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Multistage Landform Development in Various Settings and at Various Scales

Desarrollo de formas multietapa en varias situaciones geomorfológicas y a diferentes escalas

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ABSTRACT

That many landforms have their origins in the distant past is highlighted by the multistage concept, whereby the structural properties of bedrock which have been exploited by shallow groundwaters are taken fully into account. Fractures of various types are particularly vulnerable to weathering and hence to erosion. Examples are discussed from various lithological and environmental settings - plutonic, volcanic and sedimentary rocks, and different climates.

Key words: multistage; fractures; folds; magmatic, tectonic, lithological setting; underprinting.

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INTRODUCTION

Many landforms are now widely recognised as being of two-stage or etch type; and this terminology acknowledges the roles of weathering and erosion in their production. But because such forms are due to the exploitation of bedrock weaknesses by moisture at the weathering front, it has been suggested that account ought to be taken of the origin of these weaknesses and that such features would better be described as multistage (TWIDALE & VIDAL ROMANI, 1994). Multistage development is climatically and lithologically azonal. Most obvious examples involve exploitation of fractures but, as is illustrated here, other preparatory events – tectonic, magmatic, sedimentary - ought also to be considered in this context.

FRACTURES AS AVENUES OF WEATHERING

Most weathering takes place in the shallow subsurface and is due to water-related processes such as solution, hydration and hydrolysis. Any factor which facilitates contact with water is a significant determinant of the distribution of weathering and hence subsequent erosion. Fractures are particularly important in this regard, and especially in impermeable igneous rocks and such sediments as crystalline limestone. Fractures occur at various scales. The importance of fracture patterns in small scale landform development can be illustrated by reference to corestones and boulders. These forms have the additional advantage of signalling the importance of other factors and the principle of convergence in geomorphology.

Corestone boulders

Though some boulders are derived from the disintegration of sheet structures and subsequent rounding of the resultant blocks, most boulders are two-stage forms, having originated as a result of subsurface weathering, of blocks defined by orthogonal fractures. Corners and edges are rounded. This produces spherical corestones of fresh rock set in a matrix of weathered bedrock. The evacuation of the weathered detritus exposes these corestones as boulders. Corestones are remnants of fracture-defined blocks located within the regolith and separate from the weathering front, of which, however, they can be regarded as discrete parts. The operation of such a mechanism is attested not only in granitic terrains but also in various other plutonic and igneous rocks including basalt, and also in sediments such as sandstone and limestone (figure 1a). Most commonly the tranformation of angular joint blocks to rounded corestones is due to the more rapid weathering of corners and edges than of plane faces: *Nature mutat quadrata rotundis* (MacCULLOCH, 1814, p. 76; see also de la BECHE, 1839, p. 450). Thus the spacing of fractures partly determines the maximum size of corestones and hence boulders, though duration of subsurface weathering and of weathering after exposure also play a part.

But not all corestones and boulders are formed in this way. The outlines of corestones of Palaeozoic granodiorite exposed in road cuttings near the Tooma Dam, in the Snowy Mountains of New South Wales, coincide with patterns of mineral banding due to magmatic currents (figure 1b). BARBEAU & GÈZE (1957) described from the Lake Chad region of West Africa corestones of granite embedded in a matrix of rhyolite and which they attribute not to weathering of the granite followed by invasion of the rhyolite (which would be physically difficult, if not impossible), but to globules of still liquid granite being mixed with faster crystallising rhyolite, i.e. to a deep-seated magmatic process.

Pillars at Murphy Haystacks, Eyre Peninsula

Murphy Haystacks illustrate the effects of orthogonal fracture systems in which individual partings are widely spaced and where, more importantly, the exposed bedrock forms remain in physical continuity with the main mass of country rock, suggesting that the assemblage now exposed was once at the base of the regolith. The Haystacks are so called because from a distance that look like haystacks and as they stand on what was Pat

Figure 1. Corestones in basalt, southern Drakensberg, Eastern Cape Province, South Africa.

Figure 1b. Corestones and mineral banding exposed in road cutting near the Tooma Dam, Snowy Mountains, New South Wales, Australia.

Murphy's property. They stand on the crest of a low hill a short distance from the northwest coast of Eyre Peninsula, and consist of two groups of granite pillars between 3 and 4 m high, developed on fracture-defined blocks (figure 2). Tafoni are formed in many of the pillars. The flanks of the pillars are flared and calcrete developed on a dune calcarenite is lodged in the base of some of the joint clefts and tafoni (TWIDALE & CAMPBELL, 1984). The following compressed developmental sequence can be reconstructed from the field evidence:

-1. Emplacement of the granite *ca*. 1.58 Ga.

-2. Development of orthogonal fracture systems (by analogy with geometrically similar systems in the Gawler Ranges - see below - *ca*. 1.4 Ga).

-3. Subsurface exploitation of steeply inclined fractures, and development of flared bedrock surfaces.

-4. Lowering of surface and exposure of pillars with flared sidewalls.

-5. Covering or partial burial of the granitic assemblage by dune calcarenite during middle-late Pleistocene (WILSON, 1991).

-6. Formation of calcrete about 14,000 years B.P.

-7 Erosion of much of the calcarenite cover.

Hyden Rock, Western Australia

In addition to illustrating the impact of open fractures which are some tens of metres apart and which give rise to major relief features, the multistage concept as applied to Hyden Rock also helps explain certain details of morphology.

Hyden Rock is a complex domical inselberg, or bornhardt, located near the small town of Hyden about 120 km east of Perth, Western Australia. It consists of three domes, the central and western separated by a deep valley (now occupied by a reservoir), and the central and eastern linked by a low platform or large radius dome (figure 3a). Sheet structure and joint clefts are prominent, as are flared slopes, including the well-known Wave Rock (figure 3b). In addition, a wide range of minor landforms including basins, rock

Figure 2. Granite pillars at Murphy Haystacks, northwestern Eyre Peninsula, South Australia.

doughnuts, tafoni and pitting; small fault scarps and A-tents (or pop-ups); and low linear ribs and 'tram-lines' is developed.

Like most bornhardts, Hyden Rock is a two-stage form (*cf*. FALCONER 1911; TWIDALE & BOURNE, 1998). A range of evidence and argument can be marshalled in support of this conclusion (TWIDALE, 1982, pp. 124 et seq.; VIDAL ROMANI & TWIDALE, 1998, pp. 153 et seq.) but the most compelling evidence derives for those several occurrences in artificial exposures of incipient domical masses already in existence in the subsurface. Such a two-stage interpretation explains why, though very well represented in the humid tropics, bornhardts are found in many different climatic regions, for apart from the realities of climatic change, weathering is ubiquitous and low rates of weathering can be compensated by long duration.

In the southern Yilgarn Craton, the first stage of differential subsurface weathering took place in Cretaceous times, 100-130 Ma, the second, exposure, in the Cainozoic, beginning with the uncovering of the highest crest in the Eocene, about 60 Ma, for Hyden Rock was evidently exposed in stages (TWIDALE & BOURNE, 1998).

The sequence of events during which originated the various major and minor features displayed on the Rock can be identified:

-1. Emplacement of the granite about 2.64 Ga (CHIN *et al*., 1984).

-2. Development of orthogonal fracture systems in cooled brittle rock by shearing. The compressional strains were eventually manifested in sheet fractures which may have originated at this time, either directly or induced by shearing (WEISSENBERG, 1947).

-3. Intrusion of aplite sills and also veins of quartz and epidote.

[Events 2 and 3 occurred soon after the emplacement of the granite.]

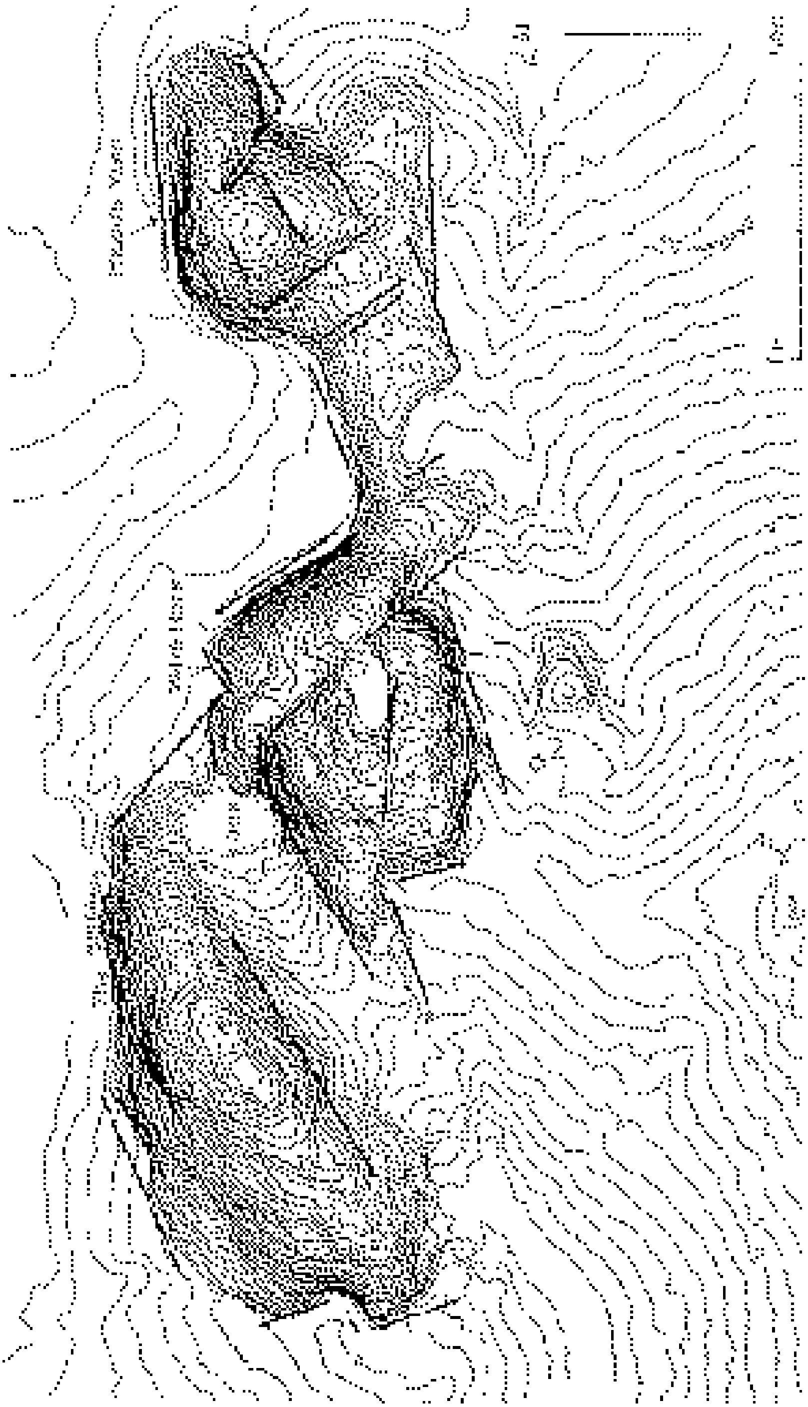

Figure 3a. Topographic map of Hyden Rock, Western Australia, with major fractures also shown. (After TWIDALE & BOURNE, 1998).

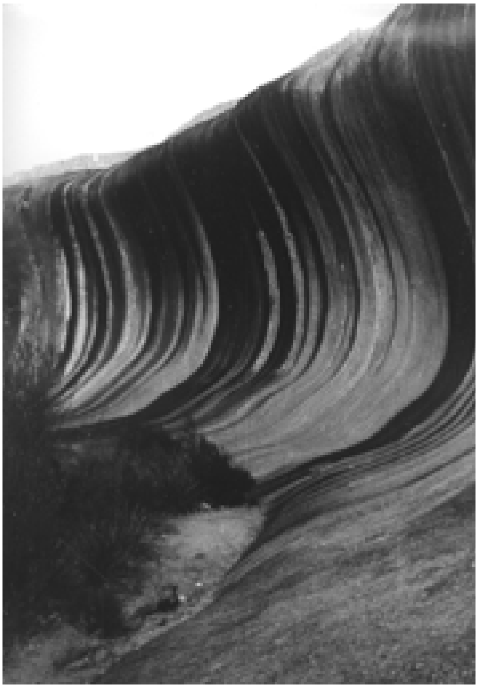

Figure 3b. Wave Rock, a flared slope 14-15 m high in the northern piedmont of Hyden Rock.

-4. Subsurface weathering beneath a lateritised land surface in Cretaceous times (100-130 Ma).

-5. Dissection of surface about 60 Ma following separation of Australia and Antarctica and tilting of what is now southern coastal area of Western Australia. Crests of Hyden Rock exposed, together with some sheet fractures, basins and gutters.

-6. Concentrated moisture attack around base of the domes: incipient flared forms, and also large depressions, later to become armchair-shaped hollow, developed at the weathering front.

-7. Further lowering of plains and exposure of more of the bornhardt with flared slopes at margins. Lowering of northern plain, adjacent to the palaeoriver Camm, greater (by about 20 m) than on southern side, so that higher flares (like Wave Rock and The Breakers) are exposed on the northern face.

-8. In recent times, (a) seismicity has caused minor fault scarps and numerous A-tents. (b) Human activities have induced changes in vegetation and hence rates of weathering and erosion, and the valley between the central and western domes was dammed (in 1951), and walls built to divert water into the reservoir. Runoff on to some flared slopes and piedmonts was thus reduced and rate of weathering on exposed slopes and also below the soil surface at the margins of the Rock presumably decreased. (c) Meantime, weathering and erosion have continued: basins and gutters, rock doughnuts and tafoni have developed, and sheet structures have further broken down. Flutings with algal veneers have developed on slopes and some have become inverted. Degradation of algal cover on some flutings has led to the disintegration of channel floors and the formation of "button holes". Areas protected against water contact and scouring remain in local relief (TWIDALE & BOURNE, 2000a).

Bornhardt landscape of volcanic origin

Though well and widely developed in granitic rocks, bornhardts and bornhardt landscapes are found in many other lithological environments, including volcanic and sedimentary. The only requirements are a preferably impermeable rock with compartments of contrasted fracture density, and stable periods sufficient to allow quite deep differential weathering.

The chronology of evolution of a bornhardt landform assemblage (figure 4a) of the Gawler Ranges, developed in a Mesoproterozoic ignimbrite sequence, and located in the arid interior of South Australia, can be traced back some 1.6 Ga (CAMPBELL & TWIDALE, 1991):

-1. Extrusion of ash layers about 1.5 km thick, circa 1.6 Ga (BLISSETT *et al*., 1993), followed by rapid cooling, welding and development of systems of columnar joints. The geometry of cooling surfaces determined the orientation of columnar jointing and hence the details of hillslope morphology typical of a volcanic region (figure 4b).

-2. Prior to 1.4 Ga, orthogonal fracture systems (figure 4c) formed in brittle rocks (formed before deposition of Pandurra Formation and intrusion of dolerite sills dated *ca* 1.1 Ga).

-3. Following the late Palaeozoic (Permian) continental glaciation (which affected most of the continent) but prior to the Early Cretaceous, the ignimbritic mass was subjected to fracture-controlled differential subsurface weathering which resulted in the subterranean formation of ordered rows of nascent bornhardts.

-4. During the Early Cretaceous (Neocomian-Aptian) and as a result of upfaulting and tilting, the regolith was largely stripped, the detritus deposited in marine sequences in the Eromanga Basin, and the bornhardts exposed.

-5. Since the Early Cretaceous, the valley floors and piedmonts of the uplands were weathered and silcreted in Eocene times, and there has been some gullying in valley floors, but the massif has remained essentially unchanged.

Figure 4a. General view of part of Gawler Ranges, South Australia, showing bornhardts and bevelled crests near Spring Hill. Note sheet structures exposed right foreground.

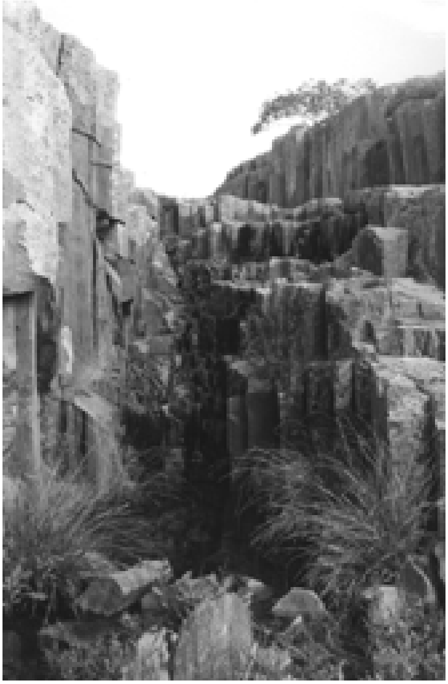

Figure 4b. Columnar joints in dacite.

Sedimentary inselbergs of Central Australia

Bornhardt landscapes are developed in sedimentary terrains as well as on plutonic and metamorphosed (welded) volcanic rocks. Examples include the cupolakarst of many limestone outcrops. Domical residuals and towers shaped in arenaceous and rudaceous rocks are exemplified by the conglomeratic towers of Meteora, conglomeratic towers in the Pyrenees (e.g. BARRÈRE 1968) and in the Logroño area of the Ebro Basin of northern Spain, and the sandstone domes of West Africa (MAINGUET, 1972).

The Olgas, Ayers Rock, and Mt Conner are three prominent but contrasted inselbergs located in the deserts of central Australia southwest of Alice Springs. All are sculpted in folded Early Palaeozoic strata, but The Olgas is a complex of conglomeratic domes, Ayers Rock an arkosic monolith, and Mt Conner an isolated mesa located in the trough of a regional basin structure. The development of The Olgas and of Ayers Rock is not due to lithological factors for similar strata underlie the adjacent plains. The three residuals are aligned along a WNW-ESE axis (bearing 100°) and are best explained by cross- or interference-folding, with effective north-south compression superimposed on NNW-SSE trending folds developed during the Devonian Alice Springs Orogeny (WELLS *et al.*, 1970; TWIDALE, 1978).

Thus the occurrence of these three inselbergs is due to tectonic events. On Ayers Rock the Kangaroo Tail is a sheet structure due to compressive stress related to continued plate migration and joggling of constituent blocks (figure 5a), and the ribbed upper summit surface and flanks reflect the steep dip of strata. The well-known Brain (figure 5b) is due to the weathering of bedding planes; and so on – the effects of past tectonism continue to be exploited.

FOLDING

Faulting and folding are expressions of crustal stress. The end result varies according to the intensity and duration of the forces applied, and the competence of the rocks affected. Conditions of sedimentation in past eras as well as structure find expression in landscape and landform development down the ages, and again at various scales.

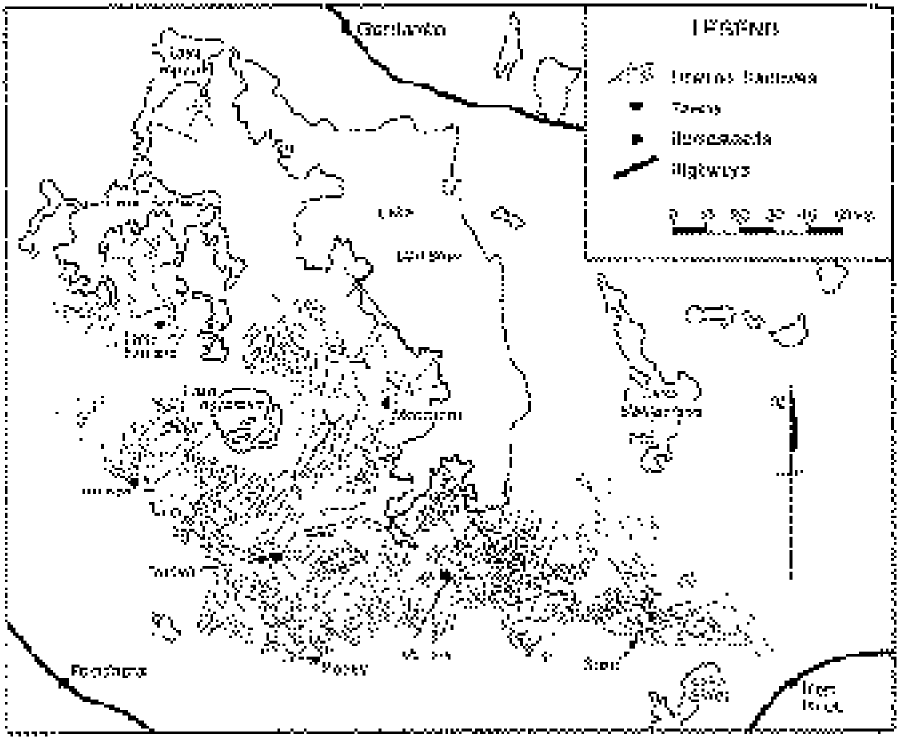

Figure 4c. Plan of steeply dipping fractures. Source: Landsat imagery. (After CAMPBELL & TWIDALE, 1991).

Figure 5a. The Kangaroo Tail, a sheet structure developed in steeply dipping Cambrian arkose on the northwestern flank of Ayers Rock.

Figure 5b. The Brain, located high on the eastern slope of Ayers Rock. The crenulations are due to the explotation by water-related weathering processes of steeply dipping bedding. The outline is fortuitous.

Flinders Ranges, South Australia

Because of the strains imposed on sedimentary sequences during folding, examples of structural highs becoming topographic highs and of lows becoming high are commonplace in fold mountain belts. In the southern Flinders Ranges, South Australia, the Willochra Basin or Plain occupies a regional anticlinorium (figure 6) and to east and west respectively, the Horseshoe and Dutchmans Stern Ranges are developed on a local basin and a pitching local syncline outlined by quartzitic beds (TWIDALE & BOURNE, 1996).

The Flinders Ranges, in the arid and semiarid interior of South Australia, is a fold mountain belt of Appalachian type. Though dominated by ridge and valley, developed on Neoproterozoic and Cambrian strata prior to the Middle Eocene and accentuated through phases of valley floor excavation, a summit surface, mostly of epigene or etch type and of Cretaceous age, but exhumed and preCretaceous in the extreme north, is also prominent (TWIDALE & BOURNE, 1996).

In large measure, the pattern of ridge and valley reflects the relative resistance of quartzitic and sandstone, and in lesser measure limestone and tillite outcrops, and the relative weakness of argillaceous, and in places limestone, beds. But the distribution of these strata (figure 7) of contrasted resistance to weathering and erosion, reflects conditions of sedimentation in the Neoproterozoic and earliest

Figure 6. East–west section across the Willochra Basin and Plain.

Palaeozoic as do the thickness of strata which in some degree – disposition and fracture density also play a part - determine the topographic prominence of a given outcrop. In the southern and central Flinders Ranges the Gawler Craton, to the west of the upland, was the main source of detritus (PREISS, 1987; PARKER *et al.*, 1993; see figure 8). For this reason the major quartzites and sandstones are thickest in the west and thin to the east. For example, the arenaceous beds of the Pound Subgroup are more than three times as thick in the west, where they give rise to the high ranges of Wilpena Pound and the Elder, Chace, Druid and Heysen ranges, as they are in The Bunkers, shaped in the easterly extensions of the equivalent strata.

To the north, however, the Curnamona Block, located to the east of the upland (figure 8) was the main source area for sediment and here formations are thickest in the east and thin to the west. Eastern ranges such as the Gammons are topographically prominent. This distribution also influences drainage patterns (figure 8). Though trellis and annular patterns due to a combination of structural control and stream piracy are characteristic of the ranges, the notable asymmetry of the Wilpena-Siccus drainage, for example, reflects the regional structure and hence Proterozoic environments. The headwaters of the Wilpena Creek rise within a kilometre of the western escarpment of the upland, but they flow east across the range before joining the Siccus and running to Lake Frome: headward erosion was more rapid through the thinner steeply dipping quartzites of the east than through the massive quartzites that form the western ramparts of the Flinders. Similarly but conversely, to the north, westerly- and northerly-flowing rivers such as the Taylor, Frome, Burr and Windy systems are areally dominant over such eastern stream systems as the Donkey Water, Mount McKinlay and Weetoota creeks.

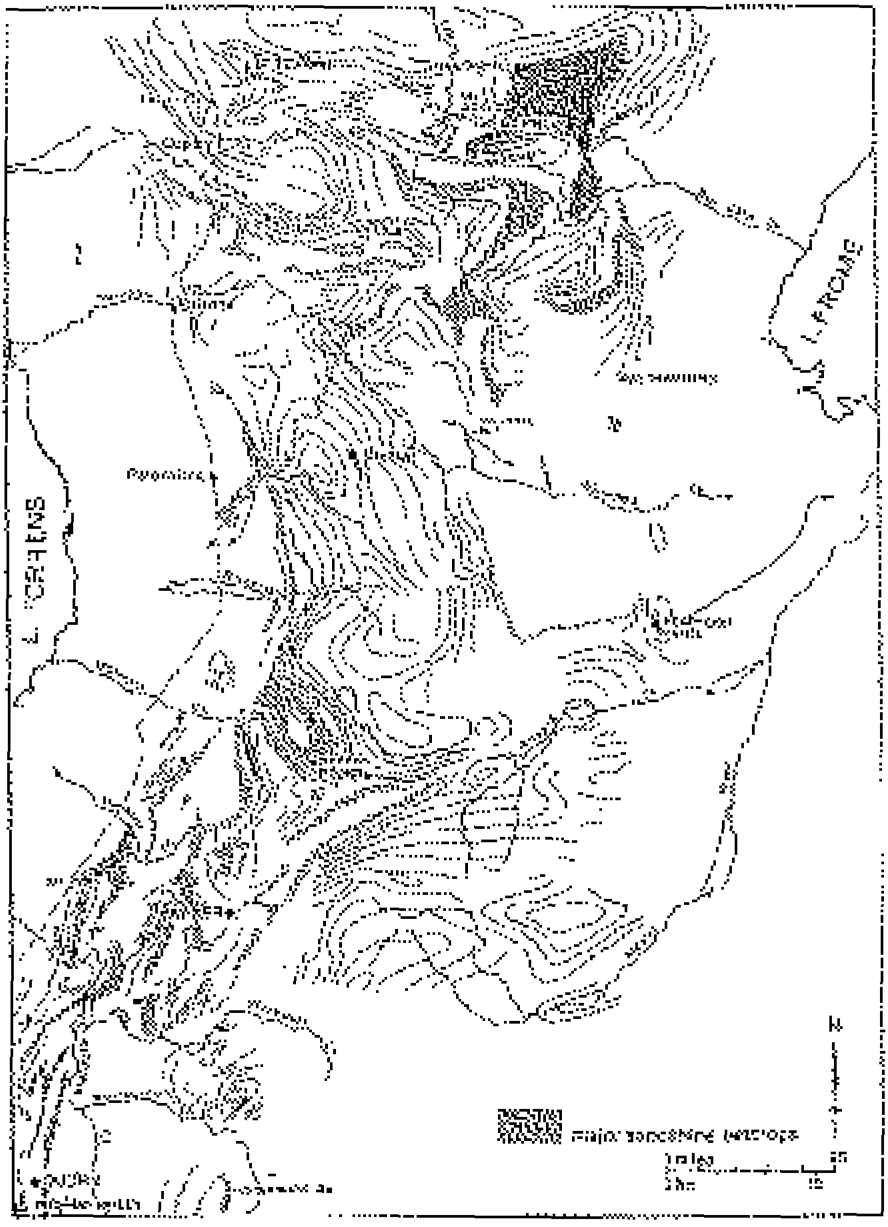

Figure 7. Structural map of the Flinders Ranges with major quartzite and sandstone formations shown in stipple.

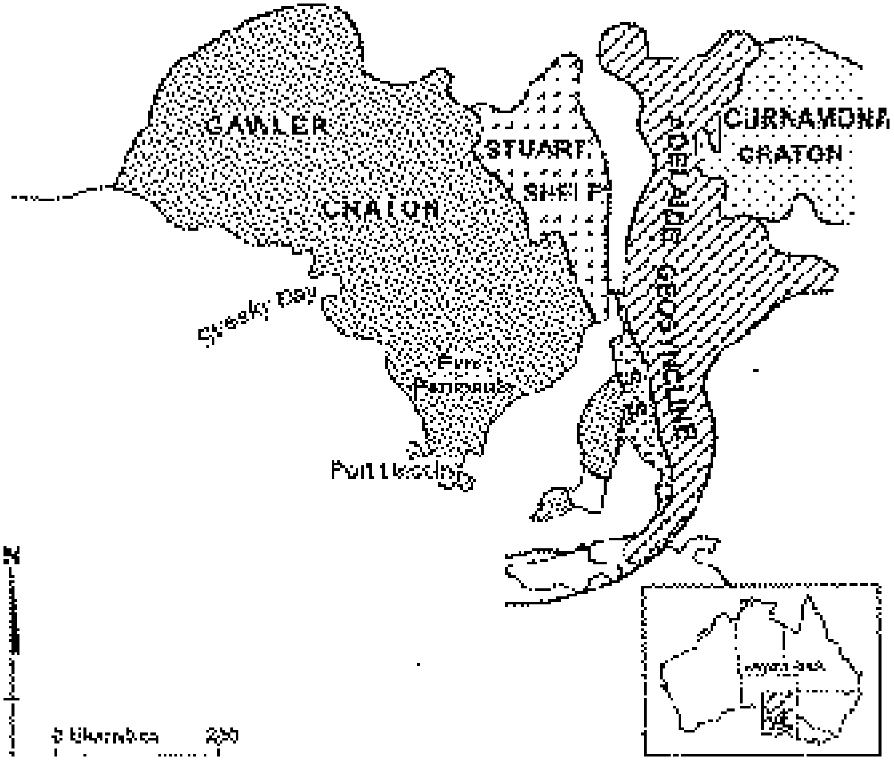

Figure 8. Tectonic setting of the Flinders Ranges (northern Adelaide Geosyncline) between the Gawler Craton and Curnamona Block.

Lochiel Landslip, South Australia

The Lochiel Landslip (figure 9a), located about 115 km north of Adelaide, represents a slippage of about 250,000 m^3 of quartzite downslope and along a bedding plane. It formed overnight on 9-10 August 1974. The Landslip occurs on the east-facing side of a valley incised into the eastern slope of the Bumbunga Range. The Range trends north-south, and is bounded on the east by an Eocene fault; there is geophysical evidence suggestive of a fault to the west also, so that the range may be a horst block. It is developed on an east-dipping sequence of cross-bedded (the detailed sedimentary structures are outlined by thin bands of magnetite) Proterozoic quartzite overlying shale. Numerous earthflows and landslides were initiated in 1916 and 1923 and have been recurrently active since, and especially in the '70s. They score the the west-facing scarp where they originate at the junction between the quartzite above and the siltstone below, and in the heads of valleys. Apart from a small slide formed at the lithological junction and low on the scarp, the Landslip is the only mass movement on the eastern slope.

The Landslip is unusual in that it is developed in quartzite. It is not due to unbuttressing by river erosion of the toe of the hillslope for the river was not running at the time of its formation and the Slip does not extend quite to the base of the slope. The winter of 1974 was wet and the Landslip originated as a crack formed high on the hillslope in the previous May. In August, strata to a depth of at least 12 m slid in three connected lobes, along bedding planes, which were lubricated by attenuated lenses of smectite. A prominent tension crack was created at the head of the movement (figure 9b). Since 1974, cracks have extended northwards along the slope. A large area will eventually move downslope (TWIDALE, 1976, 1986).

Thus in order to understand the Landslip it is necessary to go back to the Proterozoic:

Figure 9a. The Lochiel Landslip, South Australia, from the southeast.

Figure 9b. Tension crack at head of Landslip, 1974.

-1. Deposition of Tregolana Shale (*ca*. 1 Ga).

-2. Deposition of Simmens Quartzite as beach or shallow water sand plain and with intercalated lenses of clay laid down in shallow intertidal pools (1 Ga).

-3. Folding and faulting of sedimentary sequence in Delamerian Orogeny (Early Palaeozoic, *ca*. 520-420 Ma).

-4. Renewed(?) upfaulting of Bumbunga Range (Eocene, *ca*. 60 Ma).

-5. Clearing of woodland (second half of 19th Century) and development of earthflows and landslides (mainly in 1916 and also 1923 with reactivation in 1956 and the 1970s) on the western scarp.

-6. Wet winter of 1974, and lubrication of easterly dipping bedding planes, resulting in mass movement, August 9-10.

-7. Extension of cracks from Slip northwards along adjacent slope 1974 and continuing.

RESURGENCE AND UNDERPRINTING

The effects of past events is perpetuated, first, because existing weaknesses tend to be re-exploited by later tectonic events and second, because their effects are passively transmitted through overlying strata. Once formed, a fracture zone tends to be a zone of weakness on which later stresses are concentrated. This tendency finds obvious expression in recurrently active faults such as those of the Death Valley and adjacent areas, with composite fault scarps formed during more than one phase of dislocation and with such features as wineglass valleys associated with them.

Neotectonism at Minnipa Hill, Eyre Peninsula

Minnipa Hill is a low granitic dome located near the small township of Minnipa, on northwestern Eyre Peninsula. It was affected by a minor earthquake (2.3 on the Richter scale and with its epicentre 80 km to the east) in the late morning of 19 January 1999. This caused rock bursts, and the formation of fault scarps, dislocated blocks, and A-tents (TWIDALE & BOURNE, 2000b; figure 10). Mapping of these features disclosed the presence of an earlier generation of similar forms, and subsequent monitoring allowed the small suite of later forms, including an A-tent (probably formed sometime in early 2001) to be identified.

The major dislocations involved either the reactivation of dominant fracture patterns or rupture resulting from shearing along these lines. The dominant fracture patterns are related to lineaments dating from the later Proterozoic.

Straight rivers of Great Artesian Basin

The western part of the Murray Basin is underlain by a thick sequence of flat-lying Cainozoic strata, yet fracture systems concordant with Precambrian patterns, and in particular lineament trends, are clearly discernible (e.g. HILLS, 1956; FIRMAN, 1974). One strong possibility is that resurgent (or recurrent) movements along ancient fractures has led to their trends being imposed from below, or underprinted, on the cover beds.

Several major, as well as innumerable minor, sectors of rivers drain parts of the Great Artesian Basin (figure 11). The best

Figure 10. Fault developed in the late morning of 19 January, 1999, on Minnipa Hill, northwestern Eyre Peninsula, South Australia.

known example is the Darling-Culgoa river which runs straight for almost 800 km between St George and Menindee, yet which flows through Quaternary alluvia for most of this distance. Other examples are the stretches of the Bulloa, Paroo and Warrego (NNE-SSW), the Cooper, Warburton, Thompson and Diamantina (NE-SW), and the Leichhardt, Flinders, Georgina, Hay and Eyre (NNW-SSE), though the courses of the two last-named may be influenced by dune trend.

The trends indicated are well-known lineament trends (e.g. HILLS, 1956, 1961) and the suggestion is (HILLS, 1961) that the rocks beneath the various and varied Late Cainozoic covers in which the rivers have carved their channels carry the imprint of lineaments, that these fracture zones are zones of weathering and these are underprinted on the alluvia, facilitating and favouring river development. above.

The fracture patterns of the Eucla and western Murray basins, and in the latter region, associated major drainage patterns, provide further examples of large scale underprinting (HILLS, e.g. 1946, 1961, 1963; LOWRY, 1970; FIRMAN, 1974).

Dolines in dune calcarenite, Eyre Peninsula

A similar mechanism can plausibly be invoked in explanation of anomalous dolines developed in calcarenite on western Eyre Peninsula (TWIDALE & BOURNE, 2000c).

Late Pleistocene dune calcarenite underlies a broad zone inland from the west coast of Eyre Peninsula. It originated as a field of coastal dunes formed at times of lower sea level, and the rolling topography reflects the original dune morphology. The lack of surface drainage is typi-

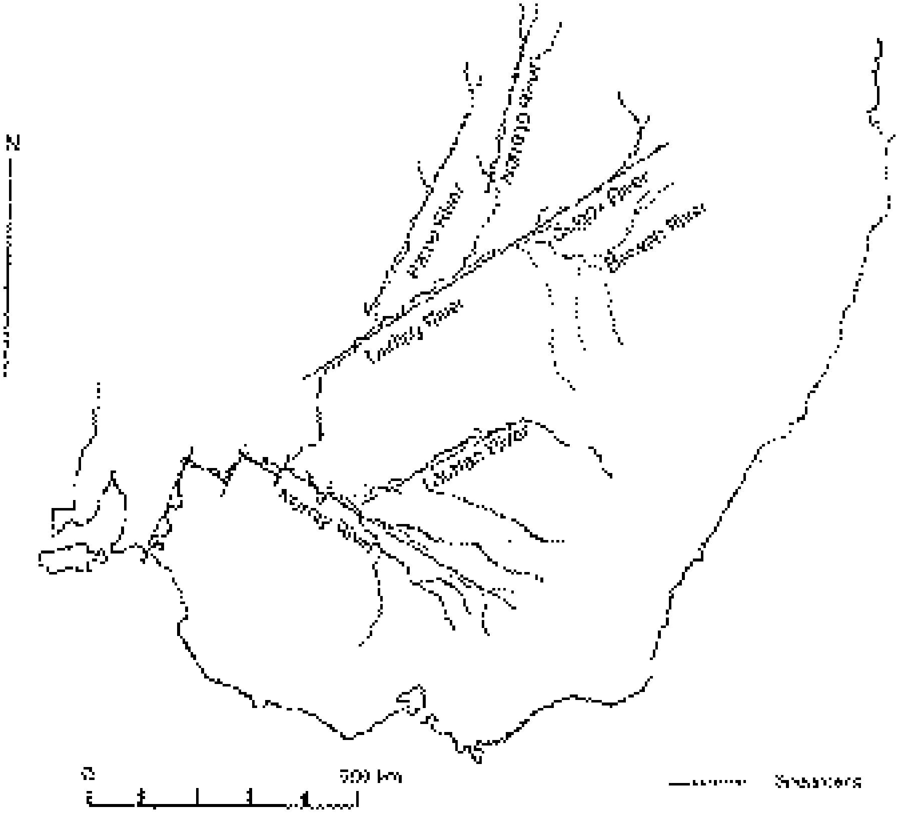

Figure 11. Map of eastern Australia showing relationship between major rivers and lineaments.

cal of karst terrains but the calcarenite is a bioclastic rock and despite buttressing by various calcrete horizons is too weak to support extensive cave development. Dolines, however, are abundantly developed. They vary in size from a few centimetres to a few tens of metres diameter. As might be anticipated, many are developed in lows in the topography, in the floors of swales or depressions. But several of the larger dolines are found high in the local relief, some on or very close to the crests of broad rises. Moreover, several large and small dolines, occur in groups and are aligned along NNW-SSE axes (WILSON, 1946-7; figure 12a). They are most plausibly explained in terms of structural conditions, not primarily in the dunerock, but inherited or underprinted from the underlying Precambrian igneous, metamorphic and sedimentary rocks, of which representatives are exposed on the coast. Fractures in the basement rock beneath the calcarenite attracted flows of groundwater, and as these in some instances are located below high points in the palaeodune topography - the pattern and topography of the dunefield is indepen-

Figure 12a. Aligned Weepra dolines east of Lake Newland, Eyre Peninsula, South Australia.

dent of local basement structure – aligned dolines form on the hills (figure 12b).

Thus the aligned large dolines can be explained:

-1. Emplacement, formation and deposition of Precambrian rocks, more than 1 Ga.

-2. Development of fractures with NNW-SSE sets prominent.

-3. Deposition of fields of coastal foredunes in later Pleistocene times (630,000-180,000 years B.P.: WILSON, 1991).

-4. Consolidation (self cementation) of dunes, and attack by meteoric waters, resulting in solution dolines. In addition surface waters were funnelled into zones above prominent NNW-SSE trending fractures in the basment rocks, and resulted in formation, by solution and collapse, of rows of large sinkholes in the calcarenite above.

CONCLUSION

Thus the origin of landscapes and landforms in various settings can be traced into the distant past:

- In some areas of igneous outcrop the size and shape of the corestones, and eventually of the associated boulders, dates from Palaeozoic magmatic events.

- At Murphy Haystacks landform evolution goes back to the formation of fracture patterns probably and by comparison with adjacent regions, to the Mesoproterozoic.

- The morphology of Hyden Rock is the result of events which can be traced back 2.64 Ga. and in the Gawler Ranges to 1.6 Ga (Mesoproterozoic) when the outlines of the present bornhardts were initiated. This landscape is one of oldest known and determined (120-130 Ma).

- In the Flinders Ranges, the topography and some aspects of drainage were determined by source areas and related sedimentation in the later Proterozoic and early Palaeozoic.

- The Lochiel Landslip is also multistage, albeit in a rather different and complex sense from the other bedrock etch forms cited here. Its origins can be traced back about 1 Ga.

- The straight rivers of the Great Artesian Basin and location and the alignment of some dolines is related to patterns of lineaments dating from the Proterozoic.

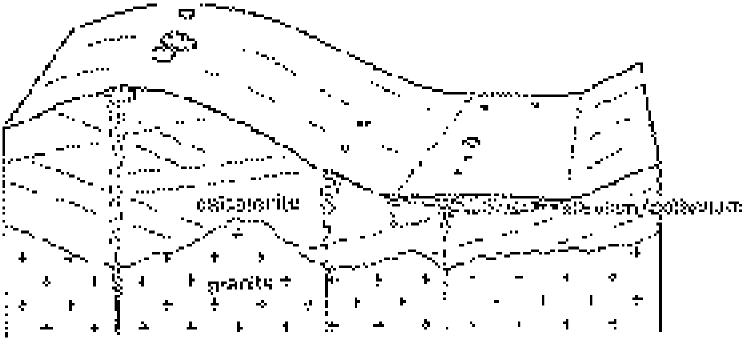

Figure 12b. Suggested development of aligned dolines through underprinting.

- Patterns of faulting and tectonic distrurbance are related to the exploitation of crustal weaknesses determined in Precambrian times.

W. M. DAVIS (1909, p. 268) stated "To look upon a landscape ... without any recognition of the labour expanded in producing it ... is like visiting Rome in the ignorant belief that the Romans of today had no ancestors"; thus emphasising the vital temporal aspect of geomorphological investigations. Many familiar landform types have complex chronologies of development. Many owe their development to the exploitation by subsurface moisture of fractures in the country rock. In order fully to attempt to understand such forms it is necessary to extend consideration far back in geological time to environments of sedimentation, early and recurrent tectonism and even to events and in magmatic chambers.

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