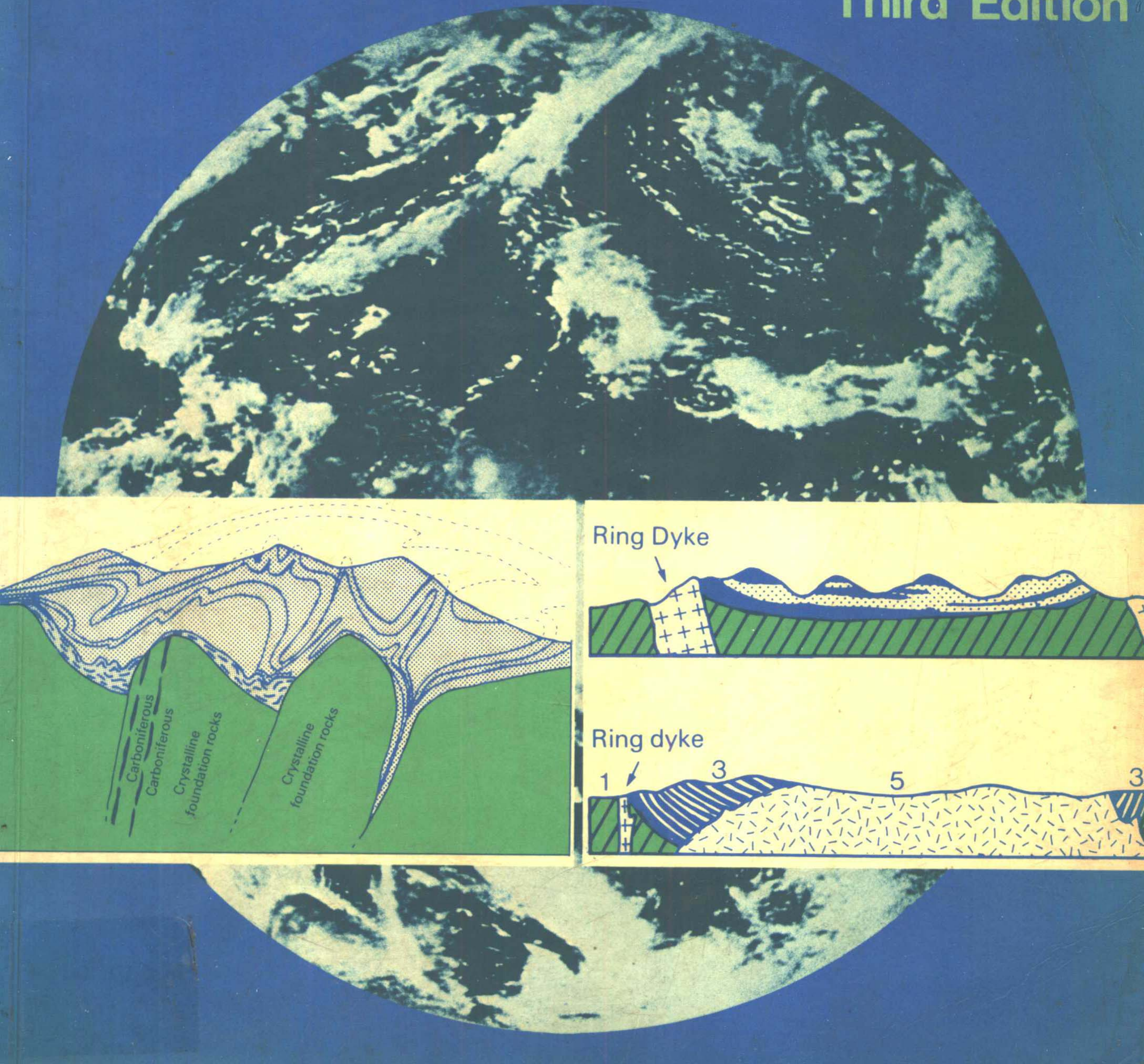
Holmes Principles of Physical Geology

Third Edition



Holmes Principles of Physical Geology

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Vetlesen Prizewinner, 1964

Third Edition, revised by

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Paricutin, Mexico,
erupting early in
April 1943, six weeks after
the first appearance
of the volcano. See pp. 207 ff.
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Preface

It would be difficult to find a more attractive and rewarding introduction to the basic concepts of science than physical geology. The activities of our planet may be compared to the combined operations of the four Elements of the ancient Greek philosophers: Fire, Earth, Air and Water, to which we should now add Life. The ever-changing interplay of these operations is responsible for a fascinating variety of natural phenomena, ranging from landscape forms and scenery to the catastrophes brought about by earthquakes, volcanic eruptions, floods and hurricanes, all of which are of daily interest and concern to a high proportion of the world's inhabitants. The effects of these activities, and—so far as current knowledge permits—their causes, are the chief topics of our subject.

In the preface to the first edition I expressed the hope that the book would appeal not only to university students and the senior classes in schools and their teachers, but also to the wide range of general readers whose wonder and curiosity are excited by the behaviour of this mysterious world of ours. My hopes have been surprisingly surpassed. Partly, I expect, this has been because the subject was presented with a minimum of jargon, with constant reference to observational evidence and with copious illustrations. Since I have found this method of treatment to be consistently successful in arousing and developing the interest of students, including those who had no preliminary acquaintance with the elementary principles of science, I have endeavoured to follow it again in this new edition. Partly, too, the timing of the original edition was auspicious, for the book appeared just as the services of geologists and geophysicists began to be required in ever-increasing numbers all over the world.

Writing in 1952 of *The Next Million Years*, Sir Charles Darwin pointed out that 'we are living in the middle of an entirely exceptional period, the age of the scientific revolution'. Throughout this century the rate of scientific publication has been doubling every few years and in many sciences, including the geological group, the rate of increase is itself increasing, like compound interest. It is not generally realised that, of all the geologists who have ever lived, about ninety per cent are now alive and actively at work. For geophysicists the percentage is naturally higher. The curves representing these remarkable increases have been rising much more steeply than those of the world 'population explosion'. Obviously, since the contrast applies to scientists in general, the upward-sloping curves must gradually turn and flatten out, probably with a few fluctuations dependent on future developments in China and Africa. Otherwise there would sooner or later be as many scientists as people. But despite the enormous wealth of geological data still to be collected and the certainty that some major surprises will continue to emerge (e.g. when the various Mohole projects are completed), it is doubtful whether there will ever again be such a profusion of unexpected discoveries concentrated into so short an interval of time as there has been during the last twenty years.

The above considerations serve to explain why the revision on which I started full-time work seven years ago has taken so long; why its completion now instead of a few years ago is more timely; and why it has resulted in what is practically a new book, almost entirely rewritten and of necessity greatly enlarged. Old chapters have been extended and new ones added, to deal with the more significant results of the explorations and researches that have revolutionised geology and geophysics during the last two decades. These include the radiometric dating of minerals and rocks, and the consequent possibility of estimating the rates of some of the earth's long-term activities; the concept of rheidity and its applications to the flow of glaciers, the formation of salt domes and the intrusion of granitic and associated rocks; fluidisation as the key to many aspects of volcanic and igneous geology; the host of complex issues raised by the occurrence of ice ages—some involving the destiny of mankind in the relatively near future and others the totally different distribution of climates in the far-off past; the extraordinary surprises, contradicting all expectations, that have rewarded the explorers of the ocean floors, particularly the astonishing thinness of the oceanic crust and its youthful veneer of deep-sea sediments, paradoxically combined in most places with a far higher rate of heat flow than anyone could have foreseen; the growing evidence that the earth is expanding rather than shrinking; the possible energy sources required to keep the earth's internal 'machinery' going; the maintenance of continents above sea-level and the uplift of plateaux; the contorted structures of mountain ranges and the recognition of gravity gliding as a major factor in the folding of rocks; and finally, the magnetism preserved in ancient rocks as a compass-guide to the wandering of continents.

In terms of observational facts alone the behaviour of the inner earth now appears even more fantastic than when we knew much less about it. In this rejuvenated book I have tried to present a balanced view of the new fields of knowledge which have been so explosively opened up. Every chapter contains exciting stories of man's achievements and speculations, tempered by the sobering reflection that while we may often be wrong, Nature cannot be. It may be noticed that inconsistencies have arisen here and there, when certain problems are approached along different lines. Such difficulties are not glossed over. By bringing them into the open, instead of sweeping them under the carpet of outworn doctrines and traditional assumptions, the reader is helped to see where further research is needed and may even be stimulated to take part in it. Primarily, however, the book has been designed to meet the needs of the same sort of audience as before: this time enlarged, I hope, by those of my former readers who may be finding it increasingly time-consuming to dig out the essentials of recent progress from the avalanche of publications in which they are recorded.

It is a pleasure to acknowledge the considerable help I have myself received in this way from the publications and pre-prints kindly sent to me by friends and correspondents in many parts of the world. By discussing various problems and reading parts of the book, generous assistance has been given by Professor Tom F. W. Barth, Dr Lucien Cahen, Dr Lauge Koch, Professor L. Egyed, Professor Maurice Ewing (and some of his colleagues at the Lamont Geological Observatory), Dr R. W. Girdler, Professor W. Nieuwenkamp and Professor C. E. Wegmann. To all of these I owe my grateful thanks for help, suggestions and constructive criticisms. To my wife and fellow geologist, Dr Doris L. Reynolds, I am, as always, more deeply indebted than can be adequately expressed. Not only has her unselfish devotion ensured the completion of this book, but her professional influence and her flair for the utmost rigour of scientific method have been never-failing sources of inspiration and encouragement. It is, however, only fair to add that I remain entirely responsible for any defects of fact, treatment, judgment or style.

As befits the subject, special care has again been taken to illustrate the book as fully and effectively as possible. Nearly all the line diagrams have been specially drawn, many of them being based on diagrams already published by others, with only slight modifications or translations of the lettering. Particular sources are credited in the captions, and a general expression of my indebtedness and thanks is given here to the many authors whose

diagrams have been so freely called upon. In addition to the photographs procured from professional photographers and press agencies (all duly acknowledged in the captions) many striking and instructive subjects have been contributed by friends and official organisations.

It will be noticed that the illustrations are not systematically listed in these preliminary pages. When such lists become unduly long, as would here have been the case, they tend to defeat their purpose. As a practical alternative, which it is hoped will facilitate easy reference, all illustrations are indexed, with their page numbers in italics, under each relevant subject or key word.

Finally, I wish to express my thanks to the staff of my publishers for their enthusiastic and helpful co-operation throughout the production of this book, and particularly to Miss Nina T. Yule and her colleagues for their editorial advice and guidance.

ARTHUR HOLMES

London
October 1964

Preface to Third Edition

In 1944, when the first edition of this book was published, it concluded with a chapter on continental drift. At that time this was very daring. Apart from masters of drift, like A. L. du Toit, who had proved its geological reality, even the few geologists who were prepared to discuss continental drift in the evening were inclined to dismiss it as too fantastic in the sober light of morning. Physicists, moreover, found it unacceptable.

By the time the second edition was published in 1965, continental drift was a confirmed reality. From remanent magnetism in rocks, geophysicists had determined the positions of the poles for past periods, and proved that the continents have moved both relative to the poles and to one another since the Cretaceous. This then formed the highlight of the second edition together with such evidence as then existed—the migration of volcanic islands for example—that the ocean floors are moving away from the mid-oceanic ridges.

During the following years geophysical discoveries continued to gain impetus, and there were many exciting and even fantastic revelations; movement of the ocean floors was firmly established from palaeomagnetic evidence, and their varying rates of movement determined. The culminating triumph was the evolution of the hypothesis of Plate Tectonics, which indeed might now be described as a theory, because it explains and correlates so many major features of the earth.

These fundamental additions to knowledge have made it necessary to reorganize and rewrite the final chapters of the book and, in conformity, to adapt parts of the early chapters. The chapter on orogenesis has been rewritten in order to present some important but overlooked discoveries that have been made by Emile Argand's successors. Argand's hypothesis, of more than 60 years ago, that collision between Africa and Europe was the cause of the uprise of the Alps is becoming regarded as fundamental to understanding the *cause* of orogenesis. Discoveries by his successors, however, cast doubt on the supposedly predominant role played by compression during orogenesis.

The sections on batholiths, granite, granitization and migmatites, although brief, have been rewritten so as to be of more general application, and 'ring-dykes' have been revised.

I am very grateful to many earth scientists for allowing me to reproduce their illustrations, and to the Officers of the Ulster Museum for generously waiving their royalties on some photographs from the R. Welch collection, of which they hold the copyright. I am particularly indebted to Dr P. S. Doughty, Keeper of Geology at the Ulster Museum, for the trouble he took examining the cliffs for many miles along the Antrim coast road in order to provide me with a photograph of faults showing black basalt downthrown against white chalk, here reproduced as Figure 17.14. To Professor P. McL. D. Duff I owe a debt of gratitude for much help concerning recent work on the production and reserves of petroleum and coal. I should hasten to add, however, that I am entirely

responsible for any defects or errors that may have been introduced in presenting this material.

Finally I wish to thank the staff of Thomas Nelson and Sons for their very helpful co-operation, and particularly Dr Dominic Recaldin and Mr. John E. Padfield on the editorial staff.

DORIS L. HOLMES, 1978

Contents

Chapter 1

Science and the World We Live in

In the first place, there can be no living science unless there is a widespread instinctive conviction in the existence of an Order of Things, and, in particular, of an Order of Nature.

Alfred North Whitehead 1927

Interpretations of Nature: Ancient and Modern

The world we live in presents an endless variety of fascinating problems which excite our wonder and curiosity. The scientific worker, like a detective, attempts to formulate these problems in accurate terms and, so far as is humanly possible, to solve them in the light of all the relevant facts that can be collected by observation and experiment. Such questions as What? How? Where? and When? challenge him to find clues that may suggest possible answers. Confronted by the many problems presented by, let us say, an active volcano (Frontispiece), we may ask: What are the lavas made of? How does the volcano work and how is the heat generated? Where do the lavas and gases come from? When did the volcano first begin to erupt and when is it likely to erupt again?

Here and in all such queries the question What? commonly refers to the stuff things are made of, and an answer can be given in terms of chemical compounds and elements. Not in terms of the four 'elements' of the Greek philosopher Empedocles (about 490–430 B.C.), who considered the ultimate ingredients of things to be Fire, Water, Earth and Air, but chemical elements such as hydrogen, oxygen, silicon, iron and aluminium. The question What? also refers to the names of things, and particularly to their forms and structures: things ranging in size from the elementary particles of atoms to the galaxies of stars that make up the Universe, with our own Earth falling manageably between these extremes of the inconceivably large and small.

The question How? refers to natural processes and events—the way things originate or happen or change—and in human activities to methods and techniques. This question leads to the very root of most natural problems, and satisfactory answers, although amongst the hardest to find, are to the scientist the most rewarding.

Where? refers to everything connected with space, and particularly to the relative positions and distributions of things. The location and distribution of oil and uranium are topical examples of current interest.

The question When? raises all the problems connected with the history of things and events. To unfold the history of the Earth and its inhabitants is the most ambitious aim of geological endeavour.

The scientific worker of today differs in one very important respect from the detective with whom we have compared him. Except when he is concerned with human nature, as the detective invariably is, and perhaps with some types of animal behaviour, the scientific worker nevers asks the question Why? in its strict sense of implying motive or purpose. It is quite useless, for example, to ask why a volcano erupts, or why the sky is blue, or why there are earthquakes, because there is no possible means of finding answers to such questions. Of course we all commonly ask Why? in the loose sense of meaning 'How does it happen or come about . . . ?' and so long as it is clearly understood that this usage is just scientific slang to avoid the appearance of pedantry, no great harm may be done.

Why? always implies the further question Who? Thus the old legends of Ireland tell us that giants were responsible for many natural phenomena.

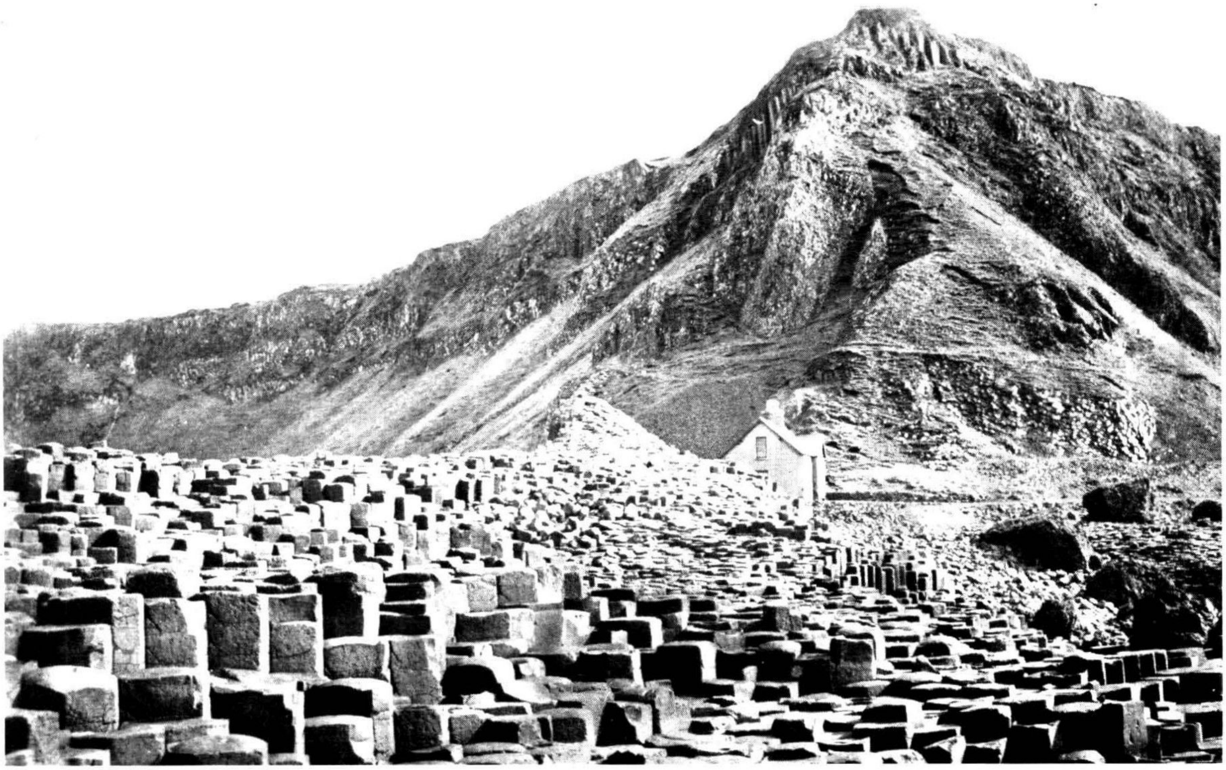

Figure 1.1 Giant's Causeway, Co. Antrim, Northern Ireland. View of the Grand Causeway, showing vertical columns. Steeply inclined columns are seen in the cliff to the right of the house. (*Northern Ireland Tourist Board*)

They were stone throwers or builders. One of them is reputed to have flung the Isle of Man into the Irish Sea, Lough Neagh being the place it was taken from. The Giant's Causeway, which is a terrace carved by the weather and the sea from a lava of columnar basalt (Figure 1.1), was 'explained' as the work of the giant Fionn MacComhal (or Finn MacCoul). This defiant stonemason began to construct a causeway across the sea, the better to attack his hated rival Fingal, who had built himself a stronghold of similar construction in the Isle of Staffa (Figure 1.2). Complacent satisfaction with such 'explanations' obviously stifles the spirit of eager enquiry which is essential for the birth and development of science.

It is only during the last century or so that the futility of reading motives and purposes into events has been at all widely realized. The ancients in particular, including Sumerians, Hindus, Babylonians and Greeks, all of whom made remarkable discoveries in mathematics and astronomy, went sadly astray as a result of inventing answers to the dangerous question Why? They regarded the phenomena of Nature as manifestations of power by mythical deities who were thought to behave like irresponsible men of highly uncertain temper, but who might nevertheless be propitiated by suitable sacrifices.

In the Mediterranean region, for example, many of the Olympian gods made familiar by the epics ascribed to Homer (about 850 B.C.) were personifications of various aspects of Nature, including quite a number of geological processes which have been named after them. Poseidon (later identified with the Roman water-god Neptune) was the ruler of the seas and underground waters. As the waters confined below the surface struggled to escape, Poseidon assisted them by shaking the earth and fissuring the ground. He thus became the god of earthquakes. Typhon, the source of destructive tempests, was a 'many-headed monster of malignant ferocity' who was eventually vanquished by the thunderbolts of Zeus, the sky and weather god, who imprisoned him in the earth. Hades, corresponding to Pluto of the Romans, was the deity presiding over the nether regions which share his name. He was not, however, the god of

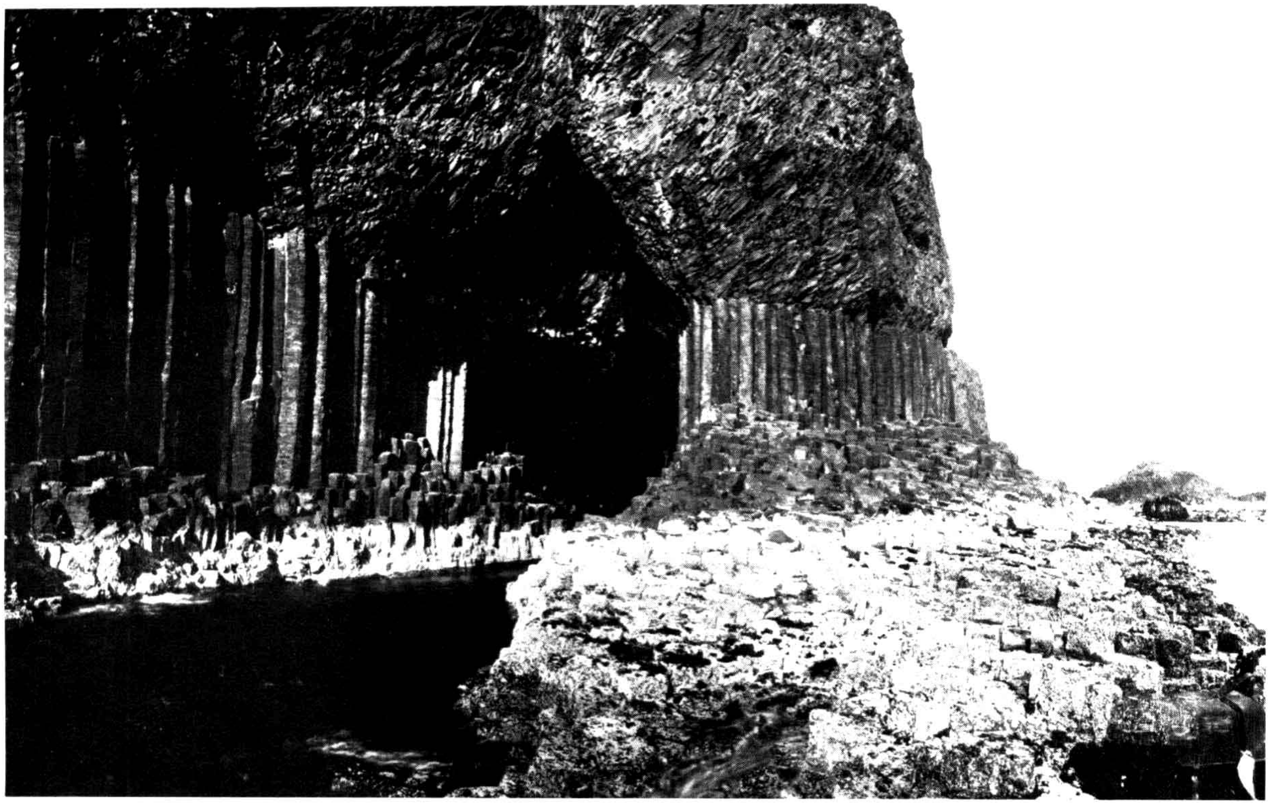

Figure 1.2 Fingal's Cave, Island of Staffa, west of Mull, Strathclyde (*Paul Popper Limited*)

subterranean fire. That responsibility was given to Hephaestus, a son of Zeus, who himself controlled fire in the form of lightning. When the Greeks settled in Sicily, Hephaestus was identified with the local volcano-god Vulcan or Volcanus. The eruptions of lava and volcanic bombs from Etna and Stromboli were feared both for their danger and as expressions of the fire-god's wrath.

The epic poems of Homer had biblical authority for the ancient Greeks, and therefore all the more honour is due to Thales of Miletus (about 624–565 B.C.) for his courage in making a clean break with all these traditional beliefs. He regarded the activities of Nature not as indications of supernatural intervention but as natural and orderly events which could be investigated in the light of observation and reason. He thus became the first Greek prophet of science. Having noticed that deposition of silt from the waters of the Nile led to the outward growth of the delta, he developed the hypothesis that Water was the source of earth and everything else. No doubt crude, but probably little more so than a present-day hypothesis that hydrogen is the primordial element. The important point is that the natural and observable activities of water took the place of the imaginary and therefore inscrutable activities of Poseidon. Science had replaced superstition.

Later Heraclitus (about 500 B.C.), celebrated for his philosophy that 'all is perpetual flux and nothing abides', picked on Fire, the most active agent of change, as the fundamental principle behind phenomena. The observable manifestations of fire took the place of the fire-gods. The next step was taken by Empedocles, who saw that both Fire and Water were necessary, for when natural water is heated it evaporates into Air (in this case steam) and leaves a residue of Earth (the material originally in solution). Thus he established the four 'elements' which roughly correspond to our concepts of energy, and the solid, liquid and gaseous states of matter.

Despite this promising start, science languished for two thousand years. The Ionian philosophers who began the scientific quest were well aware that another 'element' was necessary to account for Man. This they called Consciousness or Soul, and some of them regarded it as divine. In concentrating on this aspect of existence, Plato (427–347 B.C.)

and Aristotle (384–322 B.C.) revived the idea that Earth, Sun and Planets were all deities. So, unwittingly, one effect of their unrivalled authority was to lend support to the old Babylonian cult of astrology, as against the sterner discipline of science. Now what has this to do with geology? Two examples will suffice. Herodotus (484–426 B.C.) was a great traveller who made many significant geological observations. He speculated about the effect of earthquakes on landscapes, but nevertheless he thought it quite reasonable to ascribe the earthquakes themselves to Poseidon. Much later Pliny (A.D. 23–79), who, like Empedocles, lost his life while investigating a volcano too closely, 'explained' earthquakes as an expression of the Earth's resentment against those who mutilated and plundered her skin by mining for gold and silver and iron.

With the rise of Christianity there was no longer any incentive to study the ways of Nature. Because men had a complete theory as to *why* things happen, they were not interested in *how* they happen. Moreover, it was widely believed that the Earth had been created ready-made only a few thousand years before, and that it would soon come to an end. Two factors, amongst others, slowly brought this period of stagnation to a close. The Earth inconsiderately failed to come to an end, until at last it began to seem worth while to collect facts about the world instead of merely arguing about ideas. Another factor was a social one. Among the Greeks it had been bad form for a philosopher to become proficient in the craftsmanship and special skills demanded by any form of technology. For all such practical activities slaves were available. However, as the practice of alchemy came increasingly into vogue during the Middle Ages, a philosopher's study was quite likely to become his laboratory. Philosophy and technology—or more generally theory and practice—gradually ceased to be divorced, and with the coming of the Renaissance the occasional and increasing alliance of the two fostered afresh the spirit of science. By his unsurpassed and versatile genius Leonardo da Vinci (1452–1519) firmly established the new pattern. Were he not more renowned as painter and engineer, he would still be famous as a pioneer in many fields of natural science. He recognized that landscapes are sculptured and worn away by erosion; that the fossil shells found in the limestones of the Apennines are the remains of marine organisms that lived on the floor of a long-vanished sea that once extended over Italy; and that it could not have been the Noachian Deluge that swept them into the rocks of which they now form so important a part. But Leonardo was far in advance of his time, and three more centuries had to elapse before the Deluge ceased to obstruct the progress of geology.

Today we think of natural processes as manifestations of energy acting on or through matter. We no longer accept events as the results of arbitrary—and therefore unpredictable—interference by mythological deities. Typhoons and hurricanes are no longer interpreted as the destructive breath of an angry wind-god: they arise from the heating of the air over sun-scorched lands. The source of the energy is heat from the sun. Volcanic eruptions and earthquakes no longer reflect the revengeful behaviour of the gods of underground fire and water: they arise from the stresses and strains of the earth's unstable interior, and from the action of escaping gases and heat on the outer and crustal parts of the globe. The source of the energy lies mainly in the material of the inner earth.

In many directions, of course, and particularly where great catastrophes are concerned, our knowledge is still woefully incomplete. The point is not that we now pretend to understand everything—if we did, the task of science would be over—but that we have faith in the orderliness of natural processes. The steadily accelerating researches of the last two or three centuries have unfailingly justified our belief that Nature is understandable: understandable in the sense that if we ask her questions by way of appropriate observations and experiments, she will answer truly and reward us with discoveries that endure. But it must never be forgotten that Nature is the most perfect of expert witnesses. It is often far from easy to find the right questions and to ask them in the right way. For this reason, to say nothing of human fallibility, the discipline of science does not preclude the making of errors. 'What it does preclude,' as Norbert Wiener has expressed it, 'is the retention of an error which has clearly and distinctly betrayed its wrongness.'

The Major Fields of Scientific Study

The questions we ask when faced with a volcano in eruption are typical of the kinds suggested by all natural phenomena. They indicate that—in general terms—scientific investigation is concerned