Global Geomorphology

An introduction to the study of landforms

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LONGMAN

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Preface

If it is to present its subject matter coherently a textbook must have a point of view. The perspective of this book is that an adequate appreciation of landform genesis must encompass a knowledge of the large-scale framework of landscapes as well as an understanding of the smaller-scale processes which create individual landforms. An emphasis on small-scale, surface processes and their associated landforms has been pervasive in geomorphology since the 1960s, to the point where the larger-scale aspects of landform genesis, and in particular the role of internal mechanisms in influencing the development of major morphological features, have come to be regarded as almost incidental to the main thrust of research in the subject. To borrow an analogy from Richard Lewontin, commenting on the relationship between population genetics and evolutionary biology, 'this has led to a kind of auto mechanics concerned with carburettor settings and tyre pressures, but not with how the car was manufactured or where it is is going'.

There are growing signs that this situation is changing and this book attempts to redress the balance by giving due weight to problems of long-term, large-scale landscape development. In particular I have attempted to integrate ideas on global tectonics fully into landscape analysis and to incorporate the results of newly applied dating techniques and of research on the offshore sedimentary record. The examination of surface processes and the landforms they create still accounts for the bulk of the text, but the title of the book is intended to convey the global perspective that I wish to present.

Geomorphology has grown in scope and depth over recent years to the extent that even in a fairly lengthy text I have been forced to be selective in the topics discussed. Perhaps the major omission is applied geomorphology, but to have done this topic justice would have extended the length of the book by a further 20 or 30 per cent. With its emphasis on the way the large-scale components of landscapes develop over the long term this text is concerned essentially with the development of naturally-created landforms, an understanding of which is, of course, vital if we are correctly to assess the impact of human activity. A second significant omission is submarine geomorphology; this again is largely for reasons of space since the history of the ocean basins and the operation of submarine processes raise some quite distinct issues which I felt could not be adequately tackled without a fairly lengthy treatment.

Guide to the reader

My aim is that this book should be used as a resource which provides both basic background information and guidance towards the more advanced study of particular topics. In order to make the book more readable I have omitted references from the text, but each chapter concludes with a detailed guide to further reading and a list of references. These literature guides will be useful to those pursuing topics for essay or project preparation. The references have been selected on the basis of their importance, readability and accessibility, although the nature of the coverage in the literature of some subjects means that I have not always been successful in meeting these criteria.

I have assumed that readers have a basic knowledge of the physical environment including the main types of climate and vegetation, and the major rock types and rock-forming minerals. An introductory course in physical geography or physical geology would provide the appropriate background. Nevertheless, I have attempted to define all but the most elementary technical terms and these are printed in bold type in the text. Where possible, terms have been defined where they first occur in the text, but in all cases a page number in bold type in the index indicates where the definition of a term can be found. The mathematical competence of students taking courses in geomorphology varies enormously and this provides a major dilemma for the textbook author. The view I have gained from my own experience and discussions with numerous colleagues both in the UK and the USA is that while a fairly rigorous mathematical treatment might be desirable, such an approach would not be appropriate for the majority of students. Moreover, a strong mathematical emphasis can in some cases create the impression that certain geomorphic processes are more fully understood than they actually are. I have decided, therefore, to rely on verbal description and discussion, but I have included a mathematical representation of selected concepts and processes in boxes throughout the text. Furthermore, the text *An Introduction to Quantitative Geomorphology: An Exercise Manual* by Larry Mayer (Prentice-Hall, Englewood Cliffs and London, 1990) provides a mathematical treatment of a number of the topics covered in this book along with a range of relevant field and laboratory exercises.

Part I of the book (Chapter 1) provides an introduction to some of the major concepts applied in the analysis of landscapes; other important concepts are introduced at appropriate points in subsequent chapters. Part II, comprising Chapters 2–5, examines the effects of internal processes on the form of the landscape, while Part III (Chapters 6–14) looks at the wide range of surface processes and their associated landforms. The chapters in Part IV (15–18) consider the ways in which internal and external geomorphic processes interact and the book concludes in Part V with a survey of planetary geomorphology. Extensive cross-referencing means that to some extent the chapters do not have to be read in the order they are presented. In particular, Chapters 6–14 can just as easily precede Chapters 2–5 as follow them. Chapters 15–19, however, are to a large extent founded on material in earlier chapters. Readers with a background in physical geology might want to skip much of Chapter 2 as it provides an introduction to global tectonics. For those without a geological training some useful background material is provided in the appendices. These also contain information on the units of measurement used in the book and a brief discussion of dating techniques relevant to geomorphology.

Acknowledgements

Preparing a textbook is a major undertaking which can only be accomplished through the efforts of many individuals besides the author. The diagrams are a crucial component of the book and I have been fortunate in having the services of Ray Harris and Anona Lyons of the cartographic staff at the Department of Geography of the University of Edinburgh. Initial assistance with the typing of some of the draft chapters was provided by Mrs B. L. Summerfield and Mrs W. Rust and most of the tables were typed by Miss S. Smith. A number of individuals and organizations have been kind enough to provide me with photographs and other imagery in areas where my own resources have proved inadequate; these are acknowledged in the relevant figure captions. I would, however, particularly like to thank Nick Short who made available to me several Landsat images originally published in his co-edited book *Geomorphology from Space*. I would also like to thank those individuals and organizations who granted permission for copyright material to be reproduced or used as the basis for diagrams or tables. Specific acknowledgements are listed below.

Some of the material presented in this book relates directly, or indirectly, to my own research experience which has included fieldwork in many parts of the world, and I am grateful to those organizations that have provided financial support for this research. These include the Natural Environment Research Council, the Royal Society, Texaco Inc., British Aerospace p.l.c., the Carnegie Trust for the Universities of Scotland, the University of Oxford and the University of Edinburgh. I also owe a considerable debt to those numerous colleagues who have influenced my approach to geomorphology, both through their published work and informal discussions. Naturally this book draws extensively on the work of a great number of earth scientists, only a small proportion of whom are specifically mentioned in the main body of the text. The guides to further reading will, however, enable readers to follow-up work by individual researchers.

I am especially grateful to those colleagues who put considerable time and effort into providing comments on the draft manuscript, or parts thereof. These individuals are listed separately. The responsibility for the final text is, of course, solely my own.

Finally, I would like to thank Sue Smith for her support and encouragement.

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Chapter heading plate captions

1. View of the Earth showing landforms at a global scale. The image shows a nearly cloud-free Africa with southern Europe towards the top and the north-east of South America on the left. Landscape features evident at this scale are primarily related to the major horizontal motions of the continents over the past 200 Ma. Such movements have created the Atlantic Ocean and led to the more recent opening of the Red Sea (top right corner). (Meteostat image courtesy Satellite Remote Sensing Centre, RSA.)
2. Apollo 7 image showing a view north-east across the Sinai Peninsula and the northern end of the Red Sea with the Gulf of the Suez on the left and the Gulf of Aqaba on the right. This region is seeing the early stages of the development of a divergent plate boundary separating the African and the Arabian Plates with a spreading ridge extending northward up the Red Sea. The linear feature in the top right corner of the image is the Dead Sea Rift, a tranform plate boundary which extends northward from the Gulf of Aqaba. The eastern side of this rift is moving northward relative to the western side. (Image courtesy of NASA, Lyndon B. Johnson Space Center, Houston, Texas.)
3. Looking west towards the Himalayas and Tibetan Plateau. The dark area to the left is the lower forested slopes of the Nepal Himalaya. Mount Everest is located a little below the middle–centre of the view. (Apollo 7 image courtesy R. J. Allenby Jr and the World Data Center A for Rockets and Satellites.)
4. The summit of the Drakensburg Escarpment in Natal, South Africa, capped at this location by basalt lavas more than 1 km thick. This part of the Great Escarpment of southern Africa lies about 160 km inland from the coast and has formed along a sheared margin.
5. The snow-covered summit of Mount Taranaki (Egmont), an almost perfectly symmetric strato-volcano, North Island, New Zealand.
6. Rectangular joint system on Checkerboard Mesa, Zion National Park, Utah, USA. The fractures may have resulted from cyclic near-surface volume changes resulting from temperature fluctuations, wetting and drying or freeze–thaw.
7. Compound slope developed in flat-lying, alternating beds of shale and resistant, massive sandstone, Utah, USA.
8. Highly turbulent flow in a boulder-bed channel, River Inn, Austria.
9. The finely dissected terrain of the Loess Plateau, Shanxi Province, China. The high drainage density in combination with the ease with which the wind-borne silt (loess) covering the region can be eroded by running water causes extraordinarily high rates of erosion. The Huang He River visible flowing north to south on the right of the image is estimated to carry an annual sediment load of between 1.5 and 1.9×10^9 t where it leaves the loess plateau. The area covered is about 130 km across. (Landsat image courtesy N. M. Short.)
10. Part of the Rub'al Khali, or Empty Quarter, of southern Saudi Arabia, the largest sand sea on Earth. The large-scale regularity that can be achieved by wind-shaped depositional forms is clearly evident in this image which spans an area 140 km across. Three categories of dune form are visible; complex barchanoid ridges which interconnect to form a dune network or aklé pattern cover the bottom and right half of the image, while complex linear dunes occupying the top left quarter pass into star dunes in the extreme top left corner. Note that north is at the bottom of the image. (Landsat image courtesy A.S. Walker.)
11. Crevasse patterns and medial and lateral moraine visible on a glacier in northern Milne Land, eastern Greenland. (Photo courtesy of the Geodetic Institute, Copenhagen, Denmark.)
12. Ice-wedge polygons near Barrow on the northern

coastal plain of Alaska. The polygons range from 7 to 15 m across. (Photo courtesy United States Geological Survey Photo Library, Denver, Colorado, T. Péwé 845.)

13. Oblique, northward-looking view of the coastline of North Carolina and Virginia, USA taken with a hand-held camera on the Apollo 9 Earth-orbital mission. Cape Hatteras is the eastern extremity of the line of barrier islands cleary visible running down the centre of the image. These barrier islands, which have a total length of over 300 km in the area covered by the image, form part of a nearly continous chain of barrier islands extending from Long Island, New York, to Florida. Cape Hatteras is just one of a number of cuspate forelands along the eastern coast of the USA. Cape Lookout is the promontory at the bottom of the image and Pamlico Sound is the large body of water to the west of Cape Hatteras. (Image courtesy NASA, Lyndon B. Johnson Space Center, Houston, Texas.)

14. Landsat image of the north-central Kalahari showing a range of landforms created under alternating humid and arid conditions. East-west orientated relict dune systems evident from vegetation contrasts on the image and indicative of past aridity have been cut by river channels which thus post-date them and demonstrate later humidity. Flooded pans apparent from their dark tone are visible in the top right corner of the image. The dark channel in the extreme bottom left corner of the image is the Okavango River which has a perennial discharge fed from the Angolan Highlands far to the north-west. The broad light-toned channel running across the centre of the image is of uncertain origin but may represent a periodically active overflow from the Okavango. The area covered by the image which is about 180 km across is located within the area of Group A dunes in Figure 14.21. (Landsat image processed by the Satellite Remote Sensing Centre of the CSIR, RSA.)

15. View from the Tasman Sea eastwards to the Southern Alps, South Island, New Zealand. The Southern Alps have one of the highest sustained rates of crustal uplift known, reaching a maximum of around 10 000 m Ma^{-1}. These rapid rates are matched by equally high rates of erosion.

16. Anticline in the Zagros Mountains, Iran, at an early stage of fluvial dissection. (Photo © Aerofilms Ltd.)

17. A flight of uplifted coral reef terraces recording sea-level highstands during the past 120 ka, Huon Peninsula, Papua New Guinea. (Photo courtesy J. Chappell.)

18. Structural control of the Great Escarpment in western Cape Province, South Africa, provided by a massive sandstone unit (see Figure 18.12.)

19. The south polar region (left part of image) of Triton, one of Neptune's moons. The morphology of Triton seems to be a collage of landscapes observed on other bodies in the Solar System — certainly Triton has the most enigmatic surface of any planetary body yet explored. On this exceedingly cold world the surface appears to be formed of frozen methane and nitrogen. The dark streaks visible at the bototm left of the image may be formed by eruptions of nitrogen from volcanoes, some of which may still be active. The long features on the right side of the image are probably down-faulted blocks analogous to rift valleys on Earth. (Voyager 2 mosaic courtesy JPL and NASA.)

1

Approaches to geomorphology

1.1 The science of landforms

Geomorphology is the science concerned with the form of the landsurface and the processes which create it. It is extended by some to include the study of submarine features, and with the advent of planetary exploration must now incorporate the landscapes of the major solid bodies of the Solar System. One focus for geomorphic research is the relationship between landforms and the processes currently acting on them. But many landforms cannot be fully explained by the nature and intensity of geomophic processes now operating so it is also necessary to consider past events that may have helped shape the landscape. To a significant extent, then, geomorphology is a historical science.

Since the landsurface is located at the interface of the Earth's lithosphere, atmosphere, hydrosphere and biosphere, geomorphology is closely related to a wide range of other disciplines (Table 1.1). While having a central interest in landforms, geomorphologists must, none the less, be aware of those aspects of allied disciplines that bear on their subject. Equally, geomorphology has a potential, as yet only partially realized, of making significant contributions to these other areas of knowledge.

1.2 The development of ideas

The way geomorphologists approach the study of landforms at the present time can only be seen in a proper context if we appreciate how the central concepts of geomorphology have been developed. Long before the term geomorphology itself was introduced in the 1880s people had speculated on the forces and mechanisms that had created the natural landscape around them. Aristotle, Herodotus, Seneca and Strabo, among other Greek and Roman philosophers, wrote on phenomena such as the origin of river valleys and deltas, and the relationship between earthquakes and deformation of the landsurface. The idea that streams have sufficient power to erode their valleys was appreciated to some extent by Seneca, and certainly by Leonardo da Vinci in the fifteenth century, but it was not until the late eighteenth century that the implications of this fundamental concept began to be fully explored.

Table 1.1 Examples of relationships between geomorphology and allied disciplines

DISCIPLINE	EXAMPLE OF CONTRIBUTION TO GEOMORPHOLOGY	EXAMPLE OF CONTRIBUTION FROM GEOMORPHOLOGY
Geophysics	Mechanisms and rates of uplift	Erosional response of landsurface to uplift
Sedimentology	Reconstruction of past erosional events from a sedimentary sequence	Form of alluvial channels in interpretation of fluvial sediments
Geochemistry	Rate and nature of chemical reactions in rock weathering	Mobilization of elements in earth surface environments
Hydrology	Frequency and intensity of flooding	Sediment concentration in streams
Climatology	Effect of climatic elements on rate and nature of geomorphic processes	Effect of surface deposits and morphology on climatic variables
Pedology	Effect of soil properties on slope stability	Topographic control over soil-forming processes
Biology	Role of vegetation cover in affecting rates of erosion	Topographic control over micro-environments of plant growth
Engineering	Techniques for analysis of slope instability	Identification of morphological features indicative of slope instability
Space science	Context for understanding special characteristics of landform-creating environment on the Earth	Interpretation of planetary landscapes by analogy with terrestrial landforms

1.2.1 The age of Hutton and Lyell

In 1785 James Hutton presented a paper to the Royal Society of Edinburgh in which he argued that the landsurface had been shaped by the slow, unremitting erosive action of water rather than by the catastrophic events advocated by biblical scholars; to the history of the Earth Hutton saw 'no vestige of a beginning, no prospect of an end'. His ideas disseminated only slowly until in 1802, five years after his death, John Playfair, his friend and Professor of Mathematics at the University of Edinburgh, restated and elaborated his views with an elegance and clarity that has rarely been matched in scientific writing. In his *Illustrations of the Huttonian Theory of the Earth* Playfair provided the first detailed and closely reasoned account of several important aspects of landform genesis, most notably the relationship between rivers and their valleys:

> Every river appears to consist of a main trunk, fed from a variety of branches, each running in a valley proportioned to its size, and all of them together forming a system of valleys, communicating with one another, and having such a nice adjustment of their declivities, that none of them join the principal valley, either on too high or too low a level, a circumstance which would be infinitely improbable if each of these valleys were not the work of the stream which flows in it.

Hutton's methodology, founded on the belief that the slow but continuous operation of processes observable at the present day provided a sufficient basis for explaining the present configuration of the Earth's surface, was taken up and developed by Charles Lyell in his idea of **uniformity**. Through his highly influential work, *Principles of Geology* (1830–33), Lyell became the 'great high priest' of what became known as the principle of **uniformitarianism**, a concept frequently (but inadequately) summarized by the phrase 'the present is the key to the past'. Lyell's notion of uniformity was far more complex than is often appreciated by many earth scientists and this has led to much confusion as writers have failed to distinguish between its various meanings. In fact four distinct meanings can be identified in Lyell's *Principles*.

1. **Uniformity of law:** this is the assumption that natural laws are constant in time and space.
2. **Uniformity of process:** this is the proposition that if past events can be explained as the consequence of processes now known to be operating then additional unknown causes should not be invoked. In essence, this is the principle of simplicity adopted in all scientific explanation; if known processes are capable of explaining natural phenomena additional 'exotic' mechanisms should not be introduced. For Lyell, and Hutton before him, this principle was in fundamental opposition to notions of divine intervention as an explanation for the Earth's surface form.
3. **Uniformity of rate (gradualism):** this is the proposition that changes on the Earth's surface are usually slow, steady and gradual. Although Lyell did acknowledge that major events, such as floods and earthquakes, do take place, he maintained that such phenomena are local in extent and that they occurred in the past with the same average frequency as they do today.
4. **Uniformity of state:** this is the idea that, although change occurs, it is directionless; that is the Earth always looked and behaved much as it does at the present time. This concept was a central pillar in Lyell's grand vision of earth history as an endless succession of cycles.

These multiple meanings of uniformity led to much confusion in the vigorous debate which Lyell provoked after 1830 because it was possible to accept some of the propositions embodied in uniformitarianism while at the same time rejecting others. Opposition to uniformitarianism came from geologists who subscribed to **catastrophism** – the idea that many of the features of the landscape were to be explained by rapidly occurring events, rather than by gradual change. The great majority of catastrophists were not, as is often portrayed, believers in a landscape created by acts of divine intervention, since, by the 1830s, few serious geologists accepted a 6000 year biblical time scale for Earth history. In fact they had no argument with the uniformity of law and uniformity of process, but, on the basis of their interpretation of the available field evidence, they firmly rejected Lyell's ideas on the uniformity of rate and uniformity of state. One important type of evidence the catastrophists pointed to was the so-called 'drift' deposits formed of a mixture of boulders, gravel and sand which were known to blanket large areas of northern Europe. These materials, which were to be found on hilltops as well as in lowlands, had earlier been cited as evidence of the biblical Flood but, scriptural arguments aside, they provided a powerful argument against Lyell's extreme notions of gradualism and uniformity of state. The argument in effect centred around the extent to which the intensity of particular landscape-forming processes might change over time, and this debate has continued in various guises to the present day where the primary concern is the relative significance of rare, large magnitude (catastrophic) events in landform genesis.

The idea that these drift deposits had been laid down by glaciers gradually emerged in the early nineteenth century; but a glacial theory did not become a widely accepted explanation for drift deposits, and other landforms which were apparently inexplicable in terms of normal fluvial erosion, until after the publication in 1840 of Louis Agassiz's *Etudes sur les Glaciers*. His notion of a Great Ice Age was soon being applied by other workers to the landscapes of northern Britain, while Agassiz himself, who eventually moved to the USA from his native Switzerland, extended his glacial theory to North America. Concurrent with the acceptance of the idea of continental glaciation was a continuing debate over the relative importance of marine and fluvial erosion. By the 1870s this had been resolved firmly in favour of the predominance of rivers in shaping the landscape.

1.2.2 Developments in North America

If the foundations of the scientific study of landforms were laid in Europe in the first half of the nineteenth century, much of the conceptual structure of the modern discipline was erected in the second half of that century by a remarkably gifted group of American geologists led by John Wesley Powell and Grove Karl Gilbert. Exploring the mostly semi-arid terrain of the western USA where the detailed relationships between rock structures and landforms were largely unobscured by soil and vegetation, Powell was able to develop a structural and genetic classification of mountains, as well as classifications of valleys and drainage systems. His greatest conceptual contribution was the recognition of the importance in landform development of **base level** – the lower limit in the landscape, ultimately represented by sea level, below which rivers cannot erode.

Of even greater significance to the later development of the subject was the pioneering research of Gilbert. He created the first systematic analysis of the mutual interaction between the driving forces of erosion and the resisting forces represented by the rocks and superficial deposits of the Earth's surface. The resulting series of laws of landscape development, founded upon Gilbert's concept of dynamic equilibrium (see Section 1.3.4), were brilliantly presented in his classic monograph, *Report on the Geology of the Henry Mountains,* and developed further in a novel quantitative treatment of fluvial processes published in 1914.

Whereas Gilbert emphasized the adjustment between present forms and present processes, his compatriot and contemporary William Morris Davis founded a school of geomorphology based on the concept of a systematic progression of landform change through time initiated by rapid uplift of the landsurface. This evolutionary sequence, termed the **cycle of erosion** (see Section 1.3.4), was enthusiastically extended and applied by Davis's students and other researchers in the USA and the UK. But it was never accepted by the majority of European geomorphologists who reacted against what they saw as the overly theoretical and idealized nature of the model, as well as the way it underplayed the importance of climate in influencing landform development. A further European challenge came from Walther Penck, who rejected the crucial assumption inherent in the cycle of erosion that the Earth's surface can be stable for a sufficient period of time after an episode of rapid uplift for an evolutionary sequence of landforms to be developed. He argued instead that the overall form of the landscape would depend primarily on whether the rate of uplift was increasing, decreasing or constant through time.

1.2.3 The modern era

A lack of empirical evidence as to the nature and rate of landscape change through time, coupled with a poor level of understanding of the processes responsible for landform genesis, led to increasing doubts among many geomorphologists as to the viability of historical explanation in geomorphology. Foreshadowed by R. E. Horton's remarkable synthesis of drainage basin hydrology published in 1945, the following decades witnessed a growing emphasis, especially in the UK and North America, on both the quantitative analysis of landform morphology (landform **morphometry** or **geomorphometry**) and on the field measurement of geomorphic processes. These developments were not so evident in Continental Europe where the earlier tradition of geomorphology founded on the relationship between landform characteristics and climatic zones was strengthened after the Second World War.

The 1960s and 1970s saw a major reorientation of geomorphology in the UK and USA towards the development of predictive models of short-term landform change. These were based on a much improved knowledge of geomorphic processes founded on a greater understanding of the basic physical principles involved. Indeed, these models often reflected a significant input from research by engineers, particularly with respect to slope stability, the flow of water in river channels and the entrainment and transport of sediment. During this period there was also a rapid growth in applied geomorphology with predictive models being used to assess the likely response of the landscape to changing conditions brought about by human activities, such as land use changes and dam construction.

1.2.4 Future directions

Although greatly advancing our knowledge of surface processes, much current research in geomorphology contributes little to our understanding of how extensive areas of a landscape change over long periods of time. But revolutionary changes since the late 1960s in disciplines allied to geomorphology, together with the application of new techniques, now provide the opportunity to look at this problem anew and to develop a global perspective for geomorphology to accompany the existing disciplinary focus on small-scale, surface process studies. What new directions, then, can we see for geomorphology within such a global perspective?

The late 1960s and early 1970s saw a dramatic change in our understanding of the Earth as the notion of continental mobility embodied in the concept of plate tectonics was developed and refined (see Ch. 2). Davis's scheme of long-term landform development had no comprehensive tectonic theory with which to work, and consequently his assumptions about uplift and landsurface stability were inadequately grounded. We now have a model capable of making predictions of general patterns of uplift and stability for the

Earth's surface through time and space and know that a mode of landscape development applicable to one tectonic setting is not necessarily relevant to another. Moreover, significant advances in dating techniques mean that in many cases long-term rates of uplift and denudation can be estimated with some accuracy. One of the results of the application of these dating techniques is the realization that in relatively stable regions landsurfaces may survive without significant modification by erosional processes for several tens of millions of years.

A related advance in the earth sciences of great potential value to geomorphologists has come from the exploration of the oceans. Since the 1960s an active programme of drilling in the deep ocean basins and in the shallower waters around the margins of the continents has produced a wealth of data on the quantities of sediment that have accumulated in these environments over periods of 100 Ma or more (see Ch. 15). These sedimentary sequences provide a unique repository of information recording the erosion of adjacent land masses. There have been numerous studies by geomorphologists which have used the volume of sediment accumulating in lakes and reservoirs to quantify rates of denudation over periods of up to a few thousand years, so the approach is not novel; what is novel is the temporal and spatial scale which can now be addressed.

A third development of importance to problems of long-term landform evolution has been the revolution in our understanding of climatic change (see Ch. 14). We now know that climatic fluctuations, especially during the past 2 Ma or so, have been both more frequent and more extensive in their effects than was appreciated up to the 1960s. The implications of these new ideas of global climatic change for models of long-term landscape development have been especially appreciated by geomorphologists investigating humid tropical landscapes where earlier ideas of climatic stability have had to be dramatically revised. Given the increasing importance now being attached to the interactions between the atmosphere, the oceans and the landsurface in climatic modelling, we can anticipate that geomorphology will come to play a more central role in the understanding of climatic change itself. We now know, for instance, that atmospheric carbon dioxide is a crucial factor in determining global temperatures and that its concentration in the atmosphere is partly controlled by the rate of weathering reactions on the landsurface; this, in turn, is influenced by a range of geomorphic factors.

One further opportunity for developing a broader, global perspective for geomorphology lies in the comparative analysis of the planets and moons of the Solar System (see Ch. 19). The period since the 1960s has seen a new research frontier open for geomorphologists with the beginning of the exploration of the Solar System. As with the exploration of the then unfamiliar arid landscapes of the south-west USA which led to the pioneering work of Gilbert and Powell, the alien landscapes of the Moon (Fig. 1.1), Mars (Fig. 1.2) and the other planetary bodies have presented a major challenge to geomorphologists.

The study of planetary surfaces is a 'two-way street'; on the one hand terrestrial analogues have been invaluable in the interpretation of the surface forms of other planetary bodies (Fig. 1.3), but on the other hand planetary landscapes provide an invaluable perspective with which to consider long-term landform development on the Earth. Many planetary surfaces have experienced relatively little change for billions of years and so retain the effects of very rare, but cata-

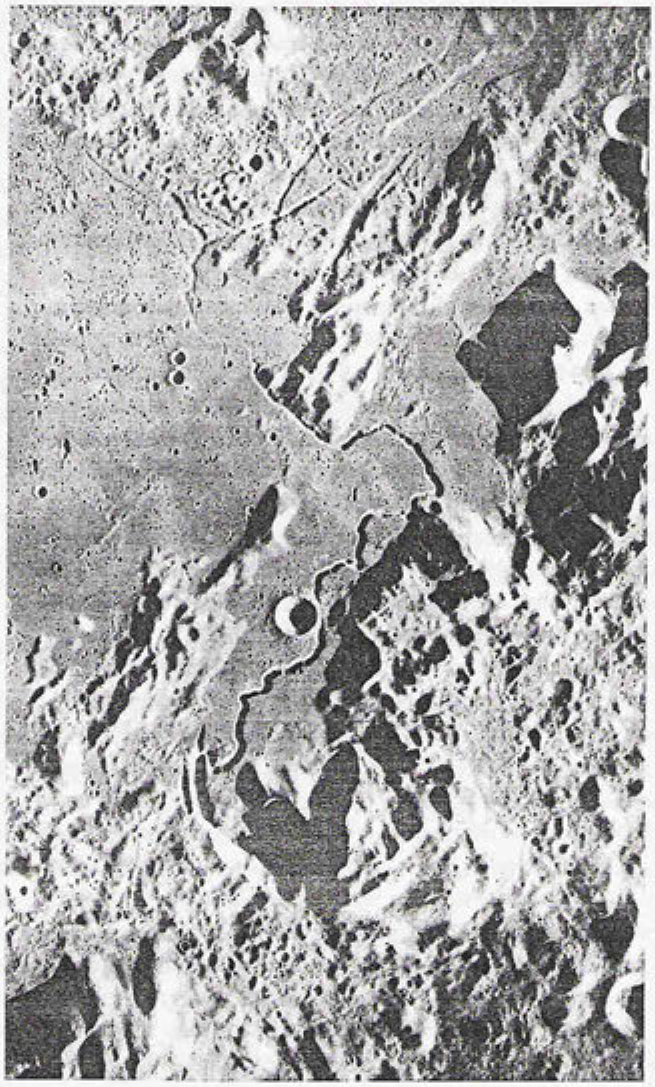


Fig. 1.1 *Hadley Rille, a sinuous channel more than 115 km in length cutting across a lava plain adjacent to the Montes Apennines (mountains on the right of the image) on the edge of the Moon's Imbrium Basin. This rille, like other similar channels on the Moon, is thought to be a lava channel on the basis of analogous landforms occurring in volcanic regions on the Earth (although the lunar versions are many times larger than their terrestrial equivalents). (Apollo 15 image, World Data Center A for Rockets and Satellites.)*

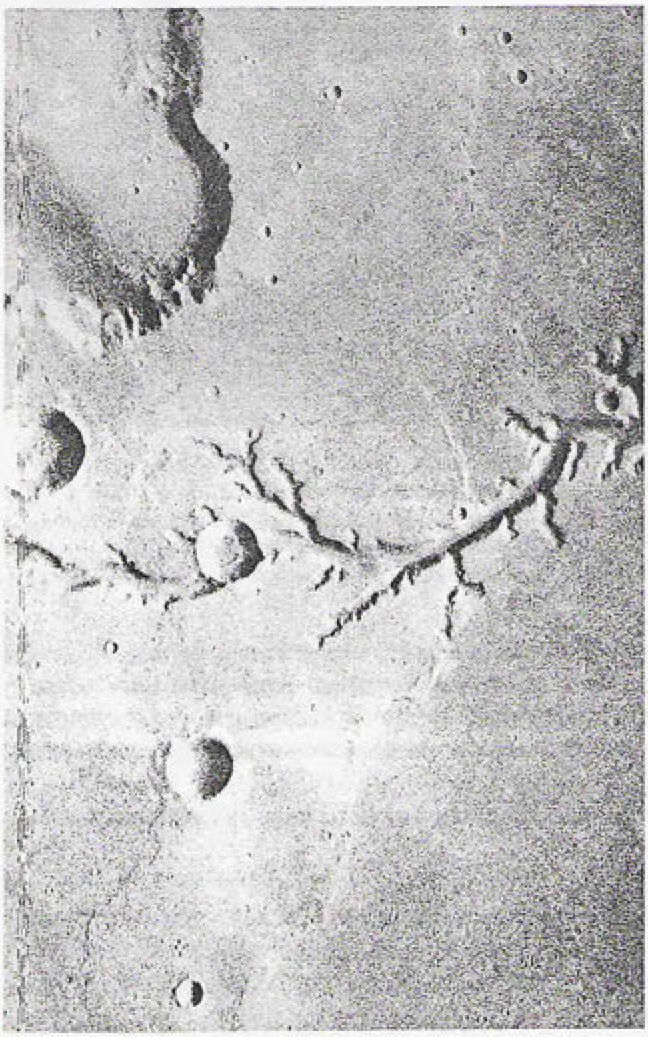


Fig. 1.2 Part of Nirgal Vallis, an 800 km long channel system on Mars incised into old cratered terrain (see Section 19.3.8). The tributary heads have an amphitheatre-like morphology and through analogies with equivalent terrestrial forms this supports an origin involving runoff emerging from springs (a process known as spring sapping or ground water sapping). Note the crater located on the channel near the left-hand edge of the image which must have been formed after the channel. The area shown is about 55 km across. (Viking 1 image, World Data Center A for Rockets and Satellites.)

Fig. 1.3 Oblique view from a height of about 10 km of the canyon of the Little Colorado River in Arizona, USA, a tributary of the Colorado River. This canyon, like many others in the Colorado Plateau in Utah and Arizona, has a 'box' form very similar to some of the channels on Mars. Such landforms provide valuable analogies for interpreting equivalent Martian features (see Figure 1.2). It is thought that such ***box canyons*** *on Earth form as a result of water percolating through a thick permeable sandstone unit and emerging where it encounters a less permeable underlying lithology. The resulting spring sapping causes the canyon head to recede.*

clysmic, landscape-forming events. On the Earth the effects of these events, such as the impact of large objects and catastrophic floods, are usually rapidly obliterated by erosional, tectonic and volcanic processes, but in some cases we can use the landscape history of other planets to assess their role in Earth history. For instance, although only about 120 craters formed by impacts rather than volcanic activity have been identified on the Earth (Fig. 1.4), we can estimate the approximate frequency of major impact events in the past caused by comets, meteorites and asteroids by using the largely preserved history of bombardment experienced by the Moon and some other planetary bodies.

1.3 Some key concepts

1.3.1 Endogenic and exogenic processes

The Earth's detailed form at any instant in time represents the net effect of surface, or **exogenic processes**, and internal, or **endogenic processes**. Exogenic (also termed exogenetic) processes, including the action of water, ice and wind, predominantly involve **denudation**, that is, the removal of material, and thus generally lead to a reduction in elevation and **relief** (Fig. 1.5). (Note that the term relief refers to a difference in height and must be distinguished from elevation and altitude which refer to height above some datum

Fig. 1.4 *Examples of impact structures identified on Earth. (A) Manicougan (Quebec, Canada), formed around 210 Ma* BP, *is about 70 km across and has a broad central upwarp and a surrounding depression now filled with water after the construction of a dam. (B) Clearwater Lakes (Quebec, Canada), a pair of depressions 20 and 30 km across which have been much eroded. (C) Serra da Cangalha (Brazil), a 12 km diameter ring structure, and the smaller 4 km diameter Riachao Ring (inset). It has been estimated that a 10 km-diameter object hits the Earth on average every 100 Ma at a velocity of about 20 km* s^{-1} *forming a 150 km wide crater. (Landsat images courtesy of J. McHone and N. M. Short.)*

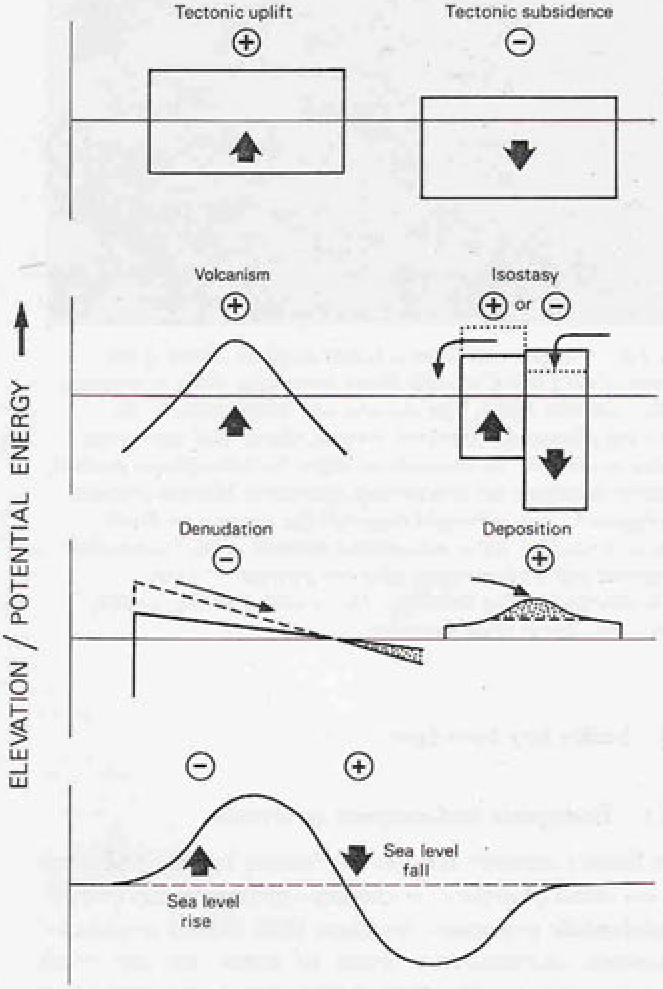


Fig. 1.5 *Schematic illustration of the change in elevation (height relative to a datum) associated with various exogenic and endogenic processes. The positive and negative signs indicate, respectively, increases and decreases in elevation and potential energy. The mechanism of isostasy is discussed in Section 2.2.4.*

– normally mean sea level.) An exception is the localized deposition of material, to form sand dunes for instance, which causes an increase in relief. Denudation can involve the removal of both solid particles and dissolved material. In this book we will generally refer to the former as **erosion** or **mechanical denudation**, and to the latter as **chemical denudation**.

The two sources of energy which power the various exogenic processes are solar radiation and the potential energy arising from the gravitational attraction of the Earth which, in the absence of sufficient resisting forces, causes the downslope movement of water, ice and particles of rock and soil. Solar radiation acts in diverse ways, providing the energy for biological activity, the evaporation of water and the functioning of the Earth's atmospheric circulation.

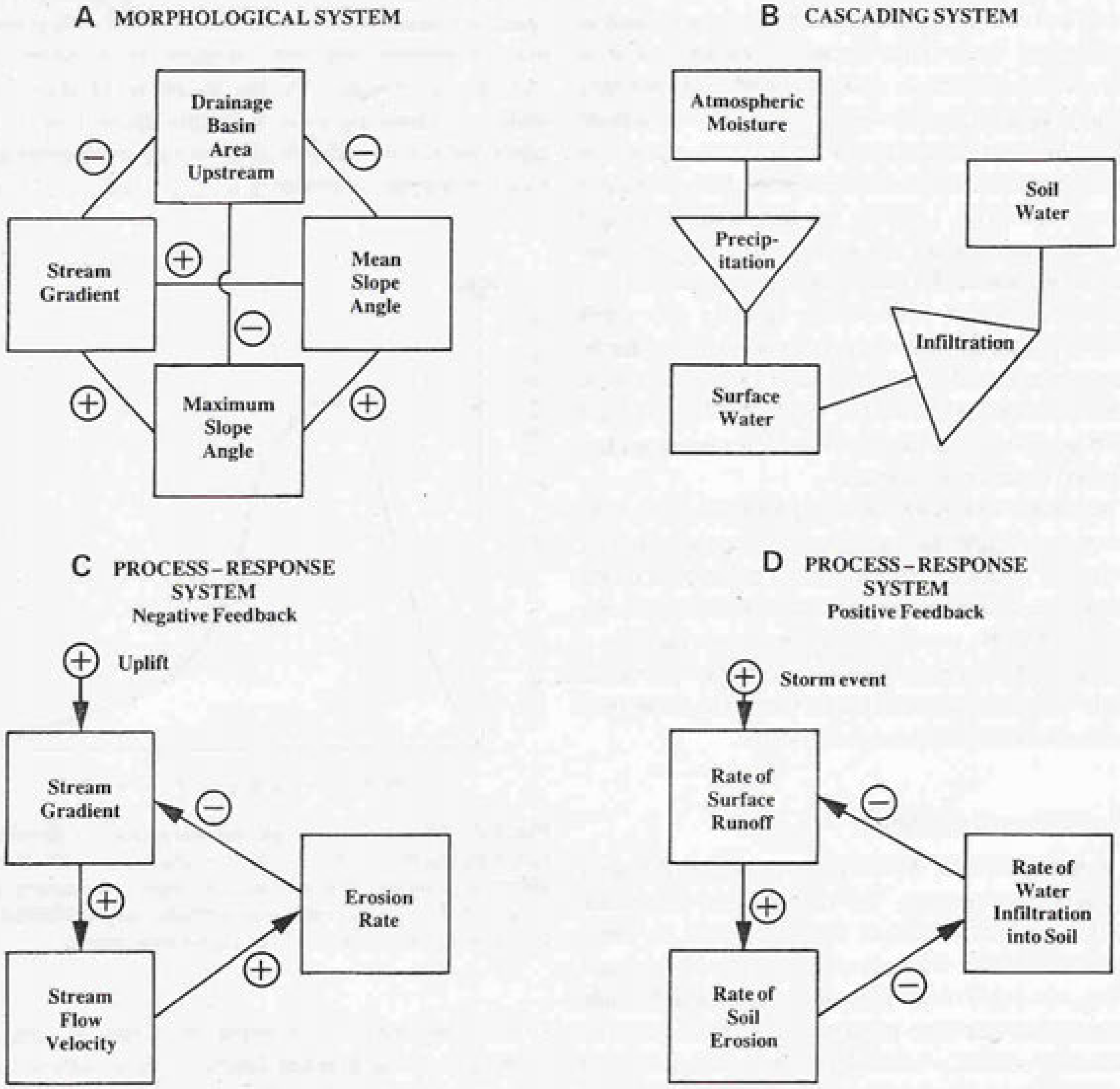
Endogenic (alternatively endogenetic) processes are generally constructional in that they usually lead to an increase in elevation and relief. Three major types of processes are involved. **Igneous activity** consists of the movement of molten rock, or magma, on to, or towards, the Earth's surface. **Orogenesis (orogeny)** is the formation of mountain belts which are typically arcuate or linear in plan form. **Epeirogenesis (epeirogeny)** is the uplift of usually large areas of the Earth's surface without significant folding or fracture. The broad structures of the Earth's crust and the processes of deformation and faulting which give rise to them are described by the term **tectonics**, while the term **morphotectonics** is applied to the interaction between tectonics and landform genesis. **Neotectonics** refers to the processes and effects of recent tectonic activity and is usually applied to Late Cenozoic events.

1.3.2 Geomorphic systems

While the application of **systems analysis** to geomorphic phenomena has, arguably, not in itself led to any great advances in understanding, there has been a widespread use of systems concepts in geomorphology and an extensive adoption of its terminology. A **system** can be defined as a set of objects or characteristics which are related to one another and operate together as a complex entity. Systems analysis focuses on the relationships between these objects or characteristics.

In geomorphology three kinds of system can be identified. Statistical relationships between the morphological properties of landform elements are represented by **morphological systems**, while movements of mass and flows of energy through the landscape are described by **cascading systems**. Interactions between these two types of system resulting from adjustments between process and form are represented by **process–response systems** (Fig. 1.6).

Before a system can be analyzed its boundaries must be defined. In an **open system** there is a movement of both energy and matter across the system boundary, whereas in a **closed system** only energy is transferred. An **input** of mass or energy into a system is transmitted through it (**throughput**) and leaves as an **output**. Changes in inputs of energy or mass usually produce changes in outputs, but may also give rise to adjustments in the structure of a part of the system (**subsystem**). Changes in the flow of energy and mass as well as adjustments to the structure of the system are controlled by the relationships between variables within the system. These variables, representing the form of the landscape, the rate of geomorphic processes acting upon it



A MORPHOLOGICAL SYSTEM

B CASCADING SYSTEM

C PROCESS – RESPONSE SYSTEM Negative Feedback

D PROCESS – RESPONSE SYSTEM Positive Feedback

Fig. 1.6 Examples of simple morphological (A), cascading (B), and process–response systems (C) and (D). Negative and positive signs indicate the nature of the relationship between variables. In (B) rectangles represent storages and triangles transfers between storages. Note that negative feedback systems (C) have an odd number of negative relationships, whereas positive feedback systems (D) have either an even number or none.

and the environmental factors influencing these geomorphic processes, may be either independent (causal) or dependent (responding to causal variables).

A very common characteristic of geomorphic systems is **negative feedback**, a condition whereby the structure of the system is capable of adjusting in a way that minimizes the effect of externally generated changes. Such an ability of self-regulation or **homeostasis**, means that a system can maintain a state of balance or equilibrium. If faulting across a river bed causes an instantaneous increase in channel gradient, for instance, the resulting increase in river flow velocity will tend to promote a local increase in the rate of channel downcutting and, as a consequence, a reduction in channel gradient (Fig. 1.6 (C)).

In other cases an input change may engender a system response which produces an output which reinforces the original input and eventually causes a shift in the system to a new equilibrium state. This 'snowball effect', as it is colloquially called, occurs in systems exhibiting **positive feedback** and is precipitated by the breaching of a **threshold** in the system. When a severe storm leads to the erosion of the uppermost, permeable layer of the soil the less permeable subsoil is exposed (Fig. 1.6(D)). As this horizon cannot absorb the water running off the surface so effectively the depth of runoff increases, the rate of erosion accelerates and subsoil material with an even lower capacity for water absorption is exposed. In this way it is possible for an entire soil profile to be removed in a single severe storm. The new equilibrium is reached when all the loose, readily erodible soil has been removed and the much more resistant underlying weathered bedrock is exposed.

A final important characteristic of systems is their hierarchical property. A specific system may be composed of numerous smaller systems, but itself form a part of a larger system. Perhaps the clearest example of a system hierarchy in geomorphology is provided by drainage basins; a medium-sized catchment may contain numerous individual streams, each with its own small basin, but at the same time form part of a much larger drainage system.

1.3.3 Magnitude and frequency

There are great variations in the rates at which different geomorphic processes operate. The rate of some processes, such as the flow of ice within an ice sheet, may be fairly constant over millennia, whereas other mechanisms, such as landsliding, are inactive for long periods, although when they do operate they act with great rapidity. Moreover, the same process may exhibit a markedly different intensity and degree of variability under contrasting climatic conditions. In a constantly humid environment lacking high-intensity storms, river discharges may not vary by more than an order of magnitude (by a factor of 10) over several years. By contrast, under a semi-arid climatic regime where predominantly dry conditions are occasionally punctuated by violent storms, river discharges may vary by two or three orders of magnitude (by a factor of 100 or 1000).

Understanding the frequency with which geomorphic events of different magnitudes occur is clearly a crucial component of any explanation of landform genesis. Measurements of the operation of various geomorphic processes over a range of time scales show that extreme, high-intensity events are rare and that low- to medium-intensity events prevail for the great majority of the time. Accordingly we find that plots of the frequency distribution of many variables which influence the operation and intensity of geomorphic processes, such as wind speeds and river discharges, have a positive (right)-skewed form (Fig. 1.7). The rarity of many types of extreme event, such as major river floods, arises from the fact that these generally require a specific combination of conditions which, while individually not uncommon, are very unlikely to coincide. A simple analogy is provided by the throwing of dice. The probability of throwing a six with one die is 1 in 6 (16.67 per cent), but the probability of obtaining three sixes from three dice thrown simultaneously is only 1 in 216 (0.46 per cent).

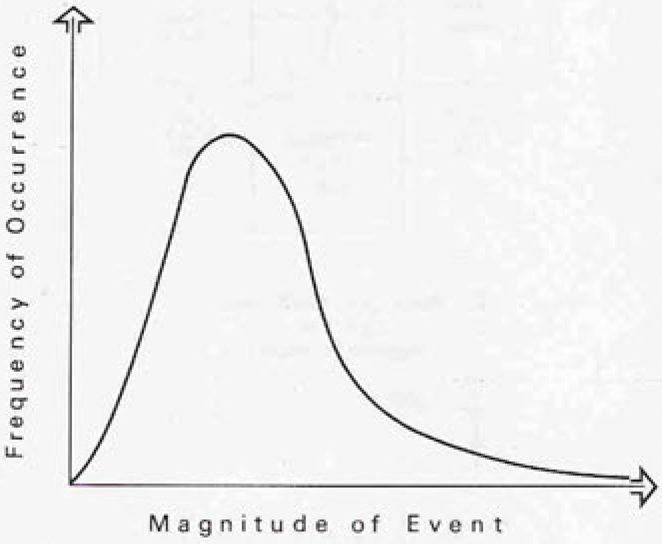


Fig. 1.7 *Characteristic right-skewed frequency distribution of variables (such as wind speed, river discharge and wave height) affecting geomorphic processes. The highest frequency of events occurs in the lower to middle magnitude range, whereas there is only a small proportion of high magnitude events.*

The frequency of an event of a specific magnitude is expressed as the average length of time between events of that magnitude and is known as its **return period** or **recurrence interval** (Fig. 1.8). If a particular maximum annual discharge of a river has a recurrence interval of 20 a this means that there is a 1 in 20 (5 per cent) chance that a flood of this magnitude or greater will occur in any one year

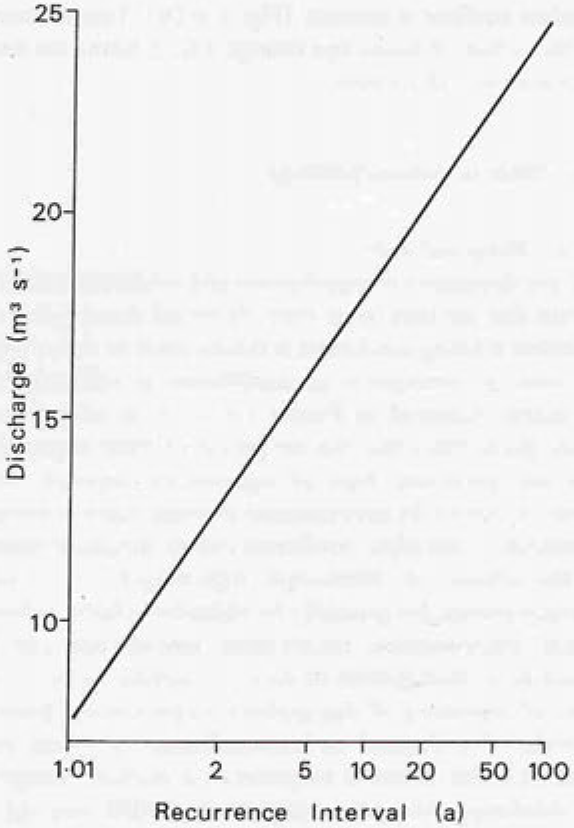


Fig. 1.8 *A typical relationship between stream discharge and recurrence interval.*

and that, *on average*, there will be one such flood every 20 a. The accurate calculation of such probabilities requires a record of measurements which is at least as long as the recurrence interval being estimated. Consequently the more extreme and rarer an event, in general the more difficult it is to estimate accurately its recurrence interval. A further problem is that over the long term the average state of a variable may change significantly. Climatic changes, for instance, can involve marked shifts in average temperatures and precipitation and these may in turn modify the **magnitude – frequency** relationship of geomorphic processes.

It is important to emphasize that for virtually all geomorphic events such recurrence intervals are averages only and do not indicate *when* we should expect an event of a particular magnitude to occur. We could, for instance, observe five separate floods with a recurrence interval of 20 a in a single year, although this would be highly unlikely. In the case of some processes, however, a degree of regularity is evident in the occurrence of events of a similar magnitude. Earthquakes, for example, represent the release of stresses which gradually build up within the Earth's crust. A large earthquake, with its related aftershocks, is therefore unlikely to be followed within a period of several years by another large earthquake in the same locality since much of the stress would have been released in the earlier event.

1.3.4 Equilibrium and evolution

Earlier in this chapter (Section 1.2) reference was made to two contrasting approaches to the understanding of landform genesis. In the first of these, pioneered by Gilbert, the emphasis is placed on the mutual adjustment between present forms and processes. This is sometimes described as the **functional approach** to geomorphology, and the kinds of geomorphic systems with which it is usually concerned commonly exhibit negative feedback and the tendency for an equilibrium form to be restored after a disturbance by a high magnitude – low frequency event. The second mode of explanation, which is indelibly linked with the work of Davis, focuses on progressive changes in the landscape through time and is usually described as the **evolutionary**, or **historical approach** to geomorphology. We clearly need to examine further this apparent paradox that landforms can be considered both to retain an equilibrium form and undergo a progressive change in form through time.

If we imagine observing the boulder-strewn bed of a mountain stream for a period of a few hours we would be very unlikely to witness any measurable change in its form (assuming, of course, that the river is not in flood). Water flows in the channel transporting fine sediment and dissolved material, but its gradient, form and elevation above sea level remain essentially the same. We can describe this situation as one of **static equilibrium** (Fig. 1.9(A)).

If we were to remain at our observation point for several months or years we might well see a major flood which, by causing a significant amount of erosion, lowers the bed of the channel by a small, but measurable, amount. Although this temporarily causes a change in the form of the channel, over the succeeding years the slow deposition of sediment will lead to a restoration of the original channel bed elevation; in these circumstances the channel can be said to be in **steady-state equilibrium** since there is no change in its mean elevation over the period in question (Fig. 1.9(B)). Note that this is essentially the kind of adjustment envisaged by Gilbert in his concept of dynamic equilibrium (see Section 1.2.2).

Stretching our powers of imagination further we could envisage continuing our observations over thousands or hundreds of thousands of years. Over such a period of time there would be hundreds of floods including many events of very high magnitude. Episodes of severe erosion would lead to a progressive lowering of the channel floor and possibly a gradual decrease in channel gradient. This situation is one which is now generally termed **dynamic equilibrium** (Fig. 1.9(C)).

Finally, we can imagine what might happen over a period of millions of years. As the altitude of the mountain carrying our stream decreases we would see a progressive reduction in the elevation of the channel bed. However, we would expect the rate of decrease in elevation to decline

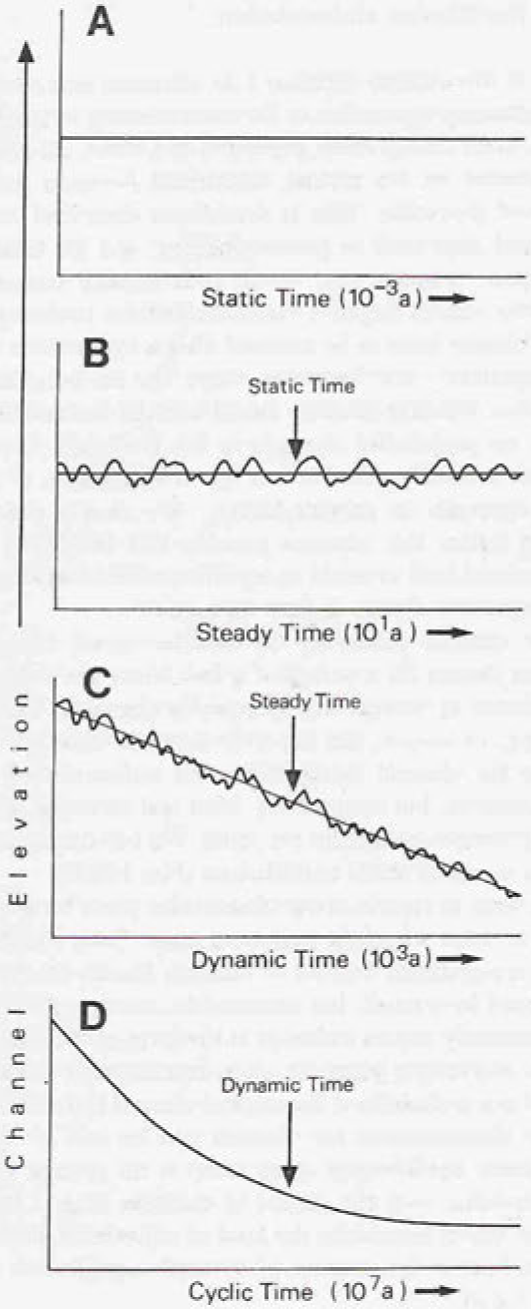


Fig. 1.9 Different types of landform equilibrium illustrated with reference to schematic changes in channel elevation over different time spans: (A) static equilibrium; (B) steady-state equilibrium; (C) dynamic equilibrium; (D) decay equilibrium. The time scales shown are merely suggestive and will vary by orders of magnitude depending on the type of landform being considered and the nature and intensity of the prevailing geomorphic processes.

through time as the channel bed approaches base level and the channel gradient becomes so low that rates of erosion reach a minimum. Over this longest time scale the landscape evolves towards a **decay equilibrium** and a landsurface of subdued relief, termed an **erosion surface** or **planation surface** is created. (Fig. 1.9(D)). This is essentially the notion of landscape change which forms the basis of Davis's cycle of erosion.

1.3.5 Scale in geomorphology

1.3.5.1 Temporal scale

From our discussion of equilibrium and evolution it will be apparent that the time scale over which the development of a landform is being considered is fundamental in determining what kind of conception of equilibrium is relevant. The time scales indicated in Figure 1.9 serve as only a very general guide since the precise period of time required to attain any particular type of equilibrium depends on a number of factors. In environments in which rates of erosion and deposition are high, landforms can be modified rapidly and the effects of occasional high-magnitude – low-frequency events can generally be obliterated fairly quickly. In such environments steady-state equilibrium can be attained in a short period of time. A second factor is the degree of resistance of the material experiencing erosion. The form of a channel in unconsolidated alluvium may change in a few hours in response to a marked change in river discharge, whereas a channel of similar size cut in densely cemented, resistant bedrock may only adjust after hundreds or thousands of years (assuming the change in discharge persists). A third factor is the size of the landform being considered. The shape of a ripple on a sand dune will adjust much more rapidly to a change in wind direction than the form of the sand dune on which it lies simply because a far smaller amount of sediment has to be moved by the wind to accomplish the adjustment. Similarly, we would expect a small mountain mass a few hundred metres high to reach decay equilibrium in a few million years, whereas tens of millions of years would probably be required for a major mountain range several thousands of metres high.

In more general terms we can talk of the speed with which a change in an input to a geomorphic system, such as an increase in rate of uplift or decrease in river discharge, is fully reflected in a change in form. This is referred to as the **relaxation time** of the system and can range from a few minutes for changes in a small section of an alluvial channel to tens of millions of years for the uplift of a major mountain range.

1.3.5.2 Spatial scale

From our discussion of temporal scale it is clear that there is a close relationship between the temporal and spatial scales at which landform change occurs. Returning to our illustration of the different types of equilibrium in Section 1.3.4, we can see that while it is appropriate to consider a small section of a stream channel in terms of static, steady-state, and perhaps even dynamic equilibrium, it is inappropriate to discuss long-term landform evolution and the attainment of decay equilibrium in terms of such a restricted spatial scale. Not all parts of a landscape can be simultaneously in a steady-state equilibrium since sediment is continuously being removed and relief progressively reduced.

Geomorphology is concerned with phenomena over an enormous range of scales from the form of an individual boulder to the morphology of the Earth's major relief features (Fig. 1.10). It is often useful to be able to categorize this range of scale and to talk, for instance, of microscale or macroscale forms. Such a classification is presented in Table 1.2 with some suggested ranges of linear and areal scale, although it must be emphasized that the divisions between each scale are somewhat arbitrary. Examples of landforms at each scale are indicated together with the main endogenic and exogenic factors influencing landform genesis at the different scales. A very approximate equivalence between these spatial scales and the temporal scales associated with the different types of equilibrium is also suggested; the exact nature of this relationship will, however, depend on the characteristics of the particular landform being considered.

1.3.5.3 Scale and causality

As the temporal scale of analysis changes so the status and interrelationships of variables in geomorphic systems alter accordingly. If we examine landforms over dynamic time then variables which only exhibit measurable change over a longer period can be regarded as fixed; that is, they are independent variables of the external environment. Over dynamic time such variables include lithology and structure and the initial relief of the region. Those factors which change over dynamic time, such as hillslope morphology and channel gradient, are elements of the geomorphic system and are therefore dependent variables at this scale. Variables such as water discharge and rate of sediment transport in a river channel which change very rapidly over dynamic time can be regarded as having mean values which are part of the system, but around which occur random fluctuations which are irrelevant to the system at this scale.

A further consideration in understanding the factors controlling landform development at different temporal and spatial scales is the relative importance of endogenic and exogenic processes. If we are examining a drainage basin of a few square kilometres in a recently uplifted mountain range the tectonic history of the area will be essentially

Table 1.2 Hierarchy of spatial and temporal scales in geomorphology

SPATIAL SCALE	DIMENSIONS		EXAMPLES OF LANDFORMS				MAJOR CONTROLLING FACTORS		TEMPORAL DURATION SCALE	
	Linear (km)	Areal (km^2)	Endogenic	Exogenic			Endogenic	Exogenic		
				Fluvial	Glacial	Aeolian				
Micro	<0.5	<0.25	Minor fault scarps	Pools and riffles in a small river channel	Small moraine ridges	Sand ripples	Individual earthquakes and volcanic eruptions	Microclimates; meteorological events	Steady time	10^1a
Meso	$0.5-10$	$0.25-10^2$	Small volcanoes	Meanders	Small glacial valleys	Dunes	Local and regional isostatic uplift; localized volcanism and seismicity	Local climates; short-term climatic change	Dynamic time	10^3 a
Macro	$10-10^3$	10^2-10^6	Block–faulted terrain	Floodplains of major rivers	Highland ice caps	Sand seas	Regional uplift and subsidence	Regional climates; long-term climatic change (glacial-interglacial cycles)	Cyclic time	10^7a
Mega	$>10^3$	$>10^6$	Major mountain ranges	Major drainage basins	Continental ice sheets	Large sand seas	Long-term patterns of uplift, subsidence and continental motion	Major climatic zones; very long-term climatic change (ice ages)		

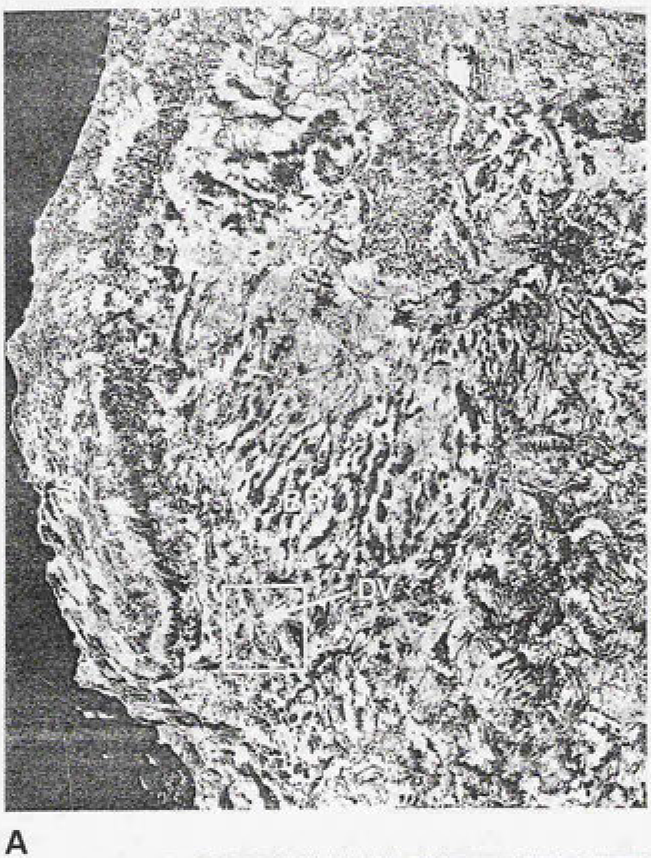
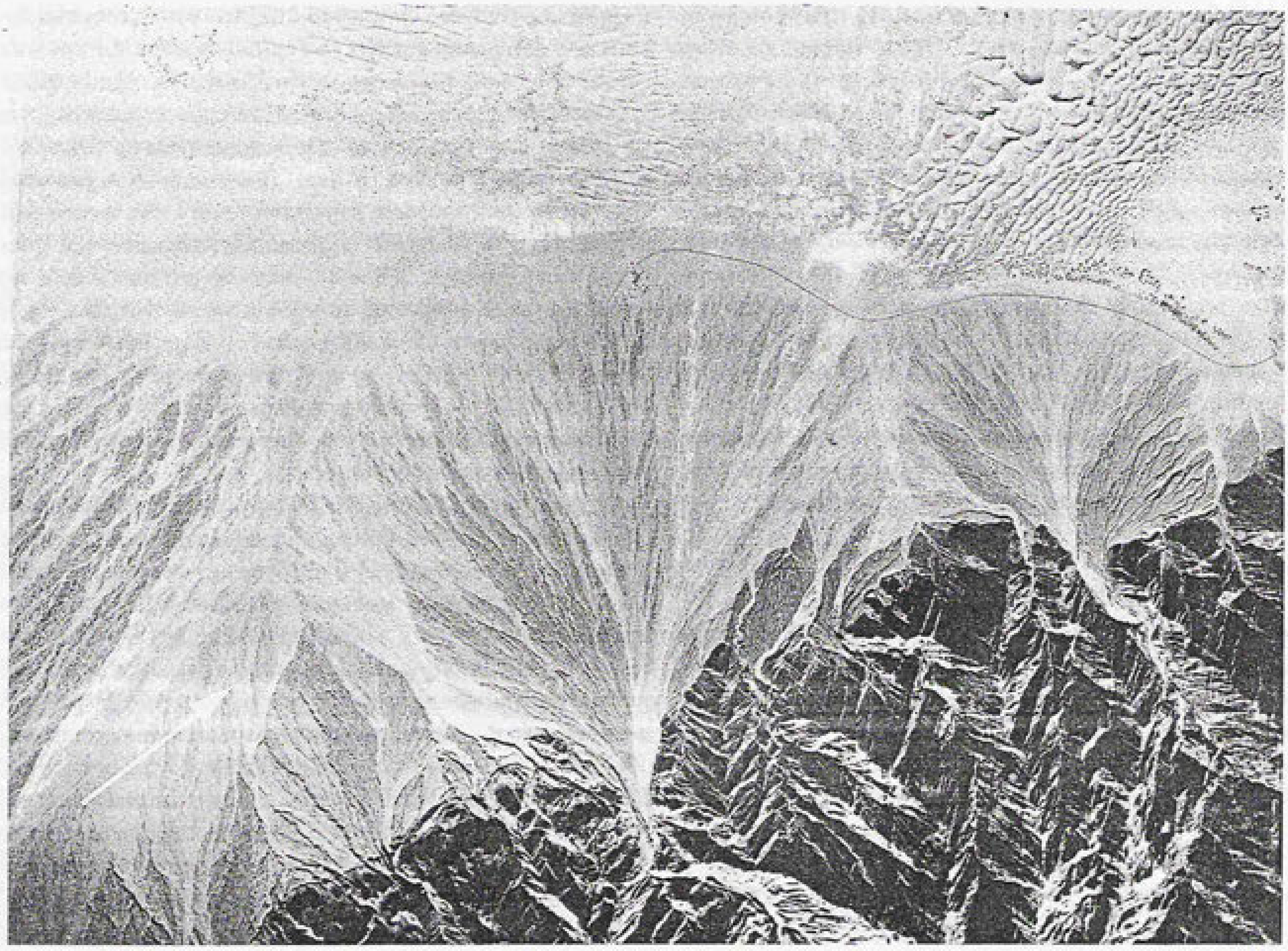


Fig. 1.10 Images illustrating the range of spatial scales considered in geomorphology. (A) The megascale landscape assemblages of the western part of the USA covering an area of about 2.25 × 10⁶ km² (linear dimension around 1200 km). At this scale the overall tectonic framework of the region is clearly visible. Among the most prominent features are the Sierra Nevada (SN) and the Basin and Range Province of Nevada and southern California (BR), a region characterized by a succession of mountain ranges and intervening basins which includes Death Valley (DV). (Part of mosaic of ERTS-1 (Landsat) imagery prepared for NASA Goddard Space Flight Center by the USDA Soil Conservation Service.) (B) The macroscale landscape of Death Valley (DV) and adjoining NW–SE-orientated basins containing extensive lake deposits (light tones) laid down during more humid periods in the past (boxed area on (A)). The western side of Death Valley is flanked by a coalescing series of alluvial fans (A) formed by sediment brought down from the adjacent mountain range. At this scale both detailed tectonic controls and the broad effects of exogenic processes are evident. The area covered is about 34 × 10³ km² (linear dimension 185 km). (Landsat image courtesy A.S. Walker.) (C) Alluvial fans at the northern end of Death Valley (boxed area on (B)). The area covered is about 70 km² (linear dimension about 8 km). At this mesoscale the effects of exogenic processes (in this case erosion and the deposition of sediment) can be clearly seen. (Air photo by United States Geological Survey.) (D) A view across the surface of one of the fans shown in (C) (arrowed). At this scale the detailed effects of exogenic processes are apparent.



C

D

irrelevant to understanding the present-day morphology of landform elements in the basin. The prevalence of steep slopes and rapid rates of erosion related to its history of uplift would be regarded as elements of the external environment outside the geomorphic system being studied. If the scale were to be expanded to a few thousands of square kilometres a full understanding of the landscape would require some consideration of its history over the previous million years or so and an assessment of the interaction between endogenic and exogenic processes over that period. At the largest scale we might be dealing with an entire mountain range covering tens of thousands of square kilometres; in this case it would be the endogenic processes that would have exerted the major control over the gross morphology of the landscape with the operation of exogenic processes playing a role in shaping the details.

1.3.6 Explanation in geomorphology

The vast range of temporal and spatial scales means that no one methodological approach to explanation is appropriate for all research in geomorphology. At very short time scales we may be concerned solely with the operation of processes and their relationships with presently existing landforms; at the other extreme we may be aiming to establish a historical sequence of landform development over a period of millions of years and relating this to long-term changes in endogenic processes. This distinction involves two aspects of reality termed by the palaeontologist G.G. Simpson the **immanent** and the **configurational**. By immanent he meant those aspects of reality to do with the inherent properties of the Universe, that is, the physical laws that govern the behaviour of matter. By configurational he meant those forms (or configurations) which arise from the operation of the physical laws of the Universe at a particular point in time.

The importance of this distinction lies in the contrasting approaches to explanation that it implies. When looking at a landscape we can either try to discover what processes are currently active and attempt to explain its present form with reference to these processes, or we can endeavour to unravel the history of the landscape and understand its present form in terms of a sequence of landscapes through time (see Section 1.3.4). The first of these (the functional approach) emphasizes the immanent aspects of reality, the second (the evolutionary or historical approach) emphasizes the configurational aspects. Whereas relating present forms to currently active processes may be a successful strategy if we are working at the small scale, or where landforms are adjusting very rapidly to the operation of geomorphic processes, this is not an adequate approach where we are considering landscapes at the large scale or which have long relaxation times (Table 1.3).

An important question raised by the historical approach to explanation in geomorphology concerns the assumptions we make about the rate at which processes have operated in the past. As we have already seen (see Section 1.2.1) Lyell emphasized the uniformity of both the rates of geomorphic processes through time and the average relief of the Earth's surface (he considered uplift at one place would be roughly balanced by subsidence at another). Such a view is, of course, untenable in the light of our knowledge of major climatic changes during the Earth's recent history. Indeed, some geomorphologists have argued that the great magnitude of these changes casts doubt on the whole idea of uniformitarianism and have instead advocated **neocatastrophism** in its place. This rejection of uniformitarianism arises from a confusion over the diverse concepts encompassed by the term – a confusion which, as we have seen (Section 1.2.1), began immediately on the introduction of the concept in the 1830s.

A valuable attempt to clarify the term has been made by S. J. Gould who distinguishes between two fundamentally different types of uniformitarianism. The first, which he calls **methodological uniformitarianism** and which encompasses uniformity of law and of process, is the proposition that natural laws are invariant – that is, they are constant in

Table 1.3 Relationship between spatial and temporal scale and approaches to explanation in geomorphology

	SPATIAL SCALE			
	Micro	Meso	Macro	Mega
Predominant genetic mechanisms	Exogenic	Primarily exogenic	Exogenic/ endogenic	Primarily endogenic
Time required for adjustment of form to process	Short	Moderate	Long	Very long
Temporal scale	Steady	Dynamic	Cyclic	Cyclic
Appropriate explanatory basis	Immanent	Immanent/ configurational	Configurational	Configurational

space and time – and that those observable at the present time are sufficient to explain past events. The second, which he terms **substantive uniformitarianism** and which incorporates uniformity of rate and of state, postulates rates of natural processes and material conditions that are essentially constant through time. This proposition involves a claim about the world which can be tested and which we now know to be false (in any strict sense), whereas methodological uniformitarianism, or **actualism** as it is also called, is a statement of scientific method and is a fundamental element of any attempt to provide scientific explanations of how landscapes have changed through time.

1.4 Methods of analysis

A battery of techniques and instruments are now available to monitor the day-to-day operation of a wide range of geomorphic processes, such as the gradual downslope movement of debris on a slope, the transport of sediment in a river or the movement of ice at the bed of a glacier. These methods of data acquisition, which include laboratory experiments as well as field measurements, have generated a wealth of data on short-term landform change, but we can rarely apply these results directly to the problem of long-term landscape change. Primarily this is because there are almost invariably changes in the magnitude–frequency relationships of geomorphic processes in the long term. Although there are now techniques which can be applied to estimate average denudation rates over millions of years, indirect strategies have to be adopted if we are to determine how the form of the landscape has changed over long periods of time. We can do this in two ways; by **space–time substitution**, where variations in form over space are interpreted in terms of changes through time, or by simulating landform changes either mathematically or through the use of hardware models.

1.4.1 Direct observations

With a few rare exceptions direct observations of changes in form are confined to features of limited dimensions over periods of months or years. Significant changes in form can occur where readily mobilized unconsolidated sediments, such as beach sand or alluvium, are subject to frequent and intense geomorphic activity. Such changes can be instrumented and monitored over periods of weeks, months or years. Occasionally it is possible to observe landform changes which, although normally occurring very slowly, under certain conditions take place sufficiently rapidly to produce measurable changes in a short period of time. In a classic study examining slope evolution in the clay badlands at Perth Amboy, New Jersey, USA, S. A. Schumm measured the depth of erosion on slope profiles over a period of ten weeks. The rate of erosion on this impermeable and largely unvegetated terrain was sufficiently high for a lowering of slopes of over 20 mm to be observed in this short period of time.

For periods longer than a few years other methods have to be employed to document landform change. Aerial photography can be particularly valuable in areas where repeated surveys are available. In the U K aerial surveys extend back to the 1940s and a similar period of coverage is available for parts of Europe and North America. This source of information can be especially valuable for tracking landscape features such as those associated with landsliding where significant landform changes may take several decades but in which the rate of modification varies enormously through time. Satellite remote sensing is now beginning to provide an important additional means of monitoring landform change, especially where extensive or remote areas are being studied.

Topographic maps provide another valuable source for documenting landscape change. In some regions accurate topographic surveying extends well back into the nineteenth century and sequences of maps have been used to reconstruct various landform changes including those affecting alluvial channels and coastal features. It is necessary to use such sources with care, however, as some early surveys may not be sufficiently accurate. In rare instances a particular landscape-forming event may be anticipated and valuable measurements recorded before a significant change in form occurs. A notable example is provided by the fall of Threatening Rock in New Mexico, U S A in 1941. The progressive movement of this vertical column away from a cliff face had been monitored over several years prior to it eventually toppling over.

1.4.2 Space–time substitution

Space–time substitution in landform analysis was pioneered by Charles Darwin in the testing of his hypothesis of coral reef formation (see Section 17.6.3). Barrier reefs, fringing reefs and atolls occurring at various locations in the world's oceans were considered by Darwin to represent different evolutionary stages of island development applicable to any particular subsiding volcanic peak in tropical waters where coral growth could occur. Influenced by Darwin's methodology, Davis found support for his evolutionary scheme of landform change through time in the form of the landscape in different localities which he considered to represent particular temporal stages of development.

Clearly this approach has its dangers. A researcher might, for instance, endeavour to fit landforms in different places into an assumed temporal sequence simply to satisfy a preconceived notion of how such landforms change through time, even though other sequences of change might be equally justified by the evidence. The essential guard against this kind of erroneous reasoning is a sufficiently specific model of landform change linked to a causal mechanism which indicates particular changes in form. In Darwin's case his causal mechanism was the growth of coral as the volcanic substrate subsided; no other explanation could so adequately account for the different forms of oceanic islands he observed. A second problem is the danger of assuming that a temporal sequence exists simply because spatial variablity in form is evident. In reality spatial variations in landforms may arise simply from random fluctuations around an equilibrium form and this possibility must be eliminated before temporal sequences are proposed. A third difficulty is that factors other than time may be responsible for systematic variations in form over space. The form of a slope, for instance, may be significantly related to lithological controls which may vary spatially in a consistent fashion.

Space–time substitution is most safely applied where there is unambiguous evidence for the sequential development of adjacent landform features. This might occur where, for example, the gradual downstream migration of a meander leads to the progressive elimination of active channel erosion at the foot of a meander bluff (Fig. 1.11). In this case it is possible to observe in the spatial sequence the progressive change in slope form after the cessation of active removal of basal debris by the river.

Some geomorphologists have attempted to set the procedure of space–time substitution in an apparently more rigorous framework by invoking the **ergodic hypothesis**. This notion was originally applied in the field of statistical mechanics and proposes that sampling in space is the equivalent of sampling through time. In order for this assumption to be valid the statistical distribution of objects or events over space and through time must be the same. If this is the case then the probabilities of sampling a property

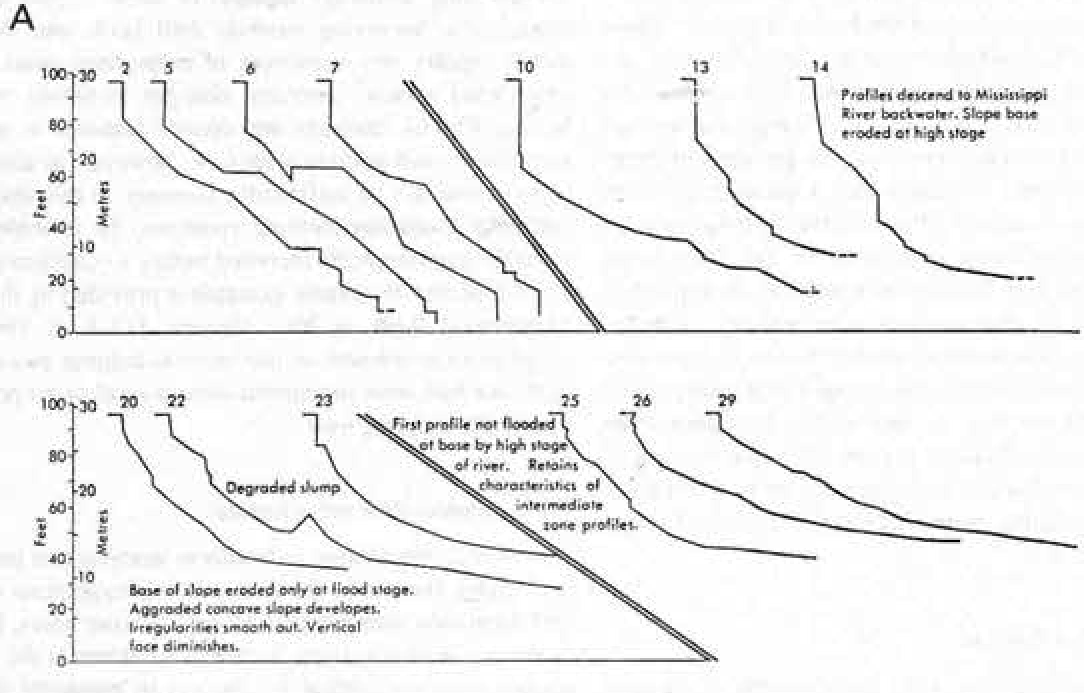
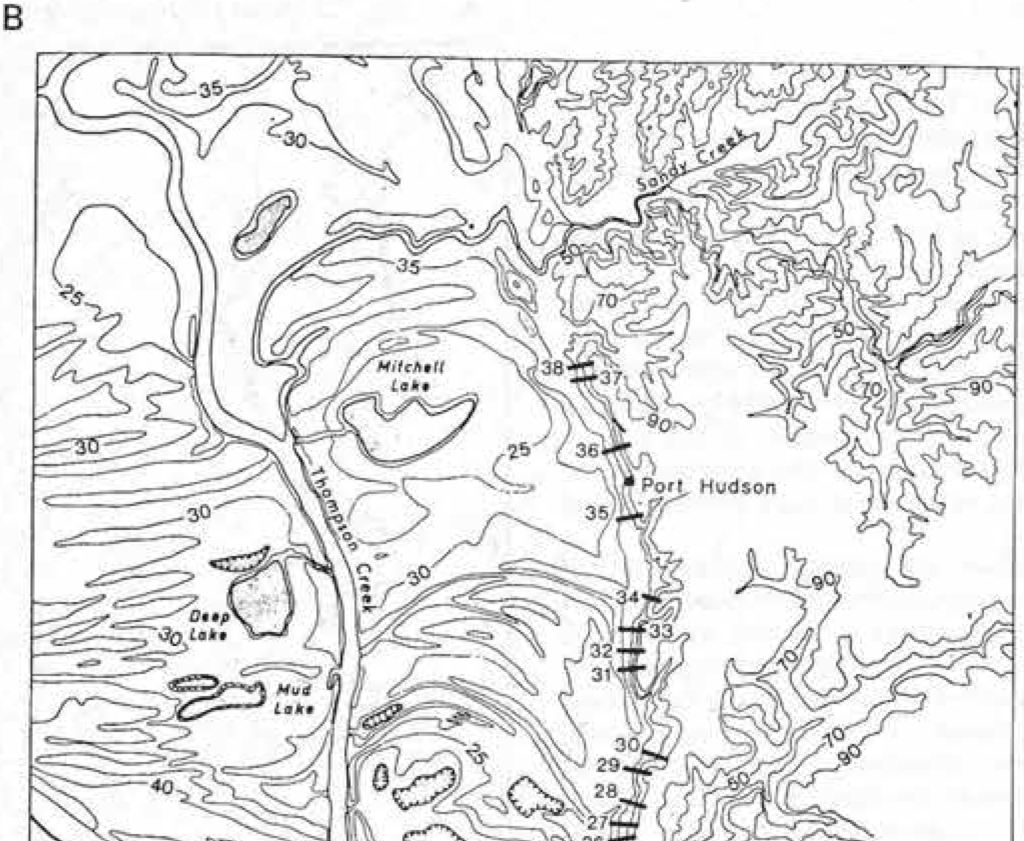


Fig. 1.11 Sequence of slope profiles along Port Hudson bluff on the Mississippi River in Louisiana, USA (A), and map showing location of profiles (B). The entire bluff segment was being undercut by the Mississippi River in 1722 since when the channel has shifted downstream about 3 km, being at the location of profile 36 in 1849, 34 in 1883, 25 in 1909 and 23 in 1941. Profiles 2–7 in (A) are being actively undercut by the river; profiles 10–14 are undercut during high flows only; profiles 20–36 are subject to basal aggradation. The profiles, which show a decline in mean slope angle from 44 to 20°, represent a temporal sequence reflecting changes in basal conditions. (From D. Brunsden and R. H. Kesel (1973) Journal of Geology *81, Figs. 4 and 6, pp. 581 and 584.)*



of the landscape through time and over space are interchangeable. It is clear that there are few instances in geomorphology where such an assumption can be shown to be justified. Space–time substitution as an approach to understanding the way landforms change over periods of time beyond those accessible to direct observation must, therefore, be based in most circumstances on specific predictions of the morphological changes arising from the operation of well-defined processes. This, of course, is a familiar notion to earth scientists in general who are concerned with the interpretation of geological structures or sedimentary bodies which they are often forced to interpret with reference to examples in different stages of development in different localities.