HEAT GENERATION AND TRANSPORT IN THE EARTH

Heat provides the energy that drives almost all geological phenomena and sets the temperature, and hence the rate, at which these phenomena operate. This book provides an up-to-date treatise on heat transport processes. It explains the key physical principles with simple physical arguments and scaling laws that allow quantitative evaluation of heat flux and cooling conditions in a variety of geological settings and systems.

The thermal structure and evolution of magma reservoirs, the crust, the lithosphere and the mantle of the Earth are reviewed within the context of plate tectonics and mantle convection – illustrating how theoretical arguments can be combined with field and laboratory data to arrive at accurate interpretations of geological observations. Recent theoretical advances on free convection in many different configurations and in fluids with complex rheologies are explained, and demonstrations of how past climate changes can be reconstructed from temperature data in deep boreholes are presented. Appendices contain up-to-date information on the thermal properties of rocks and melts, as well as measurements of the surface heat flux and rate of radiogenic heat production in a large number of rocks and terrains.

Heat Generation and Transport in the Earth can be used for advanced courses in geophysics, geodynamics and magmatic processes, and is a valuable reference for researchers in geoscience, environmental science, physics, engineering and fluid dynamics. Electronic figure files, data sets and program codes relating to topics in the book can be downloaded from www.cambridge.org/9780521894883.

CLAUDE JAUPART graduated from the Ecole des Mines de Paris before obtaining a Ph.D. in geophysics from MIT and a doctorat d'Etat at the Universite de Paris 7. He has been associated with the University of Paris Diderot and the Institut de Physique du Globe since 1982, where he served as director between 1999 and 2004 and is currently Professor of Geophysics. Professor Jaupart's research covers diverse aspects of the physics of energy transport in the Earth including volcanic and magmatic systems, continental heat flux and mantle convection. His approach is based on a combination of laboratory experiments in fluid mechanics, field observations and theoretical studies. His contributions have been acknowledged by many distinctions: the Wager prize of the International Association of Volcanology and Chemistry of the Earth's Interior (1993), the silver medal of the CNRS (1995), the

Holweck and the Mergier-Bourdeix prizes of the Academie des Sciences (1995, 1998), the Prestwich medal of the Geological Society of London (1999), and the Holmes medal of the European Geophysical Union (2007).

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Introduction

The main object of this book is to study the physical processes that have determined, and continue to determine the thermal structure and evolution of the Earth. It has always been recognized that heat provides the energy that drives all the processes internal to the Earth, and that temperature controls the state and the mechanical behavior of the Earth's interior, but few of the available books focus on the thermal structure and evolution of the Earth and its geological systems. We intend to look at geodynamics from this thermal perspective and to provide the tools and data to determine temperatures at depth in a range of natural settings. We also aim at providing basic physical understanding of key aspects of heat transport in the Earth and thorough discussion of processes and physical properties that determine temperature at depth. It is impossible to discuss geological processes and environmental problems without thermal aspects and analysis must rely on sound grasp of physics as well as on knowledge of the parameters and variables at play.

There are many excellent books on the Earth's interior and on the dynamics of the Earth. In order not to forget any of them, and not to offend their authors, we shall not try to list them. Let us simply state that, although it has become in many ways obsolete, Jeffreys' *The Earth* (1959) has set a standard that is difficult to meet. During the past few decades, our understanding of the Earth's internal dynamics has completely changed. This is of course the result of plate tectonics and of the recognition that mantle convection drives the Earth's processes. During the same recent period, the amount of information and data relevant to the Earth's interior has increased. Spectacular new advances have been made because of spatial geodesy, seismic tomography, geochemistry, high pressure experimental geophysics and planetary exploration. Constraints on the Earth's thermal structure include not only heat flux and heat production data, but use information from xenoliths, petrology, mineral physics and seismic tomography. Experiments (physical or numerical) have given a means to explore the physical processes that drive the

Earth. The time when almost all the information concerning the Earth, its structure and evolution could fit in a single book has passed.

We shall present the basic physical principles and methods used to describe the Earth's thermal regime and to provide an up-to-date review of all the recent and not so recent data that have shaped our understanding of the Earth's thermal regime and thermal history. We shall include applications to illustrate the implications for geodynamics, tectonics and the search for natural resources as well as for environmental issues. Additionally, we feel that most of the available textbooks emphasize mathematical and numerical results at the expense of physical understanding and do not foster the physical intuition that would help them address complex problems in Earth sciences.

In this book, we have tried to select the topics that illustrate best our understanding of the Earth's internal dynamics. Analytical and experimental methods are required to investigate the physical models and to compare them with data on the Earth's interior. Neither have we tried to cover exhaustively the methods of geophysical modeling, nor to present a comprehensive review of all the data. The main challenge in Earth sciences has not been to develop methods of ever increasing complexity or to compile an ever increasing amount of data, but to relate theoretical models to the Earth and to infer what the data imply for Earth dynamics. Our choices may reflect our own biases; we hope that they will present a consistent perspective on geodynamics.

As we now believe that we understand fairly well how the Earth works, it may be sobering to remember that, since Kelvin's determination of the age of the Earth in the nineteenth century until the so-called "equality of continental and oceanic heat flow" that was discussed in the 1960s, thermal data have often been misinterpreted. A historical review will not only put our present synthesis in perspective, it will suggest some caution when we claim that we now understand almost everything.

A review of present knowledge on the Earth's interior is a prerequisite to any study of its internal processes. We have access to the physical properties which are determined with variable resolution by geophysical methods. We infer the composition from geophysical, geo and cosmochemical data, and experimental petrophysics. With increasing resolution, geophysical data have shown that the Earth is not spherically symmetric and provide clear evidence that it is not in static equilibrium.

The only direct information on temperature within the Earth comes from surface heat flux measurements. These data also provide an estimate of the total energy budget of the Earth. Extrapolating the surface temperature gradients downward shows inconsistencies in our knowledge of the state of the mantle and core.

Experimental and geophysical data have shown that the Earth can behave as a very viscous fluid on a geologically short time scale (10,000 years). For the estimated viscosity of the mantle, it can not be thermally stable. The conclusion is inescapable that the Earth's mantle and core are cooling by convection. Most of our understanding of convection in the Earth's mantle comes from physical and numerical experiments.

The formation and destruction of oceanic plates is the result of convection in the mantle. The evolution of oceanic plates is easily described by a simple physical model that explains observations and the physical properties of the oceanic lithosphere. The oceanic plate can also witness and record phenomena in the mantle such as the ascent of plumes. The concept of a plate can also be applied in a strict mechanical sense: the oceanic lithosphere responds to loading and bending as an elastic plate whose properties are determined by the temperature. Temperature also determines the fate of the plate that returns into the mantle.

The lithosphere beneath the continents has recorded a long and complex history. The heat flow and thermal regime of the continents are consistent with the presence of thick rigid roots beneath their stable cores, the "cratons." Intra-continental tectonic activity takes place in the form of continental rifts, basins and plateau uplift. Active tectonic belts coincide with collision zones. The syn and post orogenic deformations are controlled by the rheology of the continental lithosphere.

New continental crust is added at the active margins of the continents. An important part of the continental crust was formed early in the Earth's history. The processes that lead to the differentiation of the continental crust from the mantle, and the stabilization of a differentiated crust were also controlled by the temperature regime.

The thermal evolution of the Earth depends on initial conditions, the slowly decreasing internal heat production and internal redistribution of heat sources, and total heat loss. As the Earth cools down, mantle convection and the nature of its surface expression in tectonic activity evolve. On a smaller scale, magma reservoirs and hydrothermal systems have proven to be formidable challenges for the geologist trying to document their mode of operation, and the physicist aiming to establish simple models. Such a wide range of thermal systems and their manifestations have stimulated the interest of scientists from many different disciplines. It has been a motivation for us and we hope to share it with the readers of this book.

This book is intended for a wide variety of readers with diverse backgrounds: advanced undergraduates and graduate students, researchers and professional geoscientists. Our aim was not to write a mathematical treatise, but a quantitative treatment of thermal conduction and convective transport of heat sometimes requires the use of applied mathematics. For the interested readers, we provide a review of some standard techniques in the appendices, but knowledge of these methods is not a prerequisite for reading most chapters. We tried to follow a logical sequence in our presentation, but each chapter can be read independently of the others, and readers are invited to skip sections that are too "technical" and to decide for themselves the order in which they want to read this book.

Credits

All the maps shown in this book were made by the authors with Generic Mapping Tools (GMT) software that was developed for and made available to the geosciences community by Wessel and Smith (1995). Figures were made by the authors with GMT and commercially available software. Data used for the maps comes from several geophysical data repositories. We wish to acknowledge the center for satellite geodesy site of David Sandwell, and the reference earth model site maintained by Gabi Laske and Guy Masters, all at the Scripps Institute of Oceanography. Seismic tomography data were obtained from the CUB2.0 site of Mike Ritzwoller at the University of Colorado and from Susan Van der Lee, at Northwestern University. We are grateful to Maria Richards and David Blackwell at Southern Methodist University for sharing their North American heat flow data base, and to Gabi Laske, and Francis Lucazeau, at Institut de Physique du Globe de Paris, for sharing their data base of world heat flow measurements.