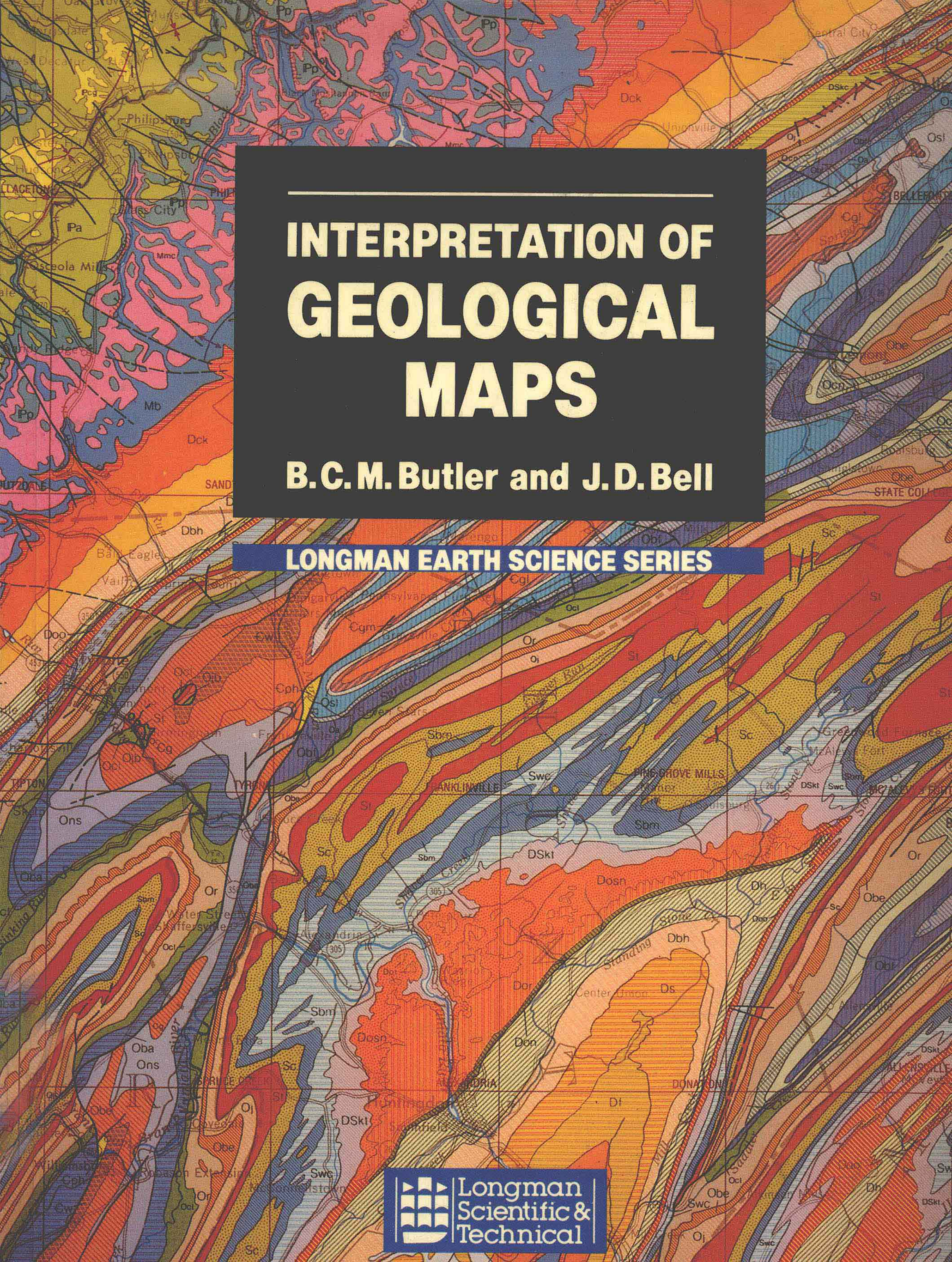

INTERPRETATION OF GEOLOGICAL MAPS

B. C. M. Butler and J. D. Bell

LONGMAN EARTH SCIENCE SERIES

Longman Scientific & Technical

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B. C. M. Butler and J. D. Bell: Interpretation of Geological Maps
P. R. Ineson: Introduction to Practical Ore Microscopy
P. F. Worthington: An Introduction to Petrophysics
B. W. D. Yardley: An Introduction to Metamorphic Petrology

PREFACE

Geological maps are the means of recording and storing information about the distribution, composition, and structure of the rocks of the surface of the Earth. They are used at every stage from the initial observations of the field geologist to the published geological survey map which may remain for years the definitive document about an area. Geological maps are thus a primary source of data about rocks and structures, a record of the environments and processes of the past, and an important element in the teaching of modern geology.

Some students and teachers may prefer to start the study of maps with synthetic examples designed to show idealised geometrical relationships; for those who prefer this approach, good simple textbooks are already available. We have found, however, that it is not only possible to teach map interpretation from the beginning using published geological maps, but by so doing, to introduce the student to maps as presentations of factual data about geological situations from the very earliest stage. Moreover this approach avoids the conceptual hurdle that some students find when idealised constructions are replaced by published maps.

In this book we explain both the geometrical and the geological interpretation of maps. We take the view throughout that maps are a cartographical representation of real rocks whose shapes and relationships must be understood as the product of geological processes operating through geological time. We make use of modern geological concepts relating to the environments of formation of sedimentary, igneous, and metamorphic rocks and mineral deposits, and of geological structures. These are summarised in Tables 2.1, 3.2, 3.3, 3.4, 7.1, and 10.1, and we recommend them to the reader for detailed study. We illustrate the determination of the rates of processes through the use of chronometric and radiometric ages and show how actualistic analogies can be made with present-day processes. We also introduce limited but meaningful interpretation of plate-tectonic environments from the evidence available on maps.

The book is designed for use by those beginning to study geology for the first time, whether at school or at university. It provides material covering the equivalent of about the first two years of instruction in most geology courses. Chapters 1 to 7 describe the basic techniques of map interpretation, using a step-by-step explanatory method, with worked examples at each stage. Chapter 8 deals with aspects of ocean-floor geology, and includes examples which are directly illustrative of plate tectonics. Chapters 9 and 10 deal in greater depth with the details of geological interpretation of maps and apply them with a comprehensively worked example.

We have drawn our examples from an international range of recently published maps which can, if the user wishes, be made into the nucleus of a teaching package

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(Appendix 6). We decided to restrict interpretation largely to what can be derived directly from the printed maps, even where we recognise that further interpretation is possible in the light of other data. This is because the stated intention of the book is to explain the methods of map interpretation rather than a discussion of the geology of individual areas.

We have chosen to refer to recent textbooks in each field of geology rather than to list large numbers of original papers, in the belief that this provides a more useful introduction to the literature of geology for the readers for whom the book is primarily intended.

Regretfully we have had to omit from consideration the numerous other types of map used by the practising geologist – geophysical, geochemical, hydrological, tectonic, palaeontological, palaeocontinental, etc. We have also omitted the interpretation of cross-sections produced directly from geophysical traverses. The principles of interpretation of these maps and sections are based on the techniques set out in this book, which forms the necessary ground-work for more specialised studies.

Acknowledgements

It is a pleasure to record the help given by our colleagues Drs P. A. Allen, W. S. McKerrow, J. P. Platt, H. G. Reading, and P. N. Taylor in reviewing parts of the manuscript. Professor E. H. Francis read the whole of Chapters 9 and 10, and his constructive comments were of great value. We are grateful to Dr N. J. Snelling for sending us a preprint of the revised geological time-scale. Mr D. S. Paterson and Mr P. J. T. Barbary greatly assisted our search for maps in the library of the British Geological Survey, and similarly Mrs Joan Morrall in our own library. Mrs Vivien Chamberlain and Mrs Andria Fowler typed the manuscript with patience and skill.

The authors wish to make special acknowledgement to the Directors and other officers of the geological surveys whose maps we have used as illustrations in this book. In particular we are grateful to the Director of the British Geological Survey for permission to reproduce Plates 1, 3, and 4 from BGS maps, to the Director General of the Department of Mines and Energy, Geological Survey of South Australia for permission to reproduce Plate 2 from the South Australia Geological Atlas Series, and to the State Geologist, Pennsylvania Geological Survey for permission to reproduce the front cover of the book from the Geologic Map of Pennsylvania.

All the line diagrams of maps in this book were traced from published maps (see Appendix 6), and we acknowledge the following sources:

British Geological Survey; Bundesanstalt für Geowissenschaften und Rohstoffe, West Germany; California Division of Mines and Geology; Commission for the Geological Map of the World and UNESCO; Elsevier Applied Science Publishers, Ltd.; Geological Survey of Canada; Geological Survey of Japan; Geological Survey of South Australia; Landeshydrologie und -Geologie, Geologische Landesaufnahme, Switzerland; Ministry of Petroleum and Minerals, Sultanate of Oman; The Open University, England; Parc Naturel Régional des Volcans d'Auvergne; Pennsylvania Geological Survey; Service Géologique National, Orléans, France; Servizio Geologico d'Italia; United States Geological Survey; Virginia Division of Mineral Resources.

We also acknowledge satellite and aerial photographs from the following sources: Aerofilms, Ltd, Borehamwood; British Geological Survey, Edinburgh; National Aeronautics and Space Administration, Houston, Texas; Royal Aircraft Establishment, Farnborough.

LIST OF COLOUR PLATES

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Plate 1

Extract from the northeast area of B.G.S. Sheet ST45 (Cheddar), reproduced by permission of the Director, British Geological Survey: N.E.R.C. copyright reserved. Scale 1 : 25 000. The map shows folded Devonian and Carboniferous sediments, unconformably overlain by Triassic.

Figure 2.14 gives the stratigraphical details. Arrows show dip direction and amount of dip. Black lines represent mineral veins (Pb and Zn). C – D is the line of section in Fig. 5.5. The vertical section on the published map is along the line labelled LINE OF SECTION.

Plate 2

Extract from the south – central area of South Australia Geological Atlas Series Sheet SH 54–9 (Copley), reproduced by permission of the Director General, Dept of Mines and Energy.
Scale 1 : 250 000. The map shows folded and faulted Precambrian and Cambrian sediments with diapiric intrusions.

Qra, Qpp, Qpz, Qpn	Pleistocene and Recent stream and lake sediments	Quaternary
Tfe, Tsi	Laterite and silcrete	Tertiary
Chn, Cho, Chr, Che, Chd, Chw, Chp	Hawker Group (limestones, dolomites, greywackes, shales, siltstones, sandstones)	Lower Cambrian
Disconformity		
Cu	Uratanna Formation (shales, sandstones)	Lower Cambrian
Unconformity		
Pwp, Pww, Pwb, Pwa, Pwr-u, Pwn	Wilpena Group (sandstones, siltstones, minor calcareous, carbonaceous and phosphatic sediments)	Proterozoic
Phl, Peb, Pec, Pfz, Pfe, Pfa, Pha, Pfb, Pft, Pfd	Umberatana Group (sandstones, siltstones, shales, minor limestones, dolomites, and conglomerates)	Proterozoic
Pyi	Unnamed tillite	Proterozoic
Dark brown	Diapiric breccia	
Fe, Mn, Cu, Zn, Pb, Ag, Au	Mineral occurrences — metal ores	
Ba, At	Ditto — barite and alunite.	

Plate 3 Extract from B.G.S. Sheet 39W (Stirling) reproduced by permission of the Director, British Geological Survey: N.E.R.C. copyright reserved. Scale 1 : 50 000. The map shows Carboniferous lavas and sediments and Upper Old Red Sandstone sediments resting unconformably on Lower Old Red Sandstone sediments in the west of the area. The west end of the Ochil Fault forms the boundary between these units in the east of the area. See Table 9.1 for abbreviations of the names of lithological units. Arrows show dip directions and amounts. A — B is the line of section shown in Fig. 9.6.

Plate 4 Extract from B.G.S. Sheet 39E (Alloa) reproduced by permission of the Director, British Geological Survey: N.E.R.C. copyright reserved. Scale 1 : 50 000. The map shows the Ochil Fault separating Lower Old Red Sandstone lavas in the north from folded and faulted Carboniferous sediments with coal seams in the south. See Table 9.1 for abbreviations of names of lithological units. Arrows show dip directions and amounts. C — D is the line of section shown in Fig. 9.7.

Front cover map

Part of the Geologic Map of Pennsylvania (1980), scale 1 : 250,000, showing the area around State College (40°48′N, 77°52′W), reproduced by permission of Donald M. Hoskins, State Geologist, Pennsylvania Geological Survey. The stratigraphical succession is Cambrian and Ordovician marine limestones and dolomites, followed by Late Ordovician to Devonian marine sandstones and shales, and then by Mississippian and Pennsylvanian shallow-water marine and terrestrial sediments including cyclic sequences of limestone, shale, sandstone, and coal.

The Allegheny Front, running northeast-southwest through the northwest quarter of the map area, marks the sharp transition from the strongly folded and faulted Cambrian to Pennsylvanian rocks of the Valley and Ridge Province in the southeast to the mildly folded Upper Silurian to Pennsylvanian of the Allegheny Plateau in the northwest corner.

The Cambrian and Ordovician rocks represent carbonate shelf deposits on a passive continental margin on the southeast side of the early North American continent, followed by clastic sediments derived from erosion of the Late Ordovician Taconian orogenic belt to the southeast. Compression in the foreland during the Alleghanian orogeny in the Late Carboniferous produced the prominent folds and thrusts of the Valley and Ridge Province, and the low amplitude folds and strike-slip faults in the Middle and Upper Paleozoic rocks of the Plateau.

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1 ACTUALISTIC INTERPRETATION OF GEOLOGICAL MAPS

1.A INTRODUCTION

The study of rocks starts where they can be seen – at the surface of the Earth. There are two principal sources of data:

1. The situations in which rocks are forming at the present day and the processes that operate within them.
2. The rock types and structures that were formed in the past and are now exposed by erosion at the surface of the Earth.

Interpretations of the two kinds of data are inter-related. By observing environments and processes at the present day we can develop the techniques for understanding the rocks and structures of the geological past. Conversely, the evidence of ancient rocks and structures known to have been formed below the surface of the Earth leads to the understanding of processes within the Earth which are not accessible for direct observation at the present day.

The techniques of geological mapping are described by Lahee (1961) and Barnes (1981). A geological map is a record of the distribution of rocks of different ages and compositions at the surface of the Earth. It is also, and more importantly, a source of evidence about how the Earth, or some small part of it, has operated as a physical, chemical, and biological system through the millions of years of its history. There are two stages in the interpretation of a geological map. The first is to show how the map reveals the two- and three-dimensional geometry of rock shapes. The second and more important stage is to show how the rock shapes are used to reconstruct the environments and processes of the past – to convert geometrical interpretation into geological understanding. We shall explain principles of both kinds of interpretation in this book. In particular, we shall show how knowledge of the dates of geological events enables us to evaluate the rates of geological processes, and so to begin to make realistic dynamic interpretations of how the geology of an area developed in the course of geological time.

In this chapter we shall briefly review some of the environments and processes that are observable at the present day as a framework for the interpretation of geological maps in subsequent chapters.

Table 1.1 Major Earth environments

	Deep oceans	*Continental shelves*
Geographical location	Oceanic regions generally deeper than 4000 m	Shallow submarine extensions of continents and island arcs
Topography	Active spreading ridges; aseismic ridges; large areas of gentle relief with isolated sea mounts or chains of sea mounts and fracture zones; deep active trenches	Generally even; gentle slope down towards deep oceans
Composition	Thin pelagic sediments covering basic igneous oceanic crust; terrigenous sediments transported by slumps from continental slope and by floating ice; metal-rich muds in some spreading rifts; manganese nodules	Clastic and carbonate sediments, evaporites and/or volcanic rocks
Age of exposed rocks	Mesozoic to Recent	Tertiary to Recent
Rate of deposition	Very low except locally near continental areas with major rivers	Variable: greatest in areas near large river systems
Rate of erosion	Very low	Generally low but locally and temporarily high in regions subject to sudden storms
Mobility	Generally very low except in spreading ridges and in trenches	Generally low; epeirogenic movements typical
Examples	Shallower linear areas: active spreading ridges in Atlantic and eastern Pacific. Aseismic ridges: 90 East Ridge in Indian Ocean. Abyssal plains in all oceans. Sea mounts in Pacific Ocean. Ocean trenches: West Pacific, west coast of South America, Caribbean.	Partially enclosed seas: Persian Gulf; North Sea; Gulf of Mexico. Recently formed oceans: Red Sea, Gulf of California. Open coastlines: Africa, Europe, Australia, Americas. Offshore areas of island arcs: western Pacific, Caribbean.

Lowland areas	*Orogenic belts*	*Shield areas (cratons)*
Inland areas of continents adjacent to orogenic belts; coastal plains bordering stabilised orogenic belts and shields; intracontinental rifts	Destructive plate margins: island arcs; edges of continents; inner parts of continents where continental collision has occurred	Inner parts of continents; edges of continents subjected to geologically recent tectonic spreading
Low and relatively even but with large volcanic piles in some areas	Very variable, from ocean trenches (−11 000 m) to highest mountains (+ 8000 m)	Low but irregular relief
Continental, fluviatile and lacustrine sediments; geologically recent glacial deposits in some areas; volcanics in some areas	Folded volcanic and sedimentary rocks in the younger belts. Metamorphic and plutonic igneous rocks exposed in the older more deeply eroded belts	Basement of high-grade metamorphic rocks formed at depths of 10–20 km, with thin veneer of sedimentary rocks in places
Palaeozoic to Recent	Precambrian to Recent	Precambrian (or later cover)
Variable: greatest in basins of subsidence and in volcanic areas	Very high to low, depending on position in orogenic belt and topographical location	Generally low
Variable: greatest during sudden storms and volcanic explosions	Very high to low, depending on age and topographical location	Generally low
Generally low; epeirogenic movements characteristic but lowland areas are liable to be involved in orogeny later; faulting in rifts	All show intense folding; young belts very mobile with strong seismic and tectonic activity; older belts more stable with seismic activity associated with faults	Resistant to folding; epeirogenic movements with block faulting in some areas
Inland depositional desert basins of Africa, Australia and Asia; Indo-Gangetic plain of India; Great Valley of California; glaciated plains of northwestern Europe; East African and Lake Baikal rifts	*Present-day*: western margins of North and South America; island arcs of the west Pacific, including Japan. *Tertiary*: Alps, Himalayas, Atlas Mountains. *Late Palaeozoic*: Ural Mountains. *Early Palaeozoic*: Appalachians of eastern North America; Caledonides of north-western Europe; eastern Australia	1. Exposed shield areas: Baltic Shield (Scandinavia), Central Australia, Canadian Shield, SW Greenland. 2. With thin cover of younger rocks: Columbia Plateau (western USA), Russian and Siberian platforms; Deccan plateau (India); much of Africa; Brazil

1.B ENVIRONMENTS

The interpretation of geological environments of the past depends on matching the rocks and structures recorded on the map with the products of analogous situations

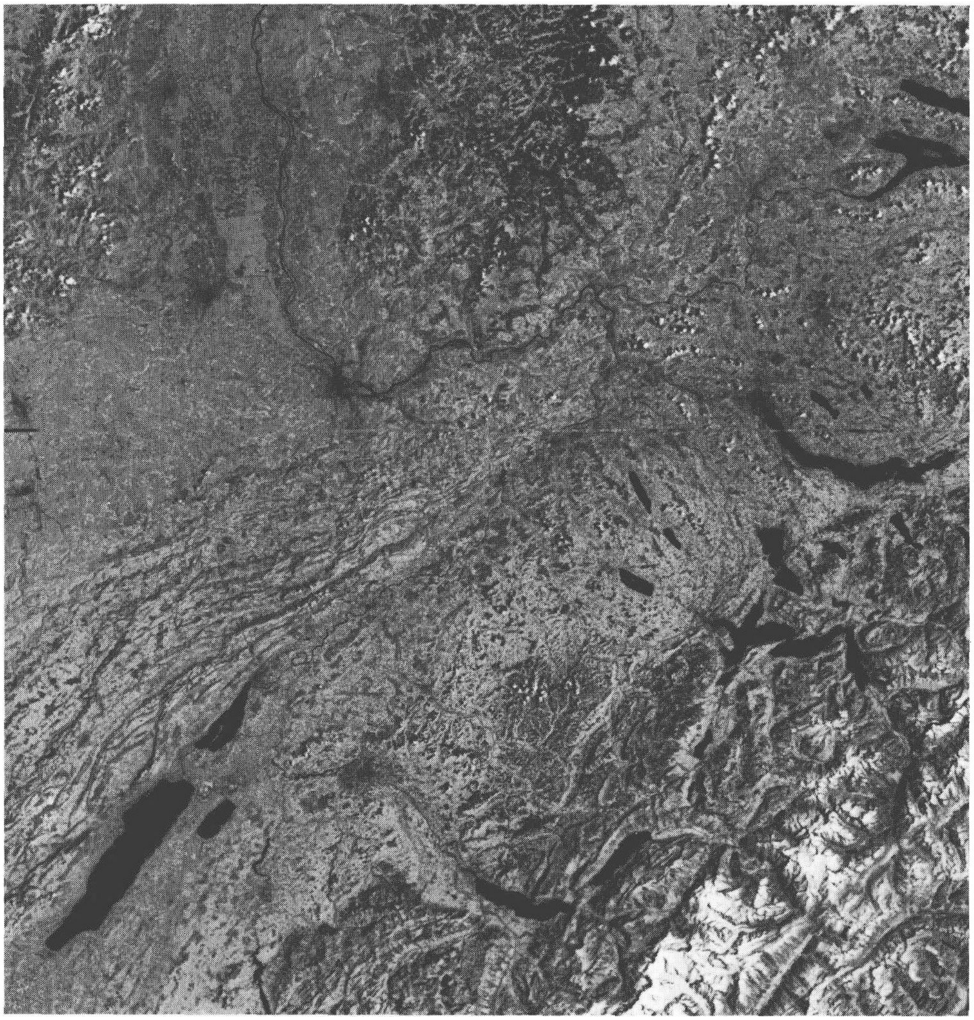

Fig. 1.1 Landsat photograph of parts of France, West Germany, and Switzerland, extending from Lac de Neuchâtel in the southwest to the west end of the Bodensee in the northeast. The area shown is approximately 115 km × 115 km. The following large-scale geographical and geological features are visible:

The Precambrian and Palaeozoic rocks of the Vosges (northwest, dark and partly cloud-covered) and of the Black Forest (north-central, dark) are separated by the Quaternary rocks of the Rhein Graben (pale); to the northeast are the flat-lying Mesozoic and Tertiary sediments of the Schwabische Alb.

The Mesozoic rocks of the Jura Mountains, folded during the Alpine orogeny, extend from the southwest corner to the centre of the photograph (striped light and dark) and are separated by the Tertiary molasse basin of the Franco – Swiss plain (pale, with numerous lakes) from the orogenic belt of the Alps (southeast corner, rugged topography, with snow on the higher ranges).

See Figs 4.17 and 7.4 for geological maps of parts of this area.

of the present day. Five kinds of broadly defined major Earth environments are set out in Table 1.1, each distinguishable by the kinds of rock that underlie them and the processes that operate within them (cf. Fig. 1.1). Finer divisions of environments based on distinctive rock types and structures are summarised in Tables 2.1, 3.2, 3.3, 3.4, 7.1, and 10.1.

1.C PROCESSES

All parts of the surface of the Earth are moving and changing (Table 1.2). We must distinguish movements of the crust as a whole, resulting from plate tectonic movements, uplift, and subsidence, from changes at the surface caused by erosion, deposition of sediments, and volcanic activity. The processes are distinct but inter-related – horizontal plate movement can produce vertical uplift and erosion in one area, while an adjacent area undergoes subsidence and deposition.

Because the rates of present-day geological processes are extremely slow it is easy to get the impression that their effects are trivial, with the exception of sporadic violent volcanic eruptions and earthquakes. However, both continuous and periodical processes are significant over the course of geological time and produce extensive changes. An average rate of deposition of only 0.1 millimetre of sediment per year persisting for 1 million years produces a pile of sediments 100 metres thick; the 3000-kilometre width of the North Atlantic Ocean between the continental shelves of Spain and Newfoundland was produced by a relative movement of the North American and Eurasian plates of 30 millimetres per year for the last 100 million years since the Cretaceous when the rifting of the two continents began.

It is perhaps helpful to think of the view of the Earth that we acquire during our short lifetime as like a single frame from a continuously running sequence. Details may vary – for example, there are no Phanerozoic analogues of Precambrian banded iron formations or of anorthosite intrusions, and the rates of some present-day surface processes are more vigorous than in preceding geological time because of after-effects of the Pleistocene ice age. But the fundamental processes – plate movement, uplift, subsidence, erosion, deposition, volcanism, and those processes that can be inferred to be operating in the interior of the Earth – form a continuum with the past. This is the basis of the **actualistic** view of geology – that the rocks and structures of past geological time were produced by essentially the same processes as those that are observable today (Holmes 1978, p. 30).

The same view of geology needs to be kept in mind when studying geological maps. A sedimentary rock unit shown with a uniform colour on a map seems at first sight to represent a single discrete event; in fact such a unit is the product of thousands or millions of years of sedimentation, and its boundaries are a convenient and artificial subdivision of essentially continuous processes. Similarly, igneous intrusions, faults, folds, and unconformities represent the products of processes that are extended over prolonged, and often determinable, durations of time. It is particularly important to think of the geology of an area as having a history which is continuous from the date of the oldest rocks (and earlier) up to the present day. Even during times when there is no solid record, in the form of rocks or structures, the area was involved in processes of some kind. Throughout the book we shall show how it is possible to evaluate the rates of geological processes by relating observations on the map to the geological time-scale (Appendix 2), and to relate them to the rates of comparable processes at the

(*Text continues on p. 10*)

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