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Plenary Lecture

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GEOMORPHOLOGY AND MOUNTAIN BUILDING

1. INTRODUCTION

The greatest need in morphotectonics is to divorce mountain building from compression and folding, which are almost universally assumed, and from subduction which is almost as pervasive. At an elementary level subduction is supposed to provide a mechanism that folds rocks and creates mountains simultaneously (fig. 1a). More sophisticated models (fig. 1b) may cause underthrust faults near the subduction site, thrust faults in the opposite direction in remote parts, and even tensional fractures either parallel or perpendicular to the direction of compression.

Geophysicists and tectonic geologists often invoke uplift (for example over subduction sites or thermal domes) without any consideration of actual landforms. Instead of accepting these orthordox but wild ideas, it would be good if geomorphologists could start from their own basic data in the study of mountains.

Changes in elevation and slope, planation surfaces, drainage patterns, and the distribution of regolith are the most obvious data to constrain tectonic theories. Planation surfaces indicate long periods of tectonic stability. Whenever present, such surfaces deny simultaneous folding and uplift, commonly assumed in hypotheses of compressional mountain building. Through feedback processes such as isostatic response and gravity spreading, some tectonic processes are actually driven by erosional processes.

Nearly all modern books on mountain-building and orogeny are confused about the mountains themselves. Hsu's *Mountain Building Processes* (1982) is all about structures and it is simply assumed that "orogeny" creates both internal structures and the present-day topographic mountains. Only Gansser, in his chapter on the «morphogenetic phase» of mountain building, distinguishing the late, verti-

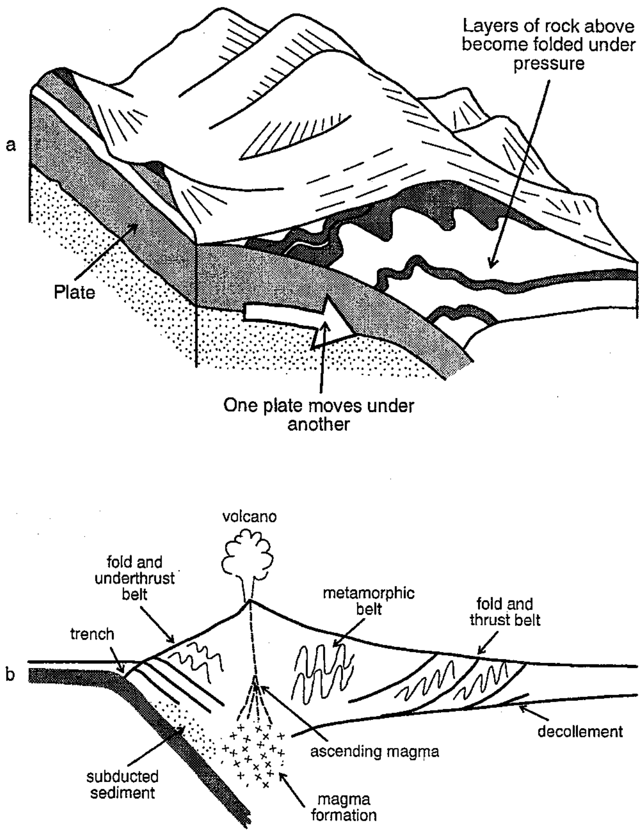

FIG. 1 a) - Elementary diagram of subduction causing simultaneous folding and mountain building; b) More elaborate figures of subduction causing mountains and other structures. Note the symmetrical structure despite the one-sided subduction.

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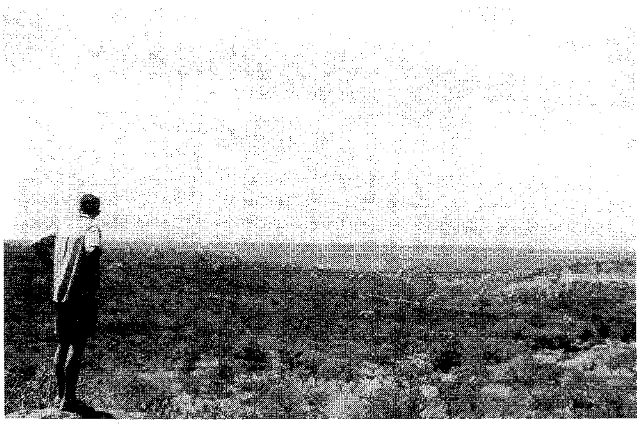
cal mountain building from earlier compression. Schaer and Rogers' (1987) book *The Anatomy of Mountain Ranges* is likewise about internal structures, tacitly assumed to be related to present day mountains. Orogeny is still equated with mountain building by many geologists, though in *Orogeny Through Time* Burg and Ford (1997) claim that «To field geologists the term orogeny represents a penetrative deformation of the Earth's crust». Few geologists really appreciate this not-so-subtle change of meaning.

1.1 Structure and surface

The plains of Western Australia and Africa are about as flat as any erosional land surface can get (fig. 2a). Very complex structures including folds, faults and highly sheared metamorphic zones underlie the plains (fig. 2b). 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. 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

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 long period of tectonic stability, to allow sufficient erosion. Uplift is vertical. 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.

Many "mountain ranges" are dissected plateaus, modified in some instances by other processes. The implications of this are illustrated by the following examples.



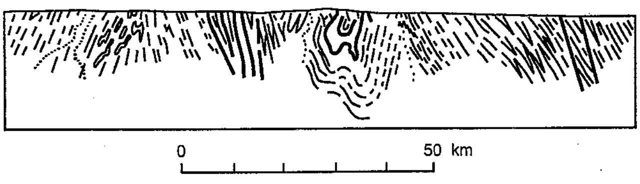


FIG. 2 a) - The Acholi Plains, a planation surface in northern Uganda (photo C.D. Ollier); b) A typical cross section in northern Uganda (J.V. Hepworth, pers. comm).

2. EXAMPLES

2.1 The Kimberley and Carr Boyd Ranges

The Kimberley Plateau in northwest Australia is underlain by gently folded sandstones and shales of Proterozoic age. The rocks were planated, and broad bevels are cut across the hard rocks (fig. 3). The plateau was uplifted, and softer rocks were eroded to form broad valleys. Nearby the Carr Boyd Ranges are strike ridges of more steeply dipping, folded rocks. The bevelled cuestas (fig. 4) are clear indications of an old planation surface, for there is no mechanism to erode flat surfaces across the hardest rocks *after* uplift and incision of valleys. The ancient Kimberley Plateau had already formed and been partly dissected by the time of a Proterozoic Glaciation, and has been a land area ever since (Ollier & *alii*, 1988).

2.4 The European Alps

The next stage of complication occurs when the planation surface is largely destroyed, as in the European Alps.

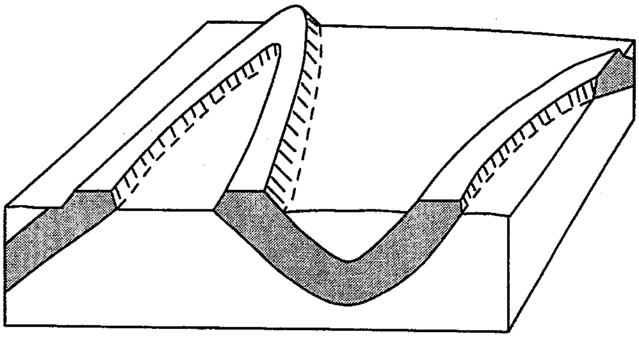


FIG. 3 - Diagram of planation cut across folded rocks, forming bevelled cuestas.

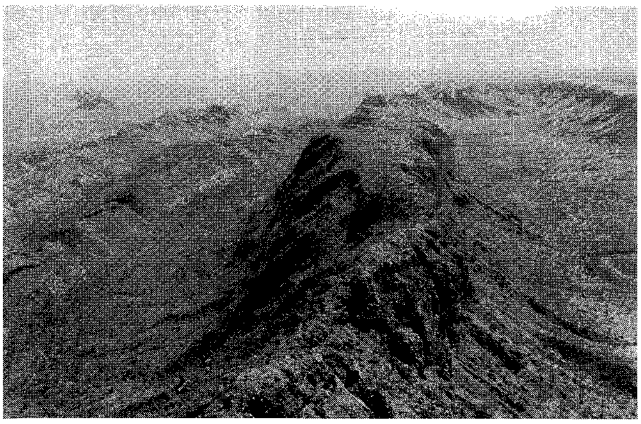


FIG. 4 - A bevelled cuesta, Carr Boyd Ranges, Western Australia. Note how the bevel can be traced around the nose of the anticline (photo C.D. Ollier).

This is, of course, the area where great battles were fought over nappe theory, those vast sheets of rock that were thrust for great distances. It seems to be generally forgotten that these nappes have very little to do with the present Alpine topography. The whole region was planated in the Pliocene, and then broadly uplifted and eroded to the present spectacular topography (fig. 5). The old erosion surface has virtually gone, but is preserved as the *Gipfelflur* or summit level (Heim, 1927; Rutten, 1969).

This idea is not new, and was described, for example, by Heritsch (1929) who wrote: (p. 194.)

«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».

Plate tectonic models applied to the Alps mean to explain the topography as well as the structures. Dewey & *alii* (1973), for example, claim «The contemporary Alpine system develops a spectrum of stages in the building of mountain belts... the Alpine system is the result of activity of accretiing, transfer and subducting plate boundaries between Europe and Africa». They totally ignore the planation, so do not explain why uplift occurred so long after collision, or why tectonic movement apparently ceased during erosion of the summit surface.

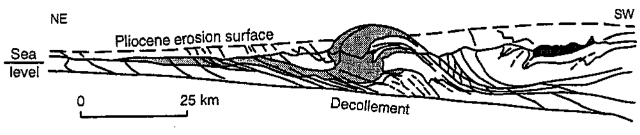


FIG. 5 - Cross section of the Alps. The wonderful nappe structures were planated before the uplift of the present mountain mass (simplified after Spencer, 1965).

FIG. 6 - A SW to NE section of the Apennines, starting south of Naples. Several nappes are thrust against the foreland in the NE, but the whole has been eroded and affected by normal faults which creates the present topography. The three shaded layers on the foreland (right) are Cretaceous, Jurassic, Triassic. The same sequence is repeated in the upper nappe in the SE. The cross-stippled layer beneath it is another nappe with rocks of the same age (simplified after a section in Cassano & *alii*, 1986).

2.5. *The Apennines*

Like the Alps, the Apennines of Italy are built of stacks of largely horizontal rocks (nappes) that were thrust for over a hundred kilometres (fig. 6). But the thrusts did not make the mountains! After the thrusting of nappes there was a period of planation, with gentle surfaces cutting across rock structures (Demangeot, 1965). Regardless of arguments about the age and perfection of the planation surfaces, the old structures associated with the nappes are eroded, and vertical uplift made the present Apennines mainly in the last 2 million years.

The drainage pattern (fig. 7) reveals an interesting feature of the tectonic geomorphology. On the Adriatic side there is a simple parallel drainage, initiated on a simple

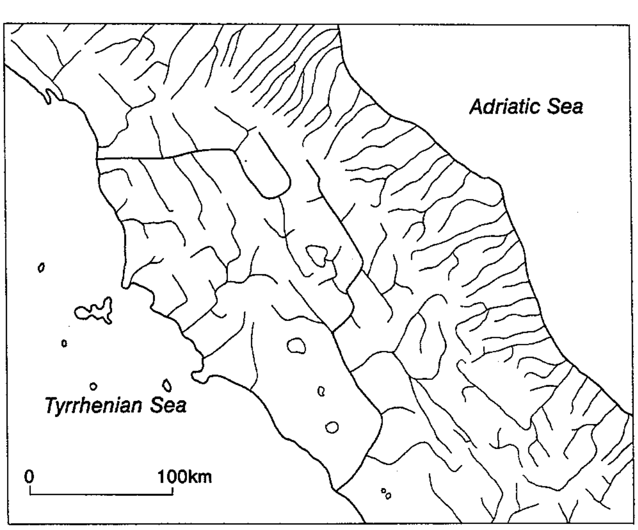


FIG. 7 - Drainage pattern of the central Apennines. Note the angular drainage on the western side, associated with normal faulting after nappe thrusting (simplified after Mazzanti & Trevisan, 1978).

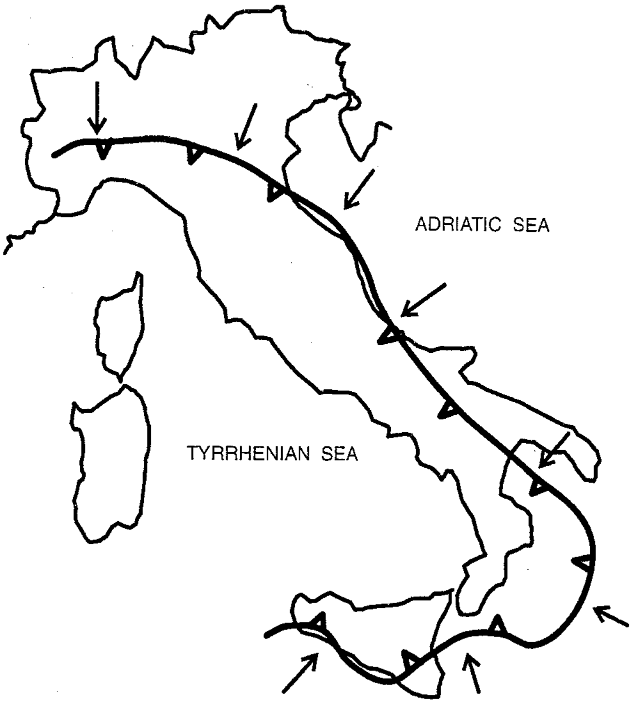


FIG. 8 - The Apennine nappe front. If subduction created the Apennines, as commonly assumed, it must have come from many convergent directions.

planation surface. Most of western Italy has an angular drainage pattern related to post-nappe normal faults, so it is post-nappe tectonics that controls the topography by dividing it into a series of fault blocks.

The nappe front is generally thought to be due to subduction, but makes a huge arc (fig. 8). There are proponents for subduction from almost all quaters. Directions range from north to south, which gives a space problem where all these underthrust rocks converge at depth. Tectonic spreading from an uplifted centre might be a more feasible explanation. Many hypotheses relate uplift to collision of Europe with Africa, but how could such a collision make an east-facing arc, and why did the landscape-forming uplift occur so much later than any possible collision?

Another interesting feature is the relationship between the Northern Apennines and the Southern Alps. As shown in fig. 9, the Apennine nappes are approaching the Po Basin from the south and the nappes of the Southern Alps approaching from the north, apparently on a collision course. But the apparent collision by no means gives rise to compression and mountain building. The Po Basin has been subsiding since the early Tertiary, and has level sediments. It does not seem plausible to subduct Italy under the Alps or the Alps under the Apennines. The Alps have also been attributed to collision of Africa and Europe, but the Po Valley does not seem to be a good contender for the site of the subduction suture.

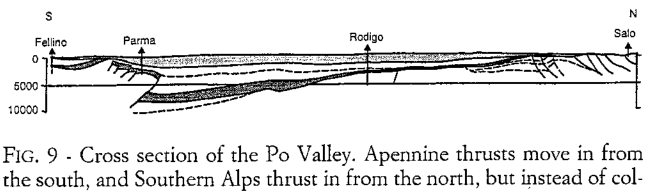


FIG. 9 - Cross section of the Po Valley. Apennine thrusts move in from the south, and Southern Alps thrust in from the north, but instead of collisional compression there is subsidence and horizontal sedimentation. Upper shaded layer is Quaternary: lower shaded layer is Upper Miocene sediment. Bedrock is Mesozoic (simplified after a section in Cassano & *alii*, 1986).

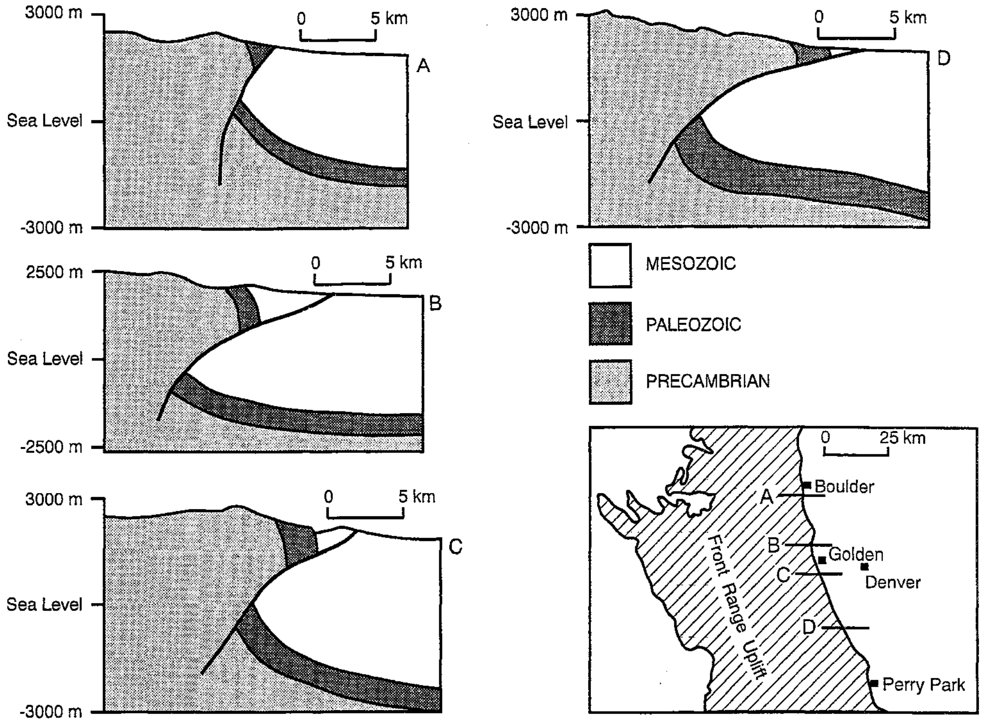
2.2 *Rocky Mountains and Plateaus of North America*

North American uplifts illustrate the next complication, which is tectonic spreading after plateau uplift. Many mountain regions in North America are plateaus, and some are known by name as such. At the close of the Cretaceous the Colorado region was nearly at sea level and was raised about 2000 m in two pulses, one in the late Miocene to Pliocene, and the second late Pliocene to present to form the Colorado Plateau. North of the Colorado Plateau the Uinta Mountains provide a classic example of a horst uplift bounded by reverse faults, showing that the rocks of the Precambrian core "bulged outward as they ascended". (Holmes, 1965). Post-uplift spreading has been described around numerous other plateaus. Excellent examples from New Mexico are provided by Woodward (1983) who wrote "The Nacimiento uplift of Cenozoic age is bounded on the west side by thrust and reverse faults that have resulted in yielding of the uplift westward over the San Juan basin" and "... anticlines along the eastern edge of the San Juan basin have been refolded... and have been overridden by the uplift". The Front Range on the western edge of the Rocky Mountains is overthrust (fig. 10), but so also is the eastern side. Jacob (1983) used the phrase "mushroom tectonics" to describe this phenomenon, and illustrated it by an example from the Front Range between South Park and the Denver Basin (fig. 11). Many other places known as ranges or mountains were also planated, and the Rocky Mountain Peneplain was one of the first peneplains ever described.

2.3 *The Andes*

The Andes provide the prime example of mountains supposedly formed by subduction and compression, but planation surfaces, cut across folded bedrock, dominate much of the landscape (figs. 12, 13). In Ecuador, for example, planation surfaces cut both the Eastern and Western Cordillera which are both underlain by folded bedrock. The Inter-Andean depression, a graben, lies between them. The planation surface is dated by ignimbrite, which covers parts of the planation surface but does not fill the depression, at about 6 million years. The formation of the Inter-Andean depression and the major uplift of the Cordillera is mainly Plio-Pleistocene, that is from about 5 million years ago to today. Similar planation surfaces with ignimbrites dated at about 7 Ma are found in Bolivia (Kennan & *alii*, 1996; Lamb & *alii*, 1997); planation surfaces of Plio-

FIG. 10 - Overthrusts on the Front Range of the Rocky Mountains (after Bieber, 1983).



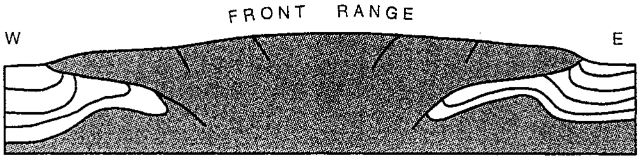


FIG. 11 - Sketch section of 'mushroom tectonics' as applied to the Front Range, Colorado, with Precambrian rocks (shaded) spreading over younger rocks on both sides (after Jacob, 1983).

Pleistocene age are reported from Colombia (Kroonenberg, 1990) and planation surfaces of about the same age are prevalent through much of the Andes.

FIG. 12 - The Andean planation surface near Cuenca, Ecuador (photo C.D. Ollier).

The Andes are possibly another example of tectonic spreading, for thrust diverge from the centre of the Andes (fig. 13). The coastal one is easily explained by subduction. The other side is explained by subduction of Brazil under the Andes, or by less specific "underthrusting" from the east, or by thrusting that is in some way connected with the Pacific subduction as in fig. 1b. An alternative is that the Andes are spreading like the uplifts in North America described earlier.

It is interesting to contrast these young ages of uplift with the 200 million year span for which alleged subduction has been occurring in South America (Burg and Ford, 1977, p. 13). The conventional wisdom is that the Andes were made by subduction of the Pacific, but why did uplift wait for millions of years? How did a pause in tectonics occur to allow planation? And what really caused the young, symmetrical vertical uplift?

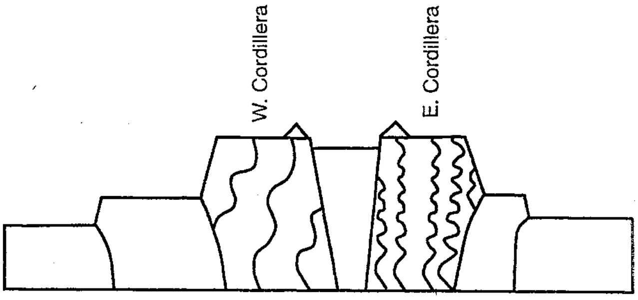


FIG. 13 - Diagrammatic cross section of Ecuadorian Andes. An originally simple horst and graben structure has been complicated by tectonic spreading.

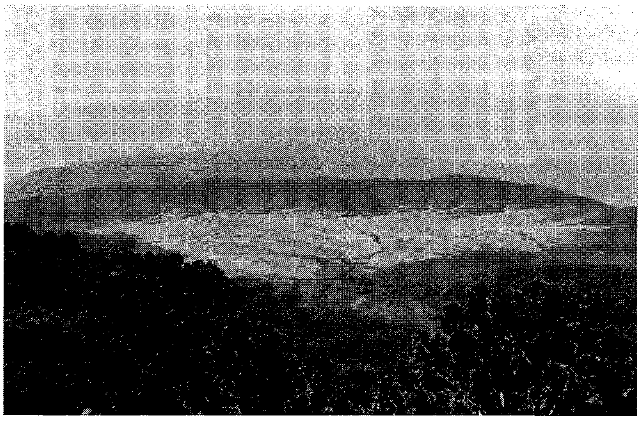


FIG. 14 - Photograph of the arched summit erosion surface, Owen Stanley Mountains (photo C.F. Pain).

2.6 The Owen Stanley Range

Papua New Guinea provides a further complication in mountain building, gravity sliding. The highlands of Papua New Guinea are generally envisaged as rugged mountains, but this is not always so. The core of old rock that was uplifted to make the spine of Papua New Guinea is an arched plateau. Part of this is known as the Owen Stanley Range (fig. 14). Löffler (1974) wrote that relict surfaces are widespread in the Owen Stanley Ranges, mainly on the principal watershed but also on some offshoot divides. Pain (1983) wrote «The Sogeri Plateau is the largest remnant of a once much larger erosion surface that may have extended over much of the Owen Stanley Ranges». Basalt overlying the Sogeri Plateau gave a K/Ar age of 5.7 million years. In the Milne Bay area the uplifted plateaus were formed in the Pleistocene (Smith & Simpson, 1972). Thus we have the familiar story of planation and young uplift, even in an area which most authors still regard as a classic site for subduction-made mountains. The Papuan Fold Belt, to the south of the axis of uplift, results from gravity sliding of Mesozoic and Tertiary sedimentary rocks away from this axis of uplift (Jenkins, 1974; Findlay, 1974). The folded rocks are separated by a decollement from the unfolded bedrock beneath. The fanciful plate tectonic scenarios that allegedly explain the mountains of Papua New Guinea (e.g. Ripper & McCue, 1982; Burchfiel, 1983) pay scant regard to bedrock geology or geomorphology (fig. 15).

2.7 The Tibet Plateau and the Himalayas

A further complication in mountain building is isostatic response to erosion. This is best illustrated by the Himalayas, but to explain the situation the Himalayas are considered together with the Tibet Plateau.

Tibet has two major planation surfaces. The highest is called the Peak surface, and the lower the Main surface (Li & *alii,* 1995). The Peak Surface was complete in the late Eocene. The distribution of giant rhinoceros and other fossils shows mountain barriers were lacking at that time, when altitude was low and the climate warm. Remnants of the Peak Surface are now preserved as plateaus, some of which have ice caps.

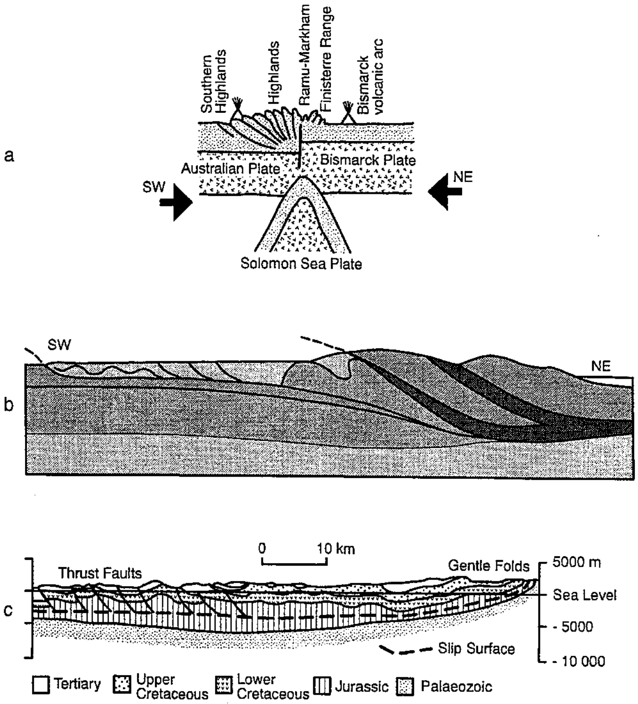


FIG. 15 - Cross sections of New Guinea mountains: a) Collision of the Bismarck Plate and the Australian Plate, pushing down the Solomon Plate (after Ripper and McCue, 1982). The Papuan Fold Belt is at top left; b) .Subduction of the Australian Plate and the Pacific Plate (after Burchfiel, 1983). The Papuan Fold Belt is at top left; c) A real cross section of the Papuan Fold Belt based on drilling (Findlay, 1974). The folds result from gravity sliding after vertical uplift of the highland zone to the right.

Uplift occurred in the Middle Miocene and a new planation surface was formed, the Main Surface, graded in part to Pliocene intermontane basins. Again warm and humid conditions prevailed, associated with tropical to subtropical forest and grassland, and there were no significant barriers (such as mountains) to migration of hipparion, rhino and giraffe. Throughout most of the Pliocene the Tibet region was not a highland but a peneplain with elevation not more than 1000 m. Today the Main surface is well-preserved but dissected into plateaus of tens to hundreds of km^2.

Intense uplift of the Tibet Plateau began about 3.4 Ma, called the Quinzang movement. The movement is divided into 3 phases:

A 3.4 Ma; B 2.48 Ma; C 1.8 Ma

Phase B corresponds to the initiation of a monsoon climate and the start of loess deposition in China.

These dates can be contrasted with the date of the initial collision of India with Asia, about 50 Ma, which is far too old to be the cause of the uplift.

A significant feature of the two planation surfaces is that they have least difference in elevation in the middle of

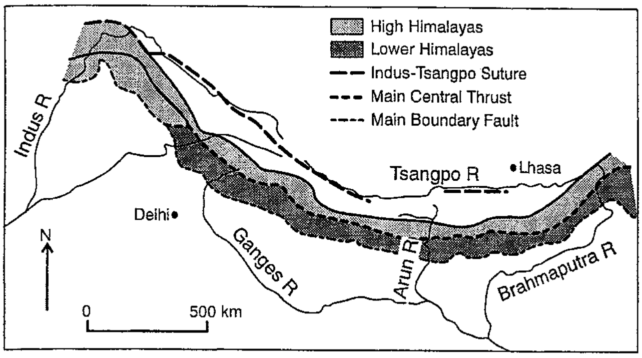


FIG. 16 - Map of mountains and major faults in the Himalayas.

the plateau and greatest (up to 1000 m) at the borders. This shows that the uplift of the edges is not the same as that of the interior of the Plateau and may have a different cause.

The southern edge of the Tibetan plateau is marked by the great arc of the Himalayas and several major boundaries (fig. 16). The Indus-Tsangpo suture zone in southern Tibet is supposed by many to mark the site where the Indian continent has been subducted under Asia. Two significant lines farther south are the Main Central Thrust and the Main Boundary Fault. The High Himalayas lie north of the Main Central Thrust, and the Lower Himalayas between it and the Main Boundary Fault.

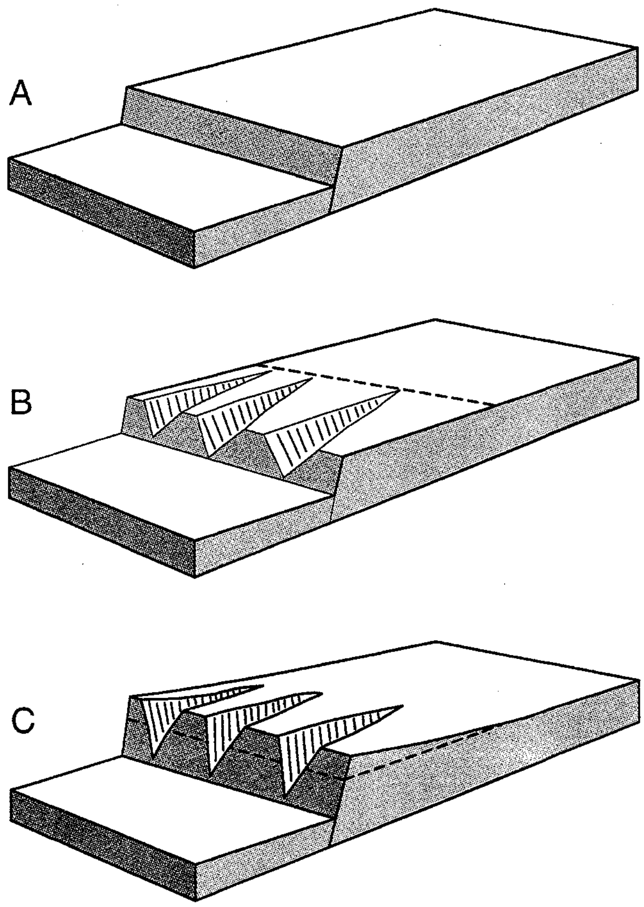


FIG. 17 - Diagram of isostatic response to erosion at the edge of a plateau.

There is now no trace of a planation surface in the Himalayan region, but clues to its origin come from the drainage that crosses it. Rivers such as the Indus, Brahmaputra and Arun rise on the Tibetan Plateau and flow through the much higher Himalayas in deep gorges. The Himalayas are not just the world's highest mountains, but also have the deepest valleys - deep enough to cause isostatic compensation.

The hypothesis of isostatic uplift of the Himalayas (Wager, 1937) starts with a simple uplifted plateau, an extension of the Tibet Plateau (fig. 17 a). Erosion was greatest on the plateau edge and cut huge valleys, deep enough to cause isostatic compensation. Considered as a whole, the belt of valleys will be uplifted (fig. 17 b). Since the uplift is general, the interfluves, and individual peaks, will rise above the height of the original plateau (fig. 17 c). In this way the Himalayas rise to be higher than the Tibetan plateau.

Linking this story of isostatic uplift of the Himalayas to the Tibetan Plateau, it is interesting to recall that the erosion surfaces on the Plateau diverge in elevation towards the Himalayas, which fits exactly the concept of erosion accompanied by isostatic uplift.

This model can be tested by topographic analysis. If the uplift of the Himalayas results from isostatic uplift in response to erosion, the average height of the Himalayas should be the same as that of the Tibetan Plateau: if there is an external force causing uplift (such as granite intrusion or pressure from a northward-migrating India) there would be no such accord. Remarkable confirmation comes from the morphometric work of Bird (1973). He carefully derived a composite mean elevation profile across the Himalayas and Tibet (fig. 18). The result was a remarkably uniform mean elevation of 5 km throughout. As he expressed it (p. 4979) «This uniformity suggests that some deeper layer of the crust is weak... It can be seen that the high peaks of the Himalayas result from adjacent deep erosion of its valleys [Wager, 1937] rather than from any maximum in the average elevation».

An individual large valley might have its own isostatic compensation, as shown in fig. 19. Isostatic uplift will cause more uplift along the valley than on the plateau as a whole. If the present topography is extrapolated across the valley, it appears that the valley has cut through a ridge.

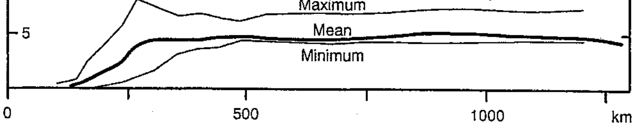


FIG. 18 - Composite mean elevation profiles of the Himalayas and Tibet, after Bird, 1973. The continuation of the same mean level from Tibet to the Himalayas suggests simple isostatic uplift.

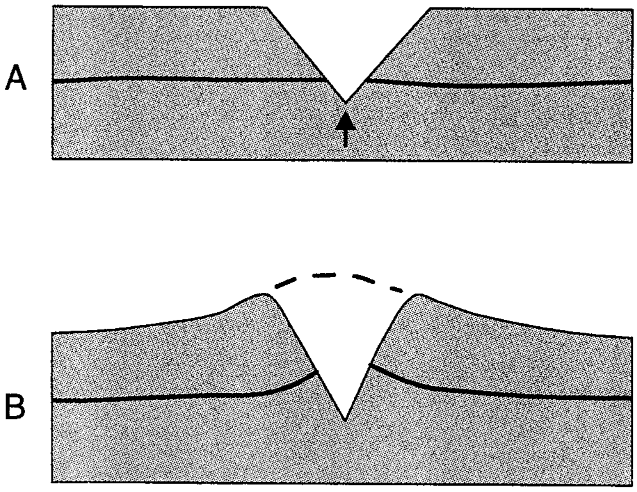


FIG. 19 - Isostatic uplift of a single major valley: a) Before isostatic response; b) after isostatic response. Because of uplift of the edges, the valley appears to flow along an anticline and across the highest part of the topography.

This situation was noted by the observant Scottish novelist John Buchan (1924, 27) who wrote:

«Curiously enough, the rivers which break through the Himalaya chose the highest parts of the range through which to cut. South of Pemakochung is the great peak of Namcha Barwa, 25, 445 feet high; north of it is the peak of Gyala Peri, 23, 400 feet. The distance between these mountains is only some fourteen miles, and through this gap, at an altitude of just under 8,000 feet, flows the great river». (The gorge is about 5 km deep and 23 km wide, which can be compared with the Indus Gorge which is 6 km deep and 21 km wide at Nanga Parbat).

Isostatic uplift along the valley not only makes a topographic high, but affects the geological structure to make a mappable anticline. Ohita (1973, p. 5) describes the Arun valley as «a deep valley, cutting along the axial zone of the Arun anticline». Ishida & Ohita (1973, p. 60) described the structure of part of Nepal where the gneiss strikes NW-SE and dips N at 30°. On this broad structure another fold trend of NE-SW is superposed. «The antiforms are located along the large river, such as the Tamba, Kosi, the Khinti Khola, the Likhu Khola and the Dudh Kosi». Furthermore the anticlines are narrow and sharp, while the synforms between the major valleys are all open folds. This is precisely what would happen with isostatic uplift along the valleys. Tectonically it is very difficult to make these folds that are parallel to the main direction of tectonic movement, and geomorphically it is difficult to locate all the large rivers on tectonically formed anticlines.

Buchan also noted that the Brahmaputra «breaks through the highest range on the globe...by means of a hundred miles of marvellous gorges, where the stream foams in rapids, but there is no fall more considerable than can be found in many a Scottish salmon river». In geomorphic terms, there are no major nick points, or in scenic terms no great waterfalls. With major scarp retreat, or river capture, these are to be expected, but with an antecedent stream they are unlikely to form. This is why the world's greatest waterfalls occur on rivers that fall over Great Escarpments (described later) and not on antecedent rivers.

Many scientists have concluded that the Himalayas are formed by vertical uplift rather than compression. Crawford (1974, p. 373) wrote «The great height of the present-day Himalaya is quite unrelated to their original formation as a geological structure. Least of all is it directly related to Tertiary collision». Ohte (1973 writing of Nepal noted: «The present height of the Great Himalayas has been resulted from block upheavals of this range in the younger geologic periods since Cretaceous...» (p. 255). The Great Himalayas...have resulted from... block movement with vertical displacement and not from the Alpine folding. No nappe structures can be found in Central and Western Nepal» (p. 258). «Even the Main Central Thrust and the Main Boundary Thrust were generated in relation to this vertical block movement» (p. 257).

Further detail of the vertical movement is provided by the long profiles of sixteen trans-Himalayan rivers (Seeber & Gornitz, 1983). North of the Main Central Thrust, in the High Himalayas, the rivers have steep gradients. Downstream, they have gentle gradients, and are not affected by the Main Boundary Fault. This shows that the increased gradients result from differential uplift of the High Himalayas, as we might suspect from the mountains themselves. We thus have a picture of the long and narrow arc of the High Himalayas being uplifted vertically during the Quaternary. The Main Central Thrust is the southern limit of uplift rather than the Indus-Tsangpo suture, and the Main Boundary Fault has little topographic importance.

The model suggested here is of isostatic uplift of the edge of the Tibet Plateau to form the High Himalayas. If this is correct, a further conclusion can be drawn. Since the Himalayan uplift relates to the uplift of Tibet it must be the same age or a little younger. This means the uplift started at 3.4 Ma, and is largely Quaternary. This has enormous impact on climatic change, both locally and globally, and may be the trigger to the Ice Age.

Because the underthrusting hypothesis is so entrenched, a few non-geomorphic extra details are elaborated here. The conventional wisdom is that the uplift of Tibet and the Himalayas results from the underthrusting of India under Asia, a thrust of over 2000 km (Burchfiel, 1983) in 50 million years. Why did uplift wait 47 million years to happen, and why were there two still-stands to allow formation of planation surfaces in Tibet? The underthrusting of India under Asia would surely require a low angle contact, but Hirn & *alii* (1984) found that the fault limiting the Lhasa block [the Indus-Tsangpo suture] is a vertical contact. They wrote «the exact coincidence of the Moho step with the edge of the Gandise granitic belt... points to a vertical contact of crustal segments».

As for timing, Burg & Chen (1984) note that «significant crustal shortening was completed by the Palaeocene». In other words crustal shortening had finished long before vertical uplift started. With even more significance to ideas

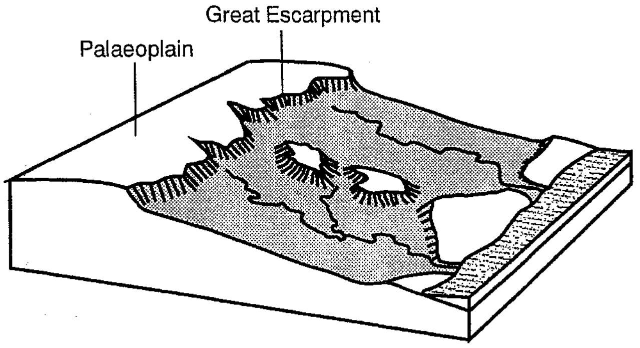


FIG. 20 - Topographic features of passive continental margins (after Ollier and Pain, 1997).

of India being thrust under Asia they write that «... the crust of the Lhasa Block might have been thickened *before* the India-Asia collision» (my italics).

2.8 *Passive Margins with Great Escarpments*

Finally we come to a group of mountains generally ignored in plate tectonic theory, because subduction is impossible - the mountains on passive margins. The Drakensberg, the Western Ghats, the Eastern Highlands of Australia and the Appalachians are just a few examples.

The basic geomorphology of passive margins with mountains is shown in fig. 20. There is a broad marginal swell, parallel to the continental edge and the coast (known in French as *bourrelets marginaux* and in German as *Randschwellen).* These are essentially plateaus. They are separated from the coast by Great Escarpments, which when seen from the coast look like mountain ranges.

Many possible causes of uplift of passive margins have been proposed and since subduction is impossible, some sort of thermal pulse seems to be most favoured. Ollier & Pain (1997) have pointed out that many lines of evidence show *subsidence* of the coast and offshore zone rather than uplift inland. In opposition, most workers on fission tracks propose uplift along offshore faults, which must parallel the coast for long distances.

In Australia a Great Escarpment runs the length of the Eastern Highlands. (Ollier, 1982; Pain, 1985; Ollier & Stevens, 1989). In most places the palaeoplain cuts across folded Palaeozoic rocks, and is referred to by Hills (1975) as the Trias-Jura Surface. The folding of the Palaeozoic rocks did *not* make the Eastern Highlands, but is much older.

The Western Ghats of India comprise a Great Escarpment that runs parallel to the western coast of India (Ollier & Powar, 1985). In the north it is cut across the Deccan Basalts and in the south across planated metamorphic and igneous rocks of the Precambrian Shield (fig. 21), with no significant change in form.

In South America the Serro do Mar (Maak, 1969) bordering the East Brazil highlands is a Great Escarpment.

Scandinavia is commonly described as having Caledonian mountains, but although the rocks and structures may be Palaeozoic (Caledonian orogeny) the present mountains are much younger. A broad and generally flat surface (generally called the palaeic surface in Scandinavia) covers much of Sweden and extends over the divide between the Atlantic and the Baltic (Gjessing, 1967). The land suddenly becomes steep at a Great Escarpment, and the rugged mountains of southern Norway are dissected below the level of the palaeic surface. The Great Escarpment is much degraded by glaciation in many places, but it is still evident in southern Norway.

Much of South Africa is a plateau (the Highveld), bounded by marginal swells and Great Escarpments (Ollier & Marker, 1985; Partridge & Maud, 1987) which goes by many local names. The Drakensberg is perhaps the most spectacular of these "mountain ranges". The Great Escarpment makes a huge arc all around southern Africa and as far north as Angola. The planation surface may be of Cretaceous age, and has been related to the sub-Cretaceous unconformity offshore (Partridge & Maud, 1987).

The Appalachian Mountains have been the centre of many controversies. They consist of folded and thrust-faulted Palaeozoic rocks, but the folding of rock generally had nothing to do with mountain building. Hall, the pioneer of Appalachian geology, visualised that folding and faulting associated with mountain belts took place during subsidence of the trough, thus anticipating later ideas of gravity tectonics. As one opponent of this view put it, Hall had «a theory of mountain-making with the mountains left out» (Spencer, 1965). All the Palaeozoic structures were planated by the Schooley Peneplain (with bevelled cuestas providing incontrovertible evidence of planation) which possibly dates back to Cretaceous or early Tertiary time. Parts of the Blue Ridge may be equivalent to a Great Escarpment. Davis (1903, p. 214 wrote «... in southern Virginia and North Carolina [the Blue Ridge] is not a ridge, with a crestline and well-defined slopes on either side; it is an escarpment», and on p. 240 «The escarpment itself is by no means a straight and simple wall. The ruins of the upland often form a labyrinth of hills and spurs at the back

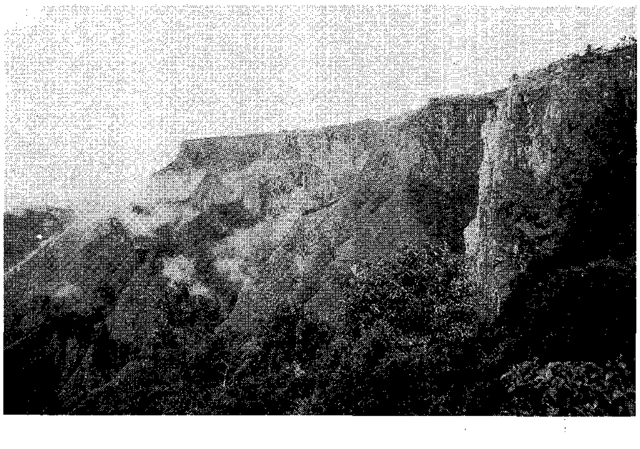


FIG. 21 - Photo of the Indian Great Escarpment on Precambrian gneiss, Kodaikanal (photo C.D. Ollier).

of the piedmont coves». The present Appalachians have nothing to do with the Palaeozoic folding and thrusting. Contrast this view with that of Deitz (1972) who interpreted the Appalachians as the result of plate collision (fig. 22). This idea is still prevalent, as shown by Pinter & Brandon (1997), who refer to the Appalachians as "old mountains" in contrast to the "new mountains" of active continental margins.

A significant point about many passive margin mountains relates to the age of the drainage. Some of the major drainage lines are older than the formation of the continental margin, and represent the drainage of Gondwana before the breakup. Some geophysicists and geologists, such as Cox (1989) and Cope (1994), present naive scenarios in which a dome is made (by a mantle plume) and a radial drainage develops related entirely to this new uplift. They fail to realise that before the doming there was an earlier drainage pattern, and that some of the old pattern will be inherited. Totally new drainage is unlikely to be found on passive margins, which have a long history and bear evidence of prior conditions. Major drainage patterns are on the same time scale as global tectonics, and often pre-date the formation of rift valleys, mountain ranges or continental margins. Most of the world's highest waterfalls occur where ancient rivers fall over Great Escarpments.

3. GEOMORPHOLOGY AND THE ULTIMATE CAUSES OF MOUNTAIN BUILDING

Mountains are made by erosion of plateaus, which are themselves made by vertical uplift of plains. What causes the vertical uplift? Over 20 mechanisms have been suggested (table 1) so how can a selection be made? Most tectonicians, convinced by the plate-tectonic paradigm, believe that the vertical movement must be derived somehow from horizontal movement, so have collision and subduction as the driving force. Burg & Ford (1997, p. 13) wrote: «The inference from both observation and modelling is that there must be subduction involved in orogens formed at plate boundaries». The complications of assumed subduction are often bizarre. Are the Apennines really being underthrust from all directions from north through east to south? Is Brazil being subducted under Bolivia? Furthermore, convergence of plates does not necessarily produce collision or high topography, as already described for the Po valley. Eocene marine sediments as old as or younger than the alleged collision between India and Asia show that the Indus-Tsangpo collision zone was below sea level (Burg & Chen, 1984). The Caribbean collision site today is under the sea (Dercourt & *alii*, 1993) as is the collision between Timor and Australia (Karig & *alii*, 1987).

TABLE 1 - Twenty suggested causes of tectonic uplift (after Ollier, 1991)

1. Thermal expansion due to a mantle plume or hot spot.
2. Thermal expansion due to overriding and subduction of a hot mid-ocean ridge or spreading centre.
3. Thermal expansion due to shear heating along a lithosphere-asthenosphere surface.
4. Expansion accompanying partial melting (the increase in volume on fusing basalt is about 8 per cent).
5. Hydraulic reactions such as serpentinisation (10 per cent expansion).
6. Introduction of volatiles due to deep-seated dehydration of hydrous minerals.
7. Expansion due to depletion of 'fertile' mantle in garnet and iron resulting from basalt genesis.
8. Crustal thickening due to horizontal transfer of mass in the lower crust.
9. Deep-seated solid state reactions such as eclogite-basalt transformation.
10. Subduction at a very shallow angle, perhaps horizontal.
11. Simple subduction, or continent-continent subduction.
12. Cessation of subduction and resulting thermal equilibrium of static slab.
13. Isolation of a plateau by listric normal faulting in the surrounding area.
14. A piece of sooling lithosphere detaches from the crust and is replaced by a counterflow of asthenosphere, which warms the crustal rocks and causes uplift (by thermal expansion) and volcanism.
15. Intrusion of magma into the lower crust.
16. Intrusion of sills.
17. Isostatic uplift after scarp retreat.
18. Isostatic rebound after regional erosion.
19. Underplating, the addition of unspecified lighter material to the base of the crust.
20. Isochemical phase change with volume increase in the lower crust or upper mantle.

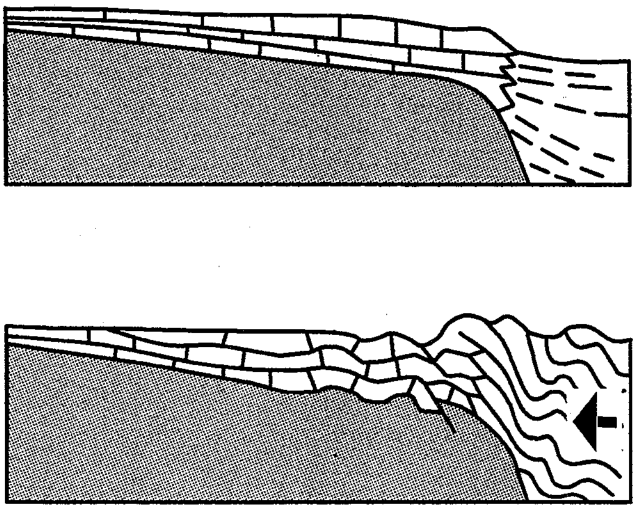


FIG. 22 - Diagram of the Appalachians caused by simple compression, simplified after Deitz, 1973.

The ultimate cause has a fatal fascination. I believe that we do not know it, and it is the thing we are striving to find out. If we first get the geometry right, then the age, we might work out the kinematics, and if we know that we might, just possibly, venture on the driving force. Until then we should not assume any particular driving force, but be open to many possibilities. We should use all available information, including that of geomorphology. Unfortunately those wrestling with these problems usually ignore the directly observable evidence of the ground surface.

The greatest weight is given to obscure geophysical evidence, while the most obvious and readily available evidence, the topography, is ignored. Yet, as Petriovsky (1985) expressed it: «The study of the relief of the earth is much easier and cheaper than the study of the earth's depths and uses direct observation».

Ideas about mountain building have been subject to fads throughout the history of earth science. The shrinking earth, geosynclines, and latterly plate tectonics have all provided «answers», usually flawed by the scientific fallacy of a single cause, and biased by selective evidence and the rule of dogma.

Gansser (1991) wrote «During the classical exploration in the 19th and early 20th centuries the ratio between facts and theories was 1:0.5. Plate tectonics changed it to 1:3 and with geophysics, geochemistry and structural analysis the ratio became 1:5». I suspect that with the dominance of modelling it is now 1:10. It would be nice to reverse this sorry state of affairs. This paper is an appeal to geomorphologists to start from their own factual information in the study of major landforms, rather than follow simplistic theories derived from other sources.

4. CONCLUSIONS

4.1 Rock structures under plains, plateaus or mountains may not be the cause of the plain, plateau or mountain.

4.2 Plains are made by erosion, and vertical uplift of plains creates plateaus.

4.3 Mountains are usually plateaus or eroded plateaus.

4.4 Some structures, especially monoclines and vertical faults, may be associated with uplift.

4.5 There are no fold mountains. Most folding of rock has nothing to do with mountain building, and is usually much older.

4.6 A plateau may spread laterally after uplift, with the formation of thrust faults and related structures.

4.7 Deep incision of a plateau can cause isostatic response, with formation of new structures including anticlines along major valleys and even major mountain ranges.

4.8 Major drainage patterns are on the same time scale as global tectonics, and often pre-date the formation of rift valleys, mountain ranges or continental margins.

4.9 Theories of mountain building must explain both the period of tectonic quiet that permitted erosion of a planation surface, and the usually young and rapid uplift that made a plateau.

4.10 Subduction is a continuous and long lived process that does not readily explain either the tectonic quiet, or the young and rapid uplift of most mountains.

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Most mountain ranges are eroded plateaus, which were once low-level planation surfaces that cut across older bedrock structures. This concept is illustrated by examples including the Kimberley Plateau, Rocky Mountains, Andes, European Alps, Apennines, Himalayas, Drakensberg and Appalachians. In any theory of mountain building it is essential to separate pre-planation from post-planation structures. Most nappes, fold belts and granitic intrusions commonly associated with mountains are pre-planation features. Steep faults and gravity spreading structures may be post-planation features. Major drainage lines are sometimes older than mountain ranges or continental margins. Major valleys may be big enough to cause isostatic compensation sufficient to cause local anticlines, and uplift of whole ranges. Mountains on passive margins cannot be created by subduction. Vertical movement dominates mountain building, and in many instances uplift is Plio-Pleistocene. Any tectonic explanation should account for both the tectonic stability that permitted planation, and the rapid vertical uplift. Subduction is supposed to occur continuously over tens or hundreds of millions of years, so it not a likely explanation of such mountains.

KEY WORDS: Mountains, Plateaus, Planation surfaces, Drainage patterns, Uplift, Isostasy.

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