Lecture Notes in Earth System Sciences

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Applied Geothermics

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Summary

This book describes the origin and characteristics of the Earth's thermal field, thermal flow propagation, and some thermal phenomena in the Earth. Description of thermal properties of rocks and methods of thermal field measurements in boreholes, underground, at near-surface conditions enables to understand the principles of temperature field acquisition and geothermal model development. Processing and interpretation of geothermal data are shown on numerous field examples from different regions of the world. The book warps, for instance, such fields as analysis of thermal regime of the Earth's crust, evolution and thermodynamic conditions of the magma-ocean and early Earth atmosphere, thermal properties of permafrost, thermal waters, geysers and mud volcanoes, methods of Curie discontinuity construction, quantitative interpretation of thermal anomalies, examination of some nonlinear effects, and integration of geothermal data with other geophysical methods.

This book is intended for students and researchers in the field of Earth Sciences and Environment studying thermal processes in the Earth and in the subsurface. It will be useful for specialists applying thermal field analysis in petroleum, water and ore geophysics, environmental and ecological studies, archaeological prospection, and climate of the past.

Introduction

Geothermics is an area of geophysics that studies the thermal state and history of the interior of the Earth. Solar heat penetrates only into the topmost layers of the Earth's crust. Diurnal soil temperature variations extend to a depth of 1.2–1.5 m; annual variations, to 10–20 m. The heat associated with solar radiation does not penetrate further, although a regular increase in temperature with increasing depth has been established, indicating the existence of sources of heat inside the Earth. Heat flows continuously from the depths to the surface of the Earth and is scattered into surrounding space. The density of the heat flow is given by the product of the geothermal gradient and the coefficient of thermal conductivity. A considerable part of the heat flow is radiogenic heat—that is, heat involved in the breakdown of radioactive elements present in the Earth.

The temperature of the Earth's interior within the boundaries of dry land is determined directly in shafts and boreholes by means of electric thermometers. Instruments for recording the thermal gradient are used for measurements on the ocean floor. Laboratory measurements are made to determine the thermal conductivity of rocks, and show that the change in temperature with depth at various places varies from 0.006 to 0.15 °/m. The density of heat flow is more constant and is closely connected with the tectonic structure. Very rarely does it extend beyond the limits of 0.025–0.1 W/m^2; individual values attain 0.3 W/m^2. Precambrian crystalline shields are characterized by low values (up to 0.04 W/m^2); platforms, by medium values (0.05–0.06 W/m^2); and technically active regions (midocean ridges, rifts, and regions of modern orogenesis), by high values (0.07–0.1 W/m^2). On average, oceans and continents yield the same values; about 0.05 W/m^2; however, this figure is not very reliable, since most of the Earth's surface has not yet been examined.

The Earth's temperature may be measured directly to a depth of only a few kilometers. Below that, the temperature is estimated indirectly from the temperature of volcanic lavas and from certain geophysical data. At depths of over 400 km, only probable temperature limits can be obtained.

The energy of the total heat flow coming from the Earth is about 2.5×10^{13} W, which is about 30 times greater than that of all the electric power stations in the world but 4,000 times less than the amount of heat the Earth receives from the Sun. Consequently, the heat coming from the Earth's interior does not affect the regional climate.

An explanation of the Earth's thermal history requires data about the original content of radioactive material of the various shells of the Earth, their shifts from one geosphere to another, energies and rates of decomposition, the Earth's age, the amount of heat received by the planet during its formation, and the amount of heat involved and absorbed in the various mechanical, physical, and chemical processes in the Earth's interior. The coefficients of thermal conductivity, the specific heat of the material of the interior, and the temperature and pressure at various depths and on the Earth's surface should also be taken into account.

Geothermic research is of great theoretical significance for various types of Earth studies. Its role is particularly important in constructing and evaluating tectonic hypotheses. For example, geothermic data contradict the thermal contraction hypothesis and other hypotheses that postulate that the Earth's heat loss is much greater than the observed values. Geothermic measurements are also used practically; they assist in prospecting for oil and minerals and in preparation for using the Earth's heat for industrial and domestic purposes.

The purpose of this book is to present methods of utilizing the data of temperature surveys in deep boreholes as well as the results of field, laboratory, and analytical investigations in geothermics in a clear and concise form to environment science engineers, petroleum reservoir and drilling/production engineers, geophysicists, and geologists. Although some aspects of this book have been discussed in a number of monographs including Lubimova 1968b; Kappelmeyer and Hänel 1974; Cheremensky 1977; Gretener 1981; Jessop 1990; Somerton 1992; Kutasov 1999; Beardsmore and Cull 2001 among others and numerous papers, no comprehensive monographs are available to Earth scientists/ petroleum engineers. This volume also incorporates the main results of publications by the authors in the last 20 years.

It is obvious that many geothermal problems (propagation of thermal waves in complex media, glaciation cycles, dangerous geodynamic events at a depth, etc.) are nonlinear. Therefore, some attention has been paid to the possible ways of solving these problems.

The objective of this book is to present the state of the art and predictions of downhole and formation temperatures during well drilling, well completion, shut-in, and production. Our intent is to reach drilling engineers (impact of elevated temperatures on well drilling and completion technology, arctic drilling); production engineers (temperature regime of production, injection, geothermal wells, and arctic production); reservoir engineers (temperature field of reservoirs, thermal properties of formations and formation fluids); well logging engineers (interpretation of electrical resistance, mud density, and temperature logs); geophysicists and geologists (interpretation of geophysical data, calculation of the terrestrial heat flow, reconstruction of the past climate). The authors also hope that this volume can be used as a textbook for senior and graduate geologists, geophysics, environmental as well as petroleum engineering students.

The potential applications of the data presented in this book are listed below.

Well drilling and oil/gas production: (1) Prediction and control of downhole mud properties; (2) Designing deep well cementing programs; (3) Evaluation of thermal stresses in casings and around borehole formations; (4) Logging tool design and log interpretation; (5) Determination of the physical properties of reservoir fluids; (6) Prediction of permafrost thaw and refreezing around the wellbore; (7) Determination of the gas hydrate prone zone; (8) Hole enlargement control in permafrost areas; and (9) Well planning in arctic areas (determination of the surface casing shoe depth, selection of low-temperature cements, design of safe casing strings to avoid pipes buckling during the freezeback).

This book will be useful for geophysicists interested in: (1) Searching hydrocarbon, ore and other economic deposits by the use of thermal methods; (2) Calculation of the terrestrial heat flow; (3) Extrapolation of temperatures to greater depths in the crust and the upper mantle; (4) Determination of the dynamics of the permafrost zone by comparing the values of heat flow in the frozen and unfrozen zones; (5) Forecasting of possible dangerous geodynamic events at a depth by the use of thermal monitoring in subsurface and deep wells; and (6) Integrated analysis of thermal and other geophysical fields.

This book will be useful for geologists interested in: (1) Calculation of the regional heat flow for various tectonic structures; (2) Preparation of regional temperature gradient maps; (3) Evaluation of geothermal energy resources; (4) Evaluation of the rates of erosion and sedimentation from temperature profiles; and (5) Studying underground water movement using the difference in vertical heat in water recharge and discharge areas.

This book will be useful for experts in geodynamics and tectonics interested in: (1) Formation and evolution of the magma-ocean; (2) Early Earth atmosphere; (3) Dynamic interactions of the asthenosphere and lithosphere; and (4) Interrelationship between the thermal regime and tectonic processes.

This book will be useful for specialists in environmental sciences interested in: (1) Reconstruction of the past climate from the temperature profiles; (2) Localization of archaeological targets by near-surface temperature survey; (3) Revealing karst terranes and other dangerous environmental features by temperature field analysis; and (4) Computation of water flow geodynamics in stratified liquids.

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Chapter 1
The Thermal Field of the Earth

The Earth is about 4.6 billion years old (Anderson 2007). In terms of its thermal regime, the planet is in the process of cooling. However, to have reached its current state, the Earth and the other objects making up the Solar System went through a number of stages such as the accretion of the planet from dust of the solar nebula, the formation of the magma-ocean, stratification of matter by density, solidification of the magma-ocean, formation of the lithosphere which is taking place today, periods of increased volcanic and metamorphic activity, numerous tectonic processes with global and regional significance (obduction, subduction, orogeny, etc.), heat production by short-lived and long-lived radioisotopes, and numerous other features and processes related to thermodynamic and temperature conditions.

All of these features and processes are related to heat: some led to the accumulation of heat (accretion, heat produced by radioactive decay, stratification of the magma-ocean, etc.), whereas others were involved in the transfer of heat energy to the surface (volcanism, obduction, formation of orogeny, hot springs, etc.) or the transfer of colder matter to greater depths (subduction, immersion, penetration of water through fractures to deeper layers within the crust and upper mantle). A number of features and processes prevent the Earth from cooling quickly. These include the Sun's radiation, heat production by long-lived radioactive isotopes, different chemical reactions, amongst others. All these processes are tightly related and have been influenced by the ever-changing thermal regime of the Earth at every step of its evolution, and are associated with or represent essential components of geothermics. All these features and processes therefore warrant special attention and analysis to paint a complete picture of the thermal evolution and conditions of planet Earth.

1.1 Hypotheses Concerning the Origin of the Solar System Throughout History

Throughout the nineteenth century an increasing amount of geological data began to conflict with religious beliefs concerning the origin of the Earth. The main controversies had to do with (1) the formation of the Solar System and Earth,

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(2) the age of Earth, and (3) the composition and conditions of Earth at the time of its formation. All these are factors that dictate the Earth's thermal regime, thermal gradient, the depth of the Curie discontinuity and many other geothermal factors.

The first scientific theory of planetary formation was the "vortex theory" put forward in 1644 by Descartes (Brandner 2006). Descartes believed that the universe was filled with vortices of swirling particles, and that the Sun was condensed from a particularly large vortex that somehow contracted, while the planets and satellites were formed from smaller vortices.

The nebular hypothesis was introduced in the eighteenth century. It was first proposed in 1734 by Swedenborg (1734), but later apparently presented independently as a complete model by both Kant (1755) and Laplace (1799–1825). This hypothesis, known as the Kant-Laplace theory, constituted a turning point in our scientific understanding of the formation of the Solar System and the Universe. The nebular hypothesis proposed by Kant (1755) is qualitative and includes such details as the slow rotation of nebulae, their gradual condensing and flattening due to gravity, and eventually the formation of stars and planets. By contrast, Laplace (1799–1825) based his hypothesis on a solid mathematical and physical foundation. In his work Laplace also proved the dynamic stability of the Solar System.

Even though the nebular hypothesis is generally the most widely accepted model of the formation of the Solar System and Earth, it faced strong criticism related to its supposed conflict with the angular momentum of the system (e.g., Woolfson 2000). This led some astronomers at the end of the nineteenth and early twentieth century to introduce the 'near-collision' hypothesis, which states that the planets were formed by the passage of another star close to the Sun. This was thought to have drawn massive amounts of matter away from our Sun, as well as from the passing star, thus forming the planets of the Solar System (Woolfson 2000). During this same time frame several other new approaches were put forward to explain the formation of the Solar System as alternatives to the Kant-Laplace hypothesis. One was the 'planetesimal theory' developed by Chamberlin and Moulton in about 1901–1905 (Chamberlin 1916; Brush 1977; Woolfson 2008). Around 1916, Jeans suggested a new version of the 'near-collision' hypothesis known as the 'tidal theory' (Woolfson 2000). The main idea was that the body of the Sun was strongly and tidally influenced by a massive passing star, creating a tide so great that it drove away some material from the Sun and eventually formed planets. However, both of these 'near-collision' models by Chamberlin-Moulton and Jeans were strongly criticized by Jeffreys (1929) and Woolfson (2000) and Whipple (2007). Instead, Jeffreys propounded the 'collisional hypothesis' (Jeffreys 1929; Whipple 2007) which posited that an approaching star actually brushed against or made contact with the Sun.

In 1944, Schmidt (Woolfson 2000; Schmidt 2001) argued that the Sun in its present form passed through a dense interstellar cloud, from which the planets were later formed. This solved the angular momentum problem for the Kant-Laplace theory. In 1961 Lyttleton (Woolfson 2000) modified Schmidt's hypothesis, which became known as the Schmidt-Lyttleton 'accretionary theory'. In 1960, McCrea put forward a 'proto-planet theory' (McCrea 1960; Woolfson 2000) which states that because a collision between cosmic bodies is not elastic, collisions lead to a gradual buildup of greater cosmic bodies which continue to accumulate, and larger aggregates continue to grow by capturing smaller bodies and increasing their diameter, and hence their gravity. This theory thus attempts to explain the simultaneous formation of the Sun and the planets.

The most recent and best accepted theory of the formation of the Solar System—the Solar Nebular Disk Model or the Solar Nebular Model—was first described in publications by Safronov (1969), Cameron and Pine (1973) and Cameron (1973, 1978). It posits that the Solar System was formed from a cloud of gas that collapsed under its own gravity. The gaseous cloud was first flattened into a disk known as the accretion disk, with all of the matter in the system in constant rotation about the center. During the accretion process—resulting from growth through the collision and coalescence of entities—objects of different sizes were formed. The largest objects initially formed in the accretion disk are called planetesimals (bodies 1–10 km in size). Collisions between planetesimals led to the formation of planetary embryos or protoplanets (exceptionally large planetesimals). Planetary embryos then continued to grow to full scale planets, accreting planetesimals and other entities of the protoplanetary disk colliding with them.

Thus overall, the Kant-Laplace model of the formation of the Solar System is still considered valid and has remained the main cosmogony theory for the past 250 years.

1.1.1 Formation of Star Systems and Planets

There is a general consensus that the Solar System was formed from the Solar Nebula (dust cloud). But where did this dust cloud and the matter composing it come from? It is obvious that it existed prior to the formation of the Sun and planets of the Solar System. According to Solar Nebula Theory (Nebular hypothesis) the starting point of planetary formation was a disk of mostly gaseous composition with about 1–2 % solid material and a temperature that increased with its proximity to the center (Woolfson 2000). A nebula initially takes a spherical form, since gravity is a centric field, with a more or less even distribution of gas and solid matter, and its initial temperature is thought to have been about 10–30 K. Figure 1.1 shows the directions of the force of gravity applied to an entity located in different parts of the nebula.

It is known that a mutual force of gravity is generated between any two entities within a nebula. The direction and speed of movement of an entity is dependent on the net force of gravity applied to it. Figure 1.1 shows that the gravitational force on a gas or dust entity outside or at the edge of a nebula (1, 2) would draw it inwards, such that the net force would direct it to the nebular center of gravity. Likewise, though an entity inside the nebula (3) would have forces of gravity pulling it in other directions, those originating from the center of gravity would overpower the others, again causing it to move towards the center. However, an

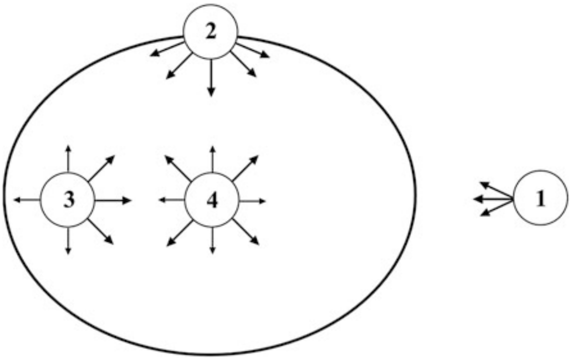

Fig. 1.1 Directions of the force of gravity applied to an entity in different parts of the star-forming nebula

entity which is already located in the gravitational center of the nebula (4) would have forces of gravity drawing it away from the center in all directions of the nebula, effectively cancelling each other out and producing a net gravity force of zero. These entities would then remain in the center of gravity. It is clear that the gravitational collapse of the nebula is inevitable, leading to the concentration of the nebula's mass at its center of gravity. This growing mass in the center would apply a gravity force F on any entity within the nebula according to Newton's law of gravity:

$$F = G\frac{Mm}{r^2}. \tag{1.1.1}$$

where G is the universal gravitational constant (6.67×10^{-11} m^3/kg s^2), M is the mass of the center of gravity of the nebula, m is the mass of an entity in the nebula, and r is the distance between the entity and the center of gravity.

From Eq. (1.1.1) it is obvious that the force of gravity increases with the increase in the central mass M and the decrease of the distance r. The central mass gets larger by absorbing and accumulating the mass of the entities in the nebula drawn into the center, and represents the mass of the growing star. The rates at which the entities in a nebula are drawn into its center are dependent on both the strength of the force of gravity [see Eq. (1.1.1)] and the acceleration g created by this force:

$$g = \frac{GM}{r^2}. \tag{1.1.2}$$

Any central gravity field can be characterized by its gravity potential, which is generated by its mass. The difference in gravitational potential ΔU between any two points is: