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The Earth's heat

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The temperature at the Earth-s surface is 10-20°C on average, although in polar region and on high mountains it is much colder, while in deep mines it is too hot to work for long periods. Temperature obviously varies with depth. In addition, there are hot springs in areas of recent volcanic activity where water emering from springs is heated up inside the crust. So the temperature in the Earth-s crust increases with increasing depth. The temperature change (in °C) with dept (in km)can be plotted an a graph to give a curve, referred to as the geotherm. Plot such a graph, using the figures in the following table (Table1). Use a scale of 1 cm = 1 km verticaly and 1 cm = 50°C horizontally; plot T°C from left to right, dept in km down the vertical axis (this may seem strange at first, but it is more convenient to plot depth in the crust downwards).

The graph is not a straigh line, but a curve, the geothermal curve or geotherm (fig 1). The slope of this curve, i.e, the tangent to it, is called the geothermal gradoent which is the rate at which temperature increases with depth in a perticular region, i.e. :

geothermal gradient = change in temperature/change in depth (°C km⁻)

Notice that the rate of temperature increase is large at first, but decreases with depth.

Table 1: variation in temperature with depth in crust

Depth (km)	0	1	2	3	4	5	6	7	8	9	10
Temperature (T °C)	15	60	110	150	180	215	230	250	265	275	285

From the graph in Figure 1 it can be seen that temperature increases with depth in the Earth. The heat from the Sun is not sufficient to cause this, so a heat source is necessary. The main energy source in the Earth responsible for internal processes, including metamorphism and mountain building, is the heat energy released by the decay or breakdown of radioactive elements. Elements have isotopes (atoms of the same element but with diferent mass), some of which are radioactive (that is they are unstable and decay with time) producing heat and more stable isotopes. Some elements in rocks of the Earth-s crust and mantle have long-lived isotopes,i.e, thier half lives (time taken for half the atoms of a radioactive isotope to disintegrate) are very long and they break down slowly.

Potassium-40 (^{40}K), uranium-238 (^{238}U) and thorium-232 (^{232}Th) are most important isotopes for heat production in the Earth.

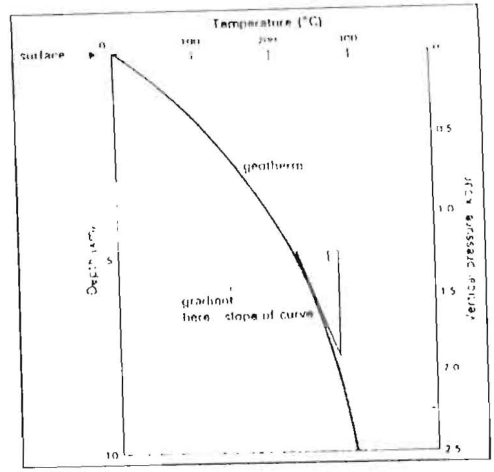

Figure 1. Temperature plotted against depth in the crust. The resulting curve is called the geotherm and the tangent to it gives the local geothermal gradient

The uranium isotope ^{235}U was important for heat production in the early history of the Earth. Tables 2 and 3 show these isotopes with their breakdown products, half live in millions of years and abundances or amounts present in rocks in parts per million (ppm, equivalent to grams per tone) in diferent rocks. Notice that all three isotopes are more abundant in acidic rocks than in basic rocks, because they have become concentrated in acidic rocks by various processed over a long period of time. Because these isotopes have been decaying since the origin of the Earth some 4600 Ma ago, they must have been more abundant then.

Table 2. Important radioactive isotopes

Radioactive isotopes	Half life (Ma)	Heat production (hpu)
uranium-238	4 500	2.30
thorium-232	13 900	0.63
potassium-40	1 300	0.67

Thorium, with the longest half lifi, would have been only a littlemore abundant, uranium about twice its present amount, potassium-40 so very much more abundant. The answer is that it has the shortest half life of the three, and so must have decayed more rapidly. It also follows than much more heat was being produced in the early stages of the Earth›s history by the decay of these isotopes.

Table 3. Avaerage concentrations of radioactive isotopes in crustal and mantle rocks

	Average concentration (ppm)			Total heat production (hpu)
Rock type	U-238	Th-232	K-40	
sediments	3.00	8.00	1500	1.50
acid igneous rocks	4.75	18.50	38000	2.50
basic igneous rocks	0.60	2.70	8000	0.30
metamorphic	0.40	2.10	22000	0.30
granulite	0.02	0.05	10	0.01
typical mantle rocks				

How does the heat travel

Within the solid outer part of the Earth (the lithosphere) heat travels mainly by conduction: heat energy is transmitted from particle to particle due to molecular vibrations induced by thermal energy. In addition, heat may be transferred relatively quickly by the upward movement of magma, or by circulating hot water and gases (hidrothermal fluids), as well as by the movements of blocks of the crust along faults.

Table 4. Heat flow distribution in various crsutal tectonic provinces

Crustal province	Heat flow (hfu)	Average age (Ma)
Precambrian continental shield	0.90	2000
Stable continental platform	1.00	1000
Caledonian orogenic belt	1.10	400
Hercynian orogenic belt	1.25	300
Mesozoic orogenic belt	1.40	200
Cenozoic orogenic belt	1.75	50
Modern volcanic zone	2.20	0
ocean basin	1.30	50
oceanic ridge	2.0	0
ocenaic trench	1.20	150

Beneath the lithosphere, in the upper mantle, heat is though to travel mainly in convection currents in a very viscous (or thick and sicky) material. Much of the heat from the mantle thus enters the base of the crust, and, together with the heat being generated within the crust, is then transmited upwards by conduction. The rate at wich heat can be transmited depends on the conductivity of rocks. Within the lithosphere, heat flows upwards by conduction towards the surface. Diferent rocks conduct heat at diferent rates, just as other materials do. Heat flow at the surface of the Earth is the total of all the heat produced within and below the crust.

Heat flow

Heat flow varies around the world, depending on the nature and age of the geological province where the heat flow is measured. Table 4 shows the heat flow distribution in different continental and oceanic tectonic province, together with the ages of the provinces.

Heat flow may be expresed in SI units of W m^{-2} (watts per square metre), although it is more convenient to work in heat flow units (hfu), where;

$$41.8 \text{ hfu} = 1.0 \text{ W m}^{-2}$$

Using the information for continents given in Table 4, plot heat flow verticaly against age of province horizontaly, in Ma (suggested scales; 2 cm = 0.5 hfu, 4 cm = 500Ma). Join the points on the graph to give a smooth curve and the note carefully its shape.The main feature to be noticed is that the average heat flow trough continental orogenic provinces decreases from 1.5 hfu for the Mesozoic to 1.0 hfu for Precambrian shields, i.e. modern heat flow is releted to the age of rocks (Fig.2). A similar pattern emerges fro oceanic heat flow.

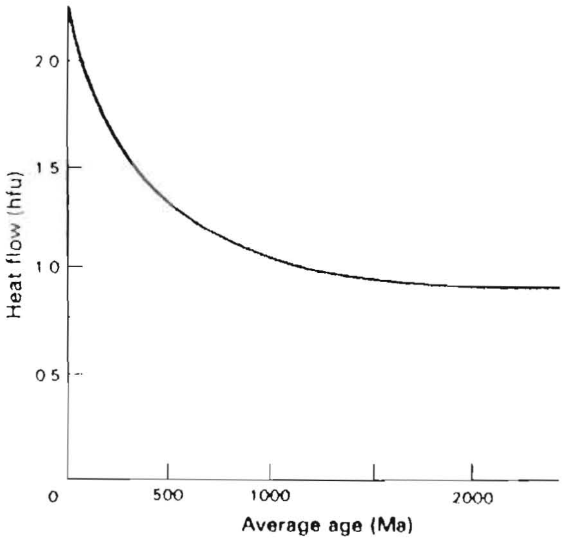

Figure 2. Heat flow plotted against age of continental crust

The geothermal gradient

The geothermal gradient is the slope of the tangent to the geotherm (fig.1). The increase in temperature with depth is measured in degrees Celsius per kilometre (Γ °Ckm^{-1}) which is the unit of measurment of the geothermal gradient.

Tabela 5 . Geothermal gradient in various crustal environments

Type of crust	Geothermal gradient (°Ckm^{-1})
Gulf Coast, USA (oil wells)	30
Middle East (oil wells)	50
active volcanic zone (modern)	100
oceanic trenches (subduction	10
zones)	20-25
Precambrian shields today	50
sialic crust in the Archean	

The temperature gradeint varies from place to place in the crust, depending of the geological environment, and it has also varied at diferent times in the Earth's history. It is occasionaly possible to measure the gradient directly, in mines and deep oil wells for example. Table 5 shows some values of the present geothermal gradient measured in regions of diferent ages. As might be expected, the gradient in volcanic zone is steep, but in ocean trenches it is shallow. The continental average is usually taken to be about 20-25 °C km^{-1}. Refer back to Figure 1 and notice again the shape of the geotherm: the gradient decreases with depth. This is the case because heat-producing elements are depleted (or reduced in amount) in the deep crust, otherwise rocks would melt at very shallow depths owing to a rapid build-up of heat. Note that Table 5 gives values of the gradient in the Earth's surface. From the table, you will also note that the gradient in the early part of the Earth's history, during the Archaen (4600-2500 Ma ago), was steep. heat flow in the early history of the Earth may have been higher than present, owing to the greater effect of the heat from the more abundant readioactive isotopes.

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