Evolution of an ancient cratonic upland, the Gawler Ranges of inland South Australia

Evolution d’un ancien plateau cratonique, les Gawler Ranges dans les terres d’Australie méridionale

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ABSTRACT

The Gawler Ranges is a massif comprising bornhardts developed on Mesoproterozoic dacite, rhodacite and granite. The country rocks are subdivided by orthogonal fractures into massive compartments within which are developed sets of concentric arcuate partings or sheet fractures. Similar arcuate structures were superimposed on the western sector of the upland by a meteorite impact during the earliest Paleozoic. Following the Permian glaciation, the area was reduced to low relief. Fracture controlled differential weathering beneath the planation surface resulted in an irregular weathering front with prominent domical rises and intervening linear depressions. Uplift near the southern limit of the Mesoproterozoic outcrops caused north flowing rivers to strip the regolith and deposit the detritus in the ocean that then occupied the Eromanga Basin. There it was intercalated with marine strata that demonstrated a Neocomian-Aptian age for the alluvial deposit, and hence also for the etch or two stage bornhardt assemblage that was revealed by the evacuation of the weathered mantle. It has persisted virtually unchanged because of resistance of the country rocks. The veracity of the great age attributed to the Gawler Ranges topography is discussed, as are the possible reasons for its survival, the origin of the sheet fractures, and the reasons for the widespread development of etch or two stage features, though it is suggested that in view of the influence of shearing and resultant fractures on landscape development, it is more accurate to regard the upland as of multistage origin.

Keywords: bornhardt, orthogonal fracture system, sheet fractures and structures, etching, two-stage/multistage landforms, Neocomian-Aptian age, long term survival, reinforcement.

1. Introduction

The Gawler Ranges massif is located to the north of Eyre Peninsula and in the arid interior of South Australia (fig. 1A). It comprises ordered rows of the domical hills known as bornhardts (Bornhardt,
1900; Willis, 1934, 1936), and shaped in dacite, rhyodacite, and granite of Mesoproterozoic ages. For convenience the suite of volcanic rocks is referred to as the GRV (Gawler Range Volcanics). The volcanic massif is bordered to the east by the plains and plateaux of the Stuart Shelf formed on essentially undisturbed alluvial and shallow water marine sediments (#1 in Figure 1A) and further to the east by the Flinders Ranges (#2 in Figure 1A) developed on the northern extension of the Adelaide Geosyncline (#3 in Figure 1A) (Preiss, 1987). To the north east the Gawler Ranges massif gives way to the Arckaringa Basin with its scatter mainly of granitic inliers and which grades into the extensive marine Eromanga Basin (EB). To the northwest stands the Everard Range (ER) and to the west the Officer and Eucla sedimentary basins (#4 in Figure 1A). South of the abrupt southern front of the Gawler Ranges upland, a broad piedmont plain gives way to the linear Corrobinnie depression and depocentre (Bourne et al., 1974) and beyond that to the granitic inselberg landscape of northern Eyre Peninsula (fig. 1B).

The Gawler Ranges upland looks like the raised rim of a huge basin that has subsided to the north, for its southern margin is marked by an abrupt escarpment that is “en échelon” in plan shape and host to several peaks that stand 450 m or so above sea level and rise 180-200 m above adjacent piedmont and valleys. Linear fracture-controlled valleys or corridors. Most of them are oriented NW-SE or NE-SW, consistent the regional pattern. They separate compartments defined in plan by steeply dipping, orthogonal, quadrangular, and rhomboidal fractures and stand in ordered rows (fig. 2). In profile, each individual residual is subdivided into slabs by sets of concentric arcuate sheet fractures (Dale, 1923) which

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**Fig. 1 – Study area location.**

A: Situation and B: setting of Gawler Craton and Ranges.

**Fig. 1 – localisation de la zone d’étude.**

A : Localisation et B : configuration du craton et des Gawler Ranges.

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**Fig. 2 – Satellite image of part of Gawler Ranges showing orthogonal fracture pattern and lakes Gairdner (right) and Acraman (left).**


**Fig. 2 – Image satellitaire d’une partie des Gawler Ranges montrant le dispositif de fractures orthogonales et les lacs Gairdner (à droite) et Acraman (à gauche).**

together with the preferential weathering of the corners and edges of the angular blocks on which they are based, cause the residuals to be domical in profile. The flanks of the hills steepen downslope and meet the adjacent valley floors or plains in an abrupt change in inclination known as the piedmont angle. Also, many of the domes are bevelled, as a result of preferential weathering beneath a paleosurface (fig. 3).

Fig. 3 – Panoramic view, with general view of Ranges from Spring Hill, located some 12 km SSE of Thurlga Homestead.

Crestal area with lichens, pan overlooking a wide flat valley floor, in the western sector of the Ranges.

Fig. 3 – Vue panoramique, avec vue d’ensemble des Gawler Ranges depuis Spring Hill, à environ 12 km au SSE de Thurlga Homestead.

Partie sommitale avec lichens, vasque dominant un fond de vallée vaste et plan, dans le secteur occidental des Ranges.

2. Sequence of events

The evolution of the Gawler Ranges massif is analysed and explained by identifying and citing in sequence the major events that shaped the contemporary landscape.

2.1. Emplacement of the country rocks

The GRV on which the bornhardt massif is founded, were emplaced about 1,592 million years ago, in the Mesoproterozoic Era. Though previously interpreted as effusive, they are now considered to be of extrusive origin, as acidic lavas that emerged via fissures and consist mainly of dacites, with a large area of rhyodacite at the southern margin (Blissett et al., 1993; Allen et al., 2003; Parker and Flint, 2005) (fig. 1B). The volume of extrusive lava was of the order of 60,000–90,000 km³. It has been estimated that the GRV deposit was some of 1,500 m thick (Blissett and Radke, 1980). The outcrops are porphyritic with laths of plagioclase feldspars and K-feldspars set in a purplish silica-rich matrix comprised mainly of quartz and feldspar (Blissett et al., 1993). A small area of intrusive granite of the Hiltaba Suite dating from roughly 1,585 million years ago (Flint, 1993) is exposed to the west, as well as in the southern piedmont and in the Minnipa and Wudinna districts of north western Eyre Peninsula (fig. 1b, 4).

Like the Hiltaba Suite Granites, the dacitic rocks vary slightly in composition and for that reason may differ in their susceptibility to weathering (Brook, 1978; Hill, 1996) but they are subdivided by similar fracture patterns and have given rise to similar landform assemblages. However, other than the major fractures that delineate the massive compartments that have given rise to bornhardts, the partings are tight and not readily penetrated by water. For this reason, chemical weathering of the massive compartments is limited to rinds of kaolinsed country rock typically with a thin basal zone...
rich in iron oxides. Only in alluviated valley floors developed on major fractures, where the rock is in constant contact with moisture, are the volcanic rocks intensely and deeply weathered. The country rocks are intruded and buttressed by veins of dacite, rhyolite and rhyodacite, as well as the granite. Banks of columnar joints are developed throughout the GRV outcrop (fig. 5). They originated soon after the cooling of successive lava beds. Although they were not exposed until much later, in terms of origin as opposed to exposure as landscape features, they are, having been created circa 1,592 million years ago, the oldest structures and eventual landforms in the Gawler Ranges. Following the extrusion of the GRV and the intrusive emplacement of the Hiltaba Suite of granitoid rocks (Flint, 1984), the rock masses were sheared, generating fracture systems and sets the patterns and chronology of which had an enduring impact on landscape development. Yet, and as suggested below, they may have developed in part by external influences.

2.2. Orthogonal fracture systems

Crustal shearing associated with the migration of plates consisting of petrologically heterogeneous rocks has generated systems of orthogonal fractures in many parts of the world (Meinesz, 1947; De Kalb, 1990). In the Gawler Ranges such systems transect both the volcanic and plutonic rocks (fig. 6A). They determine the maximum plan shape and size of the bornhardts (fig. 6B). In the eastern Gawler Ranges some orthogonal fractures are intruded by sills of dolerite that are collectively referred to as the Gairdner Dyke Swarm dating from 1,050-1,100 million years ago (Preiss, 1987). Accordingly, the orthogonal fracture systems that define the compartments on which have developed the ordered rows of domical hills are between 1985 and 1,050 million years ago old, for they predate the intrusive veins, but postdate the dacite, and the granite.

Shear stresses have been applied continuously or repeatedly, since well into the Mesoproterozoic, continually setting in train fracture propagation, the spread of partings inwards from the margins of the fracture defined blocks. Bearing in mind first that the orthogonal system predated 1,050 or 100 million years ago and second that the GRV is comparatively thin, this pattern may in part, and initially, be attributed to underprinting (Hills, 1961; Twidale and Bourne, 2000a) and reflect the structure of the basement (Archaean – Early Proterozoic) rocks, like those exposed on southern Eyre Peninsula (Flint, 1984). Howsoever this may be, the stress fields that became orthogonal fracture patterns have been maintained, reinforced and extended by later shearing.

2.3. Sets of sheet fractures

Sets of arcuate fractures defining more-or-less thick slabs of rock known as sheet fractures and structures (Dale, 1923) are superimposed on the blocks and compartments formed by the systems of orthogonal partings. Though dominated by convex upward sets, concave upward and “eggbox” patterns appear to have developed (fig. 7). Their origin has been debated for more than two centuries (Dale, 1923). Several hypotheses have been offered, some invoking external agencies, others internal (Dale, 1923; Twidale, 1973). Some, such as variations in insolation, chemical alteration, and metamorphic changes, are readily dismissed as possible general explanations, but two have found substantial support. Gilbert (1904) suggested they are offloading joints associated with lithostatic relief, and hypothesis is indeed eminently plausible, particularly as applied to granitic terrains. Granite is a plutonic rock emplaced deep in the crust, yet granitic bodies such as batholiths and stocks are exposed over about 15% of the continental area. This surely demonstrates the erosional unloading of huge masses of overburden and by
implication the expansion of the granitic masses and the creation of fractures tangential to the tensile stresses.

However, little or no unambiguous supporting evidence is cited in support of the offloading hypothesis, which implies rocks in tension. Sheet fractures found on recently eroded facets of the land surface (fig. 7) frequently have been attributed to erosional offloading (Lewis, 1957; Kiersch, 1964; Gage, 1966) but are more likely an expression of stress field adjustments consequent on topographic changes caused by erosion (Müller, 1964). Moreover, sheet fractures are well developed in sedimentary rocks that have never been deeply buried but have been stressed (Bradley, 1963; Twidale, 1978a; Sweet and Crick, 1992; Twidale et al., 1996; Bourne and Twidale, 2003) and volcanic rocks like the GRV and the Eocene Kneeling Nun Tuff of New Mexico (Mueller and Twidale, 2002).

Alternatively, most of the Australian crust is in compression (Hillis and Reynolds, 2000). Also, shearing implies the simultaneous generation of both compression and tension (Endersbee, 2005). Sheet fractures demonstrably are planes of dislocation comparable to bedding plane slips, with recrystallisation fault steps and slickensides decorating the plane surfaces. The pattern of imbrication found on some sheet fractures (fig. 8) is consistent with an informal folding, with slabs decorated with fault steps facing upslope overridden by next higher slab. Shearing may have generated concentric slabs both around core masses, at various scales from laminae and thin plates or slabs around incipient corestone-boulders (Scrivenor, 1913), to sheet structures around future bornhardts (fig. 9). An assemblage of minor forms reasonably attributed to compression is well documented and is especially well developed in, though not confined to, granite terrains (Twidale and Sved, 1978; Vidal Romani and Twidale, 1998; Twidale and Vidal Romani, 2005). Possible sheet fractures defined by steeply dipping reverse faults were developed during the 1999 Minnipa Hill Earthquake (Twidale and Bourne, 2000b).

The rounding of angular blocks due in large measure to the preferential weathering of corners and edges is real, but would be enhanced by the occurrence of sets of arcuate sheet fractures that favour the spread of groundwaters and associated mineral alteration (MacCalloch, 1814). Zones of lamination in parallel with linear fractures and clefts oriented in parallel with Kluftkarren but lacking evidence of partings have been noted (Twidale, 1993). They can be interpreted as related to stress applied but inadequate to cause rupture, yet resulting in strain that has disturbed crystal lattices enough to facilitate water penetration and hence weathering (Russell, 1935; Turner and Verhoogen, 1960; Twidale and Bourne, 2007).
Thus, both field evidence and experimental work to sheet fractures and structures being associated with tectonism, with torsion or shear, as advocated by de la Beche (1839), Harris (1888), Merrill (1887), Dale (1923), Twidale et al., (1996) and others. Yet erosional offloading is real. A substantial thickness of overburden is indicated by the exposure of the Hiltaba Suite of granite in the western sector of the Ranges but the effects of overburden removal are difficult to recognise with certainty even in closely monitored sites, but they cannot be ignored. Incipient sheet fractures (stress zones) might have been developing in the Ranges since roughly 1,592 million years ago when shearing may have created strain in country rocks brittle enough for columnar joints, due to rapid cooling of the host lavas, to develop and be cut by sheet fractures (fig. 5B). Strain patterns could have been imposed that, following planation found

Fig. 9 – Effects of shear at various scales.
A: Results of shear. B: Exposed in road cutting, Snowy Mountains, New South Wales, showing shear planes (top left, bottom right), cores and concentric arcuate partings. C: Concentric slabs around granodioritic core, exposed in road cuttings near Tooma Dam. D: same, near Cooma, Snowy Mountains. E: Large scale with bank of sheet structures exposed on basal slope, Pindo Range, NW Spain.

Fig. 9 – Effets du cisaillement à différentes échelles.
expression in sets of arcuate ruptures. Sheet fractures are planes of
dislocation and are reasonably attributed to lateral compression
induced by shear stresses powerful enough to overcome any active or
residual tensile forces associated with the erosion of overburden.
Chapman (1956) justifiably interpreted fractures in granite as an
expression of offloading, insofar as reduction in lithostatic loading
allowed patterns of shear stress and strain to find expression as
partings.

2.4. Earliest evidence of planation

Toward the end of the Proterozoic, seas lapped onto the eroded
eastern margins of the volcanic exposures. Near the Scrubby Hill
Outstation, north of Nonning Homestead, arenaceous sediments
of the Pandurra Formation (Cowley, 1995) of Early/Middle
Proterozoic age (i.e. 1,424 millions of years old) were deposited on
the surface eroded in the dacitic rocks. The sandstone outcrop was
weathered and silcreted probably in Eocene times when much of
the land surface of central Australia developed a siliceous carapace
(Mabbutt., 1965; Wopfner et al., 1974; Firman, 1983; Wopfner, 1997).
Subsequently, both sandstone and weathered mantle have been
partly stripped, causing the exhumation of a small sector of the pre
Pandurra surface, the surface on which the Proterozoic sediments
were deposited (Twidale et al., 1976). Though the exposure is of
limited extent, the Scrubby Hill Surface is nevertheless the oldest
landscape facet in the upland (fig. 10).

2.5. Acraman Meteorite impact

The regularity of the orthogonal fracture system was disturbed by
the impact of a meteorite on what is now the western Gawler Ranges,
close to a lowland corridor related to a major E-W structure that
may, however, have been created or enhanced by the extraterrestrial
event. It created a crater that, much modified, is now the site of Lake
Acraman salina (fig. 2). Such was its force that a set of concentric
fractures was imposed on the pre-existing orthogonal system (fig. 2,
6A). It also caused dacitic debris to be ejected some 240–540 km to
the east, there to be deposited in the then ocean amongst the various
sedimentary formations that later, and following the Cambrian,
were folded, faulted, and later eroded, to form the present ridge
sand valley terrain of the Flinders Ranges. The Acraman detritus
occurs in the Bunyeroo Formation which is estimated to be some
580 million years old or of latest Proterozoic age (Williams, 1986;
Preiss, 1987; Williams and Gostin, 2005).

2.6. Late Paleozoic glaciation

There followed a long hiatus in the geological record prior to the
latest Carboniferous when the cooling of the climate heralded the
formation of upland glaciers, and the onset of the early Permian
 glaciation, during which southern and south eastern Australia,
including the present Gawler Ranges was overrun by ice sheets
(Bureau of Mineral Resources, 1992) that transported much of any
regolith developed on the land surface but did not necessarily effect
major changes in the bedrock morphology (Boyé, 1950; Bird, 1967;
Lidmar-Bergström, 1997).

2.7. Mesozoic landscapes: evolution of the bornhardt massif

2.7.1. Beck Surface and associated regolith

Following the melting of the Permian ice sheets, the initiation of a
new phase of landscape development saw the regional planation of
the area now occupied by the Gawler Craton (fig. 11), including the
areas now occupied by the Ranges and the inselberg landscapes of
the Minnipa and Wudinna areas. The hypothetical surface of low
relief—"hypothetical" for though the results of having existed are
obvious, no remnant of it has been recognised—has been called the
Beck Surface (Campbell and Twidale, 1991). It is interpreted as the
first vital stage in the evolution of the present bornhardt landscape.
Field evidence strongly suggests that the distinctive field of
bornhardts that constitute the Gawler Ranges evolved in two stages.
First, weathering beneath the Beck planation surface was differential.
The resultant extensive regolith was, however, thicker over major
steeply dipping fracture zones where there was deep penetration of
groundwaters. Between the valley sections, the regolith developed on the land surface but did not necessarily effect
major changes in the bedrock morphology (Boyé and Fritsch, 1973;
Twidale and Vidal Romani, 2005).

The attribution of inselbergs, including bornhardts, to differential
subsurface weathering may have been prompted by the earlier
wide acceptance of corestone boulders as two-stage forms that
(Hassenfratz, 1791; Ruxton and Berry, 1957; Twidale, 1978b) but it
was directly based in field evidence described by Falconer (1911),
from near Kano, in northern Nigeria. There Kogon Dutsi, a capped
mesa of altered diorite with corestones preserved near its base,
rests on a plain eroded in fresh country rock, and summarised in a
general statement (Falconer, 1911). The interpretation finds support in exposures of contrasts in weathering as between hill and plain at sites as far apart as Namaqualand and peninsular India, Dartmoor and Eyre Peninsula (Twidale 1964; Büdel 1977; Twidale and Vidal Romani, 2005).

Bearing in mind this two-stage model, referring back to the foregoing discussion of sheet fractures and structures, and placing experimental work in the context of bornhardt evolution, it has been shown that when rock masses with partly confined, projections were subjected to lateral compression, they each developed sets of concentric and arcuate upward partings (Holzhausen, 1989). In this manner, horizontal compression could have generated convex-upward sheet fractures that would have facilitated water penetration and alteration and rounding of the of the country rock, whether dacite or granite.

Quarry exposures in southern Africa and southern Australia do indeed show that sheet fractures develop in the subsurface suggesting that the bedrock projections on the weathering front, incipient inselbergs or bornhardts became rounded partly by preferential weathering of corners and edges or other irregularities, a process facilitated by the formation of sets of sheet partings that allowed the reader infiltration of groundwaters and hence mineral alteration. Many of the dacitic-rhyolitic bornhardts display bevelled crests, and the granite peaks of the western ranges were reduced to smooth, large radius domes also with crestal bevels. Large residual boulders with flared sides suggestive of intense subsurface weathering stand on upper slopes (Twidale, 1962). The crestal bevels can be attributed to erosional planation bringing uppermost zones of the compartments into the former zones of fluctuating water tables and hence of intense weathering. Consequently, when base level conditions allowed, the crestal areas were stripped and the bevelled weathering front exposed (fig. 3, 11-12).

The postulated widespread weathering implies the former presence of an regolith or weathered mantle of varied thicknesses, and evidence for such a mantle is scarce but ultimately convincing. First, a huge volume of regolith is implied by the cumulative size of the many structurally controlled valleys formed by the differential and fracture-controlled weathering and erosion of the GRV (fig. 2, 11). Many dams or water storages (in the local usage 'dam' indicates a water reservoir rather than the structure that impounds it) many metres deep have been excavated in the alluvium, colluvium, and weathered country rock beneath valley floors that stand 180-200 m lower than the crests of the adjacent bedrock highs. A huge volume of regolith is implied by the weathering of GRV to form the
numerous valleys. By contrast, few relics of the former regolith have
been located on the uplands, but some 10 km WNW of Thurlga
Homestead the excavation of a shallow scrape or borrow pit exposed
dacitic corestones set in a grussy matrix of disintegrated and
altered rock (fig. 13A). In the same general area, a group of castle
koppies stands up to 3-6 m above the level of the high plain (fig.
13B). According to Godard (1977) and Twidale (1981) such residuals
develop where the crests of bedrock compartments are exposed
flush with the land surface, but the flanks of the rock masses remain
covered by the weathered mantle. The exposed surfaces are relatively
dry whereas the flanks in contact with the moist regolith continued
to be weathered and steepened (Logan, 1851). The height of the
flattish crests of such features above the adjacent slopes is a measure
of the thickness of regolith at the time of their development. This
is clearly demonstrated at Castle Rock, a granitic koppie located
in the Mt Manypeaks area east of Albany, in the southwest of
Western Australia. The residual is stepped with two concave indents
each of limited height and indicating phases of shallow piedmont
weathering and erosion (fig. 13C). Thus, the thickness of the regolith
varied between perhaps 200 m or more over the steeply dipping
fracture zones that define the major compartments of the GRV, but
much less - apparently only a few metres - over the compartments
proper.

2.7.2. Exposure of the Nott Surface - the bornhardt landscape

The bedrock surface shaped as the weathering front beneath
the Beck Surface and exposed by the stripping of the regolith or
weathered mantle became known as the Nott Surface (Campbell
and Twidale, 1991). It was formed partly by chemical weathering,
but with significant physical disintegration caused by the swelling of
hydrophilic clays. The weathered mantle formed beneath the Beck
Surface was removed but whence, how and when? Stratigraphic
studies in the Eromanga Basin (EB), scores of kilometres to the
north east of the Ranges revealed that it had been transported by
north-flowing rivers and deposited as the Mt Anna Sandstone
(Wopfner, 1969; Wopfner et al., 1970) in the sea that then occupied

Fig. 14 – Mt Anna Sandstone.
Coarse sandstone with conglomeratic phase with contained GRV cobbles, and exposed
at Mt Anna, some 240 km north of present nearest outcrop of exposed GRV (photo
from H. Wopfner). The presence of GRV cobbles is compatible with the weathering
sequence that includes a segment of a corestone featured in Figure 13A.

Fig. 14 – Grès du Mt Anna.
Grès grossier avec passée conglomeratique renfermant des gros galets de GRV, affleurant
au Mt Anna, à quelque 240 km au nord du plus proche affleurement actuel des roches
volcaniques des Gawler Ranges (护身符 de H. Wopfner). La présence de ces galets
est compatible avec la séquence d’altération incluant un fragment de cœur rocheux
apparaissant sur la Figure 13A.
the area (fig. 14). Petrological analysis of the contained boulders and cobbles identifies them as derived from the GRV massif. The alluvial formation is thickest close to the putative source area in the Gawler Ranges upland and thins to the north. No other feasible source area has been found or suggested. The Mt Anna Sandstone is intercalated with fossiliferous marine strata of the Cadna-Owie Formation (fig. 14) and is of Early Cretaceous (Neocomian-Aptian) age. The two-stage surface landscape revealed by the evacuation of the weathered mantle is some 120-130 million years old. This is the age of the Nott Surface and also that of the present landscape.

The contrast in ease of transport between bedrock and friable mantle accounts for the almost complete stripping of the Neocomian-Aptian regolith and hence the exposure of the bedrock landscape that constitutes the Gawler Ranges. Such contrasts were noted more than a century ago and have since been revisited by, for example, Jutson (1934), Noldhart and Wyatt (1962), and Baker (1988). The process was succinctly expressed by Hills (pers. comm., 1962), when he pointed out that when, for whatever reason there was an increase in erosion, there is first a pronounced “skimming off” of soil and rotten rock, followed by a marked decrease in lowering when solid rock is exposed. Coherent bedrock is untouched by run-off, but friable weathered material is readily transported to expose the bedrock configuration. The stripping of the regolith and the conversion of the Beck to the Nott surface was initiated by the uplift of what is now the southern limit of the Ranges, resulting in the present escarpment, the northward diversion and rejuvenation of the rivers, and the transformation of the landscape to that of the contemporary Gawler Ranges. As frequently happens, the age of an event, in this instance the uplift that induced river rejuvenation and a resultant landscape revival, suggests a possible causation. The separation of Antarctica and Australia was in train during the Jurassic and Cretaceous (Veevers and Eittreim, 1962), when he pointed out that for whatever reason there was an increase in erosion, there is first a pronounced “skimming off” of soil and rotten rock, followed by a marked decrease in lowering when solid rock is exposed. Coherent bedrock is untouched by run-off, but friable weathered material is readily transported to expose the bedrock configuration. The stripping of the regolith and the conversion of the Beck to the Nott surface was initiated by the uplift of what is now the southern limit of the Ranges, resulting in the present escarpment, the northward diversion and rejuvenation of the rivers, and the transformation of the landscape to that of the contemporary Gawler Ranges. As frequently happens, the age of an event, in this instance the uplift that induced river rejuvenation and a resultant landscape revival, suggests a possible causation. The separation of Antarctica and Australia was in train during the Jurassic and Cretaceous (Veevers and Eittreim, 1962). Widespread faulting produced the South Australian Gulf, the Mt Lofty and Flinders ranges were revived, and the mass of the GRV was uplifted and tilted down the north, causing the bornhardts of the Gawler Ranges to be revealed.

2.8. Tertiary events

Following exposure in the early Cretaceous, the Ranges appear to have stood unchanged for 120-130 million years. This suggestion of landscape antiquity finds support in the stratigraphy of the southern depocentre that is the Corrobinnie Depression, for it contains deposits of Eocene as well as later Cainozoic ages (Bourke et al, 1974; Binks and Hooper, 1984) suggesting that it did not develop until after uplift and the formation of the abrupt southern face of the Ranges and, ipso facto, that the upland predates the Eocene. Sediments derived from the uplands, as well as northern Eyre Peninsula were deposited in the Corrobinnie depocentre during the Eocene, Pliocene, and Quaternary, but the contributions from the GRV Ranges most likely were derived from lower slopes and valley floors, rather than the bedrock crestal areas that are not only inherently resistant but run off from them was likely diffuse and “the tools of erosion”, namely quartz sand particles, were few (Bliss Knopf, 1924; Willis, 1936). The bevelled bornhardts stand high above the depositional plains. In round figures, several peaks stand over 400 m above sea level, whereas the piedmonts stand at around 200 m and the present aggraded surface of the Depression about a hundred metres lower. Thus, and in the absence of evidence of recent orogenesis and landscape distortion, the bevelled bornhardts are older than the intervening and adjacent Tertiary plains (Rütimeyer, 1769; Baulig, 1928). This age sequence is confirmed by the occurrence of silcrete of probable Eocene age formed and later dissected at the margins of the upland (Wopfner et al., 1974) but also, and later, in various paleodrainage lines developed in the west of the Ranges (Hou et al., 2003). Occurrences of “grey billy” or silcrete are preserved on the shorelines of salinas like Lake Everard, and on some interior plains that formerly carried shallow lakes or lagoons (Opik, 1954). But these events left the characteristic landforms of the Ranges—the domical hills—unchanged and served merely to confirm the great antiquity of the bornhardt landscape insofar as Tertiary accumulations stand lower in the relief than bevelled bornhardts.

2.9. Quaternary changes

2.9.1. Tectonism

North western Eyre Peninsula, immediately to the south of the Gawler Ranges (fig. 2) has been and remains tectonically active (Twidale and Bourne, 2000b, 2003a), and the southern piedmont of the massif appears also to have been recently modified by renewed uplift. The piedmont south of Paney Homestead, and north of the granitic Waulkinna Hill has been lowered by about 2 m as indicated by “dumbbells” of that height exposed near the bouldery granite upland or nubbin (fig. 15). Similar flared cones are exposed at Houlderoo, near the Coralbignie Outstation, south of Nonning Homestead. In a similar vein, faintly flared (concave) slopes shaped in dacite occur in several of the valleys eroded by ephemeral streams that debouch on to the southern piedmont. Remnants of a bedrock platform standing up to a metres above the level of the present plain are preserved east of Paney Homestead. These exposures can be attributed either to uplift of the southern margin of the Ranges. of which there is geological evidence (Turner, 1975), or to the lowering

Fig. 15 – Dumbbell granite column, piedmont of Waulkinna Hill, 10 km SW of Paney H.S.

Fig. 15 – Colonne granitique en forme d’halêtre, piedmont de Waulkinna Hill, à 10 km au SW de Paney H.S.
of the depression to the south, but as the latter is a depocentre which has aggraded and is still receiving sediment from both north and south, a recent slight uplift of the Ranges is indicated.

2.9.2. Aridity

Recent faulting may also be invoked in explanation of the several fault angle valleys formed within and around the Ranges. The onset of phases of aridity playas and salinas replacing riverine valleys. The largest of the Gawler Ranges salinas is Lake Gairdner which extends some 160 km from north to south and is up to almost 50 km wide (fig. 2). It covers an area 9,000 square kilometres (Johns, 1968). The salina occupies a fault angle depression or half graben, for the western shore shaped in GRV sequences is in broad view arcuate, though comprised of structurally controlled linear sectors trending NW-SE and NE-SW. Most of the numerous islands occur in a NW-SE trending zone in parallel with the adjacent shoreline and the rocky shores are in detail blocky and fracture-controlled, this in sharp contrast with the smooth depositional shore which though rocky in places is mostly smooth and backed by lunettes (fig. 2, 16A). Drill holes sunk in the bed of the salina near the north western shore penetrated to a depth of about 18 m. and revealed that the surficial halite crust is underlain by gypseous sediment, grey clay, and waterlogged sand.

At present the climate of the Gawler Ranges is arid-semiarid with an average annual rainfall of 200-300 m, much of it associated with summer thunderstorms, but no desert is rainless, and from time to time short episodic rivers have flowed on to the lake bed, depositing silt and sand and also, presumably during and following especially heavy rains, blocks and cobbles of GRV derived from the rocky western shore and isolated outcrops on the eastern. The dramatic and rapid effects of salt weathering are in evidence (fig. 16B). Transported blocks boulders and cobbles have been etched by salt crystallisation with platforms cut into blocks and erstwhile spheres reduced to inverted hemispheres with the flat faces flush with the lake bed (Winkler and Singer, 1972; Twidale and Bourne, 2008). Such is the destructive power of haloclasty. The salt encrusted bed of the salina is level and stands about 121 m above sea level. However, just as the precise location of the deepest site on the bed of Lake Eyre South (and hence of the whole of Australia) varies in time and space (Dulhunty, 1990), so at any one time there are slightly higher areas positions of which vary according to the level of the most recent precipitation of halite following the latest cycle of flood and solution followed by desiccation and precipitation of halite. In broad view, however, the bed of Lake Gairdner is level. The author has seen the southernmost sector of the Lake one afternoon carrying about 10 cm of water following rain and run off, only to find the salt bed exposed and the water reported to be at the northern end of Lake the next day following an overnight reversal of wind direction from northerly to southerly.

To the north, the valley in which Lake Gairdner stands is blocked by bedrock that though cut by a NW-SE fracture zone is not breached by any valley of consequence entering or exiting the salina. Major drainages debouch on to the southern sector of the bed of the salina from the west and southwest. At the southern extremity of the lake more than 8 m of alluvium occurs in the walls and beneath the floor of the Yardea Dam, and further south the land rises gradually in the vicinity of the Thurlga Ramp and the south eastern limit of the Corrobinnie Depression, to an elevation of more than 200 m above sea level, suggesting that deposition in the Corrobinnie Depocentre caused the formation of the Lake Gairdner salina.

This, it is surmised, is linked to the blockage of a former major outlet of the rivers that at times drained the Depression, and notably the Narlaby, Tolmer and Fowler rivers (Binks and Hooper, 1984; Benbow et al., 1995a). But the outlets were blocked by the deposition of a complex stack of calcarenitic coastal dunes on the west coast of Eyre Peninsula (fig. 1B) during the Middle and Late Pleistocene (Wilson, 1991; Belperio, 1995). Accordingly, the formation of Lake Gairdner may be linked to events 100-200 km to the west and southwest, on the present west coast of Eyre Peninsula. Weathering of the stack of calcarenitic coastal dunes produced calcareous dust that was transported eastwards on the wind and after deposition, solution, illuviation and reprecipitation, formed the calcrete carapace that transformed the riverine landscape of much
of Eyre Peninsula into a karst plain, with far reaching consequences for landscape development and later land use (Bourne and Twidale, 2016).

In addition to salinas, the arid climatic phases of the later Pleistocene and middle Holocene saw the formation of fields of linear or longitudinal desert dunes. Dunes of the older field dating from between roughly 260 ka and 25 ka years ago advanced from northwest to southeast over north western Eyre Peninsula and the southern piedmont of the Gawler Ranges (Hilgers et al., 2011; Twidale et al., 2018) and also on the broad southern piedmont of the Gawler Ranges. Dunes of similar orientation were active during the middle Holocene on northern Eyre Peninsula. Within the upland and during the same climatic interval a field of well-named climbing and falling sand ridges sourced in the sediments of the western Corrobinnie Depression, advanced from the west, across hills and valleys (fig. 17) and extended east in an irregular front to roughly the Yardea-Minnipa road, prior to partial stabilisation by shrubs and small trees (Campbell et al., 1996).

2.10. Exploration and settlement

There followed, first, a lengthy Stone Age phase of Aboriginal hunting and gathering (Berndt, 1985), and second, a period of European exploration, as for instance by Eyre who mentioned “island mounts” from the southern piedmont (Eyre, 1845). They include the well named Mt Allalone. Later the western Ranges were traversed by Afghan cameleers engaged in the transportation of supplies and produce between the ports at Streaky Bay and Thevenard and inland pastoral stations. They found and noted granite outcrops and field exposures clearly illustrate Dale’s (1923) vision of “a series of undulating fractures extending entirely across a granite mass several miles in diameter and to a depth, as far as observed, of 250 feet” (roughly 76 m) “from the rock surface”.

The Gawler Ranges landscape can justifiably considered to be ofetch or two stage origin (Logan 1851; Wayland, 1921, 1934; Willis, 1936). By contrast with the present and recent aridity and semi-aridity, paleontological evidence suggests that warm humid conditions that would have facilitated and enhanced subsurface weathering, prevailed for much of the Mesozoic and the Eocene (Willis, 1936; Kemp, 1978; Frakes, 1979; White, 1990; Benbow et al., 1995b). The contemporary bornhardt landscape is probably in large measure inherited from past periods of monsoon and humid tropical environments. The subsurface weathering that played a crucial part in its evolution was dominated as it by chemical actions or etching - the eating away by acids - to produce the topographically differentiated weathering front (Willis, 1936). The impact of expanding clays in facilitating the spread of water and hence of mineral alteration is vital, so that the etching process might appropriately be described as physicochemical. Nevertheless groundwaters extend to depths of 700-800 m and the saprolithic (chemically altered) element of regoliths is justifiably reflected in the etch component of the widely applied landscape title. Also, the

3. Multistage evolution

Whether extrusive or effusive, the emplacement of the resistant GRV and the intrusion of the Hiltaba granites, taken together with the development of the orthogonal system of fractures during the later Mesoproterozoic (about 1,100 million years) signals the initiation of the present landscape, for each of the complex blocks or compartments defined by the orthogonal system became bornharts. Furthermore, the orthogonal pattern may in part may be linked by underprinting to structures in Archaean rocks exposed on southern Eyre Peninsula. Accordingly, the evolution of the Gawler Ranges landscape possibly can be traced back to distant periods.

Also, shearing within compartments has generated sheet fractures in the Gawler Ranges, then the structures that have substantially contributed to the shaping the domical hills, both directly and by facilitating subsurface weathering initiated any time during, or since, the later Mesoproterozoic. But if, as is suggested, lithostatic relief is a significant factor in the formation of sheet fractures, the most likely time for development is when the bedrock surface was located at shallow depth beneath a regolithic cover. In the Gawler Ranges that situation appears to have developed in the earlier and middle Mesozoic, prior to the north-down tilting of the southern sector of what are now the Gawler Ranges during the Neocomian-Aptian, and uplift that triggered the exposure of a topographically differentiated weathering front as the contemporary bornhardt dominated landscape. The significance of shear and compressive stress in the formation of the Gawler Ranges landscape is obvious and field exposures clearly illustrate Dale’s (1923) vision of “a series of undulating fractures extending entirely across a granite mass several miles in diameter and to a depth, as far as observed, of 250 feet” (roughly 76 m) “from the rock surface”.

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work on epigene processes germane to the overall result cannot be overlooked, for the exposure of the weathering front, the completion of the two-stage sequence was achieved by rivers, mass movements, and possibly waves.

In the western sector of the upland, the plan patterns of orthogonal fractures were disturbed about 600 million years ago by the impact of the Acraman meteorite. This was the land surface on or beneath which the Gawler Ranges bornhardt landscape developed, first by subsurface weathering in the period post Permian pre Early Cretaceous (but most likely late Jurassic and the earlier Cretaceous (Neocomian-Aptian). The exposure of the bedrock weathering front due to the stripping of the regolith occurred in the Neocomian-Aptian interval, but the pattern of differential weathering and of the subsequent topography was determined by the stress pattern and system of orthogonal fractures developed before about 1,100 million years and later than 1,592 million years. Bearing in mind the significance of the composition of the dominant country rock and other development of orthogonal and sheet fractures, in the shaping of the bornhardt landscape, and despite the crucial two-stage evolution of the later eons, it is appropriate to regard it as being of multistage origin, with chronology that is traced back certainly to the Mesoproterozoic, and, if the suggested underprinting is real, the Archaean (Twidale and Vidal Romani, 1994).

4. Antiquity

Being etch in origin, the Gawler Range bornhardt field has two ages, one relating to the period of subsurface weathering, the other to the phase of regolith stripping. The first refers to the interval between the end of the Permian glaciation and the Neocomian-Aptian tectonism, uplift and stream rejuvenation during which the Gawler Craton, including the GRV sector where planation and fracture-controlled weathering shaped as bedrock topography. The second, the Neocomian-Aptian, alludes to the period when rejuvenated northward flowing streams evacuated the regolithic veneer to reveal the contemporary massif and deposited the resultant detritus in the ocean, fortunately later to be exposed and available for analysis; an erosional landscape is of the same age as the deposits derived from that erosion. In Gawler Ranges the Neocomian-Aptian age of the Mt Anna Sandstone is based on its intercalation with the fossiliferous Cadna-Owie Formation. An erosional landscape is of the same age as the deposits derived from that erosion. In Gawler Ranges the Neocomian-Aptian age of the Mt Anna Sandstone is based on its intercalation with the fossiliferous Cadna-Owie Formation. The implied great age of the Gawler Ranges massif is confirmed by the Cenozoic stratigraphy of the sediments deposited in the Corrobinnie depocentre located to the south of and at a lower elevation than the dacitic massif.

It may be argued that the Gawler Ranges landscape is an isolated oddity due to a coincidence of conservative factors. But the ancient massif does not stand alone. To the contrary its great age receives tacit support from studies in several other parts of Australia and elsewhere (Twidale, 2016). The plateau surface of the adjacent Stuart Shelf predates the Early Cretaceous for a marine transgression of that age penetrated pre-existing basins and valleys. Though the ridge valley landscape of the Flinders Ranges dates from at least the Eocene, the bevelled crests of ridges again probably date from the Early Cretaceous (Woodard, 1955). Credible evidence of ancient landscapes is recorded or implied also from other parts of Australia (Daily et al., 1974; Beckman, 1983), including Western Australia and Victoria (Jutson, 1934; Hills 1938, 1955a, 1955b; Van de Graaff et al., 1977; Jenkin, 1988; Twidale and Bourne, 1998).

Thus, ancient landscapes are not unknown in southern Australia. Moreover, “Down Under” is not unique in this regard for very old surfaces are reported or implied from other Gondwanan remnants (King 1962; Partridge and Maud 1985; Briceno and Schubert 1990; Birkenhaurer, 1991; Partridge, 1998; Carignano, 1999; Demoulin et al. 2005; Ollier 2014).

Like any heretical notion, the suggestion that landscapes of great antiquity survive in the present scenery has been dismissed as invalid and impossible because it is in denial of common sense – how can any rock surface withstand long exposure to the elements?—as well as established theories. The dilemma may be susceptible of solution by the physical and numerical dating methods now available (Pillans, 2005; Schmidt and Williams, 2017). Results so far vary, depending in what is dated, and how. In some instances stratigraphic and topographic evidence implicitly has been refuted by results derived by a particular physical dating procedure (Watchman and Twidale, 2002). The reliable dating of surfaces could, if it appears to be internally consistent and also compatible with stratigraphic and topographic evidence, confirm the great age suggested by geological methods; or they could deny them, in which case the stratigraphical and topographic relationships would call for explanation. Notwithstanding these possibilities, geological evidence has convinced several investigators that some epigene surfaces appear to be of a great age. The ancient Gawler Ranges landscape is not a freakish or chance survival, but rather one of several known examples of landscape persistence. They are considered unreasonably ancient for epigene land surfaces. They pose problems for conventional theory that call for explanation.

5. Survival or persistence

If a thing exists it must be possible, and if the ancient landscapes hypothesis is valid, it is reasonable to consider factors that may have promoted survival; and indeed several such factors that might have contributed to the preservation of the landscape elements in the Gawler Ranges and elsewhere, have been suggested (Twidale, 1976).

5.1. Resistant country rock

The volcanic rocks that constitute the GRV are, relative to other significant outcrops in the region, physically resistant, as indicated by the results of Los Angeles Abrasion and the Schmitt Hammer tests hardness and rebound tests. Chemically they are of low reactivity, for they are highly siliceous, with an overall silica content around 70%. With the notable exception of haloclasty, the GRV appear to be resistant to all forms of weathering, and the inherent toughness of the widely exposed dacite and rhyodacite is overwhelmingly significant in the conservation of the bornhardt landscape.

5.2. Condition of fractures

The orthogonal fractures that define the bornhardt based
compartments have been exploited by groundwaters to form major valleys but otherwise the GRV are compact with the many minor partings that are tight and impenetrable by water. This can be attributed to the consistent compressive stress. Contact with water, or rather avoidance of such contact is a major factor in rock weathering. Logan (1851) and Monroe (1964) have contributed astute observation concerning the contrasted rates of weathering on dry and moist rock surfaces.

5.3. Induration of weathering front

The abrupt transition between bedrock and regolith is enhanced by the nature of the weathering front, especially in granite terrains, but also in other rock types. The basal horizon of the regolith is commonly laminated or foliated as result of physicochemical weathering, namely the alteration of ferromagnesian minerals sand feldspars to hydrophilic clays that expand and split the rock into thin slivers. Weathering commonly releases salts of iron and more is introduced in groundwaters. The resistance and stability of the rock exposed at the weathering front frequently is enhanced by accumulations of a thin zone of iron oxides at the contact between rock and soil (Twidale, 1986; Pavich, 1986; Whitehouse et al., 1986; Twidale and Vidal Romani, 2004).

5.4. Biotic protection

Bedrock surfaces commonly are colonised by algae, mosses, and lichens. Dead algae have in places induced small-scale topographic inversions with erstwhile gutters transformed into linear ridges (Twidale and Bourne, 2003b) and lichens produce oxalates such as weddellite and whewellite that are insoluble and stabilise the surfaces on which they grow.

5.5. Nature of run-off

Despite claims to the contrary (Davis, 1909) stream erosion does not extend over the entire land surface. As noted by Bliss Knopf (1924) headwater reaches are untouched by runoff and are out of reach of erosion, partly because run off is diffuse (Dunne and Aubry, 1986) but also because grains of quartz sand, the "tools of erosion", are scarce (Willis, 1936) see also Bornhardts form resistant local divides that are almost immune from erosion (Willis, 1936). Erosion is unequal (Logan 1851; Crickmay, 1976) and resistant hills, many of them having increased in height above valley floors and adjacent plains because of episodic exposure, tend to persist.

5.6. Reinforcement

Major fracture zones have been exploited by water and major valleys, in which accumulate detritus, soil, vegetation and micro faunas. This has increased the weathering potential of the valleys which have been deepened, enlarged, and perpetuated, in what is known as a reinforcement sequence (Behrmann, 1919; King, 1970; Twidale et al., 1974). In complementary developments the divides between major valleys – in the Gawler Ranges the incipient bornhardts became higher and more rounded because of the preferential weathering of the corners and edges of the compartments on which they are based, but also and possibly because of the suggested development of arcuate sets of partings or sheet fractures. This contrast in rates of weathering and erosion between upland and valley continued – and presumably, continues – but also became more pronounced as the bornhardts were relatively protected as they shed any runoff to the valleys and plains, making them susceptible to further lowering.

Repeated alternations of piedmont weathering and erosion – episodic exposure – have left the bedrock uplands higher and in many instances with a stepped morphology (Jessen, 1936; Twidale and Bourne, 1975; Bourne and Twidale, 2000). This inevitable and repeated sequence, with uplands made higher relative to the piedmonts and valley floors further accounts for the survival, persistence and enhancement of the bedrock or bornhardts.

5.7. Burial

Many very old buried surfaces have been preserved and re-exposed in relatively recent times. Such exhumed resurrected or disinterred surfaces occur on opposed flanks of the Great Australian (or Artesian) Basin (Twidale, 1956; Opik et al., 1961). The exhumed surfaces are exposed unconformities. The age of such features is estimated as less than the age of the youngest rocks transected by the erosion surface and greater than the age of the oldest cover materials. Thus, the Scrubby Surface (above and Figure 10) is younger than the GRV lava (1.592 million years) but older than the Pandurra Formation strata deposited on it (1.424 million years). Groundwaters readily penetrate along unconformities so that buried surfaces, whatever their original condition, are frequently weathered or further altered. A previously developed regolith may be stripped by rivers or waves that introduce the cover sediments. Although burial not only implies consistent wetting by groundwaters, and thus continuous alteration, but also possible lowering as a result of the evacuation of the products of alteration in solution (Ruxton 1958; Trendall, 1962), a sedimentary or volcanic cover nevertheless serves to preserve a covered surface. The Scrubby Surface is the only resurrected form recognised in the Gawler Ranges, but elsewhere exhumed features of ages ranging from deep in the Precambrian to late Pleistocene have been recorded. Interestingly, the classical bornhardt landscape, shaped in Precambrian gneiss and granite, and described by Bornhardt, from what is now Tanzania, is exhumed from beneath and predates a thick cover of Lower Cretaceous arenaceous strata (Willis, 1936).

6. Heresies and heretics

What has been described as the "ancient landscapes hypothesis" (Sandiford, pers. comm. 2006) has occasioned considerable discussion, for the general theme runs contrary to the conventional view, based on the tenets of Hutton (1788) and Davis (1909) who considered landscapes to be in a state of constant flux and therefore essentially youthful. This was taken to apply whether evolution by peneploation and lowering as urged by Davis, scarp recession as championed by King (1953) or steady state as advocated by Hack (1960). When Thornbury (1954), for instance, wrote that "Little of the earth’s topography is older than Tertiary and most of it no older than Pleistocene", (though prudently excepting exhumed forms
from his generalisation) he was reflecting voices of experience. It must be conceded that the proposed antiquity of some land surfaces also defies logic, for what features withstand the elements for millions years? Yet the stratigraphic and topographic evidence pointing to the antiquity of some landscapes and cited here appears to be sound, if unlikely. But there is more than one logic, and not everything which is incredible is untrue.

Research is incomplete until published and available for critical comment. Debate is a crucial aspect of scientific method as succinctly summarised by Popper (1963) in the title of his magisterial Conjectures and Refutations. Unfortunately, consideration of the suggestion that bedrock landscapes can persist through the ages in defiance, let it be said, of common sense, has become tendentious. For instance, the hypothesis has been described as a “con-job”, i.e., a confidence trick perpetrated on an ‘unquestioning’ scientific public. It has not only been dismissed, but the debate has been sullied by the suggestion of unprofessional conduct.

7. Concluding remarks

The Gawler Ranges massif is a structural landscape sensu lato with the impacts of passive factors and active tectonics, and of an extraterrestrial event apparent and various scales. It can be analysed and understood in terms of the Davisian triad of structure process and time, albeit with the major factors presenting aspects that probably were not considered when enunciated more than a century ago. Structure both passive and active remains of prime importance in landscape analysis. Thus, the resistance weathering and hence erosion of the major components of the GRV sequence is a key factor in the essential morphology of the Ranges and its evolution over the eons. In an anorogenic terrain, any factor or event that causes uplift sets in train a sequence that may lead to long term survival, for although it is now appreciated that many familiar landforms, major and minor, and including many bornhardts, have been initiated not under the influence of surface processes but in the subsurface at the weathering front and by the processes at work there.

This analysis and interpretation of the evolution of the volcanic upland that is the Gawler Ranges massif addresses a range of problems including the origin of sheet fractures and the impacts of strain; examples of possible underprinting; the nature and origin of etch and two stage development and the reality of multistage evolution; and the significance of reinforcement or concatenation. However, it is the putative great age of the uplands that is most obviously at odds with the conventional geomorphological wisdom.

Paraphrasing Fraser’s (1980) view of History, landscape chronology can be compared to a long avenue of hindsight, with past events and processes interpreted in terms of contemporary processes: the present is the key to the past, albeit with only vague consideration of, for example, the impacts of organic evolution. No doubt the ancient landscapes hypothesis will prove to be flawed in some details but correct in others. Nevertheless, several investigators have been driven to conclude that the landscapes they had studied are of epigene origin, but of various pre-Cenozoic ages, and thus of an antiquity greater than that allowed in the most liberal of conventional estimates (Schumm, 1963; Brown, 1980). If in some instances, and this appears to be the case, the ancient landscape hypothesis has been demonstrated. Some landscape components, such as uplands (and some discordant rivers) (Tweedale, 2004) have an inbuilt tendency to maintain themselves and to persist.

Some years ago, discussing the geomorphological contributions of Penck, also Johnson (himself a distinguished scientist and the first and only Editor of the outstanding but unfortunately short lived Journal of Geomorphology - 1938-42 and a casualty of World War II), described Penck’s relating slope geometry to tectonics as “one of the most fantastic ideas ever introduced into geomorphology” (Johnson, in Y von Engeln, 1940). This was a challenging judgement, but according to some workers the ancient landscape hypothesis is a worthy rival. Ancient landscapes heretics can take some comfort from the suggestion that many ideas that eventually became influential, initially were considered absurd; a quality in which the ancient landscape hypothesis is, according to its critics, abundantly endowed.

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Annexe

The writer was introduced to the Gawler Ranges and the adjacent north western Eyre Peninsula and their landforms 60 years ago and has maintained his interest ever since. Various students and visitors have shared that curiosity but Drs E.M. Campbell and J.A Bourne not only carried out investigations that, under the supervision of the present writer earned higher degrees but also, co-authored several peer reviewed publications concerned with the evolution of landforms in the two regions. Further work and reflection on such topics as the nature and origin of the Gawler Range Volcanic suite (GRV); the nature and impacts of sheet fractures and structures, and of the orthogonal fracture systems; the origin of Lake Gairdner; the multistage origin of the landscapes, as well as a revision of more general aspects, justify this further essay. In addition, the proposed age of the landscape and indeed the entire ancient landscapes model has been challenged. This is neither unexpected nor unjustified, for the conclusions were, and are, at odds with the conventional geomorphological wisdom, but nevertheless call for comment.

Tragically, Liz Campbell’s further studies were cut short, and the same pernicious disease later ended Jennie Bourne’s researches. Thus, although it may be unusual to cite as co-authors colleagues who died some years ago, it would be unjust not to credit their contributions as authors rather than simply acknowledging their work. The senior author, however, accepts responsibility for contentious matters discussed here.
References


York, 103–109.


Eyre E.J. (1845) – Journals of Expeditions of Discovery into Central Australia and Overland from Adelaide to King George's Sound, in the years 1840–41. T. and W. Boone, London, 2 volumes.


Hutton J. (1788) – Theory of the Earth; or an investigation of the laws observable in the composition, dissolution and restoration of land upon the globe, Transactions of the Royal Society of Edinburgh, 1, 209–304.


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Les Gawler Ranges (fig. 1-3) forment un ensemble d’inselbergs alignés, constitués des granites intrusifs de la Hiltaba Suite vieux de 1 585 millions d’années (fig. 4) et de roches volcaniques extrusives d’âge mésoprotozoïque (principalement des dacites et rhyodacites, couramment dénommées Gawler Range Volcanics –GRV–, remontant à environ 1 592 millions d’années) (fig. 5). Chaque inselberg est taillé dans un bloc ou compartiment défini par des fractures orthogonales qui étaient en place il y a 1 100 millions d’années et se décomposent en séries de fractures arquées concentriques ou diaclases d’exfoliation (fig. 6-9). Après la glaciation permienne, le secteur a été réduit à un relief très peu marqué (fig. 10). La météorisation, contrôlée par la fracturation qui a opéré sous la surface d’aplanissement, a donné naissance à un front d’altération topographiquement différencié associant dômes rocheux et zones de fracturation profondément arénisées. Le soulèvement tectonique ayant affecté la marge méridionale du massif a provoqué un rajeunissement du relief par incision et l’évacuation vers le nord de la plus grande partie du régolite, son dépôt corrélatif se retrouvant dans la mer qui occupait à cette époque le Bassin d’Eromanga. Ces sédiments terrigènes se sont intercalés dans des strates marines fossilifères qui les situent ainsi dans le Néocomien-Aptien, période à laquelle remonte également le paysage d’inselbergs exposé suite à l’évacuation du régolite. Ce paysage est donc apparemment le fruit de deux étapes, mais si l’on tient compte de la résistance des roches extrusives et intrusives constituatrices du substrat et de la configuration de la fracturation, il est plus réaliste de considérer le paysage des Gawler Ranges comme polygénique (fig. 11). Les formations cénozoïques présentes sur les plaines adjacentes suggèrent que le massif a persisté pratiquement dans sa forme initiale depuis son apparition il y a 120-130 millions d’années. La longévité de son relief est attribuée à la résistance des roches encaissantes à la plupart des processus de météorisation, et à la pérennité du ruissellement divergent sur les reliefs rocheux du GRV (effet cumulatif par rétroaction positive).