Dynamic Earth

Plates, Plumes and Mantle Convection

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CHAPTER 1

Introduction

1.1 Objectives

The purpose of this book is to present the principles of convection, to show how those principles apply in the peculiar conditions of the earth's mantle, and to present the most direct and robust inferences about mantle convection that can be drawn from observations. The main arguments are presented in as simple a form as possible, with a minimum of mathematics (though more mathematical versions are also included). Where there are controversies about mantle convection I give my own assessment, but I have tried to keep these assessments separate from the presentation of principles, main observations and direct inferences. My decision to write this book arose from my judgement that the broad picture of how mantle convection works was becoming reasonably settled. There are many secondary aspects that remain to be clarified.

There are many connections between mantle convection and geology, using the term 'geology' in the broadest sense: the study of the earth's crust and interior. The connections arise because mantle convection is the source of all tectonic motions, and because it controls the thermal regime in the mantle and through it the flow of heat into the crust. Some of these connections are noted along the way, but there are three aspects that are discussed more fully. The first is in Part 1, where the historical origins of the ideas that fed into the conception of mantle convection are described. Especially in Chapter 2 those historical connections are with geology. Another major connection is through Chapter 13, in which the relationship between mantle chemistry and mantle convection is considered. The third respect arises in the last chapter, where the broad tectonic implications of hypothetical past mantle regimes are discussed.

A theory of mantle convection is a *dynamical* theory of geology, in that it describes the *forces* that give rise to the motions apparent in the deformation of the earth's crust and in earthquakes and to the magmatism and metamorphism that has repeatedly affected the crust. Such a dynamical theory is a more fundamental one than plate tectonics, which is a *kinematic* theory: it describes the *motions* of plates but not the forces that move them. Also plate tectonics does not encompass mantle plumes, which comprise a distinct mode of mantle convection. It is this fundamental dynamical theory that I wish to portray here.

This book is focused on those arguments that derive most directly from observations and the laws of physics, with a minimum of assumption and inference, and that weigh most strongly in telling us how the mantle works. These arguments are developed from a level of mathematics and physics that a first or second year undergraduate should be familiar with, and this should make them accessible not just to geophysicists, but to most others engaged in the study of geology, in the broad sense. To maximise their accessibility to all geologists, I have tried to present them in terms of simple physical concepts and in words, before moving to more mathematical versions.

For some time now there has been an imperative for geologists to become less specialised. This has been true especially since the advent of the theory of plate tectonics, which has already had a great unifying effect on geology. I hope my presentation here is sufficiently accessible that specialists in other branches of geology will be able to make their own informed judgements of the validity and implications of the main ideas.

Whether my judgement is correct, that the main ideas presented here will become and remain broadly accepted, is something that only the passage of time will reveal. Scientific consensus on major ideas only arises from a prolonged period of examination and testing. There can be no simple 'proof' of their correctness.

This point is worth elaborating a little. One often encounters the phrase 'scientifically proven'. This betrays a fundamental misconception about science. Mathematicians prove things. Scientists, on the other hand, develop models whose behaviour they compare with observations of the real world. If they do not correspond (and assuming the observations are accurate), the model is not a useful representation of the real world, and it is abandoned. If the model behaviour does correspond with observations, then we can say that it works, and we keep it and call it a theory. This does not preclude the possibility that another model will work as well or better (by corresponding with observations more accurately or in a broader context). In this case, we say that the new model is better, and usually we drop the old one.

However, the old model is not 'wrong'. It is merely less useful, but it may be simpler to use and sufficient in some situations. Thus Newton's theory of gravitation works very well in the earth's vicinity, even though Einstein's theory is better. For that matter, the old Greek two-sphere model of the universe (terrestrial and celestial) is still quite adequate for navigation (strictly, the celestial sphere works but the non-spherical shape of the earth needs to be considered). Scientists do not 'prove' things. Instead, they develop more useful models of the world. I believe the model of mantle dynamics presented here is the most useful available at present.

Mantle convection has a fundamental place in geology. There are two sources of energy that drive geological processes. The sun's energy drives the weather and ocean circulation and through them the physical and chemical weathering and transport processes that are responsible for erosion and the deposition of sediments. The sun's energy also supports life, which affects these processes.

The other energy source is the earth's internal heat. It is widely believed, and it will be so argued here, that this energy drives the dynamics of the mantle, and thus it is the fundamental energy source for all the non-surficial geological processes. In considering mantle dynamics, we are thus concerned with the fundamental mechanism of all of those geological processes. Inevitably the implications flow into many geological disciplines and the evidence for the theory that we develop is to be found widely scattered through those disciplines.

Inevitably too the present ideas connect with many ideas and great debates that have resonated through the history of our subject: the rates and mechanisms of upheavals, the ages of rocks and of the earth, the sources of heat, the means by which it escapes from the interior, the motions of continents. These connections will be related in Part 1. The historical origins of ideas are often neglected in science, but I think it is important to include them, for several reasons. First, to acknowledge the great thinkers of the past, however briefly. Second, to understand the context of ideas and theories. They do not pop out of a vacuum, but emerge from real people embedded in their own culture and history, as was portrayed so vividly by Jacob Bronowski in his television series and book *The Ascent of Man* [1]. Third, it is not uncommon for alternative possibilities to be neglected once a particular interpretation becomes established. If we returned more often to the context in which choices were made, we might be less channelled in our thinking.

1.2 Scope

The book has four parts. Part 3, Essence, presents the essential arguments that lead most directly to a broad outline of how mantle dynamics works. Part 2, Foundations, lays the foundations for Part 3, including key surface observations, the structure and physical properties of the interior, and principles and examples of viscous fluid flow and heat flow.

Parts 1 and 4 connect the core subject of mantle convection to the broader subject of geology. Part 1 looks at the origin and development of key ideas. Part 4 discusses possible implications for the chemical and thermal evolution of the mantle, the tectonic evolution and history of the continental crust. Many aspects of the latter topics are necessarily conjectural.

1.3 Audience

The book is intended for a broad geological audience as well as for more specialised audiences, including graduate students studying more general aspects of geophysics or mantle convection in particular. For the latter it should function as an introductory text and as a summary of the present state of the main arguments. I do not attempt to summarise the many types of numerical model currently being explored, nor to present the technicalities of numerical methods; these are likely to progress rapidly and it is not appropriate to try to summarise them in a book. My expectation is that the broad outlines of mantle convection given here will not change as more detailed understanding is acquired.

In order to accommodate this range of readership, the material is presented as a main narrative with more advanced or specialised items interspersed. Each point is first developed as simply as possible. Virtually all the key arguments can be appreciated through some basic physics and simple quantitative estimates. Where more advanced treatments are appropriate, they are clearly identified and separated from the main narrative. Important conclusions from the advanced sections are also included in the main narrative.

It is always preferable to understand first the qualitative arguments and simple estimates, before a more elaborate analysis or model is attempted. Otherwise a great deal of effort can be wasted on a point that turns out to be unimportant. Worse, it is sometimes true that the relevance and significance of numerical results cannot be properly evaluated because scaling behaviour and dependence on parameter values are incompletely presented. Therefore the mode of presentation used here is a model for the way theoretical models can be developed, as well as a useful way of reaching an audience with a range of levels of interest and mathematical proficiency.

1.4 Reference

1. J. Bronowski, *The Ascent of Man*, 448 pp., Little, Brown, Boston, 1973.