

9

Mountain uplift and the Neotectonic Period

CLIFF D. OLLIER

School of Earth and Geographical Sciences, University of Western Australia, Perth, Australia

Mountains result from uplift of former plains to make plateaus, which are dissected to various degrees. There are no 'fold mountains'. When folded rocks underlie mountains the folding pre-dates planation and uplift. The one exception is post-uplift gravity spreading of very large fault blocks. A compilation of times of uplift of mountains around the world is presented, and most show uplift in the last few million years, a time known as the Neotectonic Period. This is significant in many aspects of global tectonics, geomorphology and climate.

9.1. INTRODUCTION

It is commonly assumed that folding and mountain building go together, but this need not be true. Mountains occur not only on folded rocks, but on horizontal rocks, granite, and lava flows. Ollier and Pain (2000) assembled evidence that most mountains are the products of uplift of a plain to form a plateau, which may or may not be extensively dissected. Examples of planation surfaces in mountainous areas in different tectonic settings are shown in fig. 9.1a-f.

The age of a mountain or mountain range is then the age of plateau uplift, not the last age of folding of rock. On this basis, a table of time of uplift of mountains and plateaus from around the world (table 9.I) shows a preponderance of uplift in the last few million years. This uplift of mountains appears to be a global phenomenon. It affects so-called Alpine mountains, mountains on passive continental margins, and those in deep continental interiors. The period of uplift is known as the Neotectonic Period (Morner, 1993; Ollier and Pain, 2000, 2001).

9.2. EXAMPLES

9.2.1. Tibet, Himalayas, Kunlun Mountains

As an example, consider the timing of uplift in Tibet and its bordering mountains. Gansser (1991) wrote: «... we must realise that the morphogenic phase is not only restricted to the Himalayas but involves the whole Tibetan block. This surprising fact shows that an area of 2500000 km² has been uplifted 3000-4000 m during Pleistocene time and that this uplift is still going on.» In places the uplift rate is 4.5 mm/yr (five times the maximum in the European Alps). According to Wu *et al.* (2001) from the Pliocene to the Early Quaternary (5-1.1 Myr) the Kunlun Pass area of the Tibetan Plateau was no more than 1500 m high and was warm and humid. They write: «The extreme geomorphic changes in the Kunlun Pass area reflect an abrupt uplift of the Tibet Plateau during the Early and Middle Pleistocene. The Kunlun-Yellow River tectonic movement occurred 1.1-0.6 Myr.» Zheng *et al.* (2000) concluded from sediments at the foot of the Kunlun Mountains that uplift began around 4.5 Myr.

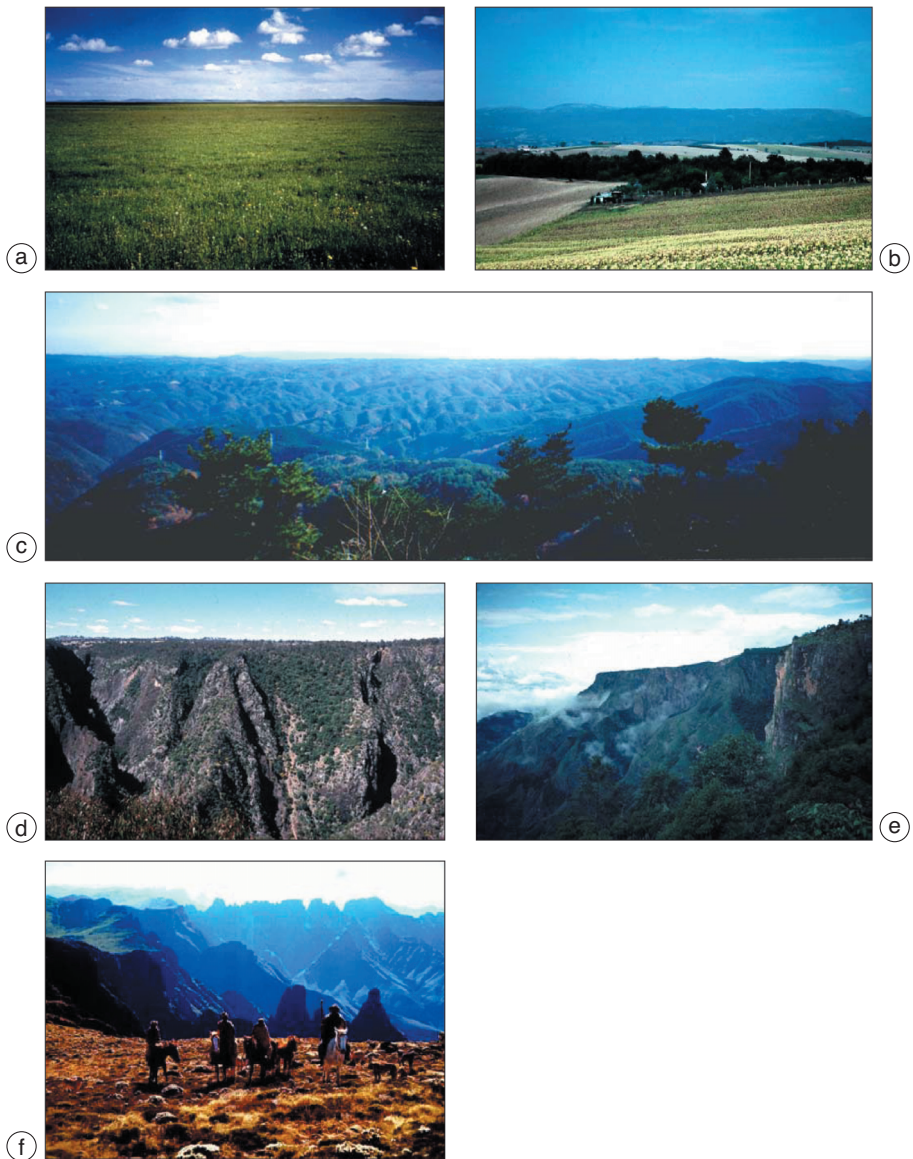


Fig. 9.1a-f. Planation surfaces in different tectonic settings: a) the Tibet Plateau, a vast planation surface uplifted to 5 km in a mid-continental setting (photo by C.D. Ollier); b) the Apennines planation surface near Ancona, Italy, in a continental margin or arc setting (photo by C.D. Ollier); c) the planation surface cut across the mountains of Southern Japan, in an island arc setting (photo by Takao Yano). d) the abrupt junction of the planation surface, cut across varied folded Palaeozoic rocks, and the Great Escarpment in the eastern highlands of Australia, in a passive margin setting. Bakers Falls, New South Wales (photo by C.D. Ollier); e) the Western Ghats in Southern India near Kodakanal. The planation surface and Great Escarpment are eroded across Precambrian metamorphic rocks and granites (photo by C.D. Ollier); f) view of the Drakensberg, South Africa, in a passive margin setting. Retreat of the Great Escarpment produces plateau remnants visible on the skyline, and irregular outlying hills (photo reproduced by permission of Art Publishers (Pty) Ltd, 022, Mayville 4058, South Africa).

Table 9.I. Some suggested ages for mountain uplift. In many areas there are precursor movements, and the ages in the table generally refer to the major or latest uplifts.

Europe		
Swiss Alps	(Trumpy, 1980)	Pliocene-Quaternary
Jura	(Holmes, 1965)	Pleistocene
Apennines	(Coltorti and Pierruccini, 2000)	latest Pliocene-Middle Pleistocene
Pyrenees	(Sala, 1984a; Calvet, 1994)	Pliocene
Central Cordilleras of Spain	(Sala, 1984b)	Plio-Pleistocene
Baetic Cordillera	(Choubert and Faure-Muret, 1974; Sala, 1984c)	Upper Miocene-Pliocene
Western Carpathians	(Földvary, 1988)	Upper Miocene-Pliocene
Eastern Carpathians	(Zuchiewicz, 2000)	Pliocene
Southern Carpathians	(Rădoane <i>et al.</i> , 2003)	2500 m about 12 Myr; 1000 m about 2 Myr
Caucasus	(Bridges, 1990)	Upper Pliocene
Ural Mountains	(Bridges, 1990)	Pliocene-Pleistocene-Middle Pleistocene
Sudeten	(Migon and Lach, 1999)	Pliocene-Early Quaternary
Asia		
Tibetan Plateau	(Wu <i>et al.</i> , 2001)	Pliocene-Quaternary
Himalayas	(Gansser, 1991; Kalvoda, 1992; Zhang, 1998)	Pliocene-Quaternary
Kunlun Mountains	(Zheng <i>et al.</i> , 2000; Wu <i>et al.</i> , 2001)	Late Pliocene-Quaternary
Tien Shan	(Holmes, 1965)	Quaternary
Pamir	(Strecker <i>et al.</i> , 2003)	Late Cenozoic
Altai Mountains	(Suslov, 1961)	Tertiary
Transbaikalian Mountains	(Ufimtsev, 1990)	Mid-Tertiary
Karakoram	(Schroder, 1993)	Late Neogene to Present
Shanxi Mountains	(Li <i>et al.</i> 1998)	Miocene-Middle Pleistocene
Japanese Mountains	(Hoshino, 1998)	Pliocene-Early Pleistocene
Taiwan	(Chai, 1972; Ho, 1986 – – Penglai orogeny)	Early Pleistocene
North America		
Sierra Nevada	(Axelrod, 1962)	Post-Pliocene
Basin and Range	(Nitchman <i>et al.</i> , 1990)	4 Myr
Colorado Plateau	(Lucchita, 1979; Trimble, 1980)	Late Pliocene to Recent
Bighorn Mountains	(Thornbury, 1965)	Middle Tertiary-Pleistocene
Rocky Mountains	(Eaton, 1987)	5 Myr
Coast Ranges	(Thornbury, 1965)	Late Pliocene
Canadian Cordillera	(Mathews, 1991)	Late Miocene-Pliocene
Canadian Coast Ranges	(Farley <i>et al.</i> , 2001)	Modern topography post 2.5 Myr
Cascade Range	(Priest <i>et al.</i> , 1983)	4-5 Myr
South America		
Colombia	(Kroonenberg <i>et al.</i> , 1990)	Plio-Pleistocene
Chile	(Hollingworth and Rutland, 1968)	Pliocene and Pleistocene
Bolivia	(Walker, 1949)	Plio-Pleistocene
Ecuador	(Coltorti and Ollier, 2000)	Upper Miocene-Plio-Pleistocene

Table 9.I. (*continued*).

Other regions		
Ethiopian Rift	(Partridge, 1997)	2.9 and 2.4 Myr
Western Rift	(Pickford <i>et al.</i> 1993)	3 to 2 Myr
Ruwenzori	(Partridge, 1997)	Within the last 3 Myr
New Guinea Mountains	(Ollier and Pain, 1988)	Plio-Pleistocene
New Zealand Mountains	(Suggate, 1982)	Pliocene
Passive margins		
East Australia	(Ollier and Taylor, 1988)	Pleistocene
Appalachians	(Pazzaglia and Gardner, 2000; Stanford <i>et al.</i> , 2001)	Miocene or younger
South Africa	(Partridge, 1998)	Pliocene (700-900 m)
Western India	(Widdowson and Gunnell, 1999)	Late Tertiary
Greenland	(Weidick, 1976)	Late Miocene or younger
Antarctica	(Behrendt and Cooper, 1991)	Pleistocene
Scandinavia	(Lidmar-Bergström <i>et al.</i> , 2000, 2002)	Neogene

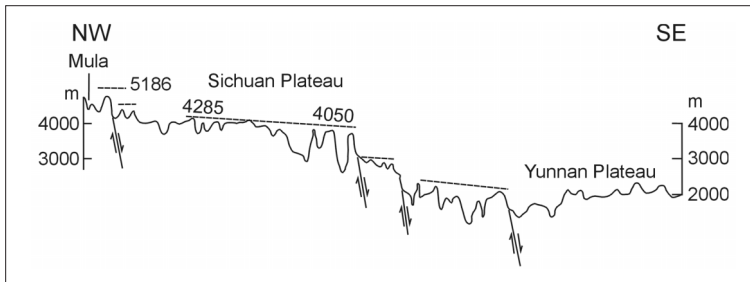


Fig. 9.2. Profile from Tibet to the Yunnan Plateau (after Gao, 1998). Various plateaus are correlated by fossil fauna and flora, revealing a once-continuous plateau that was broken up by normal faults, with a total displacement of 3000 m.

Japanese workers studying the Siwalik deposits in a sedimentary basin filled with erosion products from the Himalayas found that fine sediments give way to a boulder conglomerate at about 1 Myr, indicating a time of major uplift (Prof. T. Kosaka, pers. comm.).

The strongest uplift of the Tibet Plateau and its bordering mountains, the so-called Qinzang (Tibet) movement, occurred in three phases between 3.6 and 1.7 Myr (Li, 1995).

According to Gao (1998) there was one vast plateau over much of Asia, which has been divided by normal faults into several great plateaus that may be correlated by plant and animal fossils (fig. 9.2).

9.2.2. The European Alps

The European Alps have become a type area for ideas of mountain genesis in regions of folds and nappes. But the nappes have very little to do with the present Alpine topography. The whole region

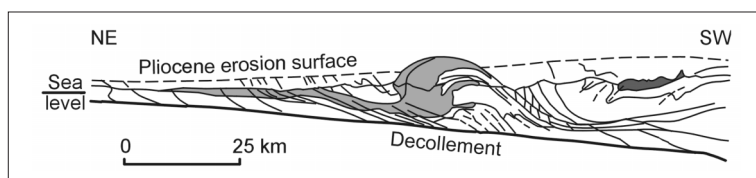


Fig. 9.3. Cross section of the European Alps. The complex nappe structures did not form the modern mountains. They were planated by a Pliocene erosion surface that was uplifted in the Plio-Pleistocene (after Spencer, 1965).

was planated in the Pliocene, and then broadly uplifted and eroded to the present spectacular topography. This idea is not new, and was described long ago by Heritsch (1929):

«The morphological studies in the Eastern Alps have further proved, from the summit-level (*Gipfelflur*) of the peaks [...] that these erosion-horizons have no sort of relation at all to the geological structure. A further result of research on East-Alpine morphology is the recognition of the fact that the upheaval of the Alps is not connected with the production of the leading features of the internal structures, but that it is related to a later process of elevation, which was of vigorous character.»

The Alpine summits levels form a broad arch between the Molasse Basin in the NW and the basin of Po Plain in the SE, with minor undulations along the arch and across it (fig. 9.3).

Towards the close of the Pliocene the Alps had been reduced to a region of low relief, the complex underlying structures being truncated by the erosion surface.

This old erosion surface was described many times in the past but it seems to have been forgotten in the many plate tectonic explanations of recent years. According to Trumphy (1980) the climax of 'orogeny' occurred in the Eocene but by the Pliocene the Alpine region was worn down to a chain of low hills. Later irregular erosion reduced the Pliocene Plateau to a *Gipfelflur*, roughly accordant summit heights suggesting a former continuous surface (Rutten, 1969).

Plate tectonic models applied to the Alps totally ignore the planation, so do not explain why uplift occurred so long after presumed collision.

9.2.3. The Rocky Mountains and related mountain ranges

In Western North America there are many uplifted blocks loosely called the Rocky Mountains. Most are related to uplift of blocks or diapirs of Precambrian rock that pushed up overlying strata which often spread or slid off the rising dome. Eardley (1963) pointed out that the largest uplifts droop over surrounding basins and so are gravitational, not compressional.

The name 'Rocky Mountains' is misleading, because they consist essentially of several dissected plateaus, with 'ranges' at the edges. The Southern Rocky Mountains Plateau, for example, is bounded by the Front Range on the east and the Park Range on the west. The Front Range is overthrust to the east, the Park Range to the west. The situation suggests original vertical faults that spread under gravity, as so-called 'mushroom tectonics' (fig. 9.4).

Foose (1973) gave an excellent summary of the bi-causal pattern of tectonism in the Rockies.

«Throughout the Middle Rocky Mountains a tectonic style may be observed that emphasises the role of two major forces that acted on the crust during the Laramide orogeny [...]. The primary and earliest force was that of vertical tectonism [...]. The secondary force [...] was that of gravity, which extensively remodelled the basically simple geometry of the initial blocks in the Middle Rocky Mountains by creating a variety of structural features that provided for the release of stress within the blocks. Release of stress was accompanied by movements of parts of the block along the newly created structures in directions outward and downward toward the adjacent basins.»

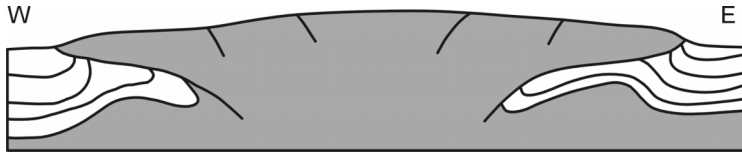


Fig. 9.4. Diagrammatic section of the Rocky Mountains, with the Front Range to the east and Park Range to the west. The ‘mushroom’ tectonics results from the uplifted Precambrian core (shaded) spreading over younger rocks on both sides (after Jacob, 1983).

Planation surfaces are widespread in the Rockies, though ignored by later, plate-tectonic, interrelations. Loomis (1937) wrote «The Northern Rocky Mountain Province is a complex of many ranges that have been revealed by dissection of a peneplain which can be traced over the whole area.» Atwood (1940) wrote «Many persons who have studied the Front Range of Colorado have called the remnants of this old-age erosion surface in that section the Rocky Mountains Peneplain.» He lists many other plateaus in the area such as the Green Ridge Peneplain and the Medicine Bow Peneplain. The age of the Rocky Mountain planation surface varies from place to place. In Central Colorado it is demonstrably Late Eocene, but in much of the Laramide and Medicine Bow mountains it is Miocene.

There are many drainage anomalies in the Rockies, where rivers go through the mountains, not around them, indicating antecedent drainage: the river courses existed before uplift (Ollier and Pain, 2000).

The fault blocks are elongated, and run in many directions from E-W (Uinta Dome), NW-SE (Owl Creek, Wind River), to N-S (Front Range). This, together with the divergent thrusts away from the centre of the blocks, makes it difficult to accept plate tectonic explanations of subduction-related uplift.

9.2.4. Japanese mountains

Island arcs are classical areas for mountain formation according to plate tectonics, where approaching ocean plates compress continental margins to form fold mountains. The Japanese mountains provide a classical example (see many articles in the Japanese journal *Island Arc*). The plate tectonic exponents accept that the major relief and structural framework of the arc-trench system of Japan was formed during the latest Cenozoic, particularly in the Quaternary (Otuka, 1933; Sugimura and Uyeda, 1973) but they usually ignore the widespread planation surface.

The Kitakami Mountains of northeast Honshu are said to be typical of the Japanese Islands (Hoshino, 1998). The summit is marked by a peneplain that was formed in the Late Miocene, and the gently inclined flanks of the range comprise an erosion surface with gravel beds that developed in the Late Pliocene. Uplift of the Kitakami Mountains took place during the Pliocene to Early Pleistocene (Chinzei, 1966). The raised peneplain, which makes the skyline of the mountains, is 1000 m in the north and falls gradually to 500 m to the south. The peneplain is also very evident in Southern Japan (fig. 9.1c). The conventional plate tectonic explanation of Japan as an island arc created by subduction completely ignores the very obvious planation and vertical uplift.

Hoshino believes the gravels that cap the southern part of the peneplain are of Late Pliocene (Villafranchian) age, and are terrestrial but were deposited very close to sea level.

9.2.5. Mountains on passive continental margins

Mountains on passive continental margins differ from others in several respects (Ollier, 2004), though they are similarly created by erosion of a plateau (fig. 9.5). They may have been originally

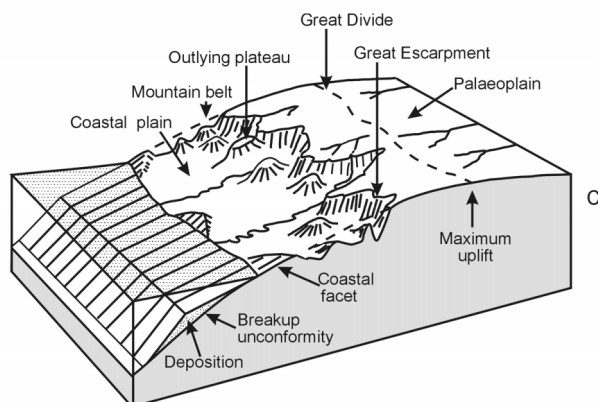


Fig. 9.5. The basic geomorphology of passive margins with mountains (after Ollier, 2004).

high, like the high plateaus bounding many present-day rift valleys, or uplifted at the time new continental margins were formed. Ollier and Pain (1997) suggest that the plateau surface may be equated with the break-up unconformity beneath marine sediments offshore.

In this situation offshore sediments may be used to determine time or times of uplift. Most passive margins appear to have two periods of movement, one around the time of creation of the new continental margin, and a later one.

Partridge (1998) has Mesozoic precursors for the landscape, and also Pliocene uplift of the South African high plains of up to 800 m. He wrote: «The evidence for large-scale Neogene uplift is now beyond question.» In Australia the eastern highlands are associated with a palaeoplain of Trias-Jura age (Hills, 1975). Uplift was attributed once to the Plio-Pleistocene 'Kosciusko Orogeny' (Andrews, 1910). This idea was replaced by general belief in Early Cenozoic uplift, but some movements of up to 1 km may have occurred in the Pleistocene (Ollier and Taylor, 1988). In Western India Widdowson and Gunnell (1999) showed several phases of laterite formation on the coastal plain. The elevation of the coastal laterite (up to 200 m) together with associated development of an entrenched drainage indicates that widespread uplift has affected the margin during Late Tertiary times.

In the Appalachians the palaeoplain might date back to the Cretaceous but there is also evidence of Miocene or younger uplift, especially in the Piedmont province (Pazzaglia and Gardner, 2000; Stanford *et al.*, 2001). The Scandinavian margin had continuous uplift from the Mesozoic, but in Southern Norway there was renewed uplift of about 1000 m in Neogene time (Lidmar-Bergström *et al.*, 2000; Lidmar-Bergström and Näslund, 2002). In Greenland the highest and oldest planation surface cuts across Late Miocene basalt, so uplift is later than that (Weidick, 1976).

The Transantarctic Mountains may have experienced major uplift since the Early or Middle Pleistocene (Behrendt and Cooper, 1991), or may have remained at their present level since the Miocene (Kerr *et al.*, 2000).

9.3. SIGNIFICANCE

9.3.1. Terminology and the nature of mountain uplift

The concept of mountain origin by plateau uplift affects even the very language that we use to describe mountains. The term 'orogeny' literally means the genesis of mountains, and when proposed

it meant just that. In later years the idea that folding and mountain building were the same thing became entrenched, and eventually 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 no longer means mountain building. For example, 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.» Unfortunately not all geologists are agreed on this, which leads to much confusion.

The nearest thing to an official definition is that of Jackson (1997): «[...] 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.»

In contrast to orogeny, early geologists used epeirogeny to mean the uplift of broad areas, as opposed to the narrow fold belts of mountain chains. I am here proposing 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.»

Most 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, distinguishing 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.

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

Because of the widespread assumption that folding and mountain building are the same thing, it is necessary to stress that folding and mountain uplift are quite different things. Both mountains and lowland plains can be underlain by folded or non-folded rocks. When folded rocks are found under a lowland plain nobody assumes the folding caused the plain! Why should the causal relationship be assumed with mountains?

Here is a summary of possible relationships: 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 Aus-

tralia); 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.

9.3.3. Classification of mountains

A traditional classification of mountains is something like this: fold mountains; fault block mountains; mountains made by erosion; volcanoes.

But if Ollier and Pain are right, there are no fold mountains. Folding precedes planation, and the process of folding does not make mountains.

The block fault mountain category is still valid.

The erosional mountains become a dominant type of mountain, and the degree of erosion determines whether a particular mountain group is a plateau, a dissected plateau, or a thoroughly dissected plateau.

Volcanoes are a separate class, and have been ignored in the present paper.

A descriptive classification of mountains might result in a list such as this: broad swells (Urals, Scandinavia); uplifted plateaus (Colorado, Kimberley); uplifted plateaus with spreading (Iran, Tibet); uplifted plateaus with spreading, and Central Graben (Andes); plateau margin ranges (Himalayas, Zagros); plateau uplift with gravity slides (New Guinea); tilt blocks (Sierra Nevada, Ruwenzori); uplifted plateaus with gravity disruption (Dolomites); passive margin warps (East Australian highlands, Drakensberg); volcanoes.

It is important to beware of over-simple classification, because it leads to over simple thinking, and obscures the wide variety of mountains in the real world. Plate tectonics demonstrates the danger of forcing mountain formation into preconceived theory.

9.3.4. Periodicity of uplift

In relation to the long-standing debate about whether there are distinct mountain-building periods or whether the process might be continuous through Earth history, the conclusion presented here suggests that at least the latest uplift was roughly synchronous over a large area of the world. We are seeing the results of a distinct and remarkably young mountain building period. This is a deviation from strict uniformitarianism.

Nevertheless there is some variation in the time of uplift. Passive margins frequently have an older uplift, possibly going back to the Early Tertiary or even Cretaceous, but they have also experienced Neotectonic uplift. In some instances this mountain uplift was preceded or accompanied by folding (Apennines, New Guinea), but in many other places it was not. Uplift of many mountains was synchronous: orogeny (in the sense of folding of rocks) was not. The folding of the Caledonian rocks of Scandinavia and Scotland is much older than the uplift that made the mountains. The structures in the Carpathians are much older than the Late Pliocene uplift that made the mountains.

Uplift occurred over a relatively short and distinct time. Some unknown process created mountains after a period with little or no significant uplift. This is a deviation from uniformitarianism.

The mountain building period is relatively short, and not on the same time scale as granite intrusion (which takes tens of millions of years), or plate tectonics which is supposedly continuous over hundreds of millions of years. The same rapid uplift occurs in areas where hypotheses such as mantle plumes are not appropriate. We do not yet know what causes this short, sharp period of uplift, but we can exclude naive mountain-building hypotheses that are on the wrong time scale.

For the past forty years plate tectonics has dominated geology, and the greatest single theme has been subduction, which allegedly formed both mountains and the structures within them. Subduction

may have a role in other studies, but because it is a continuous process that has allegedly operated for hundreds of millions of years, it is a most improbable mechanism to make mountains in a few million years, complete with their erosion surfaces. In areas of Plio-Pleistocene mountains there is no time for subduction to be an effective mechanism.

Most of the Plio-Pleistocene mountains are parts of what is generally referred to as the Alpine orogeny, including the Andes, the Himalayas, and the European Alps themselves. A few other mountain areas not regarded as 'Alpine' also have planation surfaces uplifted in the Pleistocene, such as the Urals, Ruwenzori, the ranges of Central Spain, and those of Central Asia. But in all cases the rock structures such as folds and faults were formed before the vertical uplift that actually formed the mountains.

9.3.5. Mountain building and climate change

The formation of mountains affects climate at both local, regional and global scales.

Simple elevation produces lower temperatures, induces orographic precipitation, produces of rain shadows, and affects wind circulation.

The Sierra Nevada is a tilted fault-block mountain range. At present the western side is humid, the high parts alpine and the eastern side is very arid, not far from Death Valley. In the Early Pleistocene a similar vegetation covered the whole region, a situation that could only exist if the present climatic barriers were absent, so the major uplift is well into the Pleistocene (Axelrod, 1962).

The Quaternary uplift of the Tibet Plateau and the Himalayas introduced a powerful new geographical factor in the pattern of world climate. Uplift of the Himalayan Range to its present 6000 m average elevation made it an effective climatic barrier, preventing warm, moist air from entering the Tibetan Plateau. Upheaval of the plateau essentially created the monsoons of East and South Asia (Manabe and Terpstra, 1974). The monsoon links the low pressure cell over the Tibet Plateau (India Low) to both the Pacific High and the Australia High, leading to inter-hemispheric temperature exchange, and so plays a part in global climate changes (Liu and Zhongli, 1998).

Astronomical causes such as Milankovich cycles may account for much of the glacial-interglacial change. But what caused the ice age in the first place? Perhaps mountain building is responsible.

9.3.6. Significance of still stands

Before most mountains were uplifted there was a period of tectonic stillstand or at least quietness when planation surfaces were eroded. We do not have much idea of how long it takes to form an erosion surface of low relief. Estimates are usually on the longer time scale, like those of Lester King who envisaged a series of planation surfaces initiated in the Cretaceous, Eocene, and Miocene. In other words he had whole geological periods to play with. It is generally thought, and supported by reported rates of erosion (*e.g.*, Young and Saunders, 1986) that erosion rates become slower as relief is reduced, and that to form a low relief planation surface takes many millions of years.

One of the biggest obstacles to our hypothesis of widespread Plio-Pleistocene mountain building is that the period of time available for the preceding planation is too short. Only further investigation can clarify this point.

9.4. CONCLUSIONS

Mountains are created by the vertical uplift of former plains, independent of any folding of the rocks underneath.

The age of mountains should therefore refer to the age of vertical uplift after planation, not to the last period of folding (if the underlying bedrock happens to be folded).

Most uplift occurred in the Plio-Pleistocene, or the very Late Miocene. The Neotectonic Period is demonstrated by the large amount of work listed in table 9.1.

Plate tectonics, the ruling theory of the past forty years, has no adequate explanation for the widespread planation in mountain regions, or the remarkably young uplift. Indeed it is based on an association of folding and uplift that is demonstrably untrue. Plate tectonics has no plausible explanation for mountains on passive margins or continental interiors.

From now on it is incumbent on those who propose models of mountain formation to do two things:

- Incorporate planation surfaces into the story (or prove there was no former planation).
- Either disprove the Neotectonic Period hypothesis, or show how their proposed mechanisms fit into the time scale of just a few million years.

REFERENCES

- ANDREWS, E.C. (1910): Geographical unity of Eastern Australia in Late and post Tertiary time, *J. Proc. R. Soc. N.S.W.*, **44**, 420-480.
- ATWOOD, W.W. (1940): *The Physiographic Provinces of North America* (Ginn, Boston), pp. 536.
- AXELROD, D.I. (1962): Post-Pliocene uplift of the Sierra Nevada, California, *Bull. Geol. Soc. Am.*, **73**, 183-198.
- BEHRENDT, J.C. and A. COOPER (1991): Evidence of rapid Cenozoic uplift of the shoulder escarpment of the Cenozoic West Antarctic Rift System and a speculation on possible climatic forcing, *Geology*, **19**, 315-319.
- BRIDGES, E.M. (1990): *World Geomorphology* (Cambridge University Press, Cambridge), pp. 260.
- BURG, J.P. and M. FORD (Editors) (1997): Orogeny through Time, *Geol. Soc. London, Spec. Publ.*, **121**.
- CALVET, M. (1994): Les Pyrénées Orientales, *These de Doctorat d'Etat* (Université de Paris I), (English abstract 31-38).
- CHAI, B.H.T. (1972): Structure and tectonic evolution of Taiwan, *Am. J. Sci.*, **272**, 389-422.
- CHINZEI, K. (1966): Younger Tertiary geology of the Mabechi River Valley, North-East Honshu, Japan, *J. Fac. Sci. Univ. Tokyo*, **16**, 161-208.
- CHUBERT, G. and A. FAURE-MURET (1974): Moroccan Rif, in *Mesozoic-Cenozoic Orogenic Belts*, edited by A.M. SPENCER (Sc. Acad. Press, Edinburgh), 37-46.
- COLTORTI, M. and C.D. OLLIER (2000): Geomorphic and tectonic evolution of the Ecuadorian Andes, *Geomorphology*, **32**, 1-19.
- COLTORTI, M. and P. PIERUCCINI (2000): A Late Lower Pliocene planation surface across the Italian Peninsula: a key tool in neotectonic studies, *J. Geodyn.*, **29**, 323-328.
- EARDLEY, A.J. (1963): Relation of uplifts to thrusts in Rocky Mountains, *Am. Assoc. Petrol. Geol. Mem.*, **2**, 209-219.
- EATON, G.P. (1987): Topography and origin of the Southern Rocky Mountains and Alvarado Ridge, in *Continental Extensional Tectonics*, edited by M.P. COWARD, J.F. DEWEY and P.L. HANCOCK, *Geol. Soc. London, Spec. Publ.*, **28**, 355-369.
- FARLEY, K.A., M.E. RUSMORE and S.W. BOGUE (2001): Post-10 Myr uplift and exhumation of the Northern Coast Mountains, British Columbia, *Geology*, **29**, 99-102.
- FÖLDVÁRY, G.Z. (1988): *Geology of the Carpathian Region* (World Scientific, Singapore), pp. 571.
- FOOSE, R.M. (1973): Vertical tectonism and gravity in the Big Horn Basin and surrounding ranges of the Middle Rocky Mountains, in *Gravity and Tectonics*, edited by K.A. DE JONG and R. SCHOLTEN, 443-455.
- GANSSE, A. (1991): Facts and theories on the Himalayas, *Eclogae Geol. Helv.*, **84**, 33-59.

- GAO, M.K. (1998): Late Cenozoic continental dynamics of East Asia, in *Proceedings of International Symposium on New Concepts in Global Tectonics*, Tsukuba, Japan (Organising Committee of International Symposium on New Concepts in Global Tectonics), 41-46.
- HERITSCH, F. (1929): *The Nappe Theory in the Alps*, translated by P.G.H. BOSWELL (Methuen, London), pp. 228.
- HILLS, E.S. (1975): *The Physiography of Victoria* (Whitcombe and Tombs, Melbourne).
- HO, C.S. (1986): A synthesis of the geological evolution of Taiwan, *Tectonophysics*, **125**, 1-16.
- HOLINGSWORTH, S.E. and R.W.R. RUTLAND (1968): Studies of Andean Uplift, Part 1. Post-Cretaceous evolution of the San Bartelo area, North Chile, *Geol. J.*, **6**, 49-62.
- HOLMES, A. (1965): *Principles of Physical Geology* (Nelson, London), 2nd edition, pp. 1288.
- HOSHINO, M. (1998): *The Expanding Earth: Evidence, Causes and Effects* (Tokai Univ. Press, Tokyo).
- HSÜ, K. (Editor) (1982): *Mountain Building Processes* (Academic Press, London), pp. 263.
- JACKSON, J.A. (1997): *Glossary of Geology* (American Geological Institute, Alexandria, Virginia), 4th edition, pp. 769.
- JACOB, A.F. (1983): Mountain front thrust, Southeastern Front Range and Northeastern Wet Mountains, Colorado, in *Rocky Mountain Foreland Basins and Uplifts*, edited by J.D. LOWELL (Rocky Mountain Assoc. Geol., Denver), 229-244.
- KALVODA, J. (1992): *Geomorphological Record of the Quaternary Orogeny in the Himalaya and the Karakoram* (Elsevier, Amsterdam), pp. 316.
- KERR, A., D.E. SUGDEN and M.A. SUMMERFIELD (2000): Linking tectonics and landscape development in a passive margin setting: the Transantarctic Mountains, in *Geomorphology and Global Tectonics*, edited by M.A. SUMMERFIELD (Wiley, Chichester), 303-319.
- KROONENBERG, S.B., J.G.M. BAKKER and M. VAN DER WIEL (1990): Late Cenozoic uplift and paleogeography of the Colombian Andes: constraints on the development of the high-andean biota, *Geol. Mijnbouw*, **69**, 279-290.
- LI, J. (1995): *Uplift of Qinghai-Xizang (Tibet) Plateau and Global Change* (Lanzhou University Press), pp. 207.
- LI, Y., J. YUNG, Z. XIA and D. MO (1998): Tectonic geomorphology in the Shanxi graben system, Northern China, *Geomorphology*, **23**, 77-89.
- LIDMAR-BERGSTRÖM, K. and J.O. NÄSLUND (2002): Landforms and uplift in Scandinavia, in *Exhumation of the North Atlantic Margin: Timing, Mechanisms and Implications for Petroleum Exploration*, edited by A.G. DORÉ, J.A. CARTWRIGHT, M.S. STOKER, J.P. TURNER and N. WHITE, *Geol. Soc. London, Spec. Publ.*, **196**, 103-116.
- LIDMAR-BERGSTRÖM, K., C.D. OLLIER and J.R. SULEBAK (2000): Landforms and uplift history of Southern Norway, *Global Planet. Change*, **24**, 211-231.
- LIU, T. and D. ZHONGLI (1998): Loess and palaeo-Monsoon, *Ann. Rev. Earth Planet. Sci.* 1998 (Annual Reviews Inc., Palo Alto).
- LOOMIS, F.B. (1937): *Physiography of the United States* (Doubleday Doran, Garden City, NY), pp. 350.
- LUCCHITA, I. (1979): Late Cenozoic uplift of the Southwestern Colorado Plateau and adjacent lower Colorado River region, *Tectonophysics*, **61**, 63-95.
- MANABE, S. and T.B. TERPSTRA (1974): The effects of mountains on the general circulation of the atmosphere as identified by numerical experiments, *J. Atmos. Sci.*, **31**, 3-42.
- MATHEWS, W.H. (1991): Physiographic evolution of the Canadian Cordillera, in *Geology of the Cordilleran Orogen in Canada*, edited by H. GABRIELSE and C.J. YORATH, *Geol. Surv. Canada, Geol. Canada No. 4*, 403-418.
- MIGON, P. and J. LACH (1999): Geomorphological evidence of neotectonics in the Kaczawa sector of the Sudetic marginal fault, Southwestern Poland, in *Late Cainozoic Evolution of the Sudeten and its Foreland*, edited by D. KRZYSZKOWSKI, *Geol. Sudetica*, **32**, 307-316.
- MORNER, N.A. (1993): Neotectonics and Palaeoclimate, in *Neotectonics Recent Advances*, edited by N.A. MORNER, L.A. OWEN, I. STEWART and C. VITA-FINZI, *Quat. Res. Assoc.*, Abstr. vol., p. 39.

- NITCHMAN, S.P., S.J. CASKEY and T.L. SAWYER (1990): Change in Great Basin tectonics at 3-4 Myr – A hypothesis, *Geol. Soc. America Abstr., Cordilleran Section*, **33** (3), p. 72.
- OLLIER, C.D. (2004): The evolution of mountains on passive continental margins, in *Mountain Geomorphology*, edited by O. SLAYMAKER and P.N. OWENS (Allen and Unwin, London), 59-88.
- OLLIER, C.D. and C.F. PAIN (1988): Morphotectonics of Papua New Guinea, *Z. Geomorphol. Suppl.*, **69**, 1-16.
- OLLIER, C.D. and C.F. PAIN (1997): Equating the basal unconformity with the palaeoplain: a model for passive margins, *Geomorphology*, **19**, 1-15.
- OLLIER, C.D. and C.F. PAIN (2000): *The Origin of Mountains* (Routledge, London), pp. 345.
- OLLIER, C.D. and C.F. PAIN (2001): The Neotectonic Period, *New Concepts in Global Tectonics*, **20**, 14-16.
- OLLIER, C.D. and D. TAYLOR (1988): Major geomorphic features of the Kosciusko-Bega region, *BMR J. Aust. Geol. Geophys.*, **10**, 357-362.
- OTUKA, Y. (1933): The Japanese coastline, *Geogr. Rev. Jpn.*, **9**, 819-843.
- PARTRIDGE, T.C. (1997): Late Neogene uplift in Eastern and Southern Africa, in *Tectonic Uplift and Climate Change*, edited by W.F. RUDDIMAN (Plenum Press, NY), 63-86.
- PARTRIDGE, T.C. (1998): Of diamonds, dinosaurs and diastrophism: 150 Myr of landscape evolution in Southern Africa, *S. Afr. J. Geol.*, **101**, 167-184.
- PAZZAGLIA, F.J. and T.W. GARDNER (2000): Late Cenozoic landscape evolution of the US Atlantic passive margin: insights into a North American Great Escarpment, in *Geomorphology and Global Tectonics*, edited by M.A. SUMMERFIELD (Wiley, Chichester), 223-302.
- PICKFORD, M., B. SENUT and D. HADOTO (1993): Geology and palaeobiology of the Albertine Rift Valley Uganda-Zaire, *CIFEG Occas. Publ.* **24**, vol. 1.
- PRIEST, G.R., N.J.M. WOLLER, G.L. BLACK and S.H. EVANS (1983): Overview of the geology of the Central Oregon Cascade Range, in *Geology and Geothermal Resources of the Central Oregon Cascade Range*, edited by G.R. PRIEST and B.F. VOGT, *Oreg. Dep. Geol. Miner. Ind. Spec. Pap.* **15**, 3-28.
- RĂDOANE, M., N. RĂDOANE and D. DUMITRU (2003): Geomorphological evolution of longitudinal river profiles in the Carpathians, *Geomorphology*, **50**, 293-306.
- RUTTEN, M.G. (1969): *The Geology of Western Europe* (Elsevier, Amsterdam), pp. 520.
- SALA, M. (1984a): Pyrenees and Ebro Basin Complex, in *Geomorphology of Europe*, edited by C. EMBLETON (Macmillan, London), 269-293.
- SALA, M. (1984b): The Iberian Massif, in *Geomorphology of Europe*, edited by C. EMBLETON (Macmillan, London), 294-322.
- SALA, M. (1984c): Baetic Cordillera and Guadalquivir Basin, in *Geomorphology of Europe*, edited by C. EMBLETON (Macmillan, London), 323-340.
- SCHAEER, J.P. and J. ROGERS (1987): *The Anatomy of Mountain Ranges* (Princeton Univ. Press, Princeton, NJ), pp. 298.
- SCHRODER, J.F. (1993): *Himalaya to the Sea* (Routledge, London), pp. 432.
- SPENCER, E.W. (1965): *Geology: a Survey of Earth Science* (Crowell, NY), pp. 429.
- STANFORD, S.D., G.M. ASHLEY and G.J. BREMNER (2001): Late Cenozoic fluvial stratigraphy of the New Jersey Piedmont: a record of glacioeustasy, planation and incision on a low-relief passive margin, *J. Geology*, **109**, 265-76.
- STILLE, H. (1936): The present tectonic state of the Earth, *Bull. Am. Assoc. Petrol. Geol.*, **20**, 849-80.
- STRECKER, M.R., G.E. HILLEY, J. RAMON-ARROWSMITH and I. COUTANDI (2003): Differential and geomorphic mountain-front evolution in an active continental collision zone: the Northwest Pamir, Southern Kyrgyzstan, *Bull. Geol. Soc. Am.*, **115**, 166-181.
- SUGGATE, R.P. (1982): The geological perspective, in *Landforms of New Zealand*, edited by J.M. SOONS and M.J. SELBY (Longman Paul, Auckland), 1-13.
- SUGIMURA, A. and S. UYEDA (1973): *Island Arcs: Japan and its Environs* (Elsevier, Amsterdam), pp. 247.

- SUSLOV, S.P. (1961): *Physical Geography of Asiatic Russia* (W.H. Freeman, San Francisco), pp. 594.
- THORNBURY, W.D. (1965): *Regional Geomorphology of the United States* (Wiley, NY), pp. 609.
- TRIMBLE, D.E. (1980): Cenozoic tectonic history of the Great Plains contrasted with that of the Southern Rocky Mountains: a synthesis, *Mt. Geol.*, **17**, 59-69.
- TRUMPY, R. (1980): *An Outline of the Geology of Switzerland* (Wepf, Basel), pp. 280.
- UFIMTSEV, G.F. (1990): Morphotectonics of the Baikal rift zone (U.S.S.R.), *Geogr. Fis. Dina. Quat.*, **13**, 3-22.
- WALKER, E.H. (1949): Andean uplift and erosion surfaces near Uncia, Bolivia, *Am. J. Sci.*, **247**, 646-663.
- WEIDICK, A. (1976): Glaciation and the Quaternary of Greenland, in *Geology of Greenland*, edited by A. ESCHER and W.S. WARR, *Geol. Surv. Greenland Odense*, 431-458.
- WIDDOWSON, M. and Y. GUNNEL (1999): Lateritization, geomorphology and geodynamics of a passive continental margin: the Konkan and Kanara coastal lowlands of Western Peninsular India, *Int. Assoc. Sedimentol., Spec. Publ.*, **27**, 245-274.
- WU, Y., Z. CUI, G. LIU, D. GE, J. YIN, Q. XU and Q. PANG (2001): Quaternary geomorphological evolution of the Kunlun Pass area and uplift of the Qinghai-Xizang (Tibet) Plateau, *Geomorphology*, **36**, 203-216.
- YOUNG, A. and J. SAUNDERS (1986): Rates of surface processes and denudation, in *Hillslope Processes*, edited by A.D. ABRAHAMS (Allen and Unwin, Boston), 3-27.
- ZHANG, D.D. (1998): Geomorphological problems of the middle reaches of the Tsangpo River, Tibet, *Earth Surface Processes and Landforms*, **23**, 889-903.
- ZHENG, H., C.M. POWELL, Z. AN, J. ZHOU and G. DONG (2000): Pliocene uplift of the Northern Tibetan Plateau, *Geology*, **28**, 715-718.
- ZUCHIEWICZ, W. (2000): Morphotectonics of the outer East Carpathians of Poland in the light of cartometric studies, *Stud. Geomorphol. Carpatho-Balcanica*, **34**, 5-26.