TERRESTRIAL HEAT FLOW

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Contents

Summary

Practically any geophysical phenomenon is connected in some way to the thermal physics of Earth. The principal method used to study the subsurface temperature field is to measure heat flow on the Earth’s surface.

This paper briefly reviews the relatively young history of geothermal research, and describes the major milestones from the first heat flow measurements, techniques to measure heat flow on land and on the sea bottom, and laboratory determinations of the thermal properties of rock material.

Heat flow data can be related to the tectonothermal evolution, and to the distribution of radiogenic heat sources. Heat flow maps and regional heat flow patterns are not only useful in regional and global studies, but also can serve in many applied aspects of hydrogeology, in surveys for geothermal energy, and in a number of problems of engineering geology.

One quite modern application of precise temperature logging is the possibility of inverting the present-day temperature-versus-depth profiles into the ground surface temperature history, and to interpret this in terms of the paleoclimate reconstruction.

1. Introduction

The study of the thermal structure of Earth, generally referred to as geothermics, has a long history, even though modern geothermics, one of the fundamental geophysical disciplines, is relatively young. Geothermics is closely related to a number of other geological, hydrological, and geochemical disciplines, and in its practical applications heat flow studies are related to the search for and use of geothermal energy.

Most of our knowledge of contemporary geothermics was formulated only in the last third of the twentieth century. The basic ideas of the thermal structure and thermal history of Earth, based on measurements of borehole temperatures on land and measurements of heat flow through the ocean floor, together with determinations of the thermal properties of rock material, were enabled by the rapid development of measurement techniques in the 1960s. Geothermal modeling, the assessment of the deep lithosphere temperature, and evaluations of the thermal regimes of geological processes on local, regional, and global scales were made possible by the recent massive advancement of computer techniques.

2. History

The idea of enormous amounts heat coming from the deep subsurface has a long history, closely related to the ancient occurrence of volcanic eruptions accompanied with hot lava outflow. Ancient Greeks thought of the underground as an imagined abode of gods and the souls of the dead. Many other religions, including Christianity, further adopted this conception. The extreme temperatures coincided with the hell-fires destined to punish the deadly sins. More serious ideas of the general increase of temperature with depth would only be discovered when deeper mines were dug much later, in medieval times.

It took, however, several more centuries before a modern scientific approach really started. In 1867, the British Association for the Advancement of Science formed a committee ".. to investigate the rate of increase of underground temperature in various locations of dry land and under water." Multiplying the temperature gradient and the mean thermal conductivity of rocks, the first value of the heat flow density was estimated to be 1.3×10^{-6} cal cm^{-2} sec^{-1}, that is, approximately 54 m W m^{-2} in SI units. This value is in surprisingly good agreement with the present observations.

At the time, the data acquired by the Commission of the British Association represented stupendous progress, but their further interpretation produced an enigma. If an observed temperature gradient of about 30 mK m^{-1} is to continue downwards, high temperatures sufficient to melt rocks must exist at relatively shallow depth, a fact that clearly contradicted the geological evidence. The solution of the dilemma came only later, with the discovery of radioactivity. It was pointed out that heat is generated within rocks by the decay of radiogenic elements present in small quantities in the earth material. It had to be proved that crustal rocks are more radioactive than rocks forming Earth's interior, and that the heat production sharply decreases with depth. Solving the thermal history of Earth played a central role in the development of geophysics for almost fifty years since then.

All models somehow reflected the cosmogenic origin of Earth, either:

- the primitive Earth originating from a filament of hot gaseous material drawn out of the Sun, and later cooling down from the originally fluid state (see *Solar System*); or
- the early Earth, heated up from the originally cold body due to excess heat that could not be conducted away, because of the relatively low thermal conductivity of the crustal rocks.

The deeper layers become molten and structurally unstable, and a large movement of the material occurs, carrying the excess heat to the surface. It was suggested that this convection is the “engine" of geological evolution, producing metamorphism and periodic tectonic change. A long time scale associated with the diffusion of heat within the earth, and the enormous thermal inertia of the earth, were common to all these ideas.

The very first assessment of the heat flow density was done in the 1980s, but it was about 50 years before that when the first practical heat flow measurements really started. The first heat flow data measured in boreholes were reported from Great Britain in the late 1930s, and similar studies were initiated in the USA and in Canada a decade later. The first heat flow data measured in the Atlantic Ocean came in the 1950s, when Sir Edward Bullard pioneered marine investigations. The international geophysical community soon realized that knowledge of the heat flow provides a useful tool for studying crustal structure, and helps to understand Earth’s evolution.

The year 1963 represented an important milestone in the development of the international cooperation in geothermal research. At the thirteenth General Assembly of the International Union of Geodesy and Geophysics at Berkeley, the International Heat Flow Committee (later Commission, IHFC) was formed under the chairmanship of Francis Birch.

New data on heat flow density then accumulated quickly, and in 1964, about 2000 individual heat flow values from all over the world were available. Such remarkable progress in a relatively short time allowed us to draw the first basic conclusions:

(a) It was proved that regional heat flow variations greater than 8 m W m^{-2} were significant.

(b) Spherical harmonic analysis revealed a representative global mean value of 62 m W m^{-2}, with little difference between land and sea. If heat flow observed on the surface is produced by radioactivity within the earth, this equality suggests compositional differences between the upper mantle under the continents and that under the oceans. However, later, more numerous measurements increased the value of the global mean, and showed that the characteristic marine heat flow is 20 % to 30 % higher than on continents.

(c) Heat flow values could have been well correlated with major geological features; on land, heat flow is higher and more variable in tectonically younger and active geological units; at sea heat flow increases from trenches to ocean basins, and is very high on ocean ridges.

For borehole temperature logging, a high precision (thermistor-type) thermoprobe was introduced. For laboratory thermal conductivity determinations of rock samples, a steady-state “divide-bar" apparatus was proposed. For unconsolidated rock samples, and especially for the ocean bottom sediments, a transient “needle-probe" device was constructed.

The real boom for geothermal research was in the 1970s. It was generally understood that the outflow of heat from Earth’s interior by conduction is, energy-wise, the most impressive terrestrial phenomena. Knowledge of the heat flow was indispensable for any extrapolation of the near surface temperature data to greater depth. As almost all physical properties of rocks are temperature and pressure dependent, and most geological processes need their energy, the new heat flow measurements accumulated quickly. The oil crisis, and the sharply increasing prices of oil, initiated an unprecedented interest in all practical solutions to harness geothermal energy.

3. Heat Flow

Heat transfer occurs from points at higher temperature to points at lower temperature in three distinct ways: conduction, convection, and radiation. In fluids, convection and radiation are of great importance, but in solids, convection is usually absent and radiation is negligible at ordinary temperature. Almost all Earth’s lithosphere is solid and at a rather low temperature, so the heat flow near the surface is essentially by conduction. Deeper in the earth, convection and radiation may be more important because of the higher temperature and the probably non-solid behavior of Earth’s interior. Since the temperature increases downwards, heat is flowing from Earth’s interior to the surface.

As already stated, the outflow of heat from Earth’s interior by conduction (heat flow), is, energy wise, the most impressive terrestrial phenomena. Its present rate of about 40 million megawatts is orders of magnitude greater than the energy dissipation of earthquakes or heat loss from volcanic eruptions. The study of the terrestrial heat flow is fundamental in earth sciences. It is the most direct observation of the thermal state of the earth, and geothermal processes play an important role in all theories of Earth’s origin, constitution, and behavior.

By definition, the surface (terrestrial) heat flow at a given locality is the rate of heat transferred across Earth’s surface at that place per unit area per unit time. It is determined as the product of the thermal conductivity and the vertical gradient of temperature. It is given in units of watts per square meter ($W\ m^{-2}$).

Heat flow by conduction, q, in a solid is found experimentally to be proportional to the temperature difference, where the coefficient of proportionality is the so-called thermal conductivity (k). In general, thermal conductivity is a tensor, but for a homogeneous and isotropic solid, it is a constant. For practical measurements of the surface heat flow, q is thus the product of the mean conductivity of the rocks from the borehole and the measured temperature gradient in that hole, $q = k(\mathrm{d}T/\mathrm{d}z)$, where the flow is vertically outward.

3.1Thermal conductivity

Thermal conductivity is thus the ability of the material to conduct heat, and in SI units it is expressed in watts per meter kelvin (W/(m K)). Generally, most rocks are rather poor conductors, and their conductivity varies in an interval of less than 1 W/(m K) to 10 W/m K (Figure 1). In geothermics, the related investigations have to consider the effect of temperature, pressure, mineral composition, and water content on the conductivity. Thermal conductivity is related to the thermal diffusivity (κ), the ability to equalize the temperature differences, $\kappa = k/(c\ \rho)$, where c is the specific heat (the heat capacity per weight unit) and ρ is the density.

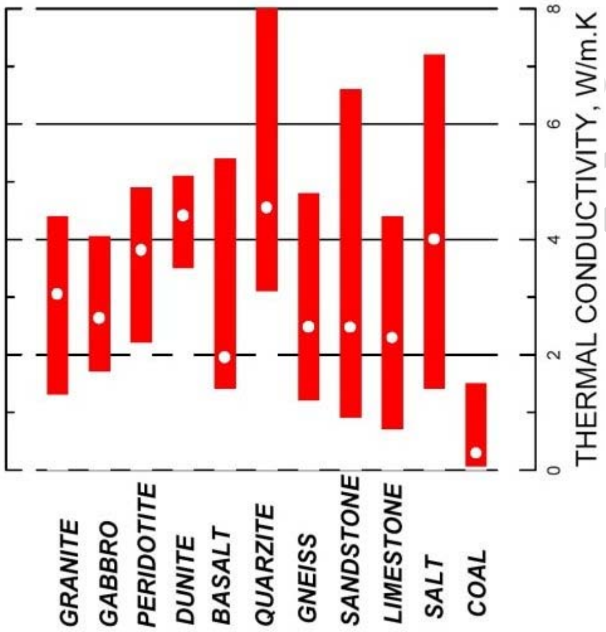

Figure 1. Range and mean thermal conductivity for several characteristic rock types (after Cermak and Rybach, 1982)

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Biographical Sketch

Vladimir Cermak ,graduated from the Charles University in Prague in 1960, obtained his PhD in 1965 and his DrSc-title from the Czechoslovak Academy of Sciences in 1982. From 1968 to 1970 he was a post-doctoral fellow at the Dominion Observatory in Ottawa, Canada. He maintained his interest in various aspects of geothermics, established the Heat Flow Laboratory in the Geophysical Institute in the 1960s, and started routine heat flow measurements in the country. From 1990 to 1998 he served the director of the Geophysical Institute, and since 1999 he has been the Chairman of the Czech National Commission for Geodesy and Geophysics.Vladimír Čermák always played an important role in international cooperation. In the 1970s he initiated the preparation of the first heat flow map on the continental scale in Europe, and together with Professor Ladislaus Rybach from the ETH Zurich, published a corresponding monograph in 1979. He joined the International Heat Flow Commission of the International Association of Seismology and Physics of the Earth Interior in 1971, serving as its secretary from 1987 to 1991, and its chairman from 1995-1999. From 1992 to 1996 he was the principle investigator of the project “Borehole and Climate” under the Czech–US cooperation program. From 1994 to 1998 he was the Vice-President of the European Geophysical Society. Presently he is a member of the American Geophysical Union, Deutsche Geophysikalische Gesselschaft, and since 1991, also a member of the Academia Europea. From 1995 to 1999 he was a member of the Board of Directors of the International Geothermal Association. He has organized a number of international workshops and conferences, edited a number of special issues of internationally recognized journals, and published over 250 scientific papers, over 30 of them with Dr. Louise Bodri from the Geophysical Department of the L.Eotvos University, Budapest. Since 1998 he has been leading one of the UNESCO projects under the International Geological Correlation Program “Borehole and Climate.” The author’s contributions have been acknowledged internationally. In 1995 he was awarded the AGU Edward Flinn medal and the O.Yu.Schmidt medal of the Institute of Earth Physics of the Russian Academy of Sciences, and in 1998 the Patricius Plakette of the Deutsche Geothermische Vereinigung.