C.D. OLLIER*

THE STRUCTURE AND ORIGIN OF MOUNTAINS: PRE-PLANATION AND POST-PLANATION GRAVITY STRUCTURES

INDEX

ABSTRACT

Mountains are not made directly by folding, but result from uplift of plains (planation surfaces) to form plateaus, which are subsequently eroded into rugged mountains.

Most folding of rocks occurs before planation and plateau uplift, but folding and faulting can also occur during and after plateau uplift. In all instances the folding may be caused by gravitational sliding or spreading rather than the “squeeze box” type of compression favoured in conventional hypotheses of mountain building.

It is important to distinguish between the tectonic structures created before planation, and those that occurred after planation and uplift. Evidence for the two types is presented, and criteria for distinguishing the two different types are proposed.

RIASSUNTO

I rilievi montuosi non sono direttamente generati dal piegamento, ma sono il risultato del sollevamento di piani (superfici di spianamento) che arrivano a formare plateau; questi ultimi successivamente vengono a loro volta erosi e generano rilievi aspri. Il maggior piegamento delle rocce avviene prima dello spianamento e del sollevamento delle superfici spianate, ma il piegamento e la fagliazione possono avvenire durante e dopo il sollevamento del plateau. In tutti gli esempi il piegamento può essere causato da scivolamento gravitativi o espandimento piuttosto che da compressione del tipo “squeeze box” ipotesi favorita nei modelli convenzionali di costruzione dei rilievi.

E’ importante distinguere tra strutture tettoniche create prima della planazione e quelle che avvengono dopo la planazione ed il sollevamento. Vengono qui presentati esempi ed i criteri per distinguere i due differenti tipi proposti.

KEY WORDS: tectonics, structure, gravity, planation, collapse, spreading, sliding, nappes

PAROLE CHIAVE: tettonica, struttura, gravità, planazione, collasso, espandimento, scivolamento, nappe.

1. INTRODUCTION

Mountains are not restricted to folded rocks. Some mountains are on horizontal strata (e.g. Drakensberg), others are on granite (e.g. Sierra Nevada), but where the mountains do coincide with folded rocks there is no reason to assume that the folding caused or accompanied the mountain uplift.

Mountains are not made directly by folding, but result from uplift of plains (planation surfaces) to form plateaus, which are subsequently eroded to form escarpments and isolated erosional mountains (Ollier, 1999; Ollier & Pain, 2000).

The plains of Western Australia and Africa are about as flat as any erosional land surface can get. Very complex structures including folds, thrust faults and highly sheared metamorphic zones underlie the plains. 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. But the scale of the structure is quite different from that of the mountains, and whatever made the structure did *not* create the mountains.

Mountains made directly by folding are non-existent or extremely rare. This is despite the common cartoons showing horizontal compression creating mountains, as the result of continental collision or subduction. The actual ground surface is never tightly folded. Broad warping of the surface (epeirogeny) undoubtedly occurs, but this is quite different from the tight, small folds in rocks that are often observed in real geological exposures or reconstructed geological sections. Unfortunately the old idea that crustal shortening and folding go together and create mountains has not been dispelled, and the folding of fold belts is referred to as an **orogeny**, which causes confusion. The

---

(*) Department of Geography, University of Western Australia, Nedlands WA 6009, Australia.
cliffol@geog.uwa.edu.au

folding may be related to a specific time, the date of which is later than the sedimentation and earlier than any igneous intrusions that follow the folding. The intrusions (of granite for example) are usually referred to not as 'post-folding granites', but as **'post-orogenic granites'**, implying once again that the folding was related to mountains building, when it might be equally reasonable to think that the granite intrusion could actually cause uplift and mountain building. There is usually no direct evidence that folding was accompanied by mountain building. Indeed some folding occurs under the sea while sediments are still accumulating.

Fold belts tend to be long and thin. They may be related to continental borders, geosynclines, island arcs, 'active margins' or any other theoretical concepts, but although they have the approximate dimensions of a mountain range they are not necessarily associated with mountain building. Many mountain ranges are not coincident with fold belts, and many fold belts are not coincident with mountain ranges. Fold belts of different age are known, and are said to be related to different "**orogenies**", with the implication that mountain chains were also formed at different times.

The study of mountain building is really the study of plateau formation, which occurs by means of vertical uplift after a period of planation. When the rocks beneath a plateau are folded and faulted the structures are Pre-planation structures. If however the plateau is broken into fault blocks, further structures can result from gravitational sliding, which can be termed Post-planation structures.

1.1. Folding, nappes and décollement

The structure of many mountain regions is dominated by great nappes, huge sheets of rock that have clearly moved over fault planes at low angles, commonly bringing old rocks to lie over younger rocks. The nearly horizontal movement may be more than 100 km. The low angle fault plane is known as a detachment or décollement. Rocks that underlie the thrust fault are not deformed by the nappe emplacement. The unfolded décollement plane beneath the folded rocks clearly shows that the folded rock mass was not pushed up from below, but that some sort of lateral force was responsible for the folding. In most instances the décollement is marked by a layer of particularly mobile material that acts as a lubricant for the movement. Salt (halite) seems to be particularly suitable, as in the Jura Mountains and the Zagros. Dolomite seems to be also very suitable, as in the Unconformity Dolomite of the Naukluft Mountains. Gypsum and anhydrite also make good lubricants. Shales may provide enough lubrication, as in the Oslo Graben.

Some geologists think that nappes result from great squeezing of a sedimentary basin, plate tectonics usually regards them as thrust by plate collision, and some regard the nappes as the result of gravity tectonics. The following examples are thought to be especially good illustrations of gravity tectonics.

2. PRE-PLANATION GRAVITY STRUCTURES

Pre-planation folding is what makes ancient folds such as those in the Palaeozoic of the Appalachians or Eastern Highlands of Australia, or the complex Precambrian structures of Central Africa, or the nappes in Alpine mountains. In fact all these areas have well defined planation surfaces on top.

2.1. Underwater folding and faulting

The concept of folding and mountain building being synchronous is so engrained that it is easy to think that folding takes place on land, where the mountains are. In reality considerable folding takes place under the sea, as indicated by the following examples.

The Agulhas slump

The Agulhas Slump (Fig. 1a) is a large submarine slump on the continental margin of southeast Africa 750 km long, 106 km wide, with a volume of over 20,000km^3 (DINGLE, 1977). It is post-Pliocene, and has many of the tensional and compressional structures found in mountains, although it has never been above sea level.

The Bengal Fan

The Ganges and Brahmaputra Rivers have combined to build a huge submarine fan, the Bengal Fan, over 2,000 km long. The oldest known sediments are thought to be of Upper Cretaceous to Paleocene age. Over most of its enormous area the sediments appear to be unfolded, but the distal parts are folded and thrust to make a fold belt (Fig 1b). WEZEL (1988) regards this folding as possibly the most distant effects of the Himalayan orogeny, but it is more plausibly caused by gravity sliding and thrusting.

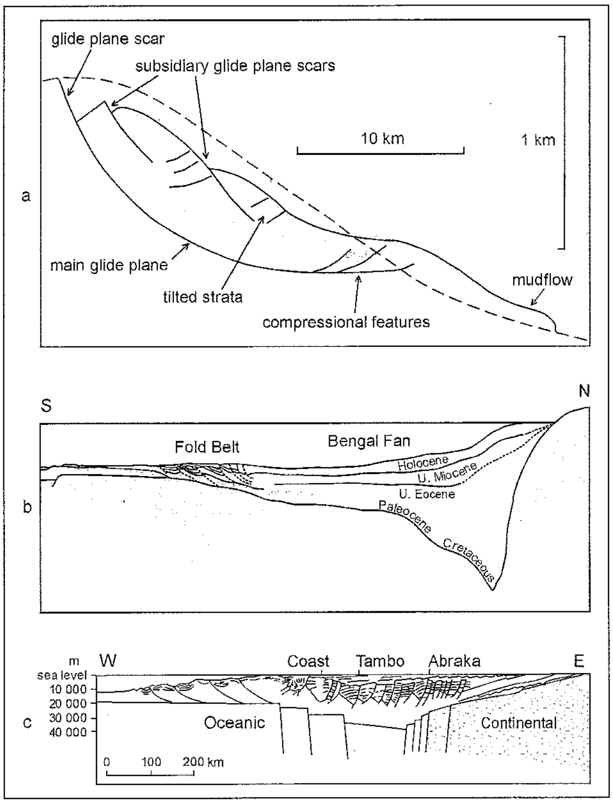

Fig. 1 – Section of the Aghulas slump offshore southeast Africa (after DINGLE, 1977). Cross section of the Bengal Fan showing thrusting in the distal portion (after WEZEL, 1988). Cross section of the Niger Delta, showing folding and thrusting beneath the sea. (after EVAMY *et al.*, 1979.

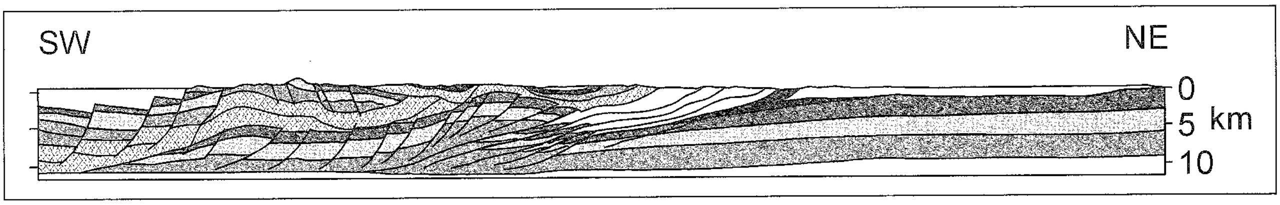

Fig. 2 - A SW-NE cross section of the Apennines starting south of Naples. Simplified after a section in Cassano *et al.* (1986). The three shaded layers on the foreland (right) are Cretaceous, Jurassic, Triassic. Nappes are thrust against the foreland in the NE but the region has been eroded and affected by younger normal faults which create the present topography.

The Niger Delta

The Niger Delta (Fig. 1c) is much faulted, with some major faults that define distinct provinces within the delta region and control sedimentary deposition to a large extent, and many smaller faults (Evamy *et al.*, 1979). These are significant because they demonstrate that not all faults are associated with topographic features on the land - some major faults never did produce fault scarps on the ground surface, and by analogy wherever we see faults in old delta sediments in older rocks we should not think of faulting as being related to younger tectonics and uplift, for they may be penecontemporaneous with the deposition as in the Niger Delta. Note the normal faults near to shore, and thrust faults on the distal portion. In many ancient settings this thrusting at the front would be interpreted in plate tectonic terms as the result of subduction, but clearly the Niger Delta is on a passive margin and subduction is impossible.

2.2. Other examples of pre-planation folding and faulting

The Apennines

The Apennines consist of a stack of nappes with a total thickness of over 10 km, very much greater than the height of the Apennine Mountains, so much of the faulting occurred when the sediments were beneath the sea. A typical cross section is shown in Fig. 2, which shows also younger normal faults associated with the vertical uplift of the Apennines. The formation of the pre-uplift planation surface is described by Coltorti & Pieruccini (1999).

The Jura

The Jura Mountains gave their name to Jura-type folding, a generic term that refers to folding that does not involve the underlying rock. The folded rocks of the Jura could not be folded by any mechanism involving the whole crust; the folding is surficial, even though the folded layer is several kilometres thick. The unfolded unconformity beneath the folded rocks (Fig. 3) clearly shows that the Jura folds were not pushed up from below, but that some sort of lateral force is responsible for the folding. The strata are mainly Jurassic.

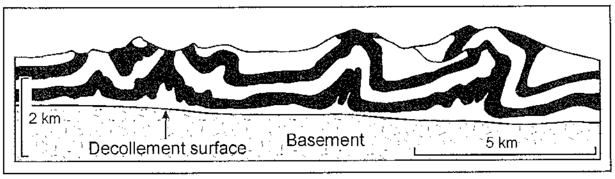

Fig. 3 - Typical Jura folding, with deformation of upper strata over a smooth décollement. The right half of the diagram is along the Grenchenberg Tunnel, Switzerland.

The Jura make a crescentic range in plan, separated from the Alps by the Swiss Plain which is underlain by unfolded rocks. At the ends of the crescent there are single anticlines, but the number of folds increases towards the middle. Unfolded tabular areas intervene between some groups of folds, separated by thrusts to the NW. On the outer side of the crescent are the tabular Jura, with the folded Jura behind, and behind this the almost unfolded sediments of the wide Swiss Plain. The idea that they were *pushed* by lateral pressure from the Alps is thus untenable: the rocks could only *slide* into their present configuration. The sliding was assisted by layers of Triassic anhydrite and salt along which the overlying beds could glide and fold.

Folding occurred mainly in the Upper Miocene and Lower Pliocene, after which the area was levelled by erosion. Further uplift, with some renewed folding, is mainly Pleistocene (Holmes, 1965).

The Pelvoux massif

The Pelvoux massif in the south of France is surrounded by nappes. This massif had emerged from the sea by the end of the Oligocene, and so presented an obstacle against which nappes were brought to a standstill when they collided, buckling and imbricating the strata of the toe. Nappes from the main axial region of the French Alps moved westwards, and piled up against the eastern side of Pelvoux massif: Nappes from the north piled up on the northern side; nappes from the south piled up on the southern slopes (Holmes, 1965). This centripetal pattern of structures demands a centripetal pattern of forces. No scheme of lateral compression can account for this pattern, but gravity sliding presents an easy explanation. Pelvoux was an island-like obstacle surrounded on three sides by slopes on which gravity sliding took place. The nappes of Pelvoux now reach heights of more than 3000 m, higher than the source area of the nappes.

The Papuan fold belt

The highlands of Papua New Guinea are mostly rugged mountains, but there are numerous plateaus - remnants of a former, more extensive planation surface. The spine of Papua New Guinea is an arched plateau. Part of this is known as the Owen Stanley Ranges. Relict surfaces are widespread in the Owen Stanley Ranges, mainly on the principal watershed but also on some offshoot divides, and have been mapped by Pain (1983). Overlying volcanics and sediments suggest the old erosion surface is Pleistocene or Pliocene. 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.

Deep drilling has shown that the folds of the Papuan fold belt are confined to the upper few kilometres, the basement is unaffected, and the main glide plane is within Jurassic strata as shown in Fig. 4c (Findlay, 1974; Jenkins, 1974). The strata slid into basins and were deformed into complex folds and faults, and folding is greatest where a sliding mass bumped into a basement obstacle. The folded rocks are separated by a décollement from the unfolded bedrock beneath. The sliding was consequent on vertical uplift of the central axis of the country. The structures of the Papuan Fold Belt are hard to explain by any mechanism other than gravity sliding.

The fanciful plate tectonic scenarios shown in Figs. 4a and 4b that allegedly explain the mountains of Papua

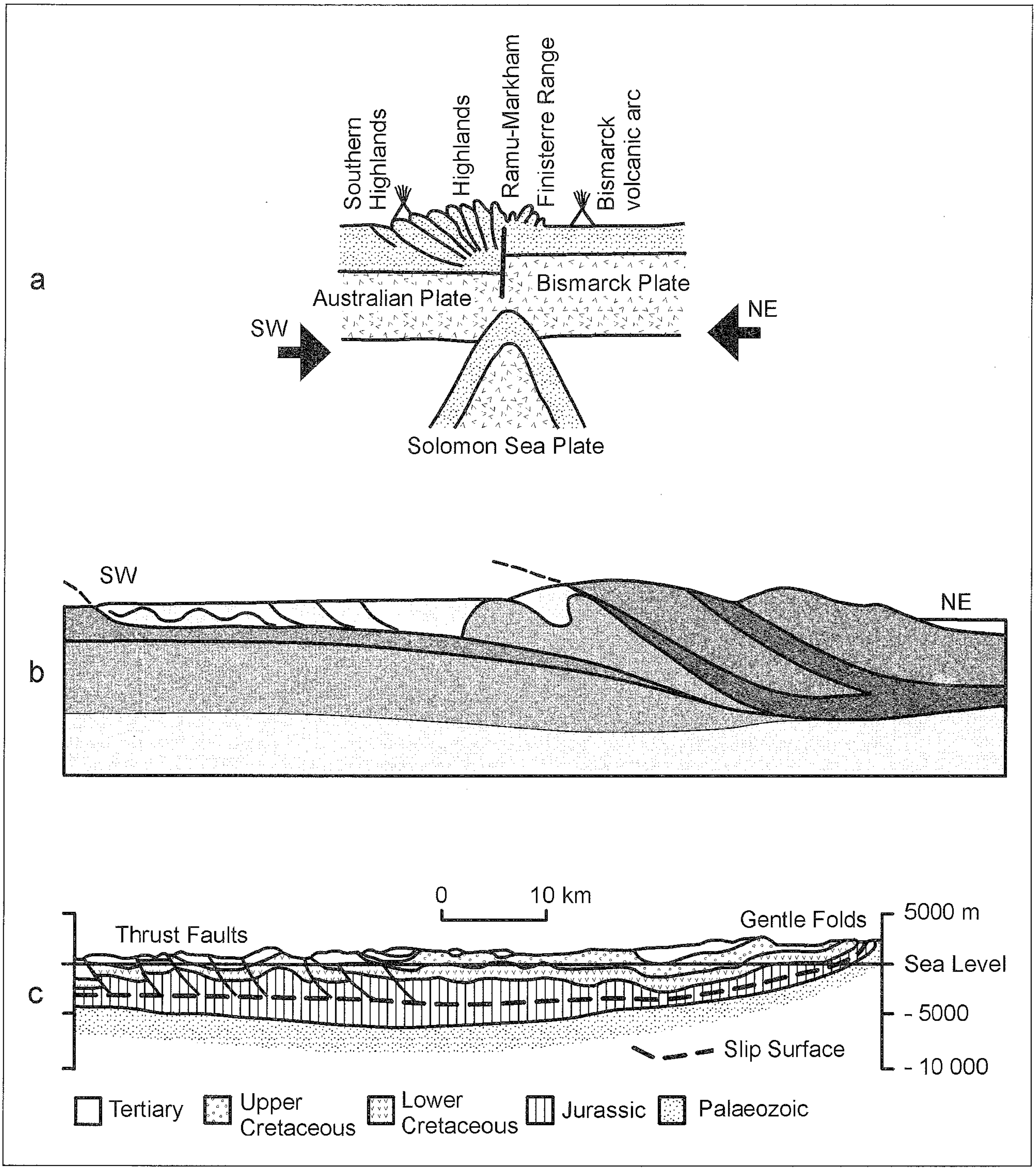

Fig. 4 - Cross sections of New Guinea mountains. a. Collision of the Bismarck Plate and the Australian Plate, pushing down the Solomon Plate, after Ripper & Mccue (1982). The Papuan Fold Belt is at top left. b. Subduction of the Australian Plate under the Pacific Plate, after Burchfiel (1983). The Papuan Fold Belt is at top left. c. A real cross section of the Papuan Fold Belt based on drilling, after Findlay (1974). The folds result from gravity sliding after vertical uplift of the highland zone to the right.

New Guinea by plate tectonic collisions (e.g. Ripper & Mccue, 1982; Burchfiel, 1983) pay scant regard to either bedrock geology or geomorphology (Fig. 4).

Taiwan

The structure of Taiwan, as described by Chai (1972) and shown in Fig. 5. seems to leave no option but gravity tectonics. The main mountain range of the island was caused by vertical uplift, and surficial sedimentary layers have slid, by gravity to form the Western Foothills and the East Coastal Range. The basic force was vertical tectonic uplift of a tilt block, and the horizontal force that made the folds was from gravity response. The Neogene sediments and thrusts seem to interfinger with Plio-Pleistocene sediments, but younger Pleistocene sediments are unaffected by gravity tectonics, though affected slightly by normal faulting.

The Naukluft Mountains

The finest example of unarguable gravity-slide tectonics is provided by the Naukluft Mountains in southwest Africa, described by Korn & Martin (1959) and shown in Fig. 6.. The bedrock of Precambrian rocks is unfolded, but is overlain by a series of intensely folded rocks which evidently moved from northwest to southeast. The intensity of deformation increases to the southeast, where the repeated thrust faults known as imbricate structure are found. This is the effect of breakers-at-the-nappe-front described later. A lateral push in the east would cause greatest deformation where applied, and its effects would die out to the west, just the reverse of what is found. A sliding mass of rock, however, is most deformed at the front end, where it crashed into the obstacle that brought it to rest. This is what is found.

But there is an even more remarkable feature in the Naukluft. After the faulted and folded rocks were emplaced they were eroded to a plain, the area subsided, and then a new series of sedimentary rocks were deposited unconformably on the lower series. The upper series would have been nearly horizontal originally. But this upper series also underwent a phase of folding and thrusting. It slid down the unconformity and was intensely deformed without any effect on the underlying rocks.

The unconformity between the two sets of folded

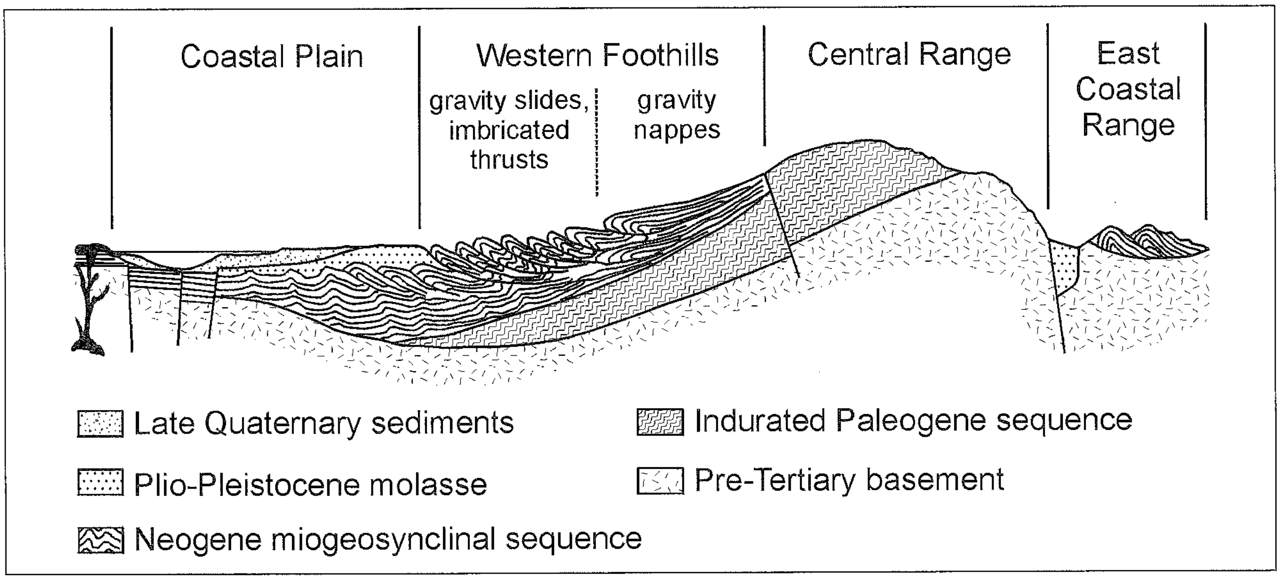

Fig. 5 - Cross section of Taiwan showing décollement and overturned folds and thrusts in the western foothills of the Central Range (after Chai, 1972). It is not implied that individual thrusts make individual hills, for the region was planated.

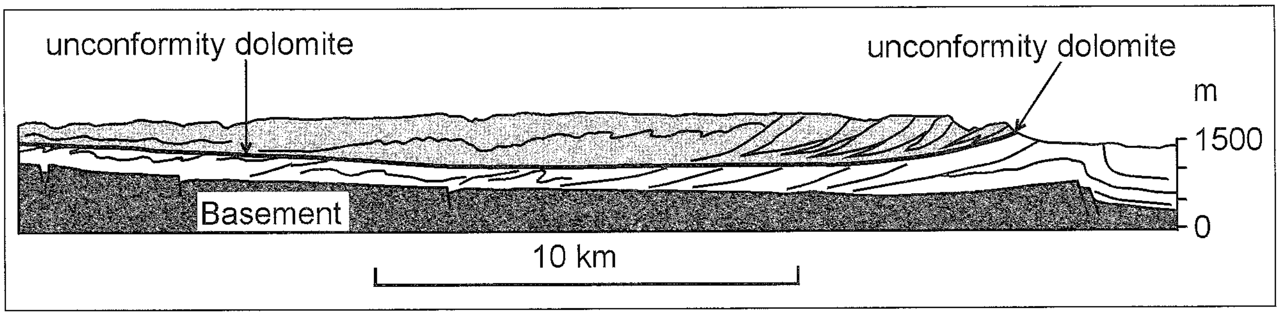

Fig. 6 - Cross section of the Naukluft Mountains showing the undeformed Unconformity Dolomite, only 10 m thick, between older and younger strata that have been intensely folded and thrust faulted. The basement rocks are affected only by minor block faulting and regional tilting. (after Korn & Martin, 1959).

rocks is marked by a distinctive yellow dolomite only five to ten metres thick. This provided the lubricating layer allowing décollement of the overlying mass. Furthermore, even the lower part of the dolomite is virtually undisturbed, and the upper part becomes gradually deformed towards the upper adjacent rocks. A slab of rocks several kilometres thick slid on a lubricated plane over a dolomite layer only ten metres thick, and without disturbing any of the underlying rocks at all. There can be no question of crustal shortening here. Everything points to gravity sliding on a huge scale.

Of course neither of these sets of gravity structures has anything to do with the present Naukluft Mountain topography. The last set of gravity structures was planated, and the erosion surface raised to form a plateau, and the plateau partly dissected to make the modern rugged mountains.

3. POST-UPLIFT GRAVITY STRUCTURES

Gravity structures that occur after planation and uplift take several forms, which may work in combination.

3.1. Gravity collapse structures

A series of gravity collapse structures in sedimentary rocks reported from Iran were perhaps the first such structures to illustrate the great importance of gravity in folding rocks (Harrison & Falcon, 1934, 1936). The structures are shown in Fig. 7, and they range in complexity from simple visor and knee folds, to structures as complex as cascades. The present vertical relief may be over 2,000 m, but the secondary gravity folds start to form when the relief is no more than 600 m. These structures could easily have been interpreted as 'normal' geological folds caused by 'compressive shortening', but the lack of folding in the underlying rock clearly shows that they are surficial features, not related to compression of the entire Earth's crust. Furthermore the folds and related structures were formed subaerially, after incision of valleys.

3.2. Gravity spreading and mushroom tectonics

The idea of gravity spreading after vertical uplift has been applied to uplifted blocks in Australia (Ollier & Wyborn, 1989), who reasoned as follows.

When a fault scarp runs almost straight for tens or even hundreds of kilometres it has to be a high angle fault because a low angle thrust fault in an area of high relief would have a sinuous outcrop. Such straight faults are the Tawonga Fault and Long Plain Fault in southwest Australia. Yet detailed examination in tunnels cut through these faults shows them to be low angle thrusts, with granite or Palaeozoic bedrock thrust over Quaternary alluvium in places. The simplest explanation is gravity spreading of an uplifted block over the alluvium.

Similarly in the Andes, the straightness of the Cordillera margins on the large scale indicates dominantly vertical faulting, but detailed studies indicate thrusting, which is a late-stage modification as uplifted blocks spread (Coltorti & Ollier, 1999).

In the Rocky Mountains the mountain front is straight on small-scale maps, but detailed work shows thrusting of up to 100 km. Bieber (1983) reported that where thrust the fault may dip at less than 60^{o} but "elsewhere along the Front Range dips are more nearly vertical." The situation suggests original vertical faults which spread under gravity and turn into apparent thrust faults. But the thrusting is symmetrical and has been aptly termed "mushroom tectonics" (Jacobs, 1983) Examples, shown in Fig. 8, include the Rocky Mountains, the Uinta Plateau, and the Andes of Ecuador.

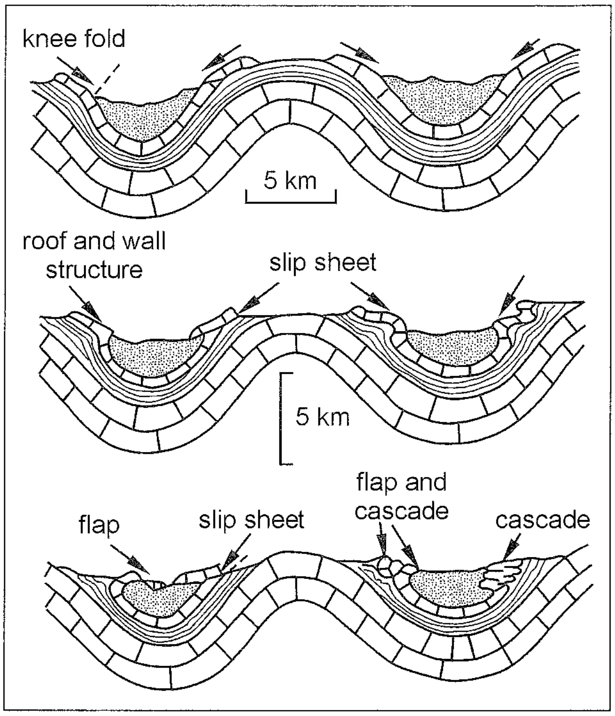

Fig. 7 - Diagram of gravity collapse structures of Iran, showing stages in the development of flaps, slip-sheets and cascades of folds. Natural scale (after Harrison & Falcon, 1934).

4. CRITERIA

4.1. Critera for recognising gravity structures in general

The evidence for surficial (gravity) slides rather than deep-seated thrust includes:

1. Folds are not deep seated, but lie on a thrust fault plane (nappe).

2. Faults are not deep seated, but originate from a thrust fault plane (nappe).

3. Folded and faulted rocks lie above a décollement, often marked by good lubricants such as halite or dolomite.

4.2. Critera for pre-planation gravity sliding

I would like to suggest that the following features are diagnostic of Pre-planation gravity sliding, especially if found in unison. Further details are provided by Rutten (1969)

1. The depth of the folded pile. After uplift, a horst usually starts to spread before an elevation of 3000 m is reached.. If the sedimentary pile that is folded, faulted, or thrust into nappes is of greater thickness, like the ten kilometres of the Apennines, then the gravity effects are pre-

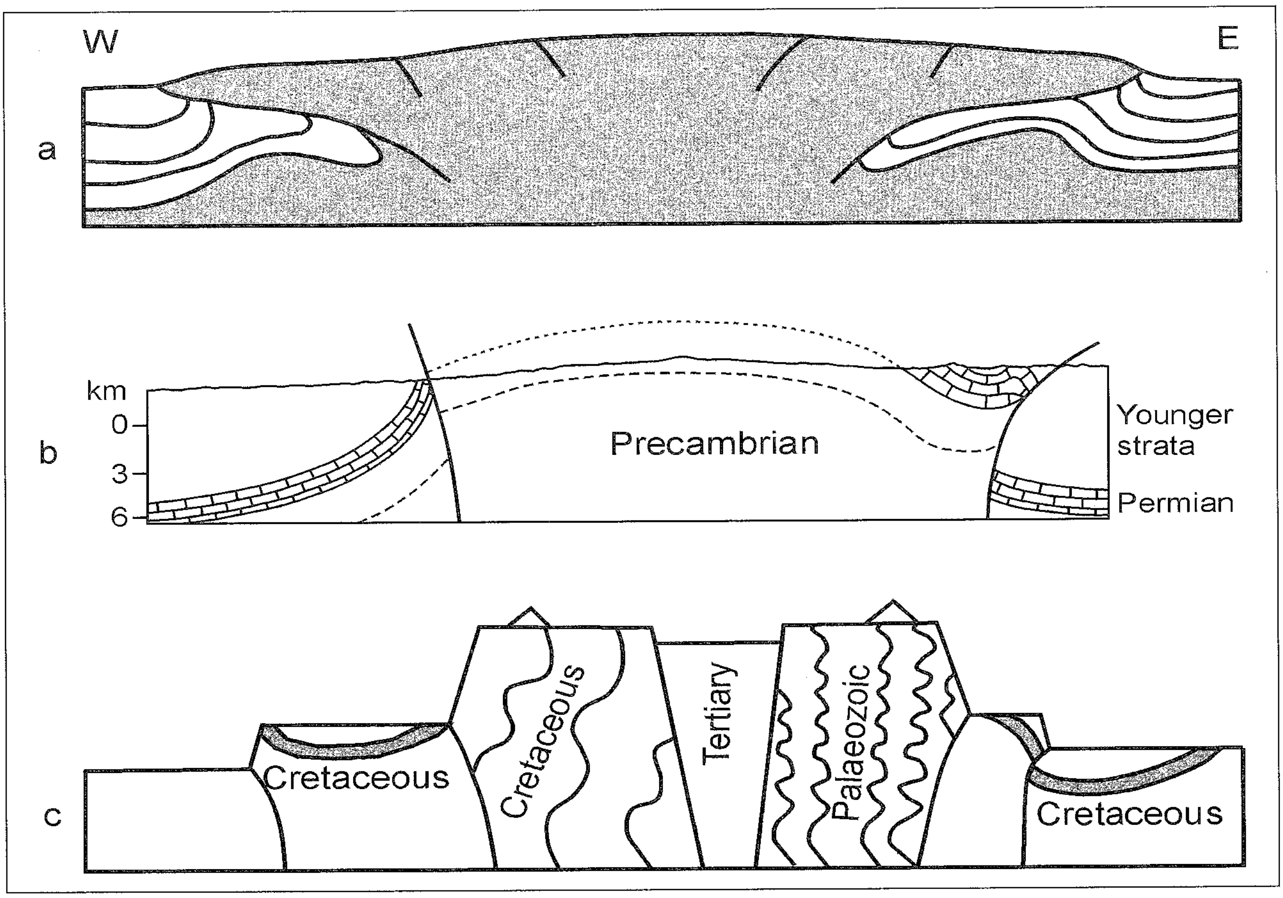

Fig. 8. Spreading structures or mushroom tectonics
a. Sketch section of 'mushroom tectonics' as applied to the Rockies in Colorado. Front Range to the East, Park Range to the west. Precambrian rocks (shaded) spread over younger rocks on both sides (after Jacob, 1983).
b. Cross section of the Uinta Uplift showing the outward spread of the uplifted Precambrian rocks along outwardly curving faults. (after Ritzma, 1959).
c. Diagrammatic cross section of the Andes of Ecuador. An originally simple horst and graben structure has been complicated by tectonic spreading (after Ollier, 1999).

planation. The total thickness of the nappes of the Apennines, about ten kilometres, is much greater than the terrestrial relief, so is not controlled by the topography. Much of the nappe would have been below sea level at the time of sliding.

2. Most folding and faulting occurs at the front of the nappe. This is described very well in German as 'Branden der Deckenstirne' or 'Breakers at the nappe front.' The nappes of the Helvetide Alps of Switzerland have a sub-horizontal structure except along the front, where they are crumpled into narrow folds. The Apennines illustrate the idea very well too. Where the reaction between moving force and resistance is greatest is where crumpling would be expected: this is at the front with gravity sliding, at the back with push. Where the reaction between moving force and resistance is greatest is where crumpling would be expected: this is at the front with gravity sliding, at the back with push. The crumpled zone often has cascade folds with axial planes dipping at 45^{0} or even less which can hardly be explained except as a series of beds sliding into a depression under the influence of gravity.

The nappe-front breakers are not restricted to the frontal part of external nappes, but normally occur in the frontal part of every nappe or nappe lobe.

3. The youngest beds travel furthest. In the Helvetide nappes, for example, the furthest travelled nappes in the north are mainly formed by Cretaceous rocks; then comes the Jura nappe formed mainly by Jurassic rocks; and lastly the Verucano nappe which is mainly Permian. The older rocks are not exposed, so cannot slide, until the rocks above have gone.

This follows from gravity tectonics, where the highest units have greatest potential energy. It is hard to see on a tangential pressure model how a differential push could move the higher parts of a series several tens of kilometres further than the lower parts. How could such a force continue to be applied once the nappe had moved away, if the pushing part is itself rooted in the crust?

4. Isolated fold sheets or intercutaneous nappes ("Chevauchement intercutanes"). This refers to a situation where a series of folded and overthrust strata are found within a mass of seemingly tranquil, apparently unmoved strata. This is common in the Alps, and also many other places. The intercutaneous nappes mark an internal zone of great disturbance that took place inside a thick series of sediments without disturbing either underlying or overlying strata. It is hard to see how this could be obtained by lateral compression, but could easily result from a gravity slide

during deposition of the sedimentary pile.

5. Convergence of forces from more than two opposed directions. With one thrust it can be argued that the block is subducted; with two opposed thrusts it can be argued that a thrust has an opposite reaction, but if thrusts converge from three directions, such as north, south and west, the only reasonable explanation is that nappes are converging on a single stable block. The nappes around the Pelvoux Massif are the prime example.

6. Divergence of thrusts in plan of more than 180^{O} suggests gravity spreading. Subduction would ideally make a plane, or a very gentle arc on the Earth's curved surface. But if the curve of a nappe front is very marked, it would require subduction from many directions, some directly opposed, which is impossible. The Apennines and the Carpathians are good examples of such arcs of thrusting.

4.3. Critera for post-uplift gravity tectonics

I would like to suggest that the following features are diagnostic of Post-uplift gravity tectonics, especially if found in unison.

1. Faults follow a straight line for long distances (many tens of kilometres) even in rugged topography, though in local detail they appear as thrusts. A continuous low angle fault would have a very irregular outcrop in rugged country.

2. Low angle thrust fault planes can be traced into steeper faults.

3. The upper slab sometimes overlies soft material such as alluvium. If underthrusting did occur, it seems incredible that such material would not be scraped off. Complications arise if a younger movement takes place along an old fault. The great nappes of the Himalayas are prime examples of pre-planation thrusts, but there has been renewed movement on some nappes in more recent times. High-grade Precambrian Nanga Parbat gneiss is thrust over unlithified glaciofluvial sediments, which is clearly a post-glacial, Quaternary movement..

4. Uplifted blocks are bounded by divergent faults. The alternative, of compression from opposite sides, requires exceptional tectonic forces.

5. Anticlinal valleys (valley bulges), where rivers appear to flow along topographic ridges and structural anticlines. A river flowing across a plain is not related to structures that lie even a few metres below its course, let alone several kilometres. So if a river follows an anticline, it is almost certainly because the anticline appeared after the river. If a dozen or more rivers follow anticlines, as in the Himalayas (OHTA & AKIBA, 1973) the causal relationship seems definite. Such anticlines have their greatest amplitude near river level, and die out with depth. Valley anticlines are totally absent from pre-planation gravity structures.

6. Minor folds that appear along the foothills of mountains are likely to result from pressure of the mountains themselves, like uplifted zones in the toe of a landslide. It is improbable that such folds would appear by compressional thrusting of plates, for any such lines of convergence would not necessarily be related to present topography.

7. Deformation and faulting is greatest near the scene of tectonic uplift and decreases with distance from the uplift. This is the opposite of the 'breakers at the front' situation in pre-planation gravity slides.

8. The thickness of the rock mass involved is generally lower than that of the massive gravity slides of pre-planation sliding. It is usually less than 3 km. There is probably a complete sequence from small landslides to massive deep gravity sliding, but the two main end members can be deciphered.

5. MECHANISMS

Most geologists seem happy to believe that they have a mechanism for folding in simple compression, which in turn might be caused by plate collision, a shrinking Earth, or other mechanism. They commonly do not appreciate mechanisms whereby gravity can result in large-scale folding, so this brief section introduces some basic concepts on gravity tectonic mechanisms.

5.1. Underwater slides and nappes

Even though field evidence for gravity tectonics is very powerful, the description of the mechanism was for a long time difficult. How could such enormous slabs of rock be brought into motion on such gentle gradients? What sort of force could trigger the process? How could the internal frictional resistance of the rocks be overcome? If sliding is brought about under gravity the strength of the rock is irrelevant, but nevertheless with normal friction there are also limits that prevent sliding.

The most probable solution to reduction of friction was provided by HUBBERT & RUBEY in 1959.

Imagine a layer of sand laid on the sea floor, which is then covered by a thick stratum of clay, and eventually many other sediments. The buried sediments are compacted by the pressure of the overlying load but water may be sealed in favourable layers. This has serious effects for water is essentially incompressible. The pressure of the overlying rock (known as the lithostatic pressure) results simply from its weight. The hydrostatic pressure on the interstitial fluid also results from the load, and if water cannot be expelled the pressure can eventually rise as the weight of sediment increases until the hydrostatic pressure is almost equal to the lithostatic pressure. At this stage the mass of sediments is virtually floating on the water-bearing stratum. Just as it is possible to push a huge floating ship away from a quayside, so a very slight force may set a mass of sediments in motion. The mass of the material hardly matters so long as it is highly buoyant. Thus if the pore pressure in deep sedimentary layers can be increased sufficiently a very slight force may be sufficient to induce gravity sliding on slopes of very gentle inclination.

Buoyancy has the effect of almost total reduction of friction and allows huge masses of rocks to slide. Such masses have great momentum and when brought to rest are liable to become very deformed, especially in the collision zone at the front of the slide. This accounts very well for the breakers at the nappe front.

5.2. Gravity spreading

In the simplest picture of gravity sliding the basal décollement dips towards the foreland. However, in many fold belts it is known that the basal décollement dipped towards the hinterland during deformation. This is the situation in the Jura, the central and southern Appalachians, the Canadian Rockies and the Idaho-Wyoming thrust belt to name just a few. With a simple gravity slide the décollement would outcrop at the back of the slide, leaving a region of tectonic denudation rather like the scar produced by a gigantic landslide. Yet no case can be made for the existence of this type of tectonic denudation in the thrust belts mentioned above (Elliot & Johnson, 1978). They proposed a more realistic theory of **gravity spreading**, rather than sliding, in which the décollement dips towards the hinterland and there is no tectonic denudation. Gravity spreading could affect submarine sediments, but could also be effective on land.

The idea of gravitational spreading was conceived quite early by Jeffreys (1931), who calculated the inevitability of gravity structures from the strength of materials and wrote that whenever an elevation over 3 km has been produced, either fracture or flow must set in; whichever it is, its general effect will be the spreading out of the elevated rocks over the surrounding country. Jeffrey's calculations were based on measurement of pure rock material, but real rocks are full of bedding planes, joints and other inhomogeneities that reduce the strength (Engineering geologists distinguish rock material from rock mass on this basis). The elevation of 3 km suggested by Jeffreys is too high, and gravity spreading could occur with elevations of as little as 800 m.

REFERENCES

Bieber D.W. (1983) - *Gravimetric evidence for thrusting and hydrocarbon potential of the east flank of the Front Range, Colorado.* In: Lowell J. D. (Ed) - Rocky Mountain Foreland Basins and Uplifts. Rocky Mountain Association of Geologists, Denver, pp. 245-255

Burchfiel B.C. (1983) - *The Continental Crust.* Scientific American, September, 86-98.

Chai B.H.T. (1972) - *Structure and tectonic evolution of Taiwan.* American Journal of Science, **272**, 389-422

Coltorti M. & Ollier C.D. (1999) - *The significance of high planation surface in the Andes of Ecuador.* In: Smith B.J., Whalley W.B. & Warke P.A. (Eds) - Uplift, Erosion and Stability: Perspectives on Longterm Landscape Development. Geological Society, London, Special Publications, **162**, 1-15.

Coltorti M. & Pieruccini P. (2000) - *The planation surface across the Italian Peninsula: a late Lower Pliocene plain of marine erosion as a key tool in neotectonic studies.* Journal of Geodynamics, **29**, 323-328.

Dingle R.V. (1977) - *The anatomy of a large submarine slump on a sheared continental margin (SE Africa).* Journal of the Geological Society of London, **134**, 293-310.

Elliot D. & Johnson M.R.W. (1978) - *Discussion on structures found in thrust belts.* Journal of the Geological Society of London, 135, 259-60.

Evamy D.D., Haremboure J., Kamerling P., Knaap W.A., Molloy F.A. & Rowlands P.H. (1979) - *Hydrocarbon habitat of Tertiary Niger Delta.* American Association of Petroleum Geologists Bulletin, **62**, 1-39.

Findlay A.L. (1974) - *The structure of foothills south of the Kubor Range, Papua New Guinea.* Australian Petroleum Exploration Association Journal, **14**, 14-20.

Harrison J.V. & Falcon N.L. (1934) - *Collapse structures.* Geological Magazine, **71**, 529-39.

Harrison J.V. & Falcon N.L. (1936) - *Gravity collapse structures and mountain ranges, as exemplified in South-western Persia.* Quarterly Journal of the Geological Society of London, **92**, 91-102.

Holmes A. (1965) - *Principles of Physical Geology.* Nelson, London.

Jacob A F. (1983) - *Mountain front thrust, southeastern Front Range and northeastern Wet Mountains, Colorado.* In: Lowell J. D. (Ed) - *Rocky Mountain Foreland Basins and Uplifts.* Rocky Mountain Association of Geologists, Denver, 229-244.

Jeffreys H. (1931) - *On the mechanics of mountains.* Geological Magazine, **68**, 433-42.

Jenkins D.A.L. (1974) - *Detachment tectonics in western Papua New Guinea.* Geological Society of America Bulletin, **85**, 533-548.

Korn H. & Martin H. (1959) - *Gravity tectonics in the Naukluft Mountains of South-West Africa.* Geological C. (Eds) - Geology of the Nepal Himalayas. Saikon. Sapporo.

Ohta Y. & Akiba (1973) - *Geomorphology and Mountain Building.* Geografia Fisica e Dinamica Quaternaria, Supplemento III, Tomo **3**, 49-60

Ollier C.D. (1999) - Society of America Bulletin, **70**, 1047-78.

Ollier C.D. & Pain C.F. (2000) - The Origin of Mountains. Routledge, London.

Ollier C.D. & Wyborn. D. (1989) - *Geology of alpine Australia.* In: Good. R. (Ed.) - *The Scientific Significance of the Australian Alps,* Australian Alps National Parks Liaison Committee and Australian Academy of Science, Canberra, 35-53.

Pain C.F. (1983) - *Volcanic rocks and surfaces as indicators of landform age - the Astrolabe Agglomerate, Papua New Guinea.* Australian Geographer, **15**, 376-381.

Ripper I.D. & McCue K.F. (1982) - *Seismicity of the Indo-Australian/ Solomon Sea plate boundary in the southeast Papua region.* Tectonophysics, **87**, 355-369.

Ritzma H.R. (1959) - Geological Atlas of Utah, Daggett County. Utah Geological Survey.

Rutten M.G. (1969) - The Geology of Western Europe. Elsevier, Amsterdam.

Wezel F.C. (1988) - *A young Jura-type fold belt within the Central Indian Ocean.* Boll. Oceanologia teorica e Applicata, **6**, 75-90.