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LANDSCAPE EVOLUTION IN THE FINKE (LARAPINTA) RIVER TRANSVERSE DRAINAGE, CENTRAL MOUNTAIN RANGES, AUSTRALIA

Abstract: The cross-axial pattern of the Finke (Larapinta) River across the central ranges of Australia developed through a complex combination of processes including early planation; deep weathering (late Mesozoic/early Cainozoic); long-term stream impression; etchplanation; progressive aridity, leading to late (Pliocene and Quaternary) changes in fluvial flood regimen; all associated with regressive river erosion, stream capture, and/or epeirogenic movements. An early phase of etchplanation explains the development on easily weathered rocks of intramontane basins and strike valleys. Combined with stream impression, this process led to the superposing of the Finke and the Hugh Rivers across resistant rock units. The most unusual aspect of the Finke is a palimpsest, developed in the Krichauff Ranges, in which an ancient, relict gorge, is incised into a local planation surface (the Shoulder Surface), and preserved as paleomeander segments, in which the original quartzite gravel fill has been cemented with iron oxides and silica. The Shoulder Surface was subsequently more deeply incised by a later manifestation of the river to produce the meandering contemporary gorge that is intertwined with the relict one. The incision of the contemporary gorge occurred in association with the change in flood regimen, and involved either (1) prior aggradation of the incised paleomeandering stream to permit alluvial meandering across the Shoulder Surface and subsequent incision into it, or (2) headward recession of a knick point created where the Finke flowed from resistant sandstones into what are now the strike valleys of the James Ranges, from which weathered mantles had been removed by etchplanation processes.

Keywords: geomorphology, etchplanation, flood regimen, stream impression, Finke River, Central Australia

INTRODUCTION

"Old, flat, and red" – such is the essence of Australia's distinctive landscapes (Pain et al. 2012). This characterization is especially apt for that continent's arid "red center," located near Alice Springs (Fig. 1) and drained by the Finke River ("Larapinta" in the language of the local Arrente people). The Finke is popularly claimed to be the "world's oldest river" (https://en.wikipedia.

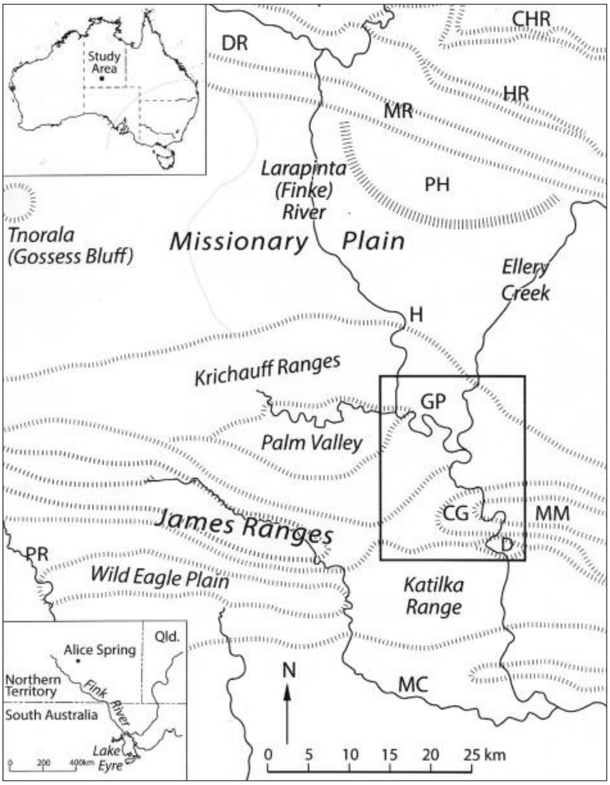

Fig. 1. Location maps of the study area. The upper left inset shows the location in central Australia, and the lower left inset shows the pattern of Finke (Larapinta) River in the states of Northern Territory and South Australia. The main map shows the study region lying southwest of Alice Springs with many features identified that are discussed in the text. Figure 2 is a spacecraft image covering much of the same area. The box at right center outlines the area covered by Figure 7 Letters refer to the locations of Circle Gully (CG), the Chewings Range (CHR), the "diamond shaped plain" (D), Davenport River (DR), Glen Helen (G), Glen of Palms (GP), Hermannsburg (H), Heavitree Range (HR), McMinn Creek (MC), Mount Merrick Anticline (MM), MacDonnell Ranges (MR), Pentjara Hills (PH), Palmer River (PR)

org/wiki/List_of_rivers_by_age). Here river age is inferred from the age of the mountains that were continuously transected and dissected by the river and its tributaries. An early scientific argument for the Finke's great age was put forth by L.K. Ward (1925), as follows:

> To the south of the MacDonnell Ranges the course of the Finke River through the Krichauff Range is remarkably circuitous...The explanation of the meandering course of the river lies in the earlier physiographical history of the region. At a time when the area occupied by the Krichauff Range was base levelled – probably at the close of the Mesozoic area – the old Finke River was crossing its flood plain in a meandering course. But when the uplift came the meandering stream was

> rejuviated and cut its gorge downwards into the solid rock while still preserving the plan of its bed.

By this reasoning it was the age of the uplift that set the clock for evolution of the Finke, and, as with much of Australia, the last orogenic, mountain-building phase in the Finke headwaters was during the Paleozoic. For the Finke drainage the relevant mountain building was the Alice Springs Orogeny lasting from 400 to 300 Ma (Warren, Shaw 1995). Orogenic thrust faulting within a broken lithospheric plate created a zone of uplift to the north that shed sediments southward. To the north lay the Arunta Block, a complex of Precambrian metamorphic and plutonic terrains, split along an east-west line by major tectonic feature, the Redbank Thrust Zone (RTZ). To the south lay the Amadeus Basin, which was deformed in a thin-skinned manner into fold structures that propagated southward along a decollement developed on salt layers of the late Precambrian Bitter Springs Formation. The modern Finke cuts across this whole assemblage of ancient structures; but is it a direct descendent of a river that existed prior to the orogeny, one that developed along with it, or one that later evolved into its current configuration?

The regional geomorphology of the central Austrian ranges was described in some detail by J.A. Mabbutt (1966), and more briefly by V. Baker (1986). A study by G. Pickup et al. (1988) drew special attention to the bedrock meanders of the Finke Gorge that had earlier been noted in studies of the late Holocene flood deposits contained therein (Baker et al. 1983). This work revealed a more complex history than that inferred by L.K. Ward (1925), the most striking feature being that described by M.E. White (2000, p. 51), as follows:

> There are, in fact, two gorges in the section of the river north of the James Range. One is currently occupied by the river; the other is not so deep and looks like another meander train intertwined with that of the main gorge. Deposits in the unused gorge are ancient, and the paleochannel probably dates to the Miocene.

ARUNTA BLOCK AND MACDONNELL RANGES

The Finke River heads in the Precambrian terrains of the Arunta Block. A western branch, the Davenport River (DR on Figs 1 and 2), is developed on the relatively soft late Proterozoic Bitter Springs Formation, a thick sequence dolomitic limestone, shale, siltstone, and evaporites that crops out south of the high points of the Chewings Range: Mount Sonder (1,320 m a.s.l.) and Mount Razorback (1,270 m a.s.l.). The latter mountains occur in a zone of thrust faulting that created recumbent folds (nappes) marked in the terrain by resistant ridges of the late Proterozoic Heavitree Quartzite (HR in Fig. 1).

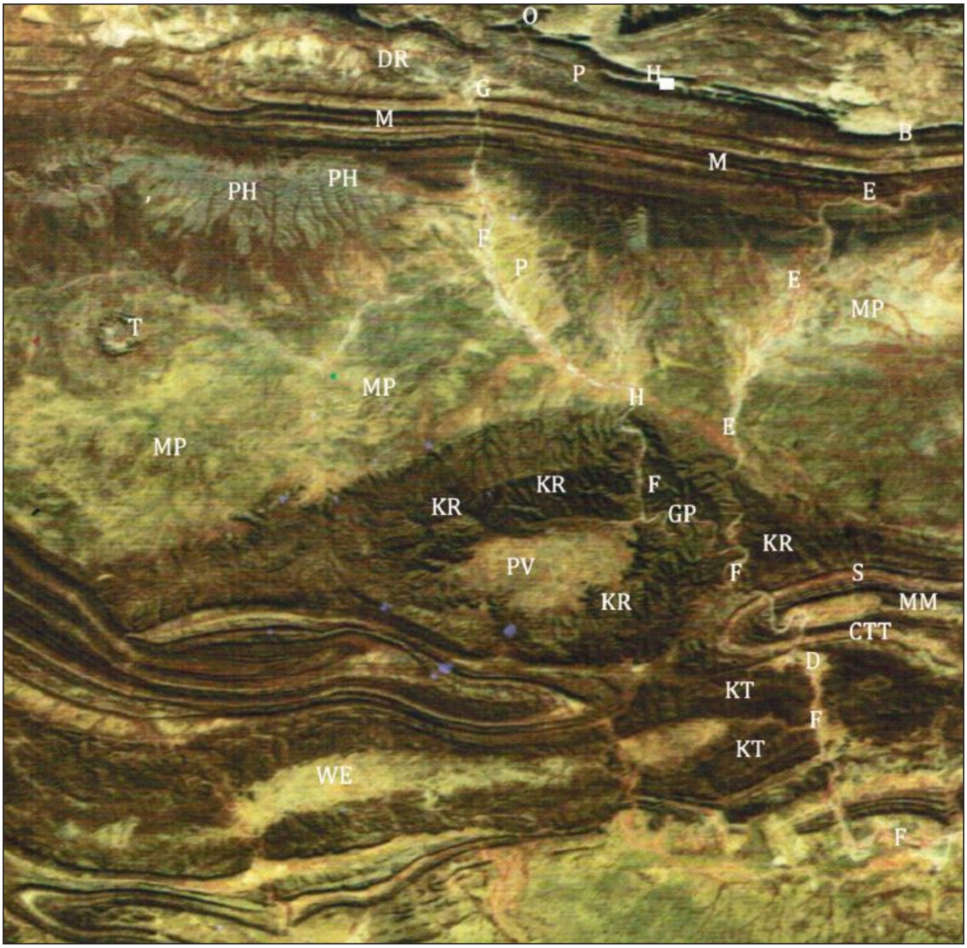

Fig. 2. Landsat image (1373-00364, July 31, 1973) showing MacDonnell, Krichauff, and James Ranges in central Australia (see also Baker 1986, for an extended description). Figure 1 covers much of the same area. Localities mentioned in the text are designated as follows: B – Ellery Creek Big Hole, CTT – Circle Gully-Teitkins Vale-Tidenvale Creek strike valley, D – Diamond-Shaped Plain, DR – Davenport River, E – Ellery Creek, F – Finke River, G – Glen Helen, GP – Glen of Palms (Finke Gorge), H – Hermannsburg, KR – Krichauff Ranges, KT – Katilka Range, M – MacDonnell Range, MM – Mount Merrick Anticline, MP – Missionary Plain, O – Ormiston Gorge, PH – Pertnjara Hills, PV – Palm Valley, S – Stokes Siltstone Strike Valley, T – Tnorala (Gosses Bluff), WE – Wild Eagle Plain. The imaged scene measures 100 x 100 km, and is oriented with north at the top

Cosmogenic dating of rock surfaces on the slopes Mount Sonder indicates an average landscape lowering rate of only about 1 m·Ma^{-1} (Heimsath et al. 2010).

As described by R.G. Warren and R.D. Shaw (1995) the Arunta Block is a cratonic zone of extremely complex Precambrian metamorphic and plutonic rocks. In the Finke headwaters the Mesoproterozoic Redbank Thrust

Zone (RTZ) separates the ancient craton into an older, northern portion and a younger southern portion. Multiple orgenic events contributed to the evolution of the Arunta Block, with the Alice Springs Orogeny (400 to 300 Ma) being the last and the most relevant for the river history. This tectonic episode severely impacted the southern Arunta Block and the intercratonic Amadeus Basin, lying immediately to the south. The filling of that basin had begun during the late Proterozoic with deposition of the Heavitree Quartzite and overlying Bitter Springs and Areyonga Formations. During the early Paleozoic the Amadeus Basin accumulated the Pertaoorrta and Larapinta Groups of marine shales, siltsones, sandstones, and limestones. The marine history terminated with deposition of the Silurian to early Devonian Mereenie Sandstone, and there followed continental sedimentation associated with the Alice Springs Orogeny. The latter involved thrust faulting that began at the RTZ and migrated southward through the Arunta Block and the adjacent Amadeus Basin, successively producing the Chewings Range thrusts and a homocline in the Pertaoorrta and Larapinta rocks, the ridge and valley expressions of which now constitute the MacDonnell Ranges. South-flowing drainage from the mountain uplift emplaced the Pertnjara Goup of mostly synorogenic fan deposits, comprising the Hermannsburg Sandstone and the Brewer Conglomerate. The deposition terminated in latest Devonian (Haines et al. 2010), and the subsequent geological history of the Finke drainage was denudational. This left any ancient Finke predecessor presumably following the same general pathway that had been established during emplacement of the Brewer Conglomerate. The area was sufficiently elevated to avoid the Cretaceous marine transgressions that covered many other cratonic regions of Australia.

The schist, granite and gneiss rocks of the Arunta Block were very deeply weathered, probably in late Cretaceous or early Cainozoic (Mabbutt 1965; Senior 1972; Senior et al. 1995). The weathering produced disintegrated rock (saprolite) of great thicknesses, perhaps hundreds of meters, but this has been extensively removed, except where preserved beneath covers of coarse gravel and/or duricrusted cap rocks (Mabbutt 1965). Locally, as in areas north of Alice Springs, east of the Finke drainage, there are remnants of the original laterite profile that overlay the saprolite (Quinlan, Forman 1968). As is typical (Ollier, Galloway 1990), the full profile consists of ferruginous, mottled, and pallid (kaolinized) zones, respectively overlying one another.

Ormiston Creek (O on Fig. 2), the eastern branch of the upper Finke, emerges from Ormiston Gorge, cut through a high ridge of Heavitree Quartzite. The ridge is part of a westward plunging fold structure related to a thrust-fault bounded nappe. The stream displays an "in-and-out" relationship to the plunging nose of this structure (Twidale 2007, p. 87), entering from a plain developed on metamorphic migmatite rocks, passing through the Heavitree Quartzite ridge on the northern limb of the anticline, traversing a plain developed on coarse granite in the anticline core, and finally passing again through the Heavitree Quartzite ridge on the southern limb of the anticline at Ormiston Gorge. Ormiston Creek subsequently occupies the same Bitter Springs strike valley as the Davenport River, with which it joins to form the Finke River proper about 2 km upstream of a ridge of nearly vertical Arumba Sandstone of latest Proterozoic/earliest Cambrian age.

The modern river level in the Bitter Springs strike valley is at about 650 m. On the north side of the valley the Heavitree Quartzite Ridge rises to elevations of 1000 to 1100 m. The summit elevation slopes gradually to the east, with crest levels at 800–900 m near Alice Springs. The ridge crest of near vertical dipping quartzite is beveled, which J.A. Mabbutt (1966) interpreted as marking an ancient planation surface that he termed the "Summit Surface." This surface, in turn, is transected by a number of broad sags, separated from the higher level by gently rounded slopes. The low points in the sags J.A. Mabbutt (1966) interpreted to be the floors of abandoned valleys that were cut into the ancient Summit Surface during a subsequent stage of ancient erosion that involved streams flowing from north to south, transverse to the structural grain.

An argument for a Cretaceous age for the crest-beveled Summit Surface was made by J.A. Mabbutt (1966, p. 95–96). This surface had earlier been correlated globally to Cretaceous-aged planation surfaces inferred for South Africa and elsewhere on the old Gondwanaland continental mass (King 1950). For Australia Cretaceous-aged planation has been documented for the ridge-and-valley topography of the Flinders Ranges (Twidale, Bourne 1996), including the likely grading of rivers on the Cretaceous plain to the nearby Cretaceous seas that also emplaced sediments over an unconformity correlating to the planation episode (Twidale 2007, p. 46–47). C.R. Twidale (1994, 2007, 2016) describes many other Australian examples of Cretaceous-aged planation surfaces.

East of the Finke River in the Bitter Springs strike valley there are mantled pediment surfaces (MP on Fig. 3; also see Baker 1986, p. 22, for a detailed map) that rise to about 100 m higher than the local base level provided by the cross-axial drainages such as the Finke River, Ellery Creek, and Hugh River. J.A. Mabbutt (1966) termed these surfaces "piedmont terraces," but he later realized (Mabbutt 1978) that there were covers of gravel overlying erosion surfaces developed on saprolite, so he changed the designation to "mantled pediments."

Field inspection of the mantled pediments (Fig. 4) was made in a high part of the strike valley (about 760 m elevation), located about midway between Ellery Creek, which crosses the Heavitree strike ridge at Ellery Creek Big Hole (B on Fig. 2), and the Hugh River, which crosses the same strike ridge at Boggy

Fig. 3. Portion of Australian National Mapping Photo NT465-855 showing an area of the MacDonnell Ranges about 15 km east of Glen Helen Gorge. Some of the important landscape features are Pioneer Creek (PC), the Heavitree Range (HR), dissected mantled pediment surfaces (MP), and an ancient gap through the Heavitree strike ridge (HG). The sequences of near-vertical bedrock units exposed in this homoclinal structure include Neoproterozoic units: Q – Heavitree Quartzite, B – Bitter Springs Formation, A – Arunta Sandstone; the Cambrian Pertaoorrta Group: H – Hugh River Shale; and the lower part of the Cambrian to Ordovician Larapinta Group: P – Pacoota Sandstone, H – Horn Valley Siltstone, and S – Stairway Sandstone. The imaged scene measures 8 x 8.5 km, and is oriented with north at the top

Hole. As noted by J.A. Mabbutt (1978), the highest mantled pediment surfaces rise to the bedrock thresholds of ancient transverse wind gaps in the strike ridges. There are three pediment levels, with the highest having pronounced iron cementation of the gravel, locally constituting ferricrete cap rocks. The intermediate surface has leached, red-earth soils. The lowest surface

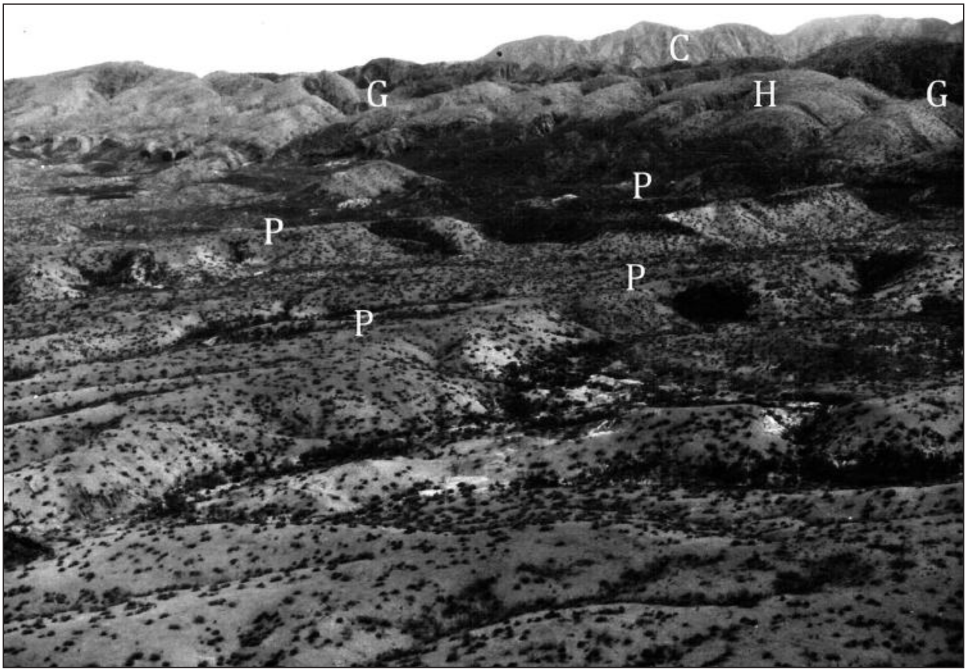

Fig. 4. Mantled pediments (P) in the Bitter Springs strike valley, east of Ellery Creek Big Hole. The higher pediment surfaces slope upward (right) toward the Summit Surface developed on the crest-beveled ridge of Heavitree Quarzite (H) that reaches elevations of about 950 m. The higher Chewings Range (C), visible on the horizon, rises to elevations of about 1,200 m. Ancient valleys, transverse to the strike of the crest-beveled Heavitree ridge, are cut into the summit surface as much as 100 to 150 m (G), and these are locally graded to the highest levels of the mantled pediment surfaces shown in the foreground. J.A. Mabbutt (1966) interpreted the convex slope forms of the ancient transverse valleys as one of several factors consistent with a warm, humid climate at the time of formation for the Summit Surface and its subsequent dissection

is capped by gravels that are cemented with calcium carbonate (calcrete). The whole sequence bears the imprint of long-term climatic change from humid to arid through the Cainozoic (Mabbutt 1966). As discussed below, this can be further interpreted as transitioning from wet-tropical conditions in the early Tertiary (high surface/ferricrete), through a tropical savanna conditions (middle surface), and finally to arid conditions during the Quaternary (lowest surface/calcrete).

At Glen Helen (G on Figs 1 and 2), the river level is 630 m. Here the Pacoota Sanstone strike ridge rises to about 250 m above river level. Cosmogenic samples from this ridge indicate long-term erosion rates ranging from 1.9 to 14.3 $m \cdot Ma^{-1}$ (Heimsath et al. 2010). The nearby Glen Helen Gorge is cut through this ridge and other units of the Larapita Group, all of which dip nearly vertically thereby expressing a structural homocline that was noted above (Fig. 5).

MISSIONARY PLAIN AND TNORALA (GOSSES BLUFF) IMPACT STRUCTURE

After the river passes the Mereenie Sandstone strike ridge of Glen Helen Gorge, it flows through the Pertnjara Group of Devonian age (Fig. 5). Its members, the Parke Siltstone and Hermannsburg Sandstone, dip vertically, but the outcrop for the next unit, the Brewer Conglomerate widens considerably as the regional structure changes from that of a steeply dipping homocline to a broad, shallow syncline, expressed topographically as the Missionary Plain (MP on Fig. 2). In the transition zone from the MacDonnell Range strike ridges to the Missionary Plain lie the Pentnjara Hills (PH on Figs 1 and 2), which rise to about 760 m elevation. These hills are underlain by coarse gravel of the Brewer Conglomerate, which was emplaced as a southward tapering wedge of Devonian alluvial fan sedimentation derived from the uplift induced by

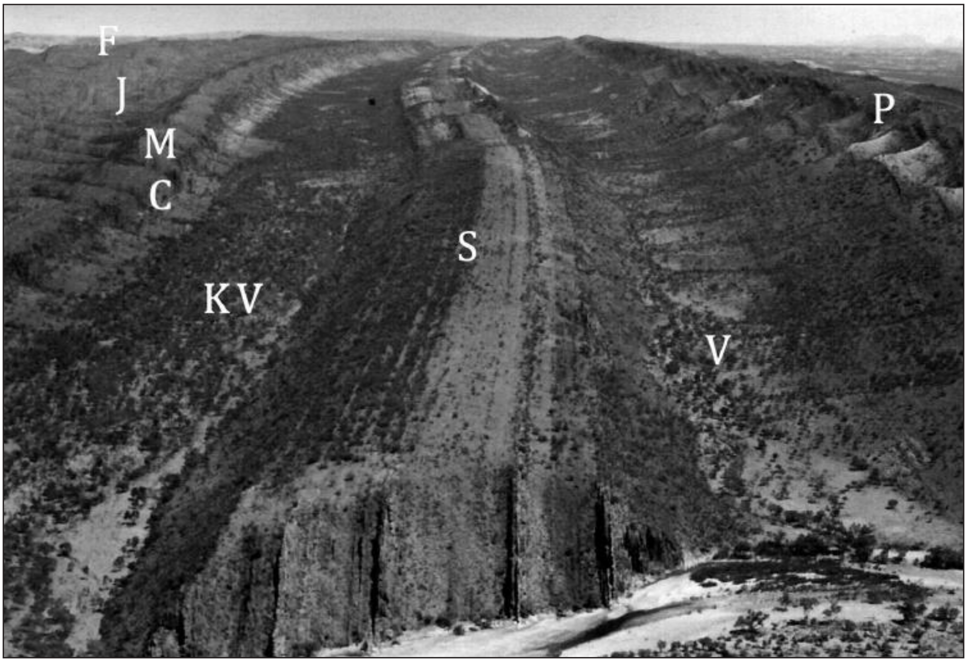

Fig. 5. Oblique aerial view of Finke River (foreground) in Glen Helen Gorge. The river has cut through near-vertical beds of the Cambrian to Ordovician Larapinta Group of sedimentary rocks. Combined with deep weathering, the incision resulted in a ridge of the resistant Pacoota Sandstone (P); a strike valley, developed on the less resitant Horn Valley Siltstone (V); a crest-beveled ridge of Stairway Sandstone (S); another strike valley, developed on the Stokes Siltstone (KV), and cliff exposures of the Carmichael Sandstone (C). More distant to the south are a crest-beveled ridge of Silurian/Devonian Mereenie Sandstone (M), and surface expressions for members of the Devonian Pertnjara Group: the Parke Siltstone (J), and the Hermannsburg Sandstone (F)

the Alice Springs Orogeny. The hills even display fanlike patterns on the satellite imagery (PH on Fig. 2). Distal to the coarse conglomerate facies is the finer-grained facies of the Undandita Member, which occupies the center of the Missionary Plain syncline, but is mostly covered by Quaternary sediments.

Midway through the Missionary Plain the Finke River level is at 580 m elevation. Here the Undandita Member shows evidence of very deep weathering. As noted for the MacDonnell strike valleys, the deeply weathered bedrock is locally preserved beneath duricrusted, Tertiary-age mantled pediments (Warren, Shaw 1995). In this area the duricrusted pediment surfaces (P on Fig. 2) grade to an elevation of about 600 m, which turns out to be a significant level in relation to morphological features further downstream in the Finke Gorge.

The Missionary Plain gradually rises in elevation westward, and important landscape relationships occur where the area displays the eroded remnants of an impact crater that originally extended to a diameter of about 20 km (T on Fig. 2). Erosion has cut down to a level within what was the original crater floor, leaving the central uplift of the impact structure standing as a 5-km-diameter ring of crest-beveled ridges rising to about 200 m above the surrounding plain (Fig. 6). This central uplift, named “Tnorala” in the language of Western Arrente aboriginal people, consists of nearly vertical

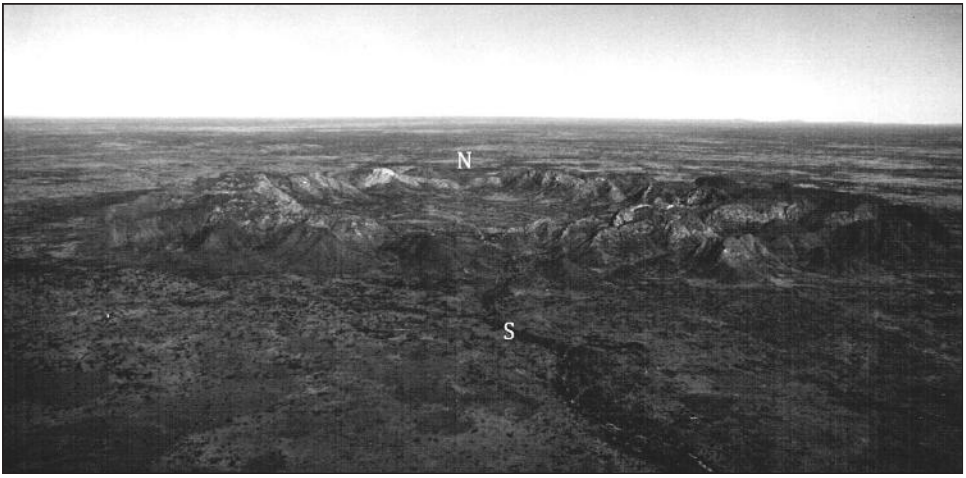

Fig. 6. Oblique aerial view west toward Tnorala (Gosses Bluff), a 5-km-wide ring of resistant sandstone ridges rising about 200 m higher than the Missionary Plain, located about 40 km west of the Finke River. The ridges are nearly vertical strata of Mereenie and Carmichael Sandstone that were part of the central peak of an impact crater that was originally 20 km in diameter. Deep weathering after the 142.5 Ma impact event probably differentially affected the softer Larapinta Group formations at the center of this uplift, and the weathering products were subsequently removed during the evolution of the outlet stream (S) exiting the structure in the center of the picture. A predecessor to this stream may have been superposed on to the ring of ridges, flowing to the present outlet point from a notch (N) cut about 100 m into the opposite side of the ring.

strata of resistant Carmichael Sandstone (uppermost Ordovician member of the Larapinta Group), Mereenie Sandstone (Silurian to Devonian), and a lithic sandstone of the lowermost (Devonian) portion of the Pertnjara Group (Milton et al. 1972, 1976). Seismic data on cratered material and shatter cone evidence relating to the impacting focal point are consistent with the effects of a low-density, high-velocity bolide, probably a comet (Milton et al. 1972). The resulting crater had a floor of impact melt (suevite) and upraised rims. The latter may have had similar relief to the central peak, but it would have been composed of Pertnjara Group rocks that are less resistant to erosion than the central peak materials. The progressive erosion of these softer rocks removed all surface expression of the crater rim, leaving only the circular ridge of crest-beveled sandstone marking the central peak of the ancient impact structure (Milton et al. 1972, Fig. 2).

Early results from potassium argon/dating and fission track dating yielded ages of between about 130 and 133 Ma (Milton et al. 1972). D.J. Milton and J.F. Sutter (1987) revised the earlier results, using 40Ar/39Ar dating, proposing a best estimate of 142.5 Ma. This puts the impact at right near the Jurassic/Cretaceous boundary, which, as noted above, is widely considered to be a starting point for major planation of the Paleozoic mountain ranges of Australia.

The available data on terrestrial impact crater rim heights versus crater diameters (Fudali et al. 1980) suggest that a 20-km terrestrial impact crater could have had an original rim height of at least few hundred meters. Much of this rim elevation had to have been removed during the last 142.5 My. If regional planation, including the crest beveling and erosion of the Tnorala central peak, occurred during the Cretaceous, then much of the rim relief was probably gone by about 60 Ma, leaving the surface of the Missionary Plain about 200 m higher than that of today, corresponding to the level of the crest bevel across the summit of Tnorela (Milton et al. 1972).

The west-to-east flowing present-day stream draining Tnorala has its headwaters near a low notch on the western end of the sandstone rim (Fig. 6). This relationship suggests that a stream flowing on the inferred Cretaceous planation surface was imposed on the Tnorala sandstone rim, and that it incised about 100 m into its crest-beveled summit, having also removed a similar amount of deeply weathered Pertnjara rocks overlying what is now Missionary Plain. If this inferred cross axial drainage correlates to Miocene-aged features described below for the Krichauf Ranges, then at about 30 Ma the Missionary Plain surface may have been at about 100 m higher than today. These considerations suggest an average landscape lowering rate of about 3.3 $m \cdot Ma^{-1}$, which is similar to the average long-term rates of landscape lowering inferred from cosmogenic isotope studies (Heimsath et al. 2010).

KRICHAUF RANGES AND FINKE GORGE PALIMPSEST

At Hermannsburg (H on Fig. 2) the Finke (river level 540 m) passes from the Undandita Member into the underlying Hermannsburg Sandstone. There is a broad bend in the valley just upstream of the nose of an eastward plunging anticline. The valley abruptly turns east-southeast for about a kilometer, and then straightens to a southerly direction perpendicular to the anticlinal axis. This linear south-trending reach passes Palm Creek entering from the west (P on Fig. 7). Palm Creek drains a large plain, Palm Valley (PV on Fig. 2), which is a planar lowland developed at an elevation of about 650 m. It has dimensions of 18 by 9 km, elongated east-west along the axis of a broad syncline. The surrounding Hermannsburg uplands rise to about 900 m elevation and are rather abruptly separated from the Palm Valley plain by steep slopes. The Palm Valley plain was interpreted to be an "intramontane basin" (*intramontanen Ebenen*) by H. Bremer (1967; see also, Büdel 1982), the significance of which will be discussed in a subsequent section.

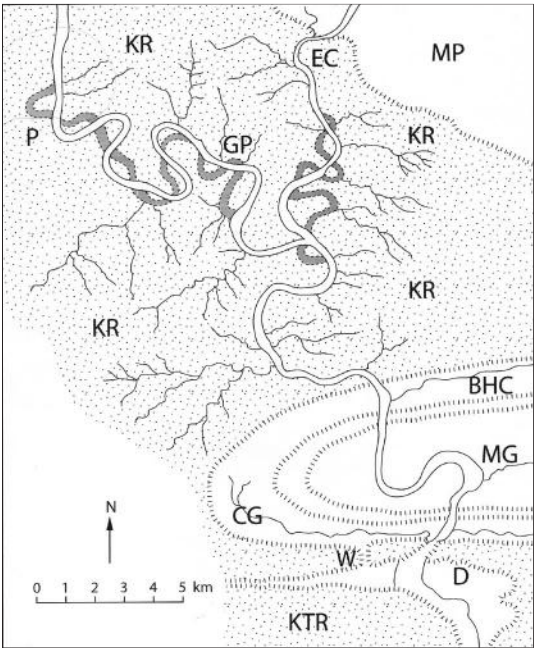

Fig. 7. Generalized map of the Finke and Ellery Creek drainages across the Krichauff and James Ranges (see Fig. 1 for general location). The stippled pattern shows the outcrop areas of the Hermannsburg and Mereenie Sandstone units. The dark shading shows the pattern of bedrock paleomeanders described in the text, while the light shading shows the pattern of the contemporary Finke Gorge meanders that transect the paleomeandering pattern to form a palimpsest. Letters refer to the locations of Boggy Hole Creek (BHC), Circle Gully (CG), the diamond-shaped basin (D), Ellery Creek (EC), Krichauff Ranges (KR), Katilka Range (KTR), Merrick Gully (MG), Missionary Plain (MG), Palm Creek (P), and the wind gap (W) shown in Figure 12

Just upstream of the junction with Palm Creek, a highly anomalous Finke River pattern appears (Figs 7 and 8), which persists for another 20 km, until the river leaves the Hermannsburg Sandstone and enters a gorge through the northward dipping Mereenie Sandstone. The most sinuous portion of this reach is locally known as the "Glen of Palms" (GP on Figs 2 and 7), and it extends for 10 linear km (20 km along the river thalweg) between the Palm Creek and Ellery Creek junctions with the Finke. The anomalous pattern, noted by V. Baker et al. (1983) and subsequently described in more detail by G. Pickup et al. (1988), consists of two meandering bedrock river gorges, each intertwined with the other (Fig. 8). The gorge currently occupied by the present river consists of contemporary bedrock meanders that are deeply entrenched with side slopes that are straight or faceted, locally even forming vertical cliffs, particularly at river bends. Contrasting with this morphology are the bedrock paleomeanders of an ancient Fink River, located higher up in the valley landscape. The paleomeanders are relict, and much older than the contemporary pattern. They consist of segments of the original bedrock paleomeander train that became isolated because of the incision associated with formation of the contemporary bedrock gorge (Fig. 8). The latter contains relatively fresh sandy alluvium associated with the present-day river.

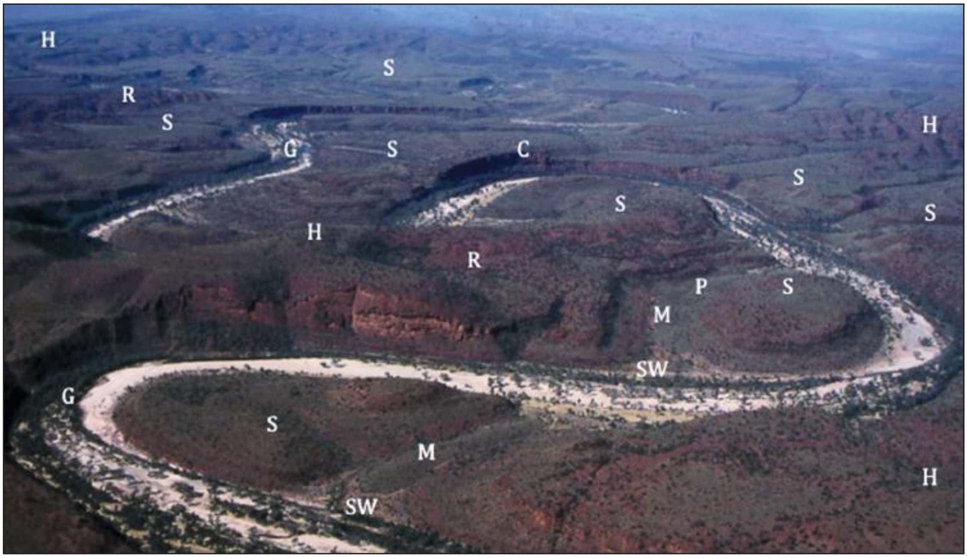

Fig. 8. Oblique aerial view of the "Glen of Palms" section of the Finke Gorge, looking southeast from above the junction with Palm Creek toward the junction with Ellery Creek. Note the linear mounds (M), composed of iron-silica-cemented gravels, located within the troughs of the paleomeanders. Also prominent are elements of the Shoulder Surface (S) that are separated from higher portions of the Hermannsburg Sandstone (H) by rounded slope elements (R). The latter contrast with the faceted slopes and cliffs (C) that are characteristic of the contemporary gorge (G)

In contrast, the abandoned paleomeander segments of the relict gorge contain ferruginous, cemented quartzite gravel, generally at levels about 10 to 15 m higher than the modern river thalweg. Thus, the paleomeanders are not cut-offs related to the modern river, but rather they comprise remnants of a complete, but much older meandering paleogorge. With a sinuosity value of 2.2 this paleogorge is slightly more sinuous than the modern gorge (value 2.0), but both gorges slope at about 1.3 m per km.

The contemporary Finke Gorge and the intertwined bedrock paleomeanders constitute a "palimpsest," a term that was applied to the writing of new manuscript script over an older one, both on the same piece of parchment. In this case an ancient meandering river pattern was cut into bedrock, probably under very different conditions than those prevailing when the contemporary pattern was subsequently created. "Overprinting" of the incised contemporary river gorge was such that elements of the ancient paleomeandering pattern and associated landforms are preserved as relict features on the present-day landscape.

Cementation of the paleomeander gravels can be very pronounced and may include enough silica that the material fractures across rather than between the individual quartzite gravel clasts. The iron-silica-cemented gravels are probably a type of ferricrete duricrust, recognized by C.D. Ollier and R.W. Galloway (1990) as forming when iron solutions move via groundwater flow to valley bottoms, where both iron and silica can precipitate as cements. The iron may have been mobilized within a deeply weathered zone on the land surface into which the fluvial valley was cut. The predominant quartzite gravel lithology is consistent with the deep tropical weathering of the region during the period of paleomeander formation, since such materials would be preferentially preserved as lag gravels during deep weathering of source-area Pertjara rocks and subsequent removal of the weathering mantle, as inferred above for the Missionary Plain.

The iron-cemented gravel must have originally been a channel fill, but today it is preserved as elongated mounds that stand out in relief above the floors of the abandoned paleomeander segments (M in Fig. 8). The side slopes of the ancient paleomeander toughs are rounded, not faceted, and the sandstone bedrock displays prominent ferruginous crusts and associated tafoni. There clearly has been long-term erosion of the sandstone bedrock that originally bounded the gravel fills. The whole assemblage of differential relief, with the cemented gravel mounds rising above the paleomeander floors and separated from the rounded sides of the paleomeander troughs, indicates that the cemented gravels were preferentially preserved as erosion removed portions of the bedrock that formerly enclosed what were originally channel fills. This resulted in a kind of locally inverted topography in which what were originally gravelly river bottoms now stand in relief above the floors of the bedrock troughs in which those gravels had formerly aggraded. Similar relief inversion involving ferricrete and/or silcrete cementation and preservation of former channel fills and/or valley bottoms occurs (though on a much large scale) in many other parts of Australia (e.g., Pain, Ollier 1995; Twidale 1997, 2007).

Both the contemporary and the relict Finke gorges are cut into a broad surface that G. Pickup et al. (1988) term the "Shoulder Surface." This surface can be traced along the general trajectory of the intertwined gorges, both of which are incised into it (Figs 8 and 9). The Shoulder Surface is especially well developed near the confluence of the Finke with Ellery Creek, and occurs at an elevation of about 600 m, which is about 70 m higher than the modern channel thalweg. The top of the surface is mantled with quartzite gravel that appears to be a lag deposit. The sandstone slopes that separate the Shoulder Surface from the higher portions of the Krichauff Ranges are rounded, and there are

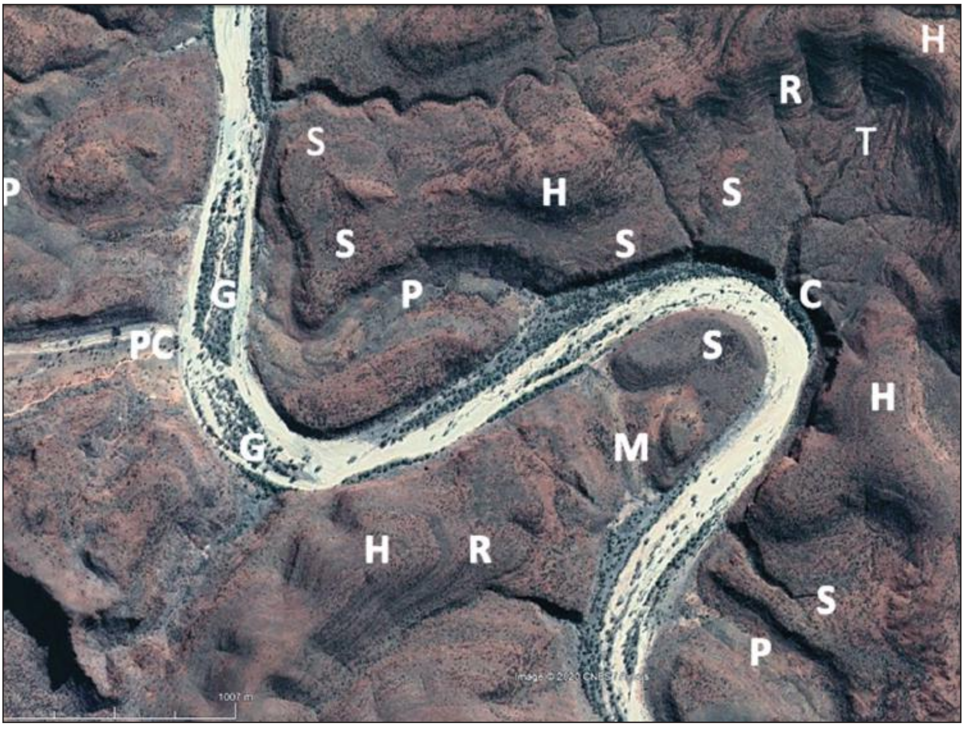

Fig. 9. Google Earth image showing the Finke River reach east of junction with Palm Creek (PC). The scene is about 4 km across and shows the contemporary gorge (G), its associated cliffs (C), segments of the paleomeanders (P), the linear mounds iron-cemented gravels (M), the Shoulder Surface (S), rounded slopes (R), higher surfaces developed on the Hermannsburg Sandstone (H), and a theater-headed valley (T). Many of the same features appear in an oblique view in the lower portion of Figure 8

local, theater-like morphologies in the drainages that emerge from the higher portions of the topography (Fig. 9). An alternative explanation for the Shoulder Surface might be that it is structural, reflecting differential resistance to erosion within portions of the relatively flat-lying Hermannsburg Sandstone. However, this would not necessarily be consistent with the inferred lag deposit of quartzite cobbles as well as with other landscape features suggestive of past, deep tropical weathering.

The summit levels of the Krichauf Ranges average about 800 m a.s.l., which is about 250 higher than the modern river level through the Finke Gorge. These general levels are similar to those reported for the crest-beveled Summit Surface above for the Finke River near Glen Helen Gorge, which occurs about 250 m above modern river levels on the MacDonnell Ranges strike ridges. As noted above, a lower surface in the MacDonnell strike valleys, at about 100 m above modern river levels, is associated with mantled pediments that are capped by ferricretes, silcretes and deep red soils that formed under tropical conditions, probably in the middle Tertiary. That assemblage may well correlate to the Finke Gorge Shoulder Surface level and to the ferruginous cemented gravels of the ancient paleomeander train.

JAMES RANGES

As the Finke River passes from the Hermannsburg Sandstone into the Mereenie Sandstone, its gorge narrows. It constricts at places to widths less than 100 m, in contrast to the widths of 300–400 m that prevail throughout the Hermannsburg Sandstone terrains. Here the Mereenie Sandstone is dipping northward from about 15 to 25 degrees, being on the northern side of an east-west anticline of the James Ranges ("Mount Merrick Anticline," informally so-named for the high point on the flatirons marking the westward plunging nose of the anticline; MM on Figs 1 and 2). A spectacular crest bevel is developed on the Mereenie Sandstone (M in Fig. 10) at about the same 600 m elevation level as the Shoulder Surface (S in Figs 8 and 9). Possible alternative explanations for these 600-m surfaces involve either some kind of regional planation at this level, or differential erosion of the rock units. However, the differential erosion hypothesis would imply exhumation of a pre-existing crest bevel on the Mereenie Sandstone (essentially an ancient angular unconformity) by selective removal of the overlying Pertnjara Group sediments. That would push the crest-beveling episode back to the early Devonian.

Emerging from the narrow gorge cut through the Meerenie Sandstone and underlying Carmichael Sandstone, the Finke crosses the low-lying plain of

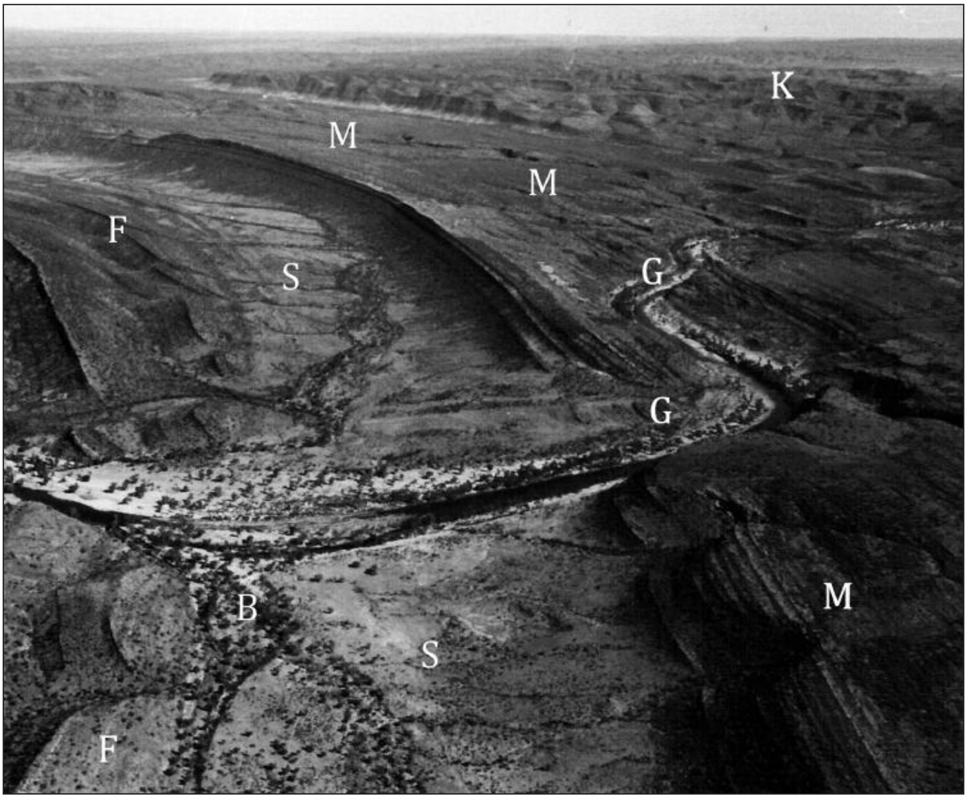

Fig. 10. Oblique aerial view looking west along the Stokes Siltstone strike valley (S), separating the crest-beveled outcrop of northward dipping Mereenie Sandstone (M) from flatirons (F) developed on strata of the Larapinta Group. Boggy Hole Creek (B) joins the Finke River at left center. The Finke enters the scene from Krichauff Ranges (K) in the north, then cuts eastward parallel to the strike of the Mereenie Sandstone before emerging from the gorge (G) on the north side of the Stokes Siltstone strike valley. It exits the scene at the left center, where it flows into the plain that is developed along the axial core of the Mount Merrick Anticline

the Stokes Siltstone strike valley (S in Fig. 2), passing Boggy Hole Creek (BHC on Fig. 7), entering from the east (Fig. 10). Within about a kilometer, the river then passes through a gap in the northward dipping beds of the lower Larapinta Group, with prominent flat irons developed on the resistant Stairway Sandstone and Pacoota Sandstone. Entering the axial zone of the Mount Merrick Anticline (MM on Figs 1 and 2), the river displays a full meander wavelength of about 3 km with an active channel that widens to about 500 m within a broad plain developed within the axial core of the anticline. Just before the river exits this plain through the southern rim of Larapinta flat irons, Merrick Gully (MG on Fig. 7) enters from the east, exposing a section through a large flood-levee deposit formed at the outside of a bend (see discussion of paleofloods below).

After passing through the southward dipping strata of the lower Larapinta Group, the Finke again crosses a strike valley formed on the Stokes Siltstone (Fig. 11). Entering from the west is Circle Gully (CG on Figs 1 and 7), which drains the lowland plain developed on the Stokes Sandstone outcrops that surround the plunging westward end of the Merrick Gully Anticline. Entering from the east is Tietkens Vale, also flowing in the Stokes Siltstone strike valley, but here extending continuously to the east. This strike valley is part of a continuous plain that extends eastward through an almost imperceptible divide separating the westward-flowing Tietkens Vale from the east-flowing drainage of Tidenvale Creek. The latter joins the Hugh River 45 km east of the Finke River. The elevation at the Finke River, at the west end of the Stokes strike valley, is about 500 m, and the elevation at the Hugh River, at the east end, is within a few meters of that. Thus, a continuous plain at an elevation of about 500 m has developed in the strike valleys now occupied by Circle Gully, Tietkens Vale, and Tidenvale Creek (CTT on Fig. 2), with the Finke and Hugh Rivers draining through opposite ends, both at the same level of about 500 m.

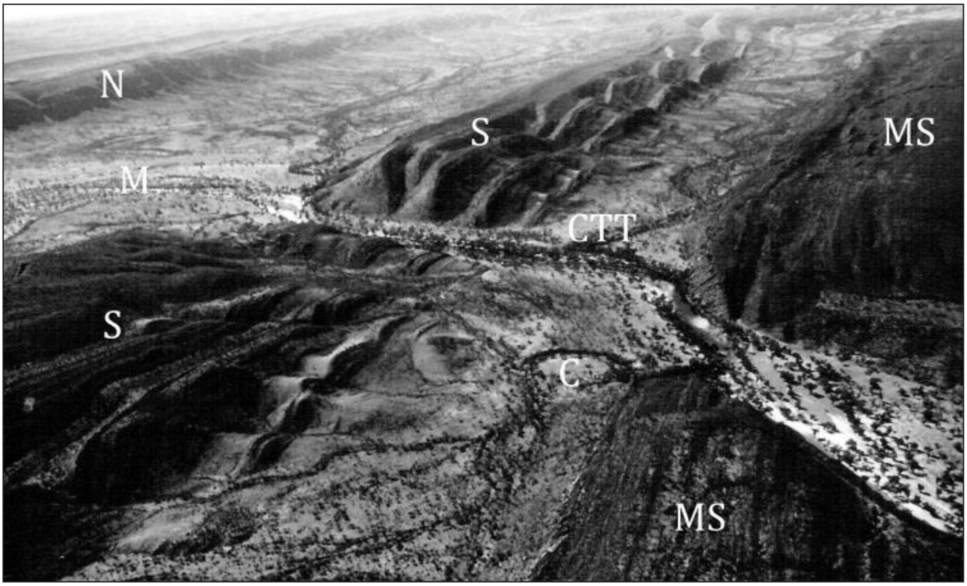

Fig. 11. Oblique aerial view looking generally east along the Circle Creek-Tietkins Vale-Tidenvale Creek strike valley (CTT) that is developed along the outcrop of the Stokes Siltstone. Northward dipping ridges of Larapinta Group sandstones are visible in the upper left (N). A large meander of the Finke River (see Figure 13) occurs on the Merrick Gully plain (M), which is developed along the axis of the Mount Merrick Anticline. Southward dipping Larapinta Group sandstone flatirons comprise a crest-beveled ridge (S) through which the Finke flows before crossing the Stokes Siltstone. It passes the unusual circular pattern (C) of Circle Gully (produced by a resistant outcrop of calcrete described in the text) before crossing a broad, crest-beveled outcrop of near vertical Mereenie Sandstone (MS). The wind gap shown in Figure 12 lies along the westward extension of this Mereenie ridge, just beyond the bottom of this image

Like the Finke, the Hugh River is a cross-axial river, rising in the Arunta Block and crossing the Missionary Plain. However, whereas the Finke crosses the James Ranges at the western end of the west-plunging Mount Merrick Anticline, the Hugh crosses the same geological units, but at the eastern end of the Mount Merrick Anticline, where it is plunging to the east. Moreover, on the northern side of that anticlinal structure, the contemporary Hugh River channel flows in a bedrock canyon that cuts across a pattern of ancient, relict paleomeanders. This occurs upstream of the junction with the Tidenvale Creek, before the Hugh flows through a narrow gorge cut through a ridge of Pacoota Sandstone. All these relationships are consistent with a history involving etchplanation and the formation of intramontane basins as will be discussed below.

On the Circle Gully side of the Stokes strike valley (C on Fig. 11) there is a particularly thick, resistant calcrete accumulation that produces the unusual circle pattern in the ephemeral stream channel, just before it joins the Finke. A streambank exposure reveals a calcrete-cemented gravel, mainly of sandstone lithology probably derived from the Pertjara Group. There are also multiple generations of laminae and pisolites. Such petrocalcic horizons can be of considerable age, being Pliocene in the arid southwestern U.S. (Machette 1989). Other exposures of calcrete are associated with portions of the contemporary river gorge, and clearly much younger than the iron-cemented paleomeander gravels.

DOWNSTREAM OF THE JAMES RANGES

On exiting through the crest-beveled Mereenie ridge on the south margin of the Mount Merrick anticline, the Finke River bends westward (Fig. 11), expanding across a diamond-shaped plain (D in Figs 1, 2, and 7) that is elongated E-W about 6 km and N-S about 2.5 km. Only 1.5 km further west there is a wind gap through the same Mereenie Sandstone ridge (W in Figs 7 and 12). Moreover, the bed of this wind gap is only slightly higher in elevation than that of the modern gap, probably because of a reddish fill that is continuous with that covering the floor of the Stokes strike valley containing Circle Gully.

Geologically the diamond-shaped plain occurs along the contact zone between the Mereenie Sandstone and the overlying Hermannsburg Sandstone, which extensively outcrops to the south in a broad synclinal trough comprising the Katilka Range (KT in Fig. 2, KTR in Fig. 7) . Thus, the diamond-shaped plain occurs in a slight synclinal warp between the Mount Merrick and Katilka anticlines. Its floor is at about 500 m elevation, about 100 m lower than the 600-m crest bevel on the summit of the Mereenie ridge transected by the contemporary Finke River. Moreover, it is connected at about the same 500-m

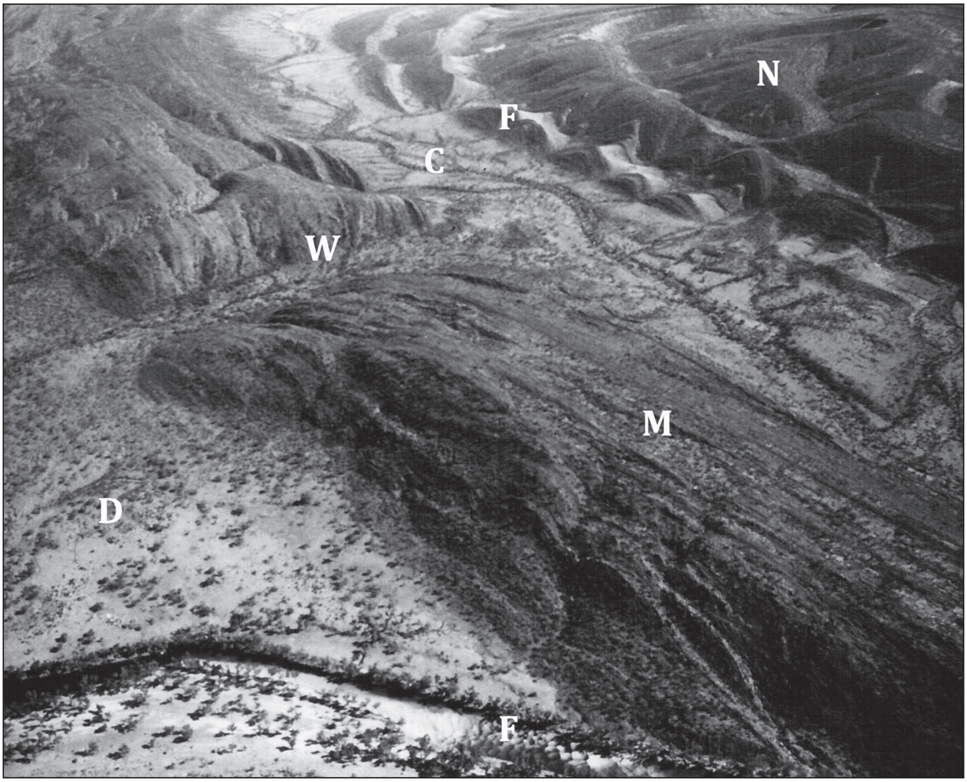

Fig. 12. Oblique aerial view looking generally west toward the wind gap (W) through the crest-beveled Mereenie Sandstone ridge (M). The active Finke River (F) in the foreground crosses the same ridge through a contemporary gorge just beyond the lower right corner of this image (see Figure 11). Also shown are portions of the diamond-shaped plain (D) discussed in the text, the Circle Gully (C) portion of the the Circle Gully-Tietkins Vale-Tidenvale Creek strike valley developed on the Stokes Siltstone, and the flatirons of Larapinta Group sandstones (F) developed on the nose (N) of the westward-plunging Mount Merrick Anticline

level to the Circle Gully-Tietkens Vale-Tidenvale Creek strike valley via two gaps, one active and the other abandoned. Once again, these relationships are characteristic consequence of an etchplanation hypothesis that was posed by H. Bremer (1967, 1975).

Downstream of the Mount Merrick anticline the Finke flows through a relatively straight section about 10 km in length, cut through the Katilka Range, a broad syncline developed in the Hermannsburg Sandstone. The valley here is much wider than the portion though the Krichauff Ranges, which also exposes the same rock units. The valley is filled with considerable Quaternary alluvium, some of it expressing extreme paleoflood features that will be described below. All the way from Glen Helen Gorge to this point, along the Finke pathway through the MacDonnell, Krichauff and James Ranges, the modern stream gradient is both uniform and low, at about 1.2 m per km. The available topographic data show no obvious knick points for the modern river profile over this entire cross-axial flow path.

After again crossing through the Larapinta Group formations cropping out on the south limb of the Katilka Range syncline, the Finke leaves the central ranges and turns abruptly to the east. It flows eastward another 8 kilometers, just south of several duricrust-mantled pediment surfaces near Parke Pass, before turning southeast and crossing a series of alluvial plains, sand plains, and dune fields, joining the Palmer River after about 60 more kilometers. Before joining the Hugh River, entering from the north, the Finke passes south of Chambers Pillar, an isolated rock tower rising to an elevation of about 560 m.

The pillar provides a spectacular exposure of the deep lateritic profile that likely occurred throughout the region. As typical for laterites (Ollier, Galloway 1990) the upper 10 m is a feruginous crust, which likely is also silicified in this region. This is underlain by another 10 of mottled zone, in which white, kaolinized pockets are interspersed with iron-stained rock. Below that another 30 m of highly kaolinized and white bedrock occurs, providing a stark color contrast to the overlying red zones (see photographs in Twidale 2007, p. 86). Given that the bed of the Finke River is at about 360 m near here, Chambers Pillar can be interpreted as a remnant of the ancient landsurface described above, which was regionally erased by long-term etchplanation (see discussion below). Other possible remnants of this ancient landsurface are Uluru (Ayers Rock) and Kata Tjuta (The Olgas), also in the Amadeus Basin, located 250 km west-southwest of Chambers Pillar. The summit areas of these inselbergs are inferred to have been exposed as low hills on the Cretaceous landscape (Twidale 2010).

The trace of the Finke continues for another couple hundred kilometers, terminating in floodout zones (Tooth 1999) along the western edge of the Simpson Desert dune field. Earlier in the Quaternary, wetter conditions enhanced runoff sufficiently that the Finke flowed further, following the route of the present-day Macumber River another 250 km to present-day Lake Eyre, at an elevation of minus 15 m.

QUATERNARY PALEOFLOODS AND CHANGING FLUVIAL REGIMEN

Extreme paleoflood hydrological phenomena were discovered in the Finke Gorge in 1980 (Baker et al. 1983). Subsequent detailed work (Baker et al. 1987; Pickup et al. 1988) showed that peak paleoflood discharges since about 1000 years ago reached about 5000 $m^3 \cdot s^{-1}$. In the eastern portion of the MacDonnell Ranges there is evidence for even larger "superfloods." Particularly near the Todd and Ross River junction there are sand sheets; large-scale ripple fields; overflow channels (Pickup 1991); large-scale paleo-braid channels; levee deposits; and broad, low-relief bars (Patton et al. 1993). Though the modern channel is about 200 m in width, the superflood paleochannel widths extend to ten times that or more (Bourke, Pickup 1999). Because a younger sequence of paleofloods occurred several hundred years ago, correlating approximately with those noted for the Finke River, and, because older, highly oxidized sands date to about 10 ka (Patton et al. 1993), the Ross River superfloods are inferred to be Holocene in age.

Although a detailed discussion of river flood regimen is beyond the scope of the present paper, some limited observations may be relevant to issues of long-term evolution for the Finke River. The relict gravel fills in the Finke River Gorge paleomeanders indicate that the paleochannels that transported them averaged no more than about 50 m in width. Competence considerations (Baker, Ritter 1975) indicate that the gravel sizes preserved in the paleomeanders could be transported at flow depths on the order of 1 m. For a channel width of 50 m, a slope of 0.0015 and reasonable estimates of roughness, the corresponding discharge would be about 150 $m^3 \cdot s^{-1}$. This contrasts with the nearby contemporary channel that has a width of about 250 m, which is documented to have achieved a late Holocene paleoflood discharge of 5000 $m^3 \cdot s^{-1}$ (Baker et al. 1987). Flow depths for such an extreme flood would be about 7 m, which seems reasonable since major flooding of the Finke River in 1988 easily inundated some of the lower-elevation paleomeanders (Geoff Pickup, personal communication).

Evidence for even larger paleoflooding related to the contemporary Finke River was discovered at the immense flood levee mentioned above for the Merrick Gully plain along the axis of the Mount Merrick Anticline. This feature is about 400 m wide and extends nearly 3 km along the outer bank of the great meander bend developed in the Merrick Gully plain (L in Fig. 13). To create this levee form, the 500-m wide Finke channel would have to convey a flow about 3 m deep, which would imply a paleoflood discharge of at least 10,000 $m^3 \cdot s^{-1}$. Another superflood indicator occurs in the broad Finke valley 7 km downstream of Circle Gully. There is a bedrock mesa 200 m in diameter (M in Fig. 14) that obstructed paleoflood flows, resulting in a streamlined pendant zar (P in Fig. 14) located 1.5 km downstream from the obstruction. Such bars are characteristic of high-energy megafloods (Baker 1973, 2009), and the hydraulic setting of this one indicates a likely generative flow of at least 15,000 $m^3 \cdot s^{-1}$. Though highly approximate these flow estimates are consistent with the importance of extreme flooding for the regimen of the contemporary Finke River.

The huge extreme paleoflood flows have implications for the changes that contributed to development of the contemporary river gorge. The humid tropical river flowing at the time of the paleomeanders would likely have had prolonged flows of relatively modest discharge. In contrast, the semi-arid

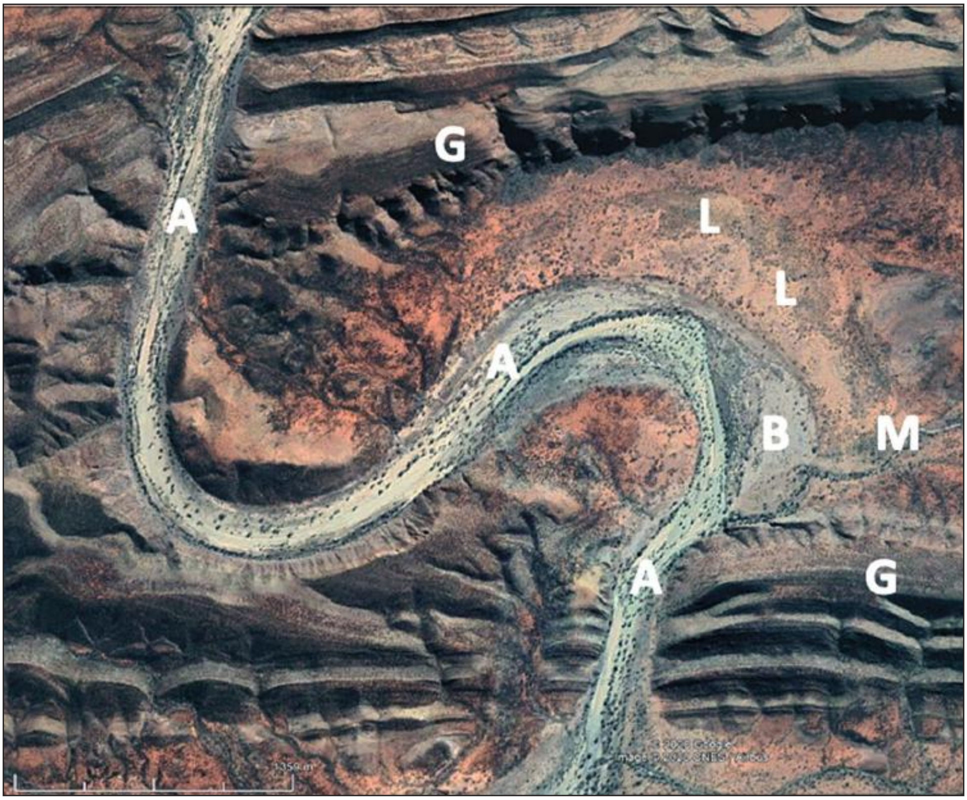

Fig. 13. Google Earth image showing the large meander bend of the Finke River developed in the axial plain region of the Mount Merrick Anticline near the junction with Merrick Gully (M). Flood-related features include the active channel (A), relict bar forms (B) that developed during extreme paleofloods, and a massive levee-like deposit (L) discussed in the text. The exit point of the river through one of the Larapinta Group sandstone ridges (G) at bottom center of the image is also shown in an oblique view in Figure 11. The imaged scene is about 3 km across, and is oriented with north at the top

conditions associated with the contemporary river would likely have had very flashy flows – long periods of no flow punctuated by rare, extreme flood peaks like those indicated by the paleoflood data described above. The change from humid tropical to semi-arid conditions would have been associated with immense changes in both discharge and sedimentation. Though most geomorphic research has focused on how such changes impact alluvial rivers (e.g., Baker, Penteado-Orellana 1977, 1978), there clearly are implications for bedrock river reaches like the Finke Gorge. Consideration of stream power (Baker, Costa 1987) suggest that the humid, tropical Miocene Finke predecessor would have had relatively minor erosive power, while the rare, but extreme floods of the present day regimen could occasionally generate immense flood power, with associated channel erosion (e.g., Baker 1977). Preliminary

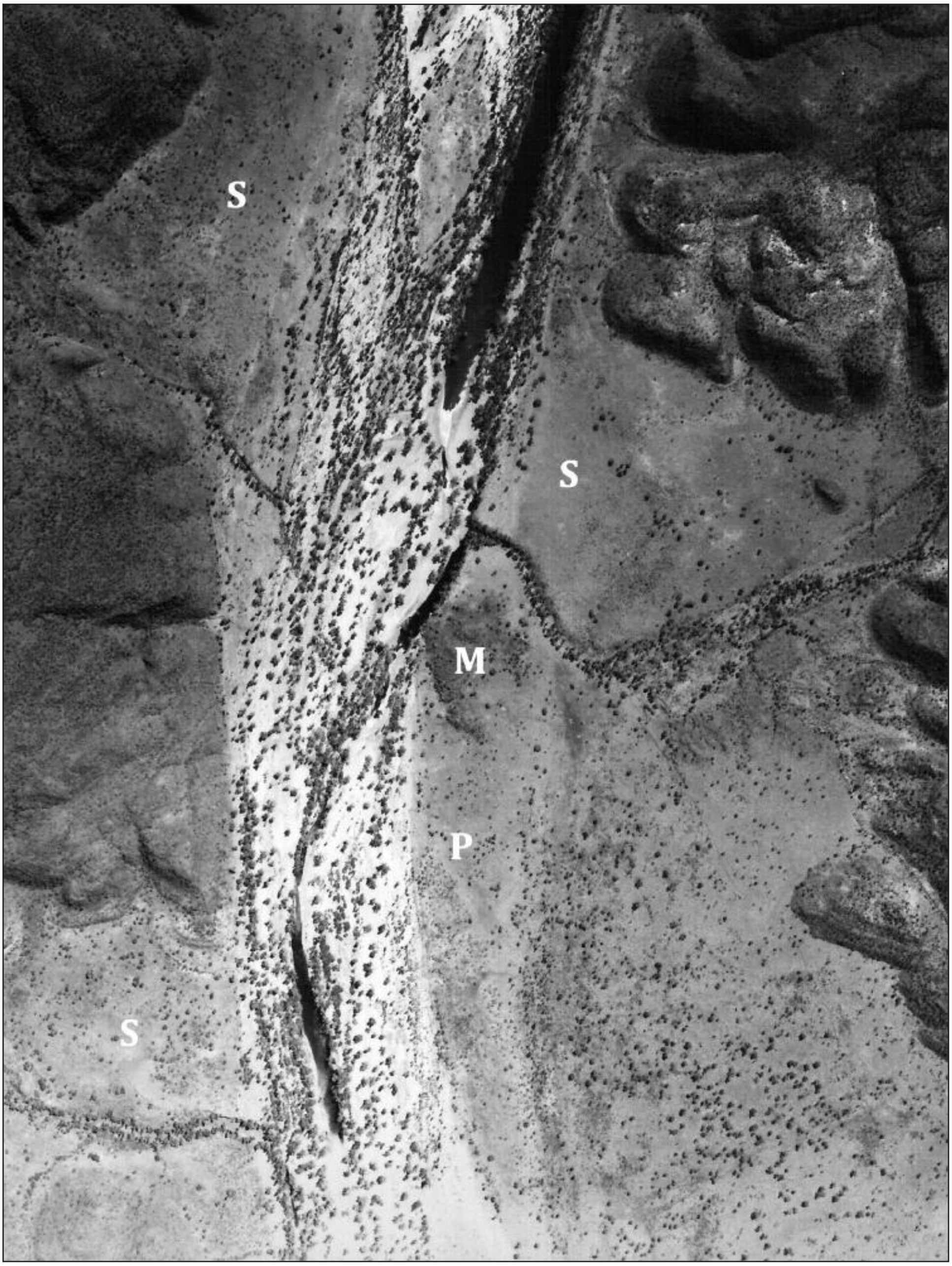

Fig. 14. Portion of Northern Territory Dept. Lands Air Photo (18-8-82, Run 10, no. 186) showing extreme paleoflood features along Finke River about 7 km downstream from the junction with Circle Gully (show in Figure 11). A 1.5-km-long pendant bar (P) is developed downstream from a small bedrock mesa (M), and extensive areas of paleoflood slackwater deposits (S) occur along the margins of bedrock valley. The imaged scene measures 1.5 x 3 km, and is oriented with north at the top

calculations of power per unit area of bed, reveal that, for the kinds of extreme floods experienced by the contemporary Finke, this parameter could easily have been a thousand times greater than that of the bedrock stream operating at the time of the relict bedrock paleomeanders.

CROSS-AXIAL DRAINAGE, FLUVIAL PERSISTENCE AND IMPRESSION

Cross-axial drainage is anomalous. Most river patterns conform to slope and/or structure, but some, like the Finke, are discordant relative to the prevailing slope or structural grain at a locality or in a region. Such anomalous drainage may develop in multiple ways, including: (1) antecedence, whereby a pre-existing river incises into the orogenic mountain range structures as they form; (2) superposition, whereby the river forms on a disconformable overmass of material, subsequently imposing itself on the mountanous undermass with its pre-existing orogenic structural grain; (3) inheritance, where the drainage pattern evolves from a pre-existing surface, which may have developed by planation (fluvial, or hillslope retreat) or because of deep weathering; (4) regressive erosion and derangement through river capture, and (5) impression, which involves deep erosion and persistence of a stream's position as it cuts downward through different levels of a complex rock structure.

C.T. Madigan (1931) proposed antecedence for the Finke drainage, which would have the river predating the beginning of the Alice Springs Orogeny at 400 Ma. This would push formation of the southerly pathway of the Finke to before deposition of the Devonian Pertnjara Group. However, as recognized by J.A. Mabbutt (1966), there is no geological evidence for a Finke River pathway in this time frame. The notion of "the old Finke River… crossing its flood plain in a meandering course," envisioned by L.K. Ward (1925), was cited above. However, it is unclear whether this implies superposition or inheritance. Superposition can effectively be ruled out because no regional covermass for possible superposition ever existed. As pointed out by J.A. Mabbutt (1966), there was no transgression of Cretaceous seas across the ranges, and the last regional depositional unit, the Devonian Pertnjara Group, was synorogenic, thereby participating in all the folding of the older rocks. J.A. Mabbutt (1966) envisioned a subaerial, post-orogenic river history involving a complex combination of inheritance and regressive erosion. His inferred crest-beveled Summit Surface could have provided a possible planation level for subsequent inheritance, but J.A. Mabbutt (1966) further recognized from the mantled pediment sequence that there must also have been multiple alternating periods of planation, deposition, weathering, and erosion, all occurring at times when there was local regressive erosion and river capture.

The accordance of elevations, at about 600 m (given the limitations of available topographic data) noted above for the Shoulder Surface and Mereenie crest bevel (Fig. 10), may be relevant to an inheritance hypothesis. The level could represent the surface of the Finke that developed during the early to mid-Cainozoic, when deep weathering was occurring. The river may have passed over the etched structure of the Mount Merrick Anticline and subsequently imposed itself upon its variously dipping rock units when the thick weathering mantle was removed.

The impression explanation for drainage development on fold-belt mountains was extensively argued by T. Oberlander (1965, 1985) for the Zagros Mountains of Iran. C.R. Twidale (1972, 2004) applied this hypothesis to examples of cross-axial drainage and in-and-out valleys of the ridge-and-valley fold mountains of the southern Flinder's Ranges, South Australia. The breaching of the snouts of plunging folds and the transection of the cores of those fold structures can be readily explained by this hypothesis. The Finke enters the Krichauff Ranges from the Missionary Plain by cutting into the eastward plunging snout of an east-west oriented anticline. It then cuts the eastern end of the similarly oriented Palm Valley syncline, which marks the beginning of the palimpsest of intertwined meandering gorges. Further downstream the Finke is cut into the snout at the western end ofthe Mount Merrick Anticline of the James Ranges, and it expands into the plain at the core of that structure before exiting on its southern limb. All of these relationships suggest impression of the Finke Rive from a pathway that had developed higher in the rock sequence, and was progressively incised into the underlying structures.

GEOPHYSICS

Central Australia is characterized by a pattern of high-amplitude free-air and Bouger gravity anomalies that parallel the trend of the central mountain ranges. Gravity highs occur over the Arunta and Musgrave Blocks, and lows occur over the Amadeus Basin that is sandwiched between them. This pattern is interpreted as representing north-south compression that could either have (1) deformed the central Australian lithosphere into a series of buckle-like undulations, or (2) broke the lithosphere into separate blocks through mechanical failure (Lambeck 1983, 1984). While the thrust faulting of the Alice Springs Orogeny was the last major manifestation of this compression, the gravity anomalies remain uncompensated today. This means that some lateral compression may still be occurring in the Amadeus Basin, and some Mesozoic and Cainozoic tilting of land surfaces is recognized (Warren, Shaw 1995).

R.G. Warren and R.D. Shaw (1995, p. 51) infer that Mesozoic and Cainozoic reactivation of the many faults in the RTZ tilted northern portions of the MacDonnell Ranges, contributing to incised drainage immediately to the south. However, the same authors do not think similar processes can be invoked south of the Missionary Plain to explain the incised meanders of the Finke Gorge (Warren, Shaw 1995, p 14).

TECTONIC DEFORMATION AND DYNAMIC TOPOGRAPHY

Relatively recent technological advances in achieving high-resolution digital topography and tomographic imagery of Earth's mantle have resulted in increased understanding of how low relief regions like Australia can display mantle-flow-driven, long wavelength surficial uplift or subsidence, which are important influences on drainage basin evolution (Braun 2010). The driving forces for these changes result from plate tectonic motions interacting with density anomalies in the mantle.

During the Miocene, the Australian plate experienced very rapid migration northward. In the same period the whole continent underwent a tilting, north-down and southwest-up. This involved a total amplitude of 300 m (Sandiford 2007), but it occurred over a horizontal distance of more than 2000 km. This tilting was very significant for Australia as a whole, elevating the Miocene-age marine formations underlying the Nullarbor Plain in the south while also submerging the southern Gulf of Carpentaria in the north of Australia (Sandiford 2007). Nevertheless, the orientation of the tilt axis for the deformation (Sandiford, Quigley 2009; fig. 8) is subparallel to the pathway of Finke River from the MacDonnell Ranges into the Lake Eyre basin. Thus, any change in the gradient of the Finke would be very minor, e.g., no more than a meter or two, and occurring over many million years.

CLIMATE HISTORY AND WEATHERING PROFILES

Until the Jurassic Australia was part of the Gondwana supercontinent, much of which was at high southern latitudes. Tectonic rifting subsequently separated Australia from what is now Antarctica, and various plate-tectonic interactions eventually led to a northward drift of the continent through the tropical latitudes (Veevers et al. 1991). Though much of Australia was flooded by the Cretaceous marine transgressions, the central Australian ranges and other interior regions were above the levels of marine incursions. Mesozoic ages for landforms and regolith can be demonstrated on geomorphic grounds for many of these areas (Twidale 2007, 2016), and paleomagnetic dating of deep weathering have suggested ages extending to the late Cretaceous and Paleocene (Idnurm, Senior 1978; Pillans 2007).

As reviewed by T. Fujioka and J. Chappell (2010) and B.J. Pillans (2018) the northward migration of Australia was the main driver of paleoclimatic change during the Cenozoic. Warm, humid climates during the early Cenozoic are clearly indicated by paleobotanical evidence (Martin 2006). These conditions favored the mobilization of iron, and subsequent deep oxidation of the regolith leading to precipitation in low-lying areas of groundwater ferricretes, which late came to be preserved as resistant caprocks because of topographic inversion (Pillans 2018). The iron-cemented paleomeander gravels of the Finke River Gorge are probably related to this process and its associated timing.

A summary of Cenozoic Australian climates by T. Fujioka and J. Chappell (2010, p. 126) shows that warm, very wet conditions prevailed through the Paleocene and much of the Eocene (from 65–40 Ma). This was followed by continued wet conditions, with some cooling and monsoonal seasonality until a period of warm/wet phase resumed in the early Miocene, about 20 Ma. There then followed a gradually increasing trend toward aridity, the early periods of which seem to have been sporadic until the late Pliocene. Clear evidence for the latter date comes from cosmogenic ^{21}Ne and ^{10}Be geochronology of stony deserts in northern South Australia (Fujioka et al. 2005). At 1 Ma in the Amadeus Basin fluvial-lacustrine sedimentation was replaced by saline playa conditions (Chen, Barton 1991).

The overall pattern seems consistent with evidence for ancient, tropical weathering throughout the central Australian ranges. This occurred over tens of millions of years, which allowed for very deep weathering that could well have penetrated hundreds of meters into softer rock formations. A second warm/wet phase then occurred in the early Miocene, perhaps about 20 or 30 Ma. Interestingly, this is a period in which silcrete crusts formed, as documented in the Lake Eyre Basin (Wopfner, Twidale 1967; Alley 1998). In the MacDonnell Ranges area silcrete-capped mesas occur south of the James Ranges and to the southeast of Alice Springs. In similar manner to the ferricretes noted above, the silcretes accumulated from solutions that were mobilized from kaolinized layers in ancient laterite profiles, and subsequently conveyed to valley bottoms where cements were precipitated. Relief inversion then occurred when the silicified valley floor deposits were preferentially preserved relative to the more easily eroded bedrock (Milnes, Twidale 1983).

The change to relatively dry conditions that became continuous in the late Pliocene is consistent with the calcrete formation noted above for the Bitter Springs strike valley and for the contemporary bedrock gorge of the Finke

River. The river regimen that led to ephemeral flows, punctuated by rather extreme floods, could be related to incision associated with the contemporary bedrock channel development.

ETCHPLANATION AND INTRAMONTANE BASINS

Related to the of long-term climatic change in central Australia is the concept of etchplanation under tropical conditions that promote the rapid decomposition of susceptible rocks. Though the concept was originally developed to explain very well developed planation surfaces in Uganda, it was subsequently generalized into a theory of *Doppelten Einebnungflächen* ("double surfaces of leveling") by J. Büdel (1957). In this theory a basal surface of weathering (*Verwitterungs-Basisfläche*) develops deep below the land surface at the interface between altered and intact bedrock. The intact rock surface is later exposed after the weathered mantle (regolith) is removed when climatic change or a base level change results in erosive stripping of the regolith. A version of this concept was s applied to central Australia by J.A. Mabbutt (1961, 1965), who argued that the change from humid tropical to drier conditions resulted in the stripping of deeply weathered rock down to the level of what he terms the "weathering front," and that surface subsequently became the active landscape.

Büdel's doctoral student Hanna Bremer extended her advisor's model to the James and Krichauff Ranges in central Australia (Bremer 1967). In this model landscape lowering during etchplanation leads to the crossing of resistant ridges by streams and rivers. H. Bremer inferred that the early phases of deep tropical weathering got focused on low-lying areas that subsequently become "intramountane basins." Deep weathering preferentially occurs on softer rocks, while resistant, ridge-forming units get preserved in the same way that inselbergs develop (e.g., Twidale 2002). As a landscape lowers, the rivers draining away the weathered materials can become superposed on resistant elements, such as strike ridges.

Bremer's type example for an intramontane basin is the Wild Eagle Plain (WE in Fig. 2), located about 50 km southwest of the Finke Gorge. This basin is drained by 4 separate streams (Palmer River, Illamuta Creek, Deception Creek, and Norman Gully), all of which drain through separate gaps in the surrounding sandstone ridges. As explained by J. Büdel (1982, p. 163–164),

> Had the intramontane plain been formed by the rivers, then four separate basins at different levels would have been formed, and not a unified surface.

J. Büdel's conclusion is that the plain can only have been formed by,

> independent and predominantly chemical lowering of the surface … [the river having] played only the passive role of carrying away the prepared material.

Other examples of the Bremer/Büdel intramontane basins occur along the Finke pathway: Palm Valley, the Circle Gully-Tietkins Vale-Tidenvale Creek strike valley, the Merrick Gully plain (developed along the axis of the Mount Merrick Anticline), and the diamond-shaped depression south of the Mount Merrick Anticline. Like Wild Eagle Plain, many of these basins are located along the axes of broad synclines, toward which water would have been preferentially focused, thereby promoting deeper weathering than would occur in more elevated surroundings.

The Missionary Plain is a broad synclinal structure with its axis underlain by the Undindita Member of the Brewer Conglomerate. The lower parts of the plain, north and east or Hermannsburg are at around 600 m in elevation. This is approximately the same elevation as the floor of Palm Valley and the level of the Shoulder Surface near the Finke/Ellery Junctions. If all these areas constituted a level produced by etchplanation, during which the weathering products were removed by an ancient Finke drainage, that river may have eventually incised into the etched surface near the end of the deep weathering period. The result would be the paleomeander stream, incised into the Shoulder Surface, and containing the relict channel fills that were cemented valley floor ferricretes. However, this landscape is relict; it was later left inactive when the younger meandering gorge was cut through the older landscape.

As with the Wild Eagle Plain, the Stokes Siltstone strike valley surrounding the Mount Merrick Anticlinal area of the James Ranges, has multiple inlets and outlets, all at the level of the lowland plain represented by the strike valley. On the north side of the anticline, going west to east, inlets to the Stokes strike-valley lowland include the gorge of the Finke River (Fig. 10), Log Hole Creek, the Hugh River, and a large wind gap partly drained by Stuart Hole Creek (also containing the Stuart Highway). On the south side of the anticline, exit points from the Circle Gully-Tietkins Vale-Tidenvale Creek stike valley (also developed on the Stokes Siltstone) include the unnamed wind gap shown in Figure 12, the gap occupied by the current Finke River (Fig. 11), and the Hugh River. In addition there are three gaps, one a wind gap, that connect the Circle Gully-Tietkins Vale-Tidenvale Creek strike valley lowland to a lowland plain (another intermontane basin) that is developed on the core axis of another (unnamed) anticline to the immediate southeast of the Mount Merrick Anticline. All of these gaps, connecting multiple lowland plains, developed in areas where deep weathering was likely differentially imposed on susceptible rock types. These relationships, including the wind gaps, are consequences that directly follow from the Bremer/Büdel model of etchplanation/intramontane basin formation.

Another drainage anomaly occurs just west of the Hugh River transect of the resistant, crest-beveled Hermannsburg/Meerenie ridge on the north side of the Mount Merrick Anticline. The Hugh River tributary, Log Hole Creek, flows for 15 km parallel to strike and imposed upon the crest-beveled ridge, before exiting into the Stokes Siltstone strike valley just before its junction with the Hugh River. The latter, in contrast, has flowed in a direct route of only 3 km perpendicular to the strike of the same crest-beveled ridge.

That Log Hole Creek does not join the Hugh by following a lowland path along the Missionary Plain immediately north of the Hermansburg/Meerenie ridge could only have arisen if stream was imposed upon that ridge (1) from a higher planation surface or (2) from a mantle of weathered materials overlying the ridge. Explanation (2) seems most consistent with other evidence from the region.

DISCUSSION AND CONCLUSIONS

In his review of "the two-stage concept of landform and landscape development" C.R. Twidale (2002, p. 65) very briefly mentioned the Finke and other rivers draining the MacDonnell Ranges in the context of etchplanation. He noted that these rivers flowed,

> across a formerly duricrusted surface, now partly eroded to form an etch plain… and across folds, faults and a multitude of rock types. The transverse courses of such rivers can be explained partly as inherited from a regolithic surface, partly as due to… stream persistence and valley impression.

These hypotheses, plus possible influences by epeirogenic movements and climate-induced changes in fluvial regimen, all seem to combine to create a plausible explanation for transverse drainage features in the central Australian mountain ranges.

Following completion of the Alice Springs Orogeny around 300 Ma, ancient drainage likely developed southward on landscapes that extended from the Arunta Block across the fold mountains of the northern Amadeus Basin toward the Lake Eyre Basin. The synorogenic deposition of Devonian Pertnjara Group was complete by then, having already eroded deeply into the Heavitree Quartzite of the nappe structures that had been generated during the orogeny. There may also have been a period of deep weathering during late Paleozoic time, as documented in South Australia (Daily et al. 1974). When the Tnorala bolide struck at 145 Ma, the level of the landscape above today's Missionary Plain was probably a few hundred meters higher than today. A period of planation seems to have occurred during the Cretaceous, as indicated by the crest bevels preserved on the strike ridges throughout the region, and on Tnorala itself. Inheritance from this surface, combined with regressive erosion plus cycles of weathering, erosion, and deposition, all seem to have combined to generate the patterns of cross-axial drainage that evolved in the MacDonnell Ranges (Mabbutt 1966).

The early Cainozoic of central Australia was a period of considerable humidity and warmth promoting deep tropical weathering that lasted for a few 10s of My. The northward drift of the continent during Cainozoic and associated oceanic and landmass changes induced progressive climatic change, with aridity dominating by the Pliocene and Quaternary. The history of climate shifts is recorded in the sequence of weathering and duricrusts, as well as by the succession of mantled pediment surfaces of the MacDonnell Ranges and the Missionary Plain. The removal of former, deep weathering mantles through etchplanation led to imposition of drainage from the surface of that mantle on to the underlying weathering front, producing multiple valleys transecting the zones of more resistant and less resisting rock, today comprising strike ridges and strike valleys. This was especially facilitated by the development of intramontane basins (Bremer 1967, 1975) though the localization of deep weathering along zones of susceptible rock types, such as the Stokes Siltstone, or in places toward which water flow converged, as in synclinal structures like Wild Eagle Plain and other portions of the James Ranges.

In the Krichauff Ranges the puzzle remains as to the shift that caused the contemporary bedrock channel to impose itself, producing a palimpsest by cutting across a prior gorge of relict ancient paleomeanders. The timing of that shift seems to coincide with the onset of continuing aridity that probably occurred during the Pliocene, perhaps a few million years ago. As noted in the discussion of paleofloods, the associated changes in the erosive ability of the semi-arid streams probably played a role, but what induced the deep incision that cuts across the relict bedrock channel trend?

One explanation might be a reset of meandering on the Shoulder Surface. The ancient paleomeander segments are incised into the Shoulder Surface, but they also contain aggradational fills of quartzite gravel. This aggradation could reflect a change to a drier climate with more sediment coming off the land surface. If the resulting aggradation caused the bed of the Finke paleo-river to rise enough to re-occupy the Shoulder Surface, the river could then flow on a layer of aggradational fill thinly mantling that surface. This would permit what would become the contemporary Finke to develop a new meandering pattern independent of the relict pattern of the paleomeanders buried beneath the fill.

Subsquently, removal of the fill layer from the Shoulder Surface and incision into the underlying Hermansburg Sandstone and iron-cemented paleochannel fills would then generate the observed palimpsest. The aggradation phase could have been a response to upstream influences on the river sediment load and flood regimen, induced by the drying climate, but the subsequent incision into the Shouder Surface and removal of its cover (except for the observed quartzite lag gravels) would likely be associated with downstream base-level effects. These could have resulted from tectonic warping or from details in the evolving pattern of denudation as explained below.

Pliocene Finke River incision through the Krichauff Ranges might have been generated by headward recession of a knick point created where the river flowed from resistant sandstones into what are now the strike valleys of the James Ranges, from which weathered mantles had been removed by etchplanation. A key location would be where the Finke now flows from its Gorge in the Hermannsburg and Mereenie Sandstones into the strike valley developed on the Stokes Siltstone (Fig. 10). If the ancestral Finke was indeed perched at the levels of both the Shoulder Surface and the Mereenie crest bevel (M in Fig. 10), then removal of the weathering mantle that formerly filled the Stokes strike valley would have created a 100-m high knick point at this location, thereby facilitating the upstream incision. This weathering mantle removal could have occurred though the multiple outlets noted above: the Hugh River, the unnamed wind gap (Fig. 12) and the current Finke River gap through the crest-beveled Mereenie ridge (Fig. 11). And, of course, all of this follows from a combination of etchplanation, stream impression, persistance, regressive erosion, climate-induced changes in river regimen, against a likely context of epeirogenic tectonism.

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REFERENCES

Alley N. F., 1998. *Cainozoic stratigraphy, palaeoenvironments and geological evolution of the Lake Eyre Basin*. Palaeogeography, Palaeoclimatology, Palaeoecology 144, 239–263.

Baker V.R., 1973. *Paleohydrology and Sedimentology of Lake Missoula Flooding in Eastern Washington*. Geological Society of America Special Paper 144, Boulder, Colorado, 1–79.

Baker V.R., 1977. *Stream channel response to floods with examples from central Texas*. Geological Society of America Bulletin 88, 1057–1070.

Baker V.R., 1986. *Regional landforms analysis*. [in:] N.M. Short, R.W. Blair Jr. (eds.), *Geomorphology from space: a global overview of regional landforms.* National Aeronautics and Space Administration Spec. Publication 486, Washington, D.C., 126.

Baker V.R., 2009. *Channeled Scabland morphology*. [in:] D.M. Burr, P.A. Carling, V.R. Baker (eds.), *Megaflooding on Earth and Mars*. Cambridge University Press, Cambridge, 65–77.

Baker V.R., Costa J.E., 1987. *Flood power*. [in:] L. Mayer, D. Nash (eds.), *Catastrophic flooding*. Allen and Unwin, London, 124.

Baker V.R., Ritter D.F., 1975. *Competence of rivers to transport coarse bedload material*. Geological Society of America Bulletin 86, 975–978.

Baker V.R., Penteado-Orellana M.M., 1977. *Adjustment to Quaternary climatic change by the Colorado River in central Texas*. Journal of Geology 85, 395–422.

Baker, V.R., Penteado-Orellana M.M., 1978. *Fluvial sedimentation conditioned by Quaternary climatic change*. Journal of Sedimentary Petrology 48, 433–451.

Baker V.R., Pickup G., Polach H.A., 1983. *Desert paleofloods in central Australia*. Nature 301, 502–504.

Baker V.R., Pickup G., Webb R.H., 1987. *Paleoflood hydrologic analysis at ungagged sites, central and northern Australia.* [in:] V.P Singh (ed.) *Regional flood frequency analysis*. D. Reidel, Boston, 325–338.

Bourke M.C., Pickup G., 1999. [in:] A.J. Miller, A. Gupta (eds.), *Varieties of fluvial form*. Wiley, New York, 249–271.

Braun J., 2010. *The many surface expressions of mantle dynamics*. Nature Geoscience 3, 825–833.

Bremer H., 1967. *Zur Morphologie von Zentralaustralien*. Heidelberger Geographische Arbeiten 17, 1–224.

Bremer H., 1975. *Intramontane Ebenen, Prozesse der Flächenbildung*. Zeitschrift für Geomorphologie, Supplement-Band 23, 26–48.

Büdel J., 1957. *Die "Doppelten Einebnungsflächen" in den feuchten Tropen*. Zeitschrift für Geomorphologie 1, 201–228.

Büdel J., 1982, *Climatic Geomorphology*. Princeton University Press, Princeton, (Translation of Büdel J., 1977, Klima-Geomorphologie. Gebrüder Borntraeger, Berlin).

Chen XY., Barton CE., 1991. *Onset of aridity and dune-building in Central Australia: sedimentological and magnetostratigraphic evidence from Lake Amadeus*. Palaeogeography, Palaeoclimatology, Palaeoecology 84, 55–71.

Daily B., Twidale C.R., Milnes A.R., 1974. *The age of the lateritized summit surface on Kangaroo Island and adjacent areas of South Australia*. Journal of the Geological Society of Australia 21, 387–392.

Fujioka T., Chappell J., 2010. *History of Australian aridity: chronology in the evolution of arid landscapes*. [in] P. Bishop, B. Pillans (eds.), *Australian Landscapes*. Geological Society, London, Special Publications 346, 121–139, DOI: 10.1144/SP346.8.

Fujioka T., Chappell J., Honda M., Yatsevich I., Fifield K., Fabel D., 2005. *Global cooling initiated stony deserts in central Australia 2–4 Ma, dated by cosmogenic ^{21}Ne–^{10}Be*. Geology 33, 993–996.

Fudali R.F., Milton D.J., Fredriksson K., Dube A., 1980. *Morphology of Lonar Crater, India: Comparisons and implications*. The Moon and the Planets 23**,** 493–515.

Haines P.W., Hand M., Sandiford M., 2010. *Palaeozoic synorogenic sedimentation in central and northern Australia: A review of distribution and timing with implications for the evolution of intracontinental orogens*. Australian Journal of Earth Sciences 48, 911–928.

Heimsath A.M., Chappell J., Fifield K., 2010. *Eroding Australia: Rates and processes from Bega Valley to Arnhem Land*. [in:] P. Bishop, P.B. Pillans (eds.), *The evolution of arid landscapes*. Geological Society, London, Special Publications 346, 225–241.

Idnurm M., Senior B.R., 1978. *Palaeomagnetic ages of late Cretaceous and Tertiary weathered profiles in the Eromanga Basin, Queensland*. Palaeogeography, Palaeoclimatology, Palaeoecology 24, 263–277.

King L.C., 1950. *The cyclic land surfaces of Australia*. Proceedings of the Royal Society of Victoria 62, 79–95.

Lambeck K., 1983. *Structure and evolution of the intracratonic basins of central Australia*. Geophysical Journal of the Royal Astronomical Society 74, 843–865.

Lambeck K., 1984,. *Structure and evolution of the Amadeus, Officer and Ngalia Basins of central Australia*. Australian Journal of Earth Sciences 31, 25–48.

Mabbutt J.A., 1961. *'Basal surface' or 'weathering front'*. Proceedings of the Geologists Association of London 72, 357–358.

Mabbutt J.A., 1965. *The weathered land surface in central Australia*. Zeitschrift für Geomorphologie 9, 82–114.

Mabbutt J.A., 1966. *Landforms of the western MacDonnell Ranges*. [in:] G.H. Dury (ed.), *Essays in Geomorphology*. Heinemann, New York, 83–119.

Mabbutt J.A., 1978. *Lessons from pediments*. [in:] J.L. Davies, M.A. Williams (eds.), *Landform Evolution in Australasia*. Australian National University Press, Canberra, 331–47.

Machette M.N., 1989. *Calcic soils of the southwestern United States*. [in:] D.L. Weide (ed.), *Soils and Quaternary geology of the southwestern United States*. Geological Society of America Special Paper 203, 1–21.

Madigan C.T., 1931. *The physiography of the western Macdonnell Ranges, central Australia*. Geographical Journal 78, 417–433.

Martin H.A., 2006. *Cenozoic climatic change and the development of arid vegetation in Australia*. Journal of Arid Environments 66, 533–563.

Milnes A.R., Twidale C.R., 1983. *Silicification in Cainozoic landscapes of arid Australia*. Australian Journal of Soil Research 21, 387–410.

Milton D.J., Sutter J.F., 1987. *Revised age for the Gosses Bluff Impact Structure, Northern Territory, Australia, based on $^{40}Ar/^{39}Ar$ dating*. Meteoritics 22, 281–289.

Milton D.J., Brett P.R., Gilkson A.Y., 1976. *Detailed Geological Map of Gosses Bluff, Northern Territory*. Bureau of Mineral Resources, Canberra, A.C.T.

Milton D.J., Barlow B.C., Brett R., Brown A.R., Gilkson A.Y., Manwaring E.A., Moss F.J., Sedmik E.C.E., Van Son J., Young G.A., 1972. *Gosses Bluff Impact Structure, Australia*. Science 175, 1199–1207.

Oberlander T., 1965. *The Zagros Streams*. Syracuse Geographical Series 1, 1–168.

Oberlander T., 1985. *Origin of transverse drainage to structures in orogens*. [in:] M. Morisawa, J.T. Hack (eds.), *Tectonic Geomorphology*. Allen and Unwin, Boston, 155–182.

Ollier C.D., Galloway R.W., 1990. *The laterite profile, ferricrete and unconformity*. Catena 17, 97–109.

Pain C.F., Ollier C.D., 1995. *Inversion of relief—a component of landscape evolution*. Geomorphology 12, 151–165.

Pain C.F., Pillans B.J., Roach I.C., Worrall L., Wilford J.R., 2012. *Old, flat and red – Australia's distinctive landscape*. [in:] R.S. Blewett (ed.), *Shaping a nation: a geology of Australia*. Geoscience Australia and Australian National University Press, Canberra, 226–275.

Patton P.C., Pickup G., Price D.M., 1993. *Holocene paleofloods of the Ross River, central Australia*. Quaternary Research 40, 201–212.

Pickup G., 1991. *Event frequency and landscape stability on the floodplain systems of arid Central Australia*. Quaternary Science Reviews 10, 463–473.

Pickup G., Allan G., Baker V.R., 1988. *History, palaeochannels, and palaeofloods of the Finke River, central Australia*. [in:] R.F. Warner (ed.), *Fluvial geomorphology of Australia*. Academic Press, Sydney, 177–200**.**

Pillans B., 2007. *Pre-Quaternary landscape inheritance in Australia*. Journal of Quaternary Science 22, 439–447.

Pillans B.J., 2018. *Seeing Red: Some Aspects of the Geological and Climatic History of the Australian Arid Zone*. [in:] H. Lambers (ed.), *On the ecology of Australia's arid zone*. Springer, Cham, Switzerland, 5–43.

Quinlan T., Forman D.J., 1968. *Hermannsburg, Northern Territory – 1:250,000 Geological Series*. Bureau of Mineral Resources, Geology and Geophysics, Canberra, Explanatory Notes SF/53–13, 1–19.

Sandiford M., 2007. *The tilting continent: a new constraint on the dynamic topographic field from Australia.* Earth and Planetary Science Letters 261, 152–163.

Sandiford M., Quigley M., de Broekert P., Jakica S., 2009. *Tectonic framework for the Cenozoic cratonic basins of Australia*. Australian Journal of Earth Sciences 56, S5–S18.

Senior B.R., 1972. *Cainozoic laterite and sediments in the Alcoota Sheet area, Northern Territory*. Bureau of Mineral Resources of Australia Record No. 1972–47.

Senior B.R., Truswell E.M., Idnurm M., Shaw R.D., Warren R.G., 1995. *Cainozoic sedimentary basins in the eastern Arunta Block, Alice Springs region*. AGSO Journal of Australian Geology and Geophysics 14, 421–444.

Tooth S., 1999. *Floodouts in central Australia*. [in:] A.J. Miller, A. Gupta (eds.), *Varieties of Fluvial Form*. Wiley, New York, 229–247.

Twidale C.R., 1972. *The neglected third dimension*. Zeitschrift für Geomorphologie 6, 283–300.

Twidale C.R., 1994. *Gondwanan (Late Jurassic and Cretaceous) paleosurfaces of the Australian craton*. Palaeogeography, Palaeoclimatology, Palaeoecology 112, 157–186.

Twidale C.R., 1997. *Persistent and ancient rivers–some Australian examples*. Physical Geography 18, 291–317.

Twidale C.R., 2002. *The two-stage concept of landform and landscape development involving etching: origin, development and implications of an idea*. Earth-Science Reviews 57, 37–74.

Twidale C.R., 2004. *River patterns and their meaning*. Earth-Science Reviews 67, 159–218.

Twidale C.R., 2007. *Ancient Australian Landscapes*. Rosenberg, New South Wales, Australia.

Twidale C.R., 2010. *Uluru (Ayers Rock) and Kata Tjuta (The Olgas): inselbergs of central Australia*. [in:] P. Migoń (ed.), Geomorphological Landscapes of the World. Springer, Vienna, 321–332.

Twidale C.R., 2016. *Enigmatic Mesozoic paleoforms revisited: the Australian experience*. Earth-Science Reviews 155, 82–92.

Twidale C.R., Bourne J.A., 1996. *Development of the land surface*. [in:] M. Davies, C.R. Twidale, M.J. Tyler (eds.), *Natural History of the Flinders Ranges*. Royal Society of South Australia, Adelaide, 46–62.

Veevers J.J., Powell C.M., Roots S.R., 1991. *Review of seafloor spreading around Australia. I. Synthesis of the patterns of spreading*. Australian Journal of Earth Sciences 38, 373–389.

Ward L.K., 1925. *Notes on the geological structure of central Australia*. Transactions of the Royal Society of South Australia 49, 61–84.

Warren R.G., Shaw R.D., 1995. *Hermannsburg, Northern Territory – 1:250,000 Geological Series*. Northern Territory Geological Survey, Explanatory Notes SF 53–13, 1–81.

White M.E., 2000. *Running Down: Water in a Changing Land*. Kangaroo Press, Sydney, Australia.

Wopfner H., Twidale C.R., 1967. *Geomorphological history of the Lake Eyre basin*. [in:] J.N. Jennings, J.A. Mabbutt (eds.), *Landform Studies from Australia and New Guinea.* Australian National University Press, Canberra, 117–143.

https://en.wikipedia.org/wiki/List_of_rivers_by_age

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