Caderno Lab. Xeolóxico de Laxe
Coruña. 1997. Vol. 22, pp. 151-182

Models of landscape evolution and the survival of Palaeoforms

Los modelos de evolución del paisaje y la supervivencia de paleoformas

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One of the factors mitigating against the recognition and acceptance of very old palaeosurfaces was, and in some measure remains, the tacit acceptance of some of the better known models of landscape evolution. Thus both the steady state and peneplanation models imply virtual contemporaneity of surface, and though scarp retreat allows for a greater age, the maximum is determined by the duration of a cycle, probably of the order of 33 Ma; much younger than many firmly dated epigene surfaces.

Basically landform and landscape persistence involves the stability, or only slow rate of change, of surfaces (divides) of bounding scarps, or both. Such slow rates of change are induced by such factors as resistant bedrock: hence the preservation of many palaeoforms on quartzites, etc. In addition, several mechanisms, such as uplift, through drainage, and consequent local «aridity»; incision and unequal activity; and reinforcement or positive feedback mechanisms, enhance the persistence of surfaces.

Key words: Landscape evolution. Climatic, geological, geographical mechanisms. Persistence of paleoforms.

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INTRODUCTION

The suggestion that some landscape elements are of great antiquity is not new, for very old land surfaces, of Cretaceous age, and essentially exposed to the elements since inception, were tentatively recognised in Australia and southern Africa in the nineteen thirties and even earlier (e.g. HOSSFELD, 1926; CRAFT 1932, 1933; HILLS, 1934; DIXEY, 1938). Advances in stratigraphic knowledge and physical dating have, however, allowed the ages of such ancient palaeosurfaces to be determined with a greater degree of certainty and precision than was previously possible.

In addition, it is now apparent that Pangaean elements are not restricted to the southern continents derived from the disintegration of Gondwana, but are also preserved in what was Laurasia. As in Gondwana, some remnants are exhumed (e.g. WATTS, 1903; FALCONER, 1911; WILLIS, 1936; COWIE, 1960; AMBROSE, 1964; RUDBERG, 1970; LIDMAR-BERGSTROM, 1989), but others are of epigene-etch type (see e.g. FOGELBERG, 1985, and, for reviews, TWIDALE, 1976, 1994; YOUNG, 1983; TWIDALE and VIDAL ROMANI, 1994a). These remnants are not odd, accidental, curiosities but rather constitute widespread, substantial and integral components of landscape (see e.g. TWIDALE and CAMPBELL, 1988). The survivor of such very old surfaces has been explained, albeit inadequately, in terms of, for example, resistant lithology, limited scope of fluvial erosion, reinforcement effects, anorogenic earth movements and various minor or localised factors (TWIDALE, 1976, 1991; TWIDALE and CAMPBELL, 1992). It has also been suggested that in respect of very old palaeoforms the conventional models of landscape evolution are misleading in their deduced. consequences. Other models, involving tectonism-isostatism and unequal erosion are, taken together with the aforementioned factors, more conducive to the survival of palaeosurfaces.

MODELS OF LANDSCAPE EVOLUTION: CRITIQUE

Several models of landscape development have been adduced in explanation of the contemporary land surface. Some such as DAVIS' (1899,1909) peneplanation model, and KING'S (1942,1953) scarp retreat model, are cyclic. Others involve dynamic equilibrium (e.g. HACK, 1960; CHORLEY, 1962). Some, like KENNEDY (1962, see Table 1, Fig.1) invoke various developmental paths depending on the interplay of tectonism (uplift), erosion (stream incision) and denudation (wasting of divides and valley-side slopes). Others have emphasised the significance of earth movements, either tectonic or isostatic (e.g. TWIDALE, 1991; TWIDALE and CAMPBELL, 1992). Yet others (e.g TRENDALL, 1962), have invoked subsurface dissolution, compaction and lowering of land surfaces. Which model has been operative, and in which contexts, is of some importance for it determines not only the morphology of landscape but also, in considerable measure, influences the chances of survival of very old palaeoforms.

The peneplanation model results in rolling or undulating plains and calls for essentially simultaneous and uniform downwasting of the entire land surface, so that any long term persistence of palaeosurfaces is effectively precluded. In detail, minor tectonism and changes of

TABLE 1. Kennedy's models of landscape evolution according torelative rates of uplift, incision and wasting

Uplift > Incision	Incision > Wasting	1	Increasing relief
	Incision > Wasting	2	Static relief
	Incision > Wasting	3	Decreasing relief - P
Uplift - Incision	Incision > Wasting	4	Increasing relief
	Incision > Wasting	5	Static relief
	Incision > Wasting	6	Decreasing relief - P
Uplift < Incision	Incision > Wasting	7	Increasing relief
	Incision > Wasting	8	Static relief
	Incision > Wasting	9	Decreasing relief - P

P: peneplain or other surface of low relief

sealevel (see e.g. TWIDALE, 1956a, 956b, 1966a) cause waves of erosional rejuvenation to migrate inland from the coast. Thus, in reality a peneplain consists of facets of various ages. A surface has not so much an age as an age range (TWIDALE, 1956a; KING, 1962). This age-range may be limited, as in northwestern Queensland and southern Africa (TWIDALE, 1956A; KING, 1962), but in some areas headward erosion of rivers has been slow (e.g. TAYLOR et al, 1985) and the temporal spead of related facets may be considerable. Nonetheless, a peneplain, subjected to constant downwasting, is perceived as being inherently youthful. How juvenile depends on the rate at which drainage networks extend upslope and inland. This is not everywhere as rapid as has been assumed (e.g. YOUNG, 1983; TAYLOR et al.,1985).

Davis cited surfaces of low relief preserved in unconformity, like those described by POWELL (1875) and later by SHARP (1940), as evidence of the capacity of external agencies to reduce land masses of regional extent to low relief, but he could not point to examples of contemporary peneplains, i.e. peneplains essentially related either to modern sealevel, or, alternatively, to regional baselevels. He resorted (DAVIS, 1909, pp. 358-359) to examples in Montana and central Asia, neither of them convincing. He and his followers also pointed to relic, dissected, forms, preserved high in the local relief as evidence of peneplanation. But these are, in Davis' own terms, impossible, for downwasting would not allow their survival.

In some ways, Davis was defeated by his own definitions and restrictions, for he took peneplains to be zonal forms developed in humid temperate regions, whereas, had he examined the tropical and subtropical landscapes of say Australia and Africa (Fig. 2), he would have found several excellent examples of rolling surfaces of low relief of regional extent (TWIDALE, 1983a, 1985), which morphologically resemble Davisian peneplains. Even in the United States, such surfaces of subdued relief are well represented in the southern Great Plains as far west as central Texas, and JOURNAUX (1978) has

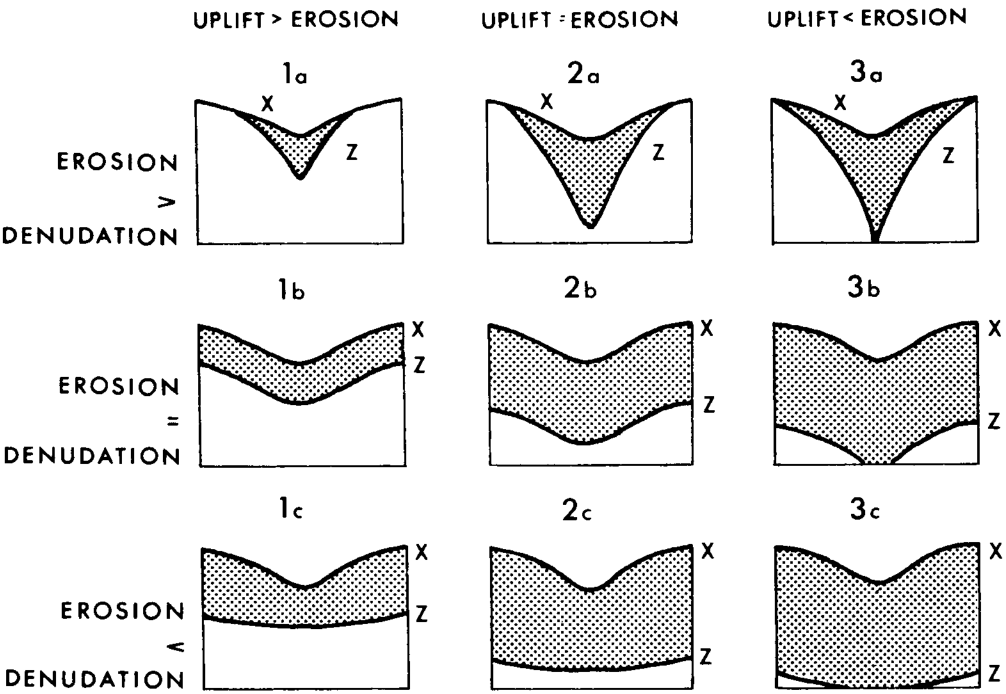


Fig. 1. Diagrammatic sections showing Kennedy's (1962) models of landscape evolution, varying according to relative rates of uplift, dissection and wasting.

described rolling plains from granitic terrains in the interior of Brazil.

Whether these «peneplains» are the result of slope decline is arguable, though corroboratory evidence and general argument continue to gain strength (STRAHLER, 1956; CARSON, 1969; KIRKBY, 1971). Slope decline is favoured by weak rocks that alone cannot maintain faceted form or steep inclination (TRICART 1957; TWIDALE, 1960), and it is true that morphological peneplains, i.e. undulating or rolling surfaces of low relief, are developed in rocks that are either inherently weak or which have been rendered weak by weathering. Thus, in the Australian context, rolling plains of low relief are well represented throughout the erosional areas of the Eromanga and Carpentaria basins. They are developed in argillaceous sediments in monsoonal northwest Queensland (e.g. TWIDALE, 1956a). They extend as far south as the Wilcannia and Cobar regions in the and and semiarid interior of New South Wales, where a range of lithologies has been reduced to rolling low relief. Such rolling erosional plains extend to the eastern margin of the Simpson Desert in southwest Queensland (Fig. 2b). The rolling Roeburne plains of northwestern Western Australia are also developed in argillaceous sediments. On the other hand, rolling plains in weathered granite are prominent in the southern Yilgarn of Western Australia and on northern Eyre Peninsula, South Australia. In the latter region, the plain has been modified

Fig. 2. (a) Rolling plains in weak argillaceous sediments east of Johannesburg, South Africa.

(b) Gibber-strewn rolling plains eroded in weathered Cretaceous argillite, southwest Queensland.

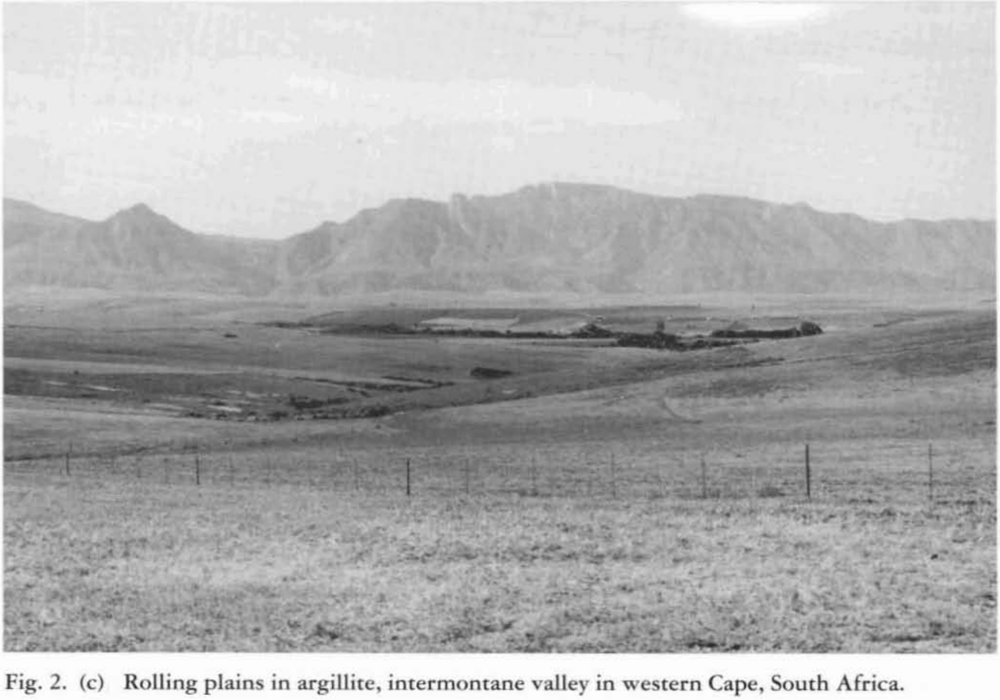


Fig. 2. (c) Rolling plains in argillite, intermontane valley in western Cape, South Africa.

(d) Sandstone scarp and, in piedmont zone, rolling plains in argillite, western Cape, South Africa.

during a (Late Pleistocene) arid phase by the spread of fields of linear dunes, and has also been stabilised by a carapace of calcrete.

Peneplains are found in similar contexts in southern Africa where rolling plains are well developed in weathered granite in the region north of Pretoria and in argillaceous sediments east of Johannesburg. Several areas of rolling relief of more limited extent are developed on argillaceous outcrops within the ridge and valley topography of the western Cape Fold Belt (Fig. 2c); though the sandstone scarps are subject to scarp retreat (Fig. 2d), suggesting that there is a lithological cofitrol of mode of landscape development.

It is not possible to demonstrate in the field that slope lowering takes place, and partly because of this and partly as a reaction to Davisian theeory, but mainly because of South African landscapes and King's perceptive eye and imagination, field evidence of scarp retreat was adduced (KING, 1942, 1953, 1957). Regardless of degree of dissection, given similar structure, the scarps bounding plateaux are of similar morphology and inclination, and also tend to the maximum inclination commensurate with stability.

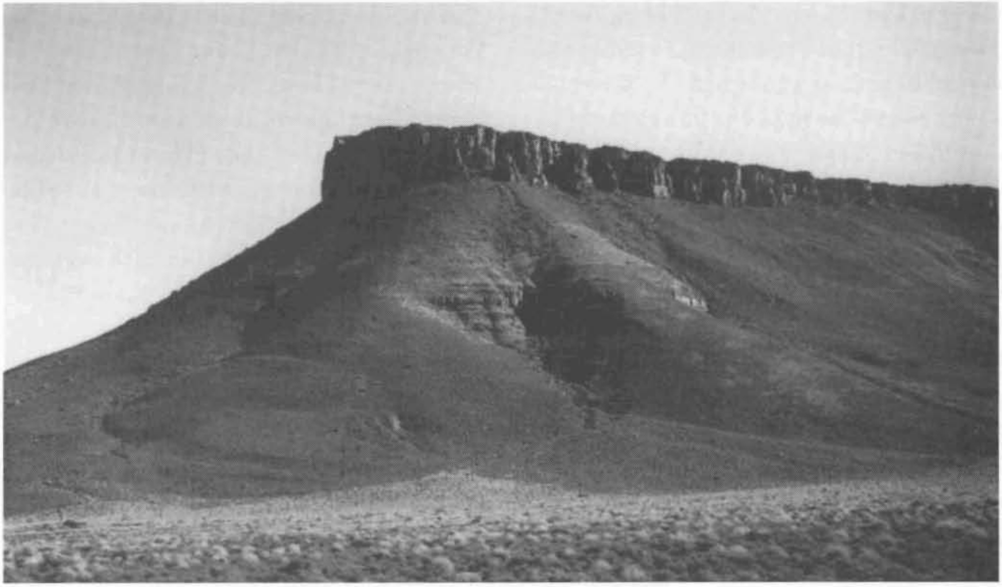
Scarp retreat is greatly favoured by a caprock, either primary or involving a duricrust due to weathering. The resultant surface of low relief left behind by scarp recession is a diachronic surface with an age range rather than a specific date, being older near the valley floors and most recent at the scarp foot. Negative baselevel movements or spasmodic uplift magnify this tendency (e.g. KING, 1962).

It is not fortuitous that King recognised both the mechanism and the critical evidence in southern Africa, for there, apart from the Cape Fold Belt, the landscape is dominated by flat-lying sequences of sediments and lavas, including several formations that are resistant and form ready made caprocks (Fig. 3a), a structural situation which, combined with regional uplift and stream incision, is ideal for scarp recession. Similar slope forms are associated with caprocks, including various types of duricrust (e.g. Fig.3b) in various parts of the world.

The mechanism is clearly demonstrable (KING, 1942), and is consistent with the concept of a slope budget (TRICART, 1957; TWIDALE, 1960).

The mechanism is also favoured by and climates, where the geomorphological importance of what little water there is, is enhanced. Scarp foot weathering and erosion lead to the constant regrading and steepening of slopes (TWIDALE and MILNES, 1983), to the wearing back of scarps, and io the development of a piedmont angle (TWIDALE, 1967), which abrupt transition between hill and plain is considered by some investigators to be typical of and and semiarid lands (e.g. HILLS, 1955).

The likelihood of backwearing of scarps taking place is enhanced by a concentration of water and weathering at the scarp foot, i.e. by an uneven distribution of weathering. King's scarp retreat model includes elements of this concept, for, though King considered that erosion continued on the initial surface, it was restricted and retarded by the capping and was clearly less effective than that operating at the new baselevel. The scarp recession model implies a stepped morphology, which is characteristic of many regions (see e.g. CRICKMAY, 1974, p. 140); though such stepped topography can evolve through the operation of mechanisms other than scarp retreat (e.g. WAHRHAFTIG,



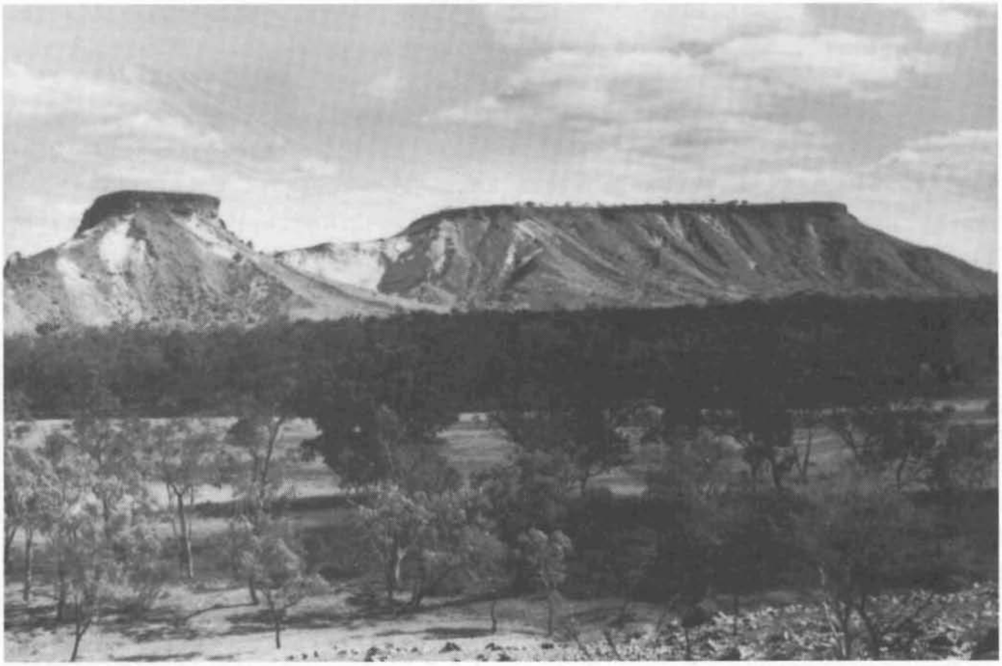


Fig. 3. (a) Basalt-capped mesa in northwestern Cape Province, South Africa. Note gully erosion of debris slope.

(b) Silcrete capped plateau near Rumbalara, south of Alice Springs, Northern Territory, Australia. Note the two generations of elements on the debris slope: the younger valleys or gullies, incised into the older debris slope which is veneered by gravel derived from caprock (CSIRO).

1965; TWIDALE, 1982). In King's scarp retreat model, remnants of the «initial» surface persist until late in the cycle but their duration is limited to that of the cycle, estimated to be of the order of 33 ma for large continents (e.g. SCHUMM, 1963; but see also PITMAN and GOLOVCHENKO, 1991). King assumed that in due time the slate was, as it were, wiped clean, and the landscape was reduced to a plain of subdued relief related to the new baselevel. He believed that the plain comprised numerous pediments which had coalesced to form a pediplain. But, *pace* King, scarp recession is not necessarily associated with pedimentation, for pediments are basically fringing forms (TWIDALE, 1978, 1981,1983a). Moreover the type examples cited by King are not multiconcave forms as required by the pedimentation hypothesis, but display convex rises (Fig. 4), as do peneplains.

Other workers have adduced evidence suggesting that erosion is grossly unequal and is effectively concentrated in river channels and their immediate environs. This has, simultaneously, become the basis of first refuting other models that call for essentially uniform wearing away of the land surface, and second of explaining the survival of palaeoforms in terms of large areas of any catchment being untouched by effective erosion. KNOPF (1924) and HORTON (1945), and, and especially CRICKMAY (e.g. 1932, 1976) and TWIDALE (1991), have emphasised the disparity between the intense and effective erosion near rivers and the stability of divides.

Fig. 4. Springbok Plains eroded in basalt, north of Pretoria, Transvaal, South Africa.

Crickmay termed this situation «unequal activity». This concept goes further than scarp retreat in attributing the preservation of upland surfaces to unequal erosion, for in contrast with the progressive recession of escarpments and the consequent reduction in area of the upland palaeosurface implicit in the scarp retreat model, unequal erosion implies essentially constant ratios of river valleys on the one hand and the intervening divides on the other.

Though based in very different assumptions, the steady state model carries implications for the rapid destruction of land surfaces 'similar to the peneplain concept, for it implies an all slopes topography and its essence is the continuous and uniform regrading of slopes in response to adjustments of river channels to various possible , environmental changes such as regional baselevel (HACK, 1960). As with peneplanation, waves of rejuvenation migrate inland, so at any one time the the surface is a palimpsest but essentially contemporary. Steady state or dynamic equilibrium seems likely to develop in humid, tectonically active areas like the Andes, Himalayas and New Guinea where uplift is active, where year-round high rainfall results in fluvial dominance and where a combination of humidity and lithology cause the development of a close stream network. This at least is the theory. Proof awaits widespread measurements of slope erosion, though some results can be construed as sustaining the concept (RUXTON, 1967).

RUXTON (1958) also deduced that strong subsurface flushing can evacuate solid fines as well as materials in solution, resulting in volume reduction, compaction and surface lowering. This theme was developed by TRENDALL (1962), whose model involves the lowering of surfaces through subsurface weathering and compaction, leaving them morphologically almost unchanged. Trendall developed his concept in relation to some of the lateritised granitic terrains of eastern Africa. It can be assumed that all rocks are subject to dissolution; only the rate at which the process takes place varying according to composition and environment. The mechanism applies quite appropriately to surfaces of low relief lacking surface drainage, such as those west of Lake Eyre, in central Australia, where the broadly rolling plains lack continuous stream systems and where indeed channels are scarce. The plains around Marla and Glendambo, for instance, are more readily understood in terms of subsurface weathering and volume reduction than of surface erosion. This model emphasises processes active in the subterranean world, in contradistinction to those directly sculpting the land surface.

Weathering, the alteration and disintegration of rocks at and near the surface, is the precursor of most erosion. In addition, however, regardless of its origin, any surface of low relief may develop a weathered mantle. The only requirement is that weathering outpaces erosion. The regolith may later be stripped to expose the weathering front as an etch surface (HASSENFRATZ, 1791; LOGAN, 1849, 1851; FALCONER, 1911; JUTSON, 1914; MABBUTT, 1966). Etch forms and surfaces reflect the interaction of groundwaters with the bedrock, so that structural factors find strong expression (FOGELBERG, 1985; TWIDALE, 1987a, 1990). The nature of the stripping agent is of only minor significance in the context of the morphology of etch surfaces, which are climatically azonal (TWIDALE, 1990). The shape of the resultant etch surface is a function of the interaction of weathering processes and bedrock. Etch surfaces are not the result of epigene erosional agents but of weathering, and they reflect, both in gross and in detail, magmatic, tectonic and thermal events, many of them dating from the distant past (TWIDALE and VIDAL ROMANI, 1994b; see also CAMPBELL and TWIDALE, 1991).

Such stripping may be triggered by relative uplift or an appropriate climatic change, though weathering itself, breaking down the country rock and thus rendering it susceptible to transport, could conceivably initiate accelerated erosion. Any of the plains, including etch plains, could be buried by sediment or lava, and later re-exposed in exhumed surfaces.

Thus, though some surfaces are a function of their chronology (epigene, etch, exhumed), which of a group of proposed models of landscape evolution has operated appears to vary with structure and tectonics - peneplanation in weak rocks, scarp retreat in caprock situations, steady state in humid areas of pronounced uplift. Increasing relief amplitude may result from isostatic adjustments, and lowering substantially by subsurface weathering in regions of intense or long-continued alteration. Several of these models are incorporated in KENNEDY'S (1962) scheme involving the interplay of uplift, stream incision and wasting of divides (Fig. 1).

SURVIVAL AND UNEQUAL ACTIVITY

Survival of palaeosurfaces over several scores and even a few hundreds of millions of years is implied by the field evidence. Some etch and exhumed surfaces were exposed so long ago that their persistence poses problems equal to those of older epigene features. For example the bevelled bornhardts of the Gawler Ranges, in the and interior of South Australia, are of etch origin but were exposedduring the Early Cretaceous (CAMPBELL and TWIDALE, 1991). Similarly the palaeodrainage system of the Yilgarn region of Western Australia, evidently originated variously during the Permian and Mesozoic, and some valleys certainly date from the Eocene (e.g. VAN DER GRAAFF et al., 1977). Palaeosurfaces can evidently survive long exposure to the elements, but for how long depends on the rate of scarp retreat, as well as on the durability of divides. Erosion is constantly active, but its need not be evenly distributed. Erosion may be unequal, as suggested by Crickmay. In broad terms, survival may be due to unequal activity allowing a very slow rate of scarp retreat over long sectors of escarpments; or to unequal erosion of uplands leading to the stability of extensive areas of high plains or plateaux; or, of course, to both factors.

(a) Migration of escarpments

Clearly, whatever else happens to palaeosurfaces preserved on divides, they survive no longer than the time taken for the new plains to encroach on the old as the intervening escarpments or bounding slopes are worn back. Thus, the rate of scarp recession is of some importance. Various processes are at work on steep slopes, but river erosion, and scarp foot weathering and erosion, leading to regrading of slopes (Figs. 5a and b) and the undermining and collapse of bluffs, are highly significant (TWIDALE and MILNES, 1983). The

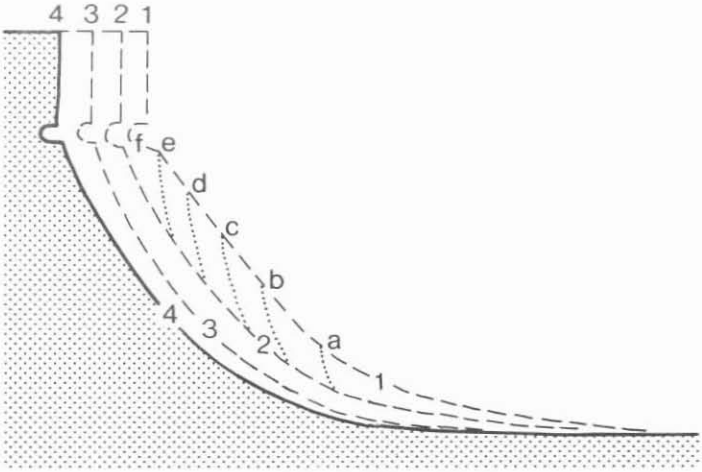


Fig. 5. (a). Diagram showing wearing back of scarp by repeated cycles of undermining and regrading (After Twidale and Milnes, 1983).

(b). Part of the northern scarp of the Chewings Range, in the Macdonnell Ranges, central Australia showing remnant of former debris slope.

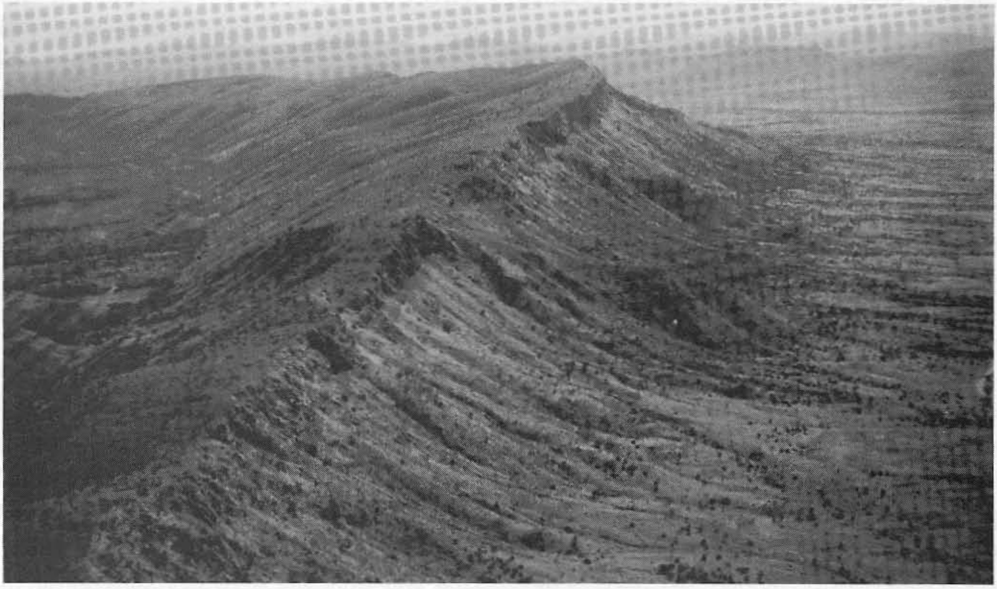


Fig. 5 (c) Part of northern scarp of the Chewings Range, showing gullied debris slope.

(d). Earth flow on western side of Bumbunga Range, about 110 km north of Adelaide, South Australia.

gullying (Fig. 5c), landslides and other forms of mass movement (Fig. 5d) evident on many steep slopes are but manifestations of these two mechanisms.

It has been assumed that rejuvenated rivers rapidly extend inland from the coast, but this assumption has been called to question by investigations in southeastern Australia (YOUNG, 1983; TAYLOR et al, 1985) where headward erosion of major rivers is of the order of some 100 km in about 60 Ma. Nevertheless, rivers have clearly breached escarpments and have extended deep into plateaux in some places, but their impacts are limited, for scarps persist unbroken to either side of the breaches and far downstream from the heads of the gorges incised in the plateaux. Rivers like the Zambezi, in southern Africa, are a case in point. At an altogether smaller scale, the development of such features as flared slopes and scarp foot *depressions (Bergfussniederungen)* surely argues a relative standstill during which subsurface weathering has taken place (see e.g. CLAYTON, 1956; TWIDALE, 1962).

The rate of scarp retreat varies in space and time. JUTSON (1914) realised that escarpments (or 'breakaways') are unevenly eroded, and cited the example of what he called bottle-necked valleys - valleys that breached scarps by way of narrow openings, and markedly expanded in area within the plateau proper (Fig. 6). CRICKMAY (1974) cited similar examples. As to variations in time, the Drakensberg escarpment is a major landform extending over several hundreds of kilometres in southern Africa. Over much of its length it is eroded in Jurassic basalts, and sedimentological evidence from the adjacent continental shelf and slope suggests that through the Cretaceous and until the end of the Eocene, erosion, and presumably backwearing of the scarp, was active. Throughout the middle and later Cainozoic, however, erosion has been minor (PARTRIDGE and MAUD, 1987).

The explanation may again lie in unequal erosion. Immediately following volcanism and uplift many small streams and rivers ran down the scarp to the sea. The scarp was worn back. But as drainage integrated, certain streams became dominant, possibly for structural reasons (e.g. fracture zones, local arching). Their valleys extended deeply back into the plateau, while other streams, reduced in volume, became impotent and over long sectors the scarp became stabilised. Clearly drainage network evolution and drainage densities are critical to any consideration of landscape morphology and evolution (e.g. WILLGOOSE et al., 1991).

Aridity contributes to the preservation of divides directly in that deserts lack permanent streams. Any rivers flowing in such regions are, in some measure at any rate, allogenic or exotic. Though the rivers themselves are actively eroding, the divides are and and stable. This situation is well exemplified by the eastern Sahara Desert, where drainage systems active during past pluvials are now inactive and buried beneath the desert sands, leaving the allogenic Nile in supreme isolation (McCAULEY et al., 1982).

Two mechanisms which in minor degree enhance retardation of scarp retreat have been identified. Gully gravure cerainly implies localised and ephemeral protection of scarps (BRYAN 1940). Reduction in area of the catchment, the high plain or plateau delimited by the escarpment, implies progressive reduction of flow over the scarp, reduction in erosion and retardation of scarp retreat (TWIDALE, 1978). Both mechanisms are real, though not everywhere operative. Gully gravure in particular appears most readily identified in and lands (e.g. BRYAN, 1940; BEATY 1959; TWIDALE et al., 1970; TWIDALE and CAMPBELL, 1986) and in association with caprocks such as quartzite or coarse (gravel, cobbles, boulders) alluvium. In any event their effects, though interesting and locally important, are of relatively minor significance in the regional context. It is the concentration of kinetic energy in, and unequal activity of, rivers that is mainly responsible for the uneven recession of escarpments.

(b) Persistence of divides

Persistence of divides may be due to several factors. Structure in all its facets and nuances is critical to the endurance of divides. As has been made clear in the commentary on the scarp retreat model, caprocks of various kinds have been and are effective in preservation of interfiuves. The nature of caprocks varies greatly and in some instances surprisingly. In southern Africa, sandstone is a common caprock but so is basalt. Laterite and silcrete also provide protective carapaces, for example in Natal and Namaqualand respectively, as does calcrete, for instance in central Namibia (Fig.7b).

In Australia also, duricrusts form widely distributed caprocks associated with which are plateau landforms (Figs. 8 and 3b). The nature of the duricrusts varies regionally: laterite in the marginal areas of the continent, silcrete inland (STEPHENS 1964, 1970; TWIDALE, 1983b). In addition, gyperete underlies the featureless plains west and southwest of Lake Eyre (WOPFNER and TWIDALE, 1967). It forms the capping of the cliffs that border the salina on its western side. This may seem surprising, but though physically soft and soluble, the rock is crystalline and cohesive and in aridity is much more resistant than the unlithified gypsiferous silts that underlie it. Calcrete cappings form a protective veneer over extensive areas of southern South Australia and adjacent areas (see e.g. MILNES and HUTTON, 1983). Calcrete indurations also account, in part at least, for the preservation of the ancient (probably Miocene) coastal dunes known as the Ooldea and Barton ranges, bordering the Eucla Basin on its northeastern margin (BENBOW, 1990).

Resistant carapaces of various types have been instrumental in inducing relief inversion at various scales. Lava flows which extended along valley floors and which have been left high in the local relief as a result of the preferential erosion of adjacent outcrops are commonly exemplified in various parts of the world. One of the best known Australian examples is El Capitan, an isolated elongate mesa located near Cobar in western New South Wales (OLLIER, 1988, p. 171). Table Mountain, near Knight's Ferry and adjacent to the Stanislaus River, in the central Sierra Nevada of California (TALIAFERRO and SOLARI, 1946), is another well known example. Spectacular sinuous mesas capped by an iron pisolite occur in and around the Hamersley Ranges of northwestern Western Australia (Fig. 9). The pisolites were originally deposited in valley floors but on drying and hardening they became more resistant than the nearby hills with the result that they now form high points in the local relief (TWIDALE et al., 1985). Several of the linear silcrete capped

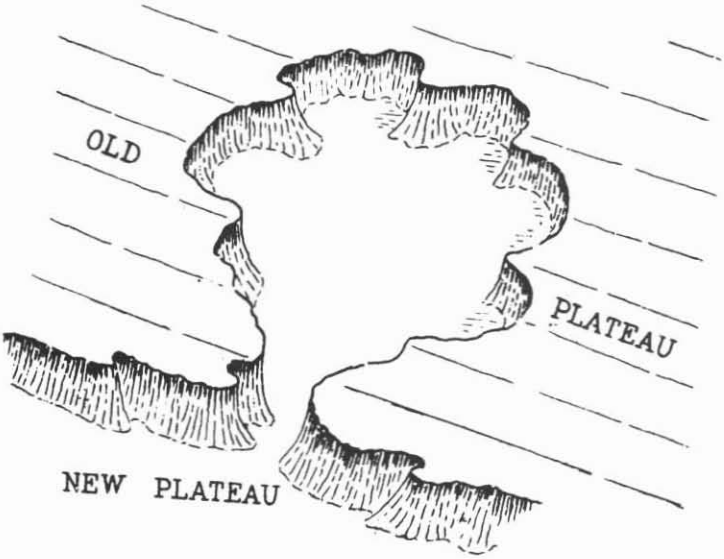


Fig. 6. Sketch of bottleneck valley, as illustrated in Jutson (1914).

Fig. 7. Plateau capped by calcrete and travertine, Kuiseb Canyon region, central Namibia. Where the capping has been stripped the underlying schists are exposed.

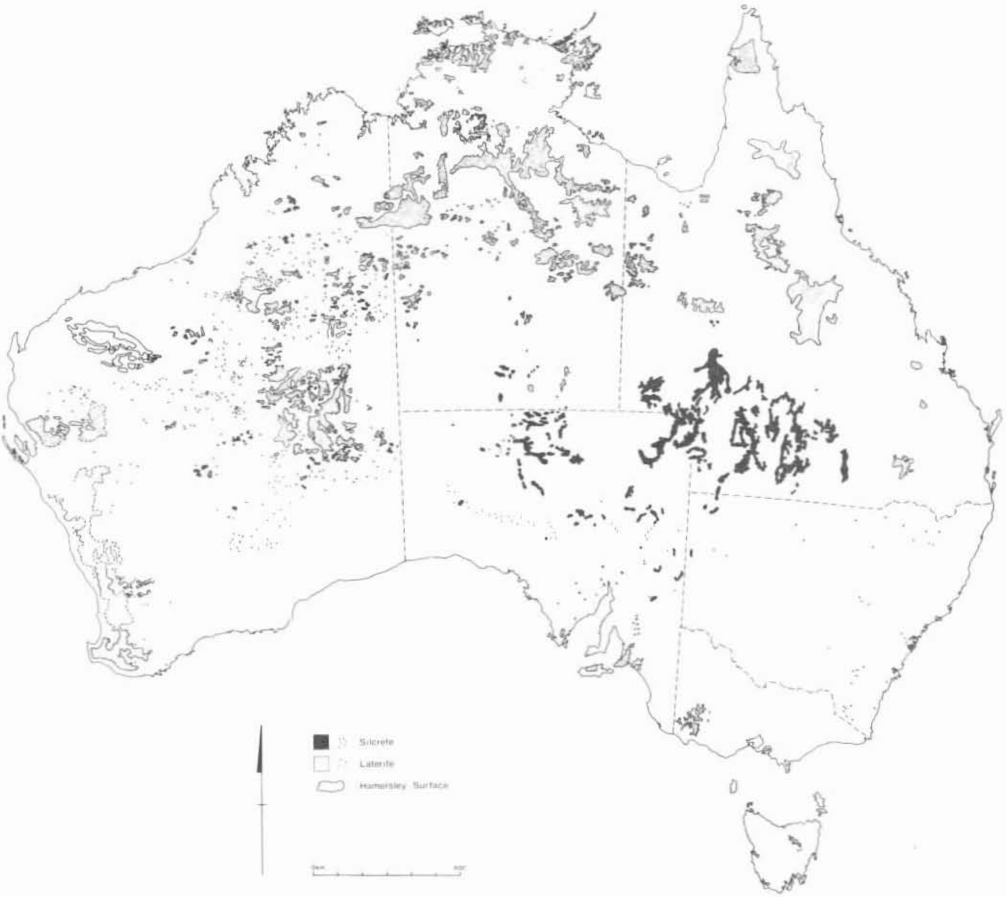


Fig. 8. Distribution of laterite and silcrete in Australia

Fig. 9. An old valley floor, now a sinuous mesa capped by Robe River Pisolite, Hamersley Ranges, north of Western Australia.

plateaux of southwestern Queensland are interpreted as old valley floors, for the silcrete contains exotic rounded pebbles and cobbles. Some silcretecapped residuals are basined normal to the long axis of mesa, reflecting the old valley morphology (TWIDALE, 1983b). Similar sinuous silcrete-capped forms are well preserved near Platbakkie, in Namaqualand, South Africa (PARTRIDGE and MAUD, 1987; TWIDALE, 1990). MILLER (1937) long ago described sinuous mesas in the eastern Arabian Peninsula preserved by virtue of a capping of travertine.

On the other hand, duricrusts are subject not only to undermining and collapse adjacent to dissection zones, but are also susceptible to dissolution and collapse. The subsurface solution and flushing advocated by Trendall and Ruxton, allows for the preservation of the surface crust, though the latter is lowered and may be disturbed locally through the development of sinkholes, even in siliceous and ferruginous rocks (e.g. HUMBEL, 1964; WIRTHMANN, 1970; TRESCASES 1975; ISPHORDING, 1983; TWIDALE, 1987b).

Structure alone, however, cannot account for the survival of divides. Most commonly a combination of circumstances causes persistence. Thus, though persistent caprocks undoubtedly assist preservation, divides in weak unlithified strata are well preserved in places. Their durability is in some instances measured in millenia rather than scores of millions of years, but some have apparently survived several scores of millions of years at least (e.g. TWIDALE, 1980).

Accelerated soil erosion in the form of gullying is commonplace in many parts of

Fig. 10 (a). Gully cut into alluvial fan apron fronting the Willunga Scarp, south of Adelaide, South Australia. Its recent origin is indicated by its location vis A vis the well (A) dug in the 1850s.

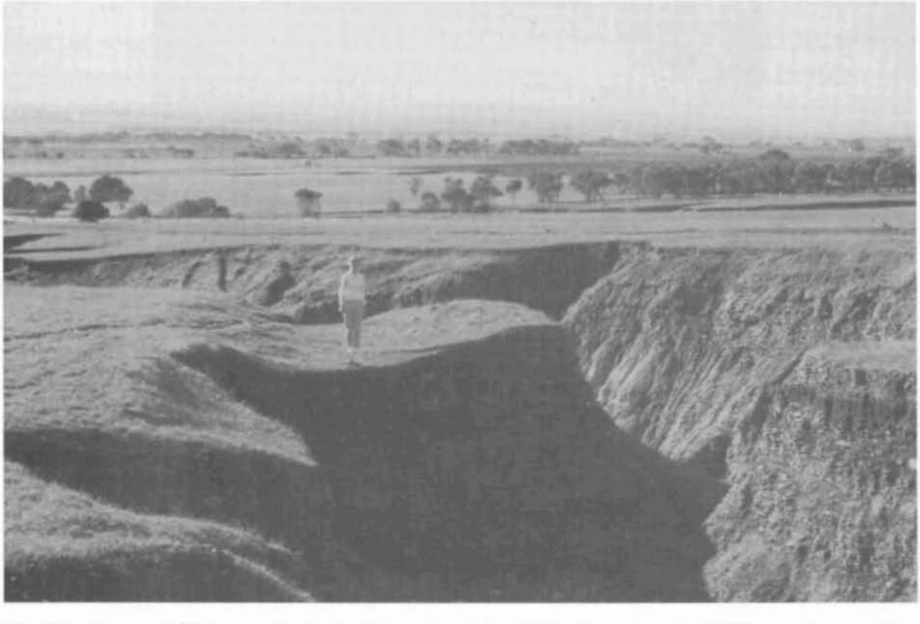


Fig. 10. (b). Cut and fill in a gully incised into the alluvial fan fronting the Willunga Scarp. The old valley floor and sides are clearly visible. A - older (Late Pleistocene) fanglomerate; B - younger valley fill; x-y, unconformity between A and B; T terrace.

(c) Remnant of stream channel associated with deposition of valley fill B in Fig. 9b.

the world, and though in a different time frame from the landscapes under immediate focus, well illustrate the effects of unequal erosion, even in weak materials. Take, for example, the gullies developed on the Willunga Scarp, south of Adelaide. They take the form of narrow valleys deeply (5-6m) incised in fanglomerates of the alluvial apron which fronts a fault scarp (Fig. 10a). The divides are smooth and gently inclined. In detail the valleys are complex for there is consistent evidence of cut and fill (TWIDALE, 1969), with two periods of incision following phases of deposition (Fig. 10b and 10c). The latest incision post-dates European settlement of the area in the eighteen fifties. The red-brown fanglomerates are, by analogy with similar deposits in the Adelaide district, of latest Pleistocene age (WILLIAMS, 1969), and the second phase of deposition, of a grey coloured valley fill, is probably Middle Holocene (TWIDALE, 1968). The first dissection must have taken place in latest Pleistocene or earliest Holocene times.

Both phases of dissection involved the erosion of deep but narrow valleys, and this despite the unconsolidated nature of the fanglomerate. What has allowed the extensive divides between adjacent gullies to be so well preserved? The rivers are deeply incised so that the water table is located well below the fan surface. The fanglomerates are permeable so that meteoric waters readily infiltrate the country rock. Though cleared of trees, winter rains allow the growth of grasses which form a groundcover and bind the soil. High summer temperatures cause the surface clay to be baked and to form a crust, which with the roots of grasses, even those that have died through lack of water, bind the soil to form a weak but effective carapace.

Vegetation is an aid rather than being essential, useful rather than critical, to the survival of divides in weak materials. This was, demonstrated in a road cutting in weathered granite or grus and exposed near Cape Town, South Africa, in 1979. Rills had incised deeply (more than 1 m) into the slope which was then totally devoid of vegetation (Fig.11). The intervening divides were undoubtedly ephemeral but it is surprising in that they existed at all. The sides of the gullies were deep, steep and in places their sidewalls were overhanging. The interfiuves were rounded, and not planate. Baking of the exposed grus in the summer sun may be a factor but vegetation cover plays no part.

On a regional scale, plateaux deeply scored by narrow gorges occur in sandstone and quartzite, as for instance in the Blue Mountains, near Sydney, New South Wales; in the Kimberleys of northern Western Australia; and, especially in the Cape Fold Belt of South Africa where the Storm River and its tributaries, for instance, have eroded deep narrow slots in the sandstone ridges (Fig.12a). Basalt too gives rise to plateau and gorge assemblages, which may seem surprising because basalt ought, on account of its mineralogy, to be readily weathered; but it is well-fractured. Where baselevel has allowed deep incision of rivers, meteoric waters readily infiltrate through the rock mass. Left high and dry, basalt, like many other rocks (see e.g. BARTON, 1916), is stable. This is the reason for the dramatic gorge of the Zambezi River below the Victoria Fails, in western Zimbabwe, inset in a featureless high basalt plain (Figs. 12b and c); the gorge of the Rio Grande near Taos, New Mexico; the Snake River Canyon in Idaho, northwestern U.S.A., and the many

Fig. 11. Deep narrow gullies eroded in weathered granite or grus exposed in a road cutting near Cape Town, South Africa.

Fig. 12 (a). Deep narrow valley cut in sandstone near Knysna, in the Cape Fold Belt, South Africa.

gorges in the basalt plateaux and high plains of north Queensland, northern Australia (Fig. 12d). As for gorges in granite there is no better example than that of the Orange River at Aughrabies, in southern Namibia (Fig. 12e). In each case, deep incision and consequent through drainage are important factors.

Vegetation is not a critical factor because in many of the cases cited the climate is arid or semiarid, and vegetation is scarce.

Uplift is critical to the preservation of these divides, for it is uplift that induces incision and through drainage, divaricating drainage off the uplifted blocks, and the essential aridity of the divides. The uplift may be tectonic, that is epeirogenic; or it may be isostatic and be triggered by the erosional unloading of some structural blocks, the depositional loading of others, and the development of a see-saw effect between the two types (see e.g. TWIDALE, 1991; TWIDALE and CAMPBELL, 1992). Or, of course, both tectonism and isostatic adjustments may be involved.

Crustal stresses play a part in the preservation of divides through the control they exert on fractures and perviousness. Only rarely are palaeosurfaces preserved in weak rocks such as mudstone and siltstone. Where they are, as in the central Flinders Ranges, it can be suggested that deep erosion has brought the land surface into the deeper compressional zone of anticlinal structures; just as some granite bornhardts are well preserved because they are sculpted from the deeper compressional zones of antiformal structures in the country rock.

These various factors achieve maximum effect when and where two or more coincide

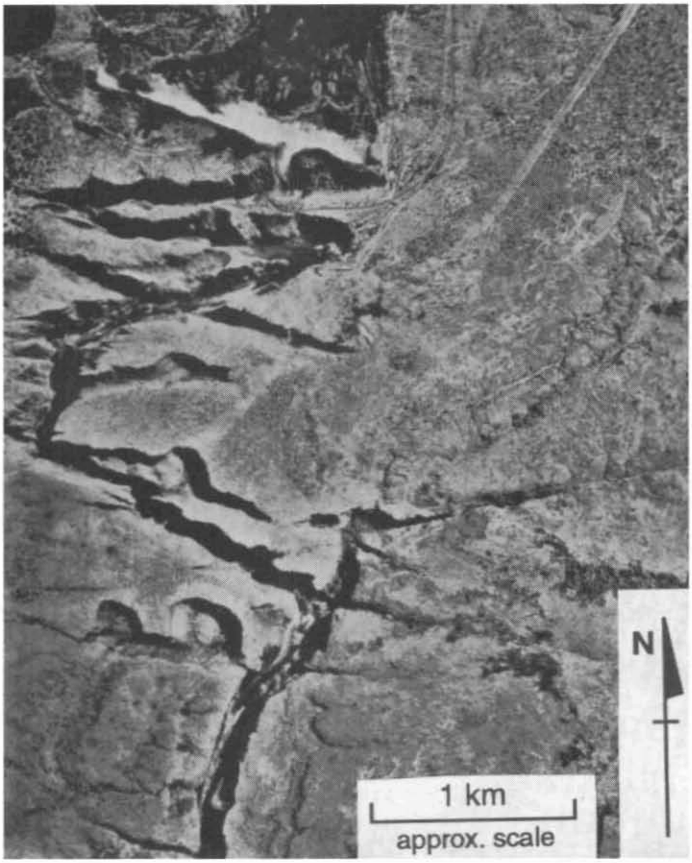


Fig. 12 (b). Air photograph of basalt plateau, showing the fracture-controlled gorge incised by the Zambezi River, downstream from Victoria Falls, western Zimbabwe (Department of Lands and Survey, Rhodesia).

Fig. 12. (c) The Zambezi River flowing in a deep narrow gorge cut in basalt just below the Victoria Falls.

in time and space, and reinforcement or positive feedback mechanisms operate. The optimal situation occurs when a land surface underlain by resistant and pervious or permeable bedrock is uplifted, either as a result of tectonic compression or because of erosional unloading and consequent isostatic adjustment, or both. Rivers draining the uplifted mass are incised. Tributaries and subsurface waters drain to the incised rivers so that erosion is concentrated in their valleys, leading to further incision and concentration of drainage. Meantime the intervening divides lack surface drainage and remain virtually untouched.

RIVERS AND REINFORCEMENT

The inherent positive feedback characteristics of rivers are a major factor in the survival of land surfaces. Once established, a few major rivers attract both surface and subsurface waters, and the deeper they incise the more drainage accrues to them. Only baselevel limits this competition between rivers for regional run off and subsurface flows. Major rivers become widely spaced, and, all else being equal, intervening scarps and divides persist essentially untouched. A physically hard, chemically relatively inert, permeable or pervious substrate, such as sandstone, quartzite and despite is composition, basalt, enhances this possibility. Aridity is also conducive to the development of master streams, and hence of unequal activity, for if a region has been subjected to desert conditions during the period of drainage development (and this may be of long duration - at least post

Fig. 12. (d) The Galah Gorge is cut into basalt in north Queensland (CSIRO).
(e) The Orange River has incised a deep, narrow,' gorge in granite at Augrabies, southern Namibia.

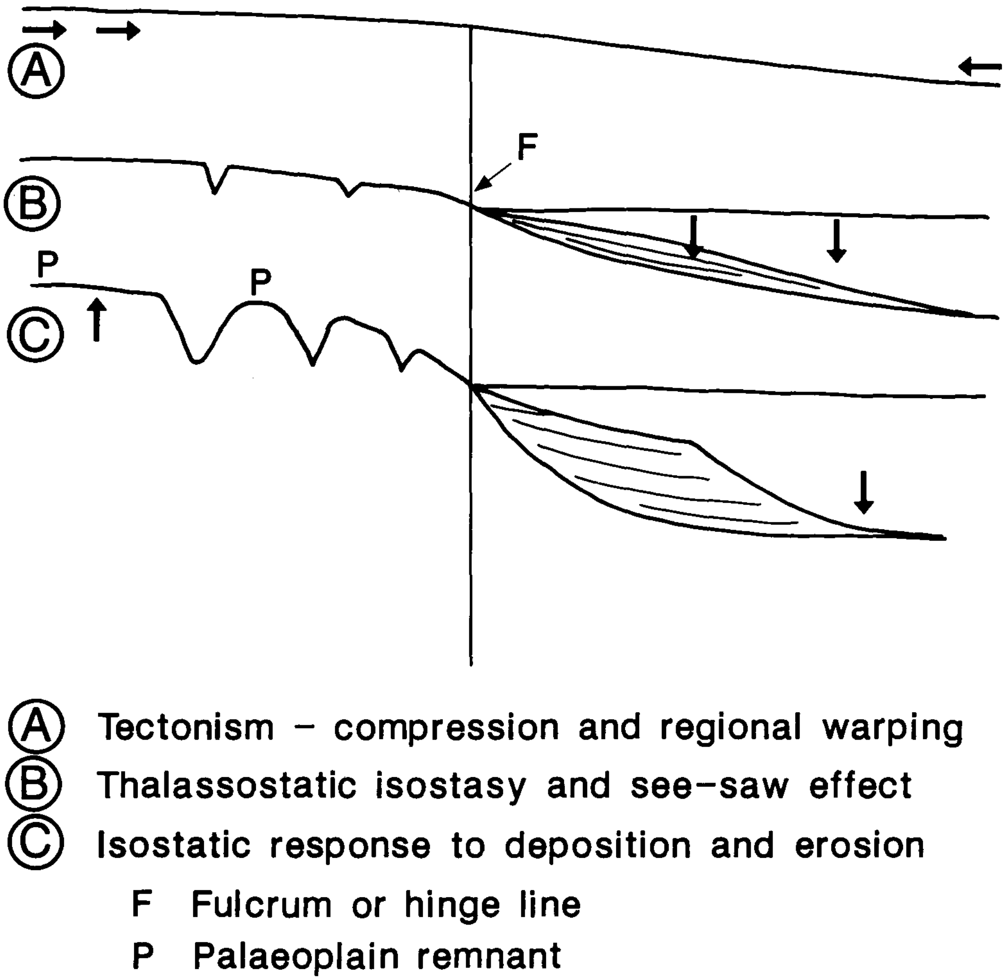


Fig. 13. Model of landscape development involving uplift and localised river activity, and resulting in survival of divides or palaeosutfaces.

Permian for example, over much of southern and central Australia) the earlier developed humid climate drainage system may have been dismembered during aridity. The surviving elements persist as the major rivers and erosional components after the restoration of more humid climates.

Reinforcement of major drainage elements at the expense of other, lesser, streams and rivers explains why river piracy is so common and why streams persist, leading to the development of transverse or anomalous drainage patterns such as are common in fold mountain belts; but which are also found in granitic terrains for example (see OBERLANDER, 1965, TWIDALE, 1966B,1972; VIDAL ROMANI and TWIDALE, 1996). Such persistence of rivers also suggests that diversions in river courses, changes in drainage pattern, can be effected only by catastrophic events such as tectonism (e.g. TAYLOR, 1911; WAGER, 1937; HARRIS, 1939; LEES, 1955; BOWLER and HARFORD, 1966), volcanic activity (e.g. SLEMMONS, 1966; STEPHENSON et al., 1980) or glacially related mechanisms (e.g. KENDALL, 1902; SHARP, 1947; STONE 1963; NICHOLS, 1969; BAKER, 1973).

A MODEL FOR SURVIVAL

Several models are more conducive than others to the long term persistence of land surfaces . The scarp retreat model intrinsically permits survival until late in the cycle. The problem is that the duration of a cycle in the continental context is, on the evidence, less than the putative age of many epigene-etch surfaces, and in a few instances their demomstrable age (TWIDALE, 1980; TWIDALE et al., 1985; CAMPBELL and TWIDALE, 1991). Trendall's subsurface wasting concept has obvious merit and ought to be an integral part of any wide-ranging hypothesis or model. Kennedy's model allows for the development not only of peneplains at various elevations in the landscape, but also includes the uplift emphasised by TWIDALE (1991) and TWIDALE and CAMPBELL (1992) as well as implying unequal erosion and the survival of divides in the manner suggested by Crickmay.

A model embracing all of these critical elements is illustrated in Fig. 13. It is envisaged that weathering and erosion result in a surface of low relief. A regolith develops on the surface. Differential weathering at the base of the regolith produces a relief, both major and minor, on the weathering front. Uplift due to tectonism, or to thalassostatic isostasy, causes erosion of uplifted blocks and deposition on the lowlands, causing further isostatic adjustments. The regolith is stripped from the uplands, exposing an etch surface. The uplands also shed water and in areas of permeable or pervious rocks, vadose waters infiltrate to the watertable. Only major rivers persist and incise deep gorges, leaving the uplifted surface essentially intact. Remnants of the old regolith are preserved in clefts and in depressions, and a new regolith may evolve in time, but widespread remnants of the etch surface remain as an integral part of the contemporary land surface.

The valley-side slopes are worn back, but only slowly. The divides are dry sites and so endure: hence the very old land surfaces preserved high in the relief in many parts of the world, and in unconformity in many basins and depressions. This model accounts for the numerous Pangaean remnants reported from many parts of the world, in low and high latitudes, in glaciated and non-glaciated lands (see e.g. TWIDALE, 1976, 1994; TWIDALE and CAMPBELL, 1988; TWIDALE and VIDAL ROMANI, 1994a). The keys to survival are uplift, unequal activity and reinforcement mechanisms. None of the conventional cyclic models is compatible with the survival of paleosurfaces, and the same comment applies to models invoking dynamic equilibrium.

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Recibido: 15/5/97

Aceptado: 11/10/97