

Effects of Poor Conductors on Continental Crustal Heat Flow Parameters.

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ABSTRACT

The purpose of this study was to compute the anomaly in the crustal heat flow parameters resulting from the presence of certain poor conductors at designated depths within the continental crust. The poor conductors considered for this study were hydrocarbons and coal. The depths considered were between 15-25 kilometres, and in this case only conduction as a means of heat transfer was considered. The computation was achieved by using the time-dependent Green's function and the radioactive heat source distribution equation to obtain simple expression for crustal temperature. JAVA Program was used for the computation and it was deduced from the computed results that ^{238}U and ^{232}Th were the major sources of heat in the continental crust.

The results obtained for the temperature distributions were plotted against the years. This helped in getting the temperature distributions at 200 m.y. at different depths. The depths considered were also plotted against the temperature at 200 m.y. This helped in calculating the geothermal gradient of the crust within which the poor conductor was lying. The geothermal gradient obtained for hydrocarbons and coal were: $98.3^{\circ}\text{C}/\text{km}$ and $50^{\circ}\text{C}/\text{km}$ respectively. Their respective heat flows were $0.0141\text{W}/\text{m}^2$ and $0.015\text{W}/\text{m}^2$, and the values of heat flow obtained from the results are in line with that of heat flow in the moho-discontinuity which ranges from $0.0167\text{W}/\text{m}^2$ to $0.0335\text{W}/\text{m}^2$. And it can also be seen from the results that the thermal conductivity of the material played a major role in the temperature distributions in the crust.

(Keywords: thermal conductivity, thermal diffusivity, thermal gradient, heat flow, temperature, ^{238}U , ^{232}Th , radioactive heat sources, poor conductors, petroleum, hydrocarbons, coal)

INTRODUCTION

Temperature plays an important role in shaping the lithospheric deformation by the way of influencing the mechanical properties of the rocks. In the continental crust, the temperature distribution depends on two factors; the heat supplied from the earth's interior, and the radioactive heat sources present in the crust. The radioactive heat sources contribute to about 40% (Smithson and Decker, 1974, Smithson and Brown, 1977) of surface heat flow in the continental regions making this an important element in determining the crustal temperature distribution.

Measurement of the concentration of these sources, however, is limited only to very shallow depth due to practical limitations. In the absence of indirect measurements, various models for the depths distribution of radioactive heat sources distribution have been proposed (Birch et al., 1968; Lanchenbruch, 1970; Lanchenbruch and Bunder, 1971.). Of these, exponential and constant distribution models have gained more importance. These models also satisfy the empirical relationship between surface heat flow and surface radioactive heat generation proposed by Birch et al. (1968).

Heat within the Earth

In the continental crust, temperature distribution depends on mainly two factors; the heat supplied from the Earth's interior and the radioactive heat sources present in the crust. The radioactive heat source contributes to about 40% of the surface heat flow in the continental regions making it important elements in determining the crustal temperature distribution.

Heat generation is not uniform within the crust, either. It is greatest in rocks of the granite family, in which the incompatible elements are most highly enriched (Heier, 1973; Smithson and Decker, 1974). This means that the rate of heat generation is greatest in the upper part of the continental crust, where granites are most abundant, and decreases with depth, so that the 35°C/km geothermal gradient applies only to the upper crust. Oceanic crust which basaltic in composition is even poorer in uranium, potassium and thorium, so volume for volume, less heat is produced there even than in the lower part of the continental crust. Once into the mantle the geothermal gradient decreases again because the mantle is even poorer in heating-producing isotopes.

Heat flow outward from the interior of the earth, and most of the heat generated at present results from decay of long-lived radioactive isotopes especially of the elements: uranium, potassium and thorium. Early on (greater than four billion years ago), some of the heat may have decay of short-lived isotopes, meteorites impacts, and gravitational compaction. As potassium, thorium, and uranium are concentrated in the upper continental crust, the heat produced by their decay accounts for some large percentage of the average continental heat flow. In contrast, heat flow within the oceanic regions comes from the mantle.

Temperature Distribution in the Crust

Heat is transferred through the upper layers mainly by conduction; only small part of the heat is transported by advection like volcanism and fluid circulations. The temperature distribution in the upper layers can be determined with information about the heat flow from the underlying convecting mantle, the distribution of radioactive elements, the surface temperature, and the thermal conductivity. All of these parameters can vary with time and location, commonly, the thermal conductivity is treated as a constant bulk property in order to derive the depth of water ice layers (Squyres, et al., 1992), to constrain the surface heat flow as function of time (Zuber et al., Solomon and Head, 1990) and to calculate the thermal evolution (Schubert et al., 1992; Spohn, 2002). This simplified view neglects that the thermal conductivity is a highly variable parameter that depends on the temperature.

Lateral variations in the thermal conductivity due to variation in the crustal thickness, in the regolith layers (i.e., variation in its thickness, structure, and composition), and in the mantle heat flow are also expected and may strongly influence the temperature distribution.

Thermal Conductivity, Thermal Diffusivity, and Thermal Capacity

In calculating temperature distribution in the crust, thermal conductivity is assumed to have a constant value in the range of 2 to 4W/m°C. This approximation is appropriate as long as only solid crust is considered. Variations in porosity and structure of the crust lead to changes in thermal conductivity of several orders of magnitude. Thermal conductivity is not only influenced by porosity but also by pressure and temperature. And when the thermal conductivity is lower the temperature will be higher and vice-versa.

The thermal capacity is the product of density ρ and the specific heat capacity c , the specific heat capacity at constant pressure was determine as a function of temperature. Thermal diffusivity describes the equilibration of a temperature imbalance. It is the function of the thermal conductivity k , density ρ and specific heat capacity c at constant temperature. The equation below showed the relationship between the thermal conductivity, thermal diffusivity and the thermal capacity.

$$a = k/c.\rho$$

Where, k is the thermal conductivity,
 a is the thermal diffusivity,
 c is the specific heat capacity and
 ρ is the density

Geothermal Gradient

The geothermal gradient is the rate of increase in the temperature per unit depth in the Earth. It varies with location and is typically measured by determining the bottom open-hole temperature after borehole drilling or on the sea floor by dropping specially designed probes into the mud.

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.

If the rate of temperature change were constant, temperature deep in the earth would soon reach the point where all known rocks would melt (Stacy and Frank, 1977). We know, however, that the earth's mantle is solid because it transmits S-waves. The temperature gradient dramatically decreases with depth for two reasons. First, radioactive heat production is concentrated within the crust of the Earth, and particularly within the upper part of the crust, as concentration of uranium, thorium, and potassium are highest there: these three elements are the main producers of radioactive heat within the earth.

Secondly, the mechanism of thermal transport changes from conduction, as within the rigid tectonic plates, to convection, in the portion of Earth's mantle that convects. Despite its solidity, most of the earth's mantle behaves over long time-scales as a fluid, and heat is transported by advection, or material transport.

On the hand, temperature increase with depth creates a problem in deep mines; in such a case the drill bits have to be cooled not only because of the friction created by the process of the drilling itself but also because of the heat of the surrounding rock at great depth. Very deep mines, like some gold mines in South Africa, need the air inside to be cooled and circulated to allow miners to work at such great depth. High temperatures at depth also complicate the drilling of oil wells.

METHODOLOGY

Heat Source Distribution

The value of heat production in the crust and the upper mantle varies with quantities of ^{235}U , ^{238}U , ^{40}K , and ^{232}Th and with their half-lives. The initial (4.5 b.y. 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). The half-lives of these four elements were taken from a table given by Hart, 1969. Table 1.0 gives a present surface heat production of about $3.41\mu\text{W}/\text{m}^3$

Table 1: Radioactive Heat Production in the Continental Crust.

Elements	Surface Heat Production ($\mu\text{W}/\text{m}^3$)		Half-Life (b.y.)
	Initial	Present	
^{40}K	4.12	0.35	1.470
^{235}U	3.89	0.05	0.713
^{238}U	3.03	1.52	4.510
^{232}Th	1.88	1.49	13.900

(Jacobs, 1956; Hart, 1969)

The determination of 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 work is exponential and is given as:

$$H(z, t) = H_0 e^{-(\lambda t + z/D)} \quad (1)$$

Where H_0 is the initial heat production, λ is the decay constant and D is a constant with the dimension depth. According to Lachenbruch, 1968, he mentioned that D should satisfy:

$$\int_0^{\infty} H(z, t_p) dz = A_0 D \quad (2)$$

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

$$A_0 = H_0 e^{-\lambda t_p} \quad (3)$$

and the linear relation between surface heat flow and present surface heat production is given as:

$$q = q_0 + D A_0 \quad (4)$$

where; q_0 is the constant heat flow for the cooling model of the earth, q is the surface heat flow, and $D A_0$ is the present heat production.

Boundary Conditions

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 may be

neglected, and the problem may be treated as one-dimensional 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. Thus the equation may be written as:

$$\rho c \frac{\partial T}{\partial t} = \frac{\partial}{\partial z} \left(K \frac{\partial T}{\partial z} \right) + H(z, t) \quad (5)$$

where $H(z, t)$ is the rate of heat production by radioactive decay per unit time per unit volume, c is the specific heat, K is the thermal conductivity, and ρ is the density. In order to get a simple expression, it will be assumed that ρ , c , and K are constants and the crust is a simple homogeneous layer. The first boundary condition and the initial condition are respectively,

$$T = 0, z = 0, t > 0 \quad (6)$$

$$T = T_0(z), t = 0, h \geq z \geq 0 \quad (7)$$

where $t = 0$ is the time of crustal solidification.

A second boundary condition is required for solving one-dimensional layer problems. The choice of this boundary condition is difficult. In MacDonald's spherical mantle model (MacDonald, 1965) a zero flux boundary is used over a surface of 1500km. This implies that additional radioactivity can be buried at a depth deeper than 1500km without perturbing the surface condition.

Since the paper is based on near-surface temperature which depends only on lattice conductivity of the solid crust and the near-surface distribution of heat sources, the zero flux boundary condition for 1500km depth seems unreasonable. Another approach is to get solutions by leaving the bottom boundary open; but the flux through the bottom boundary is assumed to always be positive. However, the solutions must provide surface heat flow values and the temperature values within the present assumed limits for moho-discontinuity. A solution based on the latter assumption is discussed below; the boundary condition is written as:

$$q = f(t), t > 0, z = h \quad (8)$$

where $f(t)$ are an undefined function and the h is the depth to the bottom boundary.

For simplicity, Equation (5) will be separated into two parts. Let $T = T_1 + T_2$, then Equation (5) and its boundary conditions and its initial condition can be expressed as;

$$\frac{\partial T_1}{\partial t} = a \frac{\partial^2 T_1}{\partial z^2} \quad (9)$$

$$\text{with } \begin{matrix} T_1 = 0 & z = 0, & t > 0 \\ T_1 = T_0(z) & t = 0, & h \geq z \geq 0 \end{matrix}$$

and

$$\frac{\partial T_2}{\partial t} = a \frac{\partial^2 T_2}{\partial z^2} + \frac{H(z, t)}{\rho c} \quad (10)$$

with

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

where $a = K / \rho c$ the thermal diffusivity and $g(t)$ is any function.

Equation (9) 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:

$$T_1 = T_0(z) \operatorname{erf} \frac{z}{2\sqrt{at}} \quad (11)$$

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. The solution to Equation (10) 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 (Denne Meyer, 1968). In this case, T_2 is expressed as

$$T_2 = \sum_{n=0}^{\infty} \int_0^h \int_0^t \frac{U_n(z) U_n(z')}{|U_n|^2} H(z', \tau) e^{-k_n^2 a (t-\tau)} dz' d\tau \quad (12)$$

U_n is the solution of the eigenvalue problem:

$$\frac{d^2 U_n}{dz^2} + k_n^2 U_n = 0 \quad (13)$$

$$\text{with} \quad \begin{aligned} U_n &= 0 & z &= 0 \\ U_n &= \alpha B & z &= h \end{aligned}$$

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

Temperature in the Crust

To obtain a simple expression for the computation of the crustal temperature distribution as a function of time and depth, the radioactive heat sources distribution given in (1) will be used. Inserting (1) into (12), the temperature production due to radioactive heat sources is given as

$$T_2 = \frac{2H_0' h^2}{K} \sum_{n=0}^{\infty} C_n \left[e^{-\lambda t} - e^{-(2n\pi + \beta)^2 a t / h^2} \right] \sin \frac{(2n\pi + \beta) z}{h} \quad (14)$$

where

$$C_n = \frac{(2n\pi + \beta) \left[1 - \sqrt{1 - \alpha^2} e^{-h/D} \right] - \frac{h}{D} \alpha e^{-h/D}}{\left[(2n\pi + \beta) - \frac{\lambda h^2}{a} \right] \left[\left(\frac{h}{D} \right)^2 + (2n\pi + \beta)^2 \right] \left[1 - \frac{2\alpha \sqrt{1 - \alpha^2}}{2n\pi + \beta} \right]} \quad (15)$$

$$\text{With } \beta = \sin^{-1} \alpha, \quad (16a)$$

$$H_0' = H_0 e^{-\lambda t^1} \quad (16b)$$

which is the initial surface heat production at the moment of redistribution of heat sources, $t^1 = 0$ at 4.5 b.y. ago, $\alpha = 0.98$. The initial and present heat productions of four radioactive elements are given in table 1.0. The total present surface heat A_0 is $3.41 \mu\text{W}/\text{m}^3$, the decay constant of each elements can be determined by:

$$\lambda = 0.693 / L \quad (17)$$

where L is the half-life.

The value of D controls the heat source distribution as a function of depth. From Equation (1), it can be seen that present heat source distribution is described as:

$$H(z, t_p) = A_0 e^{-z/D} \quad (18)$$

The values of D and A_0 used in the model computational give an acceptable surface heat flow and present mean crustal heat production. Three pairs of D and A_0 values are given in the Table 2. The values of A_0 in Table 2 are estimated from the present surface heat production for each element given in table; $D A_0$ is related to the present surface heat flow and $\langle H \rangle$ is the mean heat production between 0-30km where h is assumed to be 30km in the computation.

Table 2: Present Surface and Mean Heat Production in the Continental Crust.

D (km)	A_0 ($\mu\text{W}/\text{m}^3$)	DA_0 (W/m^2)	$\langle H \rangle$ ($\mu\text{W}/\text{m}^3$)
10	6.82	0.0682	2.18
20	3.43	0.0686	1.76
30	2.26	0.0678	1.42

Method of Computation

In this work, it was assumed that the poor conductors are embedded in the depths 15-25 kilometres in the crust. The poor conductors considered were hydrocarbons and coal. In order to get numerical results for the temperature distribution in the crust, the model assumes that the present stage of the crust was reached 200 m.y. ago (that is, it was assumed that $t = 0$ represents 200 m.y. ago and $t = 200$ m.y. represents the present). And the case considered was for $t^1 = 4.3$ b.y. which is the initial time and it is defined as the time of redistribution of heat sources at 200 m.y. (Keh-Goh Shih, 1971).

A_0 was obtained to be $2.8 \mu\text{W}/\text{m}^3$ provided that heat production within the poor conductor is negligible.

Parameters used for computation are $\alpha = 0.98$, $t = 10^7, 10^8, 10^9$ years and the one given in table 3.0 below. The computation of crustal temperature T_2 was carried out using JAVA program; see appendix B and C for the flowchart and the program respectively.

The temperature distributions due to the effects of poor conductors as function of time at 15-25km depths; see Appendix A, and their heat flows are given in the results.

Table 3: Characteristics of Target Materials.

	Hydrocarbons	Coal
Thermal conductivity, K (W/m ⁰ C)	0.15	0.3
Thermal diffusivity, a (m ² /s)	9.35E-8	1.43E-7
Density, ρ (Kg/m ³)	720	1510
Specific heat capacity, c (J/kg. ⁰ C ⁻¹)	2219.97	1379.98

www.en.wikipedia.org/wiki/list_of_thermal_conductivities.html,
www.zyra.org.uk/denslist.htm

RESULTS

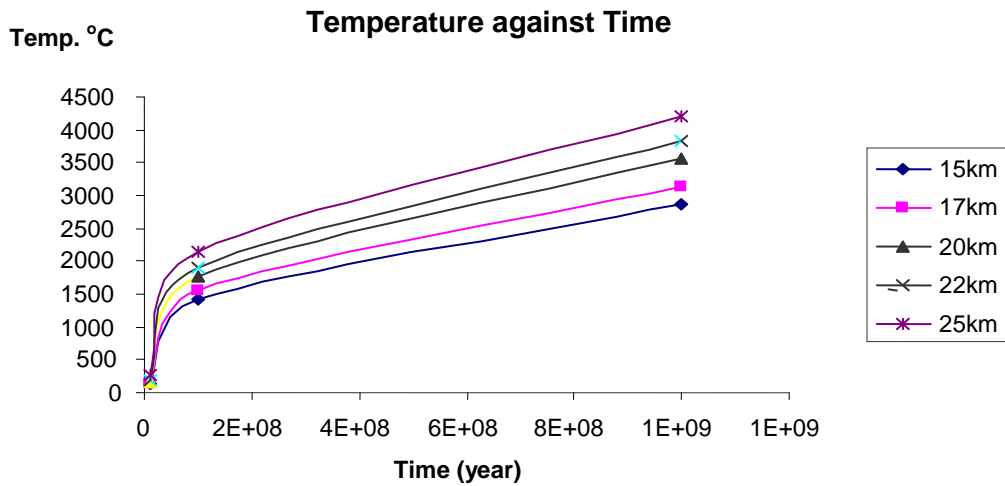


Figure 1: Variation of Crustal temperature with time for Hydrocarbons.

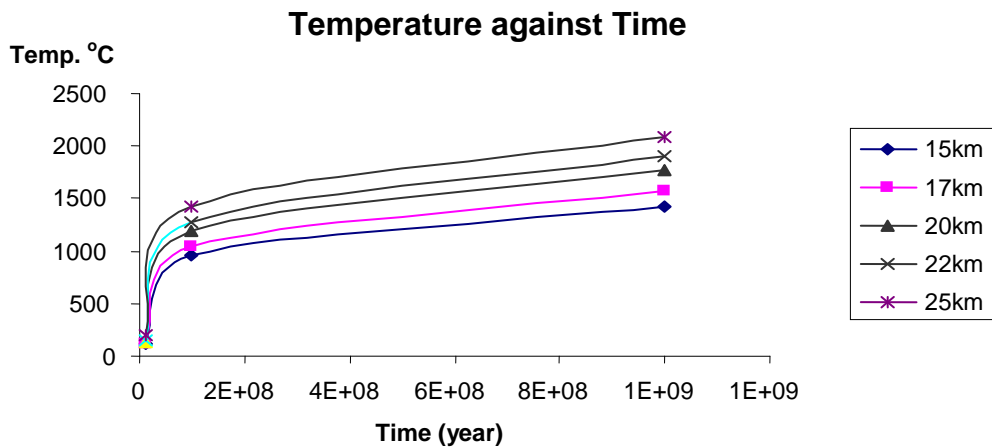


Figure 2: Variation of Crustal Temperature with Time for Coal.

Table 4: Temperature Distribution with Hydrocarbon at 200 m.y.

DEPTH (km)	TEMPERATURE (o C)
15	1500
17	1750
20	2000
22	2200
25	2500

Table 5: Temperature Distribution with Coal at 200 m.y.

DEPTH (km)	TEMPERATURE (o C)
15	1000
17	1100
20	1250
22	1350
25	1500

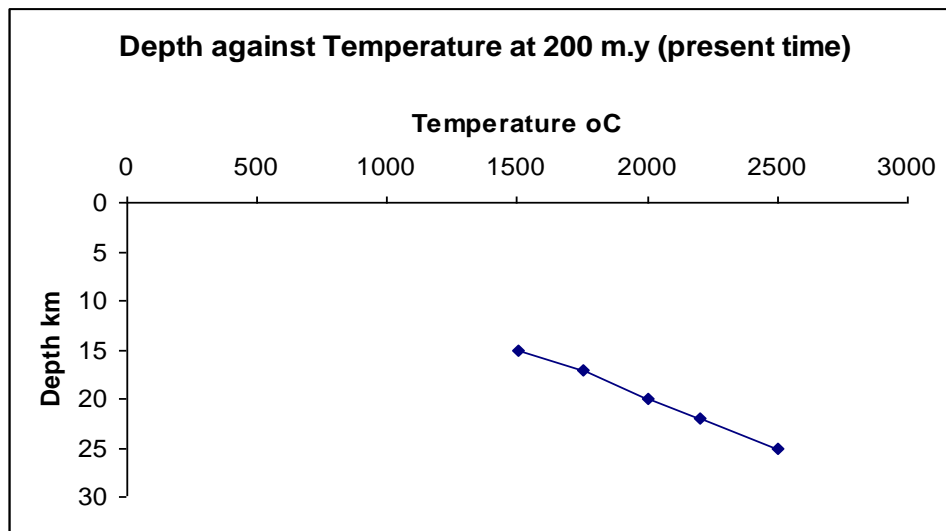


Figure 3: A Graph of Depth against Temperature for Hydrocarbons.

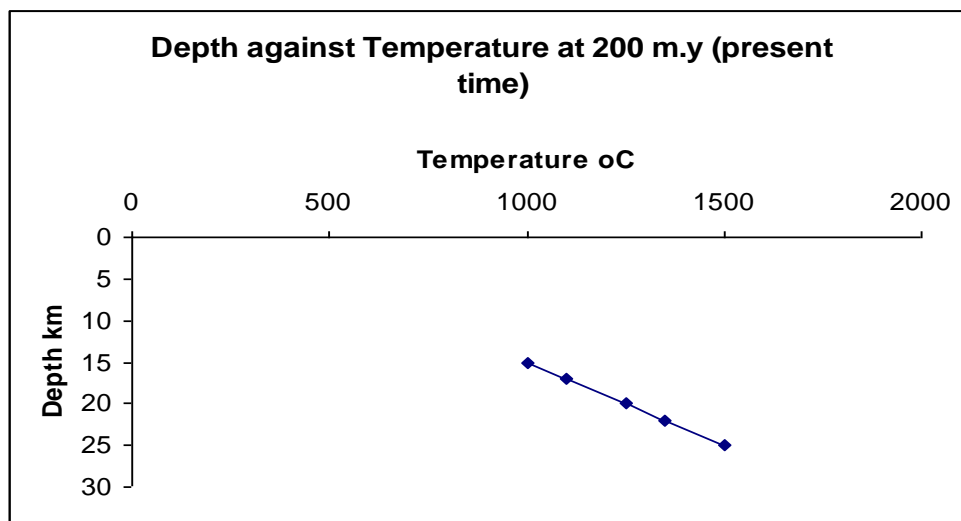


Figure 4: A Graph of Depth against Temperature for Coal.

DISCUSSIONS

The computations were carried out using a JAVA program. In order to get numerical results it was assumed that the present stage of the crust was reached 200 m.y. ago. Therefore, $t=0$ represents 200 m.y. ago and $t = 200$ m.y. represents the present. And the case considered was for $t' = 4.3$ b.y. which is the initial time and it is defined as the time of redistribution of heat sources at 200 m.y. The in appendix A show the computed temperature variations due to heat sources as function of time at 15, 17, 20, 22, and 25 km depths in the continental crust. The differences in the temperature were due to the effect of the thermal conductivities of the materials being considered at the same depth.

Figures 1-2 show the relationship between the crustal temperature and the year, which is line with that of homogeneous layer (see Appendix D). The temperatures at 200 m.y. were obtained at various depths from the graphs of temperature against time in Figures 1-2. And the graphs of depth against the temperature at 200 m.y. (present time) are shown in the Figures 3-4 and the geothermal gradient obtained for hydrocarbons and coals are: $93.8^{\circ}\text{C}/\text{km}$ and $50^{\circ}\text{C}/\text{km}$, respectively. These results were in agreement with the geothermal gradient measured from the boreholes and mines which the average ranges from $8^{\circ}\text{C}/\text{km}$ to $65^{\circ}\text{C}/\text{km}$. Their respective heat flows were: $0.0141\text{W}/\text{m}^2$ and $0.015\text{W}/\text{m}^2$.

CONCLUSIONS

Expression (14) used for computing the temperature distribution due to the poor conductor in the continental crust is shown to give a reasonable result as that of temperature production in the continental crust due to radioactive heat sources by Keh-Gong Shih, 1971.

The effects of each of radioactive elements on temperature distribution as a function of time at 15-25km depths are given in the Tables 3 and 4 (see Appendix A). It can be seen that the ^{238}U and ^{232}Th played the major role in influencing the temperature distributions. There was an increase in the temperature distribution in the crust because only conduction as a means of heat transfer was considered.

From the computed results, it can also be seen that the temperature distribution varied at the same depth within the continental crust. This was due to the differences in the thermal conductivities and the densities of the poor conductors present.

The geothermal gradient calculated for hydrocarbons and coal were: $93.8^{\circ}\text{C}/\text{km}$ and $50^{\circ}\text{C}/\text{km}$, respectively and their respective heat flows were: $0.0141\text{W}/\text{m}^2$ and $0.015\text{W}/\text{m}^2$.

The values of heat flow obtained from the results are in line with that of heat flow in the moho-discontinuity which ranges from $0.0167\text{W}/\text{m}^2$ to $0.0335\text{W}/\text{m}^2$ (Roy et al, 1968 and Hyndman et al, 1967).

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. And from this it can be inferred that region with low thermal conductivity will have high temperature and vice-versa. And at the same time, region with low thermal conductivity will have low heat flow and reverse is the case.

ACKNOWLEDGEMENTS

This paper is based on ideas developed by Keh-Gong Shih, 1971 on Temperature Production in the Continental Crust due to Radioactive Heat Sources.

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APPENDIX A

Table 6: Temperature Distribution in the Crust with Hydrocarbons at Depths 15-25 kilometres.

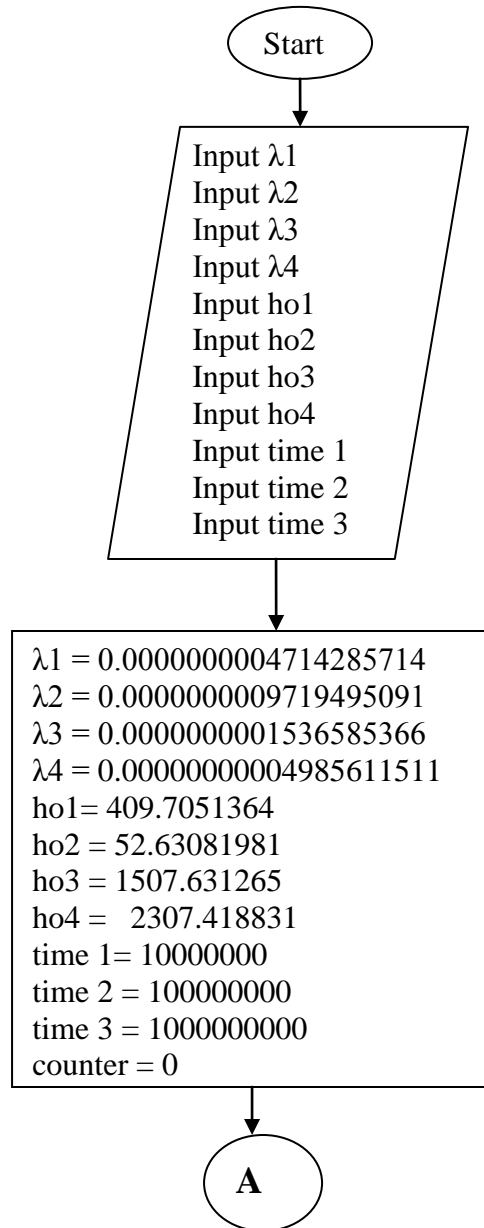
Depth 15km					
Time (year)	Temperature °C				
	K ⁴⁰	U ²³⁵	U ²³⁸	Th ²³²	Total
10 ⁷	13.3	1.7	49.0	75.0	139.0
10 ⁸	134.2	16.8	502.2	772.9	1426.1
10 ⁹	207.1	17.7	991.6	1654.9	2871.3
Depth 17km					
Time (year)	Temperature °C				
	K ⁴⁰	U ²³⁵	U ²³⁸	Th ²³²	Total
10 ⁷	12.9	1.7	47.7	73.1	135.4
10 ⁸	146.6	18.3	548.3	843.8	1557.0
10 ⁹	228.0	19.5	1096.3	1801.1	3144.9
Depth 20km					
Time (year)	Temperature °C				
	K ⁴⁰	U ²³⁵	U ²³⁸	Th ²³²	Total
10 ⁷	14.6	1.9	53.9	82.5	152.9
10 ⁸	165.8	20.7	620.2	954.4	1761.1
10 ⁹	257.7	22.0	1233.5	2058.4	3571.6
Depth 22km					
Time (year)	Temperature °C				
	K ⁴⁰	U ²³⁵	U ²³⁸	Th ²³²	Total
10 ⁷	17.0	2.4	65.3	99.9	184.6
10 ⁸	179.4	22.4	671.3	1033.1	1906.2
10 ⁹	276.5	23.6	1323.9	2209.4	3833.4
Depth 25km					
Time (year)	Temperature °C				
	K ⁴⁰	U ²³⁵	U ²³⁸	Th ²³²	Total
10 ⁷	22.5	3.3	94.1	144.0	263.9
10 ⁸	200.7	25.1	751.5	1156.7	2134.0
10 ⁹	302.8	25.8	1450.9	2422.2	4201.7

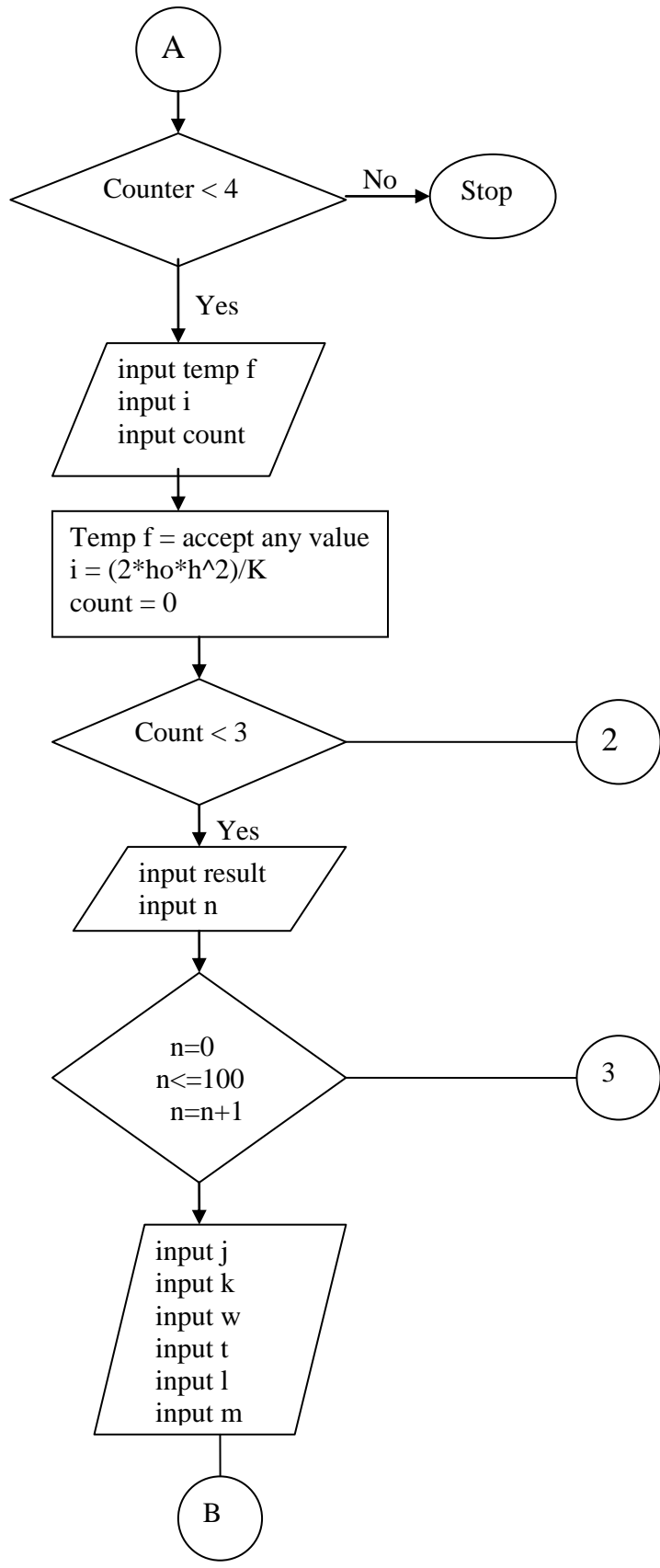
Table 7: Temperature distribution in the crust with coal at depths 15-25 kilometres

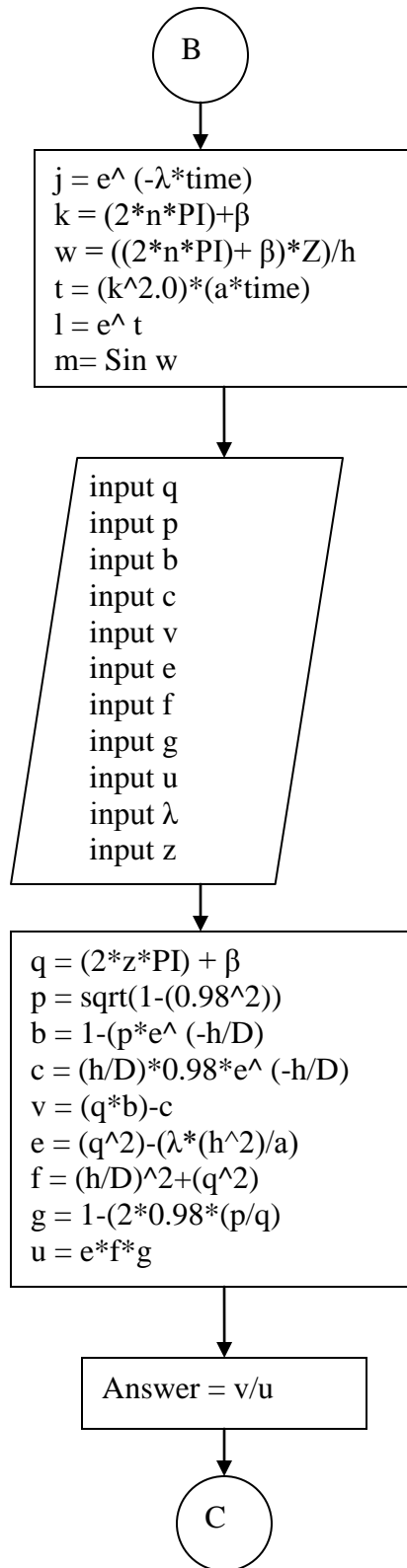
Depth 15km					
Time (year)	Temperature °C				
	K ⁴⁰	U ²³⁵	U ²³⁸	Th ²³²	Total
10 ⁷	11.0	1.4	40.7	62.4	115.5
10 ⁸	90.1	11.3	337.6	519.7	958.7
10 ⁹	100.9	8.3	492.5	826.9	1428.6
Depth 17km					
Time (year)	Temperature °C				
	K ⁴⁰	U ²³⁵	U ²³⁸	Th ²³²	Total
10 ⁷	11.2	1.4	41.1	63.4	117.1
10 ⁸	98.8	12.3	369.9	569.5	1050.5
10 ⁹	111.1	9.2	542.0	909.9	1572.2
Depth 20km					
Time (year)	Temperature °C				
	K ⁴⁰	U ²³⁵	U ²³⁸	Th ²³²	Total
10 ⁷	12.7	1.6	47.0	71.9	133.2
10 ⁸	111.7	14.0	418.3	643.9	1187.9
10 ⁹	125.6	10.4	612.7	1028.5	1777.2
Depth 22km					
Time (year)	Temperature °C				
	K ⁴⁰	U ²³⁵	U ²³⁸	Th ²³²	Total
10 ⁷	14.9	1.9	54.7	83.8	155.3
10 ⁸	120.4	15.0	451.0	694.2	1280.6
10 ⁹	134.7	11.1	657.6	1103.9	1907.3
Depth 25km					
Time (year)	Temperature °C				
	K ⁴⁰	U ²³⁵	U ²³⁸	Th ²³²	Total
10 ⁷	19.6	2.5	72.4	110.9	205.4
10 ⁸	133.4	16.7	500.0	769.8	1419.9
10 ⁹	147.6	12.2	720.8	1210.2	2090.8

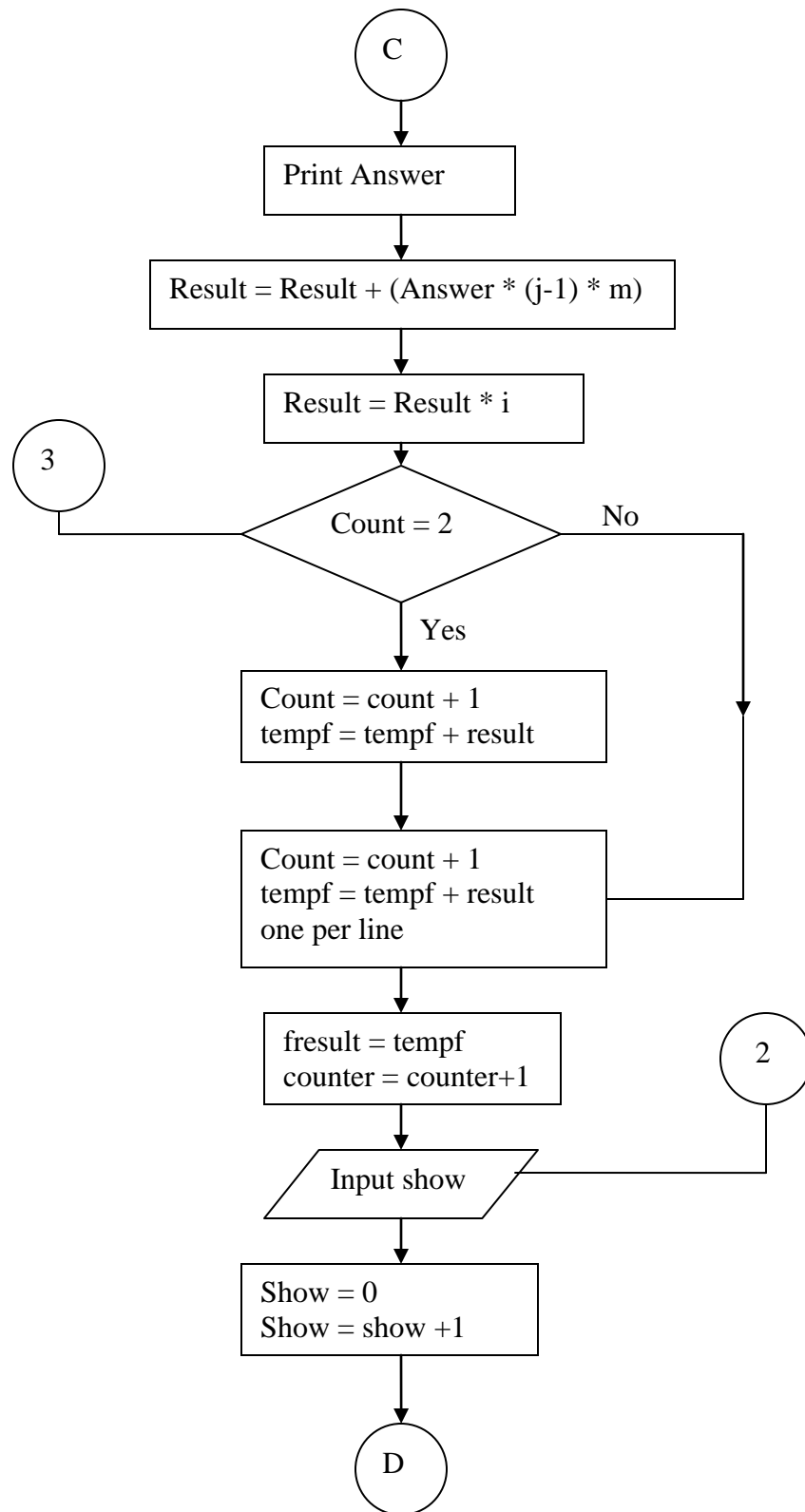
APPENDIX B

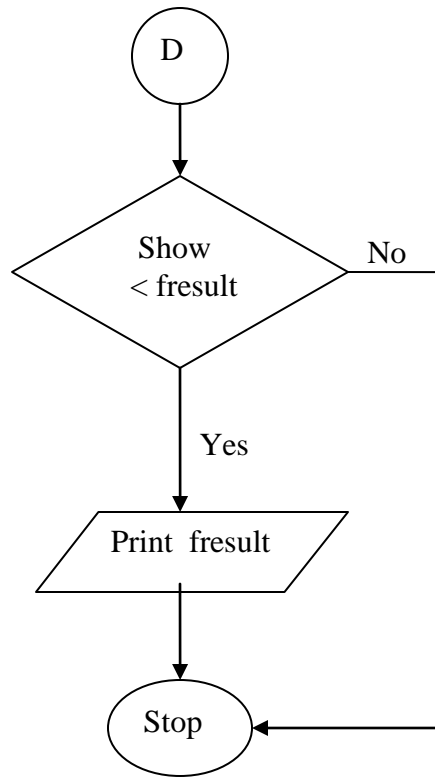
Flowchart of the JAVA Program used for Computation.











Note that $h_o = H'_o$.

APPENDIX C

JAVA Program Used for the Computation of Temperature Distributions in the Continental Crust

```
import java.text.*;
import java.util.*;

public class JavaPhysics{
public static void main(String args[])
{
    NumberFormat form = NumberFormat.getInstance( );
    form.setMinimumIntegerDigits(1);
    form.setMinimumFractionDigits(1);
    form.setMaximumFractionDigits(1);
    double lamda[]=
{0.0000000004714285714,0.0000000009719495091,0.0000000001536585366,0.0000000004985611511};
    double h0 [] = {409.7051364, 52.63081981, 1507.631265, 2307.418831};
    double []time = {10000000,100000000,1000000000};

    String fresult[] = new String[4];

    int counter = 0;

    while (counter < lamda.length)
    {
        String tempf="";
        double i = (2 * h0[counter] * Math.pow(h,2))/K;
        int count = 0;
        while(count < time.length)
        {

            double result = 0.0;

            for (double n = 0; n <= 100.0; n++)
            {
                double j = Math.exp(-(lamda[counter] * time[count]));
                double k = ((2 * n * Math.PI) + β);

                double w = (2 * n * Math.PI + β) * z/h;
                double t = -(Math.pow(k,2.0)*(a*time[count]/Math.pow(h,2)));
                double l = Math.exp(t);
                double m = Math.sin(w);

                result = result + (CN(n,lamda[counter]) *(j-l)* m);
            }

            result = result * i;
            if(count==(time.length-1))
            {
                tempf = tempf + form.format(result);
            }
            else
            {
                tempf = tempf + form.format(result) + "\n";
            }
        }
    }
}
```

```

        }

        count++;
    }
    //put the tempf into the final answer
    fresult[counter] = tempf;
    counter++;
}
int show = 0;
while(show < fresult.length)
{
    System.out.print(fresult[show] + "\t");
    show++;
}
}
public static double CN(double z, double lamda)
{
    double q = (2 * z * Math.PI) + beta;
    double p = Math.sqrt(1 - Math.pow(0.98, 2.0));
    double b = 1 - (p * Math.exp(-h/D));
    double c = h/D * 0.98 * Math.exp(-h/D);
    double v = (q * b) - c;
    double e = Math.pow(q, 2.0) - ((lamda * Math.pow(h, 2))/a);
    double f = h/D + Math.pow(q, 2.0);
    double g = 1 - (2 * 0.98 * p/q);
    double u = e * f * g;
    double answer = v/u;
    return answer;
}
}

```

APPENDIX D

Variation of Crustal Temperature with Time at Depths 10, 20 and 30 kilometres for an Homogeneous Crust.

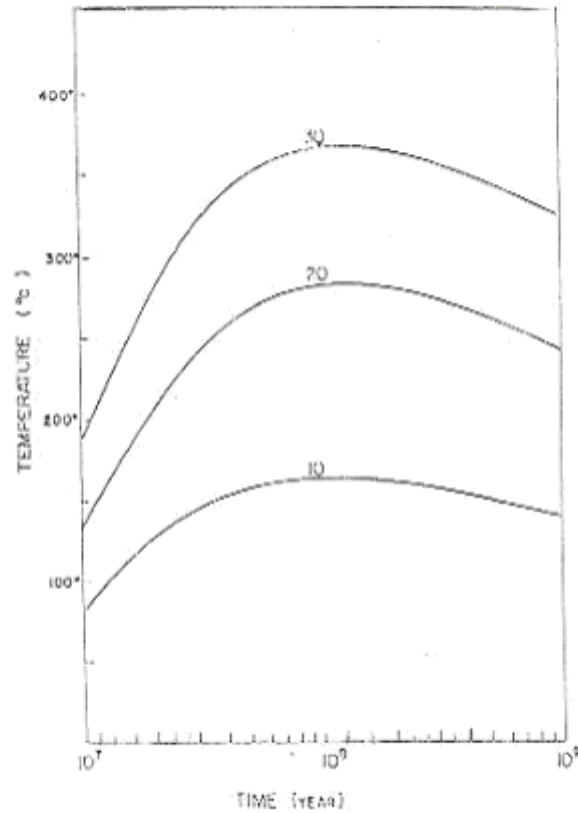


Figure 5: Variation of Crustal Temperature with Time (Numbers on the curves are depths in kilometers). Source: Keh-Gong Shih, 1971.

SUGGESTED CITATION

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