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DRAINAGE PATTERNS IN AN APPALACHIAN FOLD MOUNTAIN BELT: FLINDERS RANGES, SOUTH AUSTRALIA

C. R. Twidale & J. A. Bourne

School of Earth and Environmental Sciences, Geology and Geophysics, University of Adelaide, Adelaide, South Australia, 5005
E-mail: rowl.twidale@adelaide.edu.au

Abstract: The streams and rivers draining the Flinders Ranges are largely concordant with structure but all major elements and many other channels include sectors that cut across local structure in anomalous or transverse streams. These anomalous sectors can plausibly be explained in various ways: by capture involving headward erosion, or stream and valley impression made possible by the deep erosion of folds, or by underprinting. The possibility of referral is broached, as is the significance of catchment characteristics in relation to piracy. The impression mechanism raises the possibility that some transverse sectors are of great antiquity. But the origin of many structurally discordant elements remains ambiguous, for they are susceptible of explanation by more than one process or mechanism.

Key words: Ridge and Valley topography, transverse drainage, fluvial piracy, impression, underprinting, referral, South Australia.

Resumen: La red de drenaje desarrollada en las Flinders Ranges (Australia) es en su mayor parte concordante con la estructura geológica subyacente. No obstante, incluye importantes tramos fluviales que atraviesan la estructura geológica subyacente dando lugar a drenajes transversals anómalos. Estas zonas anómalas pueden ser plausiblemente explicadas en cada caso por varios procesos tales como, capturas por erosión remontante, procesos de superposición de canales o valles fluviales debido a la profunda erosión de los mismos o por superimposición (underprinting). La posibilidad de un redireccionamiento fluvial ha de ser entendido en relación del significado de las diferentes características de las cuencas de drenaje ante los procesos de captura. Los mecanismos de superimposición del drenaje indican que algunos de los drenajes transversos analizados tengan gran antigüedad. No obstante, el origen de muchos elementos transversals se todavía ambiguo y otros procesos pueden haber jugado un papel relevante en su formación.

Palabras clave: Topografía de Sierra-Valle, drenaje transversal, captura fluvial, superposición, sobreimposición, redireccionamiento, Sur de Australia.

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1. Introduction

The Flinders Ranges consist mainly of ridge and valley topography, which projects meridionally for some 400 km into the semiarid and arid interior of South Australia (Fig. 1a). It attains a maximum elevation of 1170 m in St Mary Peak, on the northeastern perimeter of Wilpena Pound (Fig. 2a), in the central part of the upland. Strike streams, linked by transverse dip and antidip streams and valleys to form trellis and annular patterns, according to the plan form of the outcrops, are typical of the exposed folded sedimentary sequences that dominate the upland. The dip and antidip components of these trellis patterns call for explanation, as do various other types of anomaly. The problems posed by anomalies at both regional and local scales are discussed in this essay, though only a few of the many examples of each type are discussed.

2. Background

The Flinders Ranges is part of the Adelaide Geosyncline (Preiss, 1987) which is an orogen of

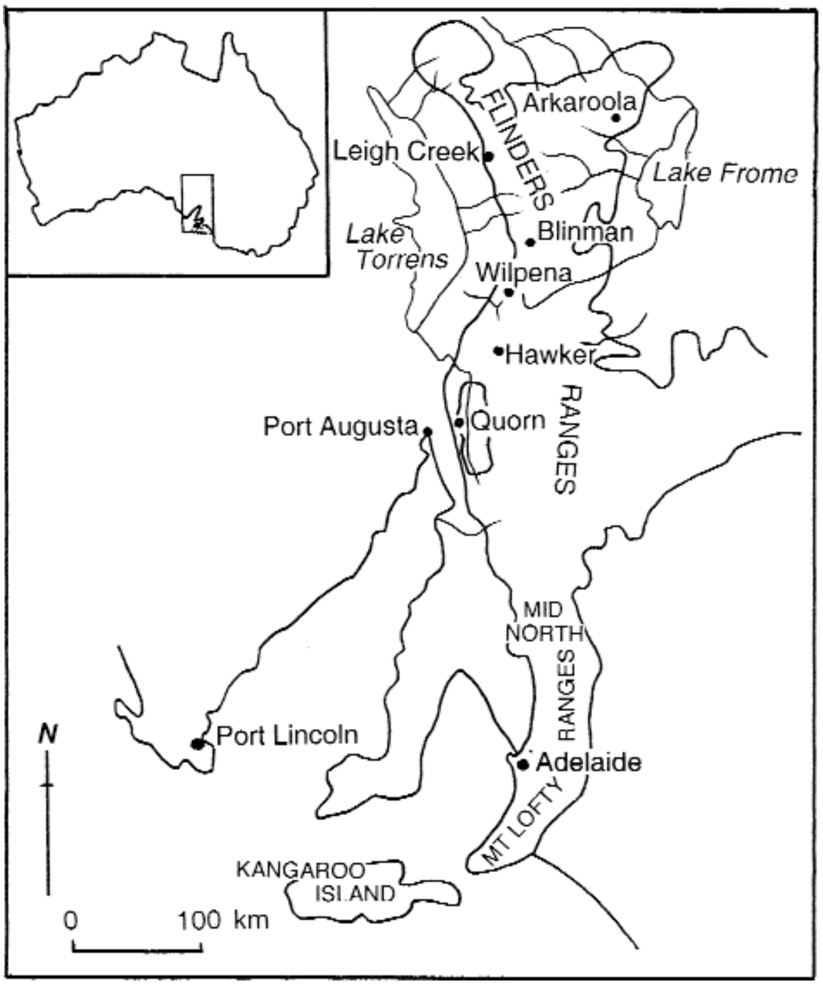
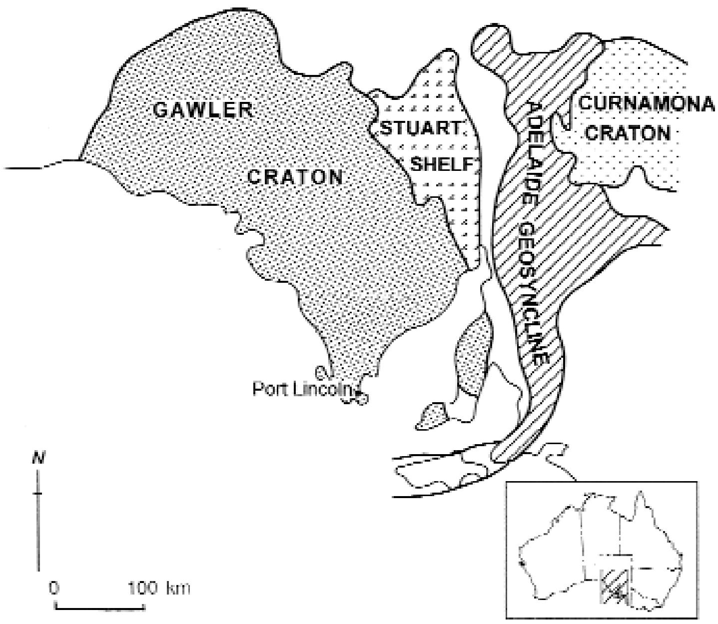


Figure 1. (a) Location map, Flinders Ranges, South Australia. Note the elongated radial pattern of major streams. (b) Structural setting of the Flinders Ranges.

Figura 1. (a) Mapa de localización, Flinders Ranges, Sur de Australia. Nótese el patrón elongado radial de la red de drenaje. (b) Contexto Estructural de las Flinders Ranges.



Early Paleozoic age developed between the Gawler Craton and Stuart Shelf to the west and the Curnamona Craton to the east (Fig. 1b). Folded Proterozoic and Cambrian strata are involved in the orogen. The folds are open and simple, but many are interrupted by diapiric intrusions. Igneous and metamorphic emplacements are prominent in the northeast. To the north the Davenport Ranges (the official name, but more widely known as the Peake and Denison Ranges) is an inlier of the fold mountain belt dominated by a prominent planate summit surface. To the south and contiguous with the Flinders Ranges, the Mid North is another region of ridge and valley developed on open folds. The Geosyncline extends to the south in the block-faulted Mt Lofty Ranges. The upland curves to the southwest in the Fleurieu Peninsula and then to the west in Kangaroo Island.

These southern sections of the orogen are less dissected than the Flinders and Mid North regions. Fenner (1931, p. 49) attributed this to aridity and concomitant greater wind erosion, but it is the lateritic capping of pre Middle Jurassic, putative Triassic, age (Daily et al., 1974) preserved in the Fleurieu Peninsula, that has resulted in the preservation of high plains and plateaux bordering the South Australian Gulfs (Fig. 1a). Laterite is clearly a significant factor in landscape development in the Adelaide Geosyncline terrains, but whether it was never developed in the Flinders and Davenport ranges for climatic reasons, or whether it was formed and later completely stripped, is not known; though the absence of Permian glacial sediments in these northerly sectors (see below) suggests that greater uplift and deeper erosion may have eliminated any duricrust capping as well as evidence of the ancient glaciation.

The separation of Australia and Antarctica in the later Cretaceous and earliest Tertiary, and the northward migration of the former, saw renewed differential earth movements at the southern margin of the Australian continent. In particular down-faulting produced the depressions that later became the Gulf St Vincent and Spencer Gulf. It also caused the reactivation of the northern extensions of the fault systems, including those delineating the Flinders Ranges. Thus, though basically an Early Paleozoic structure, the Flinders Ranges sector of the orogen was block-faulted and uplifted in Late Cretaceous-Early Paleocene times (e.g. Campana, 1958). The plan pattern of the marginal faults is such that the upland describes an hour-glass shape in plan with a relatively narrow 'waist' (Fig. 1a). Uplift continued through the Cenozoic to the pre-

Figure 2. (a) Wilpena Pound seen from the northwest. Note the platform remnants at the northwestern rim of the amphitheatre and the deeply incised Edeowie Creek. (Mapland DENR, South Australia). (b) SubCretaceous summit surface cut in various Proterozoic rocks, northern Flinders Ranges and exhumed from beneath Early Cretaceous marine (littoral) strata, a silicified remnant of which is preserved in the mesa known as Mt Babbage. (c) Planation surface eroded in sediments and metasediments, northern Flinders Ranges (B.P. Webb). (d) The Battery with high plain remnants cut across various sandstone beds (Mapland DENR, South Australia).

Figura 2. (a) Vista desde el NW del Wilpena Pound. Nótese los restos de las antiguas plataformas en el margen noroeste del anfiteatro natural, así como el fuerte encajamiento del Arroyo Edeowie (Mapland DENR, South Australia). (b) Superficie somital subcretácica elaborada sobre el sustrato proterozoico en la zona norte de las Flinders Ranges, y exhumada por debajo de los depósitos litorales del Cretácico inferior. Un retazo silicificado de esta superficie queda preservado en la Mesa del Mt. Babbage. (c) Superficie de planación elaborada sobre sedimentos y metasedimentos, Norte de las Flinders Ranges (B.P. Webb). (d) La Battery constituida por remanentes de la antigua superficie de planación sobre estratos de arenisca (Mapland DENR, South Australia).

sent. The available, though limited, evidence is confined to a few sites but the exposed marginal faults are of reverse type (e.g. Williams, 1973; Campana et al., 1961; Bourman and Lindsay 1989; Love et al., 1995; Sandiford, 2003; Quigley et al., 2006; see also Bullard, 1936).

3. Chronology of drainage development

The commencement of recognised landscape evolution dates from the Late Palaeozoic glaciation that affected most of southern and central Australia (BMR Palaeogeographic Group, 1992). No evidence of the event survives in the Flinders Ranges, however, where the oldest landscape remnants, of an exhumed subCretaceous surface (Fig. 2b), are preserved high in the relief in the extreme north of the upland (Woodard, 1955). In addition, sedimentary evidence suggests that various isolated Triassic basins served catchments of low relief (e.g. Parkin, 1953; Johnson, 1960; Kwitco, 1995, p. 99). However, no remnants of such a surface have been identified in the field.

The Early Cretaceous seas only touched the northern fringe of the upland (Alley and Lemon, 1988), so that the associated exhumed surface is of only limited extent. However, a summit surface physically contiguous with the exhumed surface and evident throughout the Ranges (Figs. 2a, 2b, 2c, 2d) is plausibly interpreted as an epigene surface shaped by rivers and streams graded to various Cretaceous shorelines (Frakes, 1987; Twidale, 2007).

The characteristic ridge and valley topography of the southern Ranges is the result of the litholog-

ically-controlled differential erosion of the Cretaceous planation surface. The age of the ridge and valley assemblage is demonstrated by sediments of Middle Eocene age (Harris, 1970) associated with a Willochra Lake (Figs. 3a, 3b), the formation of which is most plausibly explained by the blockage of the ancestral west-flowing Willochra Creek by the uplift of the southeastern margin of the upland along the still active Wilkatana and associated faults (Williams, 1973; Quigley et al.,

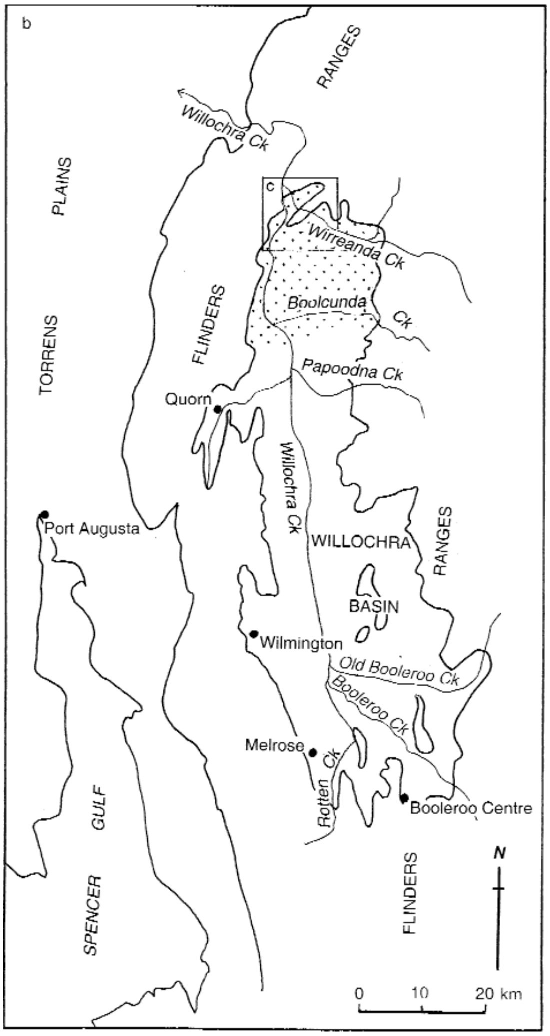
2006). Lake sediments tongue up valleys between the quartzite ridges marginal to the northern Willochra Plain and presently drained by the Kanyaka and Mount Arden creeks, the latter a tributary of the Willochra Creek (Harris, 1970; Twidale, 1994, 1997, 2007). Thus the ridge and valley topography was already shaped when the Lake came into existence and predates the Middle Eocene. Such an age for the ridge and valley topography and for the precursors of the present drainage system is likely to apply throughout the upland, not only on general grounds based in the tectonic chronology of the region, but also because silcrete of Eocene age (Wopfner et al., 1974) was accumulated in the northeastern piedmont (e.g. Campana, 1958; Campana et al., 1961). Silcrete possibly of the same age (but see also e.g. McNally and Wilson, 1995; Hou et al., 2003) occurs patchily also in the scarp-foot zones of quartzite ridges throughout the upland and also in marginal piedmonts.

Rivers cutting into the Cretaceous surface produced a relief amplitude of up to 400 m in the north but more commonly 100-300 m taking the upland as an entity. Dissected remnants of old valley floors and associated basal steepening of hillslopes attest to later Cenozoic increases in relief amplitude, typically of 5-10 metres, though major rivers have incised more deeply. Thus, a remnant of a valley floor shaped in Cambrian limestone and exhumed from beneath Middle Eocene sandstone in the lower Mt Arden Creek valley provides further proof of the antiquity of the contemporary topographic framework, as well as evidence that the

Figure 3. (a) Oblique air photo of the northern Willochra Plain seen from the north (RAAF). The Kanyaka Creek is essentially a strike valley located between the Black Jack Range (B) and Hut Hill the hooked ridge in centre view. The Willochra and Kanyaka creeks merge to the right of A before separately breaching the Partacoona ridge (see Fig. 7a). That the Middle Eocene Willochra Lake extended some distance up the valley is demonstrated by remnants of lacustrine beds, and by valley floor remnants apparently graded to the lake shore. The lacustrine beds are also found in the Mt Arden Creek valley (M). The Horseshoe Range (X) is part of the eastern limb of a faulted regional anticline, the western part of which is represented by the quartzite ridge that frames the Mt Arden Creek valley. The lake deposits demonstrate the minimum age for the ridge and valley topography, for the palaeosurface represented by the ridge crests, and for the rivers like the Kanyaka that eroded the valleys. (b) The Willochra Basin showing major drainage elements and suggested former minimum lake limits (dotted area). (c) Suggested pattern of underprinted river sectors in the northern Willochra Basin.
Figura 3. (a) Fotografía aérea oblicua de la zona norte de la planicie de Willochra vista desde el norte (RAAF). El Río Kanyaka es fundamentalmente un valle linear situado entre la Balck Jack Range (B) y la Hut Hill, situada en el centro de la imagen. Los cauces del Willochra y Kanyaka confluyen hacia la derecha de A antes de que separadamente atraviesen la Cresta de Partacoona (ver Fig. 7a). que el antiguo lago eoceno de Willochra se extendía aguas arriba del valle queda demostrado por los retazos de depósitos lacustres en el interior del valle así como por la secuencia gradada hacia el antiguo margen lacustre de depósitos de fondo de valle. Los antiguos depósitos lacustres también se encuentran en el valle del Arroyo Mt Arden (M). La Horseshoe Range (X) forma parte del flanco oriental de un anticlinal regional fallado, cuyo sector occidental queda representado por la cresta de cuarcita que enmarca el Valle de Mt. Arden. Los depósitos lacustres (Eoceno Medio) indican la edad mínima para el desarrollo del la topografía en “valles y crestas”, el de la superficie somital de las crestas y para el drenaje transeversal como el del río Kanyaka. (b) Elementos principales del drenaje y antiguos limites lacustres eocenos (línea ponteada) en la Cuenca del Willochra. (c) Posibles patrónes de drenaje sobreimpuestos en la zona norte de la Cuenca del Willochra.

Willochra Creek has incised its bed about 40 m in post Middle Eocene times. Widespread accelerated erosion of unconsolidated alluvia and colluvia and of several different causations (clearance of woodland, over-stocking, making of tracks and roads, fencing, ploughing) has taken place since European settlement, and continues (Twidale and Bourne, 1996).

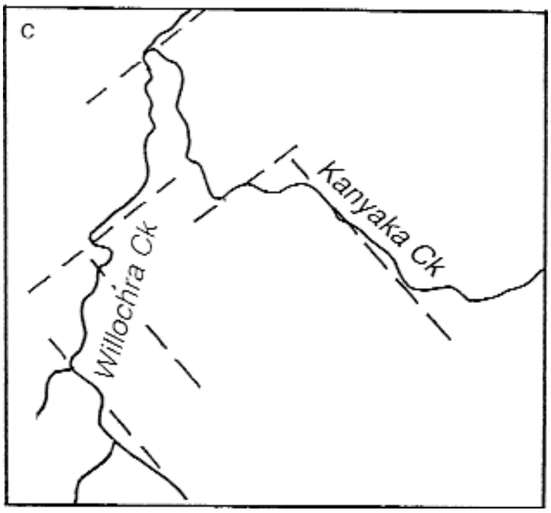
Thus, the patterns of the rivers responsible for shaping the present Flinders Ranges may have



developed patterns in folded strata over a period of at least 120–130 million years, and possibly since the Triassic. Major rivers may have incised their beds and become imprinted on the landscape following the upfaulting of the Cretaceous and the dissection of the surface of low relief developed in the Mesozoic (Twidale, 1997, 2000). Some palaeosurface remnants and associated drainage elements, however, could date back to the Permian (Samarkian) when pre-existing river valleys were occupied by glaciers. The possibility that such valleys have persisted long after any local evidence of the event had been expunged, ought not to be overlooked. To the south, on Fleurieu Peninsula, a Permian glaciated valley has been partly resurrected by the Inman River, which has incised through glacigene sediments preserved in a major preglacial valley to expose glaciated pavements preserved on Cambrian strata in the valley floor a few kilometres northwest of Victor Harbor. Thus just as in Europe pre-Pleistocene valleys swamped by glacial till have been re-opened in postglacial times, so in the Adelaide Geosyncline terrains, including the Flinders Ranges, older glaciated valleys may have been re-opened and the rivers responsible impressed on successively lower land surfaces.

4. Conventional drainage patterns

The courses of many rivers are determined by structure and slope (e.g. Zernitz, 1931). In the Flinders Ranges, major rivers flow radially from the upland (Fig. 1a), though the pattern is markedly asymmetrical in the central part of the upland where the Wilpena Creek system, which flows northeast to Lake Frome, rises less than 500 m from the headwaters of the Edeowie Creek which breaches the western ramparts of the upland to debouch on to the Torrens Plains (Fig. 2a). The asymmetry of the Wilpena Creek system can be explained in part by narrowness of the central upland, which in turn reflects the pattern of the major faults that define the upland. Furthermore, the strata exposed on the western flank of the regional anticline that dominates the central



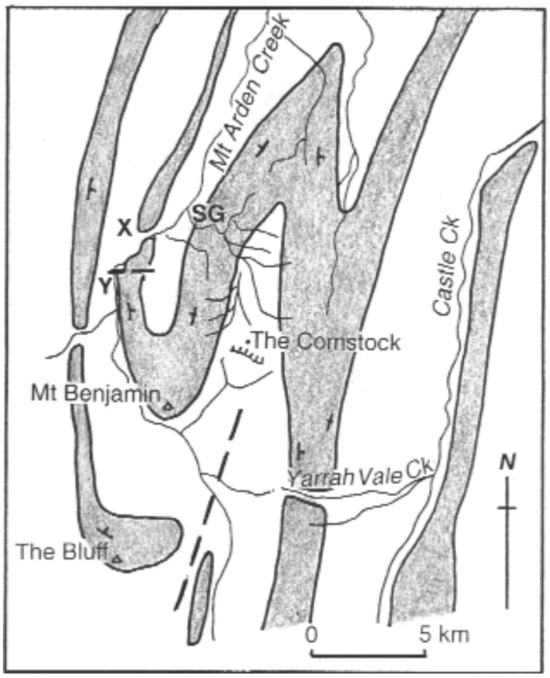
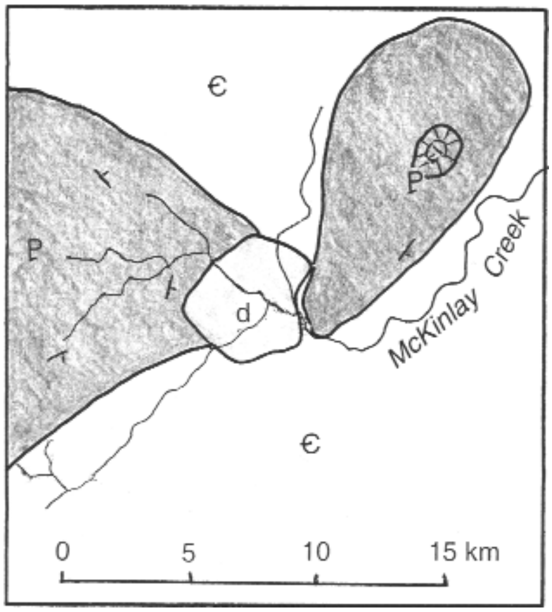


Figure 4(a). The Comstock Valley and environs, some 15 km north of Quorn, showing the Skeleroo Gorge (SG), the regression of which captured the headwaters of the Comstock Valley headwaters, the resultant 10-m-high scarp (hachured), topographic inversion in the northern Comstock Valley and the incipient breach and the head of the Yarrah Vale gorge (see Fig. 5b). A possible referred breach is indicated north of Mt Benjamin (X-Y): see also Figure 10; as is a minor fault-line river and valley near the eastern end of The Bluff ridge (after SI54-1 *Orroroo* 1:250,000 Geological Survey of South Australia). (b) Broad anticlinal snout breached by diapiric intrusion (d), exploited by McKinlay Creek, some 70 km ESE of Leigh Creek (after SH54-9 *Copley* 1:250,000 Geological Survey of South Australia).

Figura 4(a). El Valle de Comstock unos 15 km al norte de Quorn, indicando el emplazamiento de la Garganta de Skeleroo (SG). La formación de la misma dio lugar a la captura de la zona de cabecera de del Valle de Comstock, generandose un escarpe de 10 metros de altura, la inversión del relieve de esta zona y la apertura incipiente de la Garganta de Yarrah Vale (ver Fig. 5b). Un posible segmento del drenaje redireccionado está indicado al norte del Mt. Benjamín (X-Y); ver también la Figura 10 donde se observa una linea de falla condicionando el drenaje en la terminación oriental de la Cresta de Bluff (modificado de SI54-1 Orroroo 1:250,000 Geological Survey of South Australia). (b) terminación anticlinal afectada por una intrusión diapírica (d) utilizada por el Arroyo McKinlay unos 70 km al ESE del Río Leigh (modificado de SH54-9 Copley 1:250,000 Geological Survey of South Australia).

Flinders Ranges, are roughly three times as thick as their equivalents to the east. This reflects proximity to the source area to the west, in the Gawler Craton. (Conversely, to the north the thickest arenaceous sequences occur on the eastern side of the upland, adjacent to the Curnamona Craton: see Fig. 1b). The western formations are correspondingly more difficult to weather, erode and breach. Hence in this central area streams flowing radially off the uplifted orogen in the Late Cretaceous would have developed unequally, with the east-flowing components developing, regressing and capturing adjacent rivers (see below) to form a coherent system more quickly and deeply than their western competitors. The present disparity between the level of the plains bordering the Ranges cannot have influenced the development of rivers debouching from the Flinders Ranges because the basic patterns evolved long before the depositional basins and plains.

Rectangular patterns related to regional joint systems are apparent in upland areas throughout the Ranges, with NW–SE and NE–SW alignments common both at regional and local scales. These trends may be related to the occurrence of at least two major lineament or shear corridors developed in the ?Archaean basement and crossing beneath the orogen from SSW–NNW and SSE–NNW (O'Driscoll, 1986; see also Love et al., 1995). Also,



a few stream sectors run in parallel with known faults, e.g. the Mt Arden Creek tributary at the eastern base of The Bluff (Fig. 4a). Angular stream patterns prevail in the northeast where rivers dissecting the igneous and metamorphic terranes have produced an all-slopes topography. A centripetal pattern is developed in Wilpena Pound, and distributary patterns prevail on the alluvial fans and covered pediments that front the outer ramparts of the upland (Bourne and Twidale, 1998; Fig. 2a).

Some streams cutting transversely across the local structural grain appear to be anomalous, but in reality have exploited irregular lithological distributions associated with diapiric intrusions. Thus, tributaries of McKinlay Creek (which runs to Lake Frome) have breached an anticlinal quartzitic snout that has been replaced by diapiric rocks near Nantawartina Bore Spring (Fig. 4b). But viewed regionally, trellis and annular patterns are most common. They comprise long strike streams linked by short dip and antidip streams that breach intervening ridges, most of them quartzitic, and captured strike elements in adjacent valleys. The possibility of such stream piracy, involving headward erosion has been questioned and calls for explanation: even those stream patterns that are largely accordant with present structure nevertheless have been perceived as posing problems.

5. Trellis patterns and piracy

5.1. Regressive stream erosion

Some years ago, the capacity of headwater streams to erode headwards was questioned, largely because of the small volumes of water available at such headwater sites (Strahler, 1945). The inherent resistance of the arenaceous strata on which ridges are most commonly formed was also noted. But all rocks are in some measure subdivided by joints that are exploited by weathering. The ridges themselves generate runoff. Given time, even

Figure 5(a). Face of quartzite ridge – an exposed bedding plane – just to the north of Buckaringa Gorge, southern Flinders Ranges (E.M. Campbell). (b) Headwall of the Yarrah Vale Gorge (see Fig. 4a), cut through a synclinal quartzite ridge. The stream is already working in argillite and will extend into the valley of Mt Arden Creek.

Figura 5(a). Pared de una Cresta cuarcítica al norte de la Garganta de Bickaringa, Sur de las Flinders Ranges (E.M. Campbell). (b) Cabecera rocosa de la Garganta de Yarrah Vale (ver Fig. 4a) elaborada sobre una cresta synclinal cuarcítica. El cauce se encuentra todavía erosionando materials pizarrosos y puede extenderse facilmente dentro del Valle del Mt Arden.

slight sapping and incision together cause undermining and collapse of the headwall and adjacent side slopes, and thus the gradual recession of the valley. In this way are ridges breached and capture effected (see Thompson, 1939, 1949; Twidale, 2004). Various types of capture have been identified (Bishop, 1995) but all achieve a similar result. Stages in the breaching of ridges can be seen in the field, from steep-sided headwater notches the sides of which are subject to collapse, to valley heads about to break through the final barrier separating it from the adjacent valley (Fig. 5).

The Skeleroo Gorge is an example of a joint-controlled gorge that is zigzag or irregular in plan (Fig. 4a). It was cut by a stream that has regressed, mainly along fractures, through the quartzitic ridge and captured the drainage in the northern part of the anticlinal Comstock Valley, located beyond the Š breached ridge. The valley eroded by the headwaters of the Skeleroo Creek now stands lower than the original valley floor from which it is separated by a reverse scarp some 10 m high. The northern valley floor also is being lowered by a stream that has breached the western flank of the anticlinal snout (Fig. 4a). The Skeleroo Gorge is angular because the steam regressed mainly along joints Š and bedding planes which together form orthogonal systems. It can be suggested that with time, projections will be smoothed and the transverse breach will describe a more nearly linear and smooth plan form; certainly many transverse gorges are straight or almost so.

5.2. *Baselevel controls*

Local baselevel is an important factor in determining the course of piracy. Thus, the Comstock Valley is being lowered by streams related to three local baselevels, all on the Mt Arden Creek but standing at some 250, 290 and 340 metres above sea level. In the Kanyaka Valley (Fig. 6) Kanyaka Creek is in its lower reaches a strike stream that stands at about 230 m above sea level where it reaches the intermontane Willochra Plain. Formerly, it maintained its course up-valley between the Black Jack-Druid ranges (again slightly offset) and Warruwarldunha Hill (W). Indeed, its tributary in the Palmer Creek occupies that extension. The named Kanyaka Creek diverges to the north through low hilly country and across the structural grain into the Wilson Valley, underlain

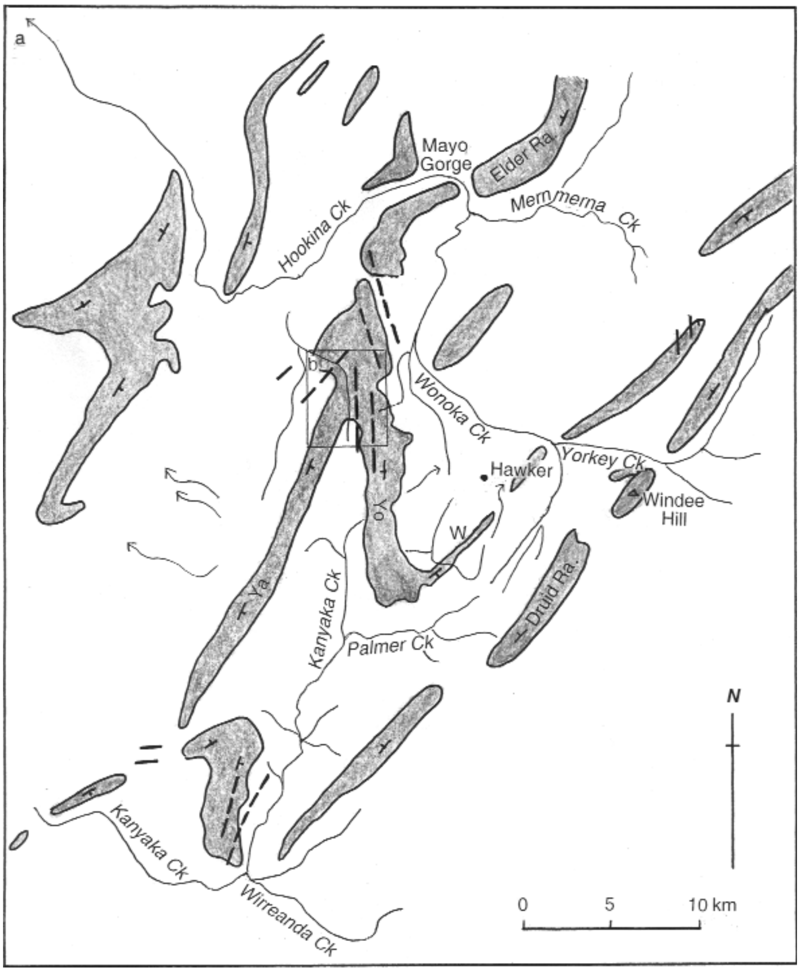


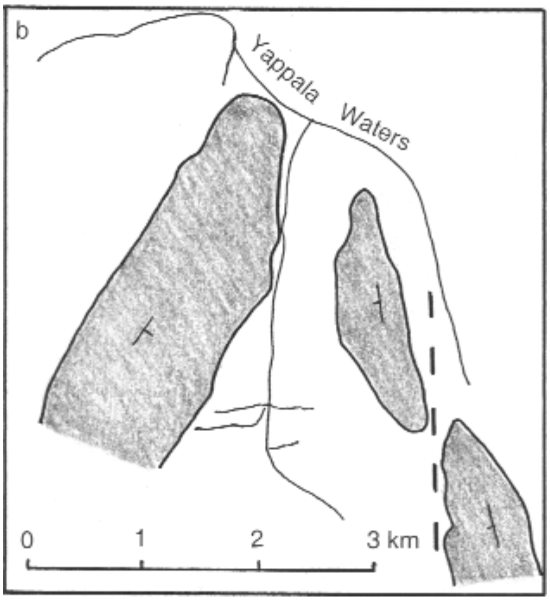
Figure 6(a). Ridges and stream patterns in the Hawker area, central Flinders Ranges. Lettering indicates Yappala (Ya) and Yourambulla (Yo) ranges, and Warruwarldunha Hill (W). Heavy dashed lines indicate faults ad inferred faults (after H54-13 *Parachilna* 1:250,000 Geological Survey of South Australia). (b) Detail of the Yappala snout.

Figura 6(a). Patrones de las crestas y el drenaje en la zona de Hawker, sector central de las Flinders Ranges. Las letras indican la posición de las montañas de Yappala (Ya) y Yourambulla (Yo) y la Colina Warruwarldunha (W). Las líneas discontinuas indican el trazado de fallas y fallas inferidas (modificado de H54-13 Parachilna 1:250,000 Geological Survey of South Australia). (b) Detalle del Morro de Yappala.

by a syncline. The Wilson branch of the Kanyaka drains a larger catchment than does the Palmer branch, so that it is this stream that has become dominant. Indeed, such is the downcutting power of the Kanyaka Creek graded to the Willochra Plain that through its tributary, the Palmer, it has captured the headwaters of the Yorkey drainage, a tributary of the Wonoka grading to the Hawker plain at a height of 340 m above sea level.

5.3. Tight folds

Where, as is commonly the case in orogens, some folds are so tight that the strike of ridges changes abruptly through 90º or more, forming angular snouts, it might be assumed that streams would exploit the strata exposed in such axial zones and consequently that such sites would be the first breached. Some are, but not all. Synclinal depressions have been exploited but few anticlinal



snouts. This is because first, a flexure implies not only tension in the outer zone of the bend but compression and possible crushing on the inner: such a flexure is partly a zone of weakness but also one of resistance. Second, local baselevels have allowed piracy that has deflected linear stream lines developed on anticlinal bends (Fig. 4a). Thus such compressed quartzite snouts as Wyacca Bluff, Mount Benjamin (570 m), and The Bluff (538 m), remain undissected. But linear stream sectors are developed in some tight folds. Thus, in and around the Comstock Valley, linear streams occupy synclinal fold axes to both east and west, but the northern anticlinal snout is only partly breached. The upper zone of a plunging anticlinal fold is in tension and here have developed streams parallel to the fold axis. But strata lower in the sequence are below the neutral plane (see e.g. Price, 1966, p. 149) and are in compression, so that the snout is preserved. Lateral streams have regressed into the flank, capturing the strike elements. Thus, given deep erosion, the linear streams in the troughs of folds adjacent to the Comstock Valley can be construed as exploiting strata in tension, whereas the deeper strata exposed in the lower parts of anticlinal snouts are in compression and resistant.

On the other hand, the essentially straight limbs of folds in quartzite and sandstone are commonly dissected and breached (Fig. 4a). There, disruption of jointing is minimal and there is no zone of compression and closed joints. Thus the western limb of the Mt Benjamin syncline is only slightly convex to the west, and it is there rather than at the apex of the fold, that the ridge has been breached by tributaries of the Mt Arden Creek.

In the rare instances where the sharply curved apices of snouts are breached, unusual circumstances apply. The northernmost quartzitic snout of the Yappala fold structure (Fig. 6), comprising the Yappala Range on the west, and the Yourambulla Range to the east, leading into the fragmented Warruwarldunha Hill ridge, is pierced by Yappala Waters, which is unusually straight. It may be fault-controlled for it runs parallel to a stream that cuts diagonally through the quartzite ridge a short distance to the southeast (Fig. 6).

Thus, not all apices of tight folds are breached but any breaches of ridges are coincident with minor flexures indicated by small offsets of strata and ridges, and caused either by warping in which imposed stresses are minimal, or by small-displacement faults.

6. Other anomalous streams

6.1. Definition

Trellis and annular patterns can be regarded as typical of fold mountain belts, but quite commonly these orderly arrangements are disturbed by transverse or anomalous stream sectors. An anomalous stream or river is one that cuts across the local or regional structural grain (hence transverse stream) or, and rarely, one that runs obliquely across or parallel with the local contours. Such streams are considered odd because they defy natural selection, in terms of which those streams that fortuitously have come to drain zones of relative weakness in the country rock become prominent and form the major elements of regional drainage patterns. The favoured streams that have incised their beds most rapidly have become the master streams of their local area or region. Once dominant, reinforcement effects (Behrmann, 1919; King, 1970; Twidale et al., 1974) ensure their perpetuation and, subject to baselevel control, enhancement.

6.2. *Mechanisms of limited application in the study area*

Anomalous drainage patterns have long attracted the attention of geologists and geomorphologists and several explanations have been offered (for reviews, see Twidale, 2004). Diversion by volcanic eruptions or lava flows, by glaciers, tectonism, and human activities have all been cited. Of these, diversions by human activities have occurred but they are minor. Though subject to past glaciations and periods of volcanism (Preiss, 1987), there is in the Flinders Ranges no evidence of drainage diversion either by ice masses or lava flows, though as mentioned, the possibility of valleys exploited and perpetuated by glaciers persisting in the contemporary landscape cannot entirely be dismissed.

Similarly there is no irrefutable evidence of diversion by upfaulted or upwarped blocks. Recent faulting is responsible for the abrupt margins of several lengthy sectors of the upland but the many faults identified within the Ranges, as well as those implied by offset strata and associated topographic features but not observed in exposure, have a passive rather than an active influence. The faults (Wilkatana, Depot Creek) that define the southwestern margin of the Ranges, north of Port Augusta have been active in Late Cenozoic times (Williams, 1973; Quigley et al., 2006) and uplift in the Eocene could account for the Willochra Lake (see above). The streams draining this sector of the mountain front are thus implicitly antecedent, but it is, as is usual with antecedence, difficult to prove (see e.g. Wager, 1937; Lees, 1955; Seefeldner, 1951; Coleman, 1958; Brookfield, 1998).

Superimposition, the lowering of a drainage pattern from a cover formation on to an underlying rock mass on which it rests in angular unconformity, undoubtedly has taken place in some areas (Jukes, 1862; Maw, 1866). There is no evidence that an appropriate overmass or cover ever extended over the Flinders Ranges, apart from the extreme north where Early Cretaceous littoral deposits are preserved in Mt Babbage (Fig. 2b). Otherwise, the field evidence suggests that the Cretaceous seas did not extend far to the south either in the Torrens or Frome embayments and certainly not within the upland (Frakes, 1987), which at that time already stood high enough to be beyond the reach of marine influences. Triassic sedimentation and associated erosion was limited to the vicinity of isolated lake basins and Cenozoic sedimentation in the Ranges was confined to a few depocentres such as the Willochra Basin. Thus, the conditions necessary for superimposition have obtained only locally.

Inheritance is the imposition of a drainage pattern developed on a weathered land surface on to the unweathered bedrock beneath (Cotton, 1948, p. 56), weathering having reduced or eliminated any bedrock structures susceptible of exploitation by rivers and streams. The mechanism is of limited application in the Flinders Ranges for though at one time weathered (e.g. Sheard, 2001), the distribution of regolith –and trellis drainage patterns– was determined by lithology and topography. Some strike elements may have persisted as they were incised, shifting laterally as the geometry of the folds, including the all-important outcrops of weak beds, changed with depth (see q.v., section 7.1). Thus some inherited strike elements may form part of the present pattern, but the necessary proof, as opposed to probability, of their antiquity is not to hand.

In passing it may be noted that some workers, such as Ward (1925, p. 84: referring to the uplands of central Australia) and Campana (1958, p. 42: considering the Flinders Ranges), suggested that incised meanders are inherited from meandering streams developed on a former summit planation surface, but such meanders are autogenic forms developed by lateral corrasion during incision (Mahard, 1942; Twidale, 1955) and do not constitute proof of inheritance.

7. Stream impression

7.1. *Partacoona twin gorges*

Some rivers that breach ridges are major elements of the regional drainage system, but cannot be explained by stream piracy. The twin gorges of the Partacoona ridge (Figs. 7a, 7b) provide a good example. The quartzitic ridge they breach is developed in quartzite that dips at a moderate angle (35-40º) to the southeast. If the former Willochra and

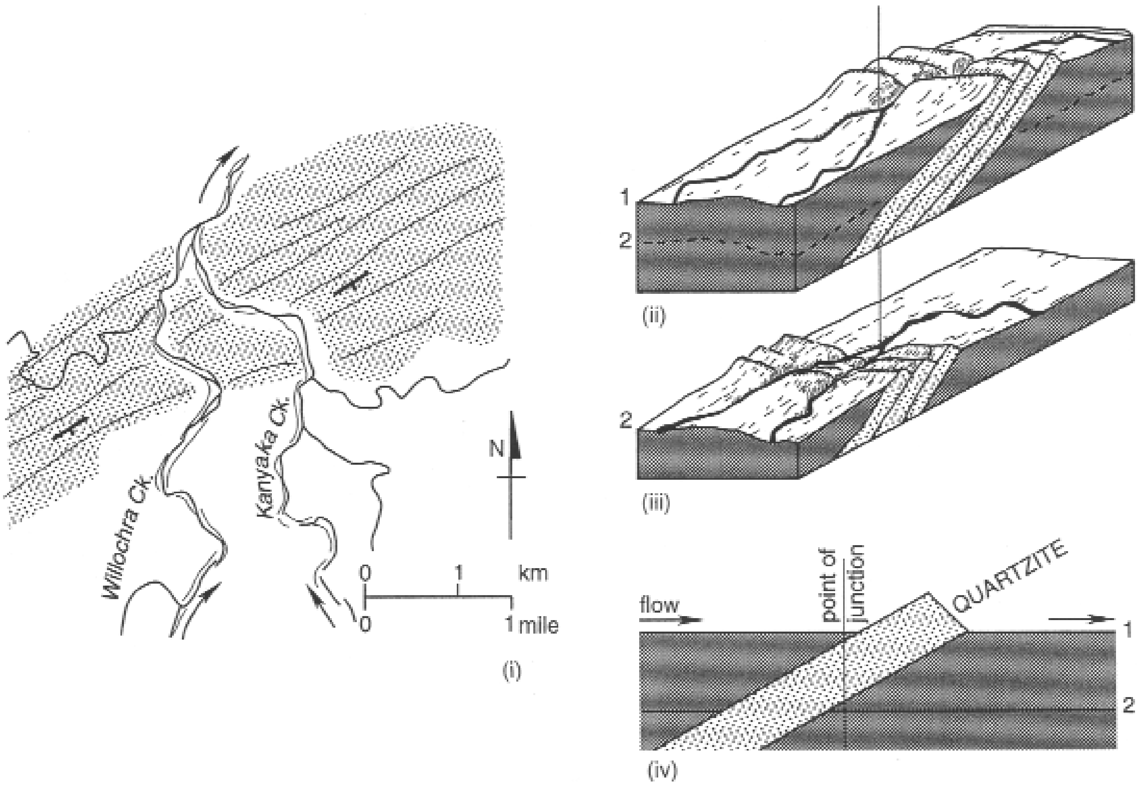
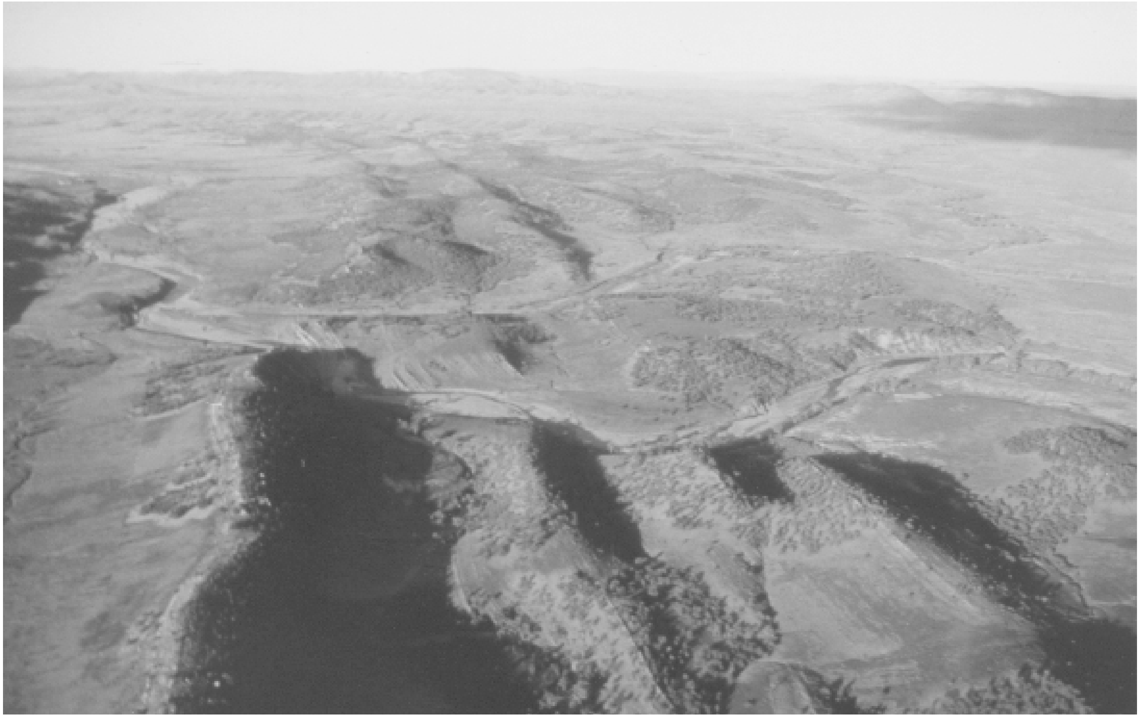


Figure 7(a). Double breach of quartzitic Partacoona ridge (i) in plan, (ii-iv) suggested sequence of development; and (b) seen from the southwest. Note in-and-out loop X–Y (D. Beng). (c) Suggested simplified impression sequence through time. I – impressed stream; FI – failed impression.

Figura 7(a). doble rotura de la Cresta cuarcítica de Partacoona (i) en planta con la secuencia propuesta para su desarrollo (ii-iv); y 8b) vista de la misma desde el SW. Nótese la entrada y salida de meandro X-Y (D. Beng). (c) secuencia de sobreimposición del drenaje propuesta. I – cauce sobreimpuesto; FI- Sobreimposición fallida.

Kanyaka creeks had headed back into the ridge from the upstream or northwestern side, it has to be argued that they simultaneously accomplished the breach and emerged upstream of the ridge, presenting a lower baselevel to their headwater streams in the northern Willochra, at the same time. This is inherently unlikely for local structure and discharge vary. The Willochra Creek, for example, probably served a much larger catchment that the competing Kanyaka Creek. But if one had preceded the other it would have attracted the drainage of the whole of the northern Willochra Plain and there would have been only one gorge. The same argument applies if the breach had occurred during the Eocene when the Willochra Lake occupied the northern part of the present Basin and Plain. Unless both regressing streams emerged at exactly the same time, the first to create a valley through the ridge would have taken the lake waters. For these reasons, the impression[1] of deeply-eroding rivers on to a dipping quartzite formation provides a more plausible solution (Twidale, 1966).

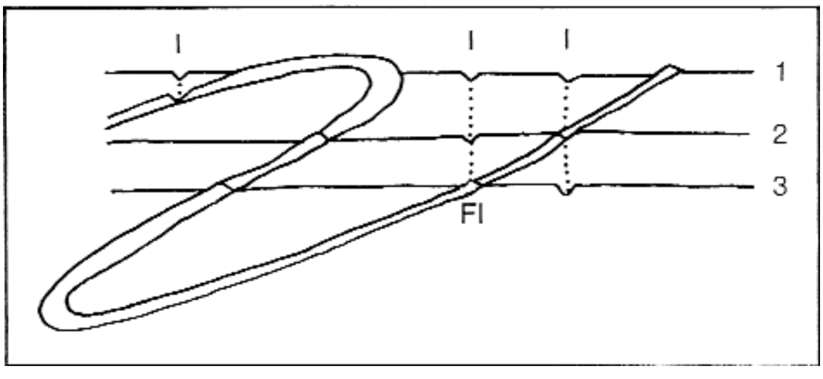
1 What is here called ‘impression’ was termed ‘autosuperposition’ by Oberlander (1965; see also Twidale, 1966, 1972). One can but agree with his interpretation of the anomalous Zagros streams of southern Iran, but the name proposed for the mechanism is unsatisfactory. The United States ‘superposition’ is the English ‘superimposition’ and both imply that the component streams, which comprise a drainage pattern developed consistently with structure on a higher overmass formation, have incised through the base of the overmass into the undermass on which the former rests unconformably. Major streams are not adjusted to the structure of the undermass formation, persist, and thus become anomalous or superposed. ‘Auto’ means ‘self’ so that the very name autosuperposition is an oxymoron for it precludes the structural essence of superposed stream setting.



The significance of the changing geometry of fold structures with depth and its significance for drainage development was appreciated by Meyerhoff and Olmstead (1936), working in the Appalachians. Strahler (1945) realised the possibilities of the concept, as did Oberlander (1965) who applied it in his classical study of the drainage of the Zagros Mountains of southwestern Iran. In theory, impression may have been of common occurrence at various stages in the long evolution of the Flinders Ranges landscape (Fig. 7c), for at least 6 km of strata have been stripped from the crest of the orogen. Thus, impression offers a possible explanation for some drainage patterns that are otherwise puzzling. In some instances the evidence is compelling but how many of the numerous transverse streams noted in the Flinders Ranges are of this origin is difficult to estimate.

7.2. *Anomalous streams in the Mern Merna Dome*

A striking example of impression is provided by the minor and nameless creek (X *in* Fig. 8a) that



begins its course as a strike stream but cuts across the core and both quartzitic limbs of the Mern Merna Dome, located some 30 km northwest of Hawker; and yet which, after cutting across the structure is, like many others, lost in the alluvia of the Torrens Plain (Fig. 8a). A further example of impression is demonstrated at the southern end of the elongate Dome (Y *in* Fig. 8a). A strike stream flowing south in the valley it has eroded in argillite, veers west into a gorge it has excavated in the massive quartzite of the snout of the Dome (Fig. 8b) thus creating a breached snout; this instead of continuing south along the existing valley and open plain. But the transverse route through the gorge

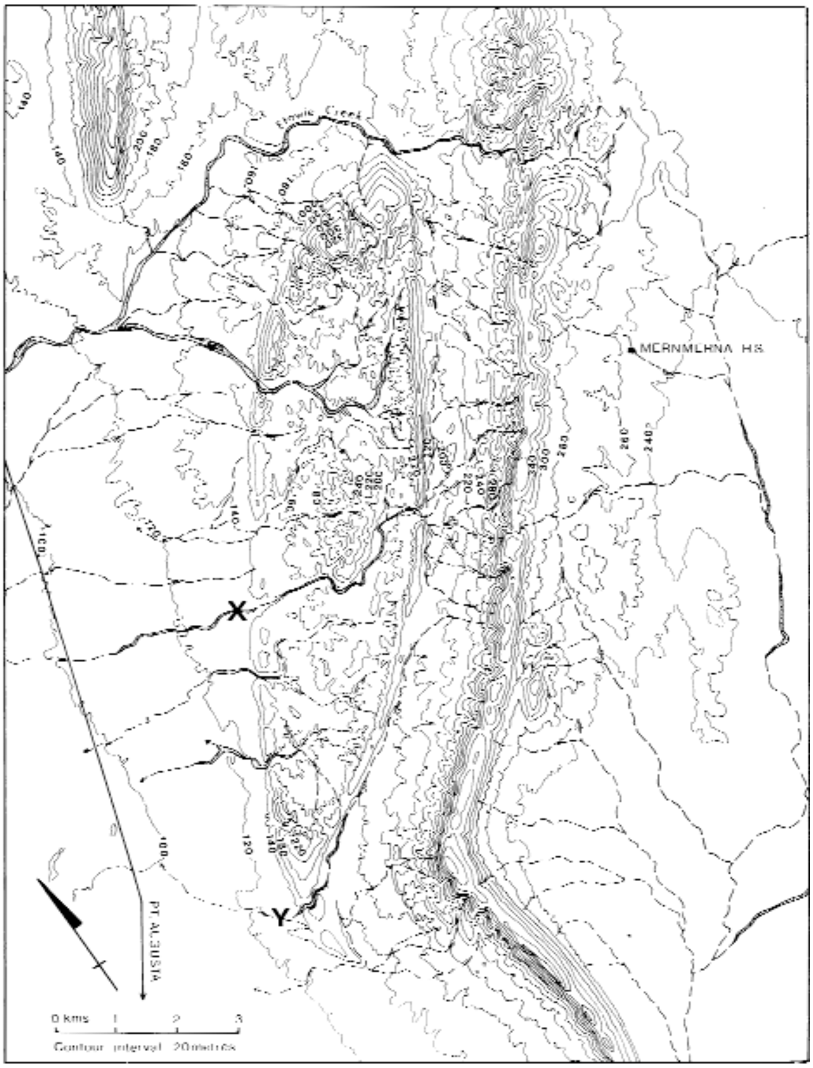


Figure 8(a). Contour map of Mern Merna Dome showing transverse stream (X), which having breached two quartzite ridges, dies out on the plain, and breached snout (Y), as well as streams in various stages of becoming transverse.
(b) View of the Mern Merna Dome from the south, breached snout in foreground (J.A. Bourne). (c) Suggested mechanism for breaching of snout by stream impression from initial position (A–B *in* section) and after erosion (C–D).

Figura 8(a). Topografía del Dome de Mern Merna mostrando el drenaje transversal (X) que habiendo atravesado dos crestas cuarcíticas muere en la llanura, una terminación periclinal abierta (Y), así como lineas de drenaje en proceso de convertirse en verdaderos drenajes transversales. (b) Vista del Domo de Mern Merna desde el sur, se observa una terminación periclinal abierta al fondo de la imagen (J.A. Bourne). (c) Mecanismo de apertura de la terminación periclinal por sobreimposición del drenaje desde su posición inicia (A-B en sección) y después de su erosión (C-D).

was simply the former path when the land surface was higher (Fig. 8c). The stream has maintained its previous course despite cutting through argillite and into quartzite.

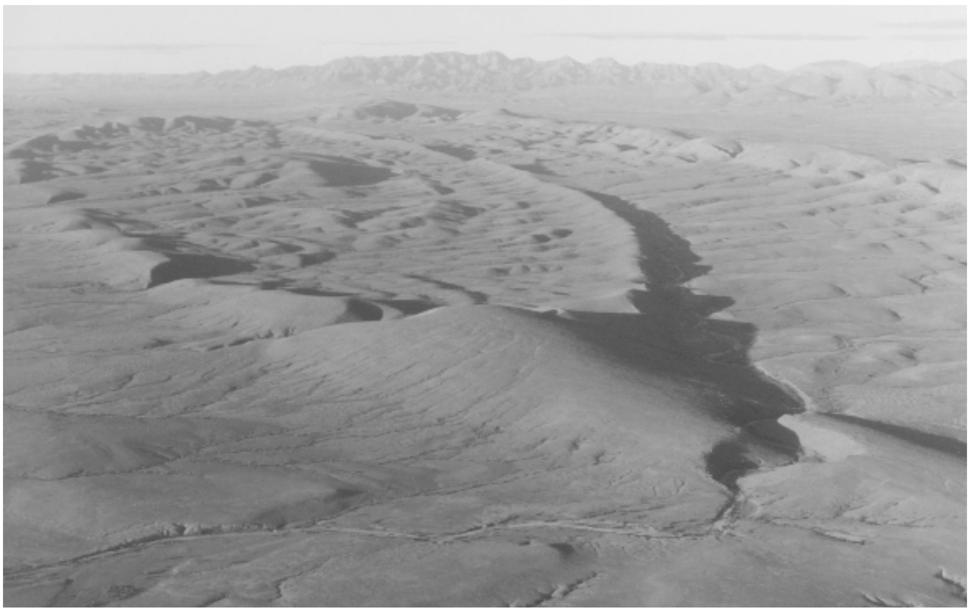
7.3. In–and–out streams

Impression can also account for in-and-out streams, a term used in a general sense, not with reference to streams marginal to glaciers (Kendall, 1902; Stone, 1963; Nichols, 1969) but to streams that breach and flow though a ridge from one valley to another only again to breach the ridge to return to the original valley. Some repeat the process several times. Examples have been noted on Buckaringa Creek, close to its junction with the Willochra at its Partacoona crossing (X-Y *in* Fig. 7b), and also near the Arkaroola Resort in the northern Flinders Ranges (Fig. 9).

7.4. Processes at work

Impression implies the persistence of rivers even when during incision they encounter resistant formations. What processes are involved? Rivers in flood generate enormous energy, as has been demonstrated in connection with the breaking of both natural and man-made dams (Tricart, 1960; Kiersch, 1964; Baker, 1973; Batalla and Balasch, 2001) as well as by general hydrological theory (e.g. Leopold et al., 1964). To take a local example, a heavy late summer rainstorm[2] caused heavy runoff on a surface virtually unprotected by vegetation (for extreme example: see Egan, 2006). The Hookina Creek ran in flood. Huge gum trees were uprooted and carried downstream, where they became battering rams. In this way some of the masonry pillars supporting the Hookina railway bridge were swept away and the bridge collapsed.

Field observations suggest that, overwhelmingly, erosion of transverse gorges has been accomplished by abrasion, attrition, and possibly cavitation generated by rivers in flood. Stream velocities increased as they entered the narrows, once the latter had been initiated. Evidently such flows were capable of lifting and carrying the huge blocks of quartzite, commonly a metre diameter, in some instances up to two, and using them as battering rams to gouge the bed and banks. Thus, more blocks were released and attrition ensured an abundant supply of sand, another tool of abrasion.



2 At Hawker, average 299 mm per annum, 124 mm of rain fell between 8 amd 13 February - near the end of a dry summer - and nearby at Arkaba Homestead 280 mm were received in the same period.

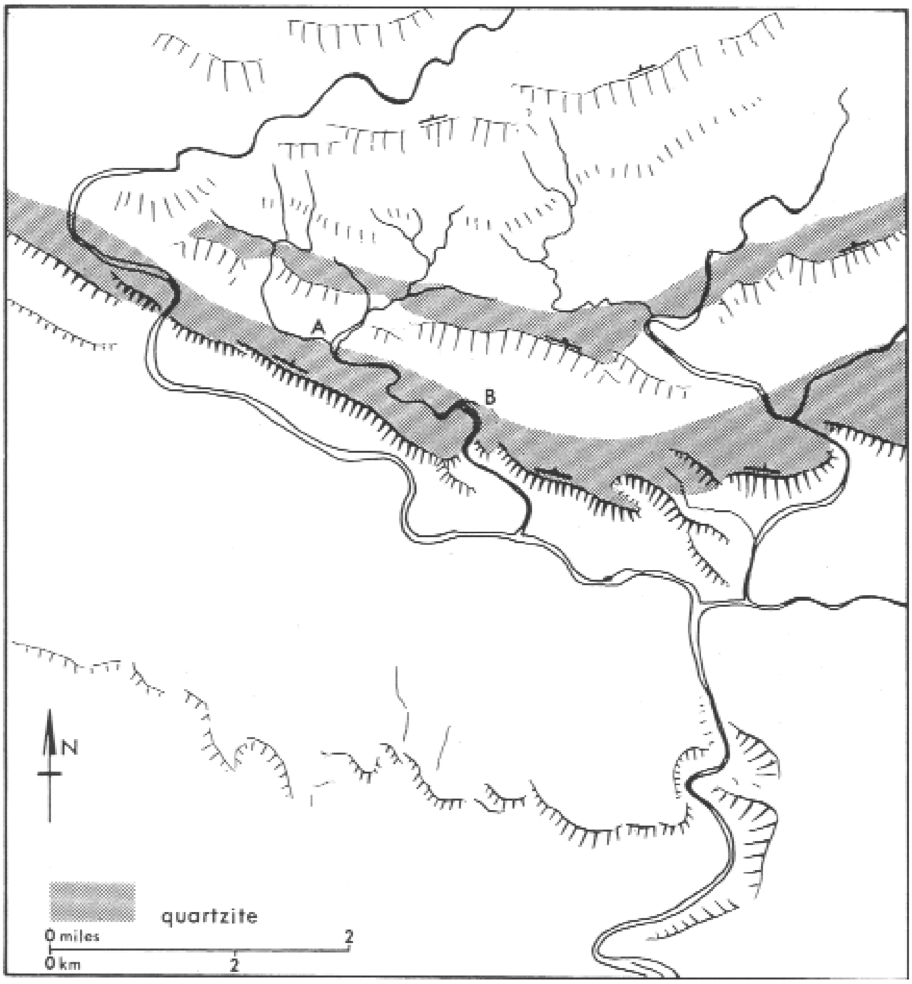


Figure 9. Plan of an in-and-out stream (A–B), cutting into a quartzite ridge, near Arkaroola, northern Flinders Ranges.
Figura 9. Vista en planta de la entrada y salida de un cauce (A-B) encajado en un cresta cuarcítica en las proximidades de Arkaroola, norte de las Flinders Ranges.

7.5. Forms relic from failed impression

Many prominent ranges display cols or breaks in the crest as well as water gaps or breaches cut by through-flowing streams. These incipient or incomplete breaches are dry and can be attributed to weathering of relatively weak (possibly well-jointed, as well as locally joggled and disrupted) rocks. Some carry minor opposed streams that do not quite intersect. They can be construed either as a gap in the making, or as two abandoned regressing stream valleys.

Despite the undoubted erosional power, and the high capacity and competence, of streams in flood, erosion in resistant quartzitic formations would surely have been slower than the incision accomplished by competing streams located in weaker formations (argillites, for example) in the lowered land surface. Thus, in a given catchment the erstwhile master stream may have been displaced as the deepest stream and the advantages of positive feedback transferred to the new master stream. The water table was lowered in response to its incision. Seepage as well as overland flows were lost to the

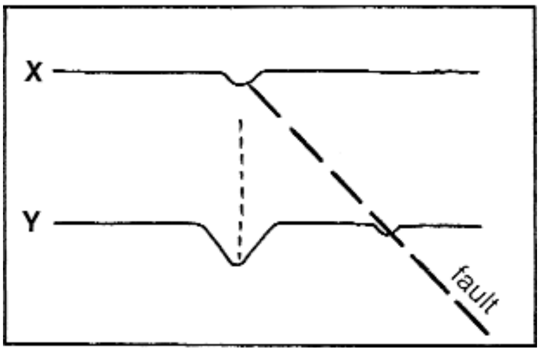


Figure 10. Referral mechanism as applied to the western limb (X-Y) of Mt Benjamin synclinal structure.
Figura 10. Mecanismo de redireccionamiento del drenaje aplicado al flanco occidental (X-Y) de la estructura sinclinal del Mt Benjamín.

stream incising in quartzite. As stream discharge decreased so did erosional power. The notch or shallow gorge was abandoned to become a col or wind gap. In such instances the opposed streams commonly interpreted as the forerunners of intersection, capture and stream diversion may merely drain abandoned incipient gorges: they may be the result of incision rather than its causation.

Similar cols or wind gaps in the Appalachians were regarded as a possible indication of superposition or superimposition (Strahler, 1945) but as has been stated no cover formation, essential to the concept, has been identified in the Flinders Ranges. Alternatively, the cols and wind gaps may represent failed impressed streams of which there must have been many. The landscape embraces not only streams which maintained their courses and created gorges but also the vestiges of some which though impressed, nevertheless were defeated by structural barriers and by competing adjacent streams flowing in weaker lithological terrains.

7.6. Referral

Deep erosion also may have produced other apparent drainage anomalies. Given that deeply incising streams encounter either different structures at depth (as in the Mern Merna snout), or structures that have changed position relative to the stream because the stratum or fault is dipping (as with the Partacoona twin gorges), then a river that has exploited a fault and created a gorge through a quartzite ridge may persist, though it and the reason for the gorge are now separated by a score of metres or more, as for instance X and Y in Figure 4a (see also Fig. 10). Several examples of such referral have been noted in the Flinders Ranges (Bourne and Twidale, in review).

8. Underprinting

So far, anomalies in consolidated rock terrains have been considered. It has been suggested that some transverse elements have been imposed from overlying strata (superimposition, inheritance, impression, referral), but some authors have invoked the transmission of structural effects from below, what is termed underprinting or the upward generation of structures and tectonic effects from the basement on to overlying strata (e.g. Wopfner, 1960; Hills, 1961; Saul, 1978). Thus, Hills (1961) suggested that the remarkably straight 700-km-long course of the River Darling flowing over a Quaternary alluvial plain is related to joggling in the deep basement but the mechanism is germane to hard rock as well as alluvial settings.

Underprinting also may explain otherwise unresolved problems in the Flinders Ranges. Thus in the northern Willochra Plain, rivers such as the Willochra, Kanyaka, and Wirreanda display broadly angular patterns despite flowing in what may be regarded as structureless alluvia, are interpreted as being underprinted from angular fractures (shears) in the deep basement (Fig. 3c). Several other anomalies can theoretically be attributed to possible underprinting but are difficult to demonstrate. For instance, the passage of Wilpena Creek through the northeast-facing rim of the Pound amphitheatre arguably is either underprinted or referred (Fig. 2a).

9. Asymmetry

The Willochra Plain (Fig. 3c) occupies an intermontane basin developed on a breached and faulted regional anticline with a meridional axial plane (O'Driscoll, 1956; Shepherd and Thatcher, 1959;

Milton and Twidale, 1978). Its flat surface is underlain by up to a few hundred metres of lacustrine and alluvial sediment. The Willochra Creek rises near Booleroo Centre and runs north before flowing in a northwesterly direction eventually to reach the Torrens Plain and the southern extremity of the salina of that name. But the original course of the main stream reflects the geometry of the regional anticline, the axis of which is meridional. The regional drainage pattern, however, is asymmetrical, with the main river close to the western margin of the plain and served by short left bank tributaries flowing from the higher rainfall areas to the west which however, also generate major rivers flowing west to the Torrens Plans. The eastern or right bank tributaries are more numerous and longer. They drain outcrops dominated by argillites and though draining lower rainfall areas and many of them failing to reach the trunk stream on the surface, their deposits have apparently diverted the main Willochra channels to the western side of the plain (*cf.* Lefevre, 1931; Grear et al., 2006).

10. Discussion and conclusions

This analysis of drainage evolution in an orogen that, though of ancient origin, is still active provides a useful comparison with developments in the much younger 'alpine' fold belts (see e.g. Brookfield, 1998, and other papers cited in this essay). In particular, though piracy is rampant in both types of landscape the possibilities of antecedence and tectonic diversion are, in the repeatedly and deeply eroded older landscape, superseded by probable impression and by likely but unproven underprinting.

It is suggested that the major features of the Flinders Ranges drainage system have evolved from an earlier pattern developed on a Cretaceous planation surface studded with many low quartzitic ridges and ranges. Deep erosion is the crucial factor on which the resolution of several of the problems discussed in this essay is based. It is germane to the consideration of similar problems evidenced in other old orogenic belts, such as the Macdonnell Ranges and other central Australian fold mountains, the Cape Fold Belt of southern Africa, and of course the Appalachians. They may be susceptible of analysis in similar terms as may anomalous drainages developed in the gently disturbed forelands of younger fold mountains, such as the Jura Mountains of northwestern France and adjacent areas of Switzerland (e.g. Umbgrove, 1950, p. 57).

As Marr (1906) pointed out concerning the superimposed radial drainage pattern of the Lake District of northwestern England, the main pattern was maintained, but minor streams adjusted to local structure during incision, and the same comment applies in the Flinders Ranges. Though there is here no evidence of superimposition, it might be thought that some of the straight gorges that breach quartzite ridges can be attributed to impression. If this were so, however, even major rivers initially would have adjusted to the structures of the strata encountered during incision. Given the known denudation chronology of the Flinders Ranges several phases of impression may have occurred (Fig. 7c) so that, as with stream piracy, gorge morphology provides an indication of relative age.

Climatic conditions may have influenced the rate at which stream patterns have developed but not the basic mechanisms. The reasons for most of the patterns exhibited by streams in the Flinders Ranges are based in structural control but there are many exceptions. Anomalous or transverse stream sectors of several different kinds and at various scales have been identified and explanations offered. But intriguing questions remain as to future events. For instance, considering only the possibilities of piracy, will Skeleroo Creek (Fig. 4a) eventually take the Arden Creek headwaters or the Yarrah Vale Creek take them out via Castle Creek? Or will the northern breach prove more potent? Will Edeowie Creek (Fig. 2a) take the Wilpena Pound drainage? There are many uncertainties but many –at times seemingly too many– possibilities. In such circumstances causal links can only be speculative.

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References

Alley, N.F. & Lemon, N.M. (1988). Evidence of earliest (Neocomian) marine influence, northern Flinders Ranges. Geological Survey of South Australia Quarterly Geological Notes, 106, 2-7.

Baker, V.R. (1973). Paleohydrology and sedimentology of Lake Missoula flooding in eastern Washington. Geological Society of America Special Paper, 144, 79 pp.

Batalla, R.J. & Balasch, J.C. (2001). Interpretacion hidrodinamica y sedimentaria de la rotura de la balsa de San Juan (Altorricon, Huesca). Revista Cuaternario y Geomorfologia, 15, 109-123.

Behrmann, W. (1919). Der Vergang der Selbstverstärkung. Zeitschrift der Gesellschaft für Erdkunde zu Berlin, 153-157.

Bishop, P. (1995). Drainage rearrangement by river capture, beheading and diversion. Progress in Physical Geography, 19, 449-473.

B.M.R. Palaeogeographic Group (1992). Australia: Evolution of a Continent. Australian Government Publishing Service, Commonwealth of Australia, Canberra. 96 pp.

Bourman, R.P. & Lindsay, J.M. (1989). Timing, extent and character of faulting on the eastern margin of the Mt Lofty Ranges, South Australia. Transactions of the Royal Society of South Australia, 113, 63-67.

Bourne, J.A. & Twidale, C.R. (1998). Pediments and alluvial fans: genesis and relationships in the western piedmont of the Flinders Ranges, South Australia. Australian Journal of Earth Sciences, 45, 123-135.

Bourne, J.A. & Twidale, C.R. (in review). Some neglected and crypto-structural effects in drainage development. Geographical Research.

Brookfield, M.E. (1998). The evolution of the great river systems of southern Asia during the Cenozoic India-Asia collision; rivers draining southwards. Geomorphology, 22, 285-312.

Bullard, E.C. (1936). Gravity measurements in East Africa. Philosophical Transactions of the Royal Society of London, 235, 445-531.

Campana, B. (1958). The Flinders Ranges. In: The Geology of South Australia. (M.F. Glaessner & L.W. Parkin, Eds.). Melbourne University Press/Geological Society of Australia, Melbourne, pp. 28-45.

Campana, B., Coats, R.P., Horwitz, R.C., Thatcher, D. & Webb, B.P. (1961). *Moolawatana*. Zone 6, Sheet 612, Geological Atlas 1 Mile Series. Geological Survey of South Australia, Adelaide.

Coleman, A. (1958). The terraces and antecedence of a part of the River Salzach. Transactions and Papers of the Institute of British Geography, 25, 119-134.

Cotton, C.A. (1948). Landscape. Whitcombe and Tombs, Christchurch. 301 pp.

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.

Egan, T. (2007). The Worst Hard Time. The Untold Story of Those who Survived the Great American Dust Bowl. Houghton Mifflin, Boston. 340 pp.

Fenner, C. (1931). South Australia. A Geographical Study. Whitcombe & Tombs, Melbourne. 352 pp.

Frakes, L. A. (coordinator: Australian Cretaceous Palaeoenvironments Group) (1987). Australian Cretaceous shorelines, stage by stage. Palaeogeography, Palaeoclimatology, Palaeoecology, 59, 31-48.

Grear, B., Bourne, J.A. & Twidale, C.R. (2006). A note on valley asymmetry in cross-section in the Adelaide area. South Australian Geographical Journal, 105, 106-110.

Harris, W.K. (1970). Palynology of Lower Tertiary sediments, southeastern Australia. Unpublished M.Sc. thesis, University of Adelaide, Adelaide, 181 pp.

Hills, E.S. (1961). Morphotectonics and the geomorphological sciences, with special reference to Australia. Quarterly Journal of the Geological Society of London, 117, 77-89.

Hou, B., Frakes, L.A., Alley, N.F. & Clarke, J.D.A. (2003). Characteristics and evolution of the Tertiary palaeovalleys in the northwest Gawler Craton, South Australia. Australian Journal of Earth Sciences, 50, 215–230.

Johnson, W. (1960). Exploration for Coal, Springfield Basin, in the Hundred of Cudla-Mudla, Gordon-Cradock district. Geological Survey of South Australia Report of Investigations, 16, 62 pp.

Jukes, J.B. (1862). On the mode of formation of some of the early river valleys in the south of Ireland. Quarterly Journal of the Geological Society of London, 18, 378-403.

Kendall, P.F. (1902). A system of glacier lakes in the Cleveland Hills. Quarterly Journal of the Geological Society of London, 58, 471-571.

Kiersch, G.W. (1964). Vaiont Reservoir disaster. Civil Engineering, 34, 32-39.

King, C.A.M. (1970). Feedback relationships in geomorphology. Geografiska Annaler, 52A, 147-159.

Kwitco, G. (1995). Triassic intermontane basins. In: The Geology of South Australia. Volume 2, The Phanerozoic (Drexel, J.F. & Preiss, W.V., Eds.). Geological Survey of South Australia Bulletin, 54, 98-101.

Lees, G.M. (1955). Recent earth movements in the Middle East. Geologische Rundschau, 42, 221-226.

Lefevre, M.A. (1931). Vallées dissymetriques. Bulletin Societé Belge d'Etude Géographique, 1, 68-71.

Leopold, L.B., Wolman, M.G. & Miller, J.P. (1964). Fluvial Processes in Geomorphology. Freeman, San Francisco. 522 pp.

Love, D.N., Preiss, W.V. & Belperio, A.P. (1995). Seismicity, neotectonics and earthquake risk. In: The Geology of South Australia. Volume 2, The Phanerozoic (Drexel, J.F. & Preiss, W.V., Eds). Geological Survey of South Australia Bulletin, 54, 268-273

Mahard, R.H. (1942). The origin and significance of intrenched meanders. Journal of Geomorphology, 5, 32-44.

Marr, J.E. (1906). The influence of the geological structure of English Lakeland upon its present features – a study in physiography. Quarterly.Journal of the Geological Society of London, 62, lxvi-cxxviii.

McNally, G.H. & Wilson, I.R., (1995) Silcrete of the Mirackina palaeochannel, Arckaringa, South Australia. Australian Geological Survey Organisation Journal, 16, 295-301.

Meyerhoff, H.A. & Olmstead, E.W. (1936). The origins of Appalachian drainage. American Journal of Science, 36, 21-42.

Milton, B.E. & Twidale, C.R. (1978). Structure of the Willochra Basin, southern Flinders Ranges, South Australia. Transactions of the Royal Society of South Australia, 102, 71-77.

Maw, G. (1866). Notes on the comparative structure of surfaces produced by subaerial and marine denudation. Geological Magazine, 3, 439-451.

Nichols, R.L. (1969). Geomorphology of Inglefield land, north Greenland. Meddelelser om Groenland, 188, 100 pp.

Oberlander, T.M. (1965). The Zagros Streams. Syracuse Geographical Series, 1, 168 pp.

O'Driscoll, E.P.D. (1956). Hydrology of the Willochra Basin. Geological. Geological Survey of South Australia Report of Investigations, 7, 58 pp.

O'Driscoll, E.S.T. (1986). Observations of the lineament-ore relation. Philosophical Transactions of the Royal Society of London, A317, 195-218.

Parkin, L.W. (1953). The Leigh Creek Coalfield. Geological Survey of South Australia Bulletin, 31, 74 pp.

Preiss, W.V. (Compiler) (1987). The Adelaide Geosyncline. Geological Survey of South Australia Bulletin, 53, 438 pp.

Price, N.J. (1966). Fault and Joint Development in Brittle and Semi-brittle Rock. Pergamon, Oxford. 176 pp.

Quigley, M.C., Cupper, M.L. & Sandiford, M. (2006). Quaternary faults of south-central Australia: palaeoseismicity, slip rates and origin. Australian Journal of Earth Sciences, 53, 285-301.

Sandiford, M. (2003). Neotectonics of southeastern Australia: linking the Quaternary faulting record with seismicity and in situ stress. In: Evolution and Dynamics of the Australian Plate (Hillis, R.R. & Muller, R.D., Eds.). Geological Society of Australia Special Publication 23, pp. 107-119.

Saul, J.M. (1978). Circular structures of large scale and great age at the Earth's surface. Nature, 271, 345-349.

Seefeldner, E. (1951). Die Enstehung der Salzachofen. Mitteilungen der Gesellschaft für Salzburge Landeskunde, 91, 153-169.

Sheard, M.J. (2001). Callabonna 1:250,000 geological map released. MESA Journal, 21, 27-29.

Shepherd, R.G. & Thatcher, D. (1959). The geology of the Quorn Military Sheet. Geological Survey of South Australia Report of Investigations, 13, 20 pp.

Stone, K.H. (1963). Alaska ice-dammed lakes. Annals of the Association of American Geographers, 53, 332-349.

Strahler, A.N. (1945). Hypotheses of stream development in the folded Appalachians of Pennsylvania. Geological Society of America Bulletin, 56, 45-88.

Thompson, H.D. (1939). Drainage evolution in the southern Appalachians. Geological Society of America Bulletin, 50, 1323-1355.

Thompson, H.D. (1949). Drainage evolution in the Appalachians of Pennsylvania. New York Academy of Science Annals, 52, 33-62.

Tricart, J. (1960). Les aspects morphodynamiques de le catastrophe de Fréjus (Décembre 1959) et leurs conséquences pour la remise en état de la vallée. Revue de Géomorphologie Dynamique, 11, 64-71.

Twidale, C.R. (1955). Interpretation of high-level meander cutoffs. Australian Journal of Science, 17, 157-163.

Twidale, C.R. (1966). Chronology of denudation in the southern Flinders Ranges, South Australia. Transactions of the Royal Society of South Australia, 90, 3-28.

Twidale, C.R. (1972). The neglected third dimension. Zeitschrift für Geomorphologie, 16, 283-300.

Twidale, C.R. (1994). Gondwanan (Late Jurassic and Cretaceous) palaeosurfaces 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. (2000). Early Mesozoic (?Triassic) landscapes in the Australia: evidence, argument, and implications. Journal of Geology, 108, 537-552.

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

Twidale, C.R. (2007). Ancient Australian Landscapes. Rosenberg, Sydney. 144 pp.

Twidale, C.R & Bourne, J.A. (1996). Development of the land surface. In: Natural History of the Flinders Ranges (Davies, M., Twidale, C.R. & Tyler, M.J., Eds.). Royal Society of South Australia, Adelaide, pp. 46-62.

Twidale, C.R., Bourne, J.A. & Smith, D.M. (1974). Reinforcement and stabilisation mechanisms in landform development. Revue de Géomorphologie Dynamique, 23, 115-125.

Umbgrove, J.H.F. (1950). Symphony of the Earth. Nijhoff, Den Hague. 220 pp.

Wager, L.R. (1937). The Arun River drainage pattern and the rise of the Himalaya. Geographical Journal, 89, 239-250.

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

Williams, G.E. (1973). Late Quaternary piedmont sedimentation, soil formation and palaeoclimates in arid South Australia. Zeitschrift für Geomorphologie, 17, 102-125.

Woodard, G.D. (1955). The stratigraphic succession in the vicinity of Mt Babbage Station, South Australia. Transactions of the Royal Society of South Australia, 78, 8-17.

Wopfner, H. (1960). On some structural development in the central part of the Great Australian Artesian Basin. Transactions of the Royal Society of South Australia, 83, 179-194.

Wopfner, H., Callen, R. & Harris, W.K. (1974). The Lower Tertiary Eyre Formation of the southwestern Great Artesian Basin. Journal of the Geological Society of Australia, 21, 17–51.

Zernitz, E.R. (1931). Drainage patterns and their significance. Journal of Geology, 40, 498-521.