the origin of mountains

Cliff Ollier and Colin Pain

The Origin of Mountains

***The Origin of Mountains* is ground breaking**. This highly illustrated book describes mountains from all over the world, emphasising their landforms, their rocks, and their structure and age. This leads to a deduction on the mechanism that formed them, causing the authors to reject the pre-conceived well-known hypothesis that plate tectonics and folding creates mountains.

The Origins of Mountains approaches mountains from facts about mountain landscape rather than from theory. It uses old and recent references, as well as field evidence. It shows that mountains are not made directly by folding, but result from vertical uplift of plains (planation surfaces) to form plateaus, which may later be eroded into rugged mountains. It also assembles the evidence that this uplift occurred in the last few million years, a time scale which does not fit the plate tectonic theory.

Another fascinating story is that the age of uplift correlates very well with climatic change. Mountain building could have been responsible for the onset of the ice age and the monsoon climate, and certainly created many new environments. Fossil plants and animals are used to work out the time of mountain formation, which in turn helps to explain biogeographic distributions.

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London and New York

First published 2000 by Routledge 11 New Fetter Lane, London EC4P 4EE

Routledge is an imprint of the Taylor & Francis Group
This edition published in the Taylor & Francis e-Library, 2005.
"To purchase your own copy of this or any of Taylor & Francis or Routledge's collection of thousands of eBooks please go to http://www.ebookstore.tandf.co.uk/.

British Library Cataloguing in Publication Data A catalogue record for this book is available from the British Library

Library of Congress Cataloging in Publication Data Ollier Cliff. The origin of mountains/Cliff Ollier and Colin Pain. p.cm. Includes bibliographical references and index. 1. Orogeny. 2. Mountains. I. Pain, C.F. II. Title.
QE621.O45 2000 551.43'2–dc21 99–058339

ISBN 0-203-00590-2 Master e-book ISBN

ISBN 0-415-19889-5 (hbk)
ISBN 0-415-19890-9 (pbk)

To Janeta and Josie

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Preface

A few centuries ago mountains were viewed with fear, awe and suspicion. Nowadays they are almost universally regarded with admiration, aesthetic pleasure and affection. We too have enjoyed working in mountains in many parts of the world, and we believe that the joy of mountains is enhanced by trying to understand them. Some scientific understanding adds to the aesthetic experience, making for a more complete comprehension and pleasure. That does not mean we know all about mountains. Far from it, but the pleasure comes from learning, and always having interesting questions to ask.

This book is about the origin of mountains. We describe mountains in many different situations, and are led to believe that mountains result from vertical uplift of old plains, followed by erosion. We cannot claim it is a modern view of the subject, because at the time of writing that title must go to the plate tectonics theory of mountain building by continental collision. Neither is it old-fashioned, because old ideas of mountains resulting from a shrinking earth like the ripples on the skin of a shrinking apple would have that title. It is not even original, for the ideas that we present have been described by numerous writers, some almost a century ago.

This explains why we refer not only to many modern papers (if only to show we have read them) but also to many authors who saw and wrote about what we see ourselves. The swing to plate tectonics since about 1965 has caused much valuable earlier literature to be neglected or revised. This is nowhere more obvious than with Holmes' book, *Principles of Physical Geology*. The edition of 1965 was one of the finest geological books of the century. The editions that have been published since then have removed much of the great man's insight, and have replaced much of his factual information with speculation and models. Many other giants of the past have a place in our book, which finds their ideas still relevant. We have an advantage over them in that communication today is better than ever before. It is possible to travel widely, and literature from many countries is now readily accessible.

The present is an interesting time for Earth Science. Tectonics is no longer an isolated branch of geology related to major Earth features such as the origin of continents or mountains. Its findings reflect on geomorphology (the evolution of landforms), biogeography (land bridges or continental drift), climatology (to what extent do mountains control the climate?), and other disciplines. Sadly, in our opinion, Earth Science has become too concerned with theory, models, and dogma. We agree with Claud Bernard (a physiologist) who wrote: 'Men who have excessive faith in their theories or ideas are not only ill-prepared for making discoveries, they also make poor observers.' We hope, in our small way, to encourage people, from students to professionals, to have a new look at mountains, without reference to pre-conceived theories, but with attention to what can really be seen.

Cliff Ollier and Colin Pain
Canberra, May 1999

Acknowledgements

We wish to thank the colleagues who provided photographs, acknowledged in the captions to figures, and Bryan Ruxton and John Hepworth who read some sections of the manuscript.

1
Introduction

Mountains are a common feature of the Earth, easily recognised by ordinary people and scientists alike. Folded rocks are also observed in many places, and a dominant idea arose very early that the same forces that folded the rocks also formed the mountains. Over the past two centuries many theories of mountain formation have been proposed, mostly based on a mechanism that could also fold rocks. An early idea was the shrinking Earth, where fold mountains were created like folds in the skin of a shrivelled apple. Since about 1965 plate tectonic ideas have dominated geology. In this hypothesis mountains are formed where plates of the Earth's crust collide, and the movement of one plate below another (subduction) causes both folding and mountain building.

These grand theories go straight to the ultimate mechanism and driving force, and miss out on some of the vital landscape-forming processes, especially the former existence of plateaus where the mountains stand today.

Geomorphologists (scientists who study landscapes) have long studied plains, many of which are erosion surfaces cut across varied rock structures such as folds and faults. If an extensive plain is raised by regional uplift it becomes a plateau, such as the Tibetan Plateau, the Highveld of southern Africa, or the Tablelands and High Plains of Australia. Erosion of plateaus can create rugged topography—in fact it makes mountains. So to understand mountains we must first know more about their geomorphic history. In most mountain studies this is not done: instead the rock structures inside the mountains are described in detail, with the tacit assumption that whatever made the structures also made the mountains.

This assumption is not warranted. The plains of Western Australia and Africa are about as flat as any erosional land surface can get (Figure 1.1). Very complex structures including folds, faults and highly sheared metamorphic zones underlie the plains (Figure 1.2). Nobody suggests that these structures formed the planation surface. Yet when similar structures are found beneath mountains many geologists assume that the forces that made the structures also formed the mountains. Even when the rock structure includes great thrusts, as in the Carpathians, the reasoning should be the same: the major structures were planated long before the present mountains

Figure 1.1 The Acholi Plain in northern Uganda (photo C.D.Ollier).

came into existence (Figure 1.3). Thus structures in the Appalachian Mountains are commonly thought of as related to the Appalachian orogeny that folded the Palaeozoic rocks and also formed the Appalachian Mountains. In reality the Palaeozoic structures were planated, and it was later uplift of the planation surface followed by further erosion of valleys that created the Appalachians of today. Similarly in Scandinavia we are told that the Caledonian orogeny (which deformed the rocks) made the Caledonian Mountains. The reality is that the Caledonian structures were eroded to a plain, the planation surface was warped up much later to form a plateau, and later erosion made the mountains of Norway.

Figure 1.2 A typical cross-section in northern Uganda (J.V.Hepworth, pers. comm.).

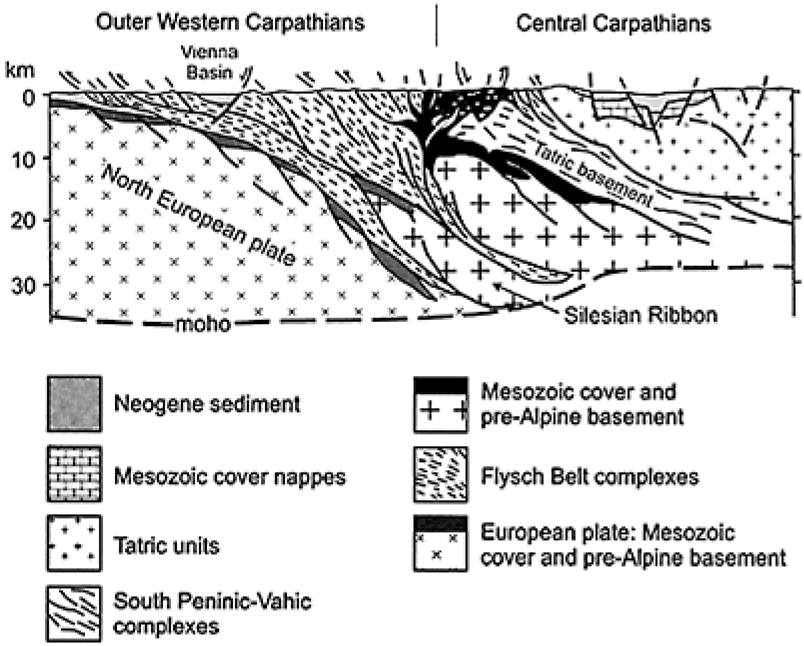


Figure 1.3 Cross-section of the Western Carpathians. The thrusting affects virtually all the crust, and in comparison all the structures are planated. The mountains of today are caused by much younger forces than those that caused the great structures. (after Plasienka *et al.* 1997).

Planation surfaces are formed by erosion to a base level, usually sea level. Uplifted planation surfaces (plateaus) indicate vertical uplift of a former low-lying plain. Widespread planation itself indicates a period of tectonic stability when erosion was not offset by uplift. Uplift is a vertical movement. Uplift does not affect the whole world, but a broad area. This is *epeirogeny,* and it is ironic that while the meaning of orogeny has changed from 'mountain building' to 'rock deformation' it now seems that epeirogeny is what makes mountains.

The study of the geomorphology of mountains all over the world leads to a remarkable conclusion. Most of the world's mountains are formed by erosion of plateaus, which are themselves uplifted erosional plains. Folding in these areas must be older than the formation of the planation surface, and of course older than the mountains. This means we must separate two processes, or sets of processes—one set causes folding and other structures, the other set causes plateau uplift. In fact we can distinguish four sets of processes:

1 processes that cause folds and other structures;
2 processes that make planation surfaces;
3 processes that cause uplift of a plain to form a plateau (gentle bends, monocline, fault block (horst), tilt block);
4 erosional processes that dissect a plateau into mountains (basically fluvial and glacial).

These four sections will be dealt with in the next chapters.

Furthermore, many of the world's mountain belts are on sites of geologically young uplift, which also leads to many interesting conclusions. Later in the book we shall present evidence for the age of mountains throughout the world, and examine the implications.

It turns out that uplift of land to make mountains results in tectonic, climatic and geomorphic changes. In other words there are feedback mechanisms between mountain building and other processes.

Volcanoes are different from other mountains in their mode of origin, and are treated separately in Chapter 9.

This book presents a detailed account of mountain building including both tectonic and geomorphic evidence so far as can be done in a single book. We also have to digress at times to discuss some basic ideas of geology and geomorphology. Finally we discuss some of the implications of this view of earth history.

Terminology

Uplift, orogeny and mountain building

This section is all about the confusing nomenclature associated with mountains. If you are not interested in details you can skip this part, but if you have a little learning, and especially if you think orogeny makes mountains, it will be best to read it before you read the rest of the book.

Nearly all modern books on mountain-building and orogeny are confused about the origin of mountains and the origin of structures inside them. Hsü's *Mountain Building Processes* (1982) is all about structures, and it is simply assumed by most contributors that 'orogeny' creates both internal structures and the present-day topographic mountains. In that book only Gansser, in his chapter on the 'morphogenetic phase' of mountain building, distinguishes the late, vertical mountain building from earlier compression. Schaer and Rogers' book *The Anatomy of Mountain Ranges* (1987) is likewise about internal structures, tacitly assumed to be related to present day mountains. Orogeny is still equated with mountain building by many geologists.

Orogeny

Orogeny is a word literally meaning the genesis of mountains, and when proposed it meant just that. Unfortunately in later years the idea of folding and mountain building being the same thing became entrenched, and with a further swing the term 'orogeny' came to mean the folding of rocks. *Orogeny is now used to refer to the folding of rocks in* *fold belts.* It does not mean mountain building, despite its etymology. We shall have to use the longer phrase *mountain building* to be clear.

If authority is needed for this practice we may note the following:

King (1969) wrote in his influential paper: 'In this account, and on the legend of the "Tectonic map of North America", "orogeny" is therefore used for the processes by which the rock structures within the mountain chains or fold belts are created.'

In *Orogeny Through Time* Burg and Ford (1997) claim that: 'To field geologists the term orogeny represents a penetrative deformation of the Earth's crust.' We are not convinced that all field geologists really appreciate this not-so-subtle change of meaning.

Jackson (1997), in what is virtually the bible for English-speaking geologists, wrote:

> *orogeny* literally, the process of formation of mountains. The term came into use in the middle of the 19th Century, when the process was thought to include both the deformation of rocks within the mountains, and the creation of the mountainous topography. Only much later was it realised that the two processes were mostly not closely related, either in origin or in time. Today, most geologists regard the formation of mountainous topography as postorogenic. By present geological usage, orogeny is the process by which structures within fold-belt mountainous areas were formed, including thrusting, folding, and faulting in the outer and higher layers, and plastic folding, metamorphism, and plutonism in the inner and deeper layers. Only in the very youngest, late Cenozoic mountains is there any evident casual relation between rock structure and surface landscape. Little such evidence is available for the early Cenozoic, still less for the Mesozoic and Paleozoic, and virtually none for the Precambrian—yet all the deformation structures are much alike, whatever their age, and are appropriately considered as products of orogeny.

However the modern usage has not filtered down to lower levels, and elementary books and dictionaries still commonly follow the old usage, and have figures like that in Figure 1.4. For example, the *Hutchin Pocket Dictionary of Geography* (1993) has the following entry:

> *orogeny* or *orogenesis*—the formation of mountains. It is brought about by the movements of the rigid plates making up the Earth's crust (described by plate tectonics). Where two plates collide at a destructive margin rocks become folded and lifted to form chains of fold mountains (such as the young fold mountains of the Himalayas).

The prestigious National Geographic Society in *Exploring Your World* (1993) states:

> Fold mountains are formed when two of the large plates that carry the earth's crust slowly collide and compress, or when one plate gradually folds and wrinkles as a result of this action.

They illustrate the idea with a diagram like Figure 1.4, leaving no doubt that they consider the folded rocks to be the direct origin of the fold mountain. Some more serious sources also maintain the old story, such as the definition in *The Cambridge Encyclopedia of Earth Sciences* (1981):

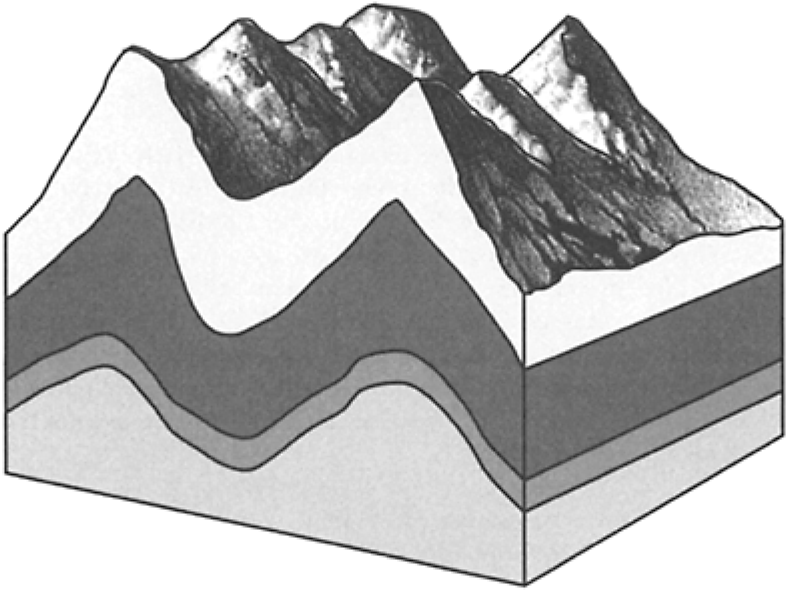
> *Orogeny* An episode of tectonic activity (folding, faulting, thrusting) and mountain building usually related to a destructive plate margin.

Some writers seem to adopt their own personal definitions of mountain building and orogeny. Miller and Gans (1997), for instance, wrote: ‘Mountain building and orogeny (i.e. thickening of continental crust) are not necessarily the result of subduction.’ We do not equate either mountain building or orogeny with crustal thickening, and suspect that few other workers do so.

Allmendinger and Jordan (1997) wrote: ‘The term “Andean Orogeny” refers collectively to all tectonism that occurred between the Jurassic and Recent.’ This would probably not be most people’s idea of orogeny, but it certainly would not be synonymous with ‘mountain building’ for, as we shall see, the Andean Cordillera were created in only a twentieth of that time.

Epeirogeny

In contrast with orogeny, early geologists used the term ‘epeirogeny’ to mean the uplift of broad areas, as opposed to the narrow fold belts of mountain chains. Gilbert (1890, p. 40) coined the word ‘epeirogeny’ and was also one of the first to use the term ‘orogeny’, so it is useful to get his



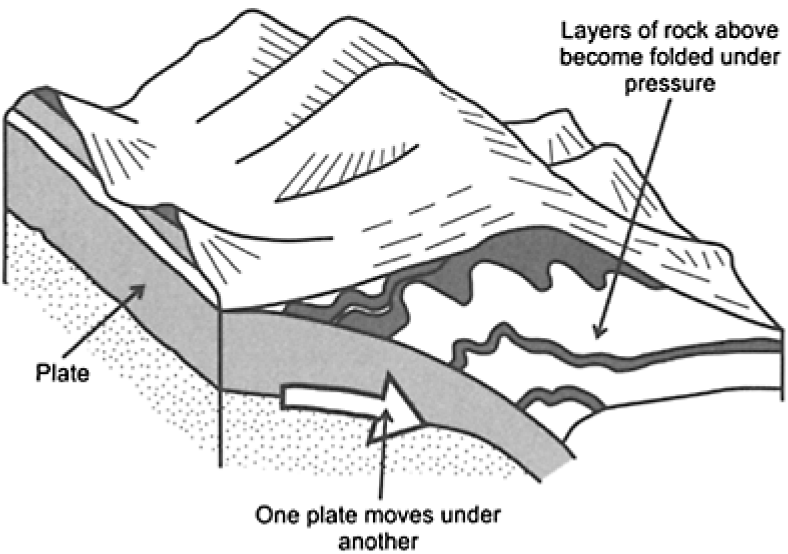


Figure 1.4. Two naive illustrations of fold mountains

Top. Elementary diagram of fold mountains, in which the actual mountains have the same shape as the folds. This does not happen in the real world.

Bottom. A diagram showing the common misconception of 'fold mountains', with the folding of the rocks and formation of the actual mountains occurring simultaneously by compression of horizontal rocks (simplified from *National Geographic,* 1993). As explained in the text, real mountains are not formed in this way. This diagram, common in popular literature, shows that the mountains are supposed to be formed at the same time as the rocks are folded, and by the same force.

views: 'The process of mountain formation is orogeny, the process of continent formation is epeirogeny, and the two collectively are diastrophism.' Probably nobody follows this usage any more. 'Epeirogeny' is still a valid term for the uplift of broad areas, but it does not mean continent formation. We believe that mountains result from erosion of areas that have been uplifted epeirogenically.

The paradox was noted long ago by Stille (1936) who expressed it thus:

> As a matter of fact, orogeny in the tectonic sense generally fails as an explanation for the existence of the topographically great mountains of the earth, such as the Alps of Europe or the Cordilleras of North America. These mountains exist—or still exist—as a result of post-orogenic en bloc movements, for the most part still going on, and belonging to the category of epeirogenic processes. Thus arises the terminological contradiction, that the mountains as we see them today owe their origin not to what is called orogeny, but to an entirely different type of movement that is to be strongly contrasted with the orogenic process.

The distinction between orogeny and epeirogeny is acknowledged in the definition provided by the McGraw-Hill *Dictionary of Earth Sciences* (1984):

> *Orogeny* The process or processes of mountain formation, especially the intense deformation of rocks by folding and faulting which, in many

> mountainous regions, has been accompanied by metamorphism, invasion of molten rock, and volcanic eruption; in modern useage, orogeny produces the internal structures of mountains, and epeirogeny produces the mountainous topography.

This definition highlights another problem: there is no one-to-one correlation of folding and mountain building. Lowland plains may be underlain by intensely folded rock, as in much of Western Australia, the Canadian Shield or Finland. Mountainous areas may be underlain by horizontal strata, like the Drakensberg of South Africa or the Blue Mountains of New South Wales. Furthermore, granite or basaltic lava flows may be found under both plains and mountains.

The relationships of plains and mountains to areas of folding and non-folding

Plains occur on horizontal strata (Murray Basin).
Mountains occur on horizontal strata (Drakensberg).

Plains occur on folded rocks (Amazon Basin).
Mountains occur on folded rocks (Alps).

Plains occur on horizontal basalt (Western Victoria Plains).
Mountains occur on horizontal basalt (Snake River).

Plains may be cut across granite (Western Australia).
Mountains may be cut across granites (Sierra Nevada).

Plains may be cut across metamorphic rock (Finland).
Mountains may be cut across metamorphic rock (Scottish Highlands).

Clearly there is a need to divorce mountain building from folding. To emphasise this point the information is shown again in Figure 1.5.

Theories

Theories about the origin of mountains are based on certain assumptions, often unstated and sometimes dubious. Many hypotheses purporting to be about mountain building are in fact concerned with geosynclines, plate tectonics, or the origin of mobile belts—belts of deformed rocks which may or may not be coincident with mountain belts or former mountain belts.

Theories come in all varieties of sophistication, but many fail to distinguish clearly between the folding of the rocks and the formation of mountains. We must include here various ideas that are really concerned with fold belts but because they are called theories of orogenesis they imply a relationship with mountain chains.

Early in the twentieth century Geikie (1912) wrote *Mountains* in which he distinguished 'Original or Tectonic' mountains from 'Subsequent or Relict' mountains. The second group is discussed in only one chapter out of 12, despite the fact that much of Geikie's book is concerned with the eroded mountains of Scotland and Europe.

	FOLDED ROCKS	HORIZONTAL STRATA	HORIZONTAL BASALT	GRANITES	METAMORPHIC ROCK
MOUNTAINS	Alps	Drakensberg	Snake River	Sierra Nevada	Scottish Highlands
PLAINS	Amazon Basin	Murray Basin	W. Victoria Plains	Western Australia	Finland

Figure 1.5 The relationship between mountains, plains and geological structure. There is no simple relationship between mountains and folding, or any other structure.

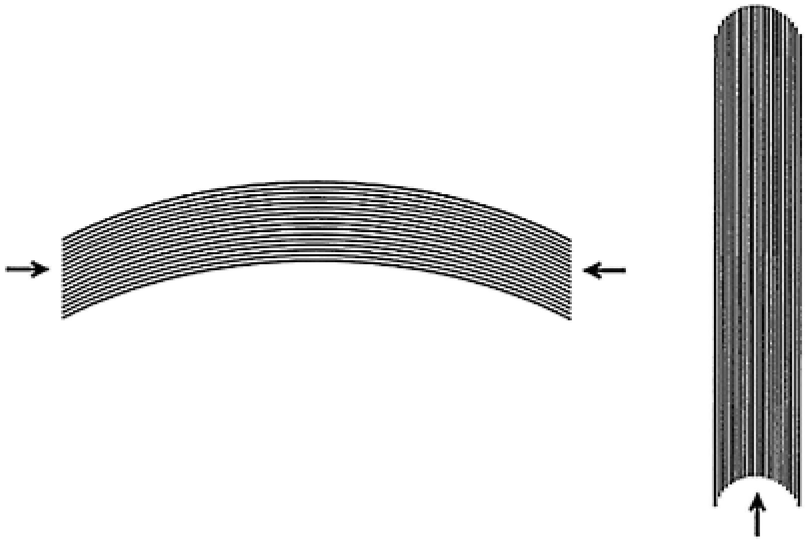


Figure 1.6 Diagram of card pack. The cards may be 'folded' with lateral compression (left) or with constant lateral dimension (right).

Two main concepts have been used to explain the creation of mobile belts: the lateral (tangential) compression hypothesis, or vice concept, and the vertical (radial) tectonic concept, with vertical uplift of broad areas.

There are then two possible related assumptions:

1 That the strata are shortened and that the two opposite sides of a sedimentary packet move towards each other during folding. As shown in Figure 1.6 it is possible to make folds without shortening,
2 That there is little shortening and there may even be extension (dilation).

We shall try to make these points clear in discussing real mountains in the rest of the book.

Finally we may mention assumptions about earth volume, which include the following:

1 Hypothesis of a contracting Earth. This was an old favourite, last presented seriously by Lees (1952), who wrote: 'Mountain building is the consequence of contraction of the interior of the earth and crustal compression from this cause has been dominant throughout revealed geological time.'
2 Hypothesis of an Earth of constant volume. This is by far the commonest assumption.
3 Hypothesis of an expanding Earth, most seriously proposed by Carey (1976, 1988).
4 Hypothesis of oscillating Earth volume. Nobody seems to have seriously proposed this, and it is included here merely to complete the list of possibilities.

The study of mountains

In the study of anything, scientists should work from observations to theory. Using any techniques available, they gather relevant facts, and then derive a hypothesis to explain them. This, we hope, is the method used in this book.

In the study of mountains we want to know:

1 the age and origin of the rocks;
2 the age and origin of geological structures;
3 the age and style of erosion;
4 the age of uplift;
5 the cause of uplift.

The last is the most difficult to know, but it is where most people start!

Outline of this book

The first chapter sets the scene for later discussions of mountains and presents essential definitions together with a brief outline of plate tectonics and geological time.

Next comes a series of chapters on mountains of particular regions, or arranged by a common theme or origin.

This is followed by a section where we discuss some generalities, processes and implications related to the study of mountains.

To put a thread through the story we present the following simple outline of mountain formation:

Some mountains are simple plateaus. Others are made by erosion of high masses of rock, and perhaps there is little trace of earlier landscape development.

The simplest kind of tectonic uplift is of fault blocks, so we deal with mountains related to simple block faulting, tilt blocks and multiple tilt blocks.

Next come those mountains that are eroded plateaus on folded rocks. Differential erosion occurs on a simple structure, but an earlier phase of planation is usually evident.

Beyond simple folds are the great thrust sheets of rocks called ‘nappes’. We deal with several mountain ranges formed on nappes, but find that a planation surface was formed after the nappe movement, and then came vertical uplift.

Some uplifted blocks apparently spread as they rise, thrusting rocks over the surrounding lowlands. Numerous examples are described.

Erosion on the edges of uplifted blocks can make valleys so big that the land rises isostatically, inducing uplift of the edges of the plateaus.

Some continents have a marginal swell of high land which is eroded on the ocean-facing side into Great Escarpments, commonly known as mountain ranges. These are the passive margin mountains.

In very many mountainous regions the common sequence of events is:

1 erosion to a plain followed by
2 uplift to form a plateau, after which comes
3 erosion of the plateau to make isolated mountains.

There are, of course, many variations on this theme.

Two groups of mountains do not fit into this general picture but are treated for completeness, and for the light they throw on other mountains. Volcanoes are constructional landforms built of lava derived from deep in the Earth and erupted at the surface. Granite mountains are formed of rock formed deep in the Earth. Most granite mountains are simply the result of great erosion, but some result from the rise of granite above the general ground level.

A brief outline of plate tectonics

As soon as the voyages of discovery had revealed the similarity in shape of the opposite sides of the Atlantic, the idea that opposing continents had drifted apart was bound to arise. It was Wegener (1929) who brought scientific knowledge and scholarship together in a serious and concentrated exposition of continental drift.

In Wegener's day the concept of drift could be supported by evidence from the distribution of plants and animals, the distribution of fossils, ancient deserts and glaciated rocks, and by matching other geological evidence. Wegener also thought that the mountains along the Pacific coast of the Americas were pushed up at the front edge of drifting continents where the continental slab buckled against the Pacific.

Continental drift was not accepted readily by the geologists, especially in the Northern Hemisphere, and 'drifters' were lepers in the geological community. But in 1958 Carey showed that the 'fit' of the South Atlantic was remarkably good, within half a degree over 45 degrees of latitude, which could hardly be accidental, and by 1965 Bullard and others showed that the entire Atlantic could be closed to give an equally good fit.

However, the evidence that was to change our views on drift came not from the continents but from the study of the ocean floor. Ocean surveys in the nineteenth century showed that the Atlantic was shallowest along the centre. A mid-Atlantic ridge runs the full length of the Atlantic and remains very close to the middle, emerging above sea level in Iceland. The ridge is split by a great rift. Perhaps the greatest geological discovery of this century is that the ocean floors are spreading. Magnetic studies showed a symmetry about the mid-Atlantic ridge, and later studies showed that the sea floor gets consistently older with distance from the ridge. New seafloor is being created at the spreading sites, and old seafloor migrates away from them.

There is overwhelming evidence that the Atlantic Ocean has been formed by the drifting apart of the continents that bound it. The sea floor grows at the centre—the mid-Atlantic rift—and spreads sideways. It seems that the Atlantic Ocean only started to open in the Triassic, about 200 million years ago.

Seafloor spreading was later demonstrated in all the oceans, though the Pacific ridge is not in the centre of the ocean, but runs into the continents of North and South America.

But if all the oceans are growing, they must disappear somewhere, unless the Earth is increasing in size. The sites where ocean disappears are called 'subduction sites', and are located at island arcs and 'active' continental margins. The driving force is thought to be convection currents, rising at the spreading sites and sinking at subduction sites.

In simple continental drift the continents were thought to drift around on a 'sea' of sub-continental material, but the ocean floors were thought to be quite passive in the process. Plate tectonics differs in having the oceans as part of the system. Seafloor is created at spreading sites, and destroyed at subduction sites. If a spreading site were to originate beneath a continental area, the continent would be rifted and drifted apart and a new ocean basin formed in the middle.

Plate tectonics is a name for the concept that the earth's crust can be divided into several plates (Figure 1.7) and the world's main tectonic features are related to activity at the edges of the plates. New crust is created at spreading sites, and old crust is destroyed at subduction zones. Beyond this simple exposition many complications are possible, and variations from writer to writer, and from place to place are almost numberless. For the past 30 years plate tectonics has been the ruling theory in geology, and has been used to account for almost everything in Earth Science.

Many phenomena follow plate boundaries. Shallow earthquakes follow the line of the sub-oceanic ridges, the spreading sites. Deep earthquakes follow the line of subduction sites around the Pacific rim and lines of deep sea trenches. A few earthquakes follow the rift valleys which might be incipient spreading sites.

The distribution of volcanoes (Figure 9.4) shows a similar pattern. Volcanoes are distributed along lines of sea floor spreading, and on the areas bordering subduction zones.

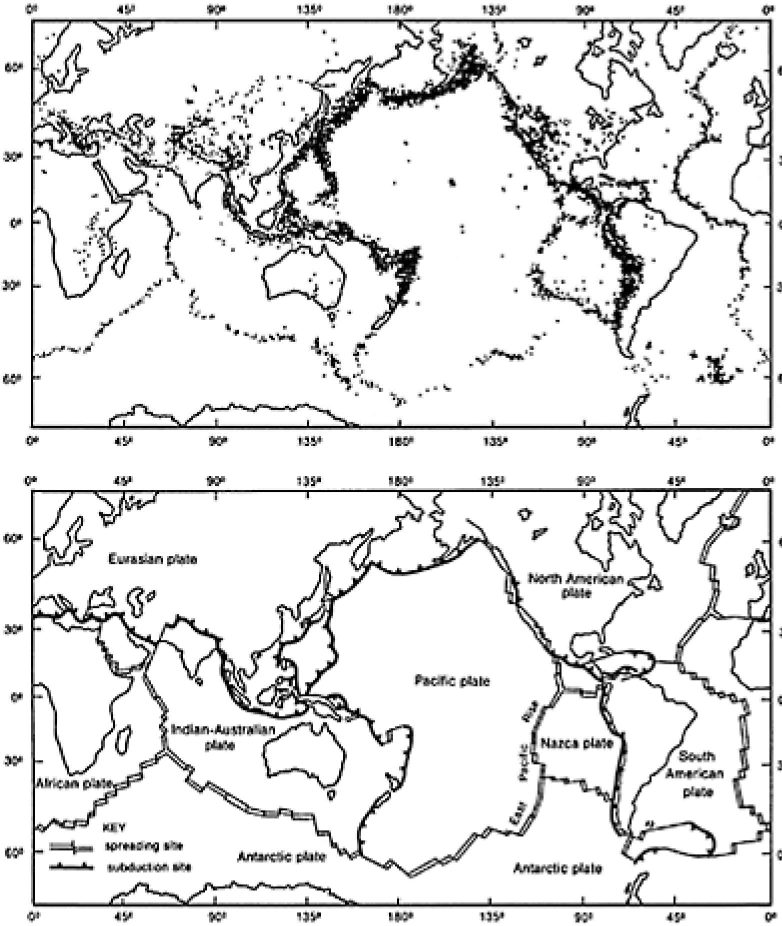


Figure 1.7 Tectonic plates and earthquakes. The top map shows the distribution of earthquakes. The bottom map depicts the 'plates' of plate tectonics, each bounded by lines of spreading or subduction.

Other evidence, including geochemical, gravity and heat flow measurements, all helps to confirm the same boundaries of the major plates of the Earth's crust, and there is no doubt that the view of the Earth in terms of plates has made a major advance in geological thinking, even though details may be disputed.

For many Earth processes, including mountain building, the 'action' is thought to occur on active margins, but as we shall see later there are also mountains on passive margins, and some on spreading sites.

Spreading sites

These are mostly under the sea, and only affect the mountain story where the rift emerges as land, or where oceanic volcanoes achieve mountain proportions.

The geomorphology of the rift area can be seen in fair approximation in Iceland, which may be regarded as a piece of the mid-Atlantic ridge above sea level. There the rocks get older as one moves away from the rift, the rocks are dominated by fissure eruptions and the topography, where not primarily volcanic, is marked by many faults and fissures parallel to the main mid-Ocean (or mid-Iceland) rift. The volcanic intrusion is permissive. That is, dyke rocks come in to fill a space created by tension. We should not imagine a thin dyke forcing its way into a crack and pushing aside a plate many thousands of kilometres across and billions of tonnes in weight. Rather there is some force pulling the plates apart and the dykes come in to fill the space created when a crack appears.

Subduction sites

Subduction sites (known also as collision sites and active margins) provide more varied tectonic settings than spreading sites, including the following types. Some of the possible effects are shown in Figure 1.8.

Continent-continent collisions (Himalayan type)

The most spectacular example of this collision type is that presumed to have occurred between India and continental Asia. The idea is that India broke away from the supercontinent of Gondwana, drifted north, and was subducted under Asia, causing the rise of the Himalayas and the Tibet Plateau. This idea is discussed further in Chapters 7 and 12.

The collision of Africa with Europe is another example of the plate tectonic explanation of mountains, especially in Europe.

Continent-ocean collision

This is the commonest sort of collision envisaged in the plate tectonic theory, but can itself be divided into two.

Simple subduction (Andes type)

This is allegedly typified by the plate junction on the west side of South America.

The Pacific Ocean is said to be subducted under the South American continent. This is supposed to account for:

the deep trench along the edge of the continent;

the rise of the Andes;

the volcanic activity of the Andes;

the granite plutons of the Andes.

The course of the slab's progress is recorded by a series of earthquakes that show a fairly consistent increase in depth with distance from the plate edge making an inclined earthquake zone known as a 'Benioff zone'.

Sometimes sediments are scraped off the down-going slab and thrust on to the continent, perhaps to form 'fold mountains' (Figure 1.8d).

Alternatively, sediment may be carried under the continent (Figure 1.8e) where it is presumed to melt and form granite, or perhaps melt and provide the magma for volcanoes along the collision zone.

Island arc subduction

Around the western edge of the Pacific the map shows many islands arranged in festoons of arcs, either single lines or double rows of islands, making a quite clear pattern of curves. These lie some distance off the continent, and in front they have a deep trench very like that off the coast of South America. These deeps also bound a Benioff zone dipping towards the continent and marked by earthquakes reaching depths of several hundred kilometres.

Some arcs face east (Indonesian arc), some arcs have no continent behind them (South Sandwich Islands), and some lines of islands have all the attributes of arcs such as Benioff zones and trenches but lack the arcuate shape (Solomon Islands). Nevertheless the island arc complex makes one of the distinctive landform and tectonic assemblages of the Earth and, despite many complexities and variations, island arcs mark plate junctions.

Obduction

In a few collision zones a slab of ocean floor is thought to have over-ridden rather than under-ridden the continent. In Papua New Guinea a slab of basic rocks with petrology, layering and structures exactly like those thought

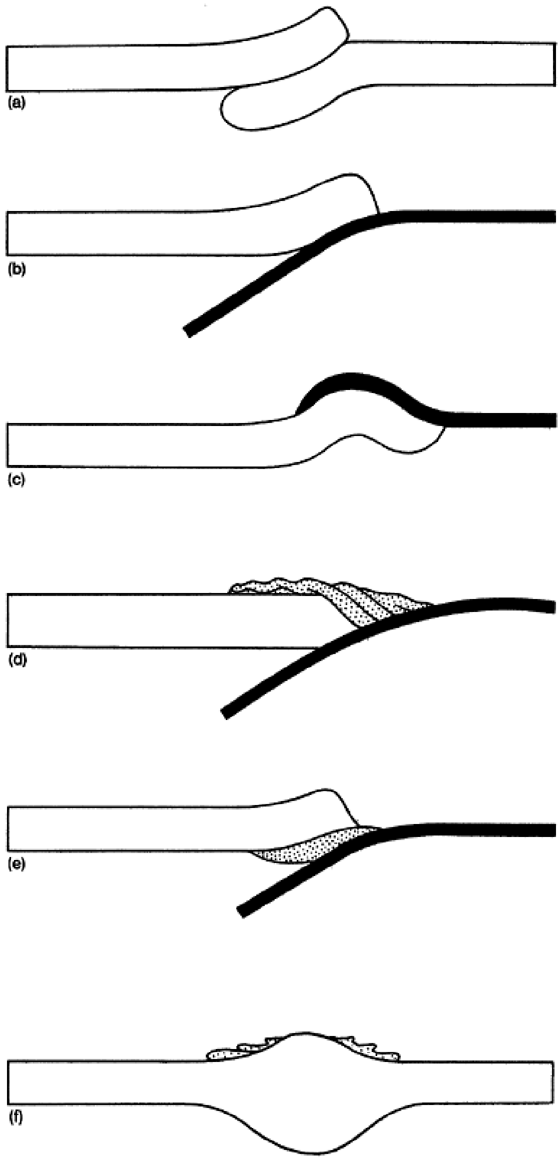


Figure 1.8 Some possible mechanisms for creation of mountains by plate tectonics.

a. Continent-continent collision (Himalayan type)