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Introduction

Given the great emphasis placed on sands and sandstones in sedimentological research, the relative neglect of the geomorphology of sandstones seems paradoxical. It seems all the more so because much of the pioneer work in modern geomorphology, from James Hutton's work in 1795 onwards, came from sandstone landscapes. Hutton's recognition of the interplay of tectonic forces and of prolonged and repeated fluvial erosion in the shaping of the surface features of the Earth was based on observations at places like Siccar Point in Scotland, where it is obvious that Silurian greywackes were folded and extensively eroded before they were buried beneath the Devonian Old Red Sandstone. And Hugh Miller's *The Old Red Sandstone*, which appeared in seven editions between 1841 and 1889, contains perceptive and evocative accounts of how changes in the properties of the sandstone give rise to distinctive types of landforms:

> We pass from the conglomerate to the middle and upper beds of the lower formation, and find scenery of a different character in the districts in which they prevail. The aspect is less bold and rugged, and often affects long horizontal lines, that stretch away, without rise or depression, amid the surrounding inequalities of the landscape, for miles and leagues, and that decline to either side, like roofs of what the architect would term a low pitch.
>
> *(Miller, 1889, p. 214)*

It was also in sandstone lands that J. D. Dana refuted Charles Darwin's marine hypothesis for the origin of the great valleys in the Blue Mountains of New South Wales. Darwin, publishing in 1839 and then in subsequent editions, argued that 'To attribute these hollows to the present alluvial action would be preposterous' (Darwin, 1839, in the 1890 edn, p. 319). Drawing on his own observations during the voyage of the *Beagle*, and also on Lyell's

Cambridge University Press
978-0-521-87733-6 - Sandstone Landforms
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advocacy of marine erosion, he proposed that these broad valleys, which leave the upland through narrow gorges, are primarily the products of marine deposition:

> I imagine that the strata were heaped by the action of strong currents, and of undulations of an open sea, on an irregular bottom; and that the valley-like spaces thus left have their steeply sloping flanks worn into cliffs, during the elevation of the land; the worn-down sandstone being removed either at the time when the narrow gorges were cut by the retreating sea, or subsequently by alluvial action.
>
> *(Darwin, 1839, in the 1890 edn, p. 320)*

Although Dana had come to a similar conclusion during his visit to New South Wales in 1840, he later concluded that Thomas Mitchell, the colonial surveyor and explorer, had been correct in attributing these valleys to erosion by streams:

> The idea that running water was the agent in these operations appears not so 'preposterous' to us, as it is deemed by Mr. Darwin; and we think that it may be shown that Major Mitchell was right in attributing the effect to this cause. The extent of the results is certainly no difficulty with one who admits time to be an element which a geologist has indefinitely at his command.
>
> *(Dana, 1850, p. 289)*

Ironically, in the same year as Dana's paper was published, J. B. Jukes, who later became the great British advocate of fluvial erosion, quoted Darwin's descriptions in likening the valleys of these same sandstone lands to winding harbours (Jukes, 1850, pp. 24–25).

That erosion by streams is the dominant process in shaping surface features, even in arid and semi-arid lands, was demonstrated during the latter part of the nineteenth century by outstanding research on the Colorado Plateau of North America. Much of this pioneering work (e.g. Dutton, 1882; Powell, 1895) was carried out in the extensive sandstone lands of the plateau. In Dutton's words:

> It would be difficult to find anywhere else in the world a spot yielding so much subject matter for the contemplation of the geologist; certainly there is none situated in the midst of such dramatic and inspiring surroundings.
>
> *(Dutton, 1882, p. 92)*

Nonetheless, important work on the impact of climatic change and on the role of seepage and solution was being carried out in the less dramatic sandstone landscapes of Europe. The work of Hettner (1887, 1903) in the 'Saxon Switzerland' of the Elbe River in Germany is a case in point, especially with regard to seepage and basal sapping of sandstone outcrops. And it should be noted that the present-day focus on solutional processes in sandstone was foreshadowed by the French geographer de Martonne who, in his a *Shorter*

Physical Geography (1927, p. 171), included the solution in sandstone under the heading of 'Origin of Karst Topography'.

Research methodology

Although important papers on sandstone landforms have appeared from time to time (e.g. Gregory, 1917, 1950; Schumm and Chorley, 1964, 1966; Mainguet, 1972), research in this field seems almost insignificant when compared with the vast output from the study of landforms on granites and, even more so, on limestones. And although interest in sandstone landforms has increased during the last decade or so, attention has been focused very much on the issue of solutional features. The disparity is not due to the sandstones themselves being spatially insignificant, for they occupy approximately the same proportion of the continents as do granites and carbonates (Meybeck, 1987). Nor is it because sandstones do not form interesting or spectacular landscapes; in a recent major book on the great geomorphological landscapes of the world, nearly a quarter are formed in sandstones (Migon, in preparation). Rather, it probably lies in the widespread assumption that the natural sculpturing of gently dipping and resistant sandstones is a relatively straightforward matter that holds few surprises. This assumption is strikingly illustrated in the selection of sandstone by Tricart and Cailleux (1972) as the ideally simple medium for demonstrating the dominant role of climate in morphological diversity. Yet lithological and structural simplicity must be demonstrated rather than assumed, for our understanding of the interaction of surface processes and the properties of rocks is far from complete. Indeed, the diversity of sandstone landscapes is the major theme of this book.

The pitfalls of premature generalization from relatively few case studies are highlighted further by the diversity of the engineering, or rock mechanics properties of sandstones. Intact rock is generally rated by Deere–Miller plots of the uniaxial compressive strength and the modulus of elasticity (Lama and Vukuturi, 1978). Some sandstones fall entirely into the very low strength group (Dobereiner and de Freitas, 1986), while others, such as the highly quartzose Proterozoic sandstones of the Kimberley region of northern Australia (R. W. Young, 1987), fall at the other end of the range in the very high strength group. Plots for just a single formation, the Hawkesbury Sandstone of the Sydney Basin in southeastern Australia, give a range from very low strength to high strength (Pells, 1977, 1985). Even the mechanisms of fracturing change dramatically from the shattering of individual grains in highly indurated sandstones to the rolling or displacement of grains in weak, poorly cemented sandstones (Dobereiner and de Freitas, 1986). Indeed, in the case of the so-called 'flexible sandstones', or 'itacolumites' (Dusseault, 1980), the lack of true cement, coupled with a tight interlocking of grains, allows the rock to bend and recover under conditions in which brittle failure would normally be expected.

The definition of sandstone adopted in this book includes orthoquartzites, which are sandstones so completely and strongly cemented by secondary quartz that they break across the grains rather than through the cement. Although it is desirable on petrographic grounds to distinguish orthoquartzites from metaquartzites produced by metamorphic recrystallization of quartz, it is not always practical to do so in geomorphological studies because some orthoquartzites and metaquartzites have similar mechanical properties. Furthermore, it is often difficult to determine whether the term ‘quartzite’ used in some geomorphological studies refers to orthoquartzites or metaquartzites. Where possible we draw attention to the way in which such terms have been used in particular studies. And, as is illustrated specifically by examples later in this chapter, we emphasize the geomorphogical differences between orthoquartzites and less strongly cemented sandstones.

Because of the relative neglect of the geomorphology of sandstones there is no soundly established methodology, like that of research on karst, which can be followed. Attempts to structure research in this field on the basis of the supposed dominance of climatic controls (Ahnert, 1960; Tricart and Cailleux, 1972) seem premature, especially in the light of the compelling evidence of major structural and lithological influences (Bradley, 1963; Robinson, 1970; Oberlander, 1977). This is not to deny a role to climate – a role which has been strikingly demonstrated by Mainguet (1972) – but simply to refuse it pride of place, and not to relegate lithology and structure to a secondary or ‘passive’ role (cf. Büdel, 1982). Notwithstanding excellent work such as Mainguet’s investigation of chemical weathering of sandstones, much of the research into climatic influences has been ‘merely a systematization of simple observations’ (Yatsu, 1966, p. 3) that has little true explanatory power. How then should we attempt to explain sandstone landforms?

Scientific explanation, as Bateson (1973, pp. 26–27) so succinctly expressed it, ‘is the mapping of data on to fundamentals’. To this definition he added that ‘in scientific research you start from two beginnings, each of which has its own kind of authority: the observations cannot be denied, and the fundamentals must be fitted. You must achieve a sort of pincers manoeuvre’. Moreover, Bateson warned against mistaking loosely defined explanatory notions, or heuristic devices, for the precisely conceptualized building blocks of science. A similar, if more vitriolic, critique has been directed by Yatsu (1966, 1988) specifically against the reliance on such heuristic devices in much geomorphological research, which he likens to *Ikebana* (flower arranging). Yatsu’s great contribution, however, has been to delineate, in detail, the fundamental concepts on which our explanations of landforms should be based. Here we have followed his lead, and have turned to fundamental concepts such as strength, stress, strain and reaction rates, developed in the allied fields of rock mechanics, silicate weathering and fluid dynamics. Nevertheless, it is a 'pincers manoeuvre' that is required, not just an application of basic concepts. The study of landforms is more than just applied geophysics and geochemistry, for selecting those phenomena which are significant to geomorphology requires an appreciation not only of theory, but more so of actual landscapes. In outlining the complexity of the task of explaining sandstone landscapes, we therefore begin with field observations (Fig. 1.1) rather than with a survey of fundamentals.

A study of variations in sandstone landforms – the East Kimberley region, Western Australia

The East Kimberley region of northwestern Australia (location 12, Fig. 1.1) contains a vast area of generally gently dipping Proterozoic and Paleozoic sandstones. These sandstones have been continuously denuded, apparently under seasonally humid tropical climates, since early in the Tertiary or late in the Mesozoic. Despite their uniform tectonic and denudational setting, the present-day topography of these sandstones is remarkably varied, even over distances of only a few kilometres (R. W. Young, 1987, 1988). Many of them have been carved into cliff-lined mesas; others have been sculptured into great domes; and some have been intricately dissected into labyrinthine complexes of towers, pinnacles and sinuous, knife-edged ridges (Figs 1.2–1.5). Explaining this diversity is no simple task.

The problem of diversity within a region of essentially uniform present-day climate is not resolved by appeals to past climatic change, especially to the expansion or contraction of the desert which lies to the south of the Kimberleys. The angular clifflines of the Cockburn Range, that seem similar to the standard models for arid regimes, are on the humid side of the region; whereas the domes and convex towers of the Bungle Bungle Range, which are more like the rounded forms supposedly typical of humid regimes, are on the arid margins. Nor is there any evidence to suggest that the angular and rounded forms represent differing generations of landforms. On the contrary, the field evidence points to continuity in the style of sculpture. Where a distinct break separating two generations of landforms can be recognized between the Cainozoic summit erosional surface and the modern flanks of the Bungle Bungle Range, essentially the same array of towers and ridge development is found on each (R. W. Young, 1987). What is more, the lateral transition from towers to domes in the Bungle Bungle Range that occurs over a few kilometres along continuous escarpments can in no way be attributed to a climatic origin, past or present. Thus, in recognizing the degree of

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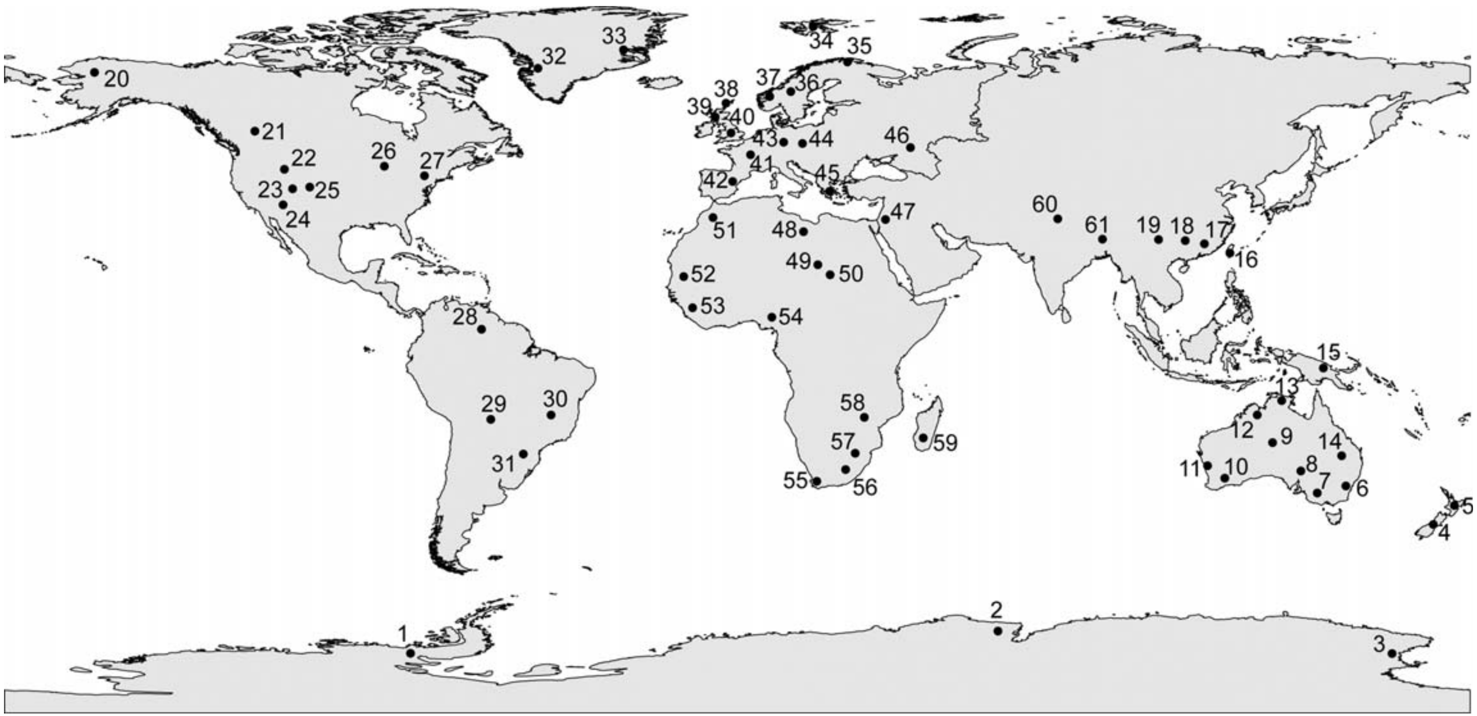

Fig. 1.1 Location of major sandstone landscapes considered in this book.
1 Ellsworth Mts; 2 Prince Charles Mts; 3 McMurdo Dry Valleys; 4 Torlesse Range; 5 Tararua Range; 6 Sydney Basin; 7 Grampian Range; 8 Flinders Range; 9 Uluru; 10 Stirling Range; 11 Murchison Gorge; 12 East Kimberley; 13 Arnhemland; 14 Carnavon Range; 15 Torricelli Mts; 16 Taiwan; 17 Danxiashan; 18 Wanfoshan; 19 Chishui; 20 Brooks Range; 21 central Canadian Rocky Mts; 22 Gros Ventre; 23 Zion Canyon; 24 Valley of Fire; 25 Monument Valley; 26 Wisconsin Driftless Area; 27 northern Appalachian Mts; 28 Roraima; 29 Chaco Basin; 30 Minas Gerais; 31 Vila Velha; 32 Nuussuaq Basin; 33 Keyser Franz Joseph Fjord; 34 Svalbard; 35 Varanger Peninsula; 36 Rondane Mts; 37 Hornelen & Solund Basins; 38 Orkney; 39 Torridonian Mts; 40 Pennines; 41 Fontainebleau; 42 Catalan Ranges; 43 Saxony-Bohemia; 44 Stolwe Mts; 45 Meteora; 46 Bashkiria; 47 Jordan; 48 Msak Mallat; 49 Tibesti; 50 Borkou; 51 Moroccan High Atlas Mts; 52 Adrar; 53 Fouta Djallon; 54 SE Nigeria; 55 Table Mt; 56 Clarens Valley; 57 East Transvaal; 58 Chimanimani Highlands; 59 Isalo; 60 Kialas; 61 Bhutan Himalayas

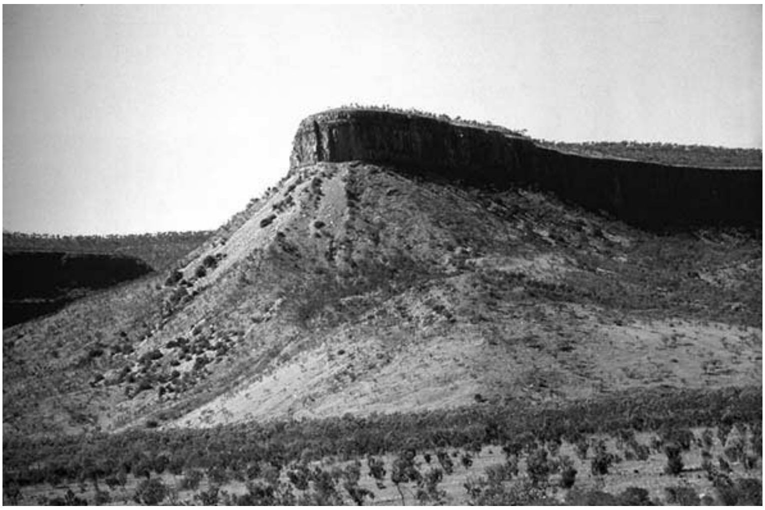

Fig. 1.2 Cliffs in the Cockburn Range, Western Australia

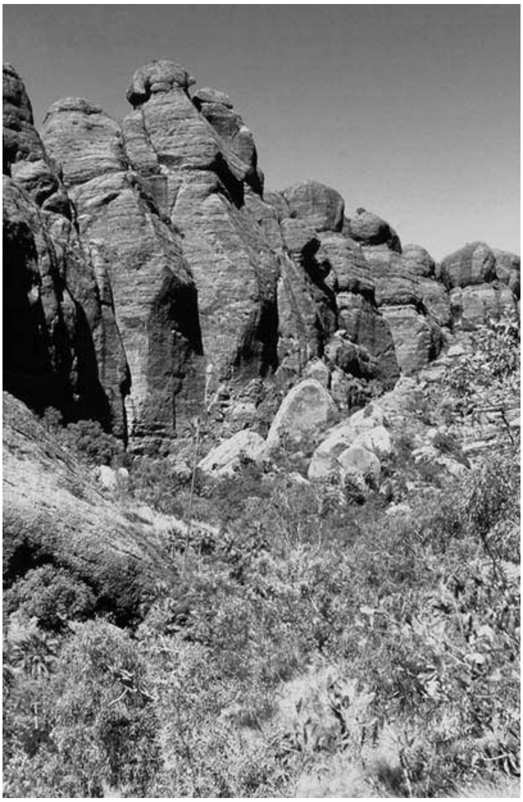

Fig. 1.3 Joint-bounded domes in conglomerates and pebbly sandstones in the Bungle Bungle Range, Western Australia

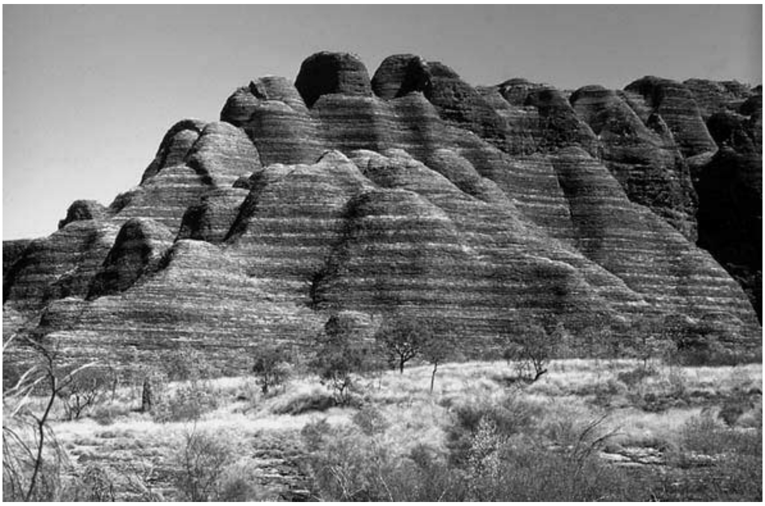

Fig. 1.4 Rounded towers cut in friable sandstones in the Bungle Bungle Range, showing marked banding on the rock surfaces

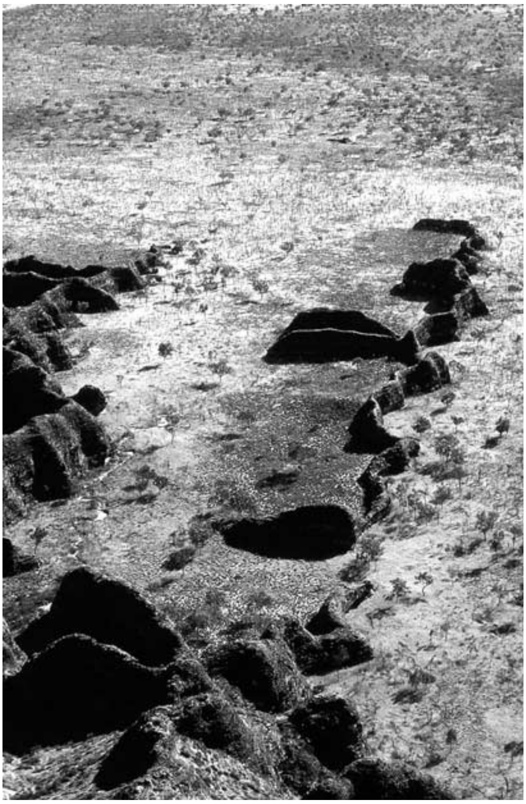

Fig. 1.5 Sinuous narrow ridges cut in friable sandstones rise abruptly from the surrounding plain, Bungle Bungle Range

diversity among these landforms, we encountered – at the very outset of our considerations – a methodological stumbling block to any attempt to fit this region into the morphogenetic systems proposed for sandstone geomorphology. Those systems are based on the comparative analysis of apparently representative type examples. But which is the type example here – the cliffs, the domes, or the towers and narrow ridges? This question cannot be dismissed by simply appealing to the scale of observation at which climatic or structural constraints are supposedly most discernible; that is to say, we are not just dealing with structurally controlled deviations from a common morphogenetic type. We have encountered here a major problem in the very rationale of the climatic classification of landforms itself, for the variety of forms within this region is greater than that found between the supposedly major morphogenetic zones (cf. Tricart and Cailleux, 1972). Whether the Kimberleys are simply the exception to a valid general rule, or whether the diversity of sandstone landforms within other morphogenetic zones really does rival the diversity between zones, is a vital issue to which we will return.

Likewise, the dominance of any other single factor, even if demonstrated elsewhere, cannot be assumed to apply here. Structure is a case in point. The constraints on topography imposed by variable jointing and bedding are expressed clearly on many outcrops in the region. Nonetheless, the domes of the Kimberley region do not display the beautifully curved unloading or spalling planes which characterize many of their counterparts on the Colorado Plateau (Bradley, 1963); nor is the preferential excavation of joints normally associated with stream erosion of sandstones displayed to any appreciable extent in the dissection of most tower and ridge complexes. On the contrary, some of the joints cutting through these complexes are case hardened, and act as lines of resistance to erosion (R. W. Young, 1986).

The role of lithology

Lithology appears to be a far more important constraint on landforms here than does structure. The cliff-lined mesas are best developed in the Proterozoic sandstones; the domes occur in Paleozoic pebbly sandstones and conglomerates; and the tower and ridge complexes are limited almost entirely to well-bedded Paleozoic sandstones. Yet, as Yatsu (1966) has emphasized, simple correlation of topography with lithological types explains little, for it is the variable mechanical properties of the rocks that must be assessed.

Most of the Proterozic sandstones in the region are strongly cemented, and some are very tough indeed. The Cockburn Sandstone, for example, has a compressive strength of around 100 MPa (1 megaPascal = 145 lb/in^2). As this massive siliceous sandstone – most outcrops of which can be classified as

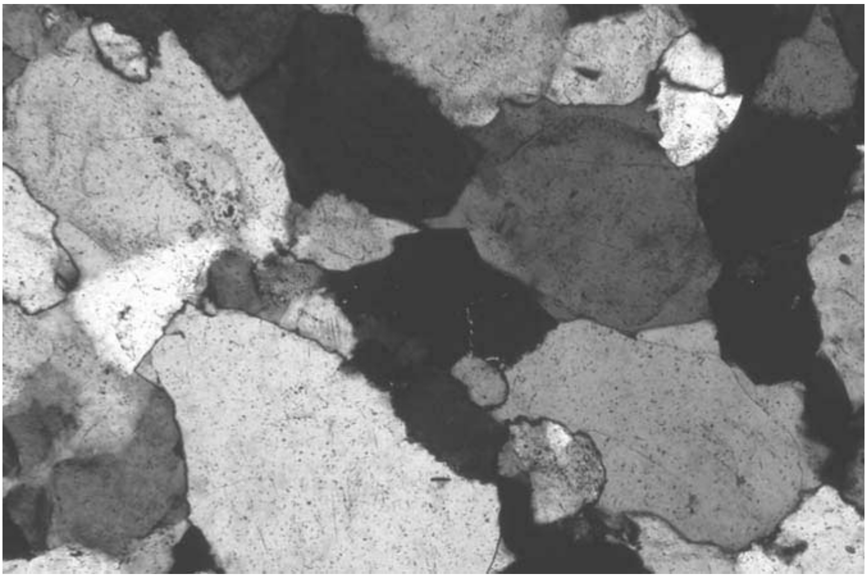

Fig. 1.6 Thin section of Cockburn Sandstone, showing high grain-to-grain contact

orthoquartzite – also has horizontal bedding and widely spaced, vertical jointing, it can be expected to stand in long-term equilibrium slopes of about 70° (cf. Selby, 1982) and, especially when undercut, to form high vertical faces. In contrast to the very tough Cockburn Sandstone, most of the Paleozoic sandstones of the region are generally more friable and easily eroded, yet still stand in quite steep, occasionally vertical, slopes. These topographic characteristics reflect the curious mechanical properties of these Paleozoic sandstones. Even the most friable of them, like the Glass Hill Sandstone that forms the Bungle Bungle Range, generally have reasonably high strengths of 40–60 MPa when in compression, but have such low strengths when tensional or shearing stresses are applied that they can be broken by hand pressure.

The reasons for the variable mechanical properties of the Kimberley sandstones can be readily seen at the microscopic level. The very tough ones, like the Cockburn Sandstone, have a high percentage of grain-to-grain contact, and are highly indurated with quartzose cement (Fig. 1.6). Friable ones, like the Glass Hill Sandstone (R. W. Young, 1988), are also composed mainly of angular, closely interlocking grains with a high proportion of grain-to-grain contact, but have virtually no cement (Fig. 1.7). In this case the interlocking fabric of grains can carry considerable compressive stresses, but individual grains can be detached by very low shearing stresses. Hence, steep slopes can still be maintained in material which is easily eroded.