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Neglected and cryptostructural effects in drainage development

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Abstract

Though structure has long been recognised as a fundamental factor in landscape analysis and interpretation, some aspects are not accorded sufficient weight. Stress and the resulting strain influence rates of weathering and hence erosion. Linear features may be referred or deferred and develop long after the tectonic event to which they are ultimately related. The pattern of many linear and arcuate river channels can be attributed to underprinting or the transmission of structures to overlying strata. Deep erosion allied with reinforcement mechanisms also can account for transverse rivers and other anomalies.

Key words: structural control, anomalous drainage, strain, cryptostructural, referred drainage, deferred drainage, underprinting.

INTRODUCTION

Fractures influence landform development in many ways, most of them obvious, as for example fracture-controlled patterns of weathering and fault-line valleys. However, though the geometry of some topographic features – linearity, parallelism – is strongly suggestive of structural control, the link between crustal characteristics and surface expression is in some instances obscure or indirect. These more subtle effects are discussed, particularly but not exclusively, with reference to Australian landscapes.

TERMINOLOGY

The term 'structural' *sensu lato* embraces forms, which are genetically related to characteristics of the rocks exposed at or located just beneath the Earth's surface. There are two types, which can be distinguished as active and passive. Tectonic forms involve earth movements (faulting and folding, some would include volcanicity) generated by crustal activities. Passive structural forms result from the exploitation of crustal weaknesses by external agencies.

Categories of drainage pattern caused by factors additional to these two basic structural effects have been recognised. Landforms and particularly drainage features associated with hidden structures are termed *cryptostructural*. Some are associated with structures the plan locations of which have changed as a result of deep erosion or dipping strata. Such structural effects are said to be *referred*. Others are associated with deep structures the impacts of which have been transmitted through effectively structureless incompetent beds. Thus, *underprinted* streams (HILLS, 1961) are caused by what has been called 'upward generation' (SAUL, 1978), or the effect of structures in deep basement rocks on overlying strata and eventually, the land surface and drainage lines.

Impression from below may be due to recurrent, resurgent or renewed dislocations along a basement fault, which eventually have been conducted through incompetent (plastic) strata. Transmission may not be instantaneous but occur over a period of time: it may be *delayed* or *deferred*. Alternatively, the underprinting may be indirect and be caused by the concentration of groundwater flow into or along the fracture zone, causing preferential weathering, volume loss, compaction and subsidence in a linear zone that is exploited by surficial agents, and especially rivers and streams. Clearly in such instances also there is a substantial time lag or deferral in the development of the surface features.

CRYPTOSTRUCTURAL FORMS

Fracture and strain

Crustal stress is manifested in fracture patterns and fold orientations at scales from the global and continental to the regional and local, from the outlines of the continents, massifs and framed basins, to the shape of residual hills and the patterns of drainage lines (e.g. DE KALB, 1990).

In orogenic terrains, stress and resultant strain are significant factors in the exploitation of folds by weathering and erosion resulting in inversions (e.g. DERRUAU, 1965, p. 173 et seq.; figure 1). The upper zones or crests of domes and anticlines are in tension and are thus susceptible to water penetration, alteration and erosion. At depth, however, beneath the neutral plane, anticlinal cores are in compression, as indicated by various kinks and minor warps such as those exposed in the cores of anticlines and domes and by the resistance to weathering and erosion of such zones (figure 2). Conversely, the upper zones of troughs, basins and synclines are in compression and thus resistant, whereas deeper zones are in tension. Deep erosion of folds and the associated distribution of strain can result in inversion, with synclines becoming topographic highs, and anticlines, lows (figure 3).

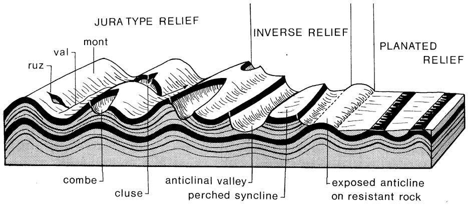


Fig. 1. Stages in the dissection of simple folds (after DERRUAU, 1965, p. 320).

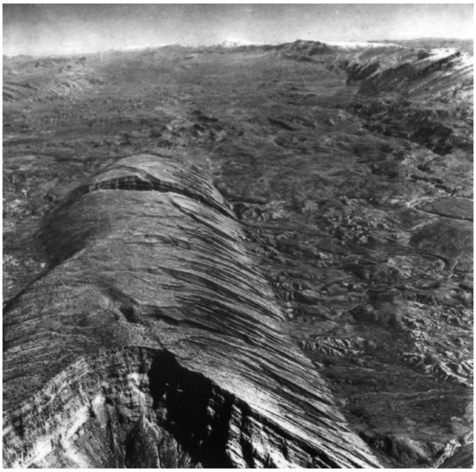


Fig. 2. Anticlinal ridge in limestone breached by river which has eroded a transverse gorge or tang, Zagros Mountains, southwestern Iran (Hunting Surveys).

Fig. 3. Wilpena Pound, central Flinders Ranges, South Australia, an example of a synclinal upland and hence of relief inversion (Department of Environment and Natural Resources, South Australia, Mapland).

Many drainage lines and patterns are, directly or indirectly, related to lineaments, which have been defined as topographic features of regional extent that reflect crustal structures (HOBBS, 1904, 1911; but see also HOBBS et al., 1976, p. 267). They have been referred to under other names (e.g. geofractures: RUSSELL, 1968). The term also has been applied in a more general sense, particularly in photo-interpretation and remote sensing to denote any linearity in the crust, so that RAJ (1983), for instance, refers to positive and negative lineaments to indicate positive or negative relief features. Most lineaments take the form of faults (O'LEARY et al., 1976). They are planes of recurrent shearing which have been exploited by major rivers such as Thredbo and other streams of the Kosciuszko region of southeastern Australia, the lower Volga in Russia, the St Lawrence in North America (figure 4), several left-bank tributaries of the Amazon in South America, and of the Congo in central Africa (e.g. HOBBS, 1904; STERNBERG and RUSSELL, 1956; TWIDALE and BOURNE, 2007).

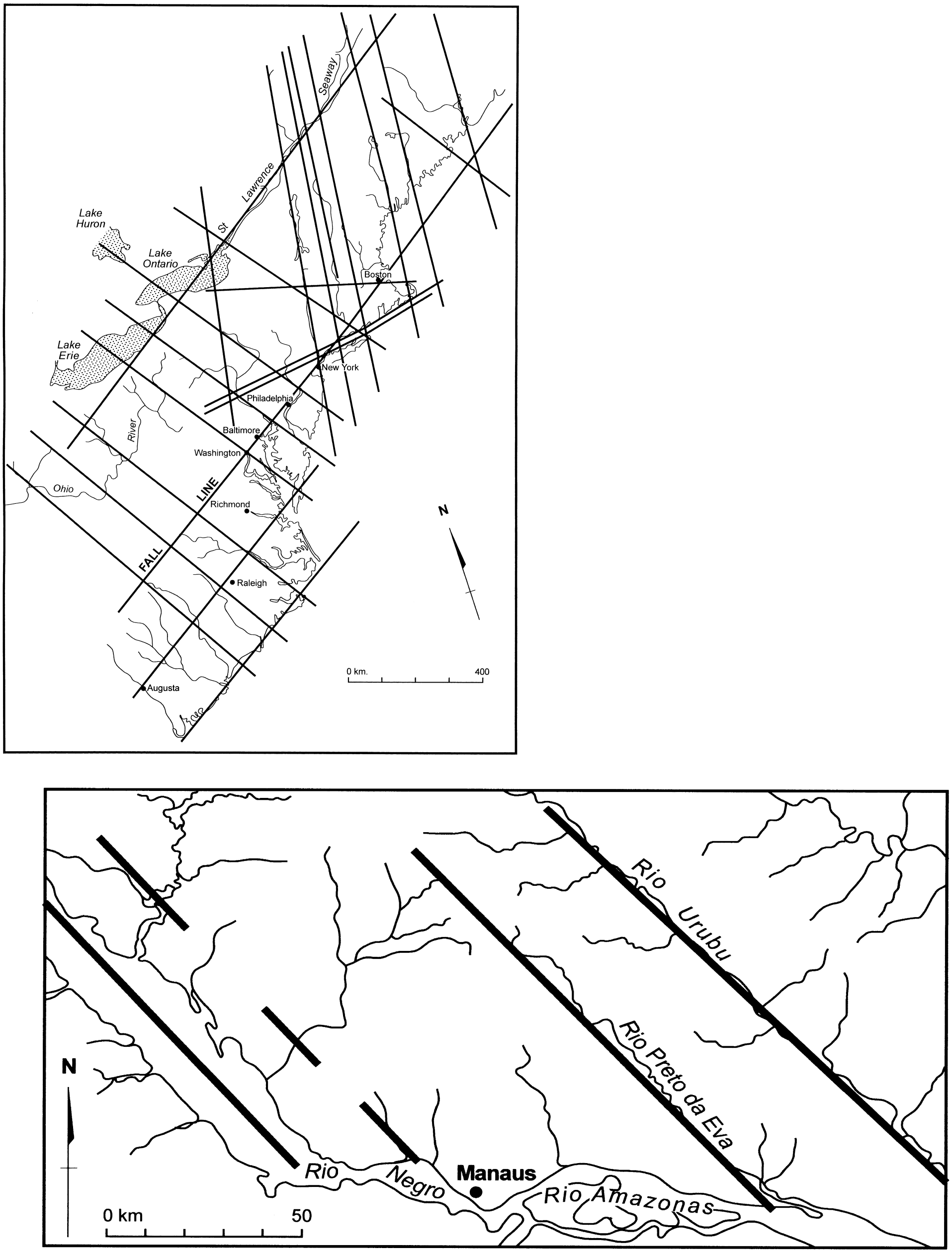


Fig. 4. (a) The linear course of the St Lawrence River and other waterways in northeastern North America (HOBBS, 1904). (b) Part of middle Amazon Basin showing linear left-bank tributaries.

Fig. 5. (a) *Kluftkarren*, and (b) *pseudoKluftkarren*, Little Wudinna Hill, Eyre Peninsula, South Australia.

Despite its successful application in mineral exploration (see e.g. BOURNE and TWIDALE, 2007) some workers reject the lineament concept, in part at least because fractures do not occur along the length of some alleged structures. But stress may find expression in zones of strain as well as in ruptures. For instance, at site scale, linear depressions are developed in granitic terrains parallel to genuine *Kluftkarren* or fracture-controlled clefts or slots. They lack visible and extensive continuous fractures (figures 5a and 5b), though the adjacent rock typically displays lineation, which stands in marked contrast with the usual random orientation of crystals in the host rock. Such *pseudoKluftkarren* are attributed to the preferential weathering of crystals under strain and hence in disequilibrium (RUSSELL, 1935; TURNER and VERHOOGEN, 1960, p. 476; NABARRO 1967, p. 4).

Recurrent shearing has caused the development of several generations of conjugate fractures, commonly of orthogonal and rhomboidal plan patterns, as well as fracture propagation. Fracture density varies because of the contrasted rheological characteristics of the country rock and as a result of repeated stress. Such spatial differences in fracture density account not only for inselberg landscapes, whether developed in granitic rocks, arenaceous materials or limestone (TWIDALE and BOURNE, 1978; TWIDALE and VIDAL ROMANI, 2005; TWIDALE, 2006), but also for fields of domical hills standing in ordered rows, the ‘egg-box’ patterns of RAMSEY and HUBER (1987). Examples are found in the Gawler Ranges of South Australia, the Kamiesberge of Northern Cape Province, RSA, and in Hausaland or northern Nigeria (e.g. BAIN, 1923; CAMPBELL and TWIDALE, 1991; TWIDALE and VIDAL ROMANI, 2005, p. 114; figure 6).

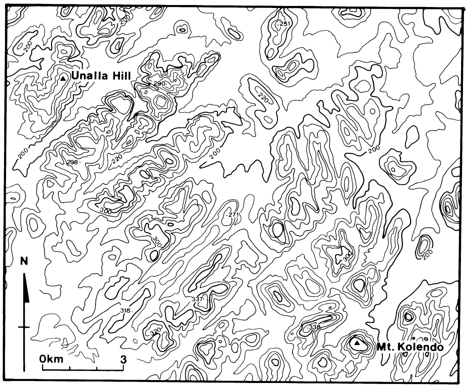


Fig. 6. Typical Gawler Ranges, South Australia, topography, with ordered rows of domical hills (bornhardts) developed in Mesoproterozoic silicic volcanics.

The residuals are defined in plan outline by steeply dipping fractures. Many are traversed by clefts caused by the exploitation by weathering and erosion of partings. The rock surfaces are also dimpled as a result of the formation of rock basins. No visible fractures coincide with the depressions or basins, yet their outlines run parallel to the lineament trends, as do the margins of some pans or shallow flat-floored basins, and are attributed to zones of strain (TWIDALE and CORBIN, 1963; DE KALB, 1990, p. 136-137).

In addition, each domical hill or bornhardt is subdivided into thick slabs by fractures or sheet fractures that are most commonly convex-upward, though some concave-upward examples have been noted (TWIDALE et al., 1996). The fractures and slabs are widely attributed to erosional offloading (GILBERT, 1904) and referred to as offloading joints, but the partings demonstrably are small-displacement faults and are more plausibly linked to compression induced by shearing (MERRILL, 1897; DALE, 1923; HOLZHAUSEN, 1989; TWIDALE et al., 1996; see also CHAPMAN, 1956).

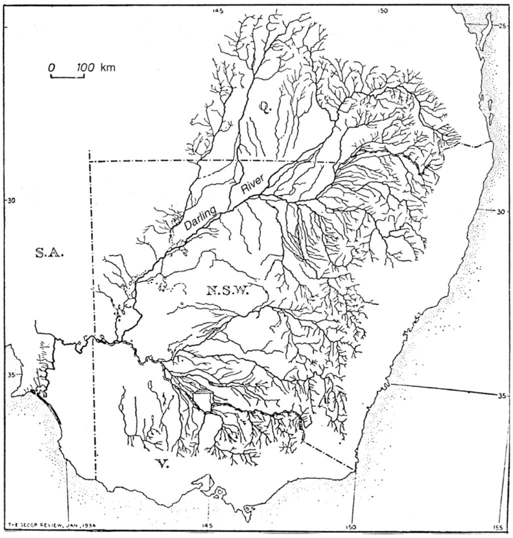
But whatever their nature, as originally defined, lineaments are zones of weakness that have been exploited by ascending gases, liquids and magmas (e.g. O'DRISCOLL, 1986; WOODALL, 1984; 1994; BOURNE and TWIDALE, 2007) and also by descending meteoric waters and circulating groundwaters, which contribute significantly to rock weathering and hence to the shaping of the Earth's surface. The influence of lineaments and related fracture systems and sets is apparent in many landscapes and at various scales (VENING MEINESZ, 1947; HILLS, 1961; DE KALB, 1990, p. 140-141).

Linear river patterns and underprinting

Most river patterns are controlled by slope or structure (e.g. ZERNITZ, 1931); those that transgress structure are said to be anomalous or transverse. River sectors have exploited linear fracture sets to produce rectangular patterns. Some major rivers, however, have eroded rectilinear channels in alluvium or similar unconsolidated materials.

In Australia, many of the major rivers of the Great Artesian Basin are sensibly straight (see TWIDALE and BOURNE, 2007), though they flow either in Quaternary alluvium or in weak Cretaceous and Tertiary sediments. Examples trending northeast-southwest include the Warburton-Diamantina, Lachlan, Warrego, Bulloo, Thompson, Cooper, and the Darling (figure 7a). Sectors of the Finke and Alberga run northwest-southeast and reaches of the Flinders, Leichhardt, and Georgina rivers are aligned

SSE-NNW. It has been suggested (HILLS, 1961; see also WOPFNER, 1960) that the linear courses of these central Australian rivers are due to underprinting, with structures developed in ancient basement rocks and recurrently revived, transmitted to the overlying alluvia or other intrinsically structureless sediments. Major linear sectors of the lower Murray River in South Australia (figure 7b) also have been attributed to underprinting through massive flat-lying Miocene limestone (O'DRISCOLL, 1960; FIRMAN, 1974; TWIDALE and BOURNE, 2009).



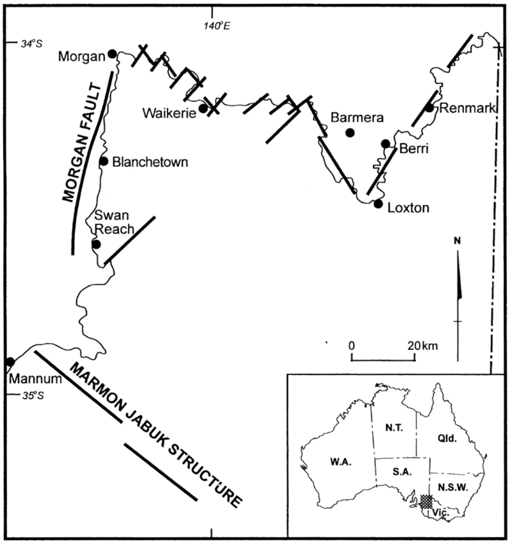


Fig. 7. (a) Linear course of the Darling River, mostly eroded in Quaternary alluvia (after FENNER, 1934). (b) Structural control of the course of the lower River Murray in South Australia. Note that the linear course south of Morgan is due to underprinting rather than control by the Morgan Fault (after O'DRISCOLL, 1960, p. 21).

Such underprinting may be effected by recurrent tectonism and repeated joggling of fault blocks and overlying strata resulting in subdued half graben and other linear depressions that though shallow are sufficient to determine stream courses. The development of surface forms has lagged well behind the original tectonic event to which they are related. The lapse time is to be measured in tens of millions of years at least. They are deferred forms.

Underprinting and arcuate patterns

Some arcuate stream and topographic patterns are associated with ring structures (e.g. VAN DE GRAAFF et al., 1977; O'DRISCOLL and CAMPBELL, 1997; see also KAMININE and RICHTER, 1956; SAUL, 1978; KHUDYAKOV et al., 1988; BAKER et al., 1992; KUTINA, 1998). Though mostly detected through geophysical signatures, some have been recognised in outcrop, and in fracture and stream patterns. The 1200 km diameter Central Australian Ring, for instance, is defined by several arcuate stream channels along its northern margin and indeed Eocene river courses in the southeastern Yilgarn Block are arcuate (figure 7c). The course of the Fitzroy River within the Kimberley Block and Circle (O'DRISCOLL and CAMPBELL, 1997) and the Derwent of central Tasmania (CAMPBELL and GLENIE, 2007) also may be determined by deep arcuate structures.

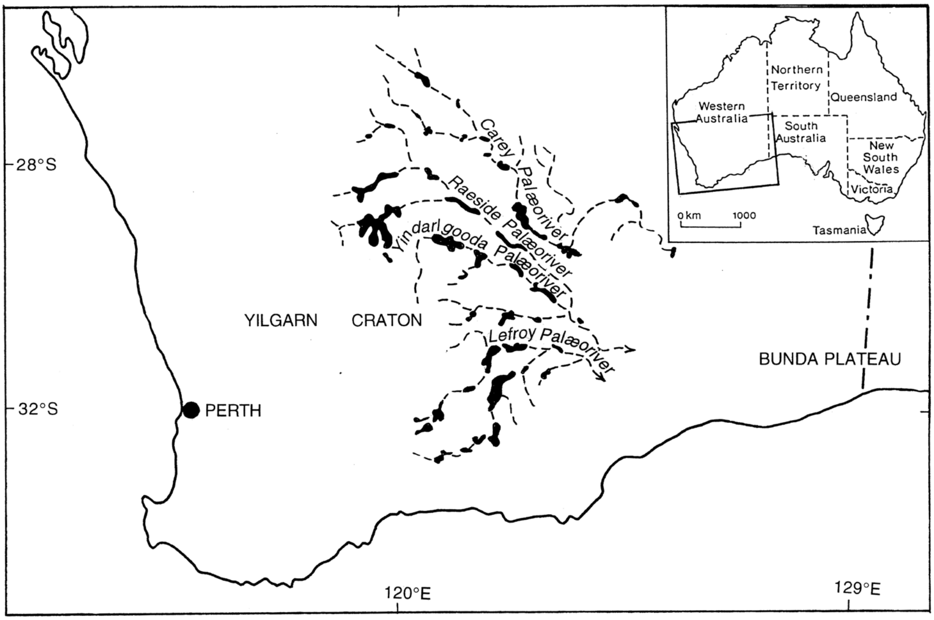


Fig. 7. (c) Arcuate rivers in the southern Yilgarn Craton, Western Australia (map extract after VAN DE GRAAFF et al., 1977).

It has been suggested that the basement from which some underprinted structures are derived may be the Mohorovicic discontinuity, regarded by some as the primordial crust of the Earth (SKOBELIN, 1992). Thus, lineaments may be inherited from shear zones in the Mohorovicic, and some of the ring structures may be derived from meteorite impacts on the original brittle crust of the Earth or on an early cover of sedimentary and volcanic rocks, and been underprinted on to near-surface strata (SAUL, 1978).

Underprinting and preferential weathering

Dolines are due to the solution and collapse of rocks, typically of limestone but including also ferruginous materials. Because solution is effected by water, dolines are characteristically developed low in the local topography. On western Eyre Peninsula, however, although many dolines are developed low in the local relief, others occur on uplands, and even on the crests of the rolling hills formed by deposits of Pleistocene dune calcarenite. For example, east of Lake Newland four dolines aligned NNW–SSE stand high on a relic coastal dune (figure 8a). This orientation roughly parallels a prominent fracture trend in the underlying granitic rocks as determined by patterns plotted in adjacent coastal sections and small but numerous inselberg inliers. For these reasons it has been suggested that these anomalously located forms could be related to underprinting, due either to joggling in the basement rocks or to a concentration of descending groundwaters in the fracture zones resulting in preferential solution and collapse in narrow structurally-related zones (TWIDALE and BOURNE, 2000; figure 8b).

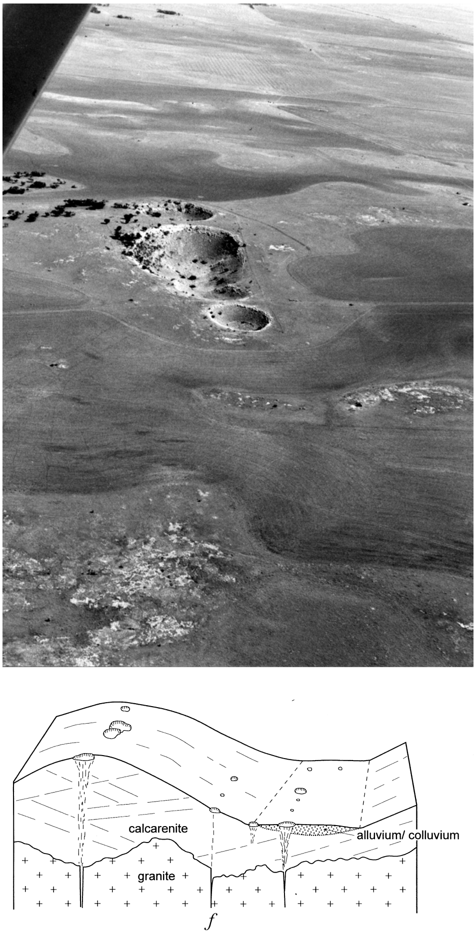


Fig. 8. (a) Aligned hilltop dolines, or sinkholes, east of Lake Newland, Elliston, western Eyre Peninsula, South Australia, seen from the southeast. (b) Diagram showing suggested development of aligned hilltop dolines in relation to basement fracture zone.

Similar landforms are developed on the Sturt Plateau, Northern Territory, which is a flat or very gently sloping lateritised surface of Miocene age developed on Cretaceous strata (figure 8c). The location and shape of the numerous dolines developed as a result of the dissolution and collapse of the underlying sediments are influenced by minor fractures in the host rock (TWIDALE, 1987).

Fig. 8. (c) Plan of part of Sturt Plateau, northern Australia, developed in laterite over Cretaceous strata, showing the relationship of dolines to fractures and palaeochannels (drawn from air photographs).

These karstic features in calcarenite and laterite are also examples of deferred forms, for the weathering of strata above the basement fracture or fracture zone leading to the necessary volume decrease, compaction and subsidence has taken some considerable time. Indeed, dolines are still forming on the Sturt Plateau (figure 8d). Thus, and as with the underprinted river courses discussed earlier, the development of the resultant surface feature occurred much later than the tectonic event with which it is ultimately associated.

Fig. 8. (d) View of doline in laterite adjacent to the Buchanan Highway, west of Dunmara, Northern Territory, and developed in stages between October 1981 and April 1982, but mostly toward the end of this period.

REFERRED STRUCTURAL FORMS

Lateral fracture displacement

In places rivers that have breached and excavated gorges through ridges in resistant rocks such as quartzite occur a short distance from faults exploited by weathering but not by rivers or streams. They can plausibly be explained in terms of deep erosion of folded structures, the exploitation of structural weaknesses in dipping strata by streams at an earlier and higher land surface, and the persistence of the stream at the original location despite the lateral shift of the zone of weakness as a result of surface lowering. Such persistence implies strong reinforcement effects (BEHRMANN, 1919; KING, 1970; TWIDALE et al., 1974).

The significance of the apparent lateral shift of structures in deeply eroded landscapes like that of the Flinders Ranges, an Early Palaeozoic fold mountain belt which remains tectonically active (TWIDALE and BOURNE, 1996), is indicated by simple calculations. A stratum inclined 10° from the vertical (hade) causes a lateral displacement of 2 m every 10 m of lowering; 20° implies 3.6 m for every 10 m; 30°, 5.8 m for every 10 m; and so on. Given the evidence for deep erosion, and in the Flinders Ranges it is of the order of several kilometres, the changing geometry and location of structure with depth is a significant factor in landform interpretation (TWIDALE, 1972).

In the northeastern Flinders Ranges, Italowie Creek flows south between the Rampart and Balcanoona ranges before turning northeast as a major braided river (figure 9a). Just before turning northeast the stream has incised a deep valley in the boulder tillite of the Bolla Bollana Formation of Neoproterozoic age dipping west and northwest. A crush zone is developed at the faulted interface between the tillite and overlying Rawnsley Quartzite (uppermost Neoproterozoic), also dipping west (LEESON, 1967). The crush zone is imbricate at the contact with the quartzite exposed on the eastern flank of the Rampart Range but is characterised by closely spaced cleavage in the argillites. Though unaltered, this shatter zone was readily exploited by streams. Italowie Creek has eroded a slightly arcuate valley to depths of 290-300 m. The arcuate crush zone, located some 100-200 m to the west and developed along a west-dipping lithological junction, is separated from the Italowie Creek valley by a high ridge of tillite. It is weathered and eroded, but most of the drainage has been captured by right bank tributaries of the Italowie Creek and the floor of the linear depression stands at elevations of more than 350 m, and well above the channel of the nearby Italowie Creek.

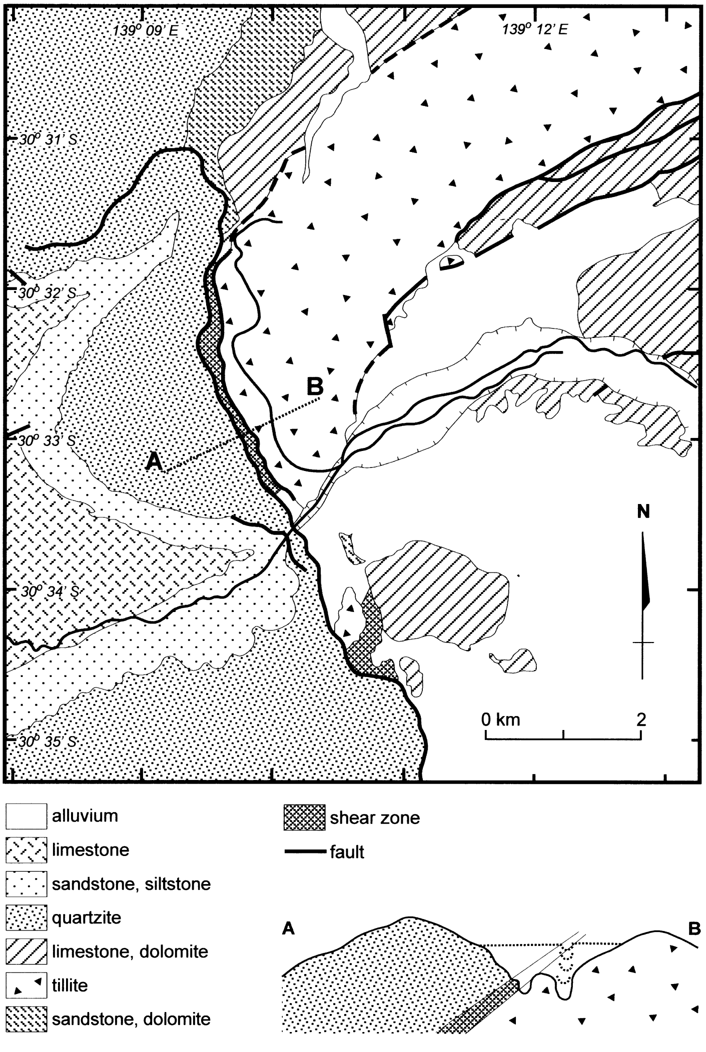


Fig. 9. (a) Generalised geological map of Italowie Creek in eastern piedmont of northern Flinders Ranges, with section A-B showing suggested offsetting of gorge and fault zone as a result of deep erosion of dipping structures.

Similarly, at the eastern end of Chace Range in the central Flinders Ranges, a right bank tributary of Wilpena Creek has breached the quartzite ridge less than a kilometre from the terminus of the upland, though a fault zone marked by a col occurs about a kilometre to the west (figure 9b). This appears to have been the structure that the stream initially exploited in order to breach the ridge.

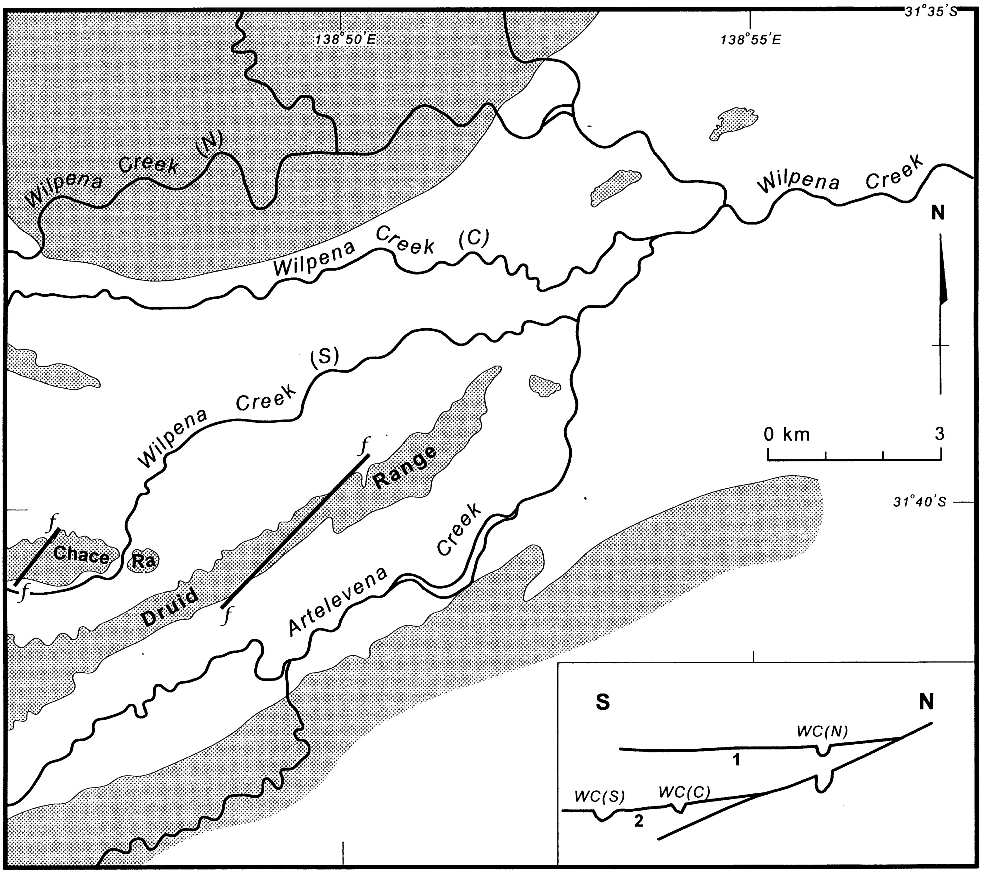


Fig. 9. b) Offset gorge and fault zone (*f* – heavy line) near the eastern end of Chace Range, central Flinders Ranges. The gorge has been excavated through a quartzite ridge despite the presence of a fault zone cutting through the strata diagonally from SW-NE less than a kilometre to the west.

These anomalous situations can be construed as being due to the ancestral rivers having initially exploited the crush or fracture zone. Each evidently had the power to erode a gorge and maintain its plan location despite the oblique dip and lateral displacement of the zone of structural weakness consequent on deep erosion. At Italowie, once incised into the fissile shatter zone the stream maintained its position even when it incised into the tillite below the dipping argillites: such is the power of rivers to maintain their courses.

Transfer from weak to resistant environment

Some patterns are anomalous in that they are incompatible with structure or slope or both, and natural selection, i.e. the emergence as master streams of those that have exploited structural weaknesses and once dominant are enhanced – the reinforcement factor. Yet whereas master streams ought to develop in weak strata, some either cut across the structural grain or they have eroded valleys, and in many instances gorges, in resistant rocks situated immediately adjacent to weaker formations. Such transverse elements are most commonly developed in fold mountain belts though they are not confined to them.

Major rivers in fold mountain belts consist of long sectors that are compatible with structure, linked by short sectors that are anomalous in that they cut across structure. They have been attributed variously to catastrophic diversion (faulting, warping, volcanism, glacial blocking), antecedence, superimposition, and inheritance (TWIDALE, 2004). River capture or piracy is also significant (THOMPSON, 1939; BISHOP, 1995). Deep erosion and the persistence of streams let down from a weak formation on to one that is resistant, was suggested by MEYERHOFF and OLMSTEAD (1936) in explanation of certain Appalachian streams and has found support from other workers (STRAHLER, 1945; OBERLANDER, 1965; TWIDALE, 1966, 1976, p. 438 and 440 et seq,). It must be noted, however, that this mechanism differs from superimposition (in US, superposition).

Though originally invoked by JUKES (1862) in explanation of the river patterns of southern Ireland, MAW (1866) was the first to use the term superimposition (or in the U.S.A., superposition). for: "… a series of valleys superimposed *in part unconformably* over an ancient buried series …' and '… denudation may … gradually lower the entire surface … after having removed the whole of the new deposit, *and will impress on the old deposit a contour partaking of that of both the old and new surface*s …". Clearly superimposition implies a younger series (or overmass) and an unconformable undermass. Nevertheless, the explanation is plausible, for many anomalous patterns including rivers that run across entire local structures, breached snouts and in-and-out valleys (figures 2 and 10) are susceptible of explanation in terms of deep erosion (e.g. TWIDALE, 2004; also UMBGROVE, 1950, p. 58). It has been suggested that such anomalous streams can be linked to what has been called stream persistence and valley impression or perhaps more simply, stream impression (TWIDALE, 1966, 1972, 2004).

Fig. 10. (a) An anomalous river channel runs across a dome located in the Krichauff Ranges, southwest of Alice Springs, Northern Territory, but strike streams run tributary to the main river (C. Wahrhaftig). (b) A winding strike stream is responsible for the valley located to the southwest of the southern limb of this anticlinal snout, located in the Petermann Hills, almost 200 km WSW of Alice Springs. The snout is in process of being breached by various antidip streams (in order of advancement) C, B, A, and X. Stream Y is regressing through the broad sandstone apex of the structure. In all but C short strike streams and valleys are developed along bedding and joints tributary to the main streams.

CONCLUSION

River patterns usually are determined by structure, but in places reflect capture, impression, underprinting, referral or deferral. Some of these more subtle structural influences are frequently overlooked, as is the significance of reinforcement.

REFERENCES

BAIN, A. D. N. (1923). The formation of inselberge. *Geological Magazine* **60**: 97–101.

BAKER, V. R., FINN, V. J. and KOMATSU, G. (1992). Morphostructural megageomorphology. *Israel Journal of Earth Sciences* **41**: 65–73.

BEHRMANN, W. (1919). Der Vergang der Selbstverstärkung. *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.

BOURNE, J. A. and TWIDALE, C. R. (Eds) (2007). *Crustal Structures and Mineral Deposits. E.S.T. O'Driscoll's Contribution to Mineral Exploration*. Rosenberg, Sydney.

CAMPBELL, E. M. and TWIDALE, C. R. (1991). The evolution of bornhardts in silicic volcanic rocks in the Gawler Ranges, South Australia. *Australian Journal of Earth Sciences* **38**: 79–93.

CAMPBELL, I. B. and GLENIE, R. C. (2007). Cerberean and Lake echo rings in southeastern Australia: ancient crustal ring and rift associations in the basement with planetary implications. In: *Crustal Structures and Mineral Deposits. E.S.T. O'Driscoll's Contribution to Mineral Exploration*. BOURNE, J.A. and TWIDALE, C.R. (Eds). Rosenberg, Sydney, p. 185–193.

CHAPMAN, C. A. (1956). The control of jointing by topography. *Journal of Geology* **66**: 552–558.

DALE, T. N. (1923). The commercial granites of New England *United States Geological Survey Bulletin* 738.

DE KALB, H. F. (1990). *The Twisted Earth*. Lytel Eorthe Press, Hilo, Hawaii.

DERRUAU, M. (1965). *Précis de Géomorphologie*. Masson, Paris.

FENNER, C. (1934). The Murray River Basin. *Geographical Review* **24**: 79–91.

FIRMAN, J. B. (1974). Structural lineaments in South Australia. *Transactions of the Royal Society of South Australia* **98**: 153–171.

GILBERT, G. K. (1904). Domes and dome structures of the High Sierra. *Geological Society of America Bulletin* **15**: 29–36.

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.

HOBBS, B. E., MEANS, W. D. and WILLIAMS, P. F. (1976). *An Outline of Structural Geology*. Wiley, New York.

HOBBS, W. H. (1904). Lineaments of the Atlantic border region. *Geological Society of America Bulletin* **15**: 483–506.

HOBBS, W. H. (1911). Repeating patterns in the relief and structure of the land. *Geological Society of America Bulletin* **22**: 123–176.

HOLZHAUSEN, G. R. (1989). Origin of sheet structure. 1. Morphology and boundary conditions. *Engineering Geology* **27**: 225–278.

JUKES, J. E. (1862). On the mode of formation of some of the river valleys in the south of Ireland. *Proceedings of the Geological Society of London* **8**: 378–403.

KAMININE, G. D. and RICHTER, L. G. (1956). Caractéristique comparative morphologique des boucliers de la partie Européenne de l'URSS. In: *Essais de Géographie*. Academie des Sciences de l'URSS, Moscow, p. 82–92.

KHUDYAKOV, G. I., KULAKOV, A. P., NIKANOVA, R. I. and EZHOV, B. V. (1988). New views on morphostructure of marginal seas of eastern Asia. *Journal of the Physics of the Earth* **36**: S179–S189.

KING, C. A. M. (1970). Feedback relationships in geomorphology. *Geografiska Annaler* **52A**: 147–159.

KUTINA, J. (1998). A major structural intersection in the basement of the Okavango Basin, NE of Tsumeb, Namibia, indicated by satellite magnetometry and other data. *Global Tectonics and Metallogeny* **6**: 205–213.

LEESON, B. (1967). *Balcanoona*. Geological Atlas 1 Mile Sheet, Geological Survey of South Australia, Adelaide.

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

MERRILL, G. P. (1897). *Treatise on Rocks, Weathering and Soils*. Macmillan, New York.

MEYERHOFF, H. A. and OLMSTEAD, E. W. (1936). The origins of Appalachian drainage. *American Journal of Science* **36**: 21–42.

NABARRO, F. R. N. (1967). *Theory of Crystal Dislocations*. Clarendon Press, Oxford.

OBERLANDER, T. (1965). The Zagros streams. *Syracuse University Geographical Series* **1**.

O'DRISCOLL, E. P. D. (1960). The hydrology of the Murray Basin Province in South Australia. *Geological Survey of South Australia Bulletin* **35**.

O'DRISCOLL, E. S. T. (1986). Observations on the lineament-ore relation. *Philosophical Transactions of the Royal Society of London*, Series A, **317**: 195–218.

O'DRISCOLL, E. S. T. and CAMPBELL, I. B. (1997). Mineral deposits related to Australian continental ring and rift structures with some terrestrial and planetary analogies. *Global Tectonics and Metallogeny* **6**: 83–101.

O'LEARY, D. W., FRIEDMAN, J. D. and POHN, H. A. (1976). Lineament, linear, lineation; some proposed new standards for old terms. *Geological Society of America Bulletin* **87**: 1463–1469.

RAJ, J. K. (1983). Negative lineaments in the granite bedrock area of NW peninsular Malaysia. *Geological Society of Malaysia Bulletin* **16**: 61–70.

RAMSAY, J. G. and HUBER, M. I. (1987). *The Techniques of Modern Structural Geology. 2. Folds and Fractures*. Academic Press, London.

RUSSELL, M.J. (1968). Structural controls of base-metal mineralization in Ireland in relation to continental drift. *Transactions of the Institution of Mining and Metallurgy* **87**: B168–171.

RUSSELL, G. A. (1935). Crystal growth in solution under local stress. *American Mineralogist* **20**: 733–737.

SAUL, J. M. (1978). Circular structure of large scale and great age on the Earth's surface. *Nature* **271**: 345–349.

SKOBELIN, E. A. (1992). Composition of the upper geospheres: the nature of the "Moho".–In: *Expanding Geospheres.*

HUNT, C.W. (Ed.). Polar Publishing, Calgary, p. 32–42.

STERNBERG, H. O'R. and RUSSELL, R. J. (1956). Fracture patterns in the Amazon and Mississippi valleys. In: *Proceedings of the International Geographical Union*, Eighth General Assembly and 17th International Congress, 1952, Washington D.C., p. 380–385.

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.

TURNER, F. J. and VERHOOGEN, J. (1960). *Igneous and Metamorphic Petrology*. McGraw-Hill, New York.

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. (1976). *Analysis of Landforms*. Wiley/Jacaranda, Brisbane.

TWIDALE, C. R. (1987). Sinkholes (dolines) in lateritised sediments, western Sturt Plateau, Northern Territory, Australia. *Geomorphology* **1**: 33–52.

TWIDALE, C. R. (2004). River patterns and their meaning. *Earth-Science Reviews* **67** (3-4): 159–218.

TWIDALE, C. R. (2006). Origin and development of Karstinselberge, with particular reference to some South East Asian evidence. *Geological Society of Malaysia Bulletin* **49**: 145–155.

TWIDALE, C. R. and BOURNE, J.A. (1978). Bornhardts developed in sedimentary rocks, central Australia. *The South African Geographer* **6** (1): 35–51.

TWIDALE, C. R. and BOURNE, J. A. (1996). Development of the land surface. In: *Natural History of the Flinders Ranges*. DAVIES, M., TWIDALE, C.R. and TYLER, M. J. (Eds). Royal Society of South Australia, Adelaide, p. 46–62.

TWIDALE, C. R. and BOURNE, J. A. (2000). Dolines of the Pleistocene dune calcarenite terrain of western Eyre Peninsula, South Australia: a reflection of underprinting? *Geomorphology* **33**: 89–105.

TWIDALE, C. R. and BOURNE, J. A. (2007). Lineaments and cryptostructural effects. In: *Lineament and Mineral Deposits. E.S.T. O'Driscoll's Contribution to Mineral Exploration.* BOURNE, J.A. and TWIDALE, C.R. (Eds). Rosenberg, Sydney, p. 153–164.

TWIDALE, C. R. and BOURNE, J. A. (2009). The course of the lower River Murray: an example of underprinting? *Proceedings of the Royal Society of Victoria* **121**: 207–227.

TWIDALE, C. R., BOURNE, J. A. and SMITH, D. M. (1974). Reinforcement and stabilisation mechanisms in landform development. *Revue de Géomorphologie Dynamique* **23**: 115–125.

TWIDALE, C. R. and CORBIN, E. M. (1963). Gnammas. *Revue de Géomorphologie Dynamique* **14**: 1-20.

TWIDALE, C. R. and VIDAL ROMANI, J. R. (2005). *Landforms and Geology of Granite Terrains*. Balkema, Leiden.

TWIDALE, C. R., VIDAL ROMANI, J. R., CAMPBELL, E. M. and CENTENO, J. D. (1996). Sheet fractures: response to erosional offloading or to tectonic stress? *Zeitschrift für Geomorphologie Supplementband* **106**: 1–24.

UMBGROVE, J. H. F. (1950). *Symphony of the Earth*. Nijhoff, Den Hague.

VAN DE GRAAFF, W. J. E., CROWE, R. W. A., BUNTING, J. A. and JACKSON, M. J. (1977). Relict Early Cainozoic drainages in arid Western Australia. *Zeitschrift für Geomorphologie* **21**: 379–400.

VENING MEINESZ, F. A. (1947). Shear patterns in the Earth's crust. *Transactions of the American Geophysical Union* **28**: 1–61.

WOODALL, R. (1984). Success in mineral exploration. *Geoscience Canada* **11**: 127–133.

WOODALL, R. (1994). Empiricism and concept in successful mineral exploration. *Australian Journal of Earth Sciences* **41**: 1–10.

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.

ZERNITZ, E. R. (1931). Drainage patterns and their significance. *The Journal of Geology* **40**: 498–521.