Effects of Metallic Conductors on Crustal Heat Flow Parameters.

O.I. Popoola, Ph.D. and N.O. Salaudeen, M.Sc., PGDE*

Department of Physics, University of Ibadan, Ibadan, Nigeria.

E-mail: salaudeenot@yahoo.com*

ABSTRACT

The heat flow due to the presence of certain metallic conductors within the continental crust was investigated in comparison to that of a homogeneous crust.The metallic conductors were iron and lead. A temperature distribution of an homogeneous earth in the continental crust due to radioactive heat sources such as U^{235}, K^{40}, U^{238} and Th^{232} were recomputed using a Java program and then modified to a case of non-homogeneous earth layers especially where there are presence of the chosen metallic conductors. A depth of 15-25 km was assumed so that heat transport by thermal conduction can be reasonably considered and also because heat generation in the upper crust is related to mineralization.

The heat flow parameters for iron and lead were then computed from the temperature production of each metallic conductors at 15-25 km based on the model that the present stage of the crust was reached 200 m.y ago. The results showed that temperature gradually increases with depth and it was deduced from the computed results that U^{238} and Th^{232} were the major sources of heat in the continental crust. The lower thermal conducting metal such as lead gave higher temperature distributions due to heat flow production unlike Iron, the highest thermally conducting metal for this work.

The present geothermal gradients obtained for iron and lead within these depths were, 0.96^{o}C/km and 2.29^{o}C/km while the respective geothermal steps were 1.04 km/^{o}C and 0.44 km/^{o}C.Their respective heat flows were 0.069 W/m^2, and 0.081 W/m^2. The result is in agreement with the fact that thermal gradient is inversely proportional to thermal conductivity. It can also be seen from the results that the thermal conductivity of the material played a major role in influencing the temperature distributions in the crust. From this it can be inferred that region with low thermal conductivity will have high temperature/temperature gradient and *vice versa*.

(Keywords: geothermal gradient, geothermal step, thermal conductivity, geothermal parameters)

INTRODUCTION

The geothermal parameters are essential in understanding the distribution of heat flows within the continental crust and this can lead to the solution of many problems related to geothermal energy sources, mineralization in the mid-upper crust, determination of shallow thermal structures (Yano et al., 1999), indirect deeper information yield better than the bore- hole logging depth as well as the thermal evolution determination of the Earth's history.

Present day heat flow is determined by the amount of radioactive elements decay, their secular decline with time, the delay between heat production and its appearance at the surface, secular cooling of the interior, and a variety of minor sources of heating which are usually overlooked (Anderson, 2007). The major contributor to continental heat flow is the crustal radioactivity. An estimated 45-90 % of the heat escaping from the Earth is said to originate from the radioactive decay of elements like K^{40}, U^{235}, U^{238}, and Th^{232}, respectively and output of the global geothermal flow or energy estimate 45 TW; 5.8-8 TW has been attributed to these decaying elements (Don, 2005).

However, the origin of the crust and its complicated structure which varies with the geology of a place is closely found to be connected to the general chemical and thermal evolution of the Earth. Recently, Sarkar and Singh (2005) had reported that there has been a considerable rise of interest in determination of equilibrium heat flux across the Earth's crust. The equilibrium thermal gradient have been known to be invaluable in the proper understanding of many geophysical processes that are connected to the Earth's interior. A distribution in the thermal gradient when measured differs due to topographic irregularity(Ibid).

In logging geo-physics, the geothermal gradient is a very important parameter (Kutasov et al., 2009). It is well established that the thermal gradient varies strongly with depth and to a large extent reflect variation of thermal conductivity, K.

Metallic conductors based on different thermal, electrical conductivity or resistivity can represent anomaly within a homogeneous earth and different manifestation of heat flow with depth can possibly be presented. Thus, the geothermal flow can often provide insight into the crustal heat flow due to presence of radioactive elements in the metallic layers resulting in High or low heat flow. This assertion found support in Rao and Rao (1982) who had opined that crustal geothermal province and radiogenic heat generation in the crustal rocks may be factor causing high heat flow density in the areas concerned. A region of metallic conductors of different geothermal parameters could be assumed to present heat flow density characteristic of these element when the radioactive sources are considered as support to other heat sources for the geology of a given area.

It is well known that the temperature increases with depth near the surface of the Earth but beyond a certain depth only an estimate can be made through the use of plausible model. The temperature of the Earth is usually studied by solution of the heat conduction equation in a spherical model. Keh-Gong (1971) reported that Holmes (1916) was the first to calculate the internal temperature distribution by using heat generation, while a detailed numerical calculations taking into account the time dependence of radioactive heat sources was done by Jacobs and Allen (1954).

A detailed calculation of the distribution of temperature within a symmetrical earth was also made by Macdonald (1961) and Clark (1961). Reseachers believed that the results largely depend on the choice of parameters used. Despite the improved calculations of radioactive contents of rocks and surface heat flow, the estimation of the temperature within the Earth is still difficult. A simplified expression for determining the crustal temperature distribution as a function of time and depth due to radioactive heat source has been developed by Keh- Gong (1971) making use of one dimensional steady state theory and a model that the present stage of the crust was reached 200 m.y. ago and it is based on the observation that there are plutons ranging in age from 80 m.yr. to 145 m.yr.in Sierra Nevada.

Heat Source Distribution

The choice of heat source model is difficult because of the existence of many heat producing isotopes such as U^{235}, K^{40}, U^{238}, and Th^{232} in the Earth. The value of heat production in the crust and upper mantle varies with the quantities of these elements and with their half lives. However, the chosen heat source model, based on the currently accepted amounts of those elements and on their initial heat production , has to meet the conditions that it gives a reasonable present surface heat production(of about 4.18 μ J/m^{3}sec) a reasonable present surface heat flow q (of approximately 0.06 J/m^{2}sec), and an acceptable present mean crustal heat production <H>, which is about 1.8μ J/m^{3}sec (Roy et al.,1968).

The initial (4.5 b.yr.ago) and present surface heat productions by different elements are given in Table 1. The initial heat production calculations for the table were based on Jacob's model for radioactive heat sources (Jacobs, 1956).

Table1: Radioactive Heat Production in the Continental Crust and Half- lives.

Element	Surface Heat Production (μW/m^3)		Half-Life(b.yr)
	Initial	Present	
K^{40}	4.1	0.35	1.470
U^{235}	3.9	0.05	0.713
U^{238}	3.0	1.52	4.510
Th^{232}	1.9	1.49	13.900

Source: Temperature production in the continental crust (Keh- Gong Shih (1971))

Table 1 gives a present surface heat production of about 3.4 μW/m^3.

The determination of the mean heat production in the crust is based on the distribution of heat sources as a function of depth. The heat source distribution used in this research is exponential and is given as:

$$H(z,t) = H_{\circ}e^{-\lambda t + z/D} \qquad \textbf{(1)}$$

Where Ho is the initial heat production, λ is the decay constant and D is a constant with the dimension depth. Lachenbruch (1968) had been reported to observed that D should satisfy:

$$\int_{\circ}^{\infty} H(z,t)dz = A_{\circ}D \qquad \textbf{(2)}$$

If there is a linear relation between surface heat production and the surface heat flow, where tp is the time at present and,

$$A_{\circ} = H_{\circ}e^{-\lambda t_p} \qquad \textbf{(3)}$$

The present surface heat flow q gives:

$$q = q_{\circ} + DA_{\circ} \qquad \textbf{(4)}$$

where $q_{\circ}$ is the constant heat flow for the cooling hearth and D is found to be 10 Km at Sierra Nevada. Using this expression , the present mean heat production between 0 to 30km of D values gives about 1.8μW/m^3 and was found to be consistent with the known values.

Figure 1 is used to interprete the above equation but Lachenbruch (1968) pointed out that the exponential relation seems more realistic from the points of view of erosion process and geochemistry of the crust. This necessitated the derivation of Equation 1 for the solution for the temperaure distribution as a function of depth and time.

Reseachers in the field had opined that the thermal history of the Earth depends on the solution of the heat conduction equation for a radioactive earth.In the continental earth, the curvature of the Earth may be neglected, and the problem treated as one of one- dimensioal heat conduction in a solid if the initial time is the time of redistribution of heat sources, and of temperature at the moment the crust regionally reached its final stage.The heat conduction equation (1 - Dimension) is written:

$$\rho c\,\frac{\partial T_1}{\partial t} = \frac{\partial}{\partial z}\left(k\,\frac{\partial T_2}{\partial Z}\right) + H(z,t) \qquad \textbf{(5)}$$

Keh- Gong (1971) had assumed that $\rho, c, k,$ are constants and that the crust is a single homogeneous layer subject to boundary coditions:

$$\begin{aligned} &T_2 = 0 && z = 0,\ t > 0 \\ &T_2 = 0 && t = 0,\ h \ge z \ge 0 \\ &T_2 = g(t) && z = h,\ t > 0 \end{aligned}$$

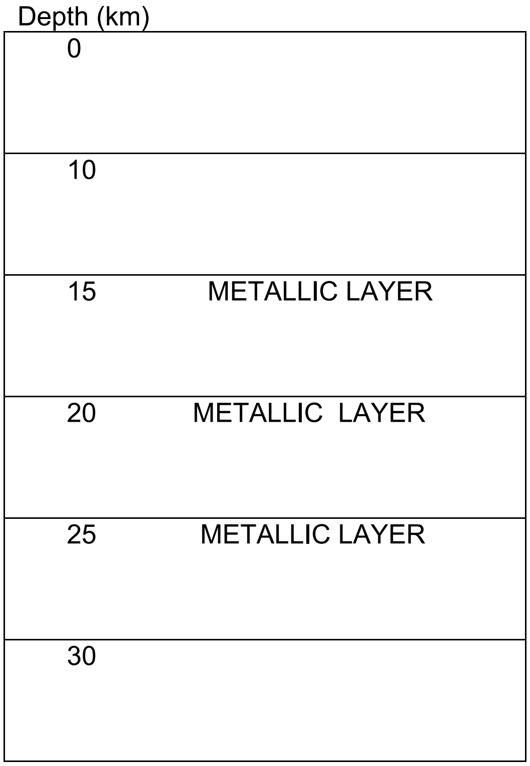

Figure 1: Layers of the Metallic Conductor within the Continental Crust.

Simplifying the above equation with the given boundary condition gives the equation for the cooling of the crust from its initial temperature:

$$\frac{\partial T_1}{\partial t} = a\frac{\partial^2 T_1}{\partial z^2} \qquad \textbf{(6)}$$

$T_1 = 0$ z =0 t >0

$T_1 = To(z)$ t =0, $h \geq z \geq 0$ where t =0 is the time of crustal solidification.

Where , $a = k\frac{\rho}{c}$ **(7)**
gives the thermal diffusivity.

Equation (6) describes the cooling of the crust from its initial temperature. But for the estimation of the near-surface thermal gradient as a function of time, the solution for the cooling crust can be expressed as:

$$T_1 = T_2(z) erf \frac{z}{2\sqrt{at}} \qquad \textbf{(7a)}$$

Where $T_0(z)$ is assumed to be a constant. If $T_0(z)$ is any function, a solution can be obtained by using the method given by (Carslaw and Jaeger, 1959). Solution to Equation (4) gives the temperature of the heating of the crust with radioactive heat production $H(z,t)$. The solution of this can be obtained by using the time-dependent Green's function (Dennemeyer, 1968).

Keh- Gong (1971) also mentioned that the solution of the above equation represent the heating of the crust with radioactive heat production H (z,t) with the aid of time –dependent Green's function. Thus,

$$T_2 = \sum_{\circ}^{\infty} \int_{\circ}^{t} \int_{\circ}^{h} \frac{U_n(z)}{|U_n|^2} \frac{U_n(z')}{} H(z', \tau) e^{-k_n{}^{2a(t-\tau)}} dz' d\tau \qquad \textbf{(8)}$$

Where U_n is the solution of the eigenvalue problem.

$$\frac{\partial^2 U_n}{\partial z^2} + k^2{}_n U_n = 0$$

$U_n = 0$ z=0

$U_n = \alpha B$ z =h

(9)

where B is the amplitude of U_n, α is used to meet the condition of the present heat flow through the Moho- discontinuity at z = 30 km, and $|U_n|^2$ is the normalization factor.

On inserting Equation 1 into the above equation gives a simple expression for the computation of the crustal temperature distribution as a function of depth and time as:

$$T_2 = \frac{2H_{\circ}^{\prime}h^2}{k} \sum_{n=0}^{\infty} C_n \left[e^{-\lambda t} - e^{-(2n\pi+\beta)^2 \frac{at}{h^2}} \right] Sin \frac{(2n\pi + \beta)z}{h} \qquad \textbf{(10)}$$

[Keh- Gong 1971].

Where,

$$C_n = \frac{(2n\pi + \beta)\left[1 - \sqrt{1-\alpha^2} e^{-\frac{h}{D}}\right] - \frac{h}{D}\alpha e^{-\frac{h}{D}}}{\left[(2n\pi + \beta)^2 - \lambda\frac{h^2}{a}\right]\left[\left(\frac{h}{D}\right)^2 + (2n\pi + \beta)^2\right]\left[1 - \frac{2\alpha\sqrt{1-\alpha^2}}{2n\pi + \beta}\right]} \qquad \textbf{(11)}$$

with $\beta = \sin^{-1}\alpha$. **(12)**

and $H'_\circ = H_\circ e^{-\lambda t'}$ **(13)**

$H'_\circ$ is the initial surface heat production at the moment of redistribution of heat sources. $t' = 0$ at 4.5 b.years ago.

The decay constant λ, of each element can be determined by:

$$\lambda = \frac{0.693}{L} \quad \textbf{(14)}$$

where L is the half – life.

In this research work, the simple expression derived by Keh- Gong (1971) was used with slight modification of the equation by substituting metallic conductors constant and assumption of a single non- homogeneous crust for the metal anomalies at the depth of 15- 25 Km.

THERMAL STATE OF THE EARTH

The ultimate source of geothermal energy is believed to be from the radioactive decay that occurs deep within the Earth's crust (Frank and Goswami, 2008). Much of the heat is believed to be created by decay of naturally radioactive elements such as U^{235}, K^{40} , U^{238}, and Th^{232}. An estimated 45-90 percent of the heat escaping from the Earth originates from radioactive decay of elements within the mantle (Anuta, 2006). The formation of thermal fields occuring on three levels has been observed to occur- global, regional and along locals. The global are associated with processes that takes place in the mantle. Regional fields are due to stationary radiogenic part of the crust as a whole while the local thermal fields are due to the formation of rocks, sedimentation ,migration of fluids and other processes occuring in the upper layers of the sedimentary thickness (Ya et al., 2005).

Other various heat sources in the Earth are:

- Heat of impact and compression released during the original formation of the Earth by accretion of in –falling meteorites.
- Heat released from the sinking of abundant heavy metals (iron, nickel, copper) as they descended to the Earth's core.
- Some heat may be created by elecromagnetic effects of the magnetic fields involved in Earth's magnetic field.
- Heat generated within the Earth's core may be in the range of 4-10TW Anuta (2006).
- Heat may be generated by tidal force on the Earth as it rotates, since land cannot flow like water it compresses and distorts, generating heat.

Estimated global terrestial heat flow within the Earth to the surface is about 45TW , out of which (Don, 2005) opined that 5.8-8TW is that due to the continental crust. Some of the heat lost to space is replaced by radiogenic heat production caused by decay of Uranium .Thorium and Potassium. Some of the heat loss results in cooling of the Earth (20% according to Schubert et al 2001). U^{238} and Th^{232} are believed to be the primary heat producers today, while U^{235} and K^{40} were found to be more important in the Earth early history. They decay faster and in much smaller abundance now.

Most radiaoctive isotopes are concentrated in the continental crust. There is a small amount in the oceanic crust and very little in the mantle. Radioactive isotopes decrease exponentially in abundance with depth.

Temperature distribution or the thermal state in the Earth's interior is complicated in view of the fact that direct penetration of the Earth interior is limited to about 6-7 km deep at maximum where temperature exceeding 200°C have been recorde. The Earth's crust which is about 10-60 km thick is only a thin layer on the surface of the globe with a radius of 6000 km. Hence , making temperature measurements at a thousandth kilometer and using this to deduce temperature distribution to the core appears impossible.

However, the origin of the crust and its complicated structure which varies from place to place is closely found to be connected to the general chemical and thermal evolution of the Earth. Thus, thermal phenomena occuring in the Earth's crust is directly linked to the thermal state of the Earth or its evolution. Therefore, earth thermal history can be divided to energy sources inside the Earth and the heat transfer process.

The study of the thermal history of the Earth depends on the solution of the heat conduction equation for a radioactive earth. In the continental crust the curvature of the Earth are neglected, and the problem treated as one – dimensional heat conduction in a solid Keh- Gong (1971). Now, it has been well established that there is an increase in the electroconductivity with depth which also suggest that temperature also increases with depth as well. That means geothermal characteristics of the local regions of the Earth's crust is the geothermal gradient Adetoyinbo (2008).

$$\mathrm{grad}T = \nabla T = \frac{\partial T}{\partial x} \bigg|_{x=0} \qquad \textbf{(15)}$$

It is well established that the thermal gradient varies strongly with depth and to a large extent reflect variation of thermal conductivity. Thus , in areas of high rugged lithology the conception of goethermal gradient in local geothermal characteristics loses its sense. Hence a more complete thermal characteristics is presented by the heat flow or flux which is defined by:

$$q = \lambda . \nabla T \qquad \textbf{(16)}$$

Akiko and Shikawa (2002) observed that heat flow measurements are often widely spaced, requiring an extrapolation of the data to estimate thermal structure in the Earth's crust in some regions of east Japan. The thermal gradient data are found useful in the indirect information about the shallow thermal structure in Japan (Yano et al., 1999) as well as the relationship between the thermal regime and the depth limit of seismicity in the crust.Different distribution of temperature and thermal fields have been observed to correspond to various tectonic regimes (Ya, 2000).

Temperature and fluid content have been suggested as the most important parameters influencing the variation of electrical resistivity with depth in the crust and upper mantle of the Earth (Brace et al., 1965). The importance of crustal temperature as an important parameter bearing on the interpretation or calculation of electrical resistivity profiles are also supported by David (1971).

GEOTHERMAL PARAMETERS

Crustal temperature, geothermal gradient, and geothermal step are the geothermal parameters considered for this research work. The fluid content is not considered as the work is primarily directed at the metallic conducting solid layers in the Earth's crust.

CRUSTAL TEMPERATURE

Temperature define the state of substance not only in the deepest earth interior but in the surface layers through which heat loss to space occur.It is the property of a system that determines whether they are in thermal equilibrium. The coldness and hotness level of a body is indicated by its measure of temperature and invariably the heat energy of a body.It is well known that the temperature increases with depth near the surface of the Earth. But the temperature beyond a certain depth can only be estimated by investigation of possible models.The temperature of the Earth is usually studied using the heat conduction equation in a spherical model (Keh-Gong, 1971).

According to Keh-Gong 1971,the internal temperature distribution by using heat generation was first done by Holmes in 1916. Jacobs and Allen(1954) were the first to give a detailed numerical calculations taking into account the time dependenc e of radioactive heat sources.Other researchers like Macdonald (1961) and Clark (1961) have also made detailed calculations on how temperature was distributed within a symmetrical earth even though their results largely depends on the choice of parameters used.Although the determinations of radioactive contents of rocks and surface heat flow have improved in recent years the estimation of the temperature within the Earth is difficult.

For estimation of the present temperature distribution in the continental crust, one dimensional steady state theory is often employed. In this model, assumption is made that the direction of the temperature variation is vertical.

Fourier's law takes the form:

$$K\frac{d^2T}{dz^2} = -A(z) \qquad \textbf{(17)}$$

Where T is the temperature, K is the thermal conductivity, and A is the heat production. Radioactive heat generation cannot be neglected in calculating the temperatures of a continental – type crust. Lachenbruch (1970) has suggested that radioactive heat generation decreases exponentially with depth in the continental crust in view of the erosion process and geochemistry of the crust. In this case, temperature is given by:

$$T = T_0 + \left(q_1 - \frac{AZ_1}{K}\right)Z + \left(\frac{AZ^2{}_1}{K}\right)\left(1 - e^{-\frac{Z}{Z_1}}\right)$$

$$T = T_0 + \left(\frac{\Delta T}{\Delta Z} - \frac{AZ_1}{K}\right)Z + \left(\frac{AZ^2{}_1}{K}\right)\left(1 - e^{-\frac{Z}{Z_1}}\right)$$

(18)

Where q_o=heat flux or flow

$\frac{\partial T}{\partial Z}$ = thermal gradient

K= thermal conductivities

A= average continental upper crust=1.0μWm

Using added assumption of a resonable thermal conductivity and heat sources as a function of depth and time, an improved simple expression using the plausible model of the crust was derived by Keh – Gong (1971): from (10-13).

GEOTHERMAL GRADIENT

It is the rate of increase in temperature per unit depths in the Earth. It varies with location and is typically measured by determining the bottom open hole temperature after bore hole drilling. To achieve accuracy the drilling fluid needs time to reach the ambient temperature. This is not always achievable for practical reasons.

Geothermal gradient/grad T is mathematically represented as:

$$\text{gradT} = \nabla T = \frac{\partial T}{\partial H} \qquad \text{in } ^{o}\text{C/km} \qquad \textbf{(19)}$$

The temperature gradient dramatically decreases with depth for two reasons:

1) Radioactive heat production is concentrated within the crust of the Earth, and particularly within the upper part of the crust, as concentrations of Uranium, Thorium and Potassium are highest.

2) Mechanism of thermal transport changes from conduction as within the rigid tectonic plates, to convection, in the portion of Earth's mantle that convects.

It is well established that the thermal gradient varies strongly with depth and to a large extent reflect variation of thermal conductivity, K.

Thermal conductivity decreases rapidly with increasing temperature and thus thermal coductivity also decreases with increasing thermal gradient and conversly (Don, 2005). Thermal conductivity variants with depth is attributed to the fact that cold outer shell of the Earth is not simply a cooling boundary layer of uniform composition and conductivity, losing heat alone through conduction (Parsons et al., 1977).

In the continental crust, the rate of increase of temperature with depth is about 30˚C/km (Brown and Mussett, 1993); some regions have a much higher gradient indicating concentrations of heat at shallow depths. Such regions have a potential for generating geothermal energy.

GEOTHERMAL STEP

This is the inverse value of the geothermal gradient Adetoyinbo (2008).

$$\text{G.step} = \frac{1}{\nabla T} = \frac{\partial H}{\partial T} \qquad \text{In km/}^{o}\text{C} \qquad \textbf{(20)}$$

THERMAL CONDUCTIVITY, K

It is the quantity of heat transmitted through a unit thickness in a direction to a surface of unit area, due to a unit temperature gradient under steady state conditions. The thermal conductivity is the property of a material that indicates its ability to conduct heat. From fourier's law for heat conduction, H:

$$H = \frac{\Delta Q}{\Delta t} = KA\frac{\Delta T}{X} \qquad \textbf{(21)}$$

Where,
Q/t = rate of heat flow
K = thermal conductivity
A = total cross sectional area of conducting surface
T = temperature difference
X = thickness of conducting surface separating the 2 temperatures

$$K = \frac{\Delta Q}{\Delta t}\frac{1}{A}\frac{X}{\Delta T} \qquad \textbf{(22)}$$

Where,

$\frac{\Delta T}{X}$ = temperature gradient

Units is W/mK

$$a = \frac{k}{\rho c} \qquad \textbf{(23)}$$

Where, a= thermal diffusivity
ρ = density of material
c= specific heat capacity

THEORY OF HEAT PRODUCTION INSIDE THE EARTH

The heat is due to radioactive heat sources that cause significant heating and temperature distribution when the crust and mantle were almost completely differentiated before 2.5 b.y. ago (Hart, 1969). The heat production due to radioactive heat sources would remelt the upper part of the Earth at a time 1 m.y. to 500 m.y. after the time commencement of solidification. Because of remelting of the upper part of the Earth the temperature and heat sources there could then be redistributed.

The choice of heat source model is difficult because of the existence of many heat producing isotopes such as U^{235}, K^{40} , U^{238}, and Th^{232} in the Earth. The value of heat production in the crust and upper mantle varies with the quantities of these elements and with their half lives. However, the chosen heat source model, based on the currently accepted amounts of those elements and on their initial heat production, has to meet the conditions that it gives a reasonable present surface heat production (of about 4.18µ W/m^3) a reasonable present surface heat flow q (of approximately 0.06 W/m^2), and an acceptable present mean crustal heat production <H>, which is about 1.8µW/m^3 (Roy et al., 1968).

The determination of the mean heat production in the crust is based on the distribution of heat sources as a function of depth. The heat source distribution used in this research is exponential and is given as:

$$H(z,t) = H_o e^{-\lambda t + z/D} \qquad \textbf{(24)}$$

Where H_o is the initial heat production, λ is the decay constant and D is a constant with the dimension depth. Lachenbruch (1968) reported that D should satisfy:

$$\int_o^\infty H(z,t)dz = A_o D \qquad \textbf{(25)}$$

If there is a linear relation between surface heat production H_o and the surface heat flow A_o, where tp is the time at present and,

$$A_o = H_o e^{-\lambda t_p} \qquad \textbf{(26)}$$

According to Keh- Gong (1971) in (1.1.9),the new temperature distribution on the homogenous crust leading to present heat production due to distribution of the radioactive heat sources can be assumed zero (initial condition of the radioactive heat source crust model)at the present stage of the solid crust.In this model, it is assumed that the present stage of the crust was reached 200 m.y. ago. This is based on the observation that there are plutons ranging in age from 80 m.y. to 145 m.y. in Sierra Nevada (Lachenbruch, 1970).

DESCRIPTION OF DATA AND MATERIAL

Much of the materials vis-a vis expression, table and models were adapted from Keh- Gong 1971.

Table 1 and some parameters:

$a = 100\ m^2/sec$
$k = 2.93 W/m^oC$
$\alpha = 0.98$

and with the assumption that the cooling crust alone will give a present uniform heat flow of 0.02 W/m^2 in the crust. Table of reference on the chosen metallic conductors from Wikkipedia comprising their density ρ, specific heat capacity c and thermal conductivity K (Appendix) was then used to find the thermal diffusivity (a):

$$a = \frac{k}{\rho c} \qquad \textbf{(23)}$$

for each chosen metallic conductor was calculated and then substituted in the simple expression for Crustal temperature at 15,18, 20, 22, and 25 km depth for t $=10^7$, 10^8, and 10^9 years.

For the heterogeneous layers, Ao =2.85 $\mu J/m^3 sec$ or $2.85 \mu W/m^3$ was obtained on the assumption that heat flow is negligible in the layer considered.

for ^{40}K,
$H'_0 = 12.99166465 \mu W/m^3$
$\equiv 409.7051364\ J/m^3\ yr$

for ^{235}U,
$H'_0 = 1.668912348\ \mu W/m^3$
$\equiv 52.63081981\ J/m^3\ yr$

for ^{238}U,
$H'_0 = 47.80666738\ \mu W/m^3$
$\equiv 1507.631265\ J/m^3\ yr$

for ^{232}Th,
$H'_0 = 73.1677714 \mu\ W/m^3$
$\equiv 2307.418839\ J/m^3\ yr$

RESULTS AND DISCUSSION

The results of the computations are presented below.

From Tables 2 and 3, the temperature calculated showed that the heat production due to U^{238} and Th^{232} significantly influences the temperature of the continental crust at the present time with higher temperature presented by the lower thermally conducting metal (lead). It can also be seen from the results that the thermally conducting metal (iron) showed the least temperature recorded.

Figures 2 and 3 shows the crustal temperature variation due to heat sources as a function of time at 15, 18, 20, 22, and 25 km depths for these metallic conductors. These follow the same pattern to that of homogeneous layer (see Appendix).

The results in Figures 4 and 5 revealed that the thermal gradient varies strongly with depth (km) and the temperature also increases with depth. This implies from the fact that the higher the thermal conductivity, K of a given metallic conductors, the lower is its thermal gradient (grad T).

In Figure 4, representing iron which has the highest thermal conductivity of 17.10, has the highest geothermal step of 0.96 $km/^oC$ shown by the slope of the graph as well as the least thermal gradient of 1.04 $^oC/km$.

Lead, with thermal conductivity of 8.41, has a thermal step of 0.44 $km/^oC$ and geothermal gradient of 2.35 $^oC/km$.

The heat flows obtained for iron and lead were: 0.069 W/m^2 and 0.081 W/m^2. These results are in agreement with the literature.

CONCLUSION

It could be inferred from this computation that heat productions are largely increased in the region of low thermal conducting metals such as Lead. This is in contrast to the lower heat flow in the high metallic conductors (iron) as depth within the continent is increased. Thus, it can be concluded that the heat flow anomaly is to be recorded in areas where these metallic conductors are present and could significantly alter the geothermal flow; a result that could be of help in proper understanding of many geophysical processes connected with the Earth's interior and also in the exploration of metallic conductors.

Table 2: Temperature Distribution in the Crust when Iron was Present at the Depths of 15-25 km.

Depth 15km					
Time (year)	Temperature ^{o}C				
	K^{40}	U^{235}	U^{238}	Th^{232}	Total
10^{7}	0.9	0.1	3.2	4.9	9.1
10^{8}	0.8	0.1	3.2	4.9	9.0
10^{9}	0.5	0.0	2.8	4.7	8.0
Depth 18km					
Time (year)	Temperature ^{o}C				
	K^{40}	U^{235}	U^{238}	Th^{232}	Total
10^{7}	1.2	0.2	4.4	6.8	12.6
10^{8}	1.1	0.1	4.4	6.8	12.4
10^{9}	0.8	0.1	3.8	6.5	11.2
Depth 20km					
Time (year)	Temperature ^{o}C				
	K^{40}	U^{235}	U^{238}	Th^{232}	Total
10^{7}	1.3	0.2	4.8	7.3	13.6
10^{8}	1.2	0.2	4.7	7.3	13.4
10^{9}	0.8	0.1	4.1	7.0	12.0
Depth 22km					
Time (year)	Temperature ^{o}C				
	K^{40}	U^{235}	U^{238}	Th^{232}	Total
10^{7}	1.7	0.2	6.1	9.3	17.3
10^{8}	1.6	0.2	6.0	9.3	17.1
10^{9}	1.0	0.1	5.2	8.9	15.2
Depth 25km					
Time (year)	Temperature ^{o}C				
	K^{40}	U^{235}	U^{238}	Th^{232}	Total
10^{7}	1.7	0.2	6.3	9.5	17.7
10^{8}	1.6	0.1	6.2	9.5	17.5
10^{9}	1.1	0.1	5.4	9.1	15.7

Table 3: Temperature Distribution in the Crust when Lead was Present at the Depths of 15-25 km.

Depth 15km					
Time (year)	Temperature °C				
	K^{40}	U^{235}	U^{238}	Th^{232}	Total
10^7	1.8	0.2	6.5	10.0	18.5
10^8	1.7	0.2	6.4	10.0	18.3
10^9	1.1	0.1	5.6	9.5	16.3
Depth 18km					
Time (year)	Temperature °C				
	K^{40}	U^{235}	U^{238}	Th^{232}	Total
10^7	2.4	0.3	9.0	13.8	25.5
10^8	2.3	0.3	8.9	13.7	25.2
10^9	1.5	0.1	7.7	13.1	22.4
Depth 20km					
Time (year)	Temperature °C				
	K^{40}	U^{235}	U^{238}	Th^{232}	Total
10^7	2.9	0.4	10.7	16.4	30.4
10^8	2.8	0.3	10.6	16.3	30.0
10^9	1.8	0.1	9.2	15.6	26.7
Depth 22km					
Time (year)	Temperature °C				
	K^{40}	U^{235}	U^{238}	Th^{232}	Total
10^7	3.4	0.4	12.4	19.0	35.2
10^8	3.2	0.4	12.2	18.9	34.7
10^9	2.1	0.2	10.6	18.1	31.0
Depth 25km					
Time (year)	Temperature °C				
	K^{40}	U^{235}	U^{238}	Th^{232}	Total
10^7	4.0	0.5	14.7	22.6	41.8
10^8	3.8	0.5	14.5	22.5	41.3
10^9	2.5	0.2	12.7	21.5	36.9

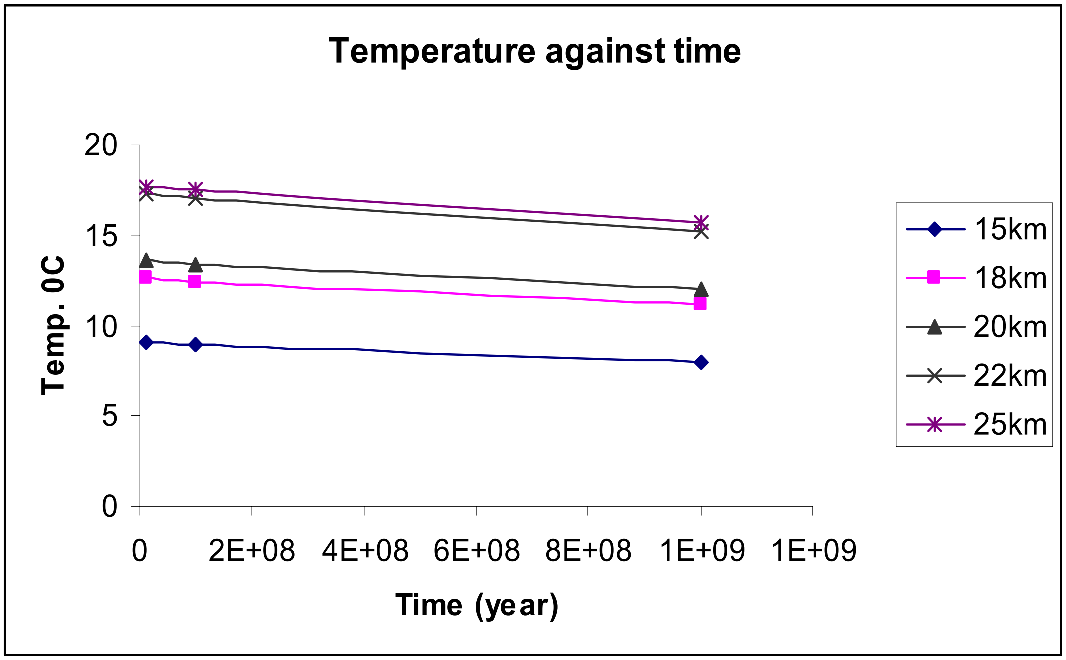

Figure 2: Variation of Crustal Temperature with Time for Iron.

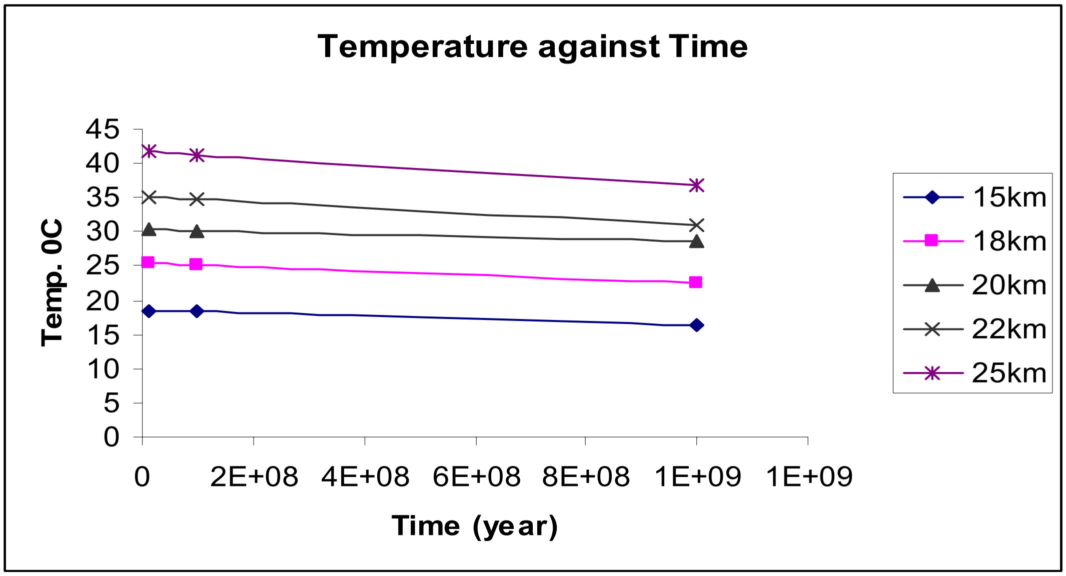

Figure 3: Variation of Crustal Temperature with Time for Lead.

Table 4: Depth (km) and Temperature (^{o}C) at 200 m.y (present time).

(a) Iron

Depth (km)	Temperature(^{o}C)
15	8.6
18	12.3
20	14.2
22	16.8
25	18.2

(b) Lead

Depth (km)	Temperature(^{o}C)
15	18.1
18	24.8
20	29.8
22	34.0
25	41.0

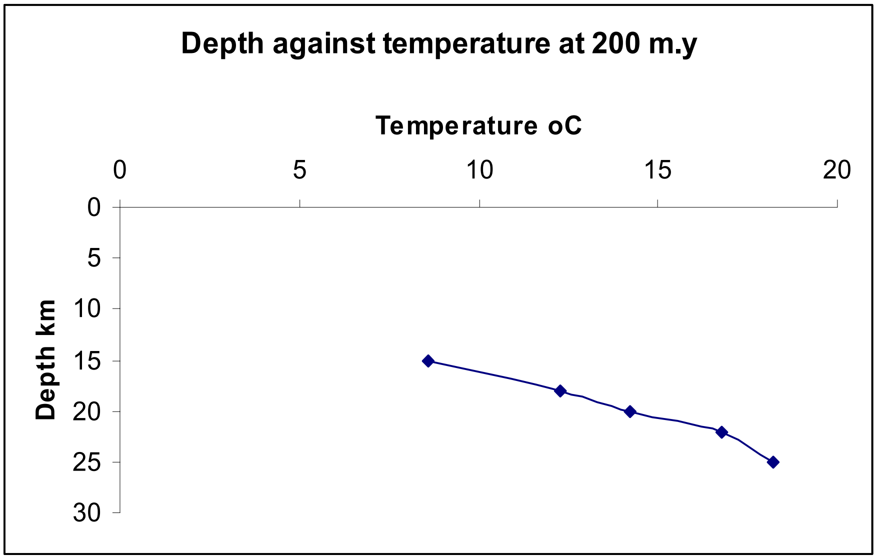

Figure 4: A Graph of Depth against Temperature for Iron at 200 m.y.

Geothermal gradient = 1.040 ^{o}C/km
Geothermal Step = 0.962 km/^{o}C

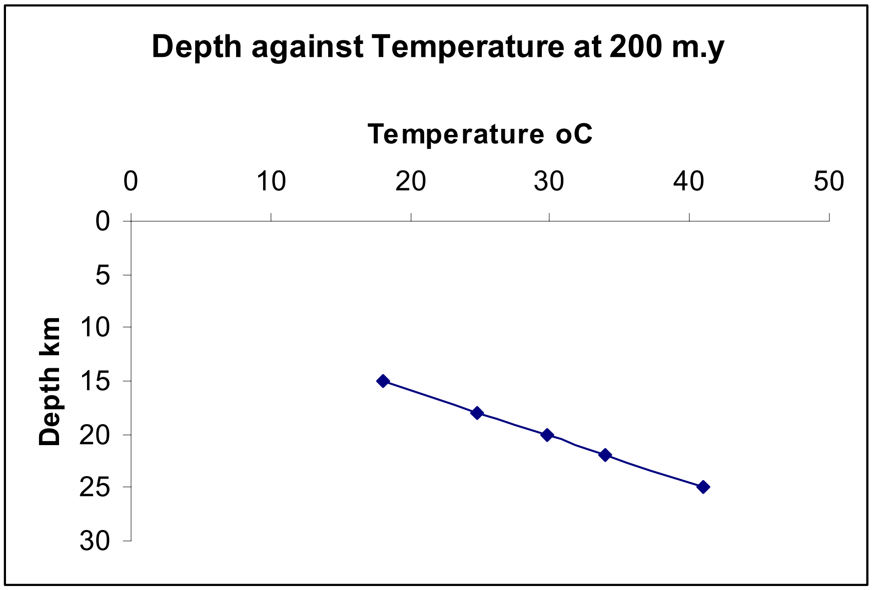

Figure 5: A Graph of Depth against Temperature for Lead at 200 m.y.

Geothermal gradient = 0.436 oC/km
Geothermal Step = 2.290 km/oC

RECOMMENDATION

Since the temperature distributions in the continental crust varied due to the presence of metallic conductor, it is therefore recommended that this method can be used to detect or explore the presence of minerals in the crust. This can be achieved by comparing the modeled temperature distribution with the measured temperature in the location being considered.

It is very advisable to use this method to detect or explore minerals that do not contain radioactive elements like uranium, and thorium. This is because these elements contribute immensely to the heat production in the continental crust.The use of geothermal parameters will be invaluable in the new field of Thermolog, obtaining of indirect information much better than the limited bore-hole logging will be possible in addition to proper understanding of many geophysical processes connected with the Earth's interior.

APPENDIX

Table of Density, Specific Heat, Thermal Conductivity, and Thermal Diffusivity of Iron and Lead.

Material	**ρ (kg m^{-3})**	**C (kJ/kgk)**	**C (cal/kg°C)**	**K/W $m^{-1o}C^{-1}$**	**Kx0.2381/$cal^{-1}m^{-1}sec^{-1o}C^{-1}$**	**K/Calmyr °C**	**a (m^2/yr)**
Pure Iron	7800	0.480	114.72	71.8	17.10	$5.393x10^8$	602.66
Lead	1130	0.127	30.35	35.3	8.41	$2.652x10^8$	7733.31

REFERENCES

1. Adetoyinbo, A.A. 2008. "Geo, Gravity and Figure of the Earth". Lecture Notes on Physics 715 for M.Sc. Students 2007/2008 Session. Department of Physics, University of Ibadan: Ibadan, Nigeria.

2. Akiko, T. and Ishikawa, Y. 2002. "Temperature Distribution and Focal Depth in the Crust of the Northeastern Japan". *Earth Planets Space*. 54: 1109-1113.

3. Anderson. CUVK615B. 2007. "The Thermal History of the Earth". P1: RNK1 HAF P2: RNK (pdf).

4. Anuta, J. 2006. "Probing Question: What Heats the Earth's Core". *Physorg.com*. Retrieved 2007.

5. Brace, W.F., Orange, A.S., and Madden, T.M. 1965. "The Effect of Pressure on the Electrical Resistivity of Water Saturated Crystalline Rocks". *Journal of Geophysical Research*. 70:5669 - 5678.

6. Brown, G.C. and Musset, A.E. 1993. *The Inaccessible Earth (2nd ed.)*. Chapman and Hall: London, UK.

7. Carlaw, H.S. and Jaeger, J.C. 1959. *Conduction of Heat in Solids*. Clarendon Press: Oxford, UK. 510.

8. Chapman, D.S. 1986. *Thermal Gradients in the Continental Crust.* Geological Society: London, UK. 24: 63-70.

9. Clark, S.P. 1961. *Temperature in the Crust in the Temperature: Its Measurements and Control in Science and in Industry*. Herzfeld C.M. (editor). Part 1. Reinhold Publishing Corporation: New York, NY.

10. David, D.B. 1971. *The Thermal Structure of the Continental Crust.* Geophysical Monograph 14. 169-184.

11. Dennemeyer, R. 1968. *Introduction to Partial Differential Equations and Boundary Value Problems*. McGraw-Hill: New York, NY. 376.

12. Don, L.A. 2005. "Energetics of the Earth and the Missing Heat Source Mystery:. *www.plumes.org.*

13. Frank, K. and Goswani, D.Y. 2008. *Handbook of Heat pumps, Energy Management and Conservation*. 9-3.

14. Hart, S.R. 1968. *Isotope Geochemistry of Crust. Mantle Processes in the Earth's Crust and Upper Mantle*. American Geophysical Union: Washington, D.C.

15. Herndon, J.M. 2001. "Thermodynamics from First Principles: Temperature and Composition of the Earth's Core". *PNAS*. 98(20):11085-11090.

16. Jacobs, J.A. 1956. "Interior of the Earth". *Advances of Geophysics*. III:183 -239.

17. Jacobs, J.A. and Allen, D.W. 1954. "Temperatures and Heat Flow Within the Earth". *Trans. Roy. Soc. Can*. 48:33-39.

18. Keh-Gong, S. 1971. "Temperature Production in the Continental Crust due to Radioactive Heat Sources". *Journal of Geophysical Research*. 90:115-124.

19. Kutasov, I.M. and Eppelbaum, L.V. 2009. "Estimation of Geothermal Gradients from Single Temperature Log Field Cases". *Journal of Geophysical Engineering (IOP) e- journals*.

20. Lachenbruch, A.H. 1968. "Preliminary Geothermal Model of Sierra Nevada". *Journal of Geophysical Research*. 73(22):6977-6989.

21. Lachenbruch, A.H. 1970. "Crustal Temperature and Heat Production: Implications of the Linear-Heat Flow Relation". *Journal of Geophysical Research*. 75:3291-3300.

22. Macdonald, G.J.F. 1961. "Surface Heat from a Differentiated Earth". *Journal of Geophysical Resources*. 66:2489 -2493.

23. Majorowicz, J.A, Jones, F.W. and Ertman, M.E. 1989. "Model of Terrestrial Thermal Effects in the Area of the Crustal Electrical Conductors of the Willston Basin". *Canadian Journal of Exploration Geophysics*. 25(1):45- 49.

24. MSN. 2008. *Encarta*. Microsoft Company: Redmond, WA.

25. Parsons, B. and Sclater, J.G. 1977. "An Analysis of the Variation of the Ocean Floor Bathymetry and Heat Flow with Age". *Journal of Geophysical Research*. 82:803-827.

26. Rao, R.U.M and Rao G.V. 1982. "Heat Flow in Indian Gondwana Basins and Heat Production of their Measurement Rocks". *Tectonophysics*. 91: 105 – 117.

27. Roy, R.F., Blackwell, D.D., Decker E.R., and Birch, F. 1968. "Heat Generation of Plutonics Rocks and Continental Heat Flow Provinces". *Earth and Planetary Science Letter.* 5:1- 12.

28. Sarkar, R.K. and Singh, Om.P. 2005. "A Note on the Heat Flow Studies at Sohagpur and Ranigary Coal Field Areas India". *Acta Geophysical Polonica*. 53(2):197-204.

29. Schubert, G., Turcotte, D., and Olson, P. 2001. *Mantle Convection in the Earth and Planets*. C.U. Press.

30. Tanaka, A., Yano, Y., Sasada, M., Umeda K., Nakatsuka, N., and Akita, F. 1999. “Compilation of Thermal Gradient Data in Japan on the Basis of Temperatures in Boreholes”. *Bulletin Geological Survey Japan*. 50:457-487.

31. Ya, K.E. 2000. “Variation of Geothermal Parameters within Local and Regional Geological Structures”. *Journal of Georesources*. 2(2):45-46.

32. Ya, K.E., Stanin, A.V., and Gavrilov, A.G. 2005. “Hydrogeological and Geothermal Parameters of Rocks by Temperature Measurements”. *Proceeding World Geothermal Congress*..

33. Yano, Y., Tanaka, A.,Takahashi, M., Okubo, Y., Sasada, M., Umeda, K., and Nakatsuka, N. 1999. “Geothermal Gradient Map of Japan”. Geological Survey of Japan: Tokyo, Japan.

SUGGESTED CITATION

Popoola, O.I. and N.O. Salaudeen. 2011. “Effects of Metallic Conductors on Crustal Heat Flow Parameters”. *Pacific Journal of Science and Technology*. 12(1):403-418.

Pacific Journal of Science and Technology