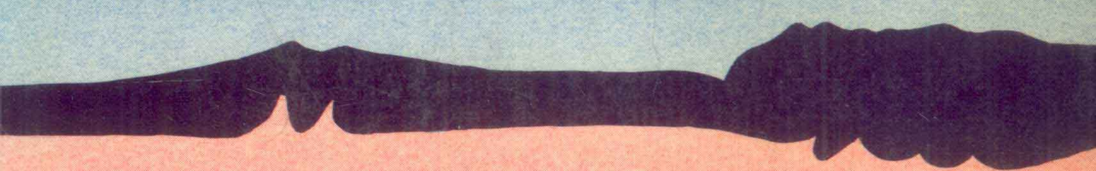
THE BOWELS OF THE EARTH

JOHN ELDER



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Preface

WRITING a book such as this is like arranging a tour of a very large art gallery. Some people want to dash past every picture in the place, others prefer just to look at a few masterpieces. I have chosen neither of these approaches. My tour takes one strong aspect of the subject—the role of scale—and follows it from large to small systems. As a result some rooms are not seen at all, and even some great masterpieces and contemporary disasters are ignored.

The material is presented in 15 chapters. Chapter 1 is an introduction. Chapters 2–6 are about the earth as it is, in the broadest terms—global geology. Chapters 7–12 deal with macro-dynamics—the behaviour of systems generally of greater scale than the thickness of the upper mantle. Chapters 13–15 are a selection of topics on meso-dynamics—more or less self-contained systems resident in the upper mantle and crust.

The first few chapters deal with matters on the largest scale and ask only the slightest of questions. In later chapters we see the highly self-interactive nature of the earth and realize that many of our early ideas were rather naïve. I prefer this gradual unfolding of the story rather than a treatment in which every part is handled on the same level. Further, I have taken considerable liberty with ordering the material, which is presented as if it were discovered in the order given, whereas often it didn't happen like that at all.

Four features of the arrangement of the book should be noted.

1. There is no explicit reference in the text to the diagrams and tables. Rather, these are exhibits, placed near the relevant text.

2. There is an extensive glossary–index, a kind of micro-encyclopedia. This avoids the distraction of having the text cluttered with important but minor items of information. The glossary includes enough details for this book as well as some information that should be helpful to the beginner when reading other related books.

3. More elaborate discussions of particular models are labelled 'Theoretical sketch'. This is an attempt to cope with the problem of variation in readers' backgrounds.

4. There are no references given in the body of the text. This was not an easy decision. The literature of the subject is vast and usually many people have contributed to each part of it. The proportion that could be

referenced in a small book like this one would give quite a false impression. The source material used in this book is taken from the books and articles referred to in the reading list and glossary–index.

Who is this book written for other than myself?

The man in the street. You should see one aspect of modern geology very clearly: our understanding of dynamical processes inside the earth—a sort of meteorological or physiological insight. The glossary–index will be especially helpful, not only for this book but for others which cover related topics. I hope you won't be put off by rather a lot of mathematical formulae.

The student. Perhaps you are studying science at school or are a university undergraduate. You will find the material in this book useful as a supplementary text in understanding the broader dynamical aspects of the earth's interior. All the topics are treated with a minimum of description but are all quite quantitative. The problems (p. 185), many of which are very difficult, are for you to tackle. I hope you find them stimulating.

The teacher. This is not a course textbook, but I expect you will find useful teaching material in it. Any teacher of a natural science faces an awful dilemma. The great scope of the subject and the technical and professional requirements demand an enormous amount of purely descriptive material. Unfortunately this tends to leave too little time for experimentation and the strictly scientific as opposed to the technical side of the subject. Teachers recognize this difficulty all too well, but should not be content with just 'tarting up' the subject with descriptions of the latest fashionable ideas. Let us take a lesson from our maths, physics, and chemistry colleagues and leave most of the description in books, making our students spend their time doing experiments, simulations, and problems. I don't pretend that this book is the answer to these difficulties, but I hope that its approach will suggest useable teaching devices to you.

The expert. I have very little here for you. None of the material is new, but some of it is in a new guise. Of this, perhaps the most novel is the thermal history story of Chapter 9 (a nice elaboration of some work of mine done in 1967) and the ideas on magmatic discharge rates in Chapter 14 (which is simply a 'translation' of my work, done in 1960 and published in 1966, on fumaroles and geysers). Although an elementary book, this is an attempt to give a quantitative and consistent scenario of the range of interior physical processes. I hope you won't mind too much when you see me skating on thin ice.

This book is based on material that I have used since 1970 in short courses on geophysics and macrogeology which form a part of the undergraduate geology programme given by members of the Department of Geology at

Manchester University. During the lectures I have given on this material I have, both for fun and with serious purpose, passed round the class various objects which are referred to as 'the earth'. For example, on the first day, after pretending to walk through the solar system, I pick up 'the earth', and say 'This is the earth. Mm, it is quite massive, and rather squashy. Here, you feel it, but be careful not to damage it.' The object is a bladder filled with sand. For the lecture on the earth as a jumping bean I use a large flat aluminium annulus. The hot earth calls for a brick saturated with hot water. And so on. The idea is to get used to thinking about the earth just as you do about any other object, to feel that it is as familiar to you as a stone held in your hand. Many objects around you will suggest analogues with the earth or one of its parts; the kitchen abounds with opportunities. As you go through this book try to think of something in your everyday experience which has properties a bit like those of that particular aspect of the earth. It is often much easier to think about a simple analogue. Of course, a multi-layered cake is not the same as the earth, but there may be things that you notice in a cake that suggest useful ideas about the earth. Even so, in this book, I am more interested in the recipe than the cake.

J. W. E.

Department of Geology
Manchester University
November 1974

Acknowledgements

I HAVE DRAWN on a wide range of material from textbooks and journals. Most of this material is readily available in the items of the reading list and glossary–index. I am grateful to the following authors and publishers for supplying photographs or giving permission to use their visual material (any minor alteration or adaptation is my own): Fig. 4.1: Geodetic Institute, Copenhagen; Figs. 8.5, 8.7, 8.8(b), 8.9(a), (b): J. W. Deardorff; Fig. 12.2: C. J. Cambell; Fig. 12.3: J. Fitch; Figs. 12.5, 14.6: H. Ramberg; Fig. 13.5: N.Z.D.S.I.R.; Fig. 13.9: the Royal Society London; Fig. 13.12: B. I. Nielsen; Fig. 14.2: P. G. Harris; Fig. 14.11: Fred Bullard (University of Texas Press); Fig. 15.1: T. Huntingdon.

Two areas of my own experience, work in the field and teaching undergraduate geology students at Manchester, have dominated the writing of this book and I wish to express my gratitude to the many people involved, especially to my friends and colleagues in the Department of Geology at Manchester University, the New Zealand D.S.I.R., the Geological Survey of Japan, the Societa Lardarello, and the Greenland Geological Survey. By no means least, many individuals have helped with the task of converting the original manuscript into its present form. I will mention only a few: Patricia M. Crook who typed it, Sue Maher who made some lovely photographs, and Dr. Bill Sowerbutts who read and commented on it. I should also like to thank the staff of the Oxford University Press for their help and encouragement during the writing of this book.

Notes on reading this book

1. Technical terms which are not defined in the body of the text are defined in the glossary–index. Symbols are defined there too. The glossary should be frequently used by the layman.

2. Information that is common knowledge and can be found in a standard dictionary or small encyclopedia is not defined in the text or the glossary. I have in general used the rule that where an item of information can be checked or followed up by reference to the *Encyclopaedia Brittanica* (1974), I have given explicit information only if the item is important to the argument.

3. Where numerical values are needed for the magnitude of quantities, standard values as given in the glossary are used, unless stated to the contrary, and are not repeated explicitly in the text. Many of these values are known to adequate accuracy but others are either unknown or, at best, known only to an order of magnitude. This is noted together with the often somewhat arbitrarily chosen value to be used here.

4. Most quantities are quoted in System International (SI) units using: m, metre; kg, kilogram; s, second; K, degree Kelvin and multiples of these units. Electrical and optical quantities are not needed in this book. SI additional units and their multiples are used for:

angle, time, mass (ton = 10^3 kg), pressure (bar = $10^5\,\mathrm{N\,m^{-2}}$), temperature (°C), viscosity (P, poise = $0{\cdot}1\,\mathrm{kg\,m^{-1}\,s^{-1}}$).

I also use d, 1 day = 86 400 s and yr, 1 year = $3{\cdot}156 \times 10^7$ s.

Densities are always given in the units $10^3\,\mathrm{kg\,m^{-3}} = \mathrm{g\,cm^{-3}} = \mathrm{ton\,m^{-3}}$ and never in multiples.

5. Some help in coping with the variety of units used in existing literature is given in the glossary. In geophysics the commonest other units are those of the centimetre–gram–second–calorie system.

Prelude: A glimpse of neolithic cosmogony

An extract from Chapter IV, *The Maori*, by ELSDON BEST, 1924 (2 vols.) (H. H. Tombs, Wellington).

IN MIST-LADEN DAYS of the remote past the sky and earth were not parted as we now see them, for Rangi the Sky Father closely embraced Papa the Earth Mother. All was darkness between them, no light existed, nothing could mature, nothing could bear fruit, all things merely existed, or moved aimlessly about in a realm of darkness. When the children [the forces of nature] of these primal parents were born they found themselves dwelling in darkness, and clung to the body of the Earth Mother, sheltering within her armpits. [The Unknowable] prevailed.

The offspring soon became discontented with their lot in the world. The conditions of life were irksome and unpleasing, so cramped they were for space. This lack of space was the result of the close contact of their parents at that remote period, for Rangi still embraced Papa; sky and earth were close together. It was Tane [light] who proposed to separate them, saying: 'Let us part our parents; let us force Rangi upward, suspend him on high, and let Papa lie in space'. That task proved to be a difficult one, so closely did the parents cling together in their great affection for each other. It was found to be necessary to sever the arms of Rangi ere he could be forced upward. The blood from his grievous wounds flowed over, and was absorbed by the body of Papa, hence the horu or red ochre found within her body even unto this day.

A time came when the grief of Papa on account of her separation from Rangi, her old-time love, came to be known to Io in the uppermost heaven. The sound of her wailing was borne upward, hence Io sent Ruatau down to seek the cause of the ceaseless lamentation. Io now commanded that the Earth Mother be turned over, so that she might no longer gaze upon her lost love Rangi. This is known as the Hurihanga a Mataaho, the overturning by Mataaho.

Even so was the Earth Mother turned over, so that she lay face down to Rarohenga, the underworld, hence man now dwells on her back instead of on her breast, as of yore. When she was so turned over, her youngest child, Ruaumoko, was still at her breast.

This child she was allowed to retain in her solitude. The brothers of Ruaumoko resolved to grant him some comfort in his dark realm, hence they gave the boon of fire. This fire was obtained for the purpose from Raka-hore, the personified form of rock. This subterranean fire is known as ahi komau, buried fire. Ruaumoko is responsible for all volcanic outbursts and earthquakes. [The first syllable of his name is the common term for an earthquake; it means 'to shake'.]

Tane despatched Tawhirimatea [wind] to procure the Cloud Children, who sprang from the warmth and perspiration of the body of the Earth Mother. And so the Wind Children were sent to fetch them. They brought Ao-nui and Ao-roa [Great Cloud, Long Cloud] and all the numerous Cloud Children to serve as a garment to cover the body of the Sky Parent. Such are the clouds above us. The body of the Earth Mother was also covered, and the garment bestowed upon her was composed of vegetation, which protected and warmed her.

Contents

1. Global jam-pot

OUR EARTH is a vast machine, insatiably reconsuming itself.

But when we first approach the earth from space it appears merely as a small stone. And as you would look at a stone you have just picked up, so do we examine the earth. For example, we can measure it and find out how much matter there is in it. But we can't break it open! And since we have only one such stone and it is too big to fiddle about with very much, we must infer what is inside it. But how are we to do that? Whereas most laboratory-scale sciences have the opportunity of isolating a system of interest and repeatedly stimulating it, we are obliged (most of the time through sheer necessity) to work with an analogous system—a model. With such models we can try to simulate the patterns found in nature. Our model becomes a theoretical tool, and its validity is measured by comparing it quantitatively with our observations of the natural system. Each model can reproduce only a small number of aspects of the actual system—but that is just what we want. Here we are simply playing the game of the laboratory scientist by isolating a process for detailed analysis. In fact there really are no more than superficial differences between these methods: we can no more go directly into an atom or gene than we can go to the centre of the earth.

Since the earliest times man has puzzled about himself and his surroundings. In recent years we have seen our planet for the first time from the outside. As yet we have not seen our planet from the inside. Our knowledge of the interior of the earth and the processes inside it which form the physiognomy of its surface is slight. Nevertheless, this book is an attempt to show you a view from the inside, a view through one pair of eyes.

But what we see depends on what we look at. This is especially true for large complex objects. The scale of a system can have a powerful effect on its behaviour. If, for example, we take some clay and bake it, we can make a brick. Chemically the brick is difficult to distinguish from the clay, but it is nevertheless quite a different thing. Now take some bricks and make a building. This is still really clay but that is almost irrelevant. Again let us take some water, air, heat, and electricity and make a cumulus cloud. Somehow these things have acquired characteristics which are more than the sum of their parts. How is this possible? Clearly the fabricated system has more degrees of freedom—the opportunity to manifest a greater variety of organization. Provided the parts or ingredients of our fabricated system are able to interact with each other, then not only do more complex patterns develop but quite new patterns of behaviour arise. Clearly, even if we knew

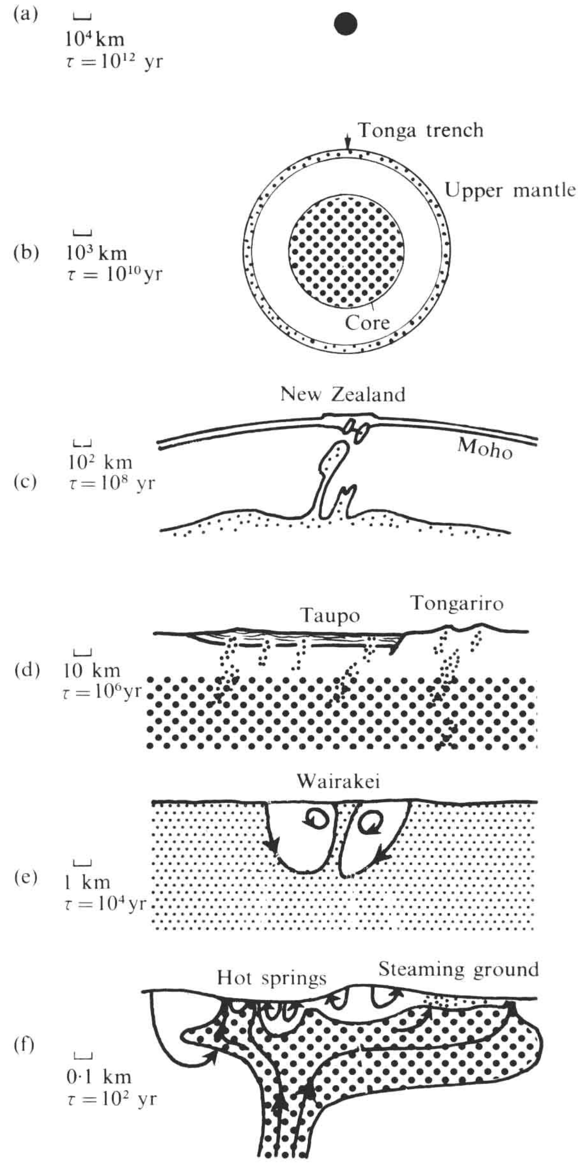

FIG. 1.1. Diagrammatic sections of the earth. The length scales of successive diagrams are in the ratio 1 : 10. (a) featureless stone; (b) the whole earth, showing mantle and core; (c) the upper mantle, near New Zealand; (d) the crust of the Taupo area; (e) the upper crust and the Wairakei hydrothermal system; (f) the surface zone of the crust. The time-scales are very roughly in the ratio 1 : 100.

more or less all there was to know about water, air, heat, and electricity as such, still we wouldn't know how a cumulus cloud works. Thus we recognize that there are aspects of the macro-environment which require descriptions quite different from those appropriate to the ingredients. This notion is often inadequately summed up by saying, 'We can't see the wood for the trees'.

Look at the earth through the eye of the geologist. Contract your time and distance scales so that 10^{10} years becomes an hour and the earth has shrunk until its diameter is 1 m. You will see the surface of the earth in a vigorous state of motion, rather like a large pot of jam cooking on a stove, with bits of scum moving erratically around in the surface, blobs popping up to the surface, and the body of the fluid moving up and down in irregular eddying motions. Let me show you the jam-pot of the earth.

Heat is transmitted through the deep layer of jam by the large-scale eddying motions. Moving about in the surface of our jam are a few patches of scum. These are our continents. Sometimes these patches are torn apart, later to be rejoined to others. Occasionally we see blobs of less viscous jam break through and ooze over the surface of the more viscous jam. This process is most clearly seen shortly after we place the pot on the stove. The regions of surface mass discharge are volcanic systems. Heat leaves our jam-pot by warming the ambient air and by losing water vapour. If we look closely at the surface we occasionally see a strong puff of vapour where this process is greatly intensified. These regions of discharge of water and water vapour in steaming ground, hot springs, geysers, fumaroles, mud volcanoes, and phreatic explosions are called thermal areas.

In order to describe these processes, we introduce, at each scale, a quantity which dominates the behaviour of structures of that scale. These quantities effectively identify the nature of the working material. Only six such quantities will be used in this book: size, mass, density, viscosity, temperature, and permeability. Thus the strategy of this book is to consider a sequence of scales with a progressively more elaborate specification of the working material. At each stage we must adjust our geological eye to the length- and time-scale of the phenomenon of interest. Let us begin with the largest scale, by setting our eye to 10^4 km and 10^{12} years.

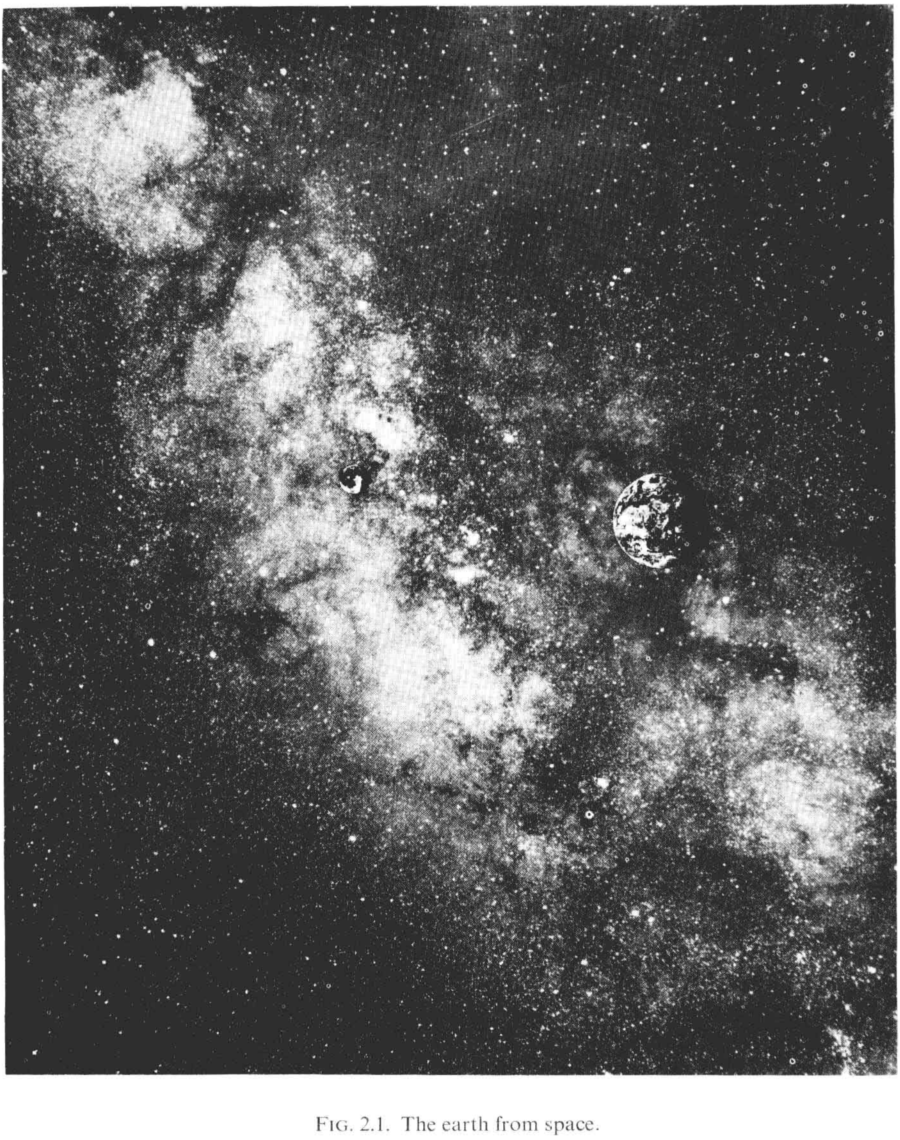

FIG. 2.1. The earth from space.

2. Stone in space

Where is it?

WHERE is the earth? This would be a difficult question to answer for a hypothetical space-traveller from another part of the cosmos. Notable objects within 2×10^{19} km of the earth are the great spiral galaxy in Andromeda and (quite near) the two Magellanic clouds. Towards the outer rim of our galaxy there is a yellow G-type star surrounded by nine planets. The third one, at a distance of $1{\cdot}5 \times 10^{8}$ km from its sun, is the earth: a planet of typical size, of mass 6×10^{24} kg, with a solitary satellite.

How old is it?

The visible universe as revealed by astronomical observation of stars and galaxies has been interpreted as a system that has been steadily developing for a period in excess of 10^{10} years. Our own sun coalesced and started its nuclear furnace 5×10^{9} years ago.

The oldest rocks so far found on earth are granodioritic gneisses from West Greenland; their age is about 4×10^{9} years. Since these must themselves have been derived as sediments from earlier rocks, the granitic crust of the earth has existed for longer than this. In this book a nominal age of 5×10^{9} years is used. This point in time is inevitably a little vague since it refers to a time before which processes on an astronomical scale were dominant in the formation of the earth; after it, geological processes within a distinct body were dominant. The instant in time when a distinct surface first formed, across which was a clear density discontinuity, is the beginning of geological time.

Shape and size: geodesy

The earth is nearly spherical; the sphere of volume equal to that of the earth has a radius of 6371 km. Careful measurement gives the over-all shape as closer to an ellipsoid of revolution about the axis of daily rotation, of ellipticity 1/298. The equatorial and polar axes are 6378·2 km and 6356·8 km respectively, with large-scale departures from this shape of typically one part in 10^{5}. The interior of the earth is thus close to being in hydrostatic equilibrium.

Direct observation from a space-vehicle unquestionably shows that the earth is nearly spherical. This has been more-or-less known since ancient times from various observations; for example, the earth's shadow during a lunar eclipse has the shape of a circular arc.

Quantitative measurement uses the simple device of finding the length of arc l between two places A and B on the earth's surface and the angle θ between plumb-lines at A and B. The local radius of curvature r is then given by l/θ, where θ is measured in radians (1 rad = 57·3°). The arc can be obtained in a variety of ways: Eratosthenes (276–192 B.C.) used the estimated distance travelled in a day by a camel train; Poseidonius

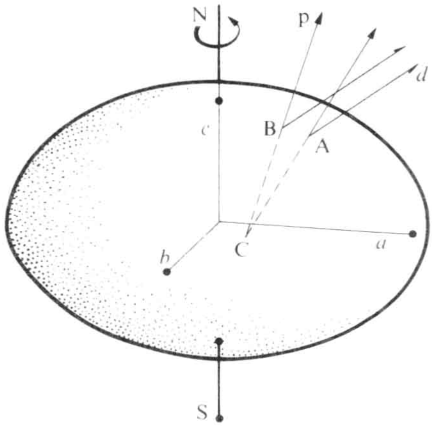

FIG. 2.2. Sketch of ellipsoid of flattening $\frac{1}{3}$ obtained by squashing a sphere so that the polar axis is $\frac{2}{3}$ the equatorial axis. The earth is squashed only 1 per cent of this. C = centre of curvature of arc AB; p, plumb-line; d, to distant object. Arc length l = AB, angle θ = ACB in radians, radius of curvature r = AC = BC related by $l = r\theta$.

(135–50 B.C.) an estimate of the speed of a sailing ship. In modern times, following Snell and Picard, we use the method of triangulation employed by surveyors. The angle is most simply obtained if A and B lie north and south of each other by observing a celestial object when it is north or south of the observer—for example, the sun at noon in midsummer. Modern instruments, including very accurate clocks, allow these measurements to be made to somewhat better than one part in 10^6; we can determine r to within a few metres.

Theoretical studies of Newton and Huygens suggested that a homogeneous self-gravitating mass would be spherical; but if it were rotating uniformly, centrifugal forces would bulge the body into an oblate spheroid. The first unequivocal measurements of the departure from sphericity were made in 1735–6 by comparing arcs in Ecuador, France, and Lapland. A more precise determination during 1792–8 followed the definition then of a new unit of length, the metre, defined as 10^{-7} of the distance from the pole to the equator on the meridian through Paris. We now know that this work was about 0·02 per cent out; the meridional quadrant is 10 002 km. Nevertheless this measurement showed that the earth was squashed along the polar axis. Modern data give the 'flattening' $e = (a-c)/a \approx 1/298{\cdot}25$. Thus, 1° of latitude corresponds to 110·6 km at the equator and to 111·7 km at the poles. The difference between these two figures, 1·1 km, is quite large!

How much matter?

On the human scale we readily obtain the mass of an object by comparison with other masses, either directly by using a balance or indirectly by using a calibrated spring. To estimate the mass of the earth two sets of measurements are necessary: a calibration measurement in the laboratory and measurements on the earth and its satellite.

The force of gravity acting between two masses m, M a distance r apart was found by Newton to be GmM/r^2, where G is a universal constant. In the laboratory, the force between two massive balls, first measured directly by Cavendish in 1791, gives $G = 6{\cdot}67 \times 10^{-11}\,\mathrm{N\,m^2\,kg^{-2}}$. This single entity characterizes our universe.

If m is the mass of a satellite orbiting a much more massive partner in a nearly circular orbit of radius r, the centrifugal force mv^2/r, where v is the orbital velocity, must balance the gravitational force. If T is the time for one revolution of the satellite around its orbit, noting that $vT = 2\pi r$ we obtain an expression for the mass of the central body: $M = 4\pi^2 r^3/GT^2$, a relation independent of the mass of the satellite. For this we thank Messrs Kepler and Newton.

For the earth and its satellite the moon $T = 27{\cdot}322\,\mathrm{d}$ (d = days), $r = 3{\cdot}84 \times 10^5\,\mathrm{km}$, and hence $M = 6 \times 10^{24}\,\mathrm{kg}$. In a similar manner by considering the earth as a satellite of the sun, the mass of the sun is found to be $2 \times 10^{30}\,\mathrm{kg}$. The mass of the earth is minute, only 3×10^{-6} that of the sun.

Moments of inertia: the spinning top

If the earth were a homogeneous sphere its moment of inertia about any axis would be $0{\cdot}4\,Ma^2$, where M is the mass and a is the radius of the sphere. For a non-uniform body let A, B, C be the principal moments of inertia. For the earth, if C is the moment about the polar axis, the moments A and B about equatorial axes are nearly equal, that is, $|A-B|/C \ll 1$. Estimates of A and C can be obtained in several ways. For example, the shape of the earth determines a value of $(C-A)$. Modern determinations use astronomical observations. The earth behaves like a spinning-top and its axis of rotation precesses about a cone of half-angle $23^\circ 27'$ in 25 735 years. Hence, $(C-A)/A = 3{\cdot}275 \times 10^{-3}$. Incidentally this shows that C and A are nearly equal—which is not surprising when the earth is so nearly spherical. Similarly the orbital plane of a satellite precesses. For example, in a typical case of an artificial satellite at a height of 600 km the normal to the orbit might precess