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# Lithologic and climatic convergence in granite morphology

# Convergencia litológica y climática en la morfología granítica

CAMPBELL, E. M., TWIDALE, C. R.

The major and minor forms common to granite (and related crystalline lithologies) and to dacite, sandstone and limestone are listed and briefly described. Factors conducive to lithologic convergence (the development of the same form in different materials) are identified. The importance of climatic factors in the development of granite landforms, is discussed, and examples of climatic convergence (landforms due to similar mechanisms but driven by different climatically controlled processes) are given. Some conclusions on the importance of granite landform evolution in general geomorphological theory are suggested.

**key words:** minor forms, granite forms,lithologic and climatic convergence, granite geomorphology.

CAMPBELL, E. M., TWIDALE, C. R. (Department of Geology and Geophysics, University of Adelaide. 5005 Adelaide. South Australia).

## INTRODUCTION

Granite outcrops display many landforms, both major and minor, that are well known and characteristic, in the sense that they are commonly associated, both in the landscape, and in our minds, with granite; and rightly so, for many are so typical of their lithological environment that a good deal of geology can be deduced from their presence. Many of these landforms are convergent in that they originate and develop in various ways, but the end product is essentially the same (CAMPBELL & TWIDALE 1995 - this volume). Thus, the field evidence suggests that most rock basins are initiated at the weathering front, but that others are wholly of epigene origin, though it is impossible to distinguish between the two evolutionary types on the basis of morphology. Again, some gutters are initiated by weathering beneath the surface, but they are undoubtedly modified by running water after exposure. Some follow fractures, but others diverge from such weaknesses in the rock to follow the steepest slope.

In addition to what might be termed mechanism convergence, lithologic convergence and climatic convergence (or azonality) are commonplace, and the remainder of this paper is devoted to a discussion of forms of these types. Examples are listed in Table 1, from which specific cases have been selected for illustration and discussion.

## LITHOLOGIC CONVERGENCE AND AZONALITY

Some landforms developed on granite have not been reported in sufficient numbers for any discernible pattern of climatic and lithologic distribution to be recognised. Studies of fonts and rock doughnuts, for example, are limited in number, and no conclusion can be reached concerning the distribution of these forms in relation to climate. They have been recorded from granite and sandstone, and they are also reported from both coastal and inland settings, but again there are too few sightings for general statements to be justified. On the other hand, it is clear that many landforms and landform assemblages characteristic of granite are also developed on other rock types and in a wide range of climates.

Corestone boulders, one of the most common and characteristic of granite landforms can be taken as an example of climatic as well as lithological convergence. They are two-stage forms due to fracture-controlled subsurface weathering. Corestones are the residual kernels of fracture-defined blocks and when exposed after the stripping of the regolith, become boulders. Such corestones and boulders are best and widely developed in granitic rocks, and from various climatic contexts ranging from the Snowy Mountains to the West Malaysian uplands, from the Rockies of Colorado and the Sierra Nevada of California, to the monsoonal north of Australia. They are also developed in sandstone (in the southern Flinders Ranges and Tennessee), from dacite, in the Gawler Ranges (CAMPBELL & TWIDALE 1991), from basalt as for example in the Drakensberg, and in limestone (where they are known as *Karrenblöcke* ), for instance in the Galong Quarry, central New South Wales (Pl. 1).

The relative importance of physical, chemical or biotic processes; whether

Table 1. Lithologic convergence

| GRANITE | OTHER LITHOLOGIES |
|---|---|
| ***Planation Surfaces*** | |
| *Rolling (peneplains)* | |
| N. Transvaal (Birot et al. 1974), N. Eyre Peninsula (Twidale et al. 1976), S. Yilgarn. | Cretaceous sediments. Carpentaria Plains (Twidale 1956, 1966), Wilcannia area, NSW. |
| *Flat (ultiplain or etch)* | |
| Bushmanland, Namaqualand (Twidale 1982a), Meekatharra, central W.A. (Twidale 1983) | Sandstone. Bushmanland, Namaqualand. Limestone. Nullarbor, W.A. and S.A. (Lowry & Jennings 1974; Twidale 1990). |
| *Pediment - covered* | |
| C. Namibia (Twidale 1982a). | Sediments. Flinders Ranges (Twidale & Bourne 1994), Cape Fold Belt, American West - Nevada, Utah, Colorado (Blackwelder 1931; Twidale 1978a, 1979). |
| *Pediment - mantled* | |
| Ucontitchie, Cocata, etc. (Twidale 1982a). | Schist. C. Namibia (Twidale 1978a, 1979). |
| *Pediment - rock* | |
| Corrobinnie, etc. (Twidale 1982a). | Mudstone. Aliena, Flinders Ranges (Twidale & Bourne 1994). Conglomerate. W of Olgas. Sandstone. Ayers Rock (Twidale 1978a, 1979). |

***Residuals***

*Bornhardts*

| | |
|---|---|
| Numerous (Twidale 1982b, 1982c). Either (a) isolated (inselbergs) or (b) as components of massifs. | Cupola karst. (a) Indonesia (Verstappen 1960), (b) W. Malaysia, S. China (Kweilin). Conglomerate. (b) Indonesia (Verstappen 1960), Olgas (Twidale & Bourne 1978). Sandstone. (a) Ayers Rock (Twidale 1978), Kimba, Eyre Peninsula (Campbell & Twidale 1990), Mali (Mainguet 1972), (b) Kings Canyon. Dacite. (a & b) Gawler Ranges (Campbell & Twidale 1991). |

*Nubbins (knolls)*

| | |
|---|---|
| Many in humid tropics (N. Australia, Hong Kong) but also Namaqualand, American Southwest (Oberlander 1972). | Dolerite. Keetmanshoop, S. Namibia, W. Pilbara, W.A. |

*Castle koppies*

| | |
|---|---|
| C. Zimbabwe, Cold or cool upland in W. Europe (SW England, Pyrenees, Massif Central, W. Iberia) (Lagasquie 1984; Linton 1955; Vidal Romani 1989). | Sandstone. Pennines (Linton 1964), Roopena, Eyre Peninsula. |

*Towers*

| | |
|---|---|
| Pitons of Arabia, Guyana (Choubert 1949). | Conglomerate. Pyrenees (Barrère 1963, Wilhelmy 1958), Meteora, S. Brazil. Sandstone. Gran Sabana (Briceño & Schubert, Schubert & Huber 1990), Bungle Bungle Ranges (Young 1987), S.Brazil. Towerkarst in many areas esp. humid tropics. N Australia - Chillagoe, Fitzroy Basin (Jennings & Sweeting 1963; Verstappen 1960), also in Yukon (Brook & Ford 1978). |

*Pillars*

| | |
|---|---|
| Murphy Haystacks (Twidale & Campbell 1986). | Rhyolitic tuff. City of Rocks, New Mexico (Mueller & Twidale 1988). Sandstone. Drakensberg (Twidale 1980a). |

***Sheet structure***

| | |
|---|---|
| Numerous (Vidal Romani et al. 1995). | Sandstone. Ayers Rock (Twidale 1978b), Colorado Plateau (Bradley 1963). Dacite. Gawler Ranges (Campbell & Twidale 1992). Limestone. Arran (Tyrell 1923), Italy (Kiersch 1964), Appalachians (Bain 1931). |

***Minor Forms***

*Corestones/boulders*

| | |
|---|---|
| Numerous (Twidale 1982a). | Sandstone. Ayers Rock, Flinders Ranges (Twidale 1978b, 1980a). Limestone. Karrenblocke, Galong, NSW. Basalt. Drakensberg. |

*Pitting*

| | |
|---|---|
| Eyre Peninsula, Darwin, NW Queensland, W.A. (Twidale 1982a). | Dolerite. Eastern Cape. Limestone. Galong, NSW. |

*Rock basins*

| | |
|---|---|
| Numerous (Twidale 1982a). | Sandstone. Ayers Rock (Twidale 1978b), C. Spain (Sanz Perez 1994). Limestone. Kamenitzas (Jennings 1985). Rhyolite. City of Rocks,New Mexico (Mueller & Twidale 1988). |

*Gutters*

| | |
|---|---|
| Numerous (Twidale 1982a). | Sandstone. Drakensberg (Twidale 1980a). |

*Grooves*

| | |
|---|---|
| Numerous (Twidale 1982a). | Sandstone. Drakensberg (Twidale 1980a) . |

*Kluftkarren*

| | |
|---|---|
| Numerous. Paarl, Sierra Nevada, Eyre Peninsula (Twidale 1982a). | Rhyolite. City of Rocks, New Mexico (Mueller & Twidale 1988). |

*Flares*

| | |
|---|---|
| Southern Australia, American Southwest, W. & S. France (Twidale 1982a). | Sandstone. Ayers Rock (Twidale 1978b) Drakensberg (Twidale 1980a).<br>Rhyolite. City of Rocks, New Mexico (Mueller & Twidale 1988).<br>Dacite. Gawler Ranges. (Campbell & Twidale 1991)<br>Basalt. Mexico. |

*Cliff foot caves, notches*

| | |
|---|---|
| Podinna, Devils Marbles (Twidale 1980b), Balladonia, Kokerbin. | Limestone. Sarawak, Malaysia (Jennings 1976, Twidale 1987).<br>Sandstone. Ayers Rock (Twidale 1978b), Sahara. |

*Scarp foot depressions*

| | |
|---|---|
| C Australia (Mabbutt 1967), Wattle Grove, Yarwondutta. | ?Schist. Egypt (Dumanowski 1960).<br>Schist & gneiss. E. Mt Lofty Ranges (Twidale & Bourne 1975). |

*Tafoni*

| | |
|---|---|
| Numerous, including coastal (Twidale 1982a). | Sandstone. NSW (Young & Young 1992), Flinders Ranges (Twidale & Bourne 1994), C. Spain (Sanz Perez 1994).<br>Schist. s. Devon (Mottershead & Pye1994) |

*Alveoles*

| | |
|---|---|
| Point Brown, Antarctica, Remarkable Rocks (Twidale 1982a). | Sandstone. Beda, Talia.<br>Basic igneous. Point Brown. |

*Minor hollows*

| | |
|---|---|
| Zimbabwe, Smooth Pool. | Sandstone . Talia. |

*Rock levées*

| | |
|---|---|
| Zimbabwe (Twidale 1993). | Sandstone. Talia. |

*Rock doughnuts*

| | |
|---|---|
| C. Texas, Kwaterski Rocks, Galicia (Vidal Romani 1989), Zimbabwe (Twidale 1982a), Catalonia (Roque & Palli 1994). | Sandstone. Talia. Drakensberg (Twidale 1980a). |

*Fonts*

| | |
|---|---|
| C. Spain (Centeno 1987), Catalonia (Roque & Palli 1994). Galicia and N.Portugal (Vidal Romaní, 1989) | Sandstone. Talia, western Eyre Peninsula ; Palmerston, South Island, New Zealand ; Cape Paterson, eastern Victoria (all coastal), Colorado Plateau, Utah.<br>Basalt. Falkland Islands (coastal). |

*Plinths*

| | |
|---|---|
| Eyre Peninsula, Zimbabwe (Twidale 1982a). | Sandstone. Talia. |

*Polygonal cracks*

| | |
|---|---|
| Eyre Peninsula, Western Australia, Galicia (Twidale 1982a; Vidal Romani 1989), Catalonia (Roque & Palli 1994). | Sandstone. Flinders Ranges, Litchfield, Fontainebleau (Robinson & Williams 1989), Colorado (Netoff 1971), C. Spain (Sanz Perez 1994). |

*Pedestal rocks*

| | |
|---|---|
| Sahara (Peel 1960), Appalachians (Crickmay 1935), Sierra Guadarrama (Centeno 1987). | Dolomite. Cuidad Encantada (Twidale & Centeno 1993).<br>Sandstone. Kimba, NE Eyre Peninsula.<br>Basalt. Death Valley, California. |

*A-tents*

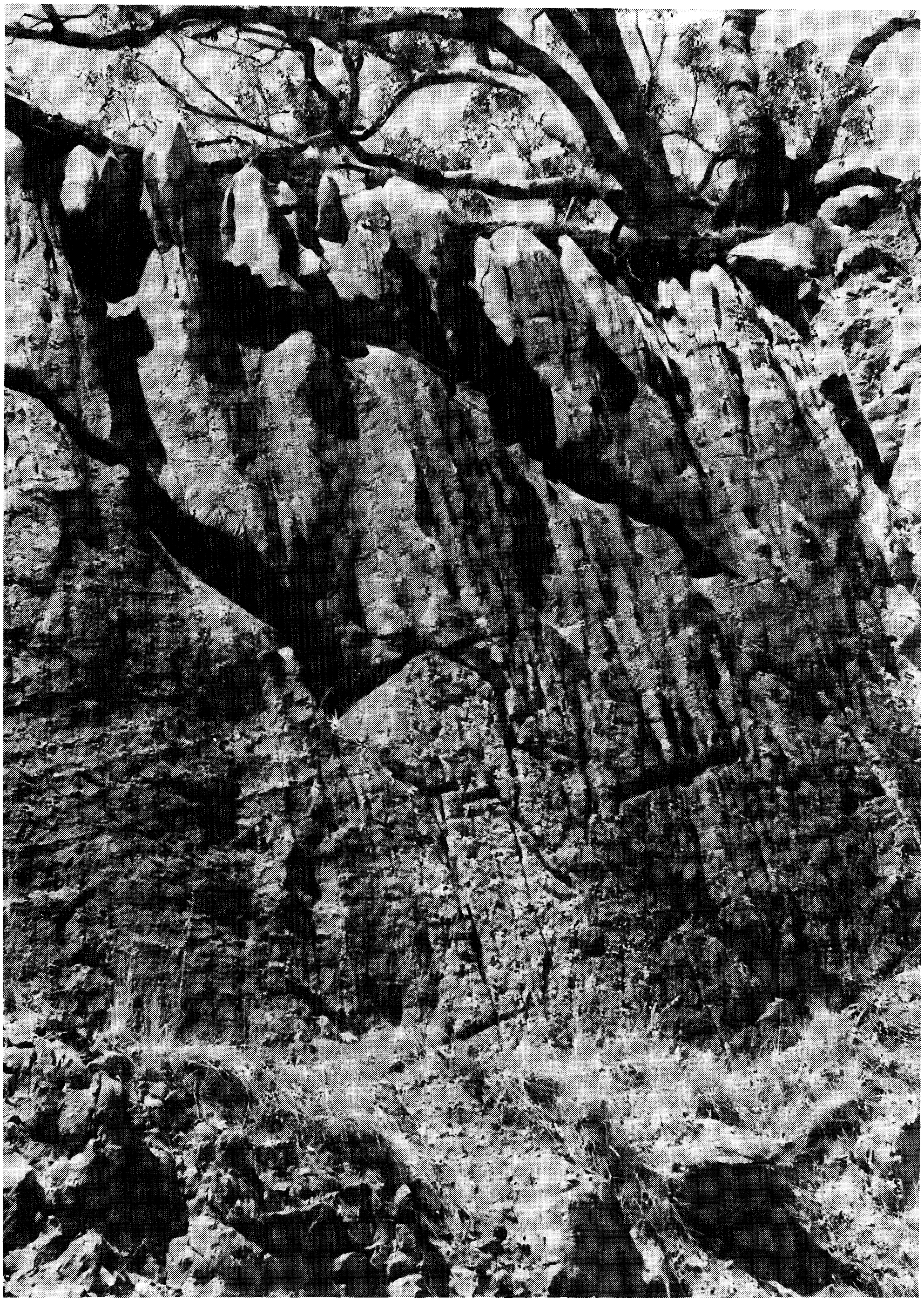
| | |
|---|---|
| Eyre Peninsula (Jennings & Twidale 1971; Twidale & Sved 1978), Western Australia (Twidale et al. 1994), Kulgera, Northern Australia, Labrador (Peterson 1975). | Limestone. New South Wales (Jennings 1978).<br>Sandstone. Utah (Scott 1932). |

*Triangular wedges*

| | |
|---|---|
| Eyre Peninsula (Twidale 1982a). | |

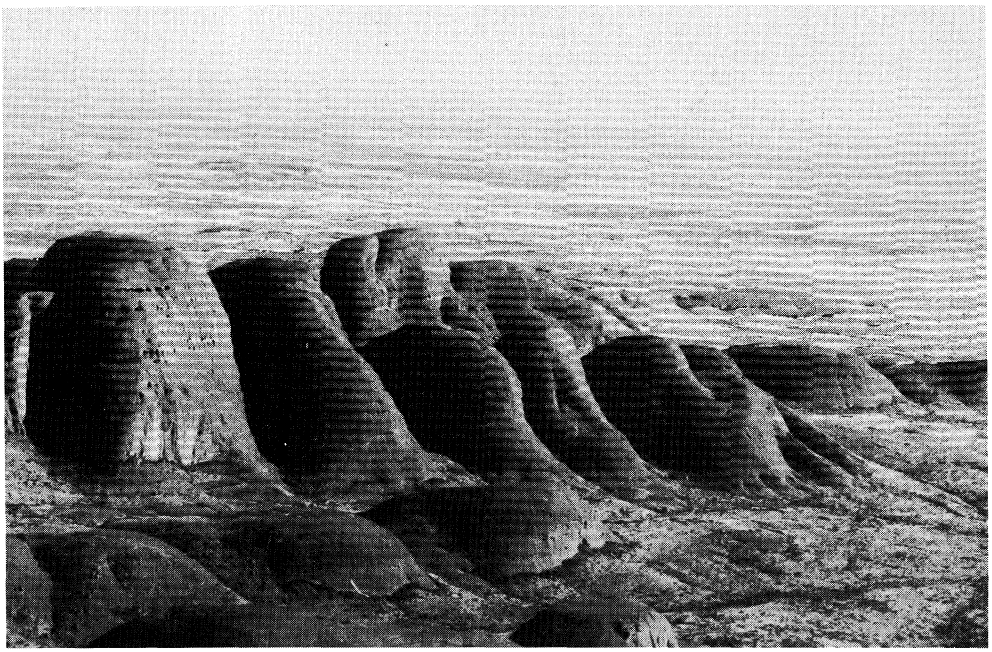
*Orthogonal cracks*

| | |
|---|---|
| Mt Magnet, Galicia (Vidal Romani 1989). | Schist. Galicia. |

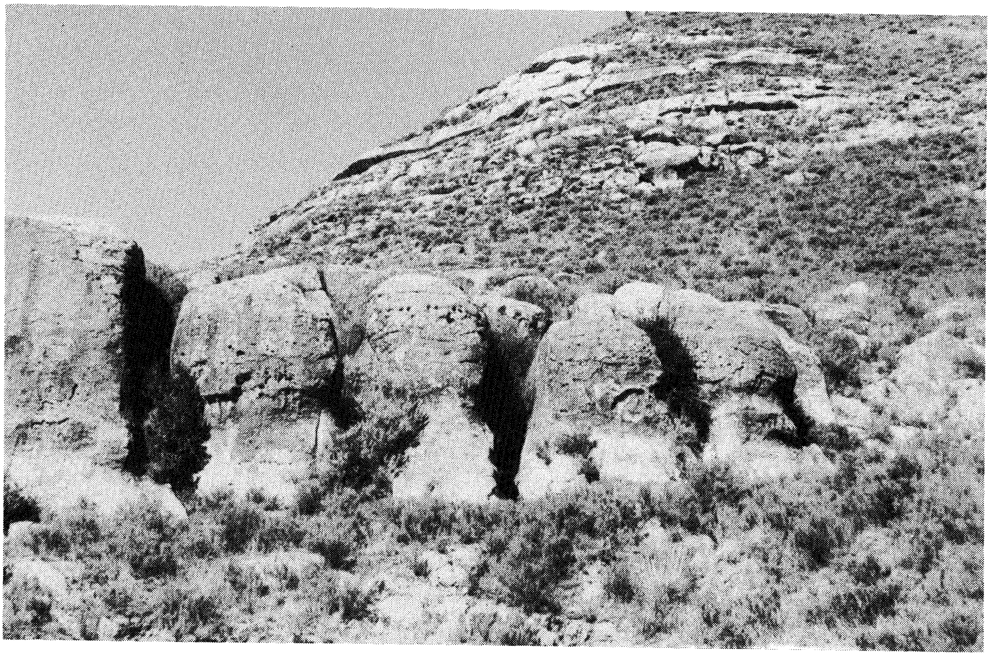


Pl. 1. Fracture-controlled subsurface weathering beneath the soil cover, exposed by quarrying, Galong, New South Wales. Note the rounded Karrenblöcke near the surface, and the pitting developed on the quarry face.

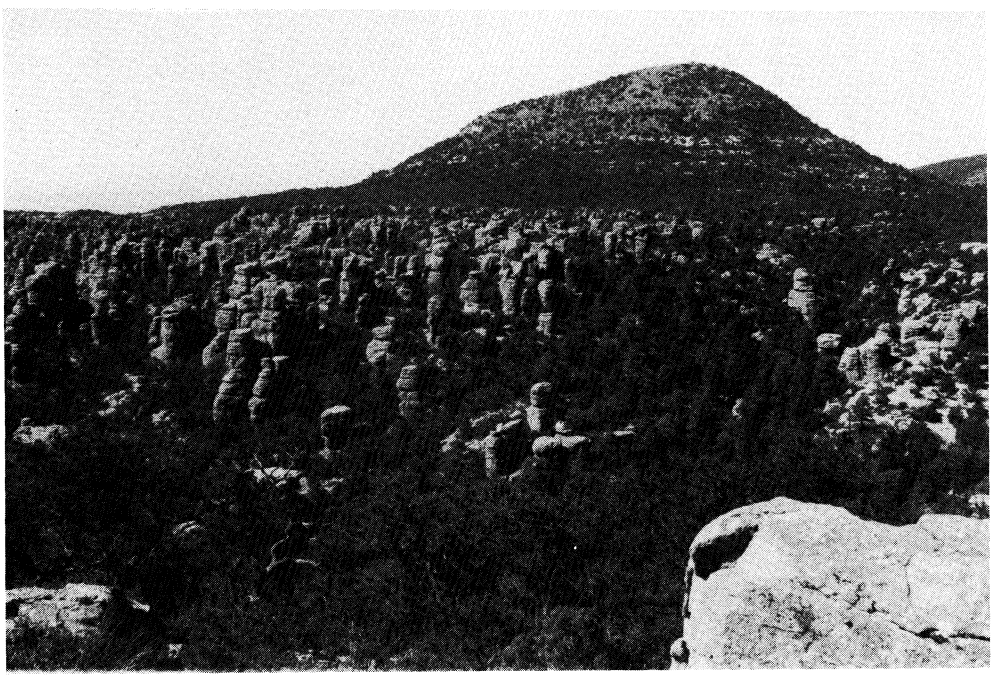
Pl. 2. Bevelled crest of bornhardts developed in acid volcanic rocks, mainly dacite, southern Gawler Ranges, South Australia.



Pl. 3. Domes and towers of the conglomeratic Olgas complex, central Australia.



Pl. 4. Tower karst from the Nahanni region, northwest Canada.



Pl. 5. Flared sandstone pinnacles, southern Drakensberg Mountains, South Africa.

solution, hydration or hydrolysis was dominant; which types of clay were produced as a result of the interaction of water with feldspar and mica - all may have varied. The overall effect, however, was to produce corestones of relatively fresh granite surrounded by a matrix of grus. Thus the climatically-controlled and varied weathering processes have produced the one particular form. To take this idea of equifinality one step further, no matter what agent of erosion removed the grus to reveal the boulders, whether water, ice, waves, gravity or, maybe, wind, the varied erosive processes all resulted in the production of the same form. Similar comments apply to pedestal rocks, developed in basalt and granite, sandstone and dolomite and in different climates. The cap of pedestal or mushroom rocks is, in some cases, lithologically more resistant than the stem, but in the majority, the cap is a reflection of subsurface initiation and the drier conditions and hence less weathering near the surface, while moisture is retained and weathering more intense at depth. Lowering of the land surface exposes the mushroom shaped blocks. Various processes may have been involved but the mechanism and resultant forms are similar (TWIDALE & CAMPBELL 1992).

Again, castellated granite forms, also due to the difference in rate of weathering between the drier, near-surface zones and the wetter areas at depth, and known in Britain as tors, are matched by the sandstone residuals of the Pennines (LINTON 1955, 1964). Bornhardts, both isolated (inselbergs) and occurring as components of massifs, have been reported from dacite and rhyolite, from sandstone and conglomerate and from limestone. The bornhardts of the Gawler Ranges in South Australia (Pl. 2), for example, are developed on Mesoproterozoic silicic volcanic rocks, and are components of a larger massif (CAMPBELL & TWIDALE 1991a). Similarly the granitic and gneissic domes of the Kamiesberge in Namaqualand are part of a larger whole, as are the sandstone domes of Mali (MAINGUET 1972) and the conglomeratic domes and towers of the Olgas complex, in central Australia (Pl. 3). On the other hand, Ayers Rock, developed in steeply dipping arkose (TWIDALE 1978), the quartzitic bornhardts of the Kimba area, Eyre Peninsula (CAMPBELL & TWIDALE 1991b) and some of those of the Zion National Park (or Monument) in Utah (YOUNG & YOUNG 1992), like innumerable congeners in granite and gneiss, and in many parts of the world, stand in splendid isolation. Many display well developed sheet fractures.

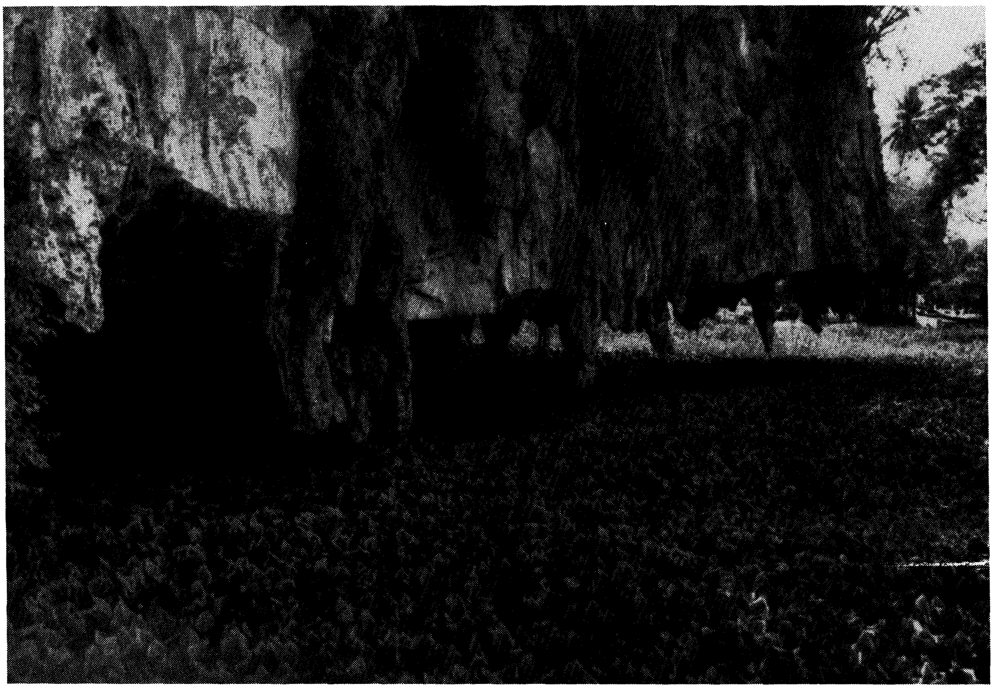
The karst domes or cupolas of such areas as Indonesia (VERSTAPPEN 1960), the Ipoh region of West Malaysia and Kweilin, southern China, and many other humid tropical regions are comparable to domical bornhardts; for like the latter, and judging by the cave systems now abandoned and located high in the residuals (LEHMANN 1954), many of the former appear to have evolved, in part at least, in the subsurface. Karst towers are mechanism convergent forms, for they evolve in at least two ways. Some owe their shape to the exploitation, by shallow groundwaters, of widely spaced vertical fractures, followed by the preferential weathering of the corners and edges of massive blocks. Where the fractures are widely spaced, or where for some reason weathering has been slow, domes are formed, but where the plan dimensions are minor compared to the depth of weathering, or where weathering has been rapid, towers emerge. Towers due to the exploitation of prominent vertical fractures, can be seen, not only in a wide range of climates including the arctic (Pl. 4; BROOK & FORD 1978), but also in various rock types including sandstone (as in southern Brazil) and conglomerate, for example in the Pyrenees (Barrère 1968). Similarly, miniature towers, pinnacles or pillars due to the exploitation of vertical fractures, are reported from sandstone in the southern Drakensberg (Pl. 5), rhyolite from the Chiricahua National Monument , (Pl. 6), rhyolitic tuff in the City of Rocks, New Mexico (MUELLER & TWIDALE 1988), as well as in granite (e.g. at Murphy Haystacks, Eyre Peninsula, South Australia).

But other limestone towers are evidently due to the conversion of domes or cupolas by pronounced moisture attack at the base of the bounding slopes. The moisture may be held in alluvium lapping against the bases of the residuals leading to intense weathering, the formation of swamp slots and cliff foot caves (Pl. 7), and the undermining, collapse and steepening of the sides. This is the origin of the *Turmkarst*, or towerkarst, of various regions in the humid tropics, and including such seasonally dry monsoonal areas as the Fitzroy Basin of northern Australia (JENNINGS & SWEETING 1963). VERSTAPPEN (1960) provided the critical observation from Indonesia, noting that cupolas occur on slighly higher and drier sites but towers where the hill bases are in contact with alluvium. Similar relationships between morphology and distribution of erosional attack are present in conglomeratic relief in the northern ramparts of the Sistema Iberico, northeastern Spain. Good examples can be found in the valley of the Rio Iregua, south of Logroño in the Sierra de Cameros. There weathering along widely spaced vertical fractures developed in the massive Miocene-Oligocene formations and preferential weathering of the corners and edges of the resultant blocks, tends to produce large beehive-like forms. However, adjacent to the valley and at other sites subject to pronounced basal erosion or sapping, tall turrets bounded by vertical cliffs are developed.

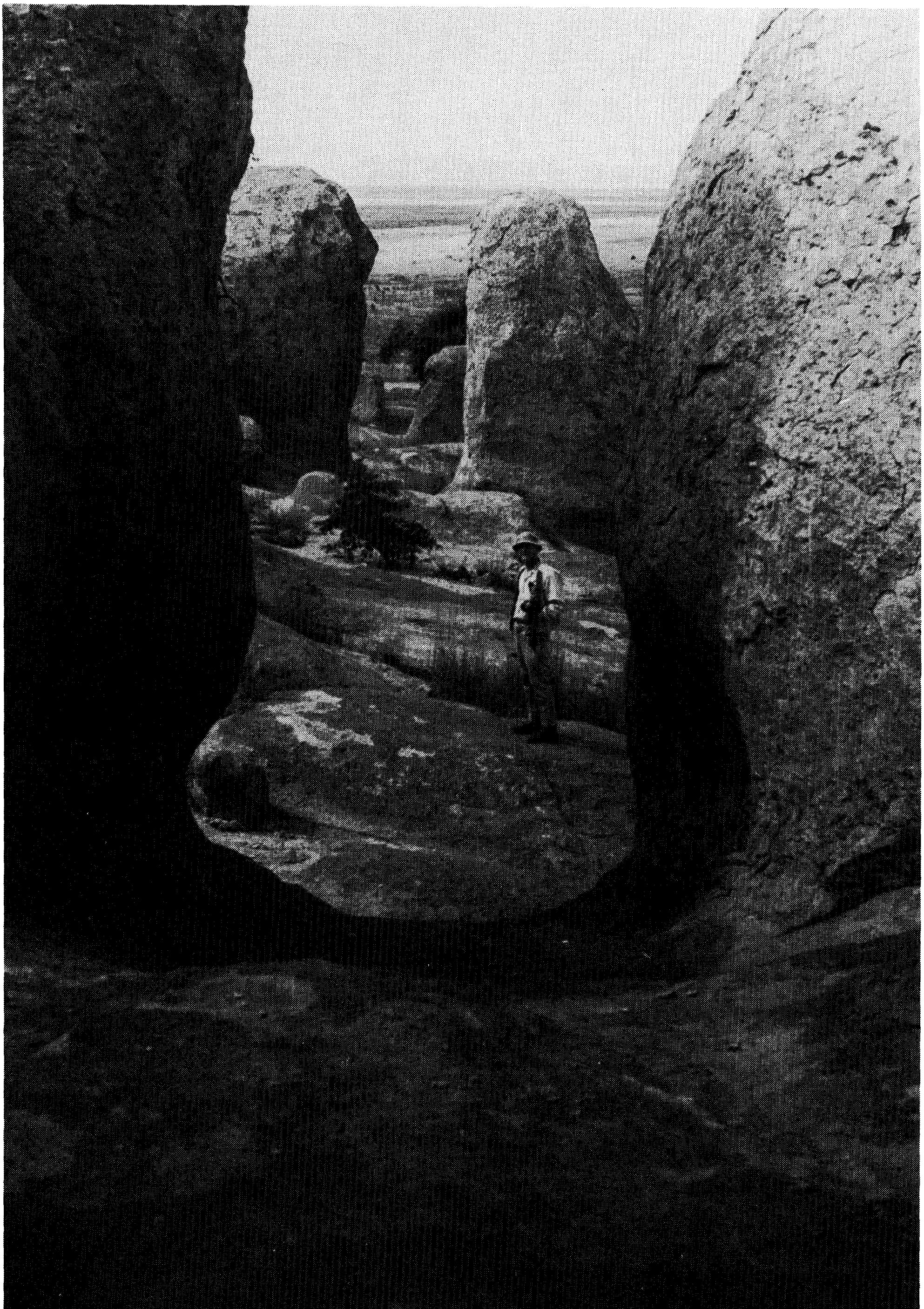
Basal sapping and undermining is not, however, restricted either to limestone or to humid lands, for cliff-foot caves are prominent around the base of the arkosic Ayers Rock, in arid central Australia, where slope collapse under gravity is prominent consequent on such undermining. Moreover, the pronounced weathering at the foot of the tower and undermining of the slope above is analagous to the development of flared slopes in granitic terrains; though most granites appear too cohesive to collapse even when undermined, though fracture spacing is critical. Flared slopes are recorded from a wide range of climatic settings from cool arid as in the Cassia City of Rocks, Idaho (ANDERSON 1931), and the Rio de Janeiro area, and are also found at the bases of the dacitic bornhardts of the Gawler Ranges, in the rhyolitic City of Rocks, New Mexico (Pl. 8; MUELLER & TWIDALE 1988), and in sandstone in the Drakensberg of South Africa and also at Ayers Rock, central Australia (Pl. 9).

Rock basins, widely developed in granitic rocks, are also well developed, and widely reported from other lithologies. Numerous flat-floored pans, so well developed on granitic residuals, are also found on the bevelled summit of arkosic Ayers Rock, on sandstone boulders in the southern Flinders

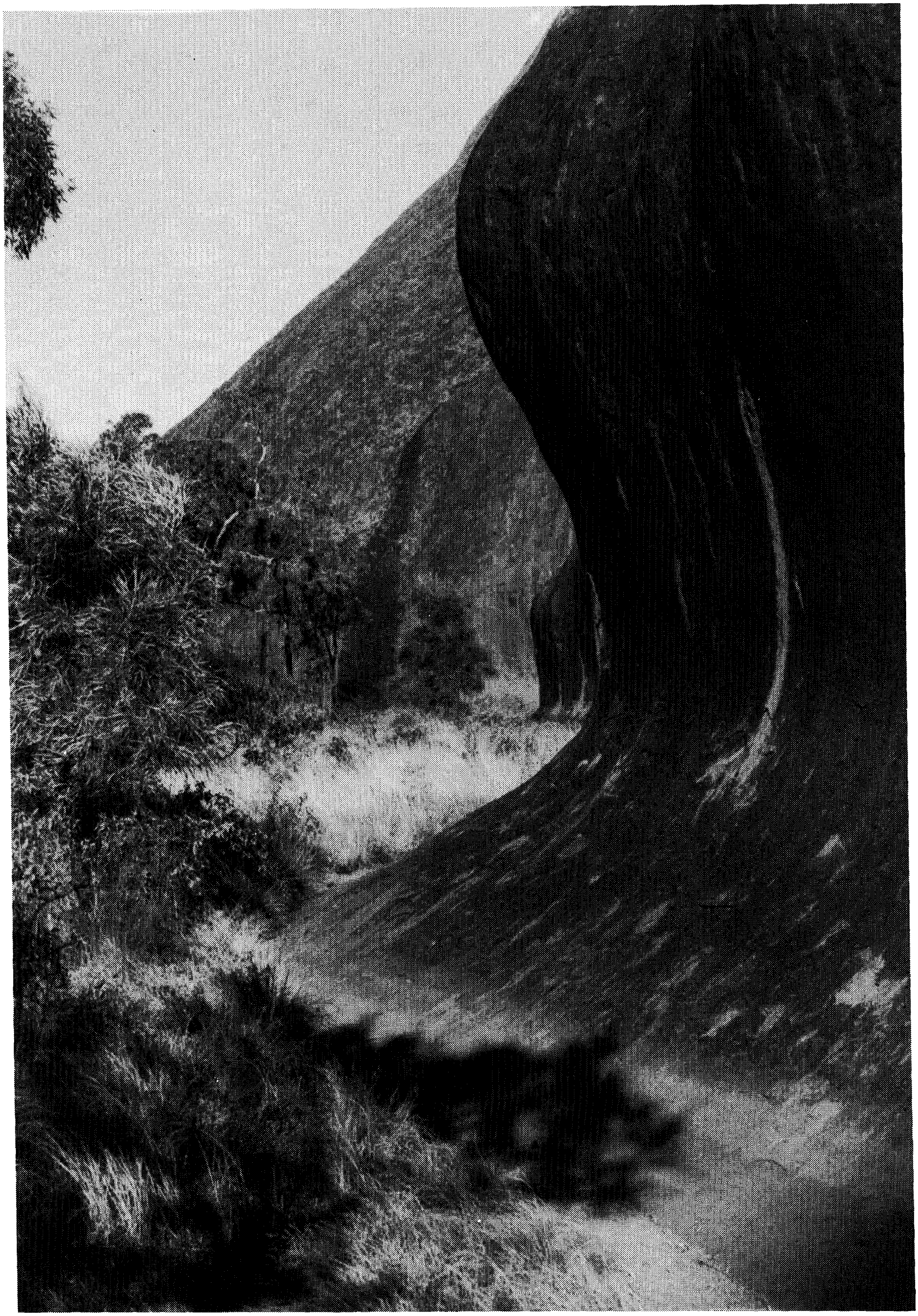
Pl. 6. Pinnacles in welded rhyolitic tuff, Chiricahua National Monument, Arizona.



Pl. 7. Cliff-foot caves or swamp slots, about 12 m deep developed in the base of a limestone tower, Ipoh, West Malaysia.



Pl. 8. Flared slopes in rhyolite, City of Rocks, New Mexico (J. E. MUELLER).



Pl. 9. Flare at the base of the arkosic Ayers Rock, central Australia.

Ranges, on sandstone benches in the Kings Canyon area of central Australia, on sandstone outcrops in the Drakensberg, as well as in limestone, in which setting they are known as *kamenitzas*, as for instance in the Tindal area of monsoonal northern Australia. Turning to their climatic distribution, flat-floored pans have been reported in granitic rocks from the tors of cool temperate Dartmoor (LINTON 1955), the high altitude, cool temperate areas of the Sierra Nevada of California (MATTHES 1930), the coastal areas of Galicia, Spain, the Karkonosze Mountains (JAHN 1974), the cold arid lands of Mongolia (DZULINSKI & KOTARBA 1979), the warm humid areas of Georgia, USA (SMITH 1941), as well as from the semiarid areas of northwestern Eyre Peninsula, South Australia and the hot arid Kulgera Hills of central Australia. The details of the weathering processes involved may vary from region to region - freeze-thaw predominant in periglacial regions, chemical solution in the warm humid areas, for example - but the resulting landforms are similar.

Planate forms well developed in granitic terrains are also well represented in other rock types. For example, the essentially featureless Bushmanland Surface of Namaqualand and Namibia is perfectly developed in sandstone and schist as well as in granite (Pl. 10). The perfection of the surface is evidently a result of long-continued subsurface weathering, for the Surface is of etch type; on the other hand, the Nullarbor Plain, the remarkable flatness of which is indicated by the fact that in one sector the transcontinental railway runs in a perfectly straight line for almost 500 km, is an etch surface developed in limestone since the end of the Miocene (TWIDALE 1990).

Pediments of various types are also represented in various lithological environments, though emphases vary. For example, though covered pediments are very well developed in sedimentary terrains as climatically diverse as Alaska, Utah, Nevada, the Pyrenees, the Cape Fold Belt and the Flinders Ranges, there are few in granite; indeed only one has been reported, from near Usakos, in central Namibia (TWIDALE 1981). Conversely, mantled and rock pediments, widely developed in granite, find expression in relatively few sedimentary areas (Pl. 11). Examples include an extensive if fragmented rock platform in conglomerate west of the Olgas, the mostly mantled pediments of the plains surrounding Ayers Rock with occasional exposures of rock pediments of etch character, and a single rock pediment at the head of the Aliena alluvial fan, amidst the covered forms of the Flinders Ranges, eroded by a river draining a catchment in which only mudstone is exposed (TWIDALE & BOURNE 1994; BOURNE 1995).

Caves are characteristic of karst but they are found, albeit rarely, and in various contexts, in granite (TWIDALE 1982a). Even constructional forms are not exclusive to any one lithological or climatic environment. Speleothems of many kinds are well known from carbonate terrains, but miniature stalactites, stalagmites and flowstone are recorded from both granite and sandstone, and from climates that range from the hot arid to the humid. Other constructional forms are related to reprecipitation of material along fractures as a consequence of weathering. Fractures are best known in a geomorphological sense as avenues of weathering, but they also have a protective role, as they permit the throughflow of water and thus reduce weathering through the mass of the rock (TWIDALE & CAMPBELL 1993). They also allow reprecipitation of minerals which result in the boxwork pattern of relief, at various scales from the ridges at centimetre scale in granite to ridges several metres high and hundreds of metres long in limestone and sandstone terrains (Pl. 12; YOUNG & YOUNG 1992).

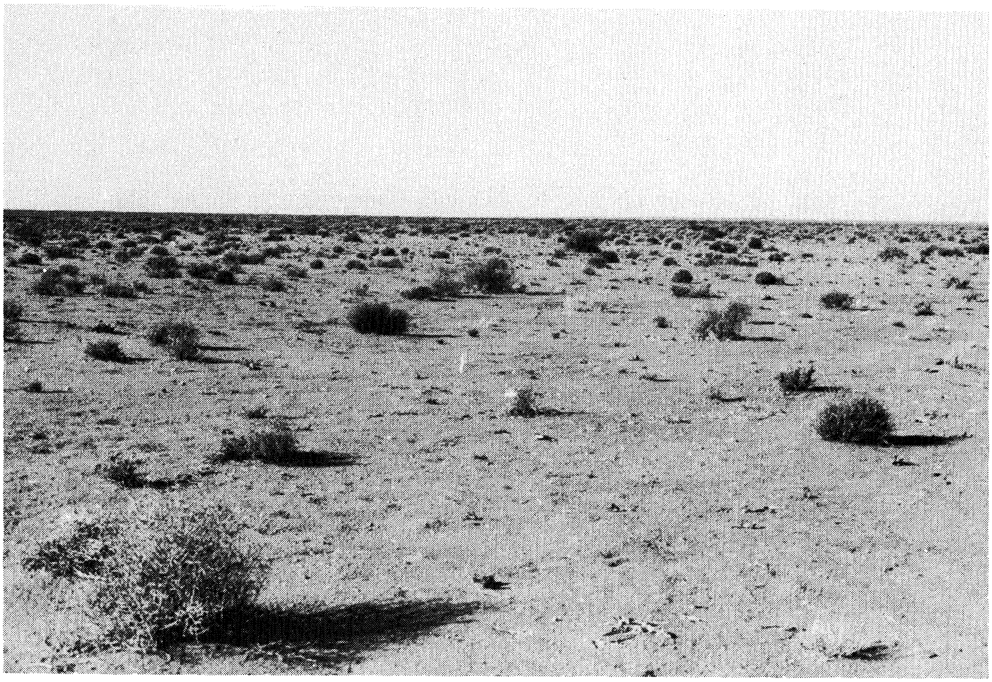
## ZONAL FEATURES

Most forms developed in granite have also been reported from other rock types. The only known example of a granite form unreported from other lithologies is the triangular wedge. Wedges are slabs of rock detached, and in some cases laterally dislocated, from the base of exposed sheets. In granite they are associated with sheet fractures and, since sheets occur in a variety of lithologies, there is, as yet, no apparent reason why wedges should not have a similar occurrence, though the crystallinity and strength of granite may be a factor.

Conversely, some of the forms associated with the structure of sedimentary rocks do not occur in granite. The ribs on the summit and sides of Ayers Rock, which are a reflection of the varying resistance to weathering and erosion of the sediments , are not found in granite. Features of some sedimentary rocks, such as cross-bedding, are not reflected in the minor forms developed on granite. Also, there is no ridge and valley topography as is so well developed in many folded sedimentary sequences, though the plateau, mesa and butte topography of horizontally bedded sedimentary strata is expressed in granite landscapes where duricrusts of various types have developed and, later, have been dissected.

Most granite forms are climatically azonal. There are, however, exceptions, though many are best developed in one or other of the conventionally defined climatic regimes, while not necessarily being restricted to them. Nubbins appear to be essentially restricted to humid tropical conditions, to northern Australia and Hong Kong, for example. In many nubbins the surficial zone of blocks and boulders overlies a massive dome. Moreover, in places it can be shown that sheet structure is disintegrated within the regolith, suggesting that the outer shells or sheet structures of bornhardts were rapidly disintegrated in the subsurface, such rapid and deep weathering being characteristic of hot humid conditions. The nubbins described from the American Southwest (OBERLANDER 1972) are said to be inherited from similar conditions that applied in the past. Those of the Alice Springs area and of small areas of Namaqualand may reflect local abundance of subsurface moisture in enclosed structural or topographic basins.

The tafone is another common form that is restricted to particular environments, for, though well-developed in aridity and in certian coastal settings, tafoni have not been reported from the humid tropics, or from cold humid areas. They have been described from hot arid and semiarid areas, such as Eyre Peninsula and Corsica, from the cold arid climates of Antarctica, as well as from arid and semiarid coastal regions and from various rock types including sandstone at Ayers Rock (TWIDALE 1978) and various metamorphic rocks (MARTINI 1978). The common factor in these areas is believed to be retention of salts: they are washed through the system in the humid tropics. The source of the salt and how it arrives at the weathering



Pl. 10. The Bushmanland plain of northern Namaqualand and central Namibia underlain in different areas by granite, gneiss, sandstone and schist.

Pl. 11. Gutters in sandstone rock pediment extending beneath the soil cover (mantled pediment), near Clarens, southern Drakensberg Mountains, South Africa.

Pl. 12. Narrow sinuous ridges and boxwork valleys cut in friable sandstone, eastern Bungle Bungle Range, northwestern Australia (K. C. WORTHLEY).

sites has not been satisfactorily explained. Also, the development of the visor, or indurated outer surface, which has a protective function in drier areas, is reduced or completely absent in the humid tropics, where general weathering may destroy it. Similarly, the absence of tafoni from areas where freeze-thaw action is pronounced, or has been in the recent past, may be explained by the prevention of the formation of the indurated visor (TWIDALE 1982a).

## DISCUSSION AND CONCLUSIONS

### What factors are conducive to lithologic and climatic convergence?

First, all the rock types are low in porosity and permeability but are highly pervious due to the presence of well-developed fracture systems. The low porosity and permeability is a reflection of their crystallinity or cementation resulting in a strong and cohesive rock. Fractures are of prime importance as avenues of weathering, and hence they determine the shape of the weathering front and the size and shape of the landforms which result.

The contribution of stress, both along fractures as a result of differential movement, and through the body of the rock by the gravitational pressure of overlying masses, has, in recent years, offered more plausible explanations to some of the details of granite landform development. Thus it is not surprising that such forms as A-tents are found in a wide range of climatic environments, and in sandstone and limestone as well as granite and gneiss. Conversely, the restriction of wedges to granite may be related to the physical properties of the rock.

Second, the subsurface initiation and development of many forms is important in all these rock types. In granite, forms such as bornhardts and other inselbergs, platforms and plains, boulders, gutters, flared slopes, scarp foot depressions, tafoni and pitting may be of etch origin. That some sandstone forms are of etch origin has been suggested (TWIDALE 1956, 1980a), and the dacitic bornhardts of the Gawler Ranges have also been interpreted as etch forms. The same idea is implicit in the classification of karst forms as covered, half covered and exposed due to such workers as ECKERT (1902), LINDNER (1930), ZWITTKOVITTS (1968) and JENNINGS (1985). As groundwaters are ubiquitous, etch development is a significant element in producing climatic azonality (TWIDALE 1987, 1990).

Third, and related to the etch concept, each of the rock types is susceptible to moisture attack, yet is stable when dry. It is this fact that can best account for the occurrence of broad, flat plains in a variety of rocks types, for example the Bushmanland Surface in sandstone and granite and the Nullarbor Plain in limestone. Water itself is an important cause of alteration in rocks, and, in addition, it transports chemicals and biota which promote further reactions. Though the precise form of weathering may vary according to rock composition, there is a sharp boundary between the fresh and the weathered rock. The development of the weathering front, its extension vertically and horizontally beneath the surface, and the processes that take place there are vital to an understanding of many features common to these rock types. Some of the details of development are modified by other factors, such as the localization of strain in rocks, but the factor of overriding importance is the development of the regolith and the extension of the weathering front. The term 'two-stage' has been used to describe the forms, but this is an oversimplification, as many factors related to deposition and diagenesis and the magmatic, thermal or tectonic history of the rocks, are not taken into account (TWIDALE & VIDAL ROMANI 1994).

There are few exceptions to the general climatic convergence of granite forms. One reason is that many are etch forms. Groundwaters, and hence regoliths, are present beneath the surface of much of the continents and are thus found over a wide range of climates. The rate of development of the different forms discussed may vary for climatic reasons: for example, higher temperatures, greater rainfall and more abundant organic matter in the humid tropics results in a more rapid development than in, for example, the high latitude and high altitude cold lands. However, the morphology is the same, provided structural and tectonic factors are uniform.

Fourth, because of the susceptibility of the rock to moisture, and hence of the contrasted stability in wet and dry conditions, reinforcement mechanisms play an important role in the development and preservation of forms. Once a rock is upstanding, it tends to shed water and is therefore a relatively dry site compared with the surrounding lower and weaker compartments which tend to receive a disproportionally heavy runoff. Thus the rock in positive relief tends to be maintained whilst the lower areas are further reduced. This mechanism applies to major forms such as bornhardts, but also to minor forms, such as flared slopes and rock levées.

The tendency towards lithologic and climatic convergence is a challenging complication in landform and landscape analysis and interpretation, for it is almost certainly not correct to attribute all like forms to the same process or complex of processes.

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