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River patterns and their meaning

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Abstract

Rivers are largely responsible for shaping the Earth's continental landscapes. River patterns, the spatial arrangements of channels in the landscape, are determined by slope and structure. At site and sector scale, channel morphology varies spatially and in time, but river patterns and drainage texture, or the frequency of stream lines per unit area, together determine the intricacy, or otherwise, of topography. Most river patterns evolve through natural selection. Slope induces the formation of such patterns as parallel, radial and distributary, while structure produces straight, angular, trellis and annular arrangements. Once established, patterns tend to persist. Nevertheless, at many sites the usual patterns have been disturbed and patterns that are anomalous in terms of slope and structure have been produced by diversion, tectonism, volcanism, glaciation, mass movements, and human activities; by antecedence, superimposition, inheritance or underprinting; by the persistence of deeply eroding rivers which encounter alien structures; and by climatic change.

River patterns provide clues to underlying structure and to the chronology of events. They have also proved significant in the search for minerals.

Keywords: River pattern; Natural selection; Adjusted streams; Anomalous streams; Climatic change; Inversion

1. Introduction

Water is critical not only to life but also to the understanding of scenery. Water occupies more than 70% of the Earth's surface, most of it (97%) in the ocean basins, but only a small part of these waters directly affects the sculpture of the land. Certainly, wind-driven waves and saline waters have helped shape the coastal zones, past and present, and sea level acts as a baselevel to which many rivers are graded, but shallow groundwaters and runoff, together amounting to a mere 0.6141% of the total water on Earth (Nace, 1960), are in large measure responsible for shaping the land surface, especially at the medium and small scales.

Groundwaters extend to depths of 10 km below the land surface but are mostly found within 700–800 m of the surface. These shallow groundwaters comprise the phreatic waters below the water table, which are fed by descending meteoric or vadose ('wandering') waters. Charged with chemicals and biota these groundwaters react with rock-forming minerals and contribute substantially to rock weathering which is an essential precursor to erosion.

Thus, groundwaters are responsible for the formation of the weathered mantle or regolith, and for

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the weathering front (Mabbutt, 1961), the interface between regolith and cohesive intrinsically fresh rock. Weaknesses in the country rock are exploited by moisture and the weathering front is frequently irregular in detail: a topography is developed. The regolith is much more susceptible to erosion than are most types of fresh rock. In many areas it has been stripped to expose the erstwhile weathering front as a landform or landform assemblage. Though the origin of such forms can in many instances be traced into the distant past and are in reality multistage (Twidale and Vidal Romani, 1994) they are also, and more commonly, referred to as two-stage, because they evolve in a more immediate sense in two distinct phases, subsurface weathering, followed by erosion of the weathering products. They are also known as etch forms because they are due to the etching or eating away of the bedrock by groundwaters (Twidale, 2002).

Evacuation of the regolith has been achieved by different agencies according to time and place, but rivers have been, and remain, dominant in shaping the land surface. The patterns of upland and lowland, valley and divide, that dominate the continents at the medium and local scales are due to differential erosion by rivers. Even in the midlatitude deserts most erosional forms have been shaped by rivers related either to humid climates of the past or to occasional floods characteristic of the present regime (Peel, 1941). Also, much of the sand moulded by the wind into desert dunes has been transported to the arid lands by rivers (e.g., Wopfner and Twidale, 1988, 2001; but see also, Pell et al., 1999, 2000). Rivers supply most of the detritus shaped by wind-driven waves to form the beaches, spits and bars found on many coasts, as well as foredunes constructed of sand blown by onshore winds from the adjacent beaches. Melting ice generates rivers that have eroded systems of valleys within and beneath the ice, as well as depositing huge volumes of sediment in various fluvioglacial forms.

Overland flow of water, or runoff, takes the form partly of diffuse wash, partly of channeled flows known as rills, runnels, rivulets, streams and rivers. This review is concerned with channeled flows which result directly from precipitation and runoff, from the melting of snow and ice, and from springs and seepages of groundwaters, in decantation flows.

2. Definitions

Some parts of the Earth's land areas lack surface drainage and are said to be areic, though in some such areas, as well as in certain lithological environments, rivers flow beneath the surface and are said to be cryptoreic or 'hidden'. Areas with surface drainage are divided into exoreic or endoreic according to whether the rivers and streams run to the sea or to basins of interior drainage. Permanent or perennial rivers run at all times, though discharge varies temporally as well as spatially. Intermittent streams flow seasonally, as in monsoon lands, but in a regular and dependable pattern, whereas the flow of episodic rivers, characteristic of the midlatitude deserts, is spasmodic and unpredictable. Rivers that rise in high rainfall areas but then survive passage across desert or semi-arid regions, rivers such as the Nile and the Murray, are termed allogenic or exotic.

Rivers flow in channels which vary in plan form both in space and in time. Different sections of the same stream may develop different channel forms: a single winding, sinuous plan shape here, multiple interlaced forms elsewhere. Drainage lines or channels can be considered from different points of view. River, or drainage, patterns are the spatial arrangements of streams. Drainage texture is the relative spacing of stream lines per unit area of catchment, and drainage density is its statistical expression, the total length of streams in a given basin divided by its area. Pattern and texture, taken together with degree of incision or relief amplitude, determines the texture or roughness of terrain and the areal extent, inclination and relative spacing of slopes.

Pattern and texture together determine form, and density can be seen as operating within the context of pattern. For instance, fractures may determine that an angular pattern develops on a given granite outcrop, but the degree of weathering and state of stress of the rock, the prevailing slope, age of the surface and various climatic factors influence the development of stream spacing within the confines of the pattern.

The significance of drainage density in understanding landscape has long been recognised (e.g., Glock, 1932; Douglas, 1977; Dunne, 1980), if only because it controls the texture of relief. Johnson (1933) claimed that the steeper the slope the more streams there were; which is questionable in some areas but Dietrich et al.

(1986) have recently reached similar conclusions. Clearly the nature of the country rock is of prime significance also, for permeability and perviousness exert a major control on runoff and infiltration (e.g., Carlston, 1963; also Fig. 1). Development through time is also significant (e.g., Ruhe, 1952). Structure controls seepage and the initiation of decantation flows, and climate, working through rainfall incidence and vegetation cover is also a major factor determining infiltration—runoff ratios and the survival of the small linear channels that spawn larger channels or streams (see, e.g., Dunne and Aubry, 1986; Willgoose et al., 1991).

Analysis is complicated by climatic change, tectonic and sea level or baselevel changes, human and other interference with vegetation cover. Also, the etch factor—the reality that bedrock topographies that determine initial drainages are initiated not at the land surface but at the base of the mantle of weathered rock, a bedrock surface which may later be exposed as a weathering front and the shape of which reflects the interaction of processes of disintegration and alteration on the one hand, and bedrock structure on the other.

This review is concerned mainly with river patterns, and particularly patterns developed on outcrops of lithified rocks. The patterns and mechanics of streams flowing in alluvia and other unconsolidated materials are well documented in the literature. Nonetheless, they cannot be wholly ignored in the present context. Some characteristics of channel morphology well developed in alluvial settings are germane to the interpretation of rivers draining bedrock outcrops and upland areas. Also, some alluvial rivers are influenced by deep structure. Thus, the interpretation of some of the spatial characteristics of stream channels is relevant to the understanding of certain aspects of upland rivers, and vice versa.

3. Channel form and some implications

3.1. Plan form

The classification and nomenclature applied to rivers and channels flowing in alluvium varies according to author. It has been suggested that they can be classified according to discharge and velocity (flow strength), which in turn involve gradient and channel characteristics (bed and bank erodibility) and sediment supply or load (e.g., Leopold and Wolman, 1957; Leopold et al., 1964; Knighton and Nanson,

Fig. 1. The impact of impermeability on susceptibility to soil erosion is illustrated in this valley in the Eastern Cape Province of South Africa. The village is sited on the hilltop as a defence against human enemies and also mosquitoes. The only water supply is the stream in the valley floor. Water has to be carried from the stream to the village. Hence the numerous pads beneath which the soil is compressed, rendered impermeable and vulnerable to wash and erosion.

1993). On this basis meandering, braided, anabranching and anastomose forms have been recognised. Meandering channels (Fig. 2a) develop where bank erodibility is low but flow and load are moderate. Braided rivers (Fig. 2b) are of high flow strength and have relatively high gradients with abundant load; they are found in upland streams. Anastomose types (Fig. 2c) have developed where flow strength, bank erodibility and gradients are low but load is moderate to high. Both braided and anastomose types may be anabranching (Fig. 3), for both can involve multi-channeled streams that separate and rejoin downstream. Both reflect flood-dominated regimes, but the braided reaches develop on high gradients, the anastomose on low.

One problem is that some criteria proposed as the basis for classification depend on sampling and analysis and are not directly observed in the field. Discharge and nature of load, for example, require measurement. Morphology surely reflects properties of stream and channel but a system of nomenclature based in form (e.g., meandering, braided) is useful as a first approximation. A genetic system (taking into account, e.g., gradient, high discharge, load), though desirable, involves isolated measurements which may be secularly unrepresentative and misleading. To be meaningful they need to be based in long-term monitoring programmes.

In addition, usage varies with author. For example, Nanson and Knighton (1996) apply anabranch to

Fig. 2. (a) Vertical air photograph of the River Murray in flood at Renmark, South Australia, in September 1956, showing the main meandering channel and winding minor but connected streams, with ox-bow lakes, together forming an anastomose pattern (Department of Lands, South Australia). (b) Braided channel of the Big John Creek, in the northeastern piedmont of the Flinders Ranges, South Australia. Note the major lateral channels and their relative straightness. (c) Anastomose river, western Otago Province, South Island, New Zealand.

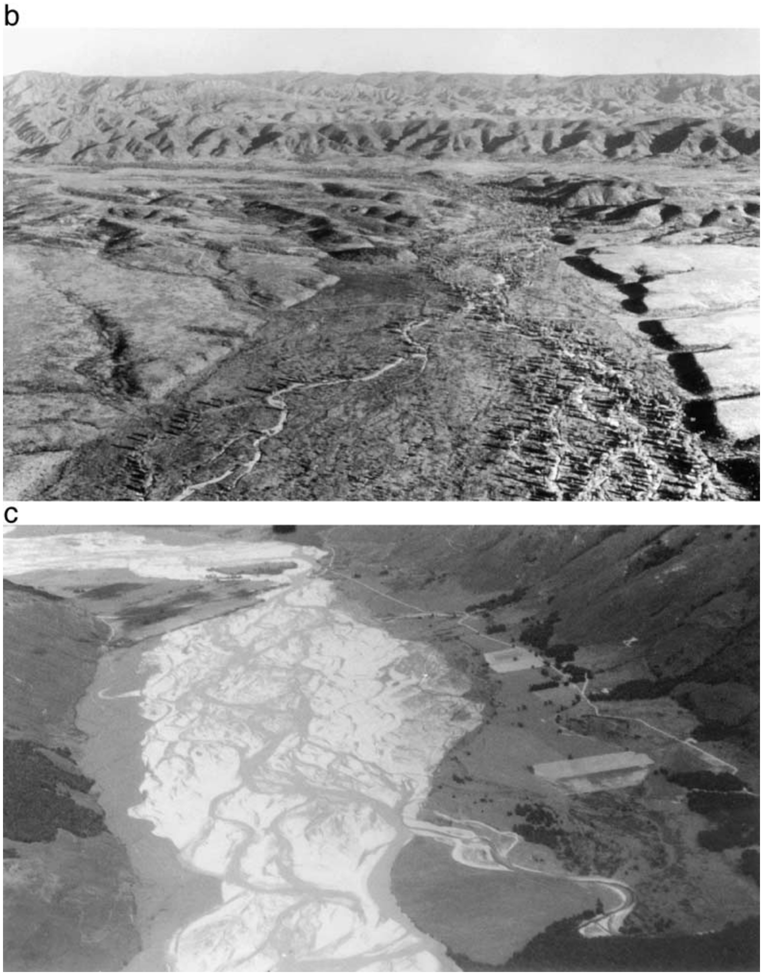


Fig. 2 (*continued*).

bedrock forms and retain anastomose for interlaced low gradient alluvial channels, as exemplified by the rivers of the Channel Country of southwestern Queensland. Bretz (1923), on the other hand, applied anastomose to the Scabland channels of northwestern USA, and Baker (1973) adhered to this practice. Also, though developed in an alluvial terrain, the drainage pattern described in Fig. 3 surely warrants the term ‘anabranching’? Bearing in mind this mild confusion, it is suggested that multi-channeled streams can be distinguished according to whether the component channels within the flood plain are relatively straight (braided: Fig. 2b), or distinctly winding (anastomose: Fig. 2c). The term ‘anabranch’ could then be restricted to channels which break away from the flood plain but rejoin it downstream, regardless of whether developed in alluvial or hard rock settings, or a mixture of the two.

3.2. Meandering

All channels are winding or sinuous. Some are described as straight, and so they are considered regionally, but at the site and local scales all are sinuous to a greater or lesser degree; even straight, constructed channels such as canals, lined as well as earthen, tend to sinuosity with erosion concentrated in specific zones, regularly spaced but alternating on opposite banks. The River Menderes (known to the Greeks as the Maiandros) in Anatolia, in what is now

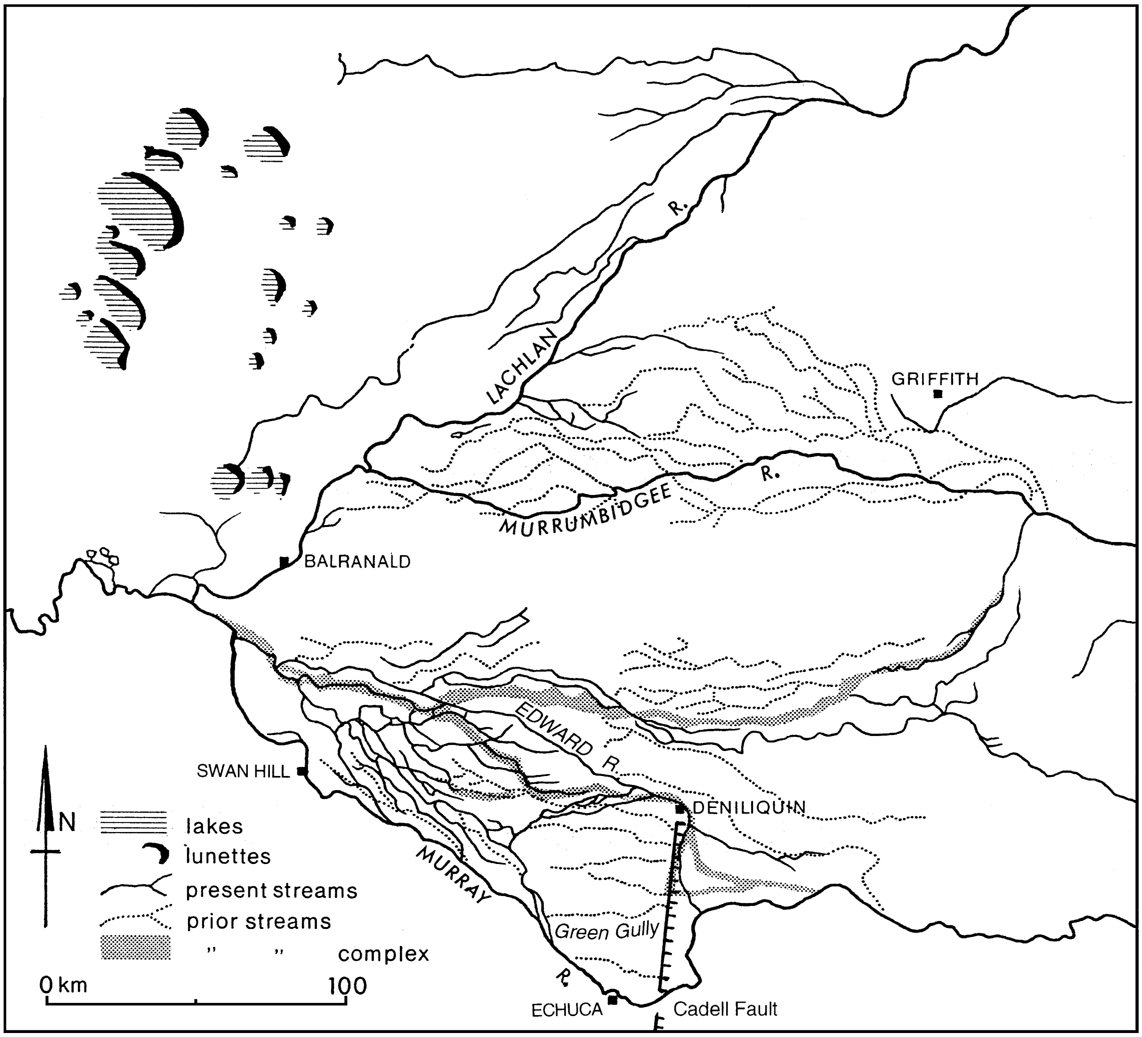


Fig. 3. Anabranches and prior streams on the alluvial plains of southwestern New South Wales. The southerly diversion of the river upstream of Echuca is due to Late Pleistocene uplift of the Cadell Fault (after Bowler and Harford, 1966; Pels, 1966). The previous channel of the river is preserved in Green Gully.

southwest Turkey, was well known for its sinuosity and has given its name to the meandering form. Alluvial meanders migrate laterally, and at times rapidly, in the channels they shape in their own deposits; for this reason it is unwise to use meandering rivers as boundaries, either local or international (e.g., Mueller, 1975). The channels are smooth, and stream velocity is relatively high, for overall stream velocity increases from source to sea (Rubey, 1952; Leopold, 1953). Irregularities are introduced by variations in bank composition, such as obstructions like clay pods, which effectively restrict lateral motion and hence meander development. Meanders are confined to a meander belt which, like the meanders within it, migrates laterally and downstream. Flood plains are largely due to lateral stream migration, though overbank deposits are laid down in floods (Wolman and Leopold, 1957).

Laboratory work (e.g., Friedkin, 1945) has shown that in time arcuate channels evolve into meander loops, the size of which increases with stream gradient (within certain limits), and with increased angle of

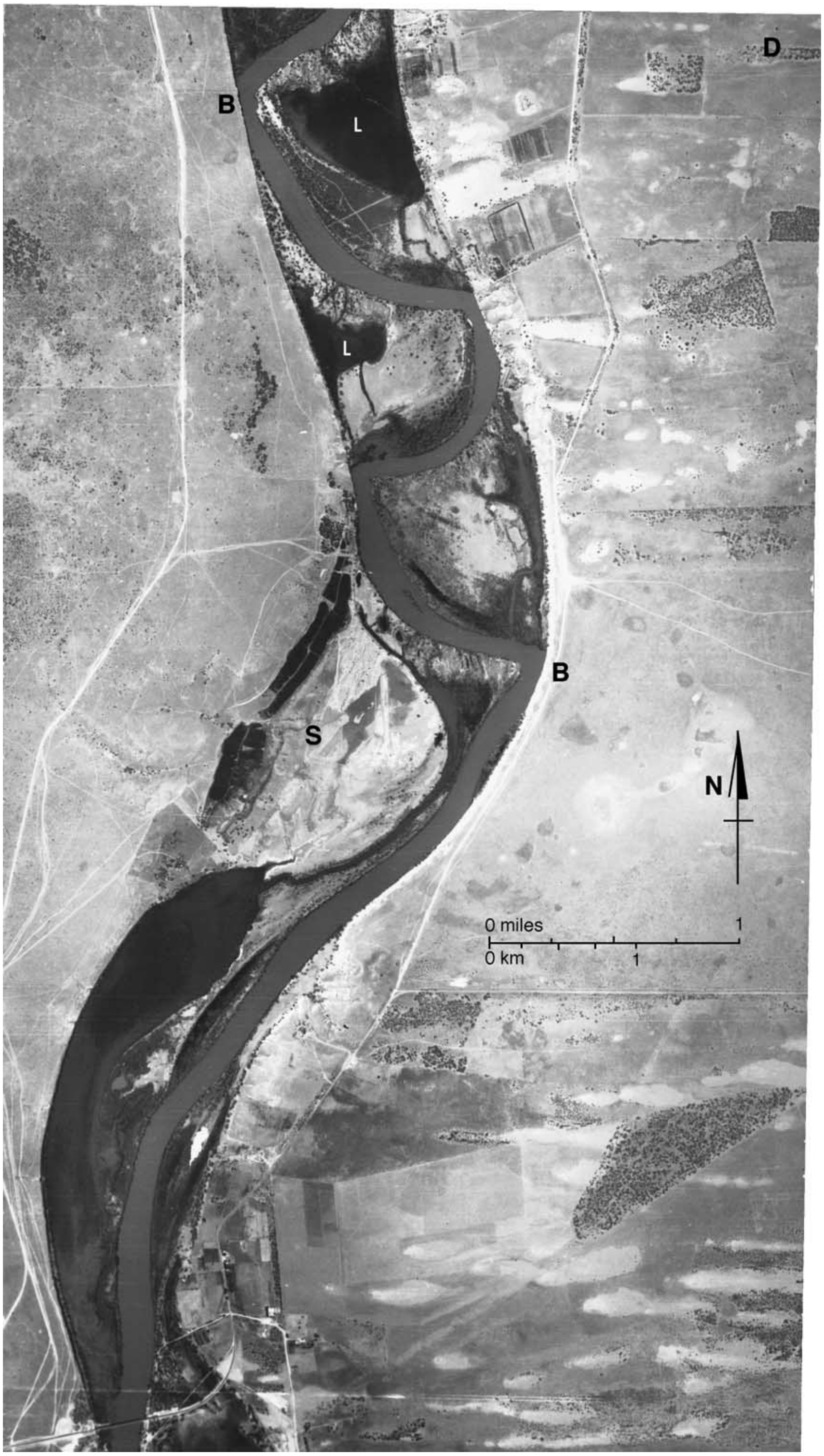


Fig. 4. Vertical air photograph of part of the Murray Gorge north of Blanchetown South Australia (bridge located near town). Note angular bends in meanders. B—undercut bluffs on outside of river curves; S—slip-off slope on inside of curve; L—lagoon; D—Late Pleistocene linear dunes.

attack or degree of non-parallelism between current and banks. Also, as more sediment enters a flow the more rapidly are loops developed. There is a fairly constant relationship between stream discharge (Q) at bankfull stage, width of channel, meander radius, and wave length, all being proportional to the square root of discharge ($Q^{1/2}$) (Leopold and Wolman, 1960; Leopold et al., 1964).

The depth of the channel is not constant, for the bed consists of regular alternations of pools, and shoals, bars or riffles in a downstream direction. All else being equal, the more sinuous a stream the deeper it is. The meander belt migrates laterally as well as downstream, and within it meanders also develop increasing sinuosity, eventually producing cut-offs or oxbow lakes. Meanders also migrate downstream, in places gradually but elsewhere so rapidly as to produce angular bends, rather than smooth curves, where the migrating channel cuts across and intersects the next loop downstream (Fig. 4). In flood, the channel tends to straighten and chutes are formed cutting across the inside of the river curves.

Most meanders are smooth so that the curvature is as gentle as possible. This suggests that frictional losses are minimal and that the meander is a 'least work' form. Chance obstructions undoubtedly induce diversions, unequal flow and curves and meanders that are transmitted downstream. Transfer of load within the channel from the inside to the outside of curves is an effect rather than a cause, for meanders form in streams of water devoid of sediment. If the rotation of the earth as expressed in the Coriolis Force affected river flow, as has been suggested, northern hemisphere rivers ought preferentially to erode their right banks and southern hemisphere flows, the left, but there is no evidence that this consistently has taken place.

It can be argued that where one medium, water, flows over another, rock, a wave motion is produced, creating areas of high and low velocity, of erosion (or non-deposition) and deposition, or pools and shoals. Deposition could cause channel widening, an increase in wetted perimeter and loss of energy. Bank erosion could be concentrated in areas of high bed velocity and hydraulic efficiency resulting in differential bank erosion, a winding course and, eventually, meanders. On the other hand, the formation of pools and shoals could be an effect, rather than a cause, of meanders.

3.3. Multi-channeled and anabranching streams

River channels are developed either in isolation or in linked intertwined complexes, though the distinction is to some extent arbitrary. The beds of all channels display highs and lows, riffles (or shoals) and swales. Where a river carries enough water to cover these, the channel is regarded as one, but where and when low discharge causes them to be exposed it comprises multiple channels.

In braided channels the two laterals are commonly the largest, i.e., widest (e.g., Leighly, 1934; Twidale, 1966a). They tend to straightness and are in many areas only slightly winding. They are characterised by higher discharge and slope than their meandering counterparts, and have high bedloads (Leopold et al., 1964; Knighton, 1984). They are hydraulically inefficient because of their comparatively long wetted perimeter in relation to cross-section area, but the numerous channels allow braided rivers to carry large volumes of water and thus can be regarded as a consequence of floods.

Anabranching streams form as new channels form by avulsion, by division and diversion (Miller, 1991; Knighton and Nanson, 1993; Nanson and Knighton, 1996). They are found in the humid tropics as well as arid lands (e.g., Garner, 1966; Pels, 1966). Anabranches are a common feature of rivers flowing over aggradational plains. They develop at various scales from the local to the regional. In southwestern New South Wales, for instance, to the east of Echuca where the River Murray has been diverted southwards by Late Quaternary faulting (Fig. 3), the Edward, and other rivers such as the Niemur and Wakool, flow north and then WNW before again linking with the Murray west of Swan Hill (Pels, 1966). Anabranches are, however, developed in bedrock terrains, as for example on the Katherine River, Northern Territory, where it traverses the sandstone plateau of the same name (Baker and Pickup, 1987).

4. Patterns and change in alluvial plains

Depending on their gradient and extent, the rivers of alluvial flats and flood plains (see Wolman and Leopold, 1957; Nanson and Croke, 1992) typically display either indefinite or dendritic patterns at the local scale, or parallel or subparallel arrangements regionally. Dendritic patterns, with channels oriented in a wide variety of directions, are commonplace in areas of nil or very slight slope, and little or no structural influence, as on coastal mud flats. Those bordering the Gulf of Carpentaria (Fig. 5a), where they are developed tributary to spectacular meanders formed on the tidal creeks (using the term in its British, as opposed to the Australian, sense) exemplify this type. There is evidence that meandrine forms dominate level paludal plains (Fig. 5b), but even a slight inclination induces parallel or subparallel patterns, despite variations in the composition and texture of the alluvia (Fig. 5c).

Fig. 5. (a) Meanders and dendritic tributaries of the Gin Arm Creek, eroded in coastal mud flats bordering the Gulf of Carpentaria, northwest Queensland (RAAF). (b) Vertical air photograph of former meanders in paludal sediments of the Wondoola Plain, part of the Carpentaria Plains, northwest Queensland (Department of National Development, Canberra). (c) Widely spaced parallel and subparallel streams of the Carpentaria Plains, northwest Queensland. Triangular dark patch right middle distance is due to grass fire (RAAF).

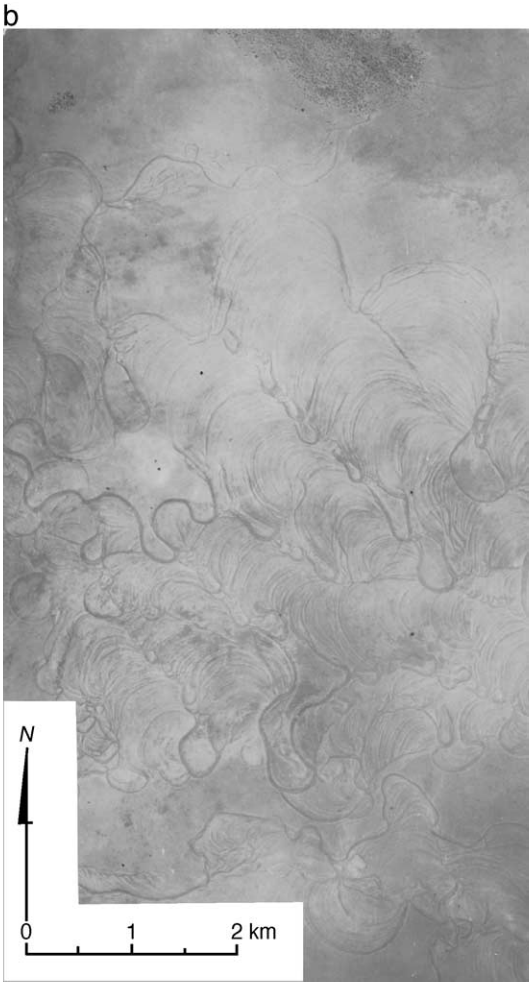


Fig. 5 (*continued*).

Rivers of alluvial plains are notorious for the rapidity with which their pattern and location change, especially when in flood. The ephemeral but high discharges primarily responsible for multi-channeled streams have several causations, including the summer rainstorms of temperate lands, spring snow and ice melt, episodic rainstorms of the desert, and monsoon rains. Such channels are typical of periglacial regions such as Alaska and Iceland (Fig. 6), and midlatitude mountain regions where streams are fed by meltwaters from glaciers and snowfields, as well as monsoon lands, and mountain regions subject to

Fig. 5 (*continued*).

heavy rainstorms (e.g., Baker et al., 1988; Costa, 1978; Garcia Ruiz et al., 1996). Thus, though climatically or meteorologically induced, braided channels are not a zonal or climatic landform. That braided channels reflect high discharge is confirmed by the development of such patterns during floods resulting

Fig. 6. A glacial outwash plain or sandur in Iceland, with complexly interlaced anastomose channels, formed by a flood due to melting of snow and ice (jokhulhaup) (S. Thorarinsson).

from catastrophic events such as dam-bursts (e.g., Kiersch, 1964). The failure of the Malpasset Dam near Fréjus (between Cannes and Toulon) in southern France, released a huge volume of water and huge blocks of rock and other debris were carried on the resultant flood (Tricart, 1960). Where it emerged from the upland, the River Reyran spread over the landscape in innumerable small channels and overland comparable with relic distributary streams on covered pediments shaped in the piedmonts of semiarid uplands (e.g., Twidale, 1981; Bourne and Twidale, 1998).

Demonstrated rates of change in rivers flowing in their own alluvium are astonishing: the Brahmaputra, 10 km in the last 150 years; the Kosi, 113 km in 228 years; the Tisza, 100 km during the Holocene, and so on (see Osborn and du Toit, 1990). Such recent changes of river position are not temporally atypical. Extant rivers have moved laterally during the later Cainozoic. For example, the Red Deer River has migrated at least 5 km in the later Pleistocene; the Missouri in northeastern Montana, some 80 km in last 10 Ma; the Yellowstone, 56 km in the last 7 Ma; in the Black Hills of Dakota, Rapid Creek has shifted 8 km since the Miocene; in Nebraska, Pumpkin Creek has moved laterally 6 km during the Quaternary, and the Potomac River about 90 km (for references, see Osborn and du Toit, 1990).

Changes wrought during floods can be dramatic, at both the local and regional scales. Chinese rivers such as the Hwang Ho (Yellow River) provide recent examples of repeated rapid change on a vast

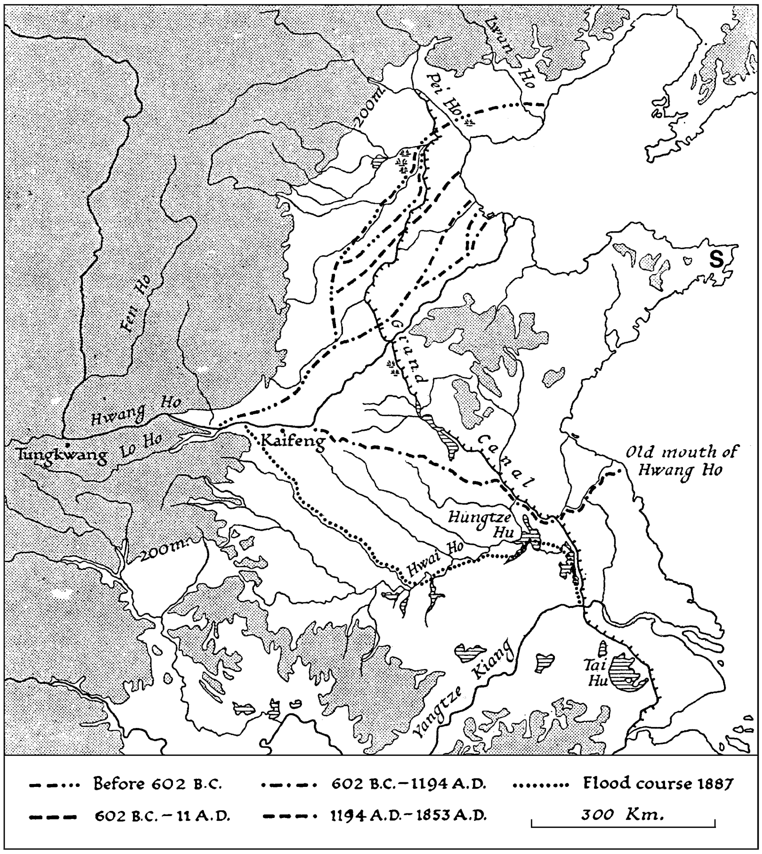


Fig. 7. Location map of northeast China showing changing course of Hwang Ho. S—Shantung Peninsula (after Naval Intelligence Division (British Admiralty), 1943).

scale (Fig. 7). The fertile plain of the lower Hwang Ho is the gift of the river in that it is a deltaic alluvial plain deposited by the river below Kaifeng. It is, however, also known as China's sorrow because of the disastrous floods frequently generated on it. In this middle sector, around Tungkwan the Hwang is joined by the Wei and Fen both of which contribute immense quantities of silt derived from the loess plateau. Here the river may carry as much as 40% by weight in sediment, and some of its tributaries as much as 48%. By contrast, it is rare to find sediment amounting to more than 10% by weight in 'normal' rivers, and even 2–3% is considered high.

What is now the Shantung Peninsula was once an island which has been linked to the mainland as a result of alluviation of the Hwang Ho. The river has repeatedly broken its banks, flooded, migrated and reestablished itself elsewhere. At one time or another it has occupied almost every part of the plain from Tiensin in the north to the lakes of northern Kiangsu in the south. From 602 BC to 1194 AD, it flowed to the Gulf of Pohai to the north of the present outlet, and before that even further north, not far south of Shanhaikwan, near where the Great Wall reaches the sea. But from 1194 to 1853 its course from Kaifeng was ESE to an outfall far south of the Shantung Peninsula, usurping the channel of the lower Hwang Ho. Then, following a great flood and destruction of dykes in 1853–1855, the Hwang changed to its present course, reaching the sea just north of the Shantung Peninsula. Floods occurred due to the river silting and building up its own bed between levees, eventually bursting or overtopping banks (Naval Intelligence Division, 1943). Yet the 1853 flood event was by no means the greatest on the river, for sedimentological evidence shows that it was exceeded four times between 6000 and 8000 years ago (Yang et al., 2000).

By contrast with the Chinese experience, however, some floods apparently achieve little in the way of either erosion or deposition. Thus during the 1974 monsoonal flooding of the Carpentaria Plains the turbid waters of rivers draining the Isa Highlands were essentially confined to the channels. There was extensive flooding near the coast, and inland the broad flat riverless plains carried standing water, which drained into marginal channels when their levels fell. There was some gullying but overall little change to the Plio-Pleistocene plains (Simpson and Doutch, 1977).

5. River patterns

5.1. General remarks on the nature of rivers and river patterns

Hills (1963, p. 439) remarked that possibly the greatest aid that geomorphology offers to structural geology is to be derived from drainage patterns. They not only provide clues as to possible structure, for example fracture patterns and bedrock type, but they also assist in unravelling local and regional geological chronology. In addition, the development of river patterns is relevant to the search for diamonds (e.g., de Wit, 1999), gold (e.g., Clark, 1966) and uranium minerals (e.g., Binks and Hooper, 1984).

River patterns develop through natural selection. On an initial slope (for the sake of discussion, a raised and tilted seafloor or a volcanic slope) runoff forms overland linear flows, the spacing of which is a function of rock permeability and discharge (in time and space) and of slope. Of, let us say, 10 channels on a particular slope sector, one will become the dominant or master stream, most likely because its course coincides with a weakness in the substrate—a less permeable outcrop or a fracture, perhaps. Alternatively, the complex of factors determining drainage density may come into play.

Once a river incises its bed more than its competitors, it attracts more groundwater flow and runoff simply because it is the local lowest baselevel. Positive feedback effects cut in and subject only to baselevel control, the erosional potential of the master river is increasingly enhanced. Moreover, erosion is unequal (Crickmay, 1932, 1976). Energy is concentrated within and near river channels. Quite extensive divides either lack enduring channels (Knopf, 1924; Horton, 1945)—even rills are ephemeral (e.g., Dunne and Aubry, 1986)—or are characterised by dry valleys (e.g., Dietrich et al., 1986). Thus, river patterns ought to be long-lasting and many are, even in terms of geological time. Extant rivers of at least Eocene age have been recognised in the Yilgarn of Western Australia (Van de Graaff et al., 1977; Commander, 1989; Clarke, 1994) and in the Mt. Lofty and Flinders ranges of South Australia (Twidale, 1997).

5.2. Incised meanders

The temporal development of alluvial meanders is germane to an understanding of the deeply incised meanders that dominate river patterns in many upland areas. Incised meanders have been interpreted (e.g., Campana, 1958) as river meanders inherited from a former surface of low relief. In reality, all incised meanders have shaped valleys that are asymmetrical in cross-section, albeit to various degrees (Fig. 8a). They are autogenic forms which develop their asymmetry as a result of lateral migration of the river during incision, as witness the development of slip-off slopes and undercut bluffs (Mahard, 1942; see also, King, 1942, p. 152; Birkenhauer, 1991, p. 297). Incised meanders evolve to such an extent that 'goose necks' (of which there are well-known examples in the canyons of the Colorado River in southwestern USA), and eventually, abandoned meander cut-offs, congeners of oxbow lakes, are also formed (Twidale, 1955; Fig. 8b).

Fig. 8. (a) Entrenched river valley in the Zagros Mountains, with well developed slip-off slopes and undercut bluffs together forming incised meanders (Hunting Surveys). (b) Vertical air photograph of the Zambezi River valley below the Victoria Falls, showing zig-zag pattern controlled by fractures in the Jurassic basalt. Note abandoned incised cut-offs (CO) (Government of Rhodesia).

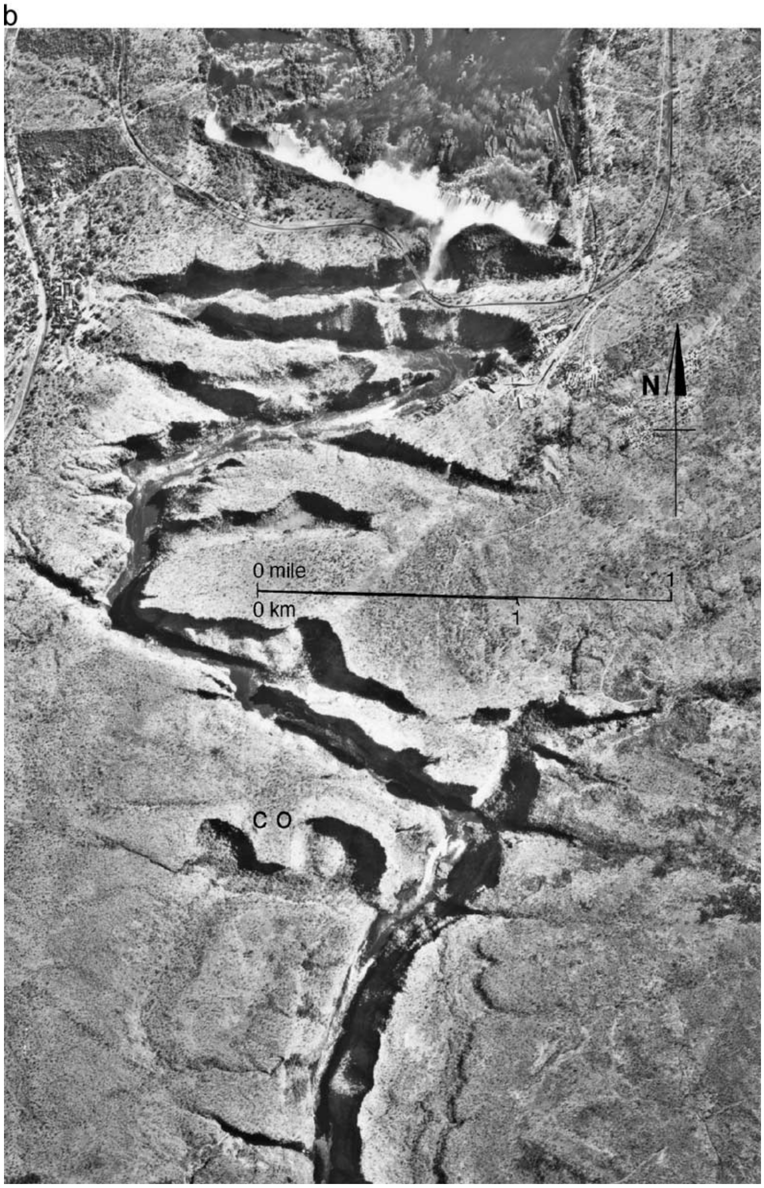


Fig. 8 (*continued*).

In greater measure than their plains counterparts, incised meanders display structural control. East of Adelaide, where the River Torrens flows through the western margin of the Mt. Lofty Ranges, it pursues a winding course in its gorge section. The river channel and gorge trend parallel to strike (in phyllite) and cleavage (in gneiss) for a substantial proportion of their length in this sector (Twidale, 1972). The straight arms of the intrenched Shenandoah River near Strasburg, VA, are other notable examples.

5.3. Adjusted and anomalous patterns

The spatial arrangements of streams and rivers can be considered adjusted to or concordant with slope and structure, or anomalous (transverse, exotic) in terms of

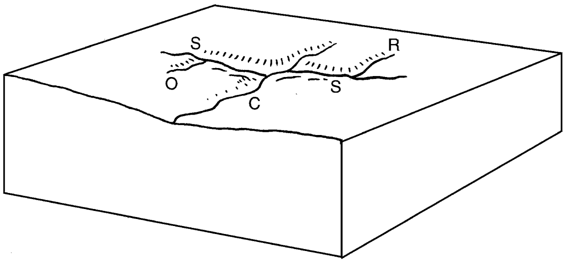


Fig. 9. Diagram showing various slope-related streams: C—consequent; S—subsequent; R—resequent; O—obsequent (after Johnson, 1932).

these two factors. Most streams are adjusted. Even rivers that are considered anomalous comprise long adjusted sectors linked by short transverse elements. Also, in detail, streams tributary to the incongruent streams are commonly adjusted to local structure.

5.4. Slope and structure

Rivers initially follow slope and then adjust to structure as they incise their beds. The names given to streams according to their relationship to slope (consequent, subsequent, obsequent, resequent: Fig. 9) have proved to be impractical or less satisfactory than alternative schemes. A consequent stream flows down the initial slope. Subsequent streams are developed along lines of structural weakness (e.g., weak strata, by headward erosion). Obsequent rivers run in a direction opposite to the consequents, i.e., on the upslope-facing or reverse sides of subsequent valleys. Resequent streams flow in the same direction as consequents but at a lower level, e.g., on the downslope-facing flanks of subsequent valleys. Insequent streams conform to neither structure nor slope.

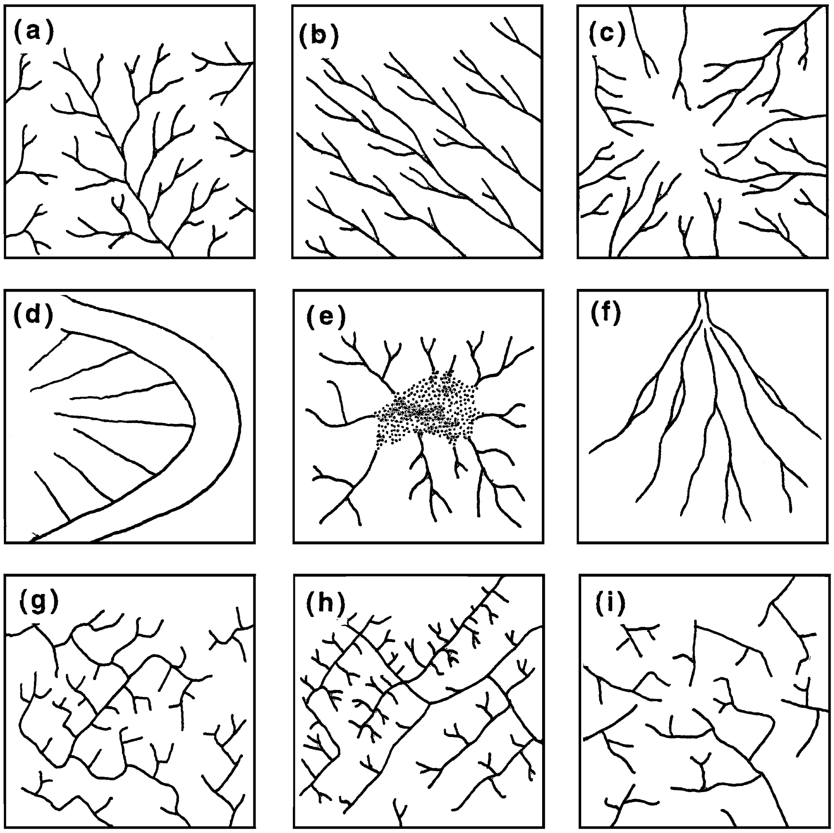


Fig. 10. Sketches of various drainage patterns determined by slope or structure. (a) Dendritic, (b) parallel, (c) radial, (d) centrifugal, (e) centripetal, (f) distributary, (g) angular, (h) trellis, (i) annular.

Rivers running down the slope of a recent volcanic cone are consequent but in most other cases the original slope cannot be identified. Thus, resequent streams cannot be recognised, and the various types of stream are best described according to their relationship to local structure: dip, strike or antidip, fault-line, and so on.

The classic paper on adjusted drainage patterns is due to Zernitz (1932), who identified structure and slope as primary determinants of spatial arrangements of stream channels, though some of the categories she listed involve other factors. Howard's (1967) is a later and more refined, but in places over-elaborate and misleading, classification. The names of slope- and structurally-generated categories are self-explanatory (Fig. 10).

5.4.1. Parallel and subparallel

Rivers flow downslope. Parallel and subparallel patterns imply control of flow by gradient and a lack of structural interference (Figs. 5c and 11). The rivers of the Atlantic coastal plain from Virginia south to the Florida border run in parallel, as do those of northern Sweden (north of Stockholm) draining to the Baltic Sea. Zernitz (1932, p. 511) cited patterns in part of northwestern Finland and also rivers running along parallel fault zones; but the latter are structural and most commonly are accompanied by conjugate fractures, giving an angular pattern.

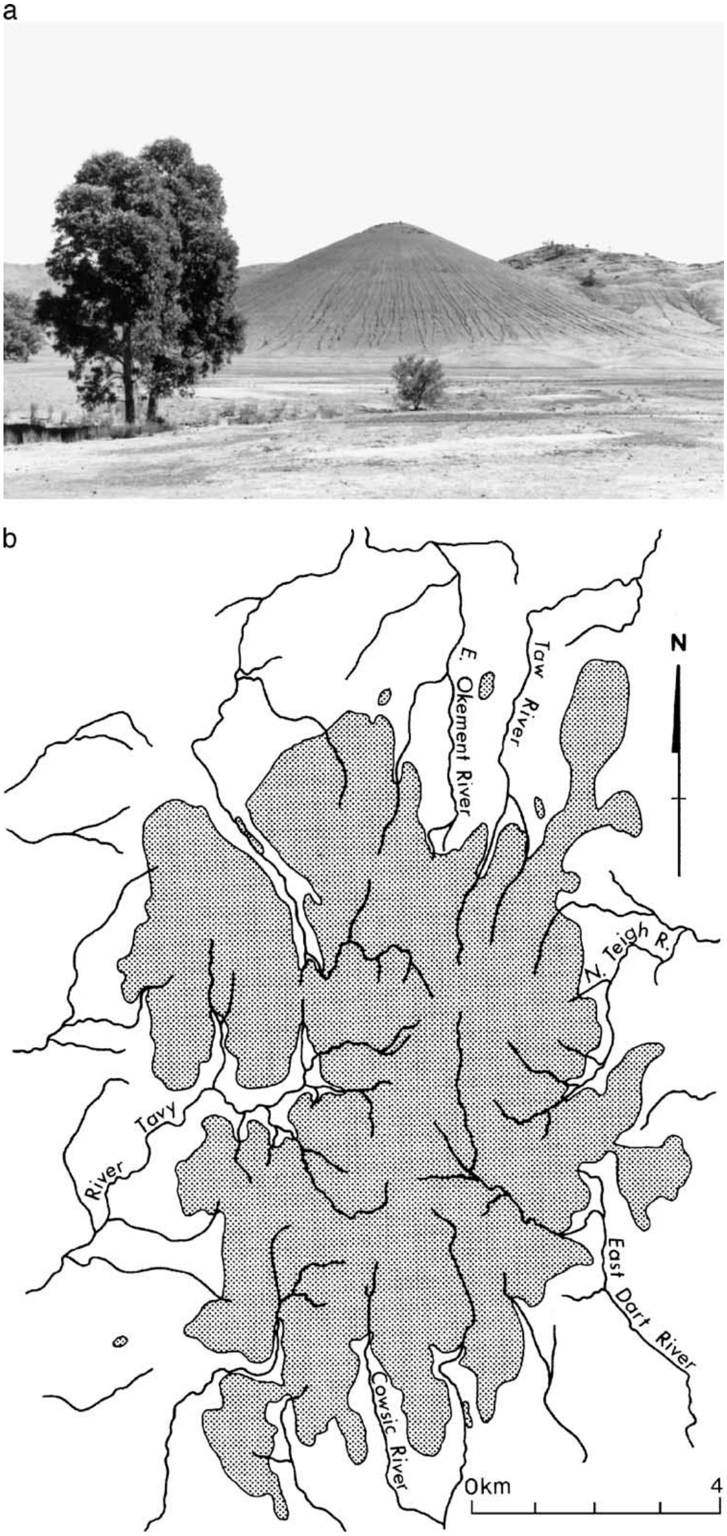
5.4.2. Radial

Rivers rising near the crest of a rise are guided by slope and flow to all quarters of the compass (Fig. 12). Volcanic cones at various scales from the Big Island of Hawaii and Tristan da Cunha to Barrington Tops, in New South Wales illustrate this pattern. The rivers of granite uplands in, for example, Dartmoor, in southwestern England, and the Benom Complex of Pahang, in West Malaysia (Ahmad, 1979) have developed a radial pattern overall, though in detail joints have induced the development of local angular patterns within the radial framework. At a local scale, Whitehouse (1944) described as radial or centrifugal gutters developed on the insides of meander loops on the tidal mudflats of coastal northwest Queensland.

Fig. 11. Deep parallel–subparallel gullies in grus, near Paarl, Western Cape Province, South Africa.

Drainages from elongate uplands frequently form irregular radial patterns, but structure has in places produced major distortions. For instance, the drainage of the central Flinders Ranges is manifestly asymmetrical. One headwater of Wilpena Creek rises within 4 km of the western ramparts of the upland and the adjacent Lake Torrens Plains. The Creek flows east, and after being joined by the Siccus River eventually reaches Lake Frome, some 130 km away. In this sector the Ranges are developed in an anticline with a meridional axis within the Neoproterozoic and Cambrian strata of the Adelaide Geosyncline. Rivers flowing east and west from the crest of the structure have breached several resistant formations and notably sandstones

Fig. 12. Radial patterns (a) on shale hill, incongruously but understandably known locally as 'Fuji Yama', in the central Flinders Ranges, South Australia: the numerous small gullies formed during a late summer storm in 1955, and (b) on the Dartmoor granite massif, southwestern England. Note the adjustment of some tributaries to jointing in the country rock.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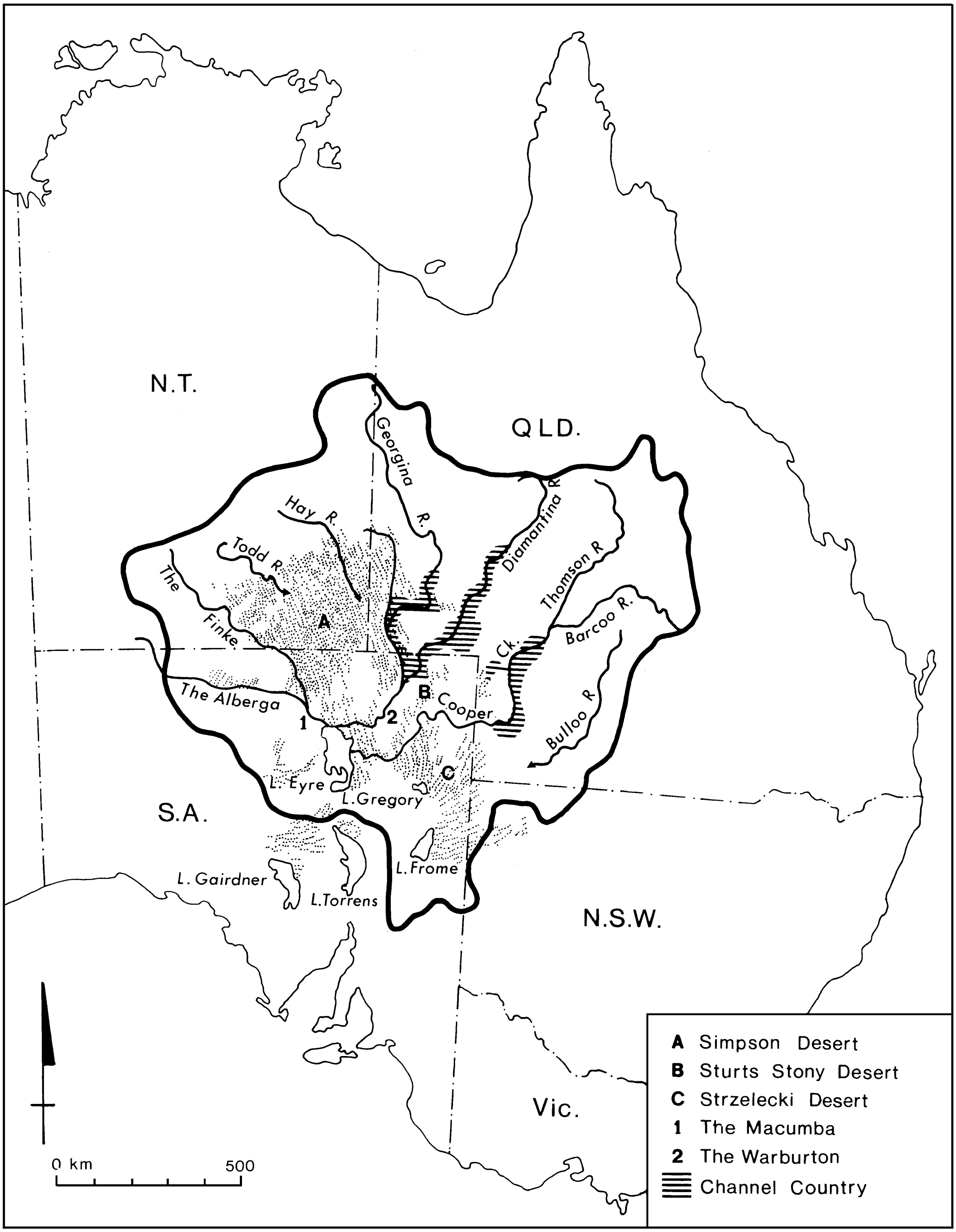

Fig. 13. Centripetal drainage pattern of the Lake Eyre catchment, central Australia.

and quartzites, but because the source of detritus deposited in the Geosyncline was to the west (the Gawler Craton), strata are thicker on the west and thinner to the east. Thus, the Pound Subgroup arenaceous beds (Rawnsley Quartzite and Bonney Sandstone) are about three times as thick in the west as to the east. For this reason the east-flowing streams were able to incise their beds more rapidly than their western counterparts, and headed back to capture many of the original west-flowing streams. The stratigraphic evidence shows that this pattern has developed over a period of at least 130 million years (Twidale and Bourne, 1996).

5.4.3. Centripetal

Rivers that converge upon a common area form a centripetal pattern. They have developed at various scales. Lake Eyre is the focus of a catchment of 1.3 million km^3 drained by such intermittent or episodic rivers as the Georgina, Diamantina, Thomson, Barcoo, and Finke (Fig. 13). Though their waters eventually drain into the Nile, rivers like the Katonga, Kagera and Mara first converge on Lake Victoria. At a local scale numerous small and episodic streams flow to the enclosed floor of Wilpena Pound, a natural amphitheatre in massive sandstone and quartzite, located in the central Flinders Ranges and drained by the Wilpena Creek, which has breached the northeastern wall of the structure.

Convergent patterns can be regarded as incomplete centripetal patterns or as the converse of distributary (below). Rivers emerging from a gorge frequently develop a distributary habit. Conversely, tributaries converge on and join rivers that breach ridges (Fig. 14). Such flows stand at a lower level

Fig. 14. Convergent drainage (C) and trellis pattern in folded sediments, with long strike streams in weak strata linked by dip streams which breach resistant outcrops, west-central Flinders Ranges, South Australia. The streams converge on the Brachina Gorge and Bunyeroo Gorge is in left foreground (RAAF).

than any others in the vicinity, and for this reason river capture (q.v.) is frequently involved in the development of convergence.

5.4.4. Distributary

Rivers debouching from narrow mountain gorges on to plains or valleys are no longer confined and,

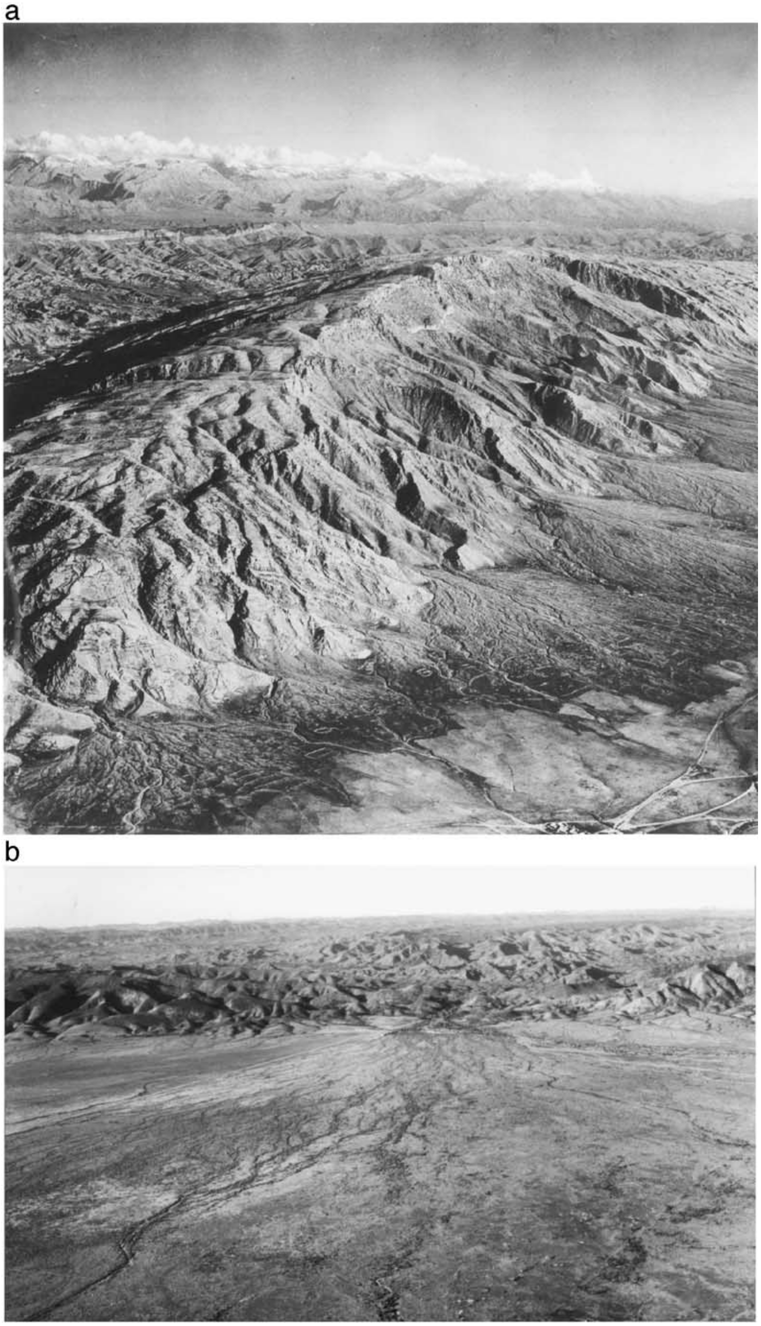

Fig. 15. Distributary patterns developed on alluvial fans (a) in the Zagros Mountains (Hunting Surveys), and (b) near Parachilna, in the western piedmont of the Flinders Ranges, South Australia.

especially in episodic or periodic floods, tend to break their banks and develop a multitude of channels (Fig. 15). Total wetted perimeter relative to total cross-section area of channels is increased and deposition is induced. In the western piedmont of the Flinders Ranges, however, both covered pediments and alluvial fans have been shaped by distributary streams. Both of these forms, one essentially erosional, the other depositional, are fan-shaped, sloping down in all directions within the half-circle originating at the apex or point of debouchment of the river. Both display radiating, distributary or divaricating (Blackwelder, 1931) stream patterns comprising numerous interlaced channels, the location of which can change in major floods. Whether pediment or fan has formed depends on the character of the load and to some extent relief amplitude, which in turn vary with the nature of the catchment (Bourne and Twidale, 1998).

Deltas form where rivers flow into the ocean or lakes. Various patterns develop according to the relative densities of the river and sea waters (Bates, 1953): long comparatively narrow deltas where the incoming flood flow is heavier than the sea or lake water (the Colorado in Lake Mead), arcuate or fan-shaped where the two are roughly the same (the Nile Delta), but elongate and distributary where the river water is less dense than the sea—the bird foot type exemplified by the Mississippi Delta.

5.4.5. Straight

Linear valleys eroded by rivers with limited meander development are due to the exploitation of fractures by weathering and then by erosion. They occur at scales from the very local to the regional. Short linear sectors (up to a few kilometres but commonly just a few tens of metres; Fig. 16) may be related either to joints or faults. Longer straight rivers are almost certainly due to the influence of faults. Minor examples of fault-line streams include sections of the Kwagia River in eastern Papua New Guinea, and the West Baines in the Northern Territory (Fig. 17a and b). Some sectors of the Orinoco and the Mississippi rivers can also be cited (Sternberg and Russell, 1952) but many other instances can be identified. Regional examples of fault-line valleys include some emphasised by glaciation, as in northern Scotland, and northwestern Canada (Fig. 17c).

At the local scale some short stream lines are essentially straight though irregular in detail but within the channel obvious fractures are either few and discontinuous, or absent (Fig. 18). These clefts or slots are probably due to linear zones of strain which, given further, continued or renewed stress may eventually develop into fractures. Crystals in strain are in disequilibrium and more vulnerable to weathering and hence erosion than are their less-stressed counterparts (Russell, 1935).

Some straight river sectors are aligned in parallel with regional lineament patterns. Lineaments are straight or gently arcuate structural lines (faults, cleavage, fold axes) which, being zones of weakness, find expression in the landscape (e.g., Hobbs, 1904, 1911; Ramberg et al., 1977; Allum et al., 1978). They are due to recurrent or resurgent shearing (Hills, 1955, 1961, 1963, pp. 333–334), and can be identified at all scales from the local to the regional. They are of great antiquity and their formation may be due to shearing associated with the Earth's rotation (De Kalb, 1990).

Lineaments have been exploited not only by ascending mineral-bearing liquids from the mantle (see, e.g., O'Driscoll, 1986; O'Driscoll and Campbell, 1997) but also by exogenic weathering and erosion leading to linear streams and valleys. Whereas epigene rivers exploit lineaments and become entrenched from above, structural control can also be imposed from below. Some notably straight rivers and valleys are found in alluvial settings (Fig. 19a). They have been attributed to underprinting, to the transmission of structures in the underlying bedrock into the alluvial sequence above. The Darling, which flows essentially straight for about 750 km between St George in southeast Queensland, to near Menindee in western New South Wales, is a well-known example. It flows in Quaternary alluvium and its linearity is attributed to the effects of a lineament transmitted from the underlying Palaeozoic and Mesozoic bedrocks (see, e.g., Hills, 1956, 1961). The Flinders and Leichhardt rivers of northwest Queensland (Twidale, 1966a) and the several straight rivers of the Lake Eyre catchment, including the lower Diamantina–Warburton, the Georgina, and the Thomson–Cooper flow in similar alluvial settings. The plan form of the gorge incised by the River Murray between Renmark and Morgan, South Australia, can be interpreted as determined by fractures underprinted from old basement rocks (Fig. 19b), a

b

Fig. 16. (a) Straight clefts or slots developed along joints exploited by weathering and runoff, Paarlberg, Western Province, South Africa. (b) *Kluftkarren* in granite developed along fracture zone, Kwaterski Rocks, northwestern Eyre Peninsula, South Australia. (c) Vertical air photograph of straight streams in schist near Otago, South Island, New Zealand. The main drainage lines run parallel to the cleavage of the bedrock. X—schist residual (N.Z. Government; see also Turner, 1952).

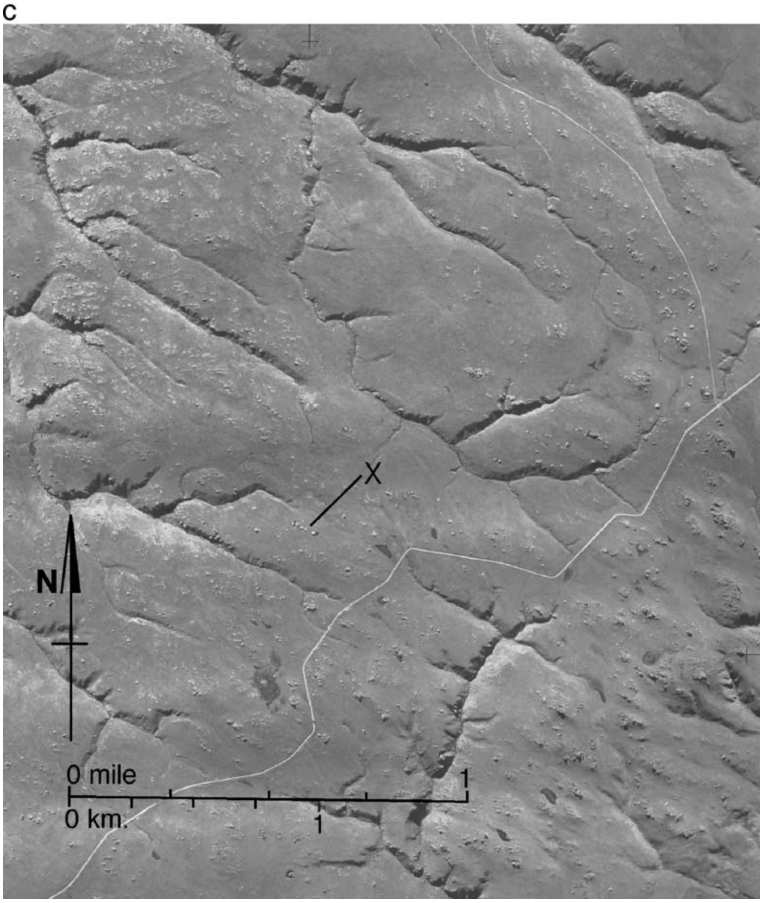

Fig. 16 (*continued*).

for the alignments of the various sectors mimic known regional fracture patterns (Firman, 1974).

The precise mechanism responsible for such underprinting is not clear. It could be that joggling in the basement has induced fracturing in the alluvia. Alternatively, deep linear fractures could attract vadose waters and expedite weathering and facilitate erosion in linear zones (cf. Twidale and Bourne, 2000).

5.4.6. Angular

Angular stream patterns consist of essentially straight streams which join in angular junctions. The disposition of the various elements reflects the spacing and arrangement of fractures in the host rock. The plan geometry of the latter and hence of associated streams, varies. Some describe orthogonal patterns, others are rhomboidal in plan. Fracture patterns are widely spaced and orthogonal where the Murchison River crosses the sandstone of the Victoria Plateau near Carnarvon in the northwest of Western Australia (Hocking et al., 1987; Twidale, 1997) and where the Katherine River crosses an outcrop of flat-lying Proterozoic sandstone near the town of the same name in the Northern Territory (Fig. 20). In some of the granite outcrops of the Mt. Buffalo area, Victoria (Baragwanath, 1925), streams are disposed roughly normal to one another, whereas in the Jurassic basalts exposed in the Zambezi Valley below the Victoria Falls, the fractures are disposed at acute angles to one another and have given rise to a compressed zig-zag pattern (Fig. 8b).

5.4.7. Trellis and annular

Trellis patterns are typical of zones of roughly parallel or only gently arcuate outcrops associated with

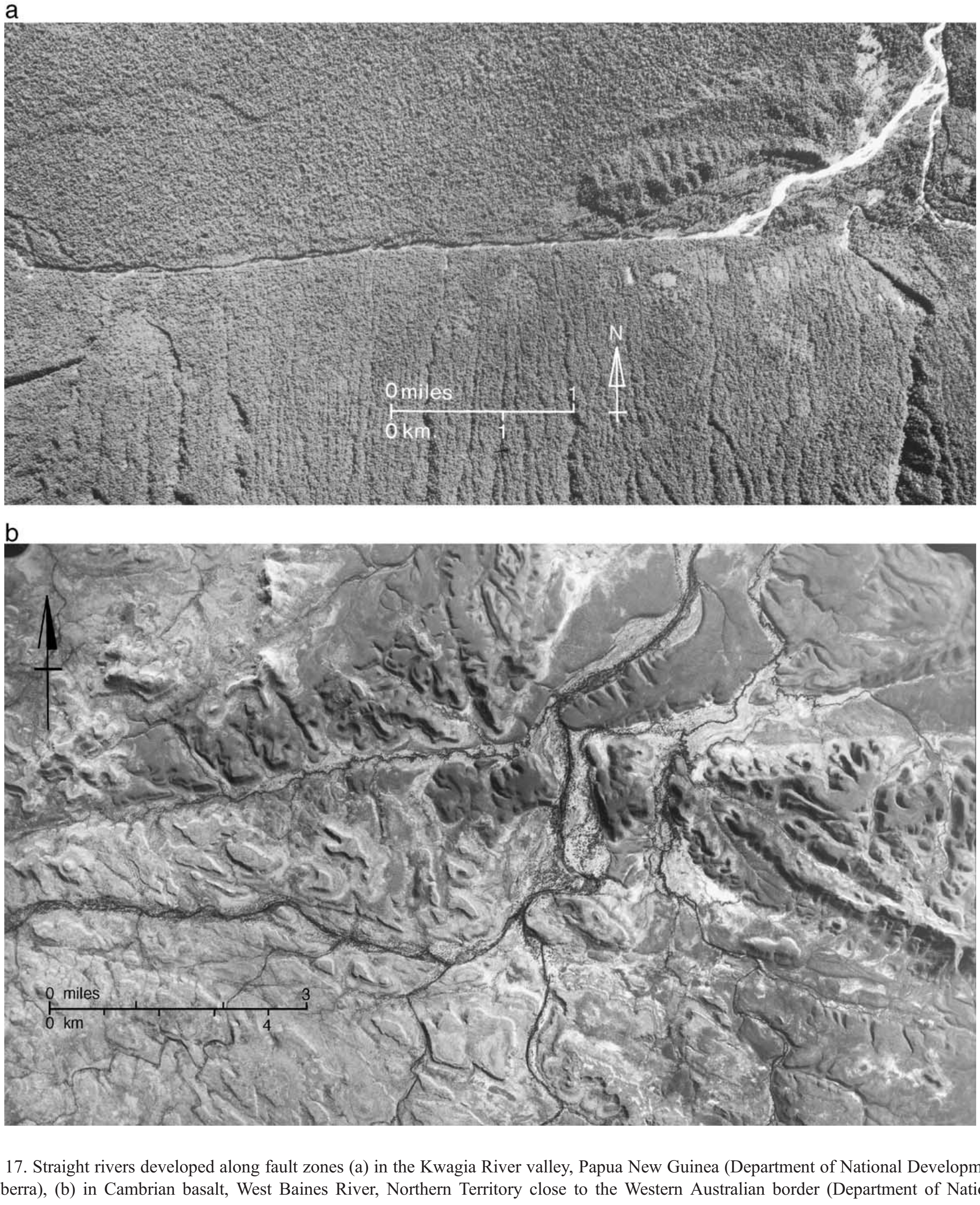

Fig. 17. Straight rivers developed along fault zones (a) in the Kwagia River valley, Papua New Guinea (Department of National Development, Canberra), (b) in Cambrian basalt, West Baines River, Northern Territory close to the Western Australian border (Department of National Development, Canberra), and (c) along fault zones (the largest, the Owikeno lineament is marked X) in the coastal ranges of British Columbia, Canada. The faults have been exploited by weathering, rivers and glaciers, and in some instances inundated by the sea (Department of Lands Forests and Water Resources, British Columbia. Photo B.C. 1231.72 taken October 1950).

Fig. 17 (*continued*).

the flanks of anticlines and synclines within folded sedimentary sequences, as in the Appalachians of the eastern United States. Trellis forms develop where outcrops are linear, annular where the outcrops are curved as in structural domes and basins, as for example in the Black Hills of Dakota, and central Flinders Ranges, South Australia, on various dome or basin structures, e.g., the Blinman Dome. The dip and antidip streams are developed by headward erosion (q.v.) along structural weaknesses (joint or fault zones).

6. Headward erosion and stream capture

Trellis and annular patterns are characteristic of fold mountain belts with ridge and valley topography. The divides between valleys frequently take the form of ridges of resistant rocks such as quartzite, or of strata which, though of the same composition as those that underlie the adjacent valleys, are massive, with more widely spaced planes and joints. No rock is devoid of fractures, and these have been exploited (Thompson, 1949) by dip and antidip rills and streams eventually to breach the ridges and link strike streams in adjacent valleys to produce the typical drainage patterns. Some authors have denied the possibility of headward erosion (e.g., Strahler, 1945, pp. 51–52), but what can be construed as stages in the breaching of divides can be seen in the field (Fig. 21). Thus notches in ridges, ridges all but breached, and completed break-throughs have been noted in the southern Flinders Ranges, for example (Fig. 22). Such regressive extension, though slow (Taylor et al., 1985; Young and McDougall, 1993), is nevertheless real.

In the Comstock Valley (Fig. 22), the anticlinal valley initially sloped down to the south, where the Comstock stream joined the Mt. Arden Creek. The Skeleroo Creek and lower tributary of the Mt. Arden Creek breached the western quartzite limb of the fold and captured the Comstock headwaters. The northern part of the plain was lowered creating an 8–10 m high north-facing erosional scarp separating the younger from the original valley floor. The elevation of the northern plain before erosion is indicated by patches

Fig. 18. Almost straight cleft developed along suggested zone of strain, with fractures visible only in parts of depression, Little Wudinna Hill, northwestern Eyre Peninsula, South Australia.

of kaolinised bedrock and associated perched platform remnants on the midslope of the quartzite ridges. Why Skeleroo Creek (1 in Fig. 22b) breached the ridge is not clear: there are indications of faulting but no clear evidence. A creek which presumably exploited open joints in the sharp nose of the pitching anticline has almost reached the margins of the northern plain, and to the south and as illustrated (2 in Fig. 22b), another creek has almost breached the eastern limb of the Comstock anticline (3 in Fig. 22b, also Fig. 21b). It will in due time compete with the headwaters of the Mt. Arden Creek.

These captures, actual and incipient, have been achieved by regressive erosion and valley extension. Mass movements and rills are more important than river or stream flow in headward extension for seepage, sheetwash (not obvious if accompanied by rainsplash; see, Dunne and Aubry, 1986) and slumping have obviously been at work at some sites. Groundwater sapping is a potent force lowering divides and extending headwater streams (Pederson, 2001). Processes generated by infrequent but potent rainstorms may be at least as significant as the same mechanisms driven by lower energy events (see, e.g., Dunne, 1980; Dietrich et al., 1986).

Headward erosion is significant not only in the evolution of trellis and annular patterns but is also widely invoked in explanations of stream capture or piracy. Bishop (1995) has identified three types of stream re-arrangement that involve not only changes in pattern but also in catchment boundaries and areas. Capture can be induced not only by headward erosion (what Bishop termed passive or ‘bottom-up’ interception) but also by lateral migration and by tectonism involving ‘top-down’ interception by streams. Even minor earth movements change slope inclinations and thus have the potential to alter stream flow.

However attained, all captures result in unusual, in places spectacularly odd, changes in stream alignment, as exemplified in such reversals of drainage direction as that exemplified in the Silverwater Stream, near Wellington, New Zealand (Lauder, 1962). The Silverwater now turns through some 120° on joining the Korori, to form a boat-hook, fish hook, or barbed pattern. Dry (‘wind’) gaps or abandoned valleys that breach ridges are formed where stream sectors have been abandoned as a result of piracy (Taylor, 1911; Thornbury, 1954, pp. 152–155; Hills, 1975; Haworth and Ollier, 1992; Bishop, 1995; Twidale and Bourne, 1996); though in carbonate terrains they may have been forsaken for other reasons (q.v.).

Whether induced by regressive stream erosion or by warping, stream capture is, like the development of meandrine forms in uplifted fold mountains, a common feature of river patterns.

7. Other circular or arcuate patterns

In addition to the annular patterns of sedimentary terrains, circular and arcuate patterns are developed on gneiss domes in many of the shields and older orogens of the world (e.g., Eskola, 1949; MacGregor, 1951). The concentric drainages around Stone Mountain and other bornhardts in Georgia have been attributed to scarp-foot weathering (Dennison, 1997; see also Clayton, 1956; Twidale, 1962). Other arcuate and circular patterns are related to meteorite impacts. For example, though orthogonal systems are most common in the Neoproterozoic ignimbrites of the Gawler Ranges, South Australia, rhomboidal patterns are developed in places, consistent with torsional strain (e.g., De Kalb, 1990) but around the Acraman impact, concentric arcuate fractures are superimposed on the regional orthogonal pattern (Fig. 23) (e.g., Crawford, 1963; Williams, 1986, 1994; Twidale and Campbell, 1990).

Arcuate patterns are developed at the regional scale in crystalline terrains around the North Atlantic (Richter and Kaminine, 1956), but they are found also in other geological settings, for instance in the Western Cordillera of North America (Alaska, Arizona, Mexico) and in the Appalachian region. They have been reported from central and northeastern Africa and adjacent parts of the Arabian Peninsula (Saul, 1978; Baker et al., 1991), and from southern Africa and Australia (Brock, 1972; Kutina, 1995). In Arizona and the Appalachians they occur in elongate clusters trending northwest and northeast, respectively.

Using geophysical (Bouguer anomaly) maps O'Driscoll and Campbell (1997) identified not only lineaments but also ring structures (Fig. 24a) (see also

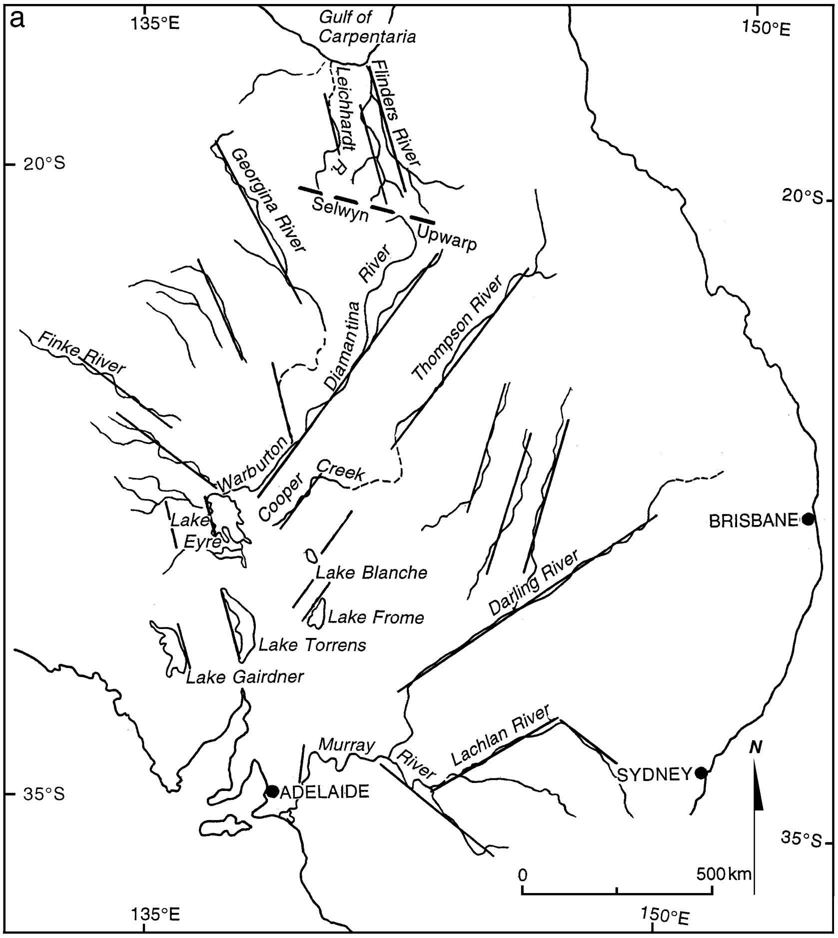

Fig. 19. (a) Underprinted straight rivers of central and northern Australia. Diversion of headwaters of the Diamantina River by the Selwyn Upwarp is also shown. Straight lines indicate lineaments. (b) Angular valley patterns developed along suggested underprinted fractures on the River Murray between Renmark and Morgan, South Australia. Downstream from A, river flows in gorge. Morgan Fault shown by heavy dashed line. The linked sector A–B is some 16 km long.

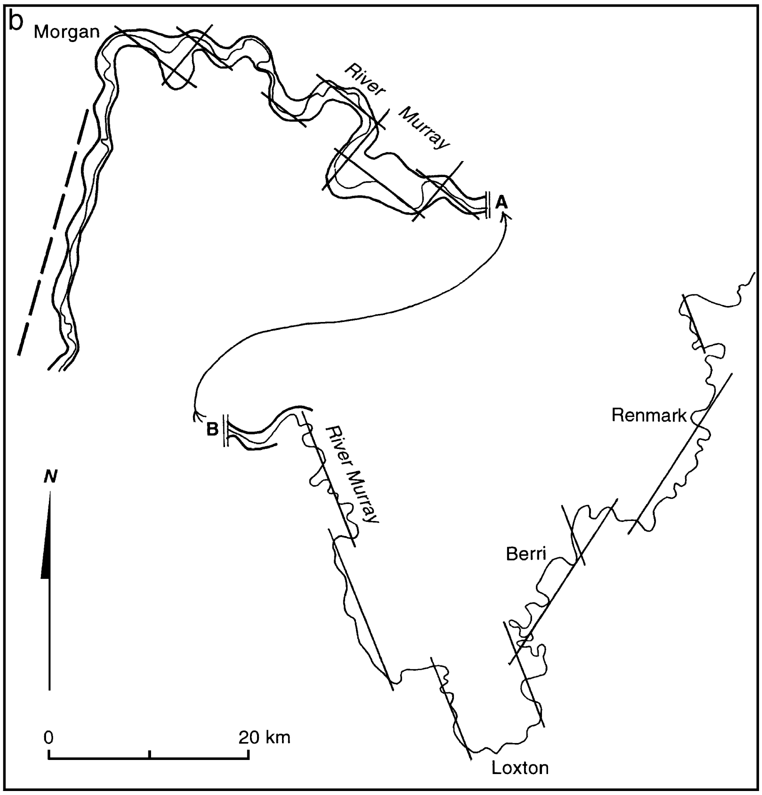

Fig. 19 (*continued*).

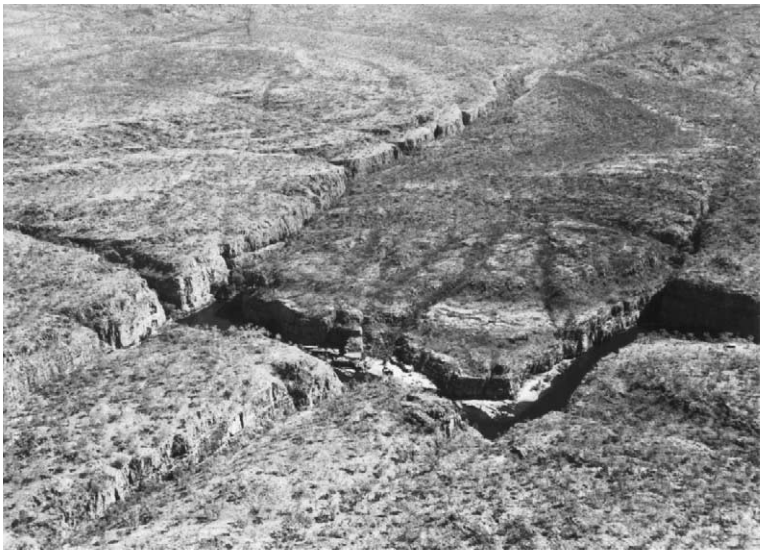

Fig. 20. Orthogonal patterns of streams and valleys in flat-lying Proterozoic sandstone, Katherine, Northern Territory.

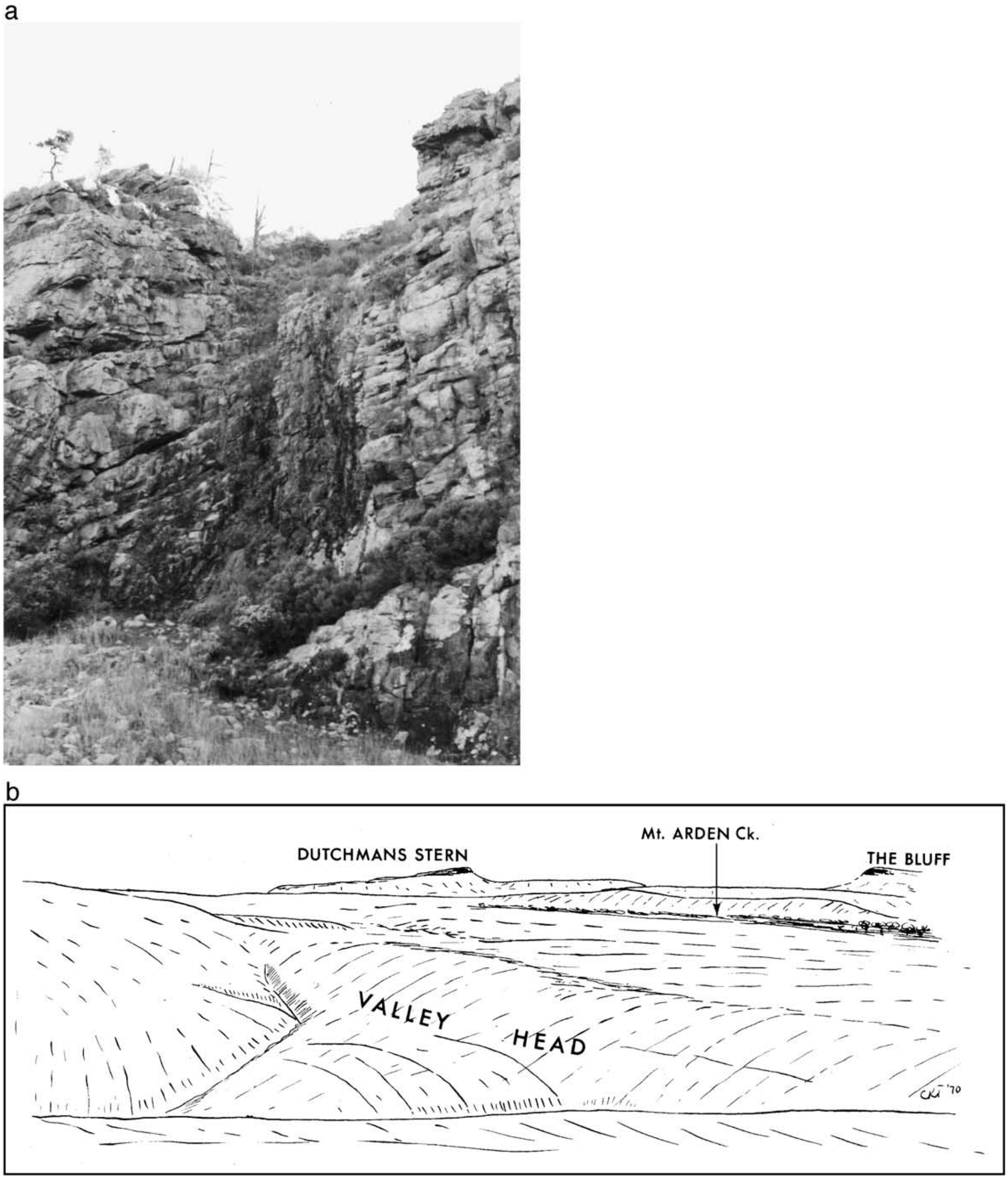

Fig. 21. (a) Shallow recess in scoured face of vertically dipping bedding plane in quartzite near Buckaringa Gorge, southern Flinders Ranges. It is due partly to weathering and sapping along exposed joints but also to runoff from within the quartzite ridge. (b) Sketch of incipient breach of quartzite ridge by a headwater of Castle Creek, near Yarrah Vale, southern Flinders Ranges. Location indicated at 3 in Fig. 22b.

Campbell, 2001). The largest is the Central Australian Ring with a diameter of more than 1200 km and outlined in part by rivers such as Sturt Creek, which flows intermittently to Lake Gregory in the north of Western Australia. Other examples are evident in the Kambalda district of the southwestern Yilgarn Craton (Fig. 24b), and sectors of the Georgina, King and Warburton creeks, which together drain substantial areas of the Northern Territory and western Queensland before entering Lake Eyre, are also arcuate in plan.

Their origin remains enigmatic, but ring structures are conceivably associated with lineaments and with recurrent shearing. They may influence surface drainage in the same ways as suggested for lineaments.

8. Anomalous patterns

Though most river patterns conform to slope and/or structure, some flow neither directly across the contours of the land, nor in conformity with the structural grain of a locality or region; they are discordant in terms of either slope, or of passive structures presently exposed at the surface and occurring at shallow depth, or with both (Fig. 25). Many such anomalous or transverse stream sectors flow in gorges but gorges are not of themselves anomalous. They merely indicate a comparatively slow rate of slope lowering compared to that of river incision.

Many explanations for anomalous drainage patterns have been developed over the years (Fig. 26).

Fig. 22. (a) Oblique aerial photograph of the Comstock region of the southern Flinders Ranges from the north, showing trellis patterns (RAAF), gorge cut by Mt. Arden Creek through sandstone, and piracy of Comstock valley drainage by Skeleroo Creek (X), a tributary of Mt. Arden Creek. Mt. Benjamin (Big Ben) is the peak in middle distance. The Bluff stands beyond. The suggested development of the gorge marked (Y) is shown in Fig. 30. Maps of same region showing (b) various stages in river capture: 1—complete capture (Skeleroo Creek); 2 and 3—incipient captures, (c) present stream pattern.

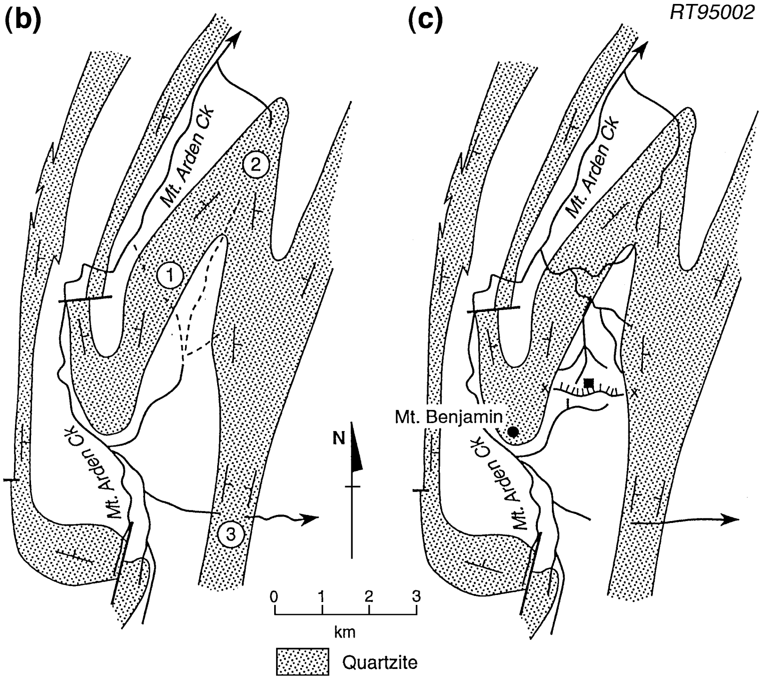

Fig. 22 (*continued*).

8.1. Diversion

8.1.1. Tectonic

In some areas pre-existing stream courses have been diverted either by faulting or warping. The southerly diversion of the River Murray at Echuca (Fig. 3), in northern Victoria (Harris, 1939; Bowler and Harford, 1966), is an example of the former. The so-called 'palm-tree' pattern, of the Diamantina headwaters (Fig. 19a), in northwest Queensland, is a diversion due to recent activity of the Selwyn Upwarp (Taylor, 1911; Öpik, 1961; Twidale, 1966b). As mentioned previously, Bishop (1995) has queried the efficacy of headward erosion as a cause of river piracy, and suggests that diversions due to warping are more common than has been supposed.

Major rivers like the Mahanadi, Godavari, Krishna and Kaweri rise in the western Ghats and flow across the breadth of peninsular India to the Bay of Bengal. Only the fault-controlled Narmada and Tapi (e.g., Kale et al., 1996; Chamyal et al., 2002) run to the west to the Arabian Sea. In southern Brazil, rivers such as the Rio Grande and Iguaɑu rise near the coast and flow inland to join the Parana River, which flows to the sea in the La Plata estuary. Such regional anomalies, as well as several in southern Africa, have been explained as due to doming of the crust related to large-radius magmatic uplift followed by rifting of the structure (Cox, 1989). Alternatively, uplift at the margins of continental crust following faulting and plate separation, could account for the drainage disturbances and reversals evident in the southern Yilgarn Craton of Western Australia (Commander, 1989; Fig. 24b).

8.1.2. Volcanic

Extensive lava fields such as that of the Deccan in peninsular India and many parts of north Queensland (Stephenson et al., 1980) have overwhelmed the pre-existing landscapes, including drainage systems. Basaltic flows have blocked pre-existing valleys, diverting pre-existing streams. At the margins of the lava fields, valley flows frequently cause one axial river to be replaced by two parallel streams, each running between the edge of the lava tongue and the declivity of the valley side slopes. Such twin channels are located on either side of a lava flow in the valley of the Einasleigh River downstream from Einasleigh township and Talaroo Homestead, with the well-named Parallel Creek to

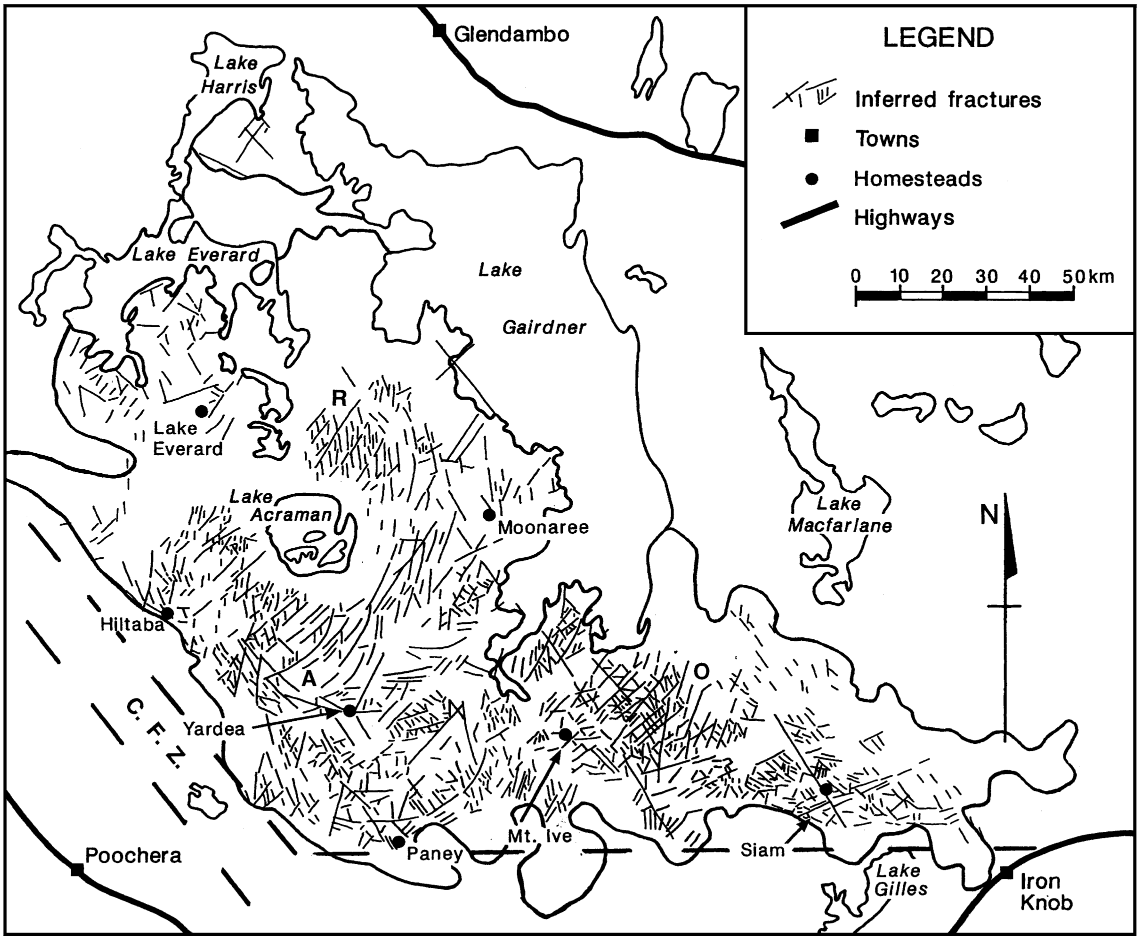

Fig. 23. Orthogonal (O), rhomboidal (R) and arcuate (A) patterns of (episodic) streams and associated structurally controlled valleys, Gawler Ranges, South Australia. C.F.Z.—Corrobinnie Fault Zone, part of the faulted southern margin of the Gawler Ranges massif.

the north of the tongue, and the Einasleigh to the south (Twidale, 1966a, p. 49; see also, Taylor, 1911). Similar diversions and twinning (e.g., of the Forth and Mersey rivers) are reported from central Tasmania (Banks, 1962, pp. 239–241; see also, e.g., Slemmons, 1966, p. 204; Ollier, 1988, pp. 141–147).

8.1.3. Glacial

Both regionally and locally, glaciers have flowed across or against the slope of the land and blocked the natural drainage. Ice decay released huge volumes of debris and many preglacial valleys were buried, though some channels choked with glacial debris have been exhumed as a result of postglacial erosion because the unconsolidated debris is weaker than the country rock.

In some areas rivers flowing from unglaciated areas, or formed by summer meltwaters have been blocked by glaciers. They have run along the ice front, carving channels that after deglaciation are anomalous in terms both of slope and structure. Contemporary examples have been noted in Greenland (e.g., Nichols, 1969). Elsewhere, proglacial lakes, of which modern examples are found in the Swiss Alps (the Marjeelen See, but see Odell, 1966) and in Alaska (Stone, 1963) were impounded at the ice front, as for example, Lake Albany, in upper New York State (LaFleur, 1968).

In the Great Lakes region of the USA, the Illinois and Wabash rivers at various times served as overflows from ancestral lakes Chicago/Michigan and Maumee/Erie (e.g., Hough, 1958; Teller, 1987).

Where these overflowed they again eroded channels some of which paralleled the ice front. The *Urstromtäler* of the north European plain consist of several such channels linked together in a series of channels associated with stages in the recession of the last ice sheet. Others, such as Newton Dale in north Yorkshire at the regional scale, and the Barnetby Gap, north Lincolnshire at the local, but both with distal deltaic deposits (Kendall, 1902; Twidale, 1956a), took water away from the ice front, again cutting anomalous channels.

Glacial deposition has disturbed pre-existing drainage patterns and together with the frozen ground typical of periglacial and nival climates, which impedes permeability, has produced local internal drainage basins characterised by swamps and lakes, as well as rivers. The Lake Plateau of Labrador is well named.

8.1.4. Landslides and other mass movements of debris

Though basically ephemeral, landslides, including lahars, have in some instances blocked channels and valleys, though in most instances only for a few days (Costa and Schuster, 1988). Tectonically active uplands provide many examples (e.g., Harrison and Falcon, 1938; Watson and Wright, 1969; Brookfield, 1998; Nicoletti and Parise, 2002).

8.1.5. Anthropogenically induced diversion

Human activities have changed stream courses at various scales and in several ways. Locally, the construction of unsealed roads has led to their being washed out to form gullies the alignment of which was determined not by the slope of the land but by, say, the position of a railway line in relation to which the road was a service track, or of a track to a water bore requiring regular maintenance. The courses of rivers flowing through settlements have been stabilised, as for example the Nile at Cairo (Said, 1993, pp. 61–68). Draining of flood-prone regions such as the English Fens involved the straightening of major rivers and unwittingly introduced subsidence of the flood plains as the soils dried and organic matter decayed (Darby, 1940). Extraction of groundwaters

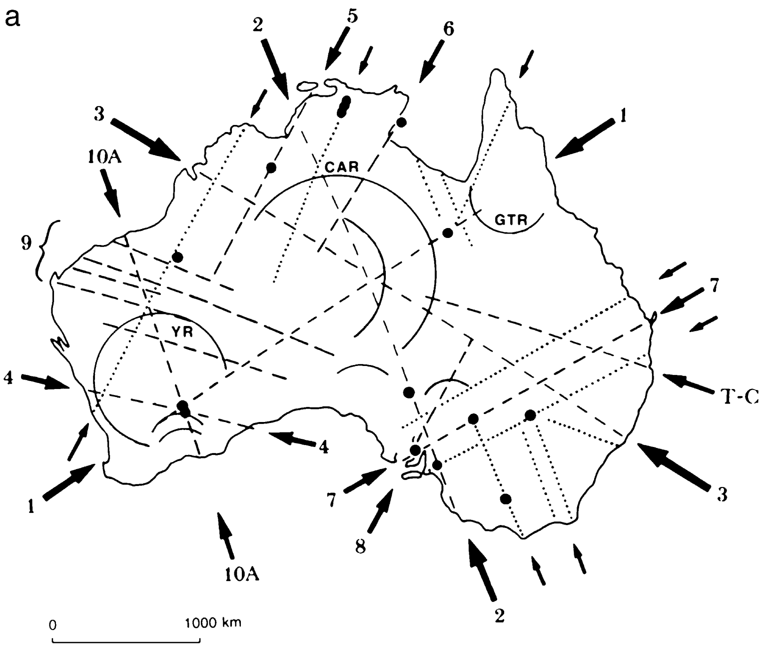

Fig. 24. (a) Numbered lineament corridors, and ring structures that have been exploited by streams, Australia (after O'Driscoll and Campbell, 1997). Black circles—major ore bodies, CAR—Central Australian Ring, GTR—Georgetown Ring, YR—Yilgarn Ring. (b) Disrupted and dismembered drainage of the Yilgarn Craton, Western Australia, with some lineament control (L) and also arcuate river remnants (A) linked to ring structures (after Van de Graaff et al., 1977).

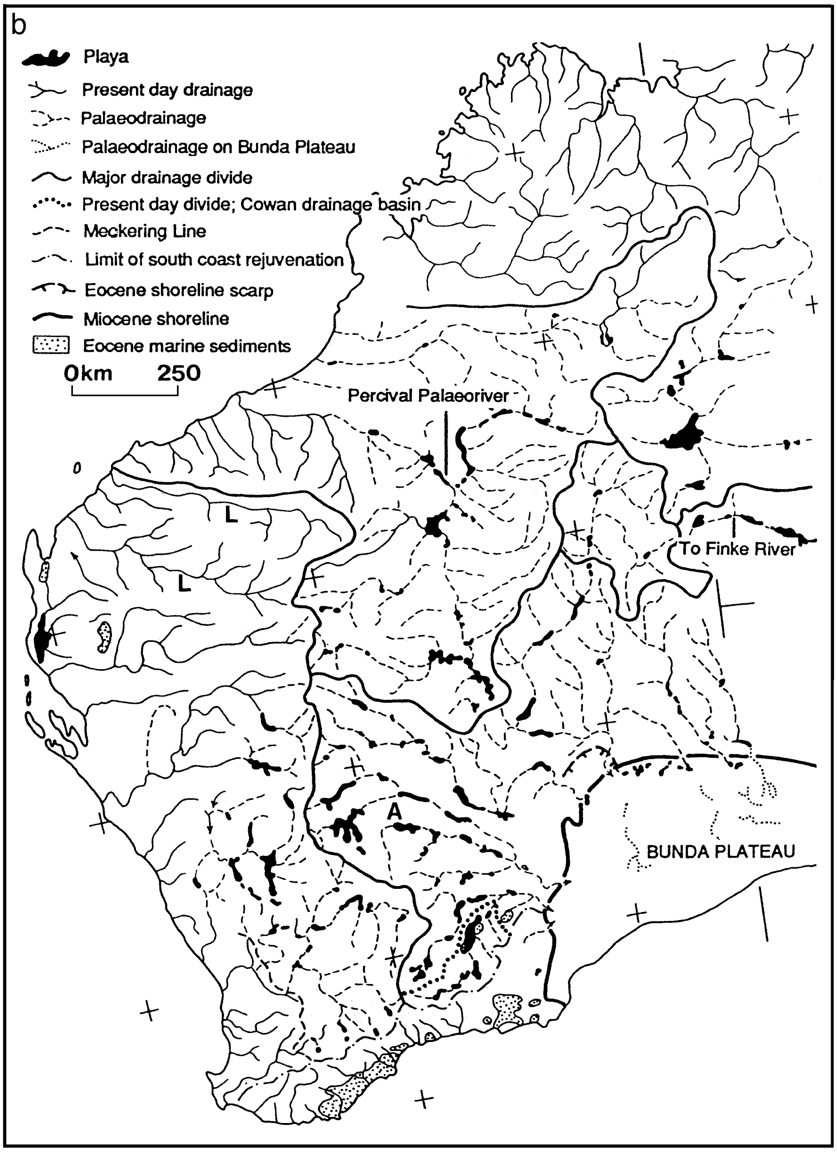

Fig. 24 (*continued*).

for irrigation purposes has caused surface lowering in such areas as the Central Valley of California (e.g., Lofgren and Klausing, 1969), and more recently on the north China Plain where a 2 m lowering over an area of some 40,000 km^2 is anticipated.

Like mild warping, such changes in slope may interfere with pre-existing drainage patterns. Where subsidence results in cracking, as in southern New Mexico, ephemeral and local development of arcuate, orthogonal and polygonal stream patterns has been induced (e.g., Contaldo and Mueller, 1991).

8.2. Antecedence

Where a river has maintained its course through an area of land that has risen either through faulting or folding, the river is said to be antecedent (Medlicott, 1860; Hayden, 1862; Powell, 1875; Dutton, 1882;

Fig. 25. Transverse drainage in the James and Krichauff ranges, central Australia. x—strike stream, y—transverse river. The latter flows across the structural dome, breaching quartzite ridges in doing so (C. Wahrhaftig).

Matthes, 1930). It is fair to state that though many rivers of tectonically active regions are probably of such an origin, but like warping in relation to river capture, it is difficult to prove. The ages of the river and of the implied tectonism have to be established, and this is rarely possible. Sharp (1954, p. 9) suggested various criteria with which to detect antecedence in the area he was discussing, namely southern California. First, and negatively, eliminate other possibilities (which, though reminiscent of Doyle's (1892) Holmesian logic, and is pragmatic pro tempore, is of dubious longer-term validity). Second, and positively, there ought to be close conformity between the amount and nature of the uplift and the present landforms. Third, topographic, stratigraphic or other evidence ought to be sought as to whether the river followed approximately its present course prior to uplift. Fourth, there ought to be deformation of terraces, gravel beds, etc., along the supposed antecedent course.

Löwl (1882) argued against the mechanism in principle but antecedence has been freely cited as a cause of anomalous drainage at the regional scale (e.g., Wager, 1937). The Ukrainian rivers such as the Dnieper and the Don, which flow in part across rising domes (Mescherikov, 1959), are probably antecedent, though some sectors appear to be diverted. Madigan (1931) thought the Finke and other transverse rivers of the central Australian uplands were of this origin. The necessary evidence was not cited, however, and later work suggests they are more probably due to inheritance (q.v.).

In more local settings, a plausible argument was put for the antecedence of the Salzach, in Austria (Seefeldner, 1951; Coleman, 1958), and Lees (1955) has satisfactorily demonstrated the antecedence of drainage canals dating from about 1750 years ago and maintaining their course across the rising Shaur Anticline, in the foothills of the Zagros Mountains in what is now southwestern Iran. Powell (1875, p. 163) cited the crossing of Green River through the Uinta Mountains as a type example of antecedence, but this has since been refuted (Sears, 1924). Sharp (1954) reported many examples from southern California, detected in detailed repeat mapping associated with the search for oil and gas (Vickery, 1927). The Los Angeles River where it flows across the Dominguez Hills, the San Gabriel River running across the Puente Hills and the Seal Beach structure, the Santa Ana River crossing the Santa Ana Mountains, the Verdugo Canyon cutting through the Verdugo Hills, the Ventura River flowing across the Red Mountain fault, the Zaca Creek across Purisima Hills and several small streams across Wheeler Ridge are cited as examples (Vickery, 1927; see Sharp, 1954, p. 9). Howard (1967,

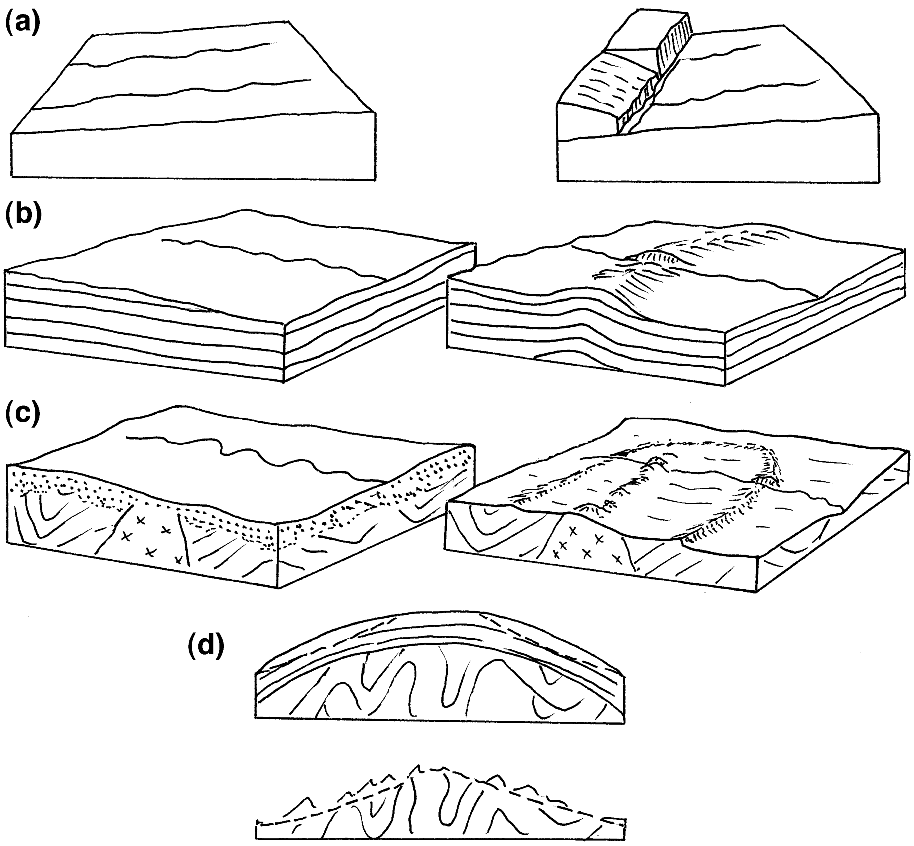

Fig. 26. Diagrams illustrating various mechanisms suggested for the development of anomalous streams: (a) diversion, by fault (rear) and lava or glacier wall (front) (b) antecedence, (c) inheritance, with regolith cover (left), (d) superimposition, with overmass (top) and undermass shown.

pp. 2252–2254) cited an example of antecedence from Taiwan but labelled it 'palimpsest', which term he also applied to an instance of superimposed drainage from the Ohio River valley in northeastern USA.

8.3. Superimposition

Drainage patterns that have been developed in adjustment with an upper or overmass sequence and then let down by erosion of the constituent stream sections into an undermass of contrasted structural characteristics are said to be superimposed (USA, superposed). The concept was recognised by Jukes (1862), and the term coined by Maw in 1866. Examples were described by such early workers as Powell (1875), Davis (1889), Strahan (1902), Marr (1906) and du Toit (1909), and later by, for example, Higgins (1952) and Hills (1975, pp. 97–98).

To demonstrate superimposition, remnants of the overmass must be preserved or strongly implied. For example, the regional drainage of the Lake District in northwestern England (Fig. 27a and b) describes a radial pattern superimposed from a Late Palaeozoic overmass on to a folded Early Palaeozoic sequence (Marr, 1906). The Griqua drainage in South Africa is said to be superimposed from Karoo deposits on to Palaeozoic though the pattern, which is strike-controlled, may essentially predate the Permian glaciation (du Toit, 1909). Similarly, King (1942, p. 215) suggested that the anomalous pattern of the Vaal River where it flows across the Vredefort dome (Fig. 27c) is superimposed from the Karoo (latest Palaeozoic and Early–mid Mesozoic) strata, but the angular pattern is not characteristic of a domal structure, and if superimposition has taken place there has been pronounced adjustment to underlying structure during incision.

What Whitehouse (1941, p. 50; also Ball, 1911) called 'incised braids' (Fig. 28a) are developed in gorges cut in Proterozoic quartzite on the spring-fed Lawn Hill and Widdallion creeks, within the upland front of the Isa Highlands, in northwest Queensland. The regional topography is ancient for it is demonstrably exhumed from beneath Middle Cambrian strata and also Mesozoic (Upper Jurassic–earliest Cretaceous) beds of which remnants are preserved on summit high plains within the upland. The occurrence of Mesozoic strata in some valleys suggests that the major rivers of the region probably predate the Early Cretaceous marine transgression (Carter and Öpik, 1961). The interlaced gorges are most likely superimposed, having been cut by rivers flowing over Mesozoic remnants lapping against the eastern hill

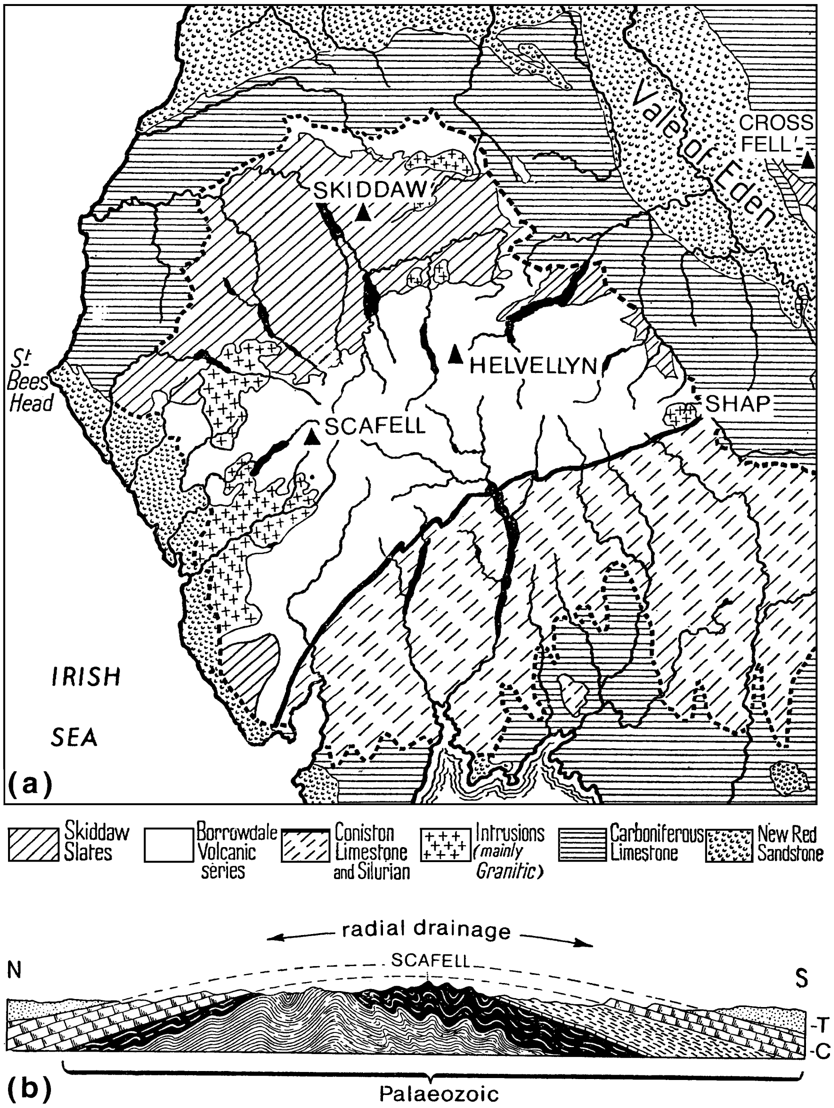

Fig. 27. (a) Map and (b) section of superimposed radial drainage, Lake District, northwestern England (after Holmes, 1965, p. 564). C—Carboniferous limestone; T—Triassic strata. (c) Anomalous drainage of the Vredefort Dome, South Africa. Ranges in black (after King, 1942, p. 194).

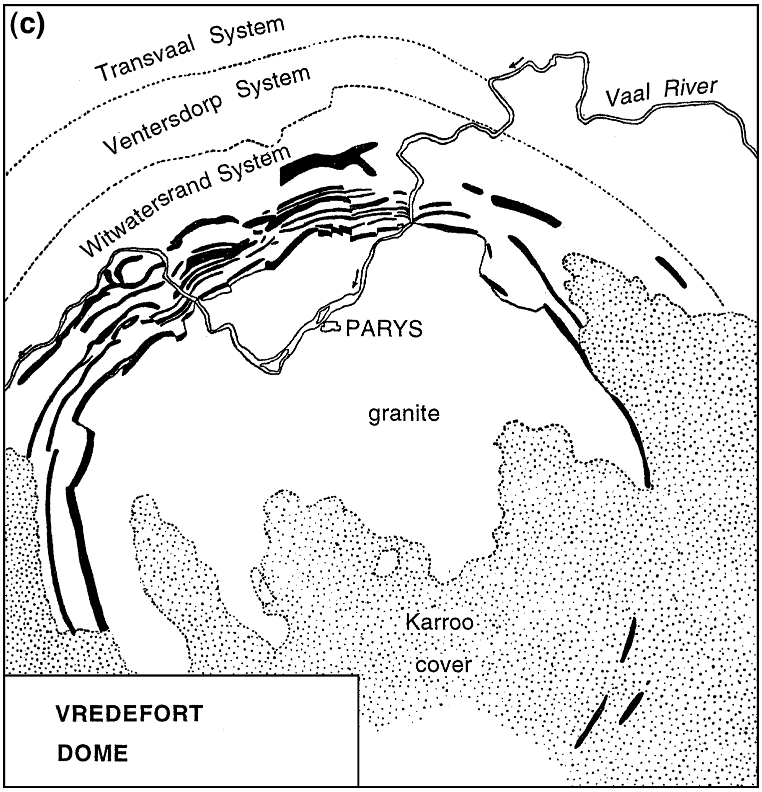

Fig. 27 (*continued*).

front and adopting a distributary and braided habit on debouching on to the plains (Fig. 28b and c). This may have taken place during the Miocene when deep weathering (lateritisation) of the then plains suggests relative stability (Twidale, 1956b).

Modern rivers behave in similar fashion (Fig. 29). This tendency for rivers to divaricate or adopt a distributary habit on leaving the confines of an upland gorge may explain the behaviour of rivers like the central Narmada in northwestern peninsular India, where one bedrock reach develops a braided habit below a fault scarp, only to revert to a single channel a short distance downstream (Kale et al., 1996). Such reversion may be due to a main stream incising more rapidly than the side channels and the latter being captured by the former; though on the Narmada sector in question incoming tributaries also favour convergence.

Some suggestions of superimposition have not been backed by evidence of a former overmass. Johnson (1931) advocated a superimposed origin for the Appalachian drainage, though the postulated Cretaceous overmass did not exist. Fenner (1930), apparently at the suggestion of Johnson when visiting the area, advocated that the Mt. Lofty Ranges drainage was superimposed from a Miocene overmass. Unfortunately no evidence of such a cover exists. On the contrary, the elevational distribution of Miocene beds and indications of shoreline conditions at relatively low altitudes near Gawler and Strathalbyn, on the western and eastern flanks of the upland, respectively, indicate that the summit surface of the Mt. Lofty Ranges stood well above the level of the Miocene seas (e.g., Glaessner and Wade, 1958; Dalgarno, 1961).

An important feature of superimposed streams is illustrated by the Walsh River in north Queensland. Where it flows through the Featherbed Range, an upland in Permian ignimbrites, it is superimposed from a Cretaceous cover, remnants of which are

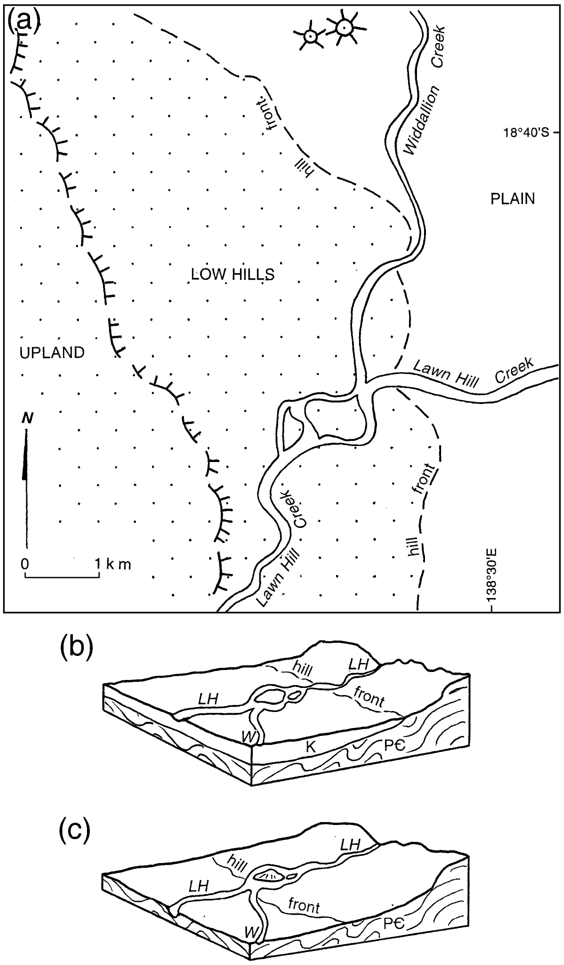

Fig. 28. (a) Sketch map of superimposed 'incised braid' on Lawn Hill Creek, Isa Highlands, northwest Queensland. (b and c) Stages in suggested mode of development.

preserved to the west and south (De Keyser and Wolff, 1964; see also, Twidale, 1956b). Having cut through the base of the sedimentary cover and into the volcanics, however, the river has adjusted to the structures in the latter, and in particular to prominent orthogonal fracture systems. Marr (1906, pp. cii–ciii) made a similar point concerning the superimposed rivers of the Lake District of northwestern England, pointing to tributary streams and valleys, locally known as gashes or 'rakes', some developed along veins but most of them along shatter belts of fracture zones developed in Early Palaeozoic country rocks.

8.4. Inheritance

Inheritance was suggested, and the term used in this context by Cotton (1948, p. 56), for drainage patterns that were let down on to the 'undermass' not from a disconformable overmass but from a plain carrying a weathered mantle, the development of which had implicitly eliminated structural control and promoted slope as the major determinant of pattern.

Campana (1958) considered incised meanders to have been inherited from a now uplifted surface of low relief, but such forms are, as discussed earlier, autogenic. In terms of the inheritance hypothesis, the plain is essentially an exposed weathering front or etch plain (e.g., Falconer, 1911; Jutson, 1914; Wayland, 1934; Willis, 1936). The concept can be invoked in explanation of some of the transverse drainage incised below the widespread duricrusted surface preserved in central Australia (Hills, 1961, p. 82; Mabbutt, 1965), though the rivers concerned probably have a previous history of superimposition (possibly from a Cretaceous cover), or of impression (q.v.).

Some inherited drainages may go unrecognised because of the difficulty of distinguishing between simple inheritance and patterns shaped by weathering front irregularities. Long-continued attack by groundwaters may produce a weathering front that is essentially regular. The virtually featureless so-called New Plateau of the Yilgarn Craton of Western Australia (Jutson, 1914) and the Bushmanland Surface of Namibia and adjacent parts of Northern Province, South Africa (Mabbutt, 1955; Partridge and Maud, 1987) are etch plains associated with the exposure of such even fronts. Even so, the thickness of recently developed regolith varies because etching exploits structural variations in the country rock and a topography is developed. Some rivers and channels may be initiated at the weathering front and as the slope of the front broadly mimics that of the surface it is difficult to differentiate between epigene and subsurface forms. Moreover, though some regoliths display no obvious structural influences, others do. Kaolinised shale, for example, at some sites retains the faint traces of folds. Also, the composition of the regolith varies according to parent material. Thus, regoliths are not necessarily devoid of structural contrasts, which, though subtle, may be enough to have influenced stream patterns.

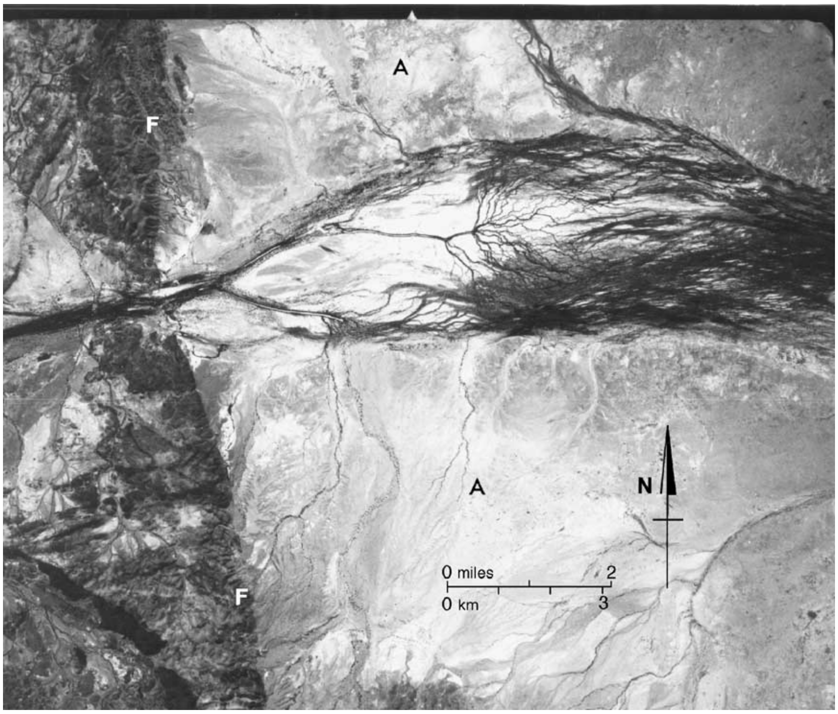

Fig. 29. Modern analogue of the suggested Lawn Hill 'incised braid'—a river debouching across the faulted margin (F) of the Peake Range, northern South Australia, and adopting a multichanneled habit, first distributary and then braided, on the alluvial plain (A) (S.A. Lands Department).

8.5. Stream persistence and valley impression

Rivers are a prime example of a reinforcement or positive feedback system. They tend to persist. The role of such persistent rivers in transverse drainage development was suggested by Meyerhoff and Olmstead (1936), supported by Strahler (1945), and revived by Oberlander (1965, 1985) who called the mechanism 'autosuperposition'. Twidale (1966c, 1972) used the term 'stream persistence and valley impression'. The mechanism calls for deep erosion of folded sequences the geometry of which changes with depth, for consideration of the third dimension.

The mechanism can be illustrated with reference to a localised drainage anomaly. Some 12 km north of Quorn, in the southern Flinders Ranges, the Mt. Arden Creek rises east of The Bluff (Fig. 22a and b) and flows northwards in a strike valley until it breaches a high quartzite ridge before flowing northwards again in another strike valley to join the Willochra Creek. Why has the stream abandoned one strike valley for another, eroding a 60–80-m-deep gorge in the quartzite ridge in doing so? Headward erosion and capture have occurred, but why there? The strata exposed in the walls of the gorge do not appear to be shattered, or more densely fractured than elsewhere, but the line of the outcrop and hence of the ridge is offset by a south-dipping fault some 600 m south of the gorge. This suggests that the gorge may have been initiated along the fault zone when the landscape stood higher than present and when the trace of the fault was located where the gorge is cut. The river exploited the weathered fault zone and, once incised, maintained its location. The fault dipped away to the south, so that it is now separated from the entrenched river and marked only by a crestal notch (Fig. 30). Thus the gorge was initiated by a river exploiting a zone of weakness but having the capacity to maintain its course in strata the character of which has changed with depth.

At a slightly larger scale, the dip slopes of cuestas and homoclinal ridges capped by quartzite are scoured

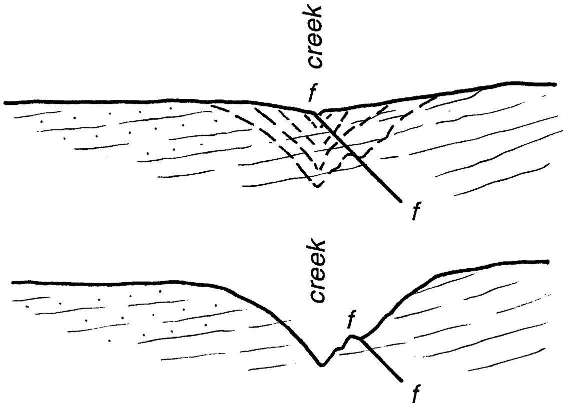

Fig. 30. Suggested stages in development of Mt. Arden Creek gorge (Y in Fig. 22a), north of Mt. Benjamin, southern Flinders Ranges.

by rivers and valleys that loop into and then leave the incline (Fig. 31a). Such in-and-out valleys (which are not to be confused with the proglacial forms of the same name: see, Kendall, 1902) are understandable in terms of a higher stand of the valley floor eroded in argillite and on which a meandering stream flowed. With the lowering of the valley the river encountered the quartzite but maintained its winding course, eroding a gorge as it did so (Fig. 31b and c). Similarly the double gorges of the Willochra and Kanyaka creeks, at the northern margin of the Willochra Plain, in the southern Flinders Ranges, are plausibly explained in terms of the rivers incising on to strata different from those in which they were initiated (Fig. 32). The lower reaches of the Buckaringa Creek, which describe an in-and-out pattern for several kilometres prior to its junction with the Willochra Creek within its gorge section (Fig. 32), are susceptible of interpretation in terms of impression from the same weaker strata in which the twin gorges originated.

Deep erosion and maintenance of stream position can explain more complex anomalies. Strike streams developed at one level are incised, encounter resistant strata and some have the capacity to erode gorges (the 'tangs' of the Zagros region: Fig. 33) and maintain their courses. The breached snouts of folds as well as rivers cutting through the cores of folds are explicable in these terms, like those of the Mern Merna Dome, developed in a Neoproterozoic sequence that includes ridge-forming quartzite, in the central Flinders Ranges (Fig. 34). In addition to the examples from central and southern Australia noted above, and the Zagros Mountains so well described by Oberlander, possible instances of impression can also be cited from other parts of the world (Fig. 35).

Persistence is an expectable consequence of deep erosion in orogenic zones, provided only that the river in question can maintain its course and not be defeated by the newly encountered barrier. It differs from superimposition, inheritance and other mechanisms in that no imaginary overmass deposit, no old surfaces and associated regoliths, no neotectonic movement, no

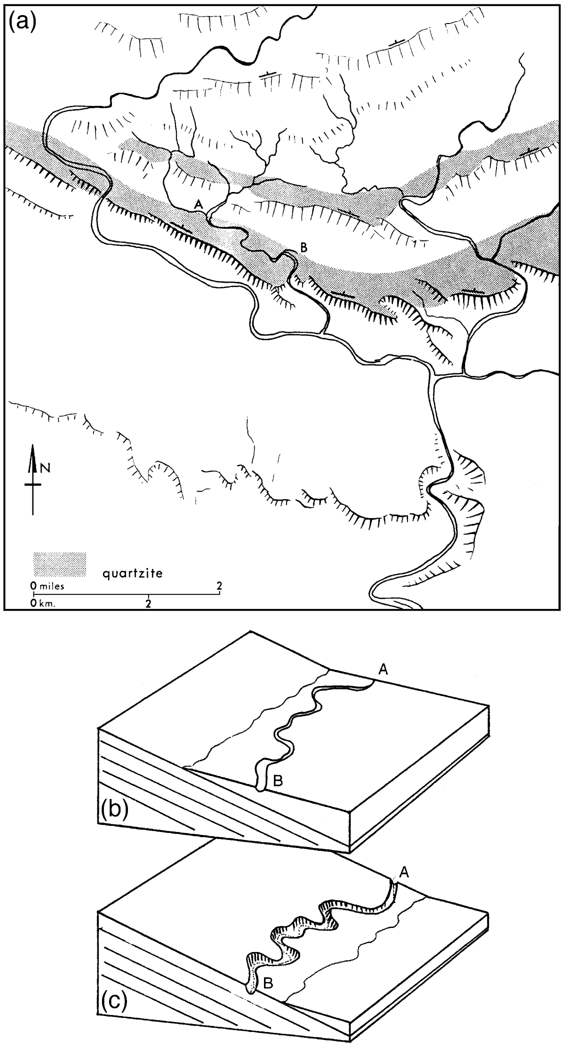

Fig. 31. (a) Plan of in-and-out gorges in the dip slope of a quartzite ridge near Arkaroola, northern Flinders Ranges. (b and c) The gorges, here seen from the north, are explicable in terms of valley impression in a dipping sedimentary sequence.

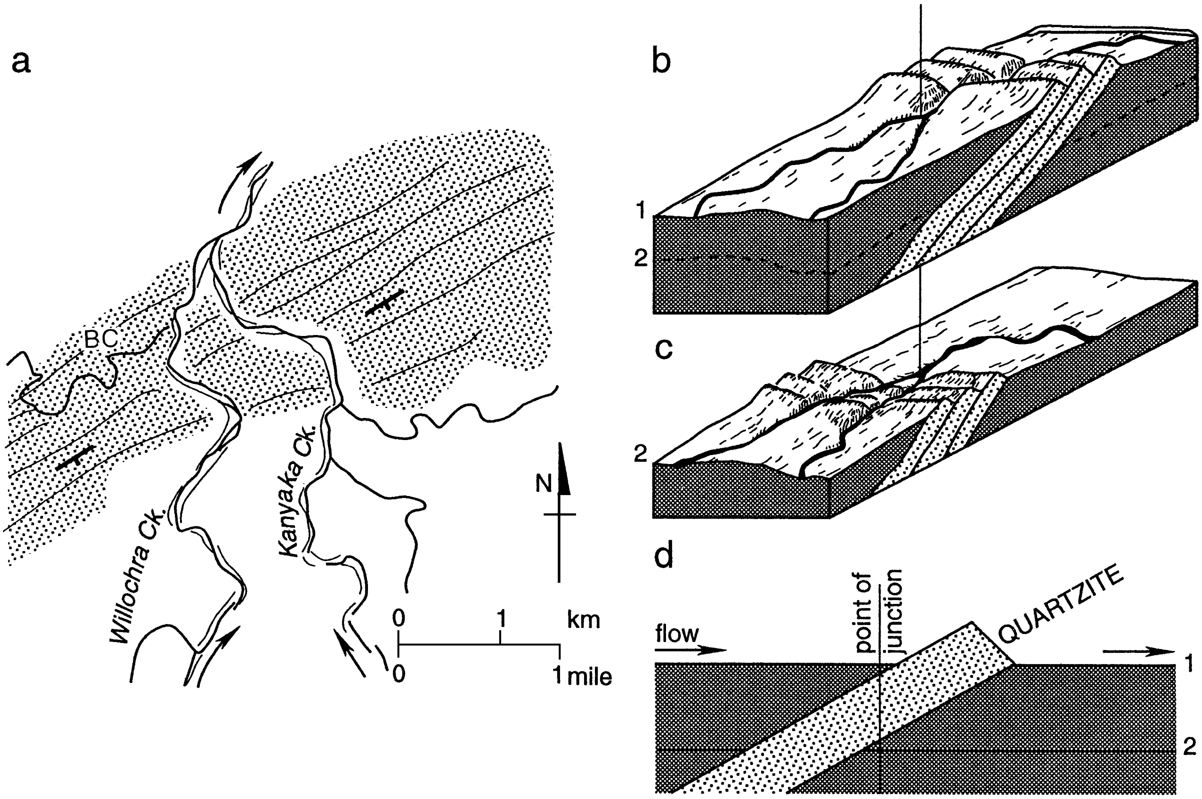

Fig. 32. (a) Plan of gorges cut by the Willochra and Kanyaka creeks in dipping quartzite strata and through the associated ridge, southern Flinders Ranges. BC—Buckaringa Creek. (b–d) Suggested development of the twin gorges.

catastrophic event, is implied. This has significant implications for stratigraphic reconstructions.

As with superimposed streams it is difficult to explain with certainty how persistent rivers have maintained their courses through resistant bedrock to dominate streams draining weaker outcrops. But antecedent streams have done so, and as the torrents of the Channeled Scabland demonstrate (Baker, 1973), rivers in flood are capable of almost incredible erosion. Unfortunately, many of the rivers under review are probably of considerable age and it is not possible to reconstruct relevant climatic chronologies and hence the likelihood and magnitude of floods. On the other hand, all rivers have been subject to flooding, and once incised, reinforcement effects cut in.

Take, for example, the rivers of the Mern Merna Dome. The strike stream that has breached the southern snout (Fig. 34a and b) has incised a gorge in quartzite but does not look inappropriately small. Unfortunately no discharge data are available and structure imposes limits on stream and valley geometry, but the stream does not appear incompatible with the valley it has incised. The trivial stream that crosses the core of the structure from east to west, however, looks impossibly small, so much so that it is lost in the alluvia of the plain soon after emerging from the western ridge. The river crossing a dome in the James Range (Fig. 25) is not enormous, and is at present episodic. Although there is evidence that in the regions under review river development has taken place over a long period, possibly since the Cretaceous (Twidale, 1994; Twidale and Bourne, 1996), it cannot plausibly be argued that this is a question of a small stream acting over a long period, for such a small discharge stream surely could never have maintained a course through any of the several barriers obstructing its passage. On the other hand, a higher discharge river capable of maintaining its course by eroding through quartzitic bedrock may have shrunk as a result of the onset of aridity, of which there is local and regional evidence.

9. Cryptoreic drainage

Some areic areas are not what they seem. Surface channels are lacking but there are rivers underground. Some drainage systems in the eastern Sahara Desert (the present Selima Sand Sheet) and the Great Sandy Desert of northwestern Australia have been buried beneath desert sands and have only been detected by ground penetrating radar (McCauley et al., 1982; Tapley, 1988).

Cryptoreic drainage may be complete as in areas of extensive karst, such as the Causses of southern France, the Dolomites of Montenegro and adjacent areas, and the Nullarbor Plain (Fig. 36), southern Australia, or interrupted, where rivers sink beneath the ground on encountering a limestone outcrop, as for instance Cave Spring Creek in the Fitzroy Valley of the northwest of Western Australia (Jennings and Sweeting, 1963), and the Andabara River in the West Highlands of Papua New Guinea (Jennings, 1985, p. 34). The subterranean stream patterns of karst regions are, however, influenced by the same factors as surface drainage, cave systems and drainage lines commonly exhibiting marked joint control. Miocene limestone in the Mt. Gambier district, in the South East of South Australia, has been dissolved along partings to form caves in plan patterns (Marker, 1975) that coincide with those of the prevailing orthogonal fracture system.

The rolling chalk ‘Downs’ or uplands of southeastern England and northern France are well known for their dry valleys. The name is somewhat misleading for some of the valleys carry streams after heavy rains but they are most commonly dry. They have been cogently explained in terms of recession of scarps eroded in dipping strata (Fig. 37) causing the water table to be lowered and leading to abandonment of the stream channels lower and lower in the dip-

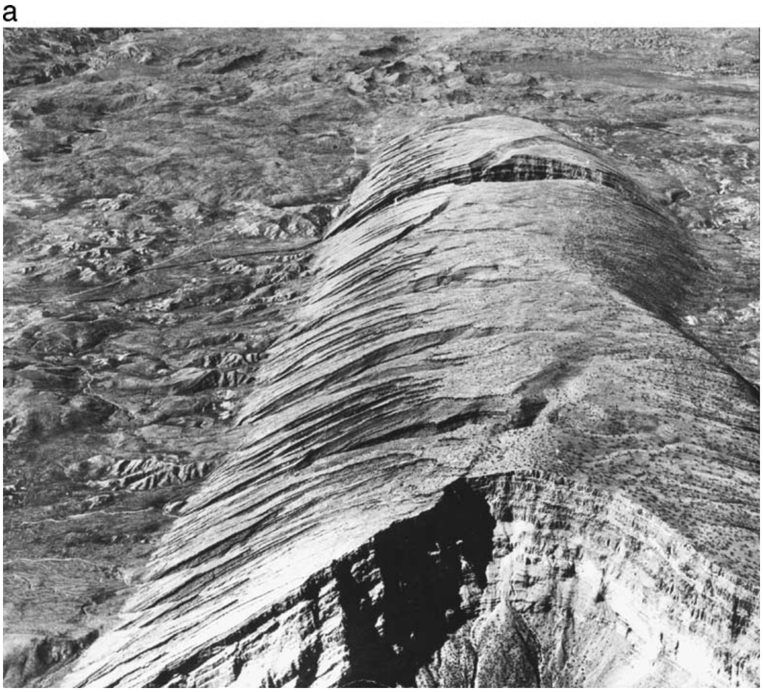

Fig. 33. (a) Breached snout of denuded anticline cut by gorges or ‘tangs’, Zagros Mountains (Hunting Surveys). (b) Diagram showing stream persistence and valley impression during deep erosion of sedimentary sequence, the character (composition, geometry) of which changes with depth.

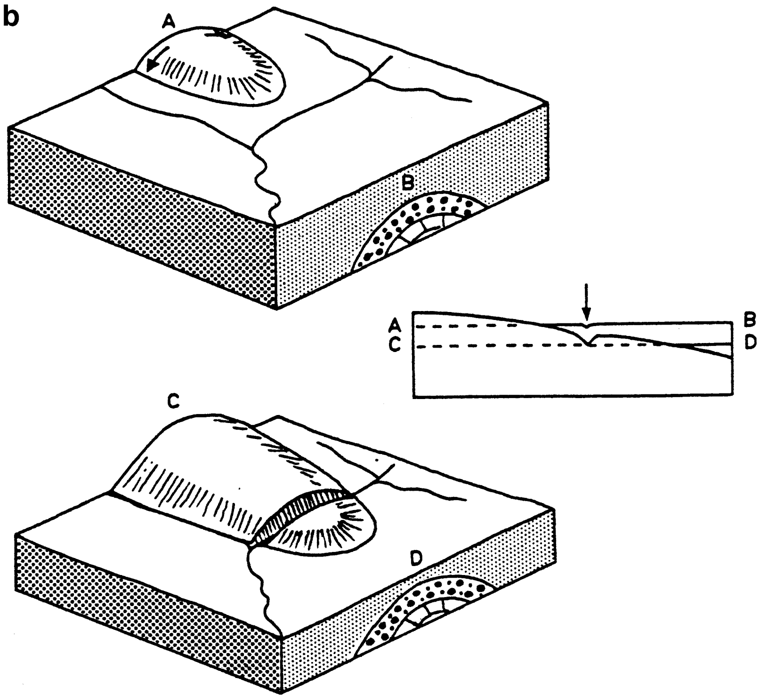

Fig. 33 (*continued*).

slope valleys (Fagg, 1923). It has also been suggested that the freezing of shallow groundwaters during nival periods of the Pleistocene converted permeable rock to impermeable, thus allowing runoff to erode the valleys. Some of the dry valleys appear to predate the Pleistocene, but cold periods of the ice ages could have contributed to the formation of these features.

10. Climatic change

The impacts of climatic change on rivers have already been alluded to with reference to glacial blockage and diversion. In addition, some patterns have been revealed only by the retreat of glaciers. For example, Derbyshire (1962) recognised marginal, extramarginal, submarginal and subglacial types—the last-named comprising chutes that are steeply inclined, run across contours, and include modified preglacial valleys. He also noted subglacial col valleys cutting across ridges, and up-and-down longitudinal profiles. Again, many proglacial valleys did not persist long after the retreat of the ice, and are now abandoned as either dry or marshy valleys draining nowhere.

Climatic change is also widely accepted as a cause of misfit streams. Quantified analysis of river flow has produced an empirical relationship linking bankfull discharge, channel width, and meander geometry so that the latter can be taken as an indicator of discharge (see, e.g., Leopold et al., 1964; Morisawa, 1968; Knighton, 1984). The geometry of some river valleys is incongruous in comparison with that of the present rivers (Fig. 38), in that the geometry of valley curves is dissimilar from that of the meanders described by the present channel. Such rivers are said to be misfit. Most commonly the rivers are too small or underfit (with the osage type indicating underfitness through the spacing of pools and shoals); but some are overfit (e.g., Dury, 1962, 1964, 1986).

Misfitness has been construed as indicating a long-term change in discharge. River capture or diversion could explain such anomalies in some instances but not most, for what are thought to be misfit streams are widely distributed, having been identified in many parts of the United States, western Europe, Britain and

Australia (e.g., Dury, 1960, 1964). This has been taken as evidence of climatic change. In areas formerly affected by continental glaciers, like many parts of northeastern and central North America, glacial meltwaters produced greatly increased discharges, and in tectonically stable areas remote from the coast, climatic change has induced dramatic changes in channel form (Schumm, 1968; Baker and Penteado-Oreallana, 1977; Schumm and Brakenridge, 1987; see also, Schumm and Khan, 1972). Even so, some estimated discharges for what are now desert or semi-desert regions are very high (e.g., Dury, 1960) though the implied increase in rainfall is not as great as might be thought initially (e.g., Dury, 1986). Also, whether the pattern of river bluffs reflects local structure as in the lower Murray Valley (Fig. 19b), the geometry of meanders, or of the meander belt also calls for consideration.

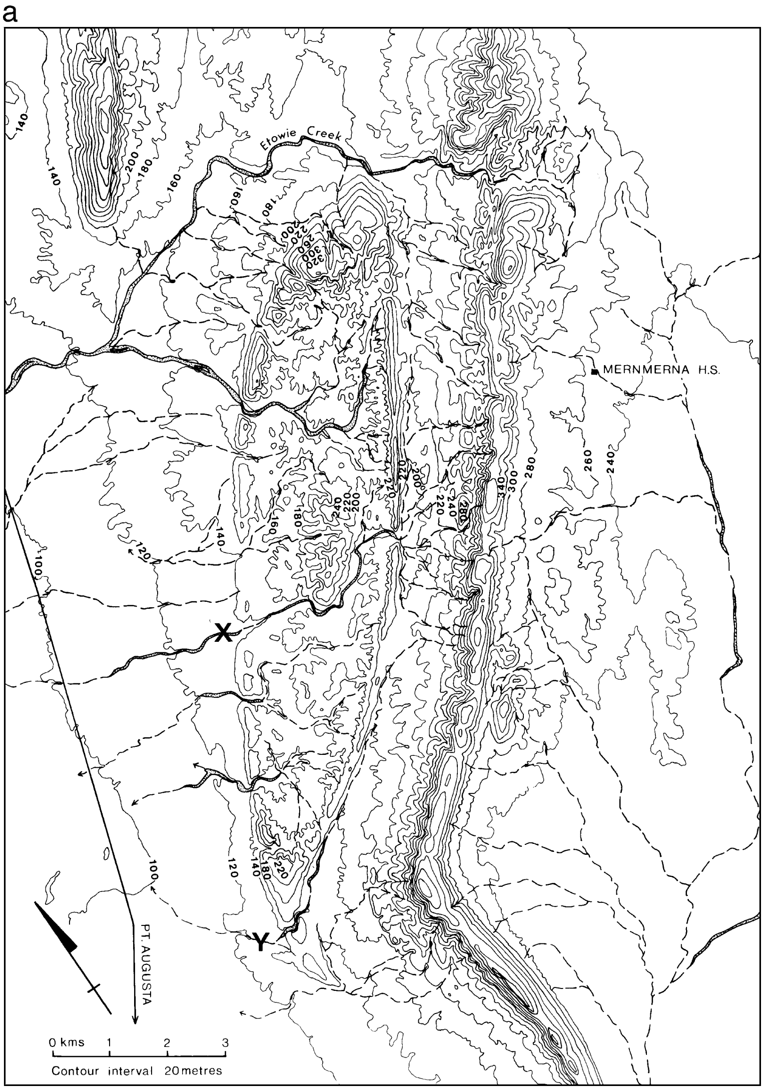

Fig. 34. (a) Contour map and (b) oblique photograph looking NNW, showing examples of impressed valleys from the Mern Merna Dome, western Flinders Ranges. X—Stream crossing entire domical structure, including several resistant beds and associated ridges, Y—breached snout in quartzite (J.A. Bourne).

Fig. 34 (*continued*).

On the other hand, considered statistically and over a long period, extreme events (floods) must have occurred in all catchments, suggesting the possibility that anomalous forms could reflect these rare high-energy events rather than secular change. The Channeled Scabland provides a classic example, with channels that are manifestly misfit. During the Late Pleistocene a glacier advancing from the north blocked the westerly drainage of what is now the Clark River, close to the present Idaho–Montana border and impounded what has been called Lake Missoula (Pardee, 1910). The glacier dam broke, presumably following a warming of climate, releasing the waters of the Lake in a catastrophic flood. The basaltic landscape was scoured by several rivers with 'anastamosing' channels up to 1.5 km wide, some with waterfalls, transporting enormous boulders and depositing large bars and current ripples. The Channeled Scabland (Fig. 39) was created (Bretz, 1923; Bretz et al., 1956) in at most a week, though many forms developed in a matter of a few hours, during the later Pleistocene. The computed maximum discharge is estimated to have been of the order of 21.3×10^6 m^3/s (752×10^6 ft^3/s) and thus is one of the greatest yet recorded on Earth (but see also Rudoy and Baker, 1993, concerning a flood of similar causation in the Ob catchment and evidence preserved in the Altai Mountains of Siberia). Basic work on fluvial dynamics (Leopold and Maddock, 1953; Leopold et al., 1964) allowed the magnitude of forces involved to be quantified (Baker, 1973). The geometry of these gigantic palaeochannels bears no relation to present rainfall and runoff. They are misfit on a grand scale.

In addition to serving as a reminder of the glacial past, the Channeled Scabland provides extreme examples of forms shaped almost instantaneously by enormous floods (Baker, 1973, 1978). It focuses attention on the importance of brief but large magnitude events in shaping the landscape. It demonstrates the value of quantified hydraulic data in estimating the orders of magnitude of forces, and thus being able to establish the feasibility of what had previously been considered an outrageous theory.

Other climatic changes did not achieve such spectacular changes. Nevertheless, the onset of aridity in central and western Australia caused the existing endoreic rivers to be dismembered. Continuous channels dating from the Eocene were replaced by strings of playas and salinas scattered along the former valley floors (e.g., Van de Graaff et al., 1977; Clarke, 1994; Fig. 24b). The Narlaby drainage system which served northern Eyre Peninsula and the Gawler Ranges during the Eocene and Pliocene has disintegrated into a series of salinas (Bourne et al., 1974; Binks and Hooper, 1984). The so-called prior streams of the Riverina of western New South Wales, though still

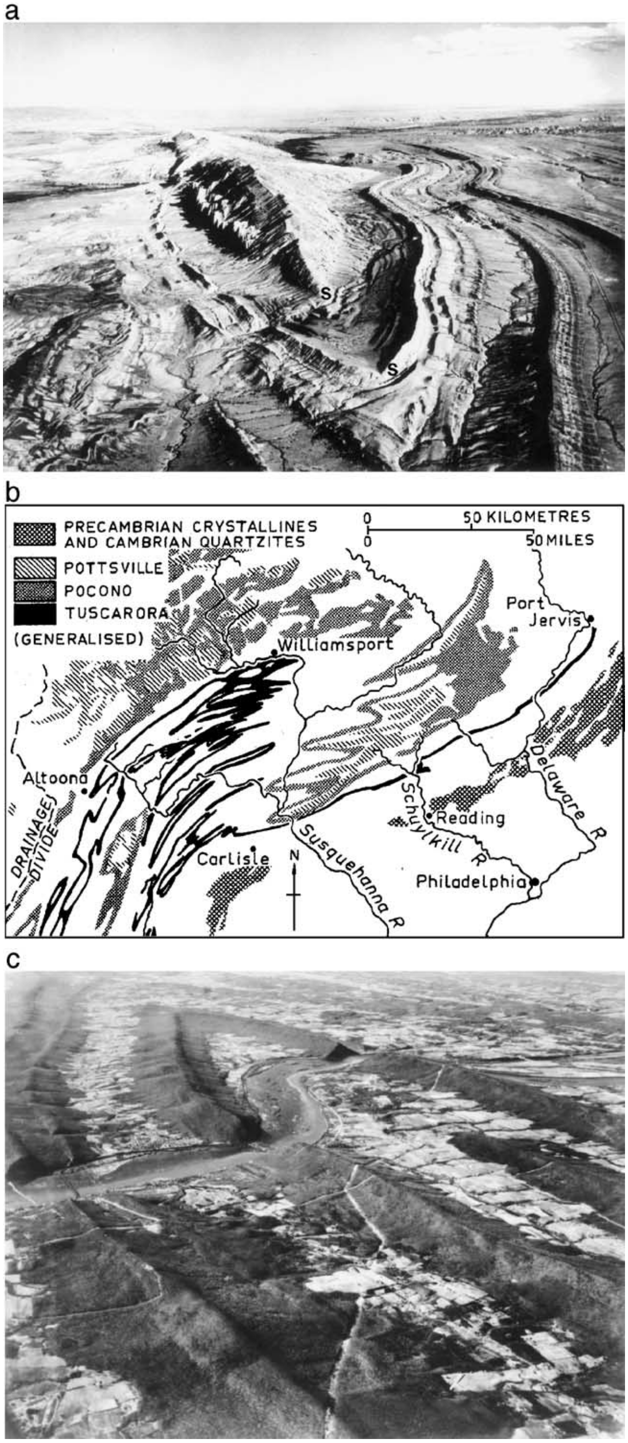

Fig. 35. (a) Incipient breached snouts (S) on Sheep Mountain, an elongate dome in folded strata near Greybull, WY (J.S. Shelton #6101, 1967). (b) Map and (c) oblique view of snouts breached by Susquehanna River in Pennsylvanian Appalachians (J.S. Shelton #4108, 1960).

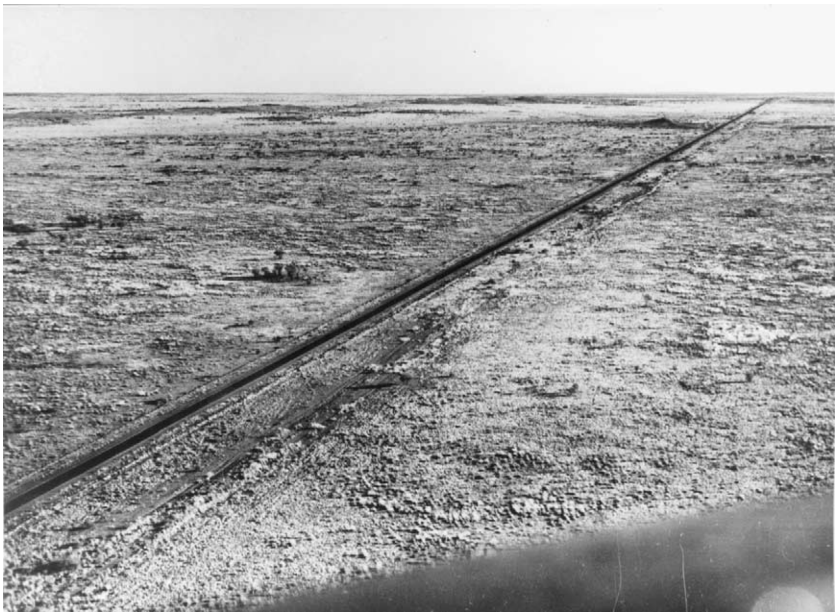

Fig. 36. The riverless Nullarbor Plain, a probable etch surface underlain by a thick sequence of Tertiary limestones (Australian News Service).

visible in the landscape, are dry (see Butler, 1950; Pels, 1966; Fig. 3). In similar fashion, whereas the Nile consistently has a sufficient volume to survive passage across the Sahara, other rivers, like the Gash and Barka, which rise in the Ethiopian Highlands, fade in the desert sands, as do innumerable minor episodic rivers rising in the interior uplands of central Australia.

Climatic change and the waxing and waning of ice sheets during the Quaternary caused sea level changes, though changes in the relative levels of land may also have occurred. Such changes caused rivers and valleys to be inundated, truncated or extended. The river patterns associated with the drowning of the Sunda Shelf, in the Indonesia archipelago, and Port Phillip Bay, in Victoria and of the Gulfs region of South Australia, are examples of truncation (Fig. 40). It might be argued that the inundated streams are no longer under consideration, for they persist, if at all, on the sea floor. On the other hand, drowning of former coastal plains explains the relationship and pattern of otherwise apparently unrelated streams and valleys as

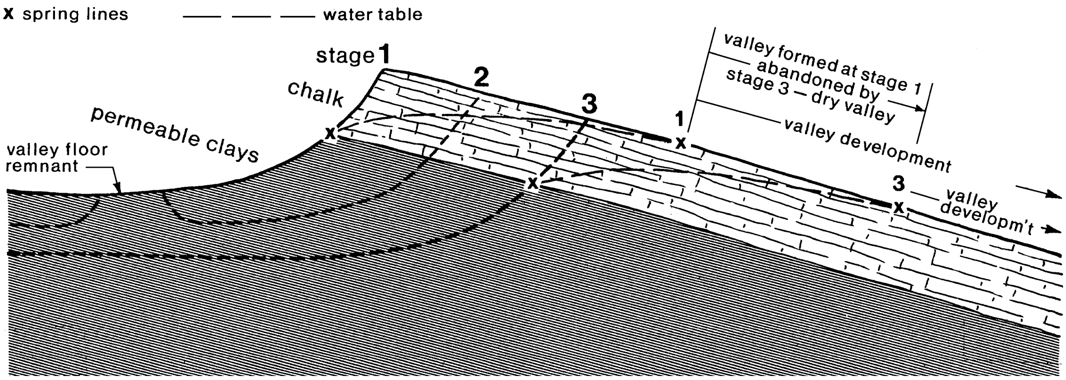

Fig. 37. Development of dry valleys in the Chalk Downs (after Fagg, 1923).

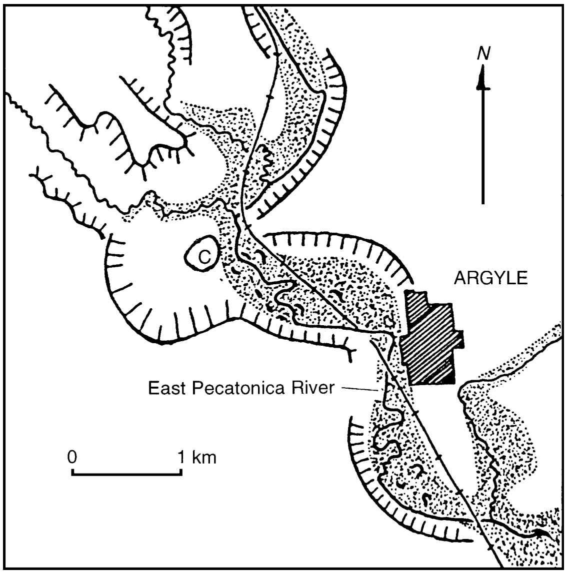

Fig. 38. An example of misfitness: the underfit East Pecatonica River near Argyle, WI, USA (after Dury, 1962). Note meander core—C.

well as, in some instances, various zoological relationships (e.g., Bishop, 1995).

During times of lower sea level than at present, many modern rivers extended far across what is now the continental shelf, and many terminated in submarine canyons scored in the continental slope. Most are due to turbidity currents (e.g., Heezen and Ewing, 1952; Heezen, 1956) but Hsü (1972) has described others which were riverine gorges inundated by the filling of the Mediterranean basin (see also, Said, 1993). Similar changes have been induced by tectonism, results of which are illustrated in accounts of the Alaskan Good Friday Earthquake of 1964, with impacts of both uplift and subsidence on a coastline and associated drainage (e.g., Grantz et al., 1964).

11. Inversion

In some areas deposits that typically accumulate in stream channels or valley floors are now found capping ridges. Miller (1937), for example, reported a creek limestone which he called calcrete—a pedogenic accumulation—but which ought to be termed travertine, capping a sinuous ridge in the Arabian Desert in Dahran. Clearly, the limestone had protected the original channel floor against erosion while the slopes to either side had been reduced: there had been relief inversion. Similarly, winding elongate mesas extend from the Hamersley Range into the adjacent plains. They are capped by a pisolitic ironstone (the Robe River Pisolite) derived from the weathering and translocation of a pedogenic ironstone formed on the rolling upper surface of the Range (Fig. 41). Plant fossils preserved beneath the Robe River Pisolite show that the translocation occurred in the (?Middle) Eocene, suggesting that the original ironstone, and the surface on which it developed are of Cretaceous age (Twidale et al., 1985); a conclusion consistent with regional stratigraphy (Hocking et al., 1987).

Silcrete forms in scarp-foot situations and also in quite extensive sheets though there are grounds for suggesting that some of the latter, which are commonly relatively narrow and elongate, and some sinuous in plan, formed in river channels and adjacent valley floors (Woolnough, 1927; Hutton et al., 1972; Young, 1985). Some silcrete contains cobbles of exotic materials, and trace elements not found in the local bedrock, suggesting lateral transport of material. Some occurrences take the form of cappings on sinuous ridges, suggesting that they are relics of meandrine valley floors (Twidale, 1985; Partridge and Maud, 1987). Again, and as with some valley fills of ferruginous lateritic detritus (e.g., Twidale and Bourne, 1998) inversion is implied, and the original single streams are frequently replaced by twin 'laterals'.

When cooled and consolidated, some lavas flowing along valleys have also resisted weathering and erosion more than the bedrock underlying the adjacent slopes and come to form elongate mesas (e.g., Slemmons, 1966; Cundari and Ollier, 1970). The alluvia preserved in some deep leads have proved a rich source of gold (e.g., McConnell, 1907; Lindgren, 1911; Fisher, 1945; Canavan, 1988; McLeod and Morison, 1996).

12. Complex patterns

Some patterns considered at the continental or regional scales can be understood in terms of structure. Thus Potter (1997) has plausibly explained the major features of continental drainage in South America in terms of tectonic control since the separation of

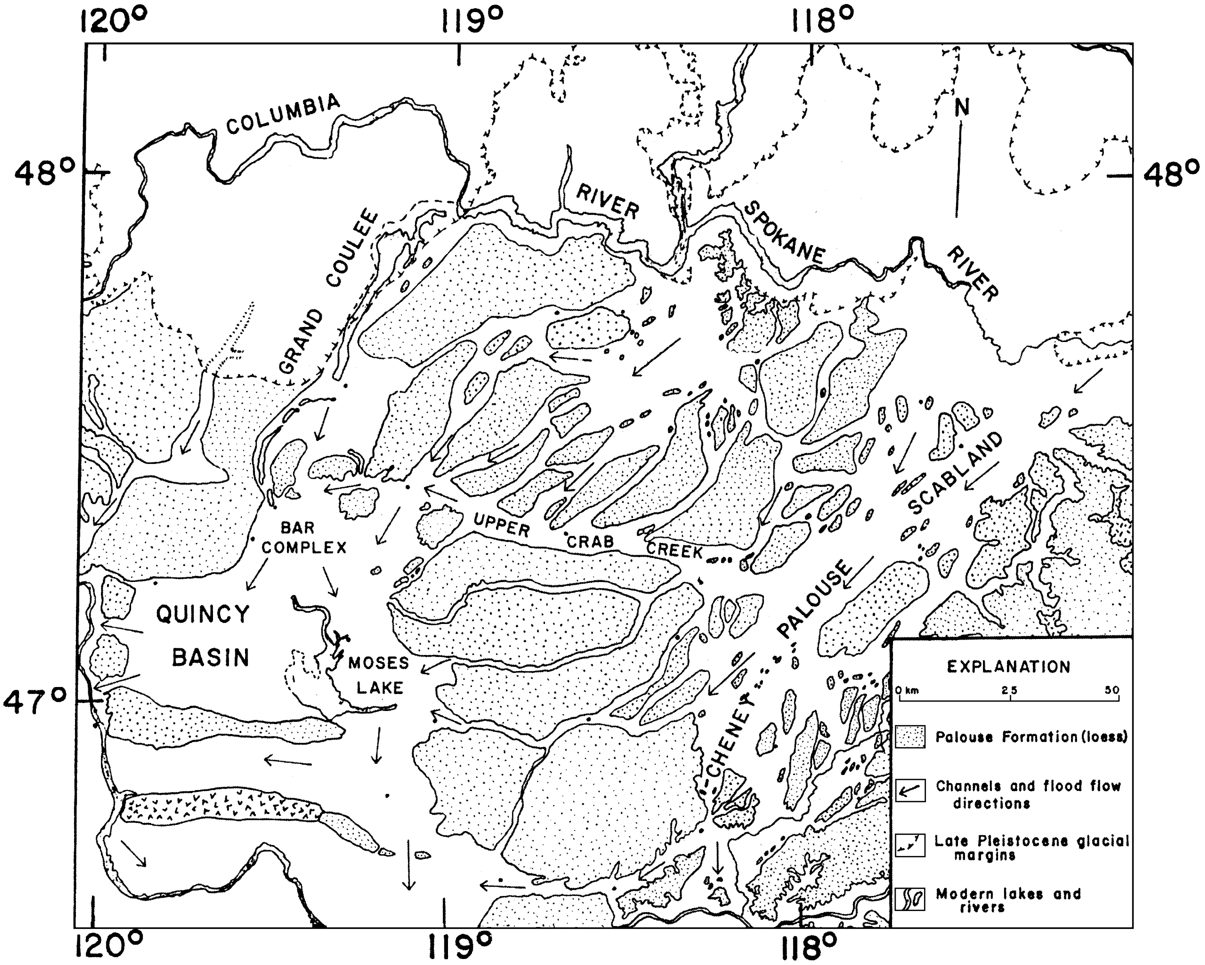

Fig. 39. The Channeled Scabland of northwestern USA showing the huge palaeochannels formed during the brief flood that followed the failure of a glacier dam that impounded Lake Missoula (after Baker, 1973).

that continent from Africa, though specific structures and other factors apply at regional and local scales. Such interpretations highlight the role of tectonics, which, though important, is only one factor amongst several.

Even at local scales the evolution of drainage patterns can be enigmatic. Thus at the eastern extremity of the Chace Range, in the central Flinders Ranges, South Australia, a ridge underlain by steeply dipping Proterozoic quartzite is breached by an unnamed strike stream tributary to Wilpena Creek. A gorge some 60 m deep has been eroded within 500 m of the eastern end of the Range. It seems more likely that a stream draining the lowland to the south, between the Chace and Druid ranges, would have become dominant and headed west to drain the broad lowland (Fig. 42). Why has the river eroded a gorge? Several explanations can be suggested. The Chace and Druid ranges are the limbs of a tight, plunging (or pitching) syncline and the river may have exploited an as yet unidentified fault zone developed in the snout of the structure. Faults are known in the locality (Fig. 42). Topographic relations suggest the breach had already developed when the plains stood some 5–10 m higher than present (remnants of the old valley floors are preserved in the area). The most likely explanation is that a fracture zone was exploited by a stream incising and persisting from a Cretaceous land surface (Twidale and Bourne, 1996).

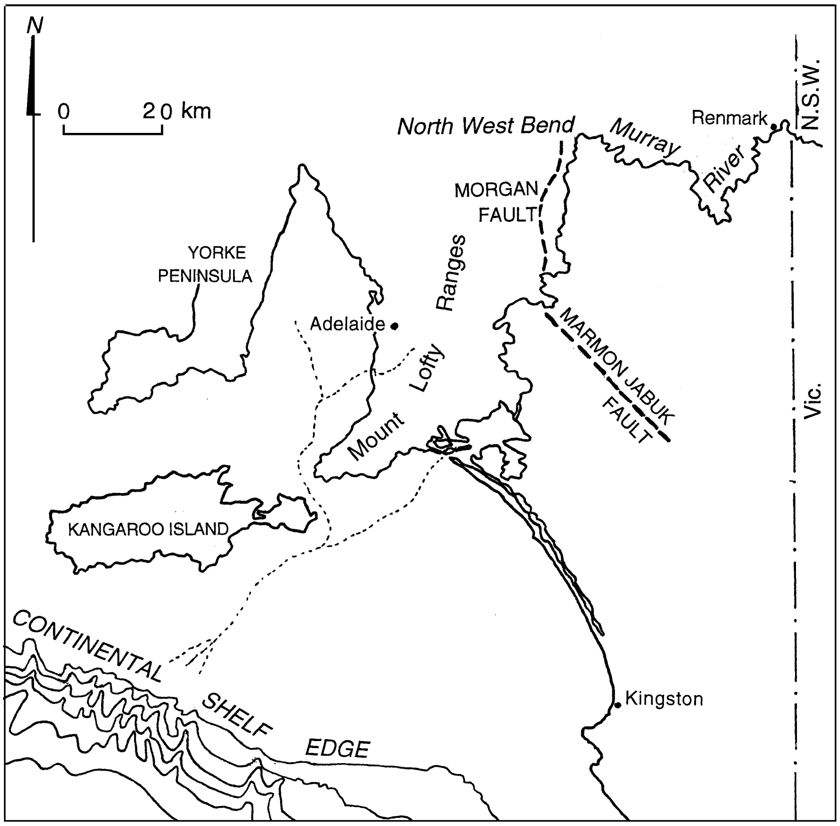

Fig. 40. Extended glacial-age rivers of the Gulfs region, South Australia, and the tectonically diverted course of the River Murray (after Sprigg, 1947; Twidale et al., 1978).

But the evidence is inconclusive, and is likely to remain so.

At the regional scale complexity is the rule rather than the exception. Understanding of the courses excavated by the Himalayan rivers, and by the Colorado in southwestern United States, calls for a combination of two or more of the factors and mechanisms cited in earlier explanations of adjusted and anomalous patterns (e.g., Longwell, 1954; Hunt, 1956; McKee et al., 1967; McKee and McKee, 1972; Lucchitta, 1990; Brookfield, 1998). The evolution of the River Nile is intimately involved with a desiccated Mediterranean Basin (see also Hsü, 1972), and later Cainozoic climatic change. Similarly, there is a continuing debate concerning the relative importance of climatic change, tectonism (rifting and warping) and river capture in determining present river patterns in southern Africa (e.g., du Toit, 1933; Nugent, 1990, 1992; Thomas and Shaw, 1988, 1992; Bootsman, 1997; Moore, 1999; Moore and Larkin, 2001; Moore and Blenkinsop, 2003), and in southeastern Australia (see Ollier and Pain, 1994, and the ensuing discussion by various authors in Pain and Craig, 1995).

To take a well-documented regional example, the River Murray is an allogenic stream which, in its lower sector (Fig. 40) in South Australia, flows in a gorge cut in flat-lying Miocene calcarenite. Its channel is meandering, but the gorge is angular in plan, and is determined by a system of orthogonal or rhomboidal fractures underprinted from the granites and other rocks that underlie the Tertiary sequence (Hills, 1956; Firman, 1974). The right-angled southerly bend in the channel at Morgan is due to diversion by low meridional fault scarps (e.g., the Morgan) which parallel the fractures that define the recurrently uplifted Mt. Lofty Ranges. The river never crossed the Ranges to emerge as the Broughton at Port Pirie (Williams and Goode, 1978), for the upland has been

Fig. 41. An example of topographic inversion south of Mt. Wall in the Hamersley Range, northwestern Western Australia. The sinuous mesa is an old valley floor capped by pisolitic iron oxides and dated by fossiliferous alluvia preserved beneath the capping.

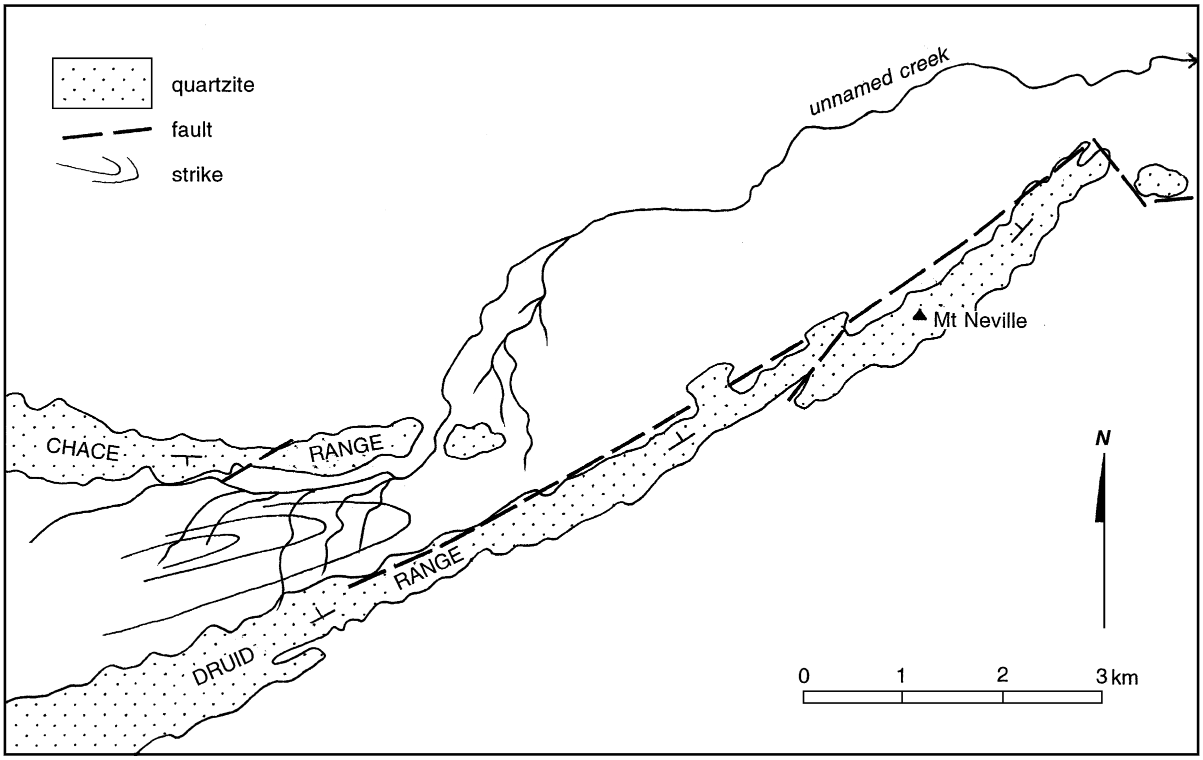

Fig. 42. Enigmatic anomalous stream course, Chace Range, central Flinders Ranges, South Australia.

in existence, with recurrent uplift and regeneration, through most of Phanerozoic time (Twidale, 1976). The river, however, is no older than the Pliocene when it took the form of an estuary, which extended to the north of Morgan as well as some distance to the east (Harris et al., 1980; Stephenson and Brown, 1989). The former valley is now preserved as a broad open valley (with remnants of cross-bedded sand and a basal oyster bed) into which the present gorge was incised in Pleistocene glacial times (Twidale et al., 1978). At Bow Hill, the river is diverted abruptly to the west for about 15 km by uplift of the WNW–ESE trending Marmon Jabuk fault, before resuming its southerly course. The sector downstream is marked by cliff-side channels formed when the river was braided due either to locally increased gradient or to increased discharge from the later Pleistocene Lake Bungunnia which may have been dammed by the Marmon Jabuk uplift (Stephenson, 1986).

During the Pleistocene glacials the River Murray extended 200 km southwest of its present mouth and across the present continental shelf during glacial periods of low sea level. At such times the river incised some 60–70 m lower than its present bed near Murray Bridge and 20 m upriver from the gorge section. It eroded its channel below the Miocene calcarenite and into the underlying Cambrian granite, schist and gneiss, which is presently exposed in only a few inliers within and adjacent to the Gorge. This was important, for whereas most of the present load of the river is carried in solution, incision into the granite landscape preserved beneath the Cainozoic sequence produced a solid load of sand and silt. Thus armed, the extended Murray formed turbidity currents which eroded deep canyons where they flowed over the edge of the continental shelf and on the continental slope (e.g., Sprigg, 1947; Von der Borch, 1968).

Thus the course of the lower River Murray is due to diversion by faulting, adjustment to underprinted structure, and changes due to fluctuations of sea level and river regime during the Quaternary. The construction of the Goolwa Barrages in 1940 near the mouth of the River and designed to prevent incursions of seawater during periods of low river flow, caused a general rise of river level of some 50 cm as far inland as Blanchetown. Many river gums were killed as a result. The extensive use of river waters for irrigation, industrial use and water supply suggests that floods like that experienced on the lower reaches in 1956 and earlier, in about 1000 B.C. (Mulvaney et al., 1964), may be a thing of the past.

13. Conclusions

Rivers constitute only a very small part of all the water on Earth yet they, with the water retained in the regolith, are largely responsible, either directly or indirectly, for the varied topography we see around us. Rivers are self-sustaining and self-augmenting positive feedback systems: they tend to permanence of position. Most river patterns are determined by structure and slope. Many patterns are determined by passive fractures but active faults and folds cause diversions or anomalies. Straight channels imply control by fractures, either exposed or induced by underprinting.

Anomalous rivers, or rivers running transversely across structural grain or topographic slope imply either diversion by a catastrophic event (climatic, tectonic, extraterrestrial or human); rivers maintaining their courses through a rising fault block or fold ridge; superimposition through an unconformity exposed during incision, or from a weathered mantle; deep erosion, and steam persistence through resistant strata, or a combination of two or more of these. Active faults and folds cause diversions or anomalies. As in other aspects of landform analysis, it has to be borne in mind that many river patterns were established in the distant past and that in the course of incision they have encountered structures different from those that initiated stream arrangement. ‘Spatially’ includes vertical as well as lateral dimensions.

The persistence of rivers incised in consolidated bedrock stands in marked contrast with the ever-changing precise location and character of the rivers of alluvial plains. Many bedrock rivers have occupied the same spatial position in the landscape for scores of millions of years, and the location of others has been determined by structures exposed in landscapes long ago eliminated by weathering and erosion.

We most frequently see that of which we are aware: as Pasteur noted: “In the field of observation chance only favours those who are prepared” (Roscoe, 1911). River patterns, past and present, help determine patterns of relief. They also frequently provide indications of structure and chronology at scales ranging from the local to the regional for those who recognise the evidence and its possible significance. They offer challenging and rewarding fields of study.

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