The Cambridge Encyclopedia of Earth Sciences

Editor-in-Chief David G. Smith PhD
Department of Earth Sciences, The Open University, 1979–1981

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First published in 1982 by the Press Syndicate of
the University of Cambridge. The Pitt Building,
Trumpington Street, Cambridge CB2 1RP
32 East 57th Street, New York, N.Y. 10022, USA
296 Beaconsfield Parade, Middle Park, Melbourne
3206, Australia

First published in the United States in 1981 by
Crown Publishers Inc. and
the Press Syndicate of
the University of Cambridge

First published in Canada in 1981 by
Prentice-Hall Canada Inc. and
the Press Syndicate of the University of
Cambridge

British Library Cataloguing in Publication Data

The Cambridge encyclopedia of earth sciences
1. Earth sciences
I. Smith, David G.
550 QE26.2 81-3313

ISBN 0 521 23900 1

Created, designed and produced by
Trewin Copplestone Books Limited
Advance House, 101–109 Ladbroke Grove,
London W11

Printed in Spain
by Mateu Cromo Artes Gráficas, S. A.

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Foreword

It is very seldom that those working in any area of scientific research find themselves caught up in an episode of conceptual change so rapid and so fundamental that external observers of the field begin to use terms such as 'scientific revolution' to describe the activity they perceive. Yet this is precisely what has happened in the Earth sciences over the last two decades.

The fires of revolt were kindled in Cambridge in the early 1960s by a visitor from Princeton, the late Harry Hess, who argued that the ocean basins must be ephemeral features of the Earth's surface, that continents were able to move apart by the generation of new ocean floor between them and to come together by the destruction of the intervening ocean by the process now known as subduction. It was in Cambridge, too, that a few years later the flames were fanned by Drummond Matthews and Fred Vine who recognized the significance of the previously incomprehensible magnetic lineations of the ocean floor and used them both to show that Hess's ideas were correct, and to establish the rates at which new ocean floor grew.

At first these ideas were received with great scepticism. After all, the ideas that continents had moved with respect to each other during geologic time were hardly new. Wegener, Taylor and others in the first decades of this century had thoroughly explored these ideas and failed to make any universal or lasting impact on geologists or geophysicists.

During the late 1960s, however, the new ideas gained further ground. Morgan in Princeton, Parker in the University of California, McKenzie in Cambridge, Oliver and his collaborators at Columbia University, and Le Pichon at Brest, all nearly simultaneously made dramatic new discoveries, which is many cases partly overlapped with each other. This was a breathless and exciting time in the subject. Not only did the new observations confirm the ideas of Hess, Vine and Matthews, but they showed that these ideas could be extended to formulate the group of concepts now known as plate tectonics, a unifying theory for the mechanical behaviour of the outer part of the Earth which provided for the first time a coherent explanation for the distribution of ocean basins, mountain ranges, earthquakes and volcanoes.

There had, of course, been attempts to explain these phenomena previously but the hypothesis of plate tectonics had one enormous advantage over its predecessors: it was testable. It predicted the character of earthquakes in the known seismic zones in different parts of the world and it predicted the age of the ocean floor.

This latter prediction led to the largest and most ambitious collaborative international experiment ever undertaken in the Earth sciences, the Deep Sea Drilling Project, begun in 1969. With a group of universities in the United States taking the lead, the technology was developed to drill holes and recover cores from the floors of the deep oceans to test by direct observation the age prediction of the new theory. This drilling programme was successful beyond all reasonable expectation; not only were the predictions verified but, almost more important, knowledge of the floor of the deep ocean and the processes which control its development was enormously increased. At the time of writing this programme is in its final phase.

Geologists, geophysicists and geochemists were faced, therefore, with a whole new conceptual framework against which to reconsider the accumulated observations and conclusions of half a century. Many of the basic dogmas to be found in the standard texts were at best half-truths and at worst quite wrong. The texts simply had to be rewritten.

For this reason, if for no other, it is a highly opportune time for this new Encyclopedia of Earth Sciences to make its appearance. The aim is both to provide ready access to the wealth of geological information which has been gleaned over the years and to show how it fits into the framework of plate tectonics.

It would be misleading if this foreword were to conclude without a word of warning. Without question plate tectonics represents the most important single conceptual advance Earth science has known; but that does not mean that it is the last. The subject is still developing rapidly with the steady growth, testing and pruning of ideas. There are still important aspects of the Earth's behaviour which we cannot begin to understand. Some of these no doubt will provide the substance for future editions of this encyclopedia.

2 June 1981

E. R. Oxburgh
Department of Earth Sciences
Cambridge

Introduction

Today the term plate tectonics is not only familiar to scientists, it is entering everyday language and finding its way into dictionaries. The resulting transformation of the way in which we regard the Earth has brought about a reappraisal of the vast accumulation of information about the surface of the Earth collected by geographers, geologists, oceanographers and others over the centuries, reviewing and reinterpreting that information in the comprehensive new framework provided by the new plate tectonic concept. But more than that, this revolution has brought about a change of approach in the scientific study of the Earth. No longer is geology a second-rate descriptive science—it has joined forces with the physical sciences in a new and more cohesive whole to which the term Earth sciences is now so much more appropriate.

This Encyclopedia is designed to be used as a work of reference, through its comprehensive index, but it is also a book that is designed to be picked up and read, as much by the interested general reader as by students of the Earth sciences using it as a reader.

We start by putting the Earth and its study into the perspective of history and its place in the universe. Part Two tackles some challenging aspects of the physical and chemical constitution and behaviour of the Earth as a whole, and introduces the materials of which it is made. As well as providing insight into the inaccessible depths of the Earth, and back into its immensely long history, these topics provide much information necessary to the understanding of the Earth's crust, which is dealt with in Part Three. Here we consider the activity of the outermost skin of the Earth, the only part of the solid Earth that we can observe directly. Most of that activity is concentrated along narrow zones, the boundaries between the plates; it is these plate margins that are the focus of our attention, together with the effect of the enormous forces involved in plate movements both on solid rocks and on their redistribution as recycled waste.

In Part Four we are treading on rather more familiar ground in dealing with those outer zones of the Earth that form our own environment, so it is perhaps surprising that so much is still being learnt about the atmosphere, the oceans and their interaction with the solid Earth. Also of highly topical interest is the study of the origins of life. Its subsequent evolution provides, in the fossil record, a time-scale for the study of the history of the Earth's surface environments. Part Five brings in human interaction with the Earth—a vast topic of which we can deal with only a limited selection here. Part Six takes us back into space again, to see how what we have learnt about the Earth can be applied to our nearest planetary neighbours, and conversely how the space programme (which happened to start at about the same time as the plate tectonic theory was being formulated) has brought better information on those oldest parts of Earth history which are not recorded here on Earth. Finally there is a glossary. Deriving from its lengthy history as a descriptive science dealing with an extraordinary range of phenomena, Earth science has accumulated a particularly rich vocabulary of its own—after all, if you come across something new which you do not fully understand, it always helps to give it a name. This terminology can be an enormous help in summing up complex concepts in a single word or phrase, but it can also be a barrier to understanding. We have therefore tried to keep the technical terms to those with which anyone seriously interested in the subject should be familiar.

The Cambridge Encyclopedia of Earth Sciences was conceived, written and published within less than three years. Its authors are all active in research in the fields in which they have written, and the standing of the editorial panel can be judged from the appearance in the text of several of their names, many of which are now firmly associated with important discoveries.

David G. Smith

Units and abbreviations

Units

Earth scientists use some of the standard international (SI) system of scientific units, some units that predate the SI system, and a few units that are particular to their own field of study.

The base units of the SI system include the metre (length), kilogram (mass), second (time), ampere (electric current) and kelvin (temperature). Other units can be expressed as mathematical combinations of these.

Multiples of SI units come in steps of one thousand. To economize on space and to make comparison between numbers easier, scientists use a form of mathematical shorthand called the powers of ten, or index notation. By this means it is possible to express all numbers as the multiple of a number between 1 and 10 (the mantissa), and a power of ten (the index); many pocket calculators use this notation for numbers which would otherwise be too large or too small for the display. The power or index is a number written as a superscript (eg, in 10^3, 3 is the power) that tells us by how many places to move the decimal point to the right. For numbers smaller than 1 the power is written as a negative number and tells us by how many steps to move the decimal point to the left. Thus $10^3 = 1000$, $10^6 = 1\,000\,000$, $10^{-2} = 0.01$, and $10^{-5} = 0.00001$. Similarly, $2.4 \times 10^4 = 24\,000$, and $5.36 \times 10^{-3} = 0.00536$.

The prefixes used to extend the magnitude of the basic units are:

giga (G) $= 10^9$
mega (M) $= 10^6$
kilo (k) $= 10^3$
milli (m) $= 10^{-3}$
micro (μ) $= 10^{-6}$
nano (n) $= 10^{-9}$
pico (p) $= 10^{-12}$

Abbreviations

A = ampere
a = year
C = Celsius or centigrade
cal = calorie
cm = centimetre
dyn = dyne
G = giga
hfu = heat flow unit
Hz = hertz
J = joule
K = kelvin
k = kilo-
kb = kilobar
kg = kilogramme
km = kilometre
kWh = kilowatt-hour
l = litre
M = mega-
m = metre
m = milli-
Ma = million years
mb = millibar
mgal = milligal
mm = millimetre
mW = milliwatt
N = newton
n = nano-
p = pico-
Pa = pascal
rad = radian
s = second
T = tesla
t = tonne
V = volt
v = velocity
W = watt
μm = micrometre (micron)

Conversion factors

length
1 metre (m) = 1.094 yards
1 centimetre (cm) = 0.394 inches
1 kilometre (km) = 0.621 miles
1 light year $= 9.4605 \times 10^{15}$ m
$= 5.88 \times 10^{12}$ miles

volume
1 litre (l) = 1000.028 cubic centimetres
= 0.220 UK gallons
= 0.264 US gallons
1 cubic metre (m^3) = 1.308 cubic yards

mass
1 kilogramme (kg) = 2.205 pounds
1 tonne (t) = 1000 kilogrammes

temperature
1 degree on the centigrade (C) scale = 1 degree on the kelvin (K) scale
0°C = 273.15 K
1 degree on the centigrade scale = 9/5 degrees on the Fahrenheit (F) scale
0°C = 32°F

acceleration
1 milligal (mgal) $= 10^{-3}$ m/s/s (metres per second per second)

force
1 newton (N) = 1 kg m/s^2 = 0.225 pounds-force (lbf)
1 dyne (dyn) = 10 micronewtons

energy
1 joule (J) = 1 newton metre = 0.239 calorie
1 kilowatt hour (kWh) $= 3.6 \times 10^6$ joules

power
1 watt (W) = 1 joule per second
1 kilowatt (kW) $= 10^3$ watts = 1.341 horsepower

heatflow
1 heatflow unit (hfu) = 0.042 W/m^2 = 1 $\mu cal/cm^2/s$

pressure or stress
1 pascal (Pa) = 1 N/m^2
= 0.000145 lbf/in^2
1 kilobar (kb) $= 10^8$ N/m^2
$= 1.45 \times 10^4$ lbf/in^2
1 millibar (mb) = 100 N/m^2
1 atmosphere $= 1.01325 \times 10^5$ Pa
= 1013.25 millibars
= 14.69 lbf/in^2

viscosity
1 poise = 0.1 Ns/m^2

frequency
1 hertz (Hz) = 1 cycle/s

angular measure
1 arc second = 1/3600 degree
1 radian (rad) = $180/\pi$ degrees

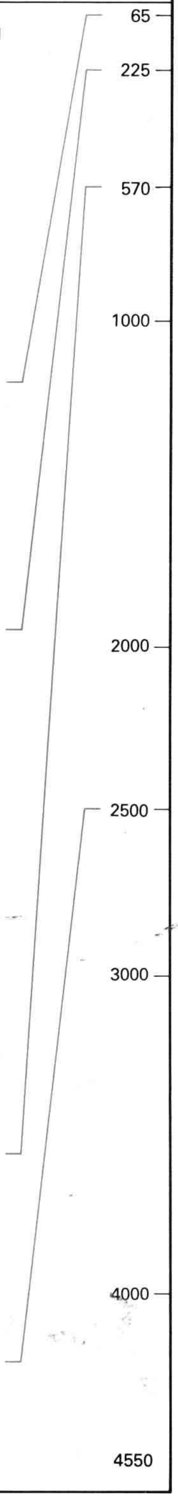
magnetic induction
1 tesla (T) = 10 000 gauss
1 gamma $= 10^{-9}$ T

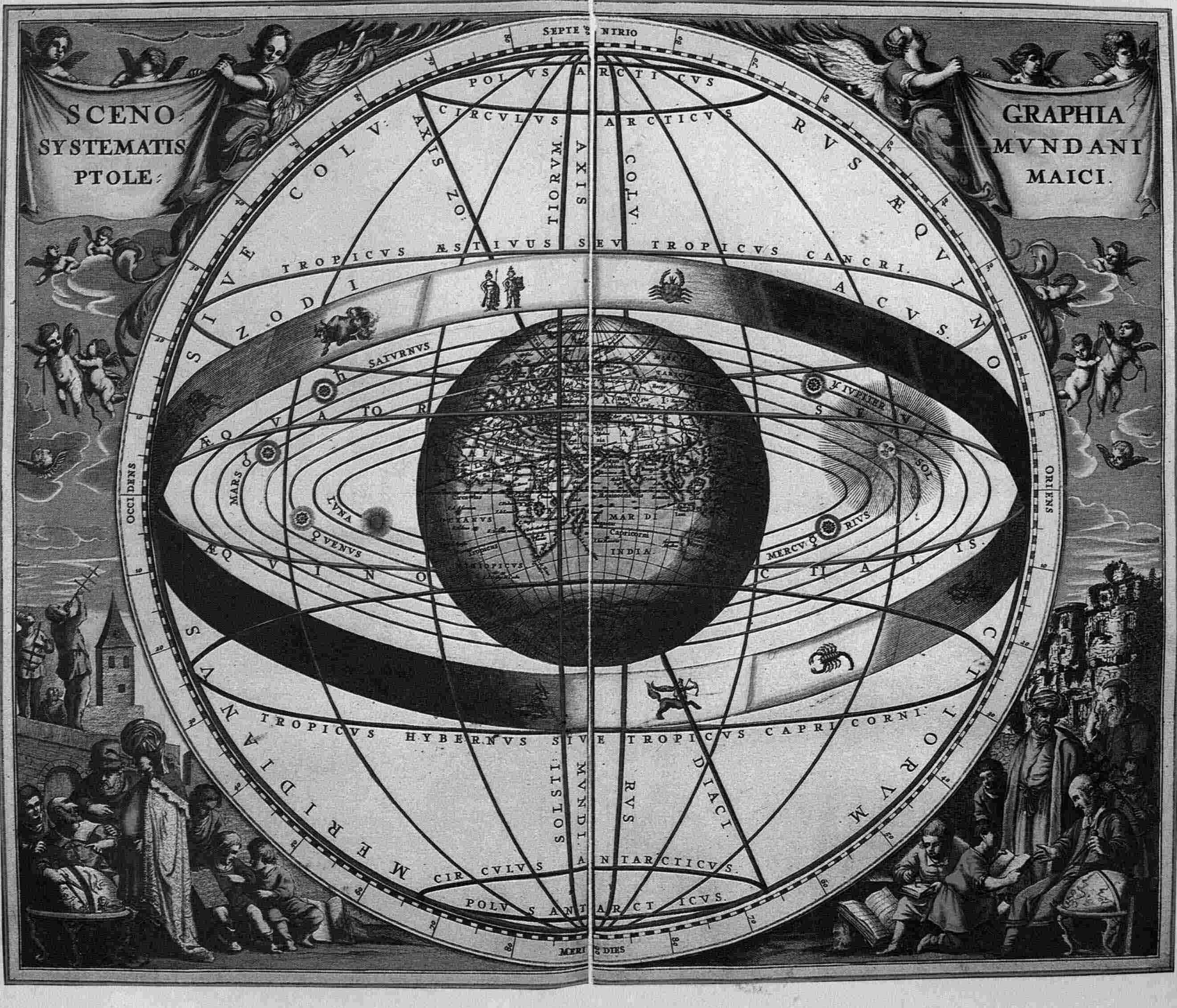
Chemical elements

Ac	actinium
Ag	silver
Al	aluminium
Ar	argon
As	arsenic
At	astatine
Au	gold
B	boron
Ba	barium
Be	beryllium
Bi	bismuth
Br	bromine
C	carbon
Ca	calcium
Cd	cadmium
Ce	cerium
Cl	chlorine
Co	cobalt
Cr	chromium
Cs	caesium
Cu	copper
Dy	dysprosium
Er	erbium
Eu	europium
F	fluorine
Fe	iron
Fr	francium
Ga	gallium
Gd	gadolinium
Ge	germanium
H	hydrogen
He	helium
Hf	hafnium
Hg	mercury
Ho	holmium
I	iodine
In	indium
Ir	iridium
K	potassium
Kr	krypton
La	lanthanum
Li	lithium
Lu	lutetium
Mg	magnesium
Mn	manganese
Mo	molybdenum
N	nitrogen
Na	sodium
Nb	niobium
Nd	neodymium
Ne	neon
Ni	nickel
O	oxygen
Os	osmium
P	phosphorus
Pa	protactinium
Pb	lead
Pd	palladium
Pm	promethium
Po	polonium
Pr	praseodymium
Pt	platinum
Ra	radium
Rb	rubidium
Re	rhenium
Rh	rhodium
Rn	radon
Ru	ruthenium
S	sulphur
Sb	antimony
Sc	scandium
Se	selenium
Si	silicon
Sm	samarium
Sn	tin
Sr	strontium
Ta	tantalum
Tb	terbium
Tc	technetium
Te	tellurium
Th	thorium
Ti	titanium
Tl	thallium
Tm	thulium
U	uranium
V	vanadium
W	tungsten
Xe	xeron
Y	yttrium
Yb	ytterbium
Zn	zinc
Zr	zirconium

Geological Time Scale

Eon	Era	Period		Epoch	Time (Ma)
Phanerozoic	Cenozoic	Quaternary		Holocene	0.01
				Pleistocene	1.8
		Tertiary	Neogene	Pliocene	5
				Miocene	26
			Palaeogene	Oligocene	37
				Eocene	53
				Palaeocene	65
	Mesozoic	Cretaceous		late Cretaceous	100
				early Cretaceous	136
		Jurassic		late Jurassic	160
				middle Jurassic	176
				early Jurassic	190
		Triassic			225
	Palaeozoic	Permian			280
		Carboniferous	Pennsylvanian		315
			Mississippian		345
		Devonian			395
		Silurian			430
		Ordovician			500
		Cambrian			570
Proterozoic	Precambrian	Vendian			650
		Riphean		late Riphean	900
				middle Riphean	1300
				early Riphean	1600
		early Proterozoic			2500
Archaean		Archaean			4550




SCENO
SYSTEMATIS
PTOLE
GRAPHIA
MVNDANI
MAICI.
SEPTENTRIO
POLVS ARCTICVS
CIRCVLVS ARCTICVS
AXIS ZODIACI
AXIS MVNDI
COLVRVS SOLSTITIORVM
SIVE COLVRVS ÆQVINOCTIORVM
TROPICVS ÆSTIVVS SEV TROPICVS CANCRI.
ZODIACVS
SATVRNVS
IVPITER
ÆQVATOR SEV ÆQVINOCTIALIS.
SOL
MARS
LVNA
VENVS
MERCVRIVS
OCCIDENS
ORIENS
TROPICVS HYBERNVS SIVE TROPICVS CAPRICORNI.
MERIDIANVS
CIRCVLVS ANTARCTICVS.
POLVS ANTARCTICVS.
MERIDIES
AFRICA
INDIA

Part One: The Earth Sciences in Perspective

A feature of all scientific endeavour is that the better we come to understand our subject matter, the less significant becomes our own small world and our place in it. It is therefore fitting to start with reminders both of the place of present-day Earth science in the history of the interpretation of geological phenomena, and of the place of the Earth in the unimaginably wider context of our Galaxy and of the universe as a whole. Geology had scarcely been born as a science before its practitioners began to delve into its history, but it is relatively recently that this interest has developed into a science of its own. The aim here is to view developments in understanding the Earth in the historical context of the general state of human knowledge and of the contemporary social and even political climate. We can see the revolutionary acceptance of continental drift as only one in a succession of upheavals, starting with the overthrow of the geocentric concept of the universe. Will future generations ridicule twentieth-century reluctance to accept the mobility of the Earth's crust in the way that we have tended to pour scorn on the dependence of eighteenth-century geologists on the biblical Flood?

An eminent scientist claimed earlier this century that there are but two areas of scientific research, comprising between them the study of everything on the Earth (geology) and everything outside it (astronomy). The boundaries between these two have been substantially eroded, particularly since the coming of the era of space exploration. At the end of the book we return to the direct application of Earth science and its methods to the study of the other bodies of the Solar System, but in this section an astronomer tells us about the nature and history of the universe, leading to the formation of the planet that forms the subject of the bulk of this book.

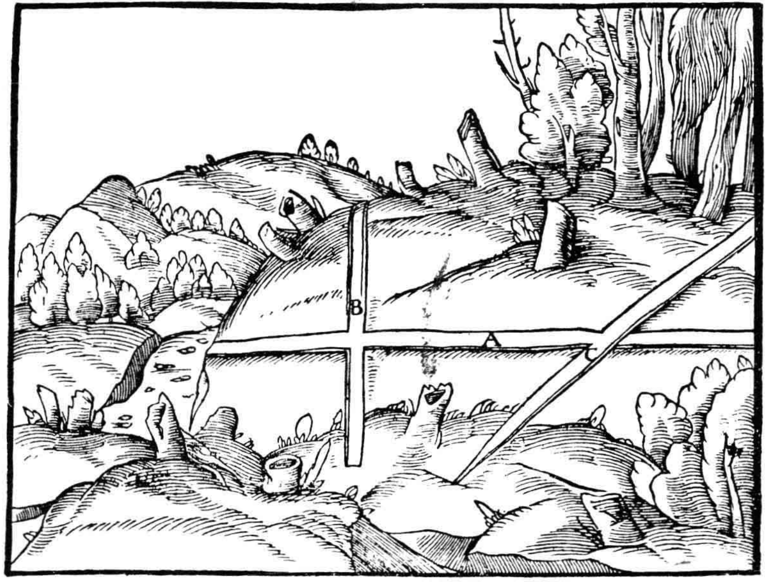
The Ptolemaic system of the universe, from Atlas Coelestis, Harmonia Macrocosmica, *by Andreas Cellarius, Amsterdam, 1660.*

1 The history of the Earth sciences

Early theories of the Earth

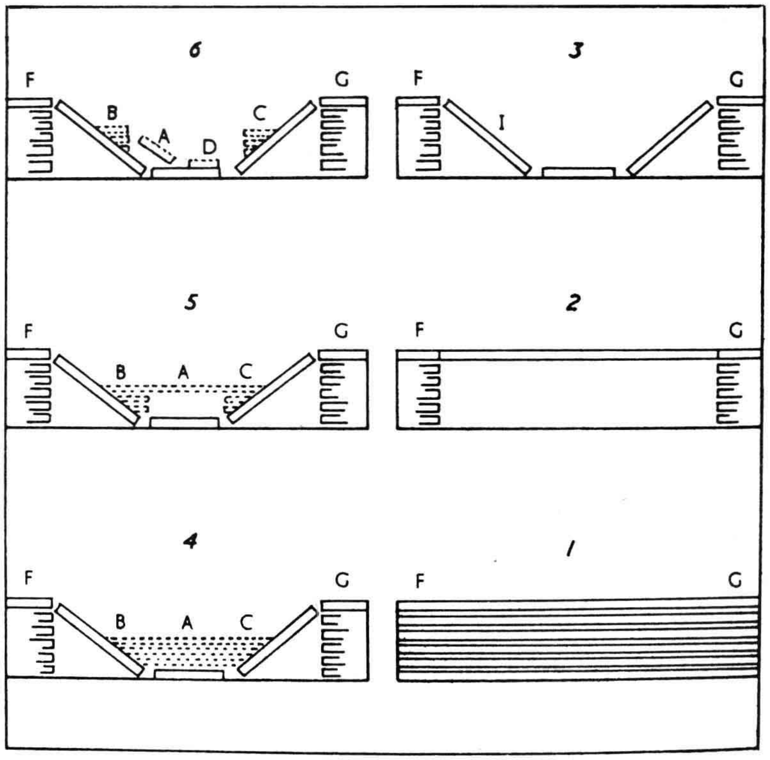
Mankind has long taken interest in the nature and origin of the rocks forming the Earth's surface. Among the ancient Greeks, Herodotus (*c* 485–425 BC) recorded the presence of marine shells far inland in Egypt and concluded that they had been left there by the retreating waters of some earlier sea. Pythagoras (sixth century BC) is said to have taken the presence of fossil marine creatures high in the mountains of Greece as evidence of the elevation of a former sea bed, and Strabo (*c* 63 BC–AD 23) certainly accepted such a view. As the Mediterranean lies in one of the world's volcanic and seismic regions many Greek and Roman authors were fascinated by the phenomena of volcanoes and earthquakes. Strabo, in common with many later writers, saw volcanoes as natural safety valves designed to permit the escape of dangerous terrestrial vapours, and the Roman, Seneca (*c* AD 3–65), regarded earthquakes as the result of those same vapours becoming turbulent within the Earth's supposedly cavernous interior. In China, in 132, Chang Hêng (78–139) invented an 'earthquake weathercock', the first seismograph ever constructed. Rather later, Avicenna (980–1037), the father of the Earth sciences in the Arab world, discussed not only earthquakes but a wide variety of other geological phenomena. He also displayed a sound understanding of many Earth processes at a time when, in western Europe, Christian scholars were more interested in saints and seraphim than in sandstones and sapphires. Some of the ideas then current in western Europe must now strike us as bizarre. Gems, for instance, were commonly believed to form as a result of some celestial energy penetrating into the Earth, the energy impinging less obliquely upon the tropics than upon higher latitudes with a result that precious stones were thought to be most abundant in the Earth's warmest climes. Yet, despite such fanciful early notions, it was in western Europe rather than in the Middle or Far East that, in the centuries following 1500, the modern Earth sciences originated.

To some extent Europeans were drawn to the Earth sciences in the aftermath of the Renaissance because of the obvious practical applications of those sciences during an age in which the demand for minerals increased. Not least, the replacement of the medieval feudal economy by capitalism resulted in a pressing need for various precious metals for coinage purposes. *De re metallica* by Georgius Agricola (1494–1555), published in Basle in 1556, offers among much else a detailed discussion of the field occurrence of mineral veins and is a superb early example of applied geology (Figure 1.1). Important though such practical matters undoubtedly were, it was theoretical questions that mostly engaged the attention of scholars interested in the Earth sciences. Here one problem above all others commanded their attention: what was the origin of the 'figured stones', or fossils, found so widely in the Earth's rocks? Some scholars dismissed fossils as meaningless sports of nature. Others saw them as growths formed within rocks as a result of the Earth's *vis plastica* (moulding force). Yet others, such as Leonardo da Vinci (1452–1519), correctly interpreted fossils as the remains of former marine creatures which had become entombed within the rocks forming on some ancient sea bed, the strata and their fossils then being elevated into their present terrestrial environments (Figure 1.2).



1.1: *One of the many illustrations by Georgius Agricola depicting mineral veins: a 'principal vein' (A), a 'transverse vein' (B) and a 'vein cutting principal one obliquely' (C). From Agricola's* De re metallica *(Basle, 1556).*

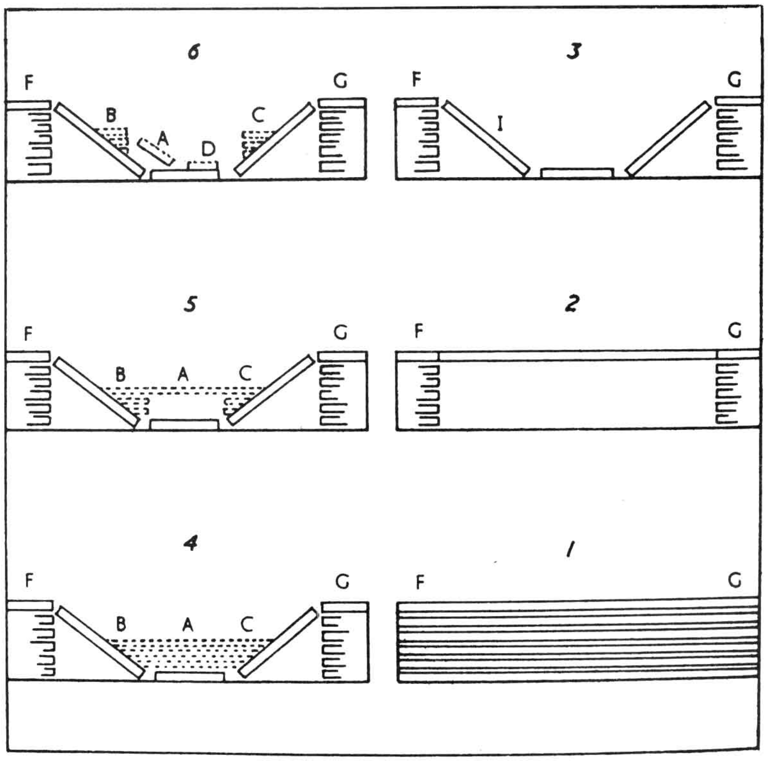
During the seventeenth century it was accepted increasingly that fossils could only be organic in origin and there developed the parallel notion that the necessary exchange of ancient sea bed into modern dry land must have occurred during that universal catastrophe



1.3: *Nicolaus Steno's interpretation of the history of the Tuscan landscapes. Redrawn from* Nicolai Stenonis de solido intra solidum naturaliter contento dissertationis prodromus *(Florence, 1669).* 1 *During the Creation the globe is submerged beneath a universal fluid from which precipitation takes place to form horizontal, superimposed beds of sedimentary rock (F–G). In the absence of continents, plants and animals the individual strata are uniform in composition and free from fossils and all other heterogeneous material.* 2 *The newly formed strata have emerged from the fluid to become the Earth's pristine continents. Beneath the continents water is sapping the continental foundations, eating away the strata, and opening up great caverns.* 3 *Large areas of the continents have now been undermined, and the roofs of the great caverns collapse (I). The resulting valleys are drowned by the sea and this explains the Flood.* 4 *In the Flood's waters new sedimentary strata are formed (B–A–C). These younger rocks incorporate plant and animal remains from the antediluvial world and are therefore fossiliferous.* 5 *These new rocks emerge at the close of the Flood and are themselves undermined as a second generation of caverns develops.* 6 *A period of renewed crustal collapse reduces the youngest strata to their present disordered state (A–D) and forms the Earth's modern topography.*

Concurrently with these detailed field investigations attempts were made to incorporate the fresh discoveries into a new generation of more securely grounded theories of the Earth. One of those theories proved to be very influential in its own day—the theory devised by Abraham Gottlob Werner (1749–1817), who was Professor of Mining and Mineralogy in the Saxon Mining Academy at Freiberg. Werner believed that the Earth originally consisted of a primeval nucleus with an uneven surface completely enveloped in the waters of a universal liquid. The oldest of the Earth's rocks, he claimed, were formed in this liquid as chemical precipitates, their bedding either reflecting the configuration of the nucleus itself or else being a result of the slumping of the deposits while they were still in a plastic condition. Most bedding structures were thus regarded as original to the stratum in question, and since there were as yet neither living organisms nor continents, all these ancient rocks were held to be devoid of both fossils and clastic material. Such ancient deposits Werner termed 'Primitive rocks' (*Urgebirge*), and they included rocks such as granite, gneiss, schist and quartzite. Next, as a result of a gradual lowering in the level of the fluid, the Earth's continents began to emerge and were soon colonized by the first plants and animals. Some of the rocks formed in the liquid at this time thus contain both fossils and clastic debris, but the continents were still small in extent and most of the rocks dating from this stage are therefore still chemical precipitates. The rocks belonging to this stage, Werner claimed, included greywackes, slates and some limestone and, since they were supposed to be partly chemical in origin and partly clastic, he termed them 'Transition rocks' (*Übergangs-gebirge*). His final major class of rocks was the Floetz (*Flötz-gebirge*). By the time of their deposition the level of the fluid had subsided still further and the continents had become much more extensive. Thus the Floetz rocks—rocks such as limestone, mudstone and sandstone—are almost entirely clastic in origin and replete with fossils, but, since the fluid now occupied a much diminished area, the Floetz rocks themselves are much more restricted in extent than the earlier Primitive and Transition rocks. The final Floetz rocks consisted of deposits such as alluvium, shingle and tufa, and after their deposition the fluid sank to its present level to become the waters of the world's modern oceans. According to the theory all veins and dykes were fissures which had been filled by percolating solutions seeping down from the fluid above. The fluid played so important a role in this entire system that the theory came to be known as the Neptunian theory.

The theory clearly had its deficiencies. How, for instance, could the fluid once have held virtually all of the Earth's rocks in solution? What brought about temporal variation in the type of material being precipitated? Above all, what caused the fluid gradually to disappear? Contemporary critics of the theory were not slow to raise such problems, and later historians have tended to ridicule the entire Neptunian system. The theory is nevertheless important for three reasons. First, it was a pioneer attempt to establish a universal stratigraphical sequence, because the various formations within the Primitive, Transition and Floetz categories were supposed to occur in the same order the world over. Second, by pretending to offer a universally valid key to stratigraphy, the theory encouraged its adherents to make detailed studies of the rocks in localities throughout the world in an effort to ascertain the position of those rocks within the Neptunian hierarchy. Finally, the theory stimulated a major controversy over the nature of basalt, and efforts to resolve that issue led to a quickening of interest in the Earth sciences generally. That controversy itself merits more than just a mere mention. According to the Neptunian theory basalt was a chemical precipitate formed in the universal liquid, but many of Werner's con-



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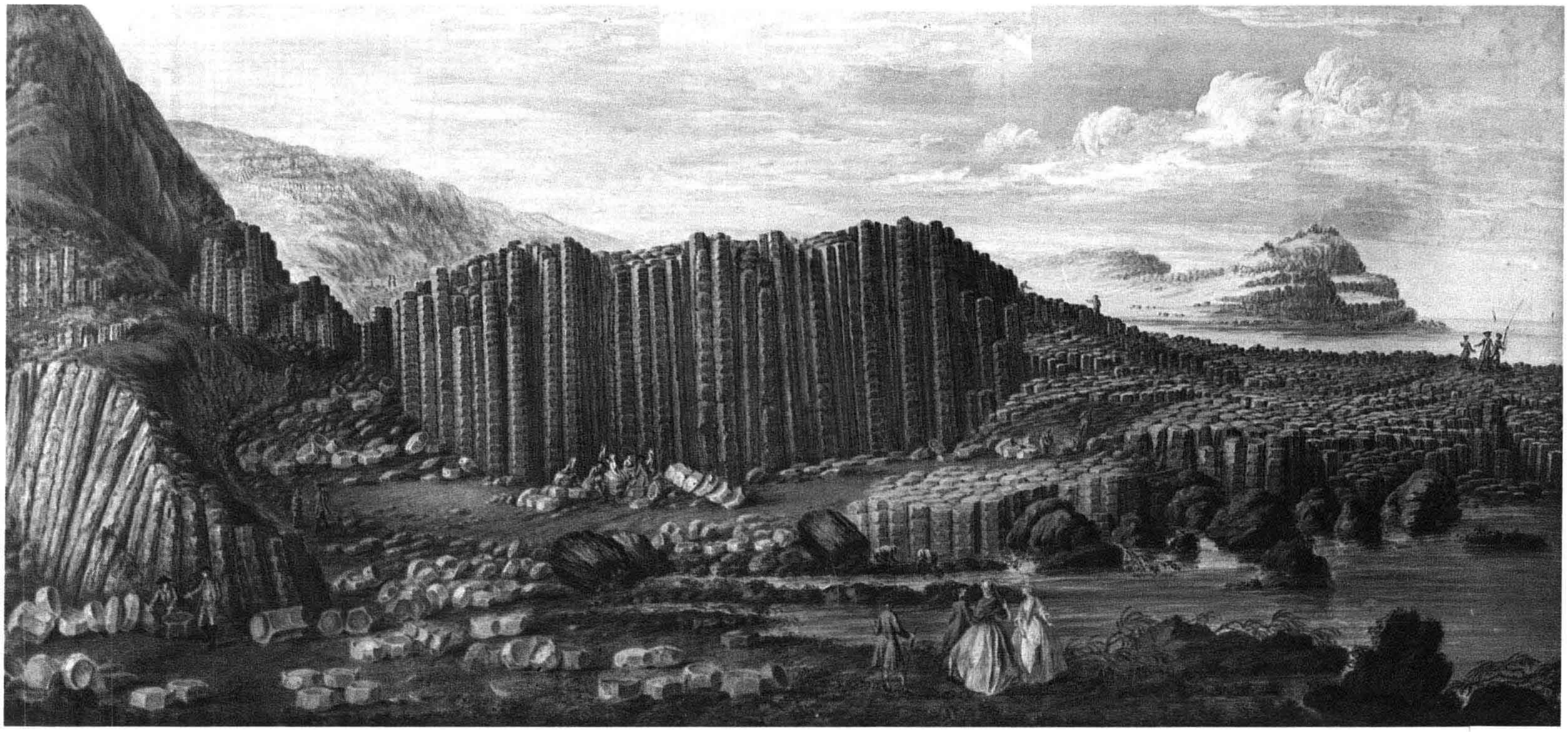

1.4: *Columnar basalts at the Giant's Causeway, County Antrim, Ireland. A painting executed by Susanna Drury in the 1730s.*

temporaries had already accepted Desmarest's view that basalt was an igneous rock extruded from ancient volcanoes. One of the sites that became crucial in the debate was the finely displayed basalt at the Giant's Causeway in northern Ireland (Figure 1.4). When the Vulcanists, as Desmarest's supporters came to be called, urged that basalt, such as that at the Causeway, was identical in character to some of the material extruded from modern volcanoes, the Neptunists responded that in these cases normal 'sedimentary' basalt lying at depth had been melted by the subterranean fires associated with the volcano and then extruded in the molten state before finally cooling and regaining its original 'sedimentary' form. Not until the early years of the nineteenth century did the Vulcanists finally emerge victorious.

Werner's theory, like all its predecessors, offered a linear view of Earth history. It envisaged both a clear beginning to Earth history, with the commencement of precipitation from the universal liquid, and an equally clear end, with the conversion of the final remnants of the liquid into the world's modern oceans. Since the fluid was now gone, there clearly could be no further precipitation of rocks, but behind this fact there lurked a major problem. The continents are clearly undergoing steady reduction under the ceaseless attack of the forces of denudation, and obviously the continents are doomed to eventual destruction. This was an unpalatable fact in an age when an anthropocentric view of nature predominated. If the continents were destroyed, then where would man live? Strangely, it was an attempt to reconcile the anthropocentric view of nature with a belief in denudation—what has been termed the denudation dilemma—that stimulated the formulation of another theory of the Earth—a theory that gave modern geology its dynamic framework. The author of that theory was James Hutton (1726–97) of Edinburgh, where a modern plaque upon his grave now hails him as 'The Founder of Modern Geology'.

Hutton first propounded his theory publicly in 1785, although it was not published in its final form until 1795. Unlike previous theories of the Earth, Hutton's theory was in no way concerned with the origin of the Earth. His theory is merely an account of the operation of the Earth-machine and not a discussion of its original construction. Fundamental to the theory was Hutton's conception of geological time. He dismissed the scriptural time scale of most earlier theorists and instead argued that the Earth was immensely old. He concluded his essay of 1785 with the now famous phrase that to Earth history 'we find no vestige of a beginning,—no prospect of an end'. Hutton fully accepted the reality of denudation. He regarded all the continental topography as the product of rain and river action, and he admitted that incessant and prolonged denudation could only result in the eventual destruction of the present continents. But he resolved the denudation dilemma by noting that the Earth machine possessed a built-in mechanism for self-repair. The debris worn from the continents is transported by rivers into the sea and there, he observed, the debris accumulates upon the sea bed layer by layer. Gradually, he argued, this material is compacted and lithified under the influence of the terrestrial heat, thus bringing new sedimentary strata into being. Eventually, as the old continents become dank lowlands following long-continued denudation, the new rocks are elevated from the sea bed to form the fresh generation of continents necessary to ensure a continuity of human habitat. This uplift he attributed to the expansive power of the terrestrial heat, and he believed that during the uplift the rocks had acquired most of those contortions so widely evident in the continental strata today.

In contrast to the linear Neptunian theory, Hutton's theory was cyclical: the sequence of denudation, transportation, sedimentation, lithification, uplift and renewed denudation can be repeated for as long as the Earth exists. It is a theory that, in its broad outline, has proved to be valid. As the geostrophic cycle, it forms the basis of present-day geology. But Hutton did more than provide geology with its conceptual framework; inherent in his theory are three other ideas of great importance. First, there are his views on granite. The Neptunists had claimed granite as a 'Primitive rock', part of the Earth's primeval surface, but in the Huttonian system, with its conception of continent succeeding continent in endless succession, there was no place for primitive rocks dating back to the Earth's origins. Hutton therefore claimed that granite was an intrusive rock consolidated from an igneous melt and that it was thus younger, not older, than the adjacent strata. Likewise, he claimed that all dykes and mineral veins had been formed by molten material rising from the Earth's hot interior. Indeed, terrestrial heat played so important a part in Hutton's theory that it soon came to be known as the Plutonic theory. Second, he believed that there should exist what he termed 'compound masses'—places where the rocks of one continent had been later submerged, coated with fresh strata and then re-elevated to form a new landmass. In such cases, Hutton argued, the older of the two rock sequences must have been transformed as a result of its being subjected to the influence of the terrestrial heat not once but twice. His theory thus contained the germ of the idea of rock metamorphism. The identification of actual examples of such 'compound masses', containing what today would be termed an unconformity, was for Hutton a matter of importance as offering significant confirmation of his theory. It was with much satisfaction that he identified three such sites in Scotland during 1787–8 (Figure 1.6). Finally, having set his theory against a background of limitless time, Hutton had no need to invoke sudden catastrophes in explanation of natural phenomena. In his eyes all the major transformations of the Earth's surface, from the excavation of valleys to the elevation of continents, were a cumulative response to innumerable trivial changes occurring through an eon of time. He held that the processes that had acted in the past differed neither in kind nor degree from those processes active in the world today. Hutton thus replaced the catastrophism of his contemporaries by a new philosophy of nature, which was shortly to be entitled Uniformitarianism.

1.5: *James Hutton '. . . rather astonished at the shapes which his favourite rocks have suddenly taken'. From* A Series of Original Portraits and Caricature Etchings, by the late John Kay *(Edinburgh, 1838).*

The development of geological cartography and stratigraphy

Several decades elapsed before Hutton's theory earned general acceptance, but these were the decades during which geology began to be recognized as a fully fledged and independent subject. It was around 1800 that the science came to be known by its modern name of geology and that it began to be institutionalized. The world's first geological society—the Geological Society of London—was founded in 1807, and journals devoted to the publication of research in the discipline came into being. For example, the *Transactions of the Geological Society of London* began publication in 1811 and *The American Journal of Science* in 1818. Geology was added to the curriculum of many European and American universities, and the first generation of geological textbooks appeared—a generation that included such classics as Robert Bakewell's *An Introduction to Geology* (London 1813), Parker Cleaveland's *An Elementary Treatise on Mineralogy and Geology* (Boston 1816) and