Geothermal heat flow as a problem: the history and the present state

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Abstract: The theory of the Earth as a planet which gradually gets cold prevailed the geological thought for a long time. In 1883 the first reliable estimates of the heat flow from the Earth interior were obtained. In 1954 at the X General Assembly of IUGG it was concluded that there is no sufficient evidence of systematic difference in heat flows values at different regions. That conclusion contradicted existing different geological models for the continental and ocean floor crust. The heat flow is also measured for the Moon, Jupiter and Saturn. The increase of the Earth radius length can be considered as an additional mechanism to supply energy for the geotectonic processes.

1. Introduction

The planets and their satellites are considered as a celestial bodies with the inner structure and certain energy balance. The planets and satellites surface has its own complicated pattern – tectonic structure, reflecting the celestial body's formation history as the result of internal and external factors interaction.

At present the heat flow going through the planetary surface is an observable value.

In order to calculate the Earth's energy balance we should estimate the volume of initial heat reserves and annual heat losses due to seismic processes, volcanism, slow geological movements and tectonic processes. This balance can be used for estimation of the possible thermal effect of the heat flow on the Earth's biosphere.

2. Early history

Greek philosopher Plato (5-4 cent. BC) in his «*Phaedo*» dialogue describes the underground rivers of flames (fires) and molten lava and mentions explosive eruption mechanism.

Giordano Bruno (1548–1600) in his works paid special attention to underground heat in connection with volcanism (Macdonald, 1975).

The idea that the Earth initially was the small star and as a result it possesses the red-hot core belongs to Renй Descartes and was introduced in his "*Principles of Philosophy*" (1644). According to Descartes conception our planet was born as a cooling star and in consequence has a certain amount of internal heat. Gottfried Leibniz in his "*Protogaea*" (1691) also suggests the idea that the Earth is a cooling star.

In 1675 the Italian astronomer Giovanni Domenico Cassini who worked in Paris noticed that the temperature in Paris observatory' cellarage is constant. Later, in 1730, the French astronomer Philippe de La Hire came to the same conclusion.

In 1783 Jean-Dominique, comte de Cassini together with Antoine-Laurent de Lavoisier put the sensitive thermometer (placed inside the glass vase filled the sand) in the cellarage for the perennial observations. At the beginning of the 19^{th} century the scientist came to the conclusion that the temperature in the cellarage is constant independently of the season changes.

It is assumed traditionally that the first scientist who pointed out that any theory of Earth inner structure should explain the existence of the Earth internal heat was Georges-Louis Leclerc, Comte de Buffon (the honorary member of St.–Petersburg Academy of Sciences from 1776). In his «*Les йpoques de la nature*» (1778) Buffon estimated the time interval of the Earth cooling based on the cooling rate of iron as 75 000 years. Yet, 15 years before Buffon, Russian scientist M.Lomonosov in his writing "*The short description of different voyages in northern seas and the evidences for the possible passage through the Siberian ocean into Eastern India*" writes that the lands and waters of the Siberian ocean are heated not only by solar radiation, but by the geothermal heat as well, which is demonstrated by a finite thickness of permafrost layer and by the presence of active volcanoes in the northern latitudes.

The French mathematician Jean Baptiste Joseph Fourier in his memoir «*Sur les temperatures du globe terrestre et des espaces planetaires*» (1827) proposed the theory that Earth's is gradually getting cold and estimated that the time interval for decreasing of the internal heat flow by half is much longer than 30 000 years.

In 1827 Pierre Cordier summarized for the first time the mining observations data and determined that the temperature gradient is 20-25 °C/km and also suggested that the red-hot state of the Earth depths explains the volcanic phenomena (Burke, 1974).

In 1829 the French geologist Йlie de Beaumont proposed the contraction theory saying that the tectonic processes are the result of Earth's crust compression due to the cooling. This theory for the whole century was a paradigm in geology.

In 1835 the S.D.Poisson, contrary to the earlier idea of the liquid core came to the conclusion that the Earth interior is solid and rigid.

In 1864 the famous geologist Charles Lyell in his "*Geological Evidences of the Antiquity of Man*" admits two possibilities to explain the volcanic activity: thermal expansion and thermal compression of the crust.

Baron Kelvin (William Thomson) in his work "*On The Secular Cooling Of The Earth*" (1864) published the first valid estimate of the solidified Earth's crust age as 98–200 million years.

The systematic study of the temperature distribution within the inner parts of the planet was initiated by the British Association for the Advancement of Sciences, which founded a special committee for this purpose in 1869. The 15-th Report of this Committee, printed in 1883, contained the generalized data on temperature gradient measurements, rocks thermal conductivity and the determination of the heat flow from the inner parts of the planet value q = 0,068 W/m^2 (Kraskovskii, 1966). The reason for this figure to be so close to the value estimated today, is the uniformity of the Earth's heat flow in different regions of the Globe.

3. The new age history

As the technologies of drilling advanced, the data on temperature profiles were accumulated. In the USSR for the first time the thermometers were placed in the drillhole in 1932. The measurements were taken up to the depth of 700 m, the single measurement lasted 40 min (Kraskovskii, 1933).

In December 1936 V.G.Khlopin, later one of the leading scientists in the Soviet atomic project, made in Moscow a presentation named "*The radioactivity and the thermal regime of the Earth*" (Khlopin, 1937). Using the earlier A.Holmes data he estimated the heat flow value as 0,07 Вт/м^2 and also stated that due to the dependence of radioactive decay "the thermal effect 2 billions years ago was almost twice as powerful as today" (op. cit., p. 222). V.G.Khlopin data and calculations were used by V.I.Vernadsky in his plenary report at International Geological Congress XVII Session (Moscow, August, 1937). Two important articles devoted to the thermal regime of planetary bodies were published by the well-known Russian mathematician A.N.Tikhonov in 1937: "*On the radioactive decay influence on the temperature of the Earth crust*" and "*On the cooling down of the bodies following Stefan-Botzman law*".

In September 1954 in Rome at the X General Assembly of IUGG it was concluded that the systematic difference in heat flows values at different regions (either land or ocean floor) is not observed. The typical value for the heat flow was derived as 0,04 W/m^2 (Belousov, 1955).

In 1949 the first indications for the existence of zones of the hot salty waters at the bottom of the Red Sea were received. The first article on this subject was published in 1965 (Shallow J.C., Crease J., 1965). Soon three thermo-anomalities were investigated, several square kilometers each (Gushtchenko, 1979). In 1976-1977 in the Galapagos Islands region (Pacific Ocean) the "black smokers" were discovered by the Woods Hole Oceanographic Institute expedition.

At November 19, 1962 the V.D.Krotikov and V.S.Troitskii article named "The detection of heat flow from the Moon's depths" was delivered to the Editorial board of the soviet "Astronomical Journal". By comparison of Moon's radio-brightness at different wave lengths the authors measured the heat flow from inner layers of the Moon as 0,055 W/m^2, practically equal to that one of the Earth (Krotikov, Troitskii, 1963_1; Krotikov, Troitskii, 1963_2). Before 1980 the heat flow from the inner layers of Jupiter and Saturn was reliably established (see, e.g., (Ingersoll e.a., 1980)).

4. Modern state of the problem

It is important to compare the annual energies of a seismic and volcanic processes in the Earth crust and upper mantle with the geothermal flow value.

The geothermal flow value equal to 0,05 W/m^2 acting at the area of the Globe ≈5Ч10^{14} m^2 supplies 2,5 Ч 10^{13} W of the thermal power which equals to annual thermal loss 0,8Ч10^{21} J·year^{-1}. Let us estimate the additional share of anomalous heat flows in mid-ocean ridges rift valleys. The total mid-ocean ridges system length is about 60 000 km. Taking the rift valley width to be 10 km one can conclude that total area of such zones of high heat flows is about 0,001 of the Globe surface area. Even the 10-fold higher heat flow in such regions could not have influenced sufficiently the total Earth annual heat losses. The extra argument is the absence of the oceanological evidences of such anomalous heat flows.

The total annual earthquakes energy, which is determined by the strongest earthquakes, is well established and amounts to 10^{19} J·year^{-1}. The total annual energy of explosive volcanic eruption on land is determined by the output of 3ч5 cubic km of dense rocks heated up to 1300 K temperature (specific heat c ≈ 1,0 J/g·K). It equals to the annual heat losses of about 10^{19} J·year^{-1} (Zemtsov, Tron, 1985; Zemtsov, Tron, 1987). Both values (seismic and volcanic heat losses) make up 0,01 of the total Earth's inner heat flow.

The gravitational energy reserve of a gas sphere with mass equal to that one of the Earth M_E = 6,0Ч10^{24} kg and radius 10 times larger that Earth radius R= 6,4Ч10^7 m is equal, by the order of magnitude, to

E_{grav} ~ GM_E^2/R ≈ 3,5Ч10^{31} J,

where G = 6,7 Ч 10^{-11} $m^3/kg·s^2$ – gravitational constant.

Such value of gravitational energy reserve is close to the estimates of Earth interior elastic stresses' energy and total heat reserve of the Earth (10^{31}–10^{32} J) (see, e.g., (Sorokhtin, Ushakov, 1991)). Taking into account that this gravitational energy reserve should be distributed between thermal particles' energy and radiation and that annual heat losses nowadays are ~10^{21} J·year^{-1}, we come to the conclusion that this energy reserve can compensate for the Earth heat losses during about 10^9 years.

A similarity in the statistics for the numbers of seismic events (earthquakes) and volcanic eruptions is discovered.

For the earthquakes with different magnitudes (energies) the so-called "recurrence law for earthquakes" is well established (Sadovskii, 2004, p. 325):

lg N_E = б – г lg E, or $N_E = \frac{10^{\alpha}}{E^{\gamma}}$,

where N_E is the number of earthquakes with energy values $E \geq E_0$ during the certain observation period. The б and г in the equation are constants, and it is known that б has different values for different regions, while г ≈ 0,5 for majority of regions.

For the volcanic eruptions it is found that the same type power law is implemented for the number of volcanic eruptions for the certain period – "recurrence law for strong volcanic eruptions" (Zemtsov, Tron, 2007). The coefficient г ≈ 0,5ч0,6. The power law with г < 1,0 corresponds to the case when total energy output is provided by the most powerful events. This unifies the mechanisms of seismic and volcanic processes.

The discovery of radioactivity have led to the proposition that radioactive decay is the source of heat flow from interior of the Earth (J.Joly (1903); F.Himstedt (1904)). Yet the data on concentration of U, Th and K in magmatic rocks show that in such case the radioactive elements should be located in the relatively thin 10 miles (16 km) crust layer, otherwise the heat flow will be too high. Chemical reactions and phase transitions are also under the consideration as a possible source of a heat flow. However none of such models work properly for the Moon because of it has smaller mass and basaltic type of rocks found on its surface.

The changes in the Earth radius' value are also considered in geology and geotectonics as the energy source for the processes in the Earth crust and upper mantle (Carey (ed.), 1983; Problems…, 1984). In (Taganov, Zemtsov, 2007) an attempt is made to examine as possible source for heat allocation (calorification) in the Earth interior the increase of Earth radius due to the cosmological expansion. It is shown that the expansion based on the present-day Hubble constant value could ensure a sufficient source of energy supply for geotectonic processes. As the Earth interior volume accessible for the cosmological expansion the fractured and non-condensed part of the inner volume should be considered. This volume is located within the planet surface and the level of the deepest earthquakes focuses (appr. 700 km). The Earth radius' increase with the rate v_R = 0,33 mm·year^{-1} corresponds with volume increase rate of 165 km^3·year^{-1}, which exceeds the rate of volcanic ejections and could be balanced by the fresh magma intrusions through the mid-ocean ridges system (such an idea was earlier discussed in (Dicke, 1962)).

The heat flow value through the surface of the Earth is also of a great interest from Kyoto protocol point of view (Zemtsov, Savina, 2003). The annual registered consumption of natural fuels (oil, coal, gas) by the global population and industry makes about 9 billions metric tons of oil equivalent per year (see, e.g., UN Energy Statistics Yearbooks) or 3,7Ч10^{20} J·year^{-1}, which constitutes almost S of a heat flow power from the Earth's interior. The Kyoto protocol controls the discharge of CO_2 into the atmosphere caused by the burning of 3,74 billions of metric tons of pure carbon, or less than 50% of natural fuel consumption.

For the realization of Kyoto protocol the following problem is of general importance: whether the heat flow from the Earth's interior increases or decreases. We do not expect to receive an answer in the nearest future. However, the expansion of the Earth can be interpreted as tendency to lower the heat flow density, thus making the Earth crust to cool. In such case the Mankind activity in managing the greenhouse effect in the planet's atmosphere seems reasonable.

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