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Historical notes

1.1 Introduction

The important questions that relate to the Earth's thermal regime and energy budget were raised a long time ago and some are still waiting for a complete answer. These past debates have more than historical interest. Our present understanding of the Earth's dynamics is based on the answers that were given to these questions.

People who live in volcanic areas always had the intuition that temperature increases with depth in the Earth. That it must be so everywhere became clear to scientists and engineers with the development of coal mining and the construction of deep tunnels in the nineteenth century.

Among the many advances in physics during the nineteenth century, development of the theory of heat conduction and of thermodynamics had immediate implications for the understanding of the internal structure and evolution of the Earth. The scarcity of data did not hamper physicists in speculating about the temperature regime inside the Earth.

1.2 Kelvin and the age of the Earth

When Fourier first published *Théorie Analytique de la Chaleur*, the temperature gradient of the Earth was estimated to be $\approx 20\ \mathrm{K\,km^{-1}}$, a value not very different from our present estimates. Fourier analyzed the temperature inside the Earth and concluded that the Earth had retained most of the heat from its formation. This conclusion was the basis for the calculation by Lord Kelvin of the age of the Earth (Thompson, 1862). Kelvin's study triggered a very serious debate between physicists and geologists and has received much attention from the historians. Indeed, it was one of the first examples of the difficult dialogue between physicists and geologists. It had long lasting consequences, not only because for many geologists it discredited the approach of the physicists, but mainly because Kelvin's approach influenced many leading geophysicists during the first half of the twentieth century. Sir Harold Jeffreys, who was the most influential geophysicist of that time, held views on the thermal history of the Earth that were not very different from those of Kelvin. Kelvin's calculation rested on two assumptions, i.e. (1) that the Earth is cooling by conduction, and (2) that there are no sources of heat inside the Earth. All the important questions concerning the Earth's thermal structure and evolution are related to these two assumptions: (1) What is the energy budget of the Earth? (2) What is the mechanism of heat transport inside the Earth? (3) What is the exact amount and distribution of radioactive elements in the continental crust and mantle?

At the time of Kelvin's paper, the Earth's temperature gradient had been estimated to be in the range 20–30 K km^{-1}. Kelvin thought that this data would constrain the age of the Earth. He assumed that the Earth was initially at a uniform temperature of 2000 K and that its surface stayed at constant temperature, $\approx 0\,^{\circ}$C. Such an initial temperature seems extreme today but it appeared reasonable at the time of Kelvin and is of the correct order of magnitude. Kelvin also assumed that there were no internal heat sources. The only internal heat sources that were known at the time were chemical reactions, or conversion of gravitational potential energy into heat. Chemical reactions were assumed to contribute little because they are not reversible and hence could not go on for a long time. Although Kelvin knew from the mean Earth density and from moment of inertia measurements that density increases inside the Earth, he did not consider gravitational settling of a dense core as a source of energy.

For a conductive half-space, with initial temperature T_0, and with constant surface temperature $T = 0$, Kelvin showed that the surface temperature gradient decreases with time t as $t^{-1/2}$. It is given by

$$\frac{\partial T}{\partial z} = \frac{T_0}{\sqrt{\pi \kappa t}}, \tag{1.1}$$

where κ is the thermal diffusivity of the Earth. Kelvin could thus use this equation to determine how long it would take for the temperature gradient to drop to 20 K km^{-1}. The calculation yields ≈ 100 My. At that time, many geologists were influenced by Hutton's view that there was no beginning or end to geological time ("No vestige of a beginning, no prospect of an end"). Kelvin's result came as a shock and was rapidly challenged. Geologists proposed alternative methods to date the Earth and obtained older ages. They estimated from sedimentation rates and the thickness of sedimentary deposits that the age of the Earth was at least 500 My. It is correct that Kelvin ignored the Earth's radioactivity and convection in his calculation. It is more likely that ignorance of the energy source for the Sun was the main source of Kelvin's error. The only source of solar energy known to Kelvin was the conversion of gravitational potential energy into heat. Dividing the total

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gravitational potential energy available by the present rate of energy radiation by the sun yields an upper limit for the age of the Sun, which was on the same order as his estimated age of the Earth. This coincidence convinced Kelvin that his calculation was essentially correct.

One should note that in Kelvin's cooling model, the surface heat flow and temperature drop very rapidly and there is no cooling of the deep interior of the Earth: Kelvin's estimate is for the cooling of a shallow boundary layer. It would have made a difference if Kelvin had assumed an isothermal well-mixed "mantle" that cools due to the heat lost through a thin conductive plate < 100 km thick. It takes only a few tens of My for the temperature gradient to drop to 20 K km^{-1}. If applied to oceanic heat flux measurements, Kelvin's method yields a reasonable estimate of the age of the sea floor. Perry (1895a,b,c) showed that the temperature gradient would imply a much greater age if the thermal conductivity increases with depth. This higher thermal conductivity could account for the effect of convection beneath the thin skin of the Earth (England *et al.*, 2007).

Kelvin favored an initial temperature of $\approx$2000 K, close to contemporary estimates of the melting temperature in rocks at room pressure. A much higher estimate of the age of the Earth could have been obtained by including the melting temperature gradient. Assuming an initial temperature of 2000 K at the surface and a melting temperature gradient of 3 K km^{-1}, Jeffreys (1942) obtained an age of 1.6 Gy. Many historical studies have discussed these calculations and the assumptions that went into them. One must remember that Kelvin relied on an estimate of the temperature gradient that had been obtained in continents and could not appreciate the fundamental differences between oceans and continents. After his paper, the debate rapidly focused on internal heat generation by radioactive decay and on the distribution of heat-producing elements within the Earth. The issue of heat transport by convection was raised much later.

1.3 The discovery of radioactivity

Kelvin's assumption that there is no long-lived source of energy in the Earth was soon to be disproved. By 1895, Kelvin was convinced that all the laws of physics had been established and that the end of physics was in sight. The discovery of radioactivity by Becquerel in 1896 was to lead to a revolution in physics and it changed completely our understanding of the Earth's energy budget. Until then, it had been assumed that the Earth is cooling from an initial hot state. The presence of long-lived radioactive elements provided a source of energy that could balance the loss of heat through the Earth's surface. The importance of radioactivity for the Earth's energy budget was soon appreciated and discussed by Strutt (1906), Joly (1909) and Holmes (1915a,b).

The question was raised as to whether the Earth was heating because of radioactivity or whether the heat flow contained also a component due to the cooling of the Earth. Although it is now clear that the Earth must be cooling, the contribution of secular cooling to the energy budget remains very poorly constrained today.

Another consequence of the discovery of radioactivity is that radiogenic heat production of rocks could be compared with the heat flow and used to constrain the composition of the Earth. Strutt (1906) used estimates of radiogenic heat generation and the heat flux at the Earth's surface to conclude that the Earth had a crust that could not be thicker than 60 km. This suggestion was made three years before the confirmation of the existence of the crust by seismology.

Seismology provided the first models of composition of the continental crust. It suggested that the crust was made up of two main layers with seismic velocities consistent with granitic and gabbroic compositions for the upper and lower crust respectively. Granitic rocks that are very enriched in U and Th have an average heat production of $\approx 3\ \mu\text{W m}^{-3}$. A granitic composition for the upper 20 km of the Earth's crust was consistent with seismic velocity, but not consistent with heat flux data.

1.4 The debate on the cooling mechanism of the Earth

The other assumption by Kelvin was that in the Earth heat is transported by conduction only. This assumption was not challenged on physical grounds but was questioned by a minority of geoscientists in the wake of the debate following Wegener's continental drift hypothesis. In retrospect, one can see that the most damaging flaw in the various arguments put forward at that time was the lack of reliable heat flux measurements and, more specifically, of measurements at sea. Had Kelvin known that the surface heat flux varies by more than a factor of three over the limited extent of his own country, he would not have been able to advocate a simple cooling model for the whole planet. The large lateral variations of heat flux that occur on Earth provide information on cooling mechanisms and heat sources that are as important as the global average.

Holmes (1931) was among the first to suggest that radioactivity would cause heating of the Earth and that convection was the most efficient mechanism of transporting this heat to the surface. He suggested that the higher heat production in continents would heat the mantle underneath and cause rising convection currents and continental breakup. Pekeris (1935) and Hales (1935) also examined the differences in continental and oceanic thermal regimes. Both authors assumed that the continental mantle was hotter than the oceanic mantle because of the crustal radioactivity. They concluded that these temperature differences would induce large stresses that were probably sufficient to cause convection. Convection in the Earth's mantle was rejected by the vast majority of geophysicists who believed the Earth's mantle could not sustain large deformations, despite the evidence from post-glacial rebound that the mantle can deform on a 10,000 years time scale.

1.5 Heat flux measurements

Few reliable heat flux estimates had been obtained before 1939, although it was becoming increasingly clear that heat flow data would provide constraints on crustal composition. Heat flow measurements require simultaneous determination of the temperature gradient in the Earth and of the thermal conductivity. Anderson (1934) made the first estimates of heat flow in England from temperature gradients measured in boreholes and the thermal conductivity of the main rock sections. From values in seven drill-holes, he concluded that the average heat loss of the Earth was 63 mW m^{-2}. In two papers reporting on measurements in England and South Africa, Benfield (1939) and Bullard (1939) established the standard procedure for measuring continental heat flux. Some ten years later, following the first determinations by Petterson (1949), Bullard *et al.* (1956) took the initiative of developing a program of oceanic heat flux measurements. He developed a probe that measures and records temperature and the thermal diffusivity of sea-floor sediments. Bullard had conjectured that heat flux would be lower in the oceans because of the absence of a radioactive crust. The first heat flux measurements suggested an approximate equality of continental and oceanic heat flow. This "equality" was interpreted as suggesting that the continental crust had differentiated from the underlying mantle, now depleted in radioelements, while the oceanic crust rested on a mantle that had retained its heat producing elements. The implication was that the oceans and continents were fixed relative to the mantle. The so-called equality of oceanic and continental heat flux was used as an argument against continental drift even after oceanic heat flux and bathymetry were explained by the cooling plate model. The inconsistency of the argument had not escaped Bullard (1962) who pointed out that heat originating from the lower mantle can not be brought to the surface of the Earth by conduction in the time available.

1.6 Energy budget of the Earth

Kelvin's basic assumption was that the Earth is cooling from an initially hot state. Following the discovery of radioactivity, the flow of heat out of the Earth no longer required the Earth to be cooling. The Earth's energy budget could not be determined as long as the total amount of radioelements in the Earth was not known. Holmes (1931) argued that, with continental heat flux low relative to heat production, the Earth might even warm up. He also proposed that the Earth's surface gets rejuvenated and shaped by convection currents. Following Jeffreys (1921), most of the opponents to convection in the mantle argued for cooling of the Earth because thermal contraction was their favored mechanism of mountain building. The mechanism of heat transfer and the energy budget are two independent issues, however, as convection can occur in both cooling and heating planets. Ironically, that part of Earth's topography which lies below sea level is indeed due to thermal contraction, but we know now that it is one of the most prominent manifestations of convection. Once again, the different processes that affect continents and oceans confused the best physicists of their time.

Urey (1964) noted that if the Earth had a composition identical to that of the chondritic meteorites, its heat production would be equal to the heat loss (then estimated at 30 TW), suggesting that the Earth's energy budget could be in equilibrium. However, Birch (1965) and Wasserburg *et al.* (1964) noted that the Earth is depleted in K relative to the chondrites and that a K-depleted chondritic Earth could account only for a fraction of the Earth's energy budget. The value of the ratio of total heat production to total heat loss of the Earth, the *Urey* ratio, remains controversial today with estimates ranging between 0.2 and 0.8.

The analysis of Pb isotopes by Patterson (1956) yielded an estimate of 4.55 Gy for the age of the Earth. Calculating the thermal history of a conducting Earth requires knowledge of the distribution of heat sources and of variations in thermal conductivity within the Earth, as well as the initial and boundary conditions. Only the boundary conditions are known. With improved understanding of heat production and the physical properties of the interior of the Earth, it became feasible to investigate conductive thermal evolution models for the interior of the Earth. Jacobs and Allan (1956) and MacDonald (1959), had to introduce questionable initial conditions in their calculations to obtain a thermal history consistent with the few constraints on temperature in the interior of the Earth. The thermal models of MacDonald (1959) required that radiation be the dominant mechanism of heat transfer in the Earth's mantle, which was later ruled out by experimental data.

1.7 Plate tectonics

The failure of conductive thermal evolution models of the Earth was not an important factor in the establishment of plate tectonics. On the contrary, it is the geophysical and geological evidence that led to recognition that the motion of tectonic plates accompanies mantle convection and cooling of the Earth's mantle.

As plate tectonics was emerging, thermal evolution models successfully explained the thermal regime of the oceanic lithosphere and could address that of the Earth's mantle. The success of the cooling plate model to explain variations in sea-floor heat flux and bathymetry was one of the first examples of the successful application of physical models in geology. The discrepancy between heat flux observations and model predictions led to discovery of hydrothermal circulation near the mid-oceanic ridges and to an understanding of the physical processes that control it.

On a different scale, although the actual numbers have not changed by orders of magnitude, the energy budget of the Earth is much better quantified today than it was 50 years ago. Not only is the total heat loss estimated with greater precision than before, but other terms that enter into the budget have been identified and estimated.

Kelvin's model of a cooling Earth raised two questions: what is the cooling mechanism? what are the sources of energy? Today, there can be no doubt that mantle convection is the dominant mechanism of heat transport in the Earth, even though many details of how it operates remain elusive. On the other hand, uncertainties about the different terms that enter the energy budget remain incapacitating. This is only one among many open questions about the Earth's thermal history and convection regime. This short historical account illustrates that significant advances have been achieved through both theory and observation. With no theory, the effect of time, a key variable, cannot be accounted for properly. With insufficient data, theoretical assumptions cannot be tested convincingly and calculations may run on empty. Kelvin would probably have thought differently had he realized how variable the heat flux and temperature gradient are at the Earth's surface. We shall see in this book that convection theory must still be considered as being in a development stage and that some critical data are still missing. This statement is valid for both the large-scale question of secular cooling of the Earth, intermediate-scale tectonic problems which require good control of crustal rheology and hence temperature, as well as small-scale issues on the behavior of magma bodies and their effects on crustal processes.

2

Internal structure of the Earth

Objectives of this chapter

The Earth can be compared to a big thermal engine: its internal heat provides the energy that drives all geodynamic processes and its long term evolution is governed by cooling. The total energy of the Earth depends on its internal structure and composition. How energy is transported in the Earth depends on its physical properties, which are controlled by the thermal structure. Here, we review some basic geophysical information about the present state of the Earth's interior and show how it is related to the thermal regime and the energy budget of the Earth. This chapter is not intended as a comprehensive description of the Earth and its main units and is focused on aspects that are most relevant to heat generation and transport.

2.1 Introduction

This chapter is focused on the silicate Earth which is made of a thin crust over a thick mantle, lying above a central metallic core. For the sake of brevity, we do not explain plate tectonics and assume familiarity with some of its basic premises and terminology. Mid-ocean ridges are zones of shallow sea floor where volcanic eruptions and earthquakes occur frequently. The sea floor is formed out of the mantle there, moves horizontally, and eventually returns into the mantle through deep trenches in a process called *subduction*. The implicit assumption is that the sea floor does not deform as it moves away from a ridge so that the velocity field at the Earth's surface can be accounted for by the relative motions of a small number of rigid plates. Their velocities have been determined by many different methods, from geophysical and geological techniques tracking displacements on time scales of several million years to land-based or satellite-based laser ranging on time scales of a few years. Velocity values vary by about one order of magnitude between ≈ 1.5 and 15 cm y^{-1}. We know a lot about the surface of the Earth for obvious reasons and the challenge we face is to link surface activity to the deep mantle motions and forces. On Earth, the main driving force is buoyancy, which involves large volumes and hence large depth extents. Buoyancy forces maintain movement in a viscous material through a process called *convection*. Convection also transports heat and may be contrasted to *conduction*, a process that transports heat through a motionless material. We shall often refer to the lithosphere, which has several different definitions. We shall discuss this in detail in various parts of the book. For the moment, we will use the term lithosphere to denote the rigid outer shell of the Earth that moves coherently in response to convective forces. The energy that must be expended to sustain deep mantle motions as well as surface deformation can only be drawn from the interior of the Earth. Thus, solutions to the vast majority of geological problems must ultimately be sought at depth, in the mantle. Due to current limitations, neither theory nor observation can on their own provide the required answers and must be used in combination. This will be a recurrent theme of this book.

The general method used in geophysics is to determine an average spherically symmetric structure described by radial profiles of the relevant properties and variables, and to seek lateral deviations from this gross structure, called *anomalies*. We shall see, however, that even radial profiles provide useful information on dynamics and convection. By 1940, the gross structure of the Earth had been worked out. There is surprisingly little difference between that structure, revealed by Jeffreys and Bullen in 1940, and recent Earth reference models like PREM or IASPEI91 (Dziewonski and Anderson, 1981; Kennett and Engdahl, 1991). Today, these reference models serve a completely different purpose: they provide the standard from which departures from spherical symmetry are determined. This change in objective reflects the evolution from a static perspective of the internal structure of the Earth into a dynamic one.

The Earth and meteorites have approximately the same age of 4.55 Gy. It is thought that Earth and the planets accreted very rapidly from planetesimals that formed in the nebular cloud. In the Earth, the differentiation between the metallic core and the silicate mantle took place in <100 My, during the accretion. It is also believed that, at the end of the accretion, the Earth was impacted by a Mars-sized body and the ejecta from this collision formed the Moon and may have re-homogenized the Earth. After impact, the Earth had reached a mass close to present, and the core possibly differentiated for a second time. The oldest preserved crust dates to 4.18 Gy, but older ages from recycled minerals (zircons) indicate that some crust had already formed at 4.4 Gy, i.e. very soon after the Moon forming impact event. There are also clear indications from extinct isotopes in very old gneisses that crustal differentiation started very early in Earth history. The heat released during accretion, core formation and the impact event determined the initial thermal state of the Earth. The early stabilization of some crust provided some constraint on the cooling of the young Earth.

Most of the recent progress in geodynamics has followed technological advances that provide more and better measurements, in particular the development of space geodesy, and the capability to process large amounts of data. Satellite measurements provide very precise and high resolution data sets for sea-floor bathymetry and land topography, continuous data sets for potential fields and high resolution local images. It is now possible to measure directly deformations of the Earth surface over wide areas thanks to satellites. Global and regional seismic networks provide three-dimensional images of the mantle. Gravity anomalies provide information on departure from spherical symmetry. Finally, theory, laboratory and numerical experiments allow us to investigate the underlying physical processes.

The crust is much thicker under continents than under oceans. More subtle differences between continents and oceans extend to great depth (300 km) and involve lateral variations of both composition and temperature. The nature of these differences and their implications for geodynamics are beginning to be understood in part because sufficient heat flux and heat production data are now available.

2.2 Gravity and geodesy

The shape of the Earth and its gravity field depend on internal density structure and rheology. The large free-air gravity anomalies that are observed indicate the presence of lateral variations in density due to temperature and composition. These anomalies are associated with large buoyancy forces that drive convective motions.

2.2.1 Moment of inertia, angular momentum and energy of rotation

The moment of inertia of a body relative to an axis is

$$I = \int_V \rho r^2 dV, \tag{2.1}$$

where r is the distance to the axis. The moment of inertia is measured in kg m^2. For a sphere of mass M with uniform density and radius R, the moment of inertia $I_H = 0.4\ MR^2$. For the Earth, the polar moment of inertia (i.e. relative to the axis of rotation) $C = 0.33\ MR^2$, which is less than I_H. Using equation 2.1, one can deduce that density increases toward the Earth's center. This had been noted in the early nineteenth century and led to the discovery of a core denser than the mantle. The moment of inertia is a powerful constraint on the radial density distribution of the Earth. For example, the density distribution that was first derived from seismic velocity through the Adams–Williamson equation (equation 3.48) failed to