 1. Heat flowing on OABC normal to *x*-coordinate $W_x dydz$.

$$W_x dydz = -k\frac{\partial T}{\partial x}dydz \qquad (1)$$

Heat flowing through DEFG normal to *x*-coordinate

$$\left[W_x + \frac{\partial w}{\partial x}dx\right]dydz = -\left[k\frac{\partial T}{\partial x} + \frac{\partial}{\partial x}\left(k\frac{\partial T}{\partial x}\right)dx\right]dydz$$

Net heat flow into volume normal to *x*-coordinate

$$-\frac{\partial w_x}{\partial x}dxdydz = \frac{\partial}{\partial x}\left(k\frac{\partial T}{\partial x}\right)dxdydz \qquad (2)$$

Net heat flow into volume normal to *y*-coordinate

$$-\frac{\partial w_y}{\partial y}dxdydz = \frac{\partial}{\partial y}\left(k\frac{\partial T}{\partial y}\right)dxdydz \qquad (3)$$

Net heat flow into volume normal to z-coordinate

$$-\frac{\partial w_z}{\partial z}dxdydz = \frac{\partial}{\partial z}\left(k\frac{\partial T}{\partial z}\right)dxdydz \qquad (4)$$

The increase of heat in material per unit time is

$$C\rho dxdydz\frac{\partial T}{\partial t}$$

where ρ is density and C is the specific heat of the material.

$$-\overline{\nabla}.\overline{w} = C\rho\frac{\partial T}{\partial t} \qquad (5)$$

If k is constant with respect to coordinates, then

$$k\nabla^2 T = C\rho\frac{\partial T}{\partial t} \text{ or } \alpha\nabla^2 T = \frac{\partial T}{\partial t} \qquad (6)$$

where $\alpha = \frac{k}{C\rho}$ is called thermal diffusivity.

An important case to be considered is the periodic flow of heat into the earth of diunal, seasonal or long-period variation in the surface temperature. If we assume a daily or annual temperature cycle of the form $T = T_0 Coswt$. T is temperature variation for the mean daily or annual temperature. T_0 is half the total temperature, w is the circular frequency associated with a period of one day or one year. Seek solution to 1-D equation.

$$\alpha\frac{\partial^2 T}{\partial z^2} = \frac{\partial T}{\partial t} \qquad (7)$$

z is depth satisfying the initial condition

$$T = T_0 Coswt \qquad (8)$$

Using separation of variables,

$$T = Z(z).H(t)$$

$$\alpha Z''\Theta - Z\Theta' = 0$$

or

$$\frac{Z''}{Z} - \frac{\Theta'}{\alpha\Theta} = 0 \qquad (9)$$

To have any relation, each of the term must separately be a constant, i.e.

$$\frac{Z''}{Z} = -\gamma^2 and \frac{\Theta}{\alpha\Theta} = -\gamma^2$$

The solutions are

$$Z = \alpha_1 e^{iyz} + \alpha_2 e^{-iyz} \qquad (10)$$

$$\Theta = a_3 e^{-xy^2 t}$$

For the solutions to satisfy the initial condition,

$T = T_0 Coswt$, we choose $\gamma^2 = \frac{iw}{\alpha}$ or $\gamma = (1+i)\sqrt{\frac{w}{2\alpha}}$

Since $\sqrt{i} = e^{i\pi/4} = 1 + \frac{i}{\sqrt{2}}$

$$Z = a_1 e^{(i-1)Z\sqrt{w/2\alpha}} + a_2 e^{(-i+1)Z\sqrt{w/2\alpha}}$$

$$\Theta = \alpha_3 e^{-iwt} \qquad (11)$$

The heat must decrease towards large Z, which implies $a_2 = 0$

$$T = Z\Theta = a_1 a_2 e^{(i-1)Z\sqrt{w/2\alpha}} e^{-iwt} = a_1 a_3 e^{i\left(Z\sqrt{w/2\alpha} - wt\right)} \qquad (12)$$

To satisfy the initial condition, $T = T_0 Coswt$ and $a_1 a_3 = T_0$

$$\Rightarrow T = T_0 e^{-Z\sqrt{w/2\alpha}} Cos\left(Z\sqrt{w/2\alpha} - wt\right) \qquad (13)$$

For more general solutions to the heat conduction equation, we consider equations (7) and (10) and the solution will take the form

$$T = Be^{-a\gamma^2 t} Cos(\gamma z)$$

$$T = Ce^{-a\gamma^2 t} Sin(\gamma z)$$

These particular solutions may be generalized to an integral

$$T = \int_{0}^{\infty} \left[BCos(\gamma Z) + CSin(\gamma Z) \right] e^{\alpha\gamma^2 t} dy \qquad (14)$$

If we have an initial temperature distribution $f(z)$ at $t = 0$, we can evaluate B and C. At $t = 0, T(z,0) = f(z)$ then

$$T(z,0) = f(z) = \int_{0}^{\infty} \left[BCos(\gamma z) + CSin(\gamma z) \right] dy \qquad (15)$$

From the Fourier integral theorem,

$$B = \frac{1}{\pi} \int_{-\infty}^{+\infty} f(\xi) Cos(\gamma\xi) d\xi$$

$$C = \frac{1}{\pi} \int_{-\infty}^{+\infty} f(\xi) Sin(\gamma\xi) d\xi$$

Substituting for B and C in equation (15), we have

$$T(z,t) = \int_{0}^{\infty} \left[\frac{1}{\pi} \int_{-\infty}^{+\infty} f(\xi) Cos(\gamma\xi) d\xi Cos(\gamma z) \right] + \frac{1}{\pi} \int_{-\infty}^{+\infty} \left[f(\xi) Sin(\gamma\xi) d\xi Sin(\gamma z) \right] e^{-\alpha\gamma^2 t} dy$$

$$= \int_{-\infty}^{+\infty} f(\xi) d\xi \int_{0}^{\infty} e^{\alpha\gamma^2 t} Cos\left[\gamma(\xi - z)\right] dy$$

$$= \frac{1}{\pi} \int_{-\infty}^{+\infty} f(\xi) d\xi \left[\frac{\sqrt{\pi}}{2\sqrt{\alpha t}} e^{-(\xi - z)^2 / 4\alpha t} \right]$$

$$\therefore T(z,t) = \frac{1}{2\sqrt{\pi\alpha t}} \int_{-\infty}^{+\infty} f(\xi) e^{-(\xi - z)^2 / 4\alpha t} d\xi$$

This is the final equation used to find the temperature variation of any type of hot body

Location

Agbor, the headquarter of Ika South Local Government Area of Delta State, Nigeria is situated around Latitude 06^0 10^I and 06^0 20^I and Longitude 06^0 15^I. It has a river called Orogodo which flows north south. Before this river used to be the source of water for domestic and industrial use, but now because of pollution resulting from high erosion, it is no more used to the inhabitant of the area.

Methodology

Measurement of temperature in well holes is the oldest logging technique. It is used to determine heat flow and to locate thermal anomalies caused by fluid flow in the ground.

The computation of heat flow at a locality requires two measurements. The thermal conductivities of a representative suite of samples of the local rocks are measured in the laboratory. The temperature gradient is measured in the field at the site of investigation usually carried out in a borehole.

The platinum resistance thermometer and the thermistor were used for the measurement of the borehole temperature. The sensitivity of the thermistor makes feasible the measurement of temperature differences of 0.001 - 0.01 degree Kelvin. The cable with down-hole logging thermometers are lowered into the hole step-by-step (10m at a time) and readings were taken [3]

From the measured temperature distribution, the average temperature gradient is computed for a geological selected depth interval of 10m. The gradient is multiplied by the mean thermal conductivity of the rocks to obtain the formation heat flow. Four wells (well A, B, C and D) located within the town were used for the field work.

Certain assumptions were made to have an effective and a meaningful value. These are

(i) Heat flow is only vertical

(ii) The surfaces of the wells are of constant temperature.

(iii) The surface of the earth is presumed to be locally isothermal (i.e. to have constant temperature near to the boreholes).

(iv) The near surface isotherms adapt to the topography, but heat flow measured in a borehole must be corrected for the effect of local topography.

To investigate whether the temperature values obtained through these two types of probes are compatible, one comparison test run was made with boreholes located in well A – Okoh Street, Agbor. The temperature data provided by these two probes seem to be in good agreement. This is shown in figure 3. The diagram shows temperature versus time curve, showing the results of combination test run for comparison between platinum resistance thermometer and the thermistor.

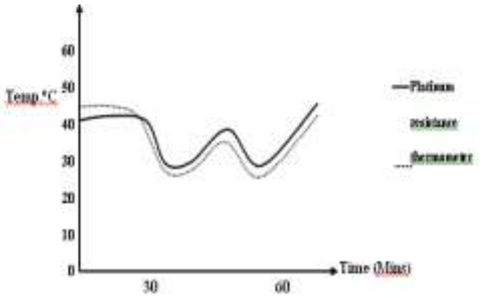


Fig. 3: Temperature versus time curve showing the results of combination test run for comparison between platinum resistance thermometer and thermistor

Results and Causes of Heat Anomaly

Heat flow values around a well A in Okoh Street very close to the River is conspicuously high. This may be as a result of the presence of the river, which resulted in temperature difference. The direction of heat flow is from the east of well A to the westward. This is also applicable to well B – Imudia Street. The heat flow in well C (Charles Street, Agbor) is very moderate, but it is lower around well D, (Whyte Street, Agbor).

Heat flow varies with crucial age. The weighted sum gives a mean heat flow of $65mWm^{-2}$ for the continental data, while the weighted mean heat flow is $10mWm^{-2}$ for the oceanic data. The average heat flow for wells A, B, C and D are respectively 75, 68, 60 and $56mWm^{-2}$. The average heat flow for Agbor generally is $64.75mWm^{-2}$, very close to the continental weighted average.

Nwankwo et al 2010 result analysis on geothermal gradient of Nupe Basin, Nigeria shows that the geothermal gradient varies between 10 and 45^0Ckm^{-1} while the ensuring heat flow varies between 30 and $120mWm^{-2}$. He found that in the Southeast and Southwest of the study area heat flows were found to be less than $60mWm^{-2}$ while heat flows more than $100mWm^{-2}$ are found in the Northern and northwestern parts.

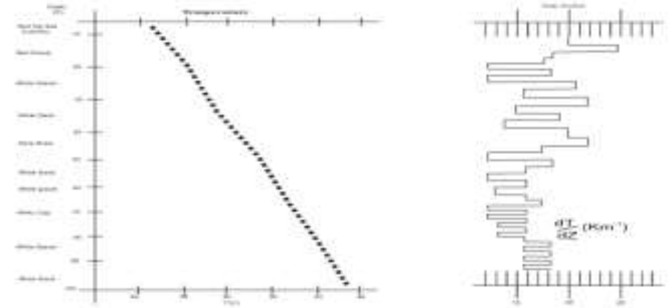
Allis et al 1995,observed a high heat flow anomaly over the northern Taranaki peninsula, North Island, New Zealand, with the heat flow rising to a maximum of $73mWm^{-2}$ in oil exploration wells drilled in New Plymouth. This compares to an average heat flow of close to $60mWm^{-2}$ for the whole of the Taranaki Basin.

The heat flow north of the Taranaki Peninsula ranges from 53 to $63mW/m^2$ depending on whether there has been relatively rapid sedimentation or erosion since the Pliocene. Towards the south of the Taranaki peninsula, the heat flow decreases to $<50mWm^2$, due to effects of crustal thickening since the Miocene (Armstrong et al 1994).

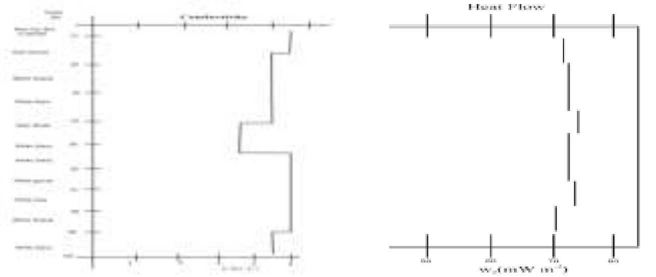
The result of heat flow from temperature log data is as shown in figure 3 (a – d).

Fig. 3(a): Computation of heat flow

(b) Temperature gradient from temperature log data-depth versus temperature



(a) Computation of heat flow **(b) Temperature gradient from temperature log data**



(c) Depth versus Conductivity **(d) Heat flow by interval method**

Fig 3: Computation of heat flow from temperature log data

(a) Depth versus temperature
(b) Temperature gradient
(c) Depth versus conductivity
(d) Heat flow by interval method

Some specific causes of high heat flow anomaly might be (a) a hot plate, (b) mobility of heat carrier through some structural boundary, and (c) chemical reactions of some organic matters.

If we compare heat flow anomaly with other geophysical characteristics, such as the conductivity anomaly and the residual gravity anomaly suggest a deep origin of the heat flow anomaly. The isotherms, which are drawn from regional heat flow values, are aligned parallel to the electrical conductivity distribution (Uyeda 1972)..

The mechanical squeezing of pore water out of deforming sediments during subduction is not powerful enough to generate a heat flow anomaly of the present magnitude (Yamano et al 1984). Hence, we suggest an alternative mechanism, that is, hydrologic circulation to produce high heat flow in the area of the research.

Chemical Reaction

The area contains organic matter, raw carbonate, and raw metals, which are subject to decomposition. The end product of the decomposition, and oxidation is the production of gas and heat. These sink into the subsurface and cause some differences in heat flow resulting in heat flow anomaly in the area of the research.

Conclusion

The results reveal that a concentrated high heat flow anomaly was observved for wells A and B reaching 75 and 68mWm^{-2} respectively when compared to the estimated values of 65mWm^{-2} from the semi-empirical law of heat flow versus lithospheric age.

The result also reveals that a hot plate mobility of heat carrier through some structural boundary and chemical reactions of some organic matters are some specific causes of high heat flow anomaly in Agbor, Delta State.

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