NEGLECTED GEOMORPHOLOGICAL CONCEPTS: SOME CANONS REVISITED, REVIEWED AND REVIVED

[Conceptos geomorfológicos infravalorados: corrección, revisión y reposición de algunos de ellos]

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A little neglect may breed mischief… (Benjamin Franklin, 1758: 280).

RESUMEN: Aunque los tres conceptos davisianos de estructura, proceso y tiempo se muestran útiles para el análisis del relieve, en la actualidad resulta una simplificación excesiva. Conceptos que implican los de presión y tensión (en particular la formación de lineamientos y cizallas conjugadas), su aumento, su disminución, los relieves impresos bajo la superficie, la corrosión química (a techo y muro del perfil), actividad diferencial y sus causas, aspectos importantes sobre meteorización, restos de antiguas superficies y de ríos, así como de viejas formas heredadas que implican un origen policíclico, no han recibido la atención que se merecen. Por otra parte, los controles climáticos tienden a estar sobrevalorados. Los efectos de la estructura, la corrosión química y el trabajo de los ríos son azonales. Sólo los extremos de carácter climático encuentran una clara expresión en el paisaje.

Palabras clave: Azonal, aplazar, corrosión, origen, lineamientos, causas, aumento, impreso, actuación diferencial.

ABSTRACT: Though the Davisian triad of structure, process and time provides useful guidelines for landscape analysis, it is now an oversimplification. Concepts involving stress and strain (and particularly the formation of lineaments and conjugate shears), reinforcement, underprinting and deferral, etching (two-stage

development), unequal activity and referral, positive aspects of weathering, survival of very old surfaces and rivers, and long lineages, which imply multistage origins, are not accorded the attention they merit. On the other hand, climatic control tends to be overemphasized. Structural effects, etching, and river work are azonal. Only climatic extremes find clear expression in the landscape.

Key words: Azonality, deferral, etching, lineage, lineament, referral, reinforcement, underprinting, unequal activity.

INTRODUCTION

Though still providing useful guidelines for analysis, the Davisian axiom that landscape is a function of structure, process and time (DAVIS, 1899) has in many respects been overtaken by events and found to be an oversimplification. Structure was considered static and obvious, whereas it is in reality dynamic, complex and subtle. The processes Davis had in mind were those active at the surface, and controlled by climatic factors. This led to the concept of climatic geomorphology with its various and varied morphogenetic regions (DAVIS, 1909; PELTIER, 1950; TRICART, 1957a; TRICART & CAILLEUX, 1958; BÜDEL, 1977) whereas many landforms are now known to originate in the shallow subsurface. They are of etch type and are azonal, a quality also attaching to many structural landforms, while the work of rivers is germane to the interpretation of all landscapes including glaciated and desertic. These "extreme climate" types are in any event typical of only a small percentage of geological time, whereas the development of landscapes per se can be traced back to Palaeozoic times in a general sense and to as early as the Archaean in particular instances. This also is relevant to the third factor in Davis' triad. Time was equated with stage in hypothetical though not entirely unreal cycles of landscape development (DAVIS, 1909; see also, JOHNSON, 1919). Landscapes were considered to be essentially Cenozoic, and most probably later Cenozoic in age, whereas Mesozoic elements survive in the cratons and older orogens that occupy substantial areas of all the continents.

Later, models were proposed in which scarp recession and dynamic equilibrium are dominant (KING, 1942, 1953). Also the interplay of tectonism, stream incision, and mass wasting was discussed (PENCK, 1924; HACK, 1960; HACK & GOODLETT, 1960; KENNEDY, 1962). Though these suggestions, and particularly the scarp retreat model, find support in the landscape, they do not take account of several concepts that, though occasionally cited in landform interpretation and fitting into the Davisian triad, are not accorded the prominence they warrant.

STRUCTURE

Forms associated with faults and folds, lithological provinces and plate tectonics have received due attention, but a sense of dynamism is limited or missing. Volcanism, past and present, is fully considered but the implications of the crustal stresses flowing from plate migrations are commonly neglected.

Figure 1. (a) Kluftkarren and (b) strain cleft, Little Wudinna Hill, near Wudinna northwestern Eyre Peninsula, South Australia. The two are located adjacent to each other and in the same orientation.

In particular, lineaments and related features are frequently overlooked, because many geologists question their very existence.

LINEAMENTS

Lineaments are straight or gently arcuate crustal structures of regional extent that find expression in the landscape (e. g. HOBBS, 1904, 1911). Most commonly they are fault zones (O'LEARY et al., 1976) and apparently form a global pattern (VENING MEINESZ, 1947; KALB, 1990). They are of great antiquity. SKOBELIN (1992), for example, linked them to structures of the primordial crust of 4 billion years ago, which he suggests may be what is presently recognised as the Mohorovicic discontinuity. Lineaments are dynamic features and associated fracture sets and systems are conduits, not only for the downward percolation of meteoric waters charged with chemicals and biota, but also for magmas, gases and fluids welling up from the deep crust and mantle (e. g. O'DRISCOLL, 1986).

CONJUGATE SHEARS

Lineaments also are shear planes which generate conjugate fractures at scales ranging from the regional to the site (e. g. KALB, 1990). Such fractures delineate tectonic forms like fault scarps, horsts and grabens, and displaced blocks. Recurrent activity is common because once a weakness, such as a fracture zone, develops in a rock mass subsequent stresses tend to be concentrated in that weakness. Stress fields change and some fractures are sealed by intrusions or by weathering products, so that new fracture sets and systems may be formed, but crustal weaknesses frequently are revived.

Shearing generates conjugate patterns in brittle rocks such as granite. Compressional and tensional stresses are developed simultaneously (WEISSENBERG, 1947). This is germane to the development of sheet fractures and structures, which though commonly attributed to pressure release (GILBERT, 1904), are arguably associated with compressional stress (MERRILL, 1897; DALE, 1923; GILBERT, in DALE, 1923: 29; TWIDALE et al., 1996).

Fracture systems that are square, quadrangular or rhomboidal in plan are commonplace, and are well-exemplified in the Gawler and Everard ranges of South Australia (e. g. TWIDALE, 1971: 46; CAMPBELL & TWIDALE, 1991). After weathering and erosion, regular patterns of hill and valley are developed as passive structural forms. Rather than rupture, shearing may cause strain which at crystal scale may cause distortion of lattices and increased susceptibility to weathering and hence erosion (RUSSELL, 1935; TURNER & VERHOOGEN, 1960: 476). Thus clefts and valleys of slightly irregular plan form and lacking long or continuous fractures, run in parallel with genuine Kluftkarren (figure 1). For these reasons, not only are the outlines of many inselbergs determined by fractures that conform to regional patterns (see e. g. TWIDALE, 1971: 51) but clefts within the hills and the outlines of rock basins (gnammas) also conform to those trends. Recurrent movement also induces

fracture propagation, with fractures gradually extending from the primary partings into the rock mass.

NEOTECTONISM

As is demonstrated by recent and contemporary earthquakes, crustal disturbances and dislocations are not a thing of the past but continue to the present day. They are more frequent and more severe along and near plate junctions but no place on Earth is tectonically stable in an absolute sense; it is just that some regions are more unstable than others. Tectonic landforms of post-Miocene age are now termed neotectonic (OBRUCHEV, 1948; HILLS, 1961; BATES & JACKSON, 1987: 445). Such features have long been recognised but were formerly described as "contemporary", "recent" or "present day" (see TWIDALE, 2007a). The most dramatic changes take place near plate junctions (e. g. Japan, the Himalaya, California, New Zealand) but neotectonic forms related to faulting and warping have been demonstrated from oldlands also (on the one hand, e. g. LAWSON, 1908; LEES, 1955; GRANTZ et al., 1964; and on the other, e. g. MESHCHERYAKOV, 1959; GORDON & LEWIS, 1980; MAUD et al., 1998; TWIDALE & BOURNE, 2004). That such movements continue, even in shield areas, is attested by repeat observations (WELLMAN & TRACEY, 1987; TWIDALE & BOURNE, 2000a, 2003).

UNDERPRINTING AND DEFERRAL

The influence of fractures and other structures is not confined to the materials or areas originally affected. Joggling of brittle basement rock underlying a sedimentary basin may in time be transmitted upwards through plastic or unlithified strata not directly affected by the earth movements. Thus the open and now dissected folds affecting superficially silicified (silcreted) Cretaceous basin strata in southwest Queensland and adjacent areas have been attributed to transcurrent movements in the underlying basement that were transmitted into the overlying beds (WOPFNER, 1960). This is an example of underprinting or the upward generation of structures (SAUL, 1978). Similar underprinting could account for the small meridional fault scarps noted by JENNINGS (1963) that interrupt the regularity of the eastern Nullarbor Plain. The Holocene diversion of the River Murray east of Echuca by uplift of the meridional Cadell Fault (HARRIS, 1939; BOWLER & HARFORD, 1966) may be of similar origin.

Warping generated in Proterozoic rocks but transmitted through Cretaceous beds is responsible for the Pleistocene diversion of the headwaters of the Flinders River, northwest Queensland, into the Diamantina, and hence from an exoreic to an endoreic system (TAYLOR, 1911: 10; ÖPIK, 1961; TWIDALE, 1966). Underprinting of a major lineament has been cited in explanation of linear rivers flowing in unstructured and incompetent country rock. HILLS (1961) suggested that the 700-km-long straight course of the River Darling, which flows in Quaternary alluvia and other unlithified or weakly structured materials for much of its course, was determined by underprinted shallow half-grabens and synclinal depressions. The latter may

have developed gradually, and some time after the initiating basement dislocation. It is thus deferred. Other straight channels flowing in essentially unlithified beds in the Lake Eyre basin may be of similar origin as may be streams flowing in alluvium in, for example, the lower Mississippi and Amazon basins (STERNBERG & RUSSELL, 1956). Meteorite impact structures in basement rocks may have been generated upward to produce circular structures, some of which have been exploited by weathering and river erosion (SAUL, 1978; WOODALL, 1994; O'DRISCOLL & CAMPBELL, 1997; see also KAMININE & RICHTER, 1956; BAKER *et al.*, 1992).

ALTERNATIVE UNDERPRINTING MECHANISM

An alternative mechanism for underprinting is suggested by dolines or sinkholes developed either in unusual materials or in anomalous topographic positions. Take, for example, dolines in laterite. Such dolines are reported from many parts of the world (for review, see TWIDALE, 1987) including the Sturt Plateau of the Northern Territory. Developed in lateritised Cretaceous sandstone and argillite, the depressions obviously postdate the Miocene laterite, and indeed, are still forming. That silica and ferruginous oxides are susceptible to dissolution is attested by pipes formed in such materials (e. g. URBANI, 1986; TWIDALE & MILNES, 1983; TWIDALE *et al.*, 1985). On the Sturt Plateau, dissolution of the ferruginous capping may have been enhanced by the presence of chemicals, including polyphenols (BLOOMFIELD, 1957; HINGSTON, 1962) derived from the decay of eucalypt litter. Many dolines occur in groups and frequently are aligned. They have developed in palaeovalleys and along minor fractures which are the equivalent of what O'DRISCOLL (e. g. 1986) called "chicken tracks" or minor planes of shearing related both genetically and geometrically to lineaments (TWIDALE, 1987).

Dolines are formed as a result of solution and collapse. For this reason they tend to occur low in the local relief. However, some developed in Pleistocene dune calcarenite on the west coast of Eyre Peninsula are unusual, for as well as standing in SSE-NNW alignment they occur high on slopes and on or near the crests of rolling hills (figure 2). The dolines may have been caused by solution (and subsequent collapse) by shallow groundwater flows which are concentrated over and in basement fractures of a similar orientation to those known to be developed in the underlying Mesoproterozoic granitic basement which is exposed to the north in the western Gawler Ranges, in small inselberg inliers, and particularly in coastal outcrops (TWIDALE & BOURNE, 2000b). Here the basement fractures are passive and their exploitation by groundwaters to produce solution and collapse in the superincumbent strata was deferred for some 1500 millions of years.

FRACTURES AND INTRUSION

Besides being zones of weakness readily accessible to descending meteoric waters, lineaments and associated fractures are avenues along which pass ascending magmas. Some are extruded as volcanoes, many of which are

Figure 2. Aligned dolines developed in Middle-Late Pleistocene dune calcarenite near Elliston, west coast of Eyre Peninsula, South Australia.

Figure 3. The Pinnacles, isolated buttressed inselbergs east of Broken Hill, western New South Wales.

aligned in parallel with known fractures in the underlying basement strata. Others of silicic composition are explosive and form effusive deposits. Some magmatic materials are injected and are cooled and solidified either as massive, planar or irregular bodies. Sills are concordant with the structure of the host rock, whereas dykes are discordant. Where of different composition or texture to the host but of similar resistance the intrusion may have no topographic expression. Frequently, however, depending an the relative resistance to weathering and erosion of the host rock and the intrusion, sills form clefts (geos on the coast) or walls, whereas dykes give rise to irregular patterns either in intaglio or in relief. The same intrusion can be in intaglio in one sector but in positive relief on adjacent slopes underlain by a different host.

Such intrusions may strengthen the host rock and cause the particular mass to be more resistant than the surrounding rock, hence such residuals as The Pinnacles, near Broken Hill in western New South Wales (figure 3), which are upstanding by virtue of pods of quartz injected into the local schistose country rock; and many of the granitic and gneissic inselbergs of the Yilgarn and Pilbara cratons, which are upstanding because they are "scaffolded and fortified" by sills and dykes (Holmes, 1918: 92).

Mineral deposits may be associated with intrusions (e. g. O'Driscoll, 1986; Bourne & Twidale, 2007), but in landform development the prime
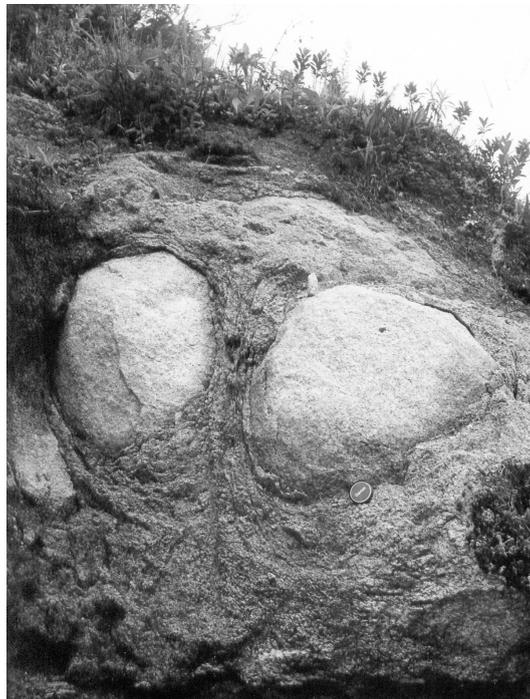

Figure 4. Corestones surrounded by weathered and laminated rock, foothills of Agulhas Negras, NNW of Rio de Janeiro, Brazil.

significance of fractures is that they are avenues along which permeate meteoric and groundwaters, which have been detected at depths of several kilometres (Borevsky *et al.*, 1987) though most occur within 700-800 m of the land surface (e. g. Nace, 1960).

PROCESS

WEATHERING

In geomorphology the word "process" embraces weathering, erosion, and deposition, which taken together are referred to as denudation. For instance, the "denudation chronology" of a region, implies an interpretation of the landscape in terms of weathering, erosion, and deposition through the ages.

As indicated in the foregoing discussion of passive structural forms, destructive weathering is effective and widespread. Certainly such activities are a crucial precursor of soil formation, and mechanical processes active in cold environments - such processes as gelifraction, haloclasty and ground ice, have profoundly changed and made angular the divides in such areas. They continue to do so. As fractures are avenues of water penetration and hence of weathering, fractured rock tends to be altered. All the rock mass may be so affected, but quite commonly cores of coherent rock remain as kernels or corestones (figure 4) within joint blocks (Scrivenor, 1913). After differential erosion and the stripping of the weathered matrix the corestones are revealed as boulders. On a larger scale, the differential weathering of a rock mass results in nascent bornhardts within compartments produced by fracture propagation consequent on recurrent shearing. Related

Figure 5. Row of granite bornhardts, Everard Ranges, northern South Australia.
Note bevelled crests.

compressional stresses are responsible for the formation of sheet fractures within the orthogonal or rhomboidal blocks (TWIDALE *et al.*, 1996). Many bornhardts (FALCONER, 1911; TWIDALE, 1982a) stand in isolation, as inselbergs, but others occur in alignment as components of massifs (figure. 5).

But weathering also has constructive aspects. Duricrusts such as laterite, calcrete and gypcrete form as accumulative horizons within weathering profiles, and some silcretes may be of like origin though many are valley deposits that have been indurated by salts derived from river and groundwaters. Such duricrusts form cappings to plateau landscapes in many parts of the tropical and subtropical worlds (figure 6). Even gypcrete acts as a caprock where the underlying sediments are unlithified and weak. The cliff bordering Lake Eyre on its western side, for instance, is capped by gypcrete which is cohesive and, in the prevailing hyperarid climate, more resistant than the underlying, friable, gypseous silts; all is relative.

Another constructional effect related to weathering (in this instance, dissolution) is due to meteoric waters that pass along and occupy fractures. Dissolved solids are precipitated and fill the partings as well as voids in the adjacent rock. This results in low ridges based on fractures but buttressed by iron oxides, silica or carbonate, like the fractures and adjacent sandstone impregnated by haematite-goethite and exposed in shore platforms on the west coast of Eyre Peninsula and the boxwork patterns formed on some granite surfaces. Infilling of solution pipes or low density zones in the kaolinised zone of a laterite by iron oxide has produced spectacular but ephemeral groups of fragile columns (see TWIDALE *et al.*, 1999).

Figure 6. *Laterite developed on granite and capping a butte and mesas in the southern Isa Highlands, northwest Queensland (C.S.I.R.O.).*
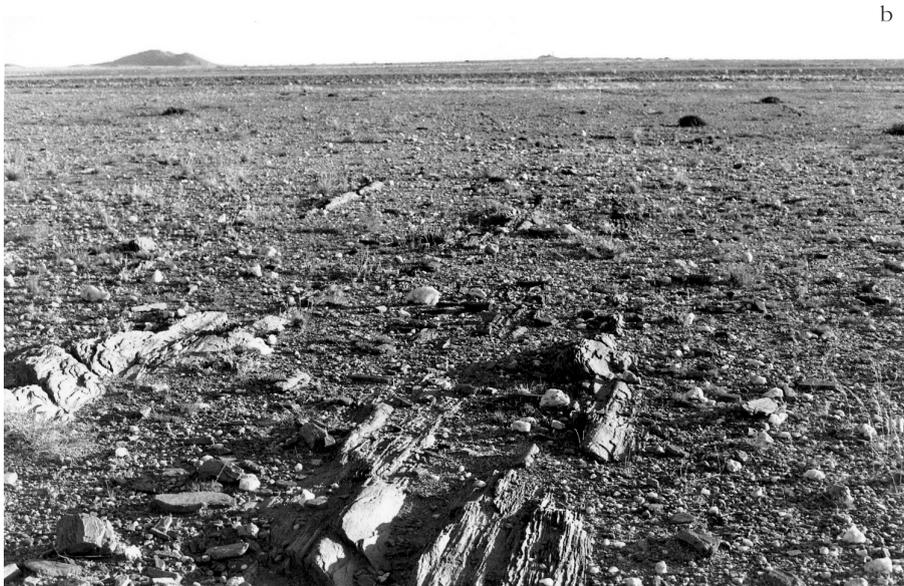
Figure 7. (a) Dissected etch plain in Kuiseb Canyon area, central Namibia. Prior to dissection the region was reduced to low relief beneath a regolith capped by calcrete, remnants of which survive in right and central middle ground. (b) Featureless etch plain cut in schist, central Namibia, part of the Bushmanland Surface.

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UNEQUAL ACTIVITY AND REINFORCEMENT

Many erosional surfaces are of etch or two-stage type, that is, they are exposed weathering fronts (MABBUTT, 1961; TWIDALE, 2002). They are widely and well developed because most regoliths are friable and readily stripped. Many have been dissected subsequent to erosion but some are of a remarkable regularity (figure 7). Many extensive plains, including glaciated surfaces of low relief such as the Labrador Plateau (TWIDALE, 1990), are of this type. Many familiar karst forms are also of subsurface derivation are referred to as covered and half-covered karst (JENNINGS, 1985). It has been suggested that even shore platforms may be partly of etch origin (TWIDALE *et al.*, 2005).

Corestone boulders and many bornhardts are etch or two-stage forms that were initiated by differential weathering at the weathering front by waters penetrating from fractures into the fracture-defined blocks (figure 4). Karst inselbergs are of the same origin (TWIDALE, 2002, 2006a). In granite, mica and feldspar are converted to clay which takes in water, swells, and disrupts the rock, forming laminae. Such laminations are not caused by shearing. Most are not associated with primary petrological features (but see TWIDALE & VIDAL ROMANI, 2005: 91; TWIDALE, 2006b). Further alteration causes the laminae to break down into granular fragments. These changes cause a dramatic increase in rock permeability (e. g. KESSLER *et al.*, 1940): a small initial invasion of water, whether along crystal junctions, fissures or fractures, causes weathering that allows more water to enter the system. That induces more weathering, more water access and so on: another reinforcement effect.

Unequal activity follows close on the heels of topographic inequalities, for once formed, such features as boulders, inselbergs, ridges and ranges, tend to persist because they shed water, the major agency of weathering and erosion (e. g. LOGAN, 1851). In an immediate sense, the water that drains from uplands enhances weathering and erosion of the piedmont zone, resulting in an assemblage of basally steepened (some flared) slopes, basal depressions and false cuestas; and more generally of surrounding areas which are lowered, so that the residuals come to stand higher and higher in the local relief. Pauses in this process of piedmont lowering are indicated by steps on the flanks of inselbergs (TWIDALE & BOURNE, 1975; TWIDALE, 1982b). Similarly, flat-topped remnants of old valley floors and piedmont platforms testify to valleys having been lowered, whereas the adjacent ridges remain essentially untouched. Uplands at all scales are reinforced and protected by their topographic position while the adjacent plains are weathered and eroded: relief amplitude has increased. Blocks and boulders also create unequal activity where they shield the underlying bedrock from moisture attack (figure 8), resulting in their standing on plinths (see also TWIDALE & BOURNE, 2000c).

Structural conditions also may directly induce inequalities and reinforcement. First, the recurrent dislocation of faults induces the development of genetically and geometrically related fracture systems. These are exploited by weathering by meteoric waters. This is an example of

Figure 8. Granite boulders on plinth, Domboshawa, some 20 km north of Harare, central Zimbabwe.

reinforcement; in this instance, the perpetuation and enhancement of an existing feature. Second, contrasts in permeability within a sedimentary sequence cause water concentration at critical junctions. For instance, the Hummocks Range, some 115 km north of Adelaide, South Australia, is a meridional upland capped by west-dipping Proterozoic quartzite resting conformably on argillite. The western scarp of the Range is scored by numerous earthflows that occur in valley heads and which originate at the junction between quartzite and mudstone, where water percolating through the pervious arenaceous strata meets the impermeable argillite. They formed only after the land had been cleared in the late 1800s and in years of heavy winter rains: some in 1916, one in 1923 and all either originated or were reactivated in 1956. Many were reactivated in the 1970s and others in wet subsequent years. Such recurrent activity again is attributable to reinforcement, for the earthflows leave behind a tension crack and depression into which flows water, which lubricates further movement.

In addition, unequal activity may be initiated by contrasted spatial moisture distribution either within a regolith or on slopes. Given a drainage channel or a pool, the regolith adjacent to the depression is drained. Weathering of the country rock at the weathering front is slower than it is a few centimetres distant from the depression. Thus rims develop along the channel or around the basin. When the regolith is stripped the channel is bordered by rock levees, and the pool by a rock doughnut (figure 9a). Once in positive relief such rises persist. If a regolith remains on the adjacent
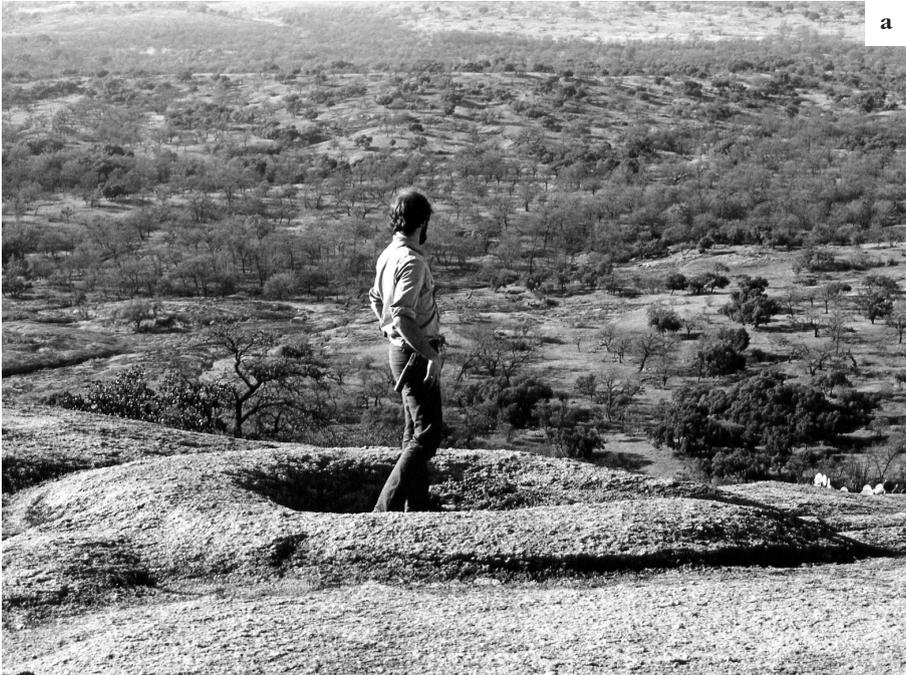
*Figure 9. (a) Rock doughnut on Enchanted Rock, central Texas, U.S.A.
(b) Font in sandstone, Rock Creek Bay, Glen Canyon National Recreation Area,
southwestern Utah. Note figures at base: the font is 34 m high (D. I. Netoff).*

slopes or platforms, subsurface weathering and lowering of the bedrock surface continues. The doughnuts increase in relief amplitude and are transformed into fonts (TWIDALE, 1993; TWIDALE & CAMPBELL, 1998). Such differential weathering is in places initiated and amplified by structural factors (e. g. NETOFF & SHROBA, 2001) but they are not essential to the mechanism (figure 9b). Just as a mesa arbitrarily becomes a butte when its longest crestal axis is less than its height above the adjacent plain, so a doughnut can be regarded as a font when the height of the annular ring above the platform or flat exceeds its diameter.

Even in landscapes lacking a caprock, scarp recession is favoured by the gravitation of runoff and soil moisture. For this reason rocks exposed on lower slopes are more rapidly and intensely weathered than are those that underlie upper facets. Slopes tend to be undercut and attain the steepest inclination commensurate with stability, and are also worn back with only minor variations in steepness. Local water distribution as well as structural factors have induced regional scarp retreat (JUTSON, 1914; HOLMES, 1918; PEEL, 1941; KING, 1942, 1953, 1957; TRICART, 1957b; TWIDALE & MILNES, 1983).

Structural weakness can lead to relative concentrations of weathering and hence erosion. Most land surfaces have been shaped by rivers that have exploited bedrock altered by water-related weathering processes. Fractures favour weathering and river development, and many river patterns closely reflect the disposition of fractures. Eventually one fracture-controlled stream incises its bed more rapidly than those adjacent to it and it becomes the master stream in the catchment. Master streams imply that kinetic energy is

Figure 10. Breached snout in the Appalachians, Pennsylvania, U.S.A. (J. S. Shelton).

concentrated in river and stream lines (Crickmay, 1932) and that the intervening divides are left high and dry. Once this happens surface runoff and groundwaters gravitate to the master stream and within limits set by baselevel it cuts its channel even more deeply and rapidly and so attracts more drainage. It may capture streams from adjacent catchments. Thus rivers are reinforcement systems for once the most deeply incised in a catchment, its increased development is assured and enhanced. Hence the persistence of rivers, the demonstrated great age of some rivers, and the persistence of anomalous rivers that have deeply eroded their channels and breached structural snouts (figure 10), and transverse rivers that flow across the local or regional structural grain (Meyerhoff & Olmstead, 1936; Oberlander, 1965; Twidale, 1972, 1997, 2004). The position of some river courses is determined by steeply-dipping structures such as fault zones the plan location of which changes with erosional lowering. As a result of unequal activity and reinforcement, some rivers have maintained their courses despite no longer being coincident with the initiating structure and are said to be referred (e. g. Twidale & Bourne, 2007).

Thus both tectonic and structural landfoms persist and are amplified as a consequence of unequal activity and reinforcement or positive feedback mechanisms. Such inevitable sequences of events and forms has been referred to as "concatenation" (Twidale, 2007b).

EXTREME CLIMATES AND MORPHOGENETIC REGIONS

The effects on landscape of climatic extremes are distinctive. This stimulated the concept of climatic geomorphology and of morphogenetic regions. Cold and arid climatic phases have left their signatures not only in the stratigraphic column but as inherited forms in contemporary landscapes. Glaciated pavements, relic pingos, and palaeodunefields record the former existence of midlatitude arid, glacial, and nival or periglacial regimes. Otherwise, however, morphogenetic regions are difficult to define and even more difficult to identify in the field (Twidale & Lageat, 1994). Tectonic and passive structural forms are azonal as are many etch forms. Riverine forms also transgress climatic boundaries: the mechanics of stream work are well established (e. g. Leopold, 1953; Leopold & Wolman, 1957; Leopold *et al.*, 1964) and operate wherever rivers flow. The impacts of floods have also been demonstrated and quantified (Bretz, 1923; Baker, 1973). The work of wind attains its maximum expression in the deserts, both hot and cold. The midlatitude desert plains are dominated by fields of constructional sand dunes, and in many areas such as the Tirari Desert of the lower Lake Eyre basin and the Mojave Desert of California, the immediate source of the sand is alluvium (e. g. Russell, 1932; Madigan, 1946; Wopfner & Twidale, 1967, 1988). The riverine origin of the many alluviated valleys and playas, past and present, is obvious but even the reg, gibber, or stony deserts owe something to water, for the occasional runoff helps winnow fines and helps concentrate coarse surface debris, while water-induced churning (the gilgai effect) takes the coarse fraction of regoliths to the surface (e. g. Twidale & Bourne, 2002).

As to erosional landforms, most are shaped by rivers related either to the episodic rains that are part of the current climatic regime, or to pluvial periods of the past (PEEL, 1941). Yardangs and some large-scale deflation hollows are exceptions (BOBEK, 1969; MAINGUET, 1970; BREED *et al.*, 1989), and dust storms imply a general lowering of some desert land surfaces (and the construction of others), but many landforms attributed to wind action are, in part at least, due to water weathering and/or erosion. Thus a mushroom rock in granite, in the Mauritanian Sahara (PEEL, 1966) may in part and in an immediate sense be attributed to sand-blasting, but it may have been earlier weakened by chemical alteration below a higher, former land surface.

Similarly the shape of an hourglass rock, in basalt in Death Valley, California (figure 11), is, according to an official notice at the site, caused by sand-blasting, but its location on a slope and well above the valley floor

Figure 11. The shape of this hourglass rock, Death Valley, California, said to be caused by sand-blasting, but possibly due to weathering in the shallow subsurface. Note that two of the blocks in foreground are so weathered.

gives cause for thought. It may be that saline solutions and haloclasty have contributed to its formation (GOUDIE & VILES, 1997: 163). Such salt-related weathering may have been active once the rock mass was exposed. However, the base of the rock (and of smaller blocks nearby) is altered where covered by debris. The hourglass form could reflect shallow subsurface moisture attack when the slope surface was 50 cm or so higher than it now is, either in earlier humid phases (e. g. OBERLANDER, 1972) or as a result of occasional rains and runoff.

Aridity or at least the occurrence of dry seasons or periods favours relief inversion, for certain alluvia (coarse but cemented by fines, or rich in iron oxides) dry and harden on desiccation causing what were stream channels to become relatively resistant (figure 12). As such they have been converted to ribs (in gully gravure: BRYAN, 1940; TWIDALE & CAMPBELL, 1986) and to narrow sinuous plateau forms (PARTRIDGE & MAUD, 1987; TWIDALE *et al.*, 1985; PAIN & OLLIER, 1995).

The glaciers of cold climates also may not be as erosionally effective as was once thought. In most instances, pressure-temperature effects ensure that glaciers act as bulldozers that effectively transport regolithic debris but have little impact on fresh rock (BOYÉ, 1950; BIRD, 1967; LIDMAR-BERGSTRÖM, 1997). They accentuate pre-existing riverine valleys, which stand in marked contrast with the angular frost-shattered slopes and peaks above.

Some forms thought to be diagnostic of past climates are open to dispute (e. g. DAILY *et al.*, 1973). Others are common to more than one climatic regime. Thus braided stream patterns are generated by floods, but these can be caused by episodic desert rains, monsoon rains, spring melt of snow and ice, or catastrophic events (e. g. BAKER, 1973). Again, pediments, once thought to be characteristic of semiarid lands, and to a lesser degree hot deserts, are reported from cold areas such as the Rockies and from Alaska, as well as monsoon lands (WAHRHAFTIG, 1970a, 1970b; AKAGI, 1972; VAN HORN, 1976).

Thus the climatic control of landscape is far from simple. Many forms are azonal, others convergent and the origin of others is misunderstood. The concept of morphogenetic regions must be viewed with caution and possibly limited to extreme regimes and instances where climatic change is independently established (see TWIDALE & LAGEAT, 1994). For instance, HOLMES (1918: 93), working in Mozambique, attributed stream incision to a pluvial or humid climatic phase, but considered the subsequent backwearing of slopes to have occurred in aridity. Yet the events were not dated and the suggested climatic phases were not independently identified. Some workers have linked specific forms to particular climatic phases (e. g. BREMER, 1965; OBERLANDER, 1972) and their interpretations are plausible; but the forms concerned are shaped or at least were initiated at the weathering front and are thus azonal.

Figure 12. (a) Gully gravure associated with protective veneer of gravel capping forming in channels scored in the shale cliff, Swallow Bluff, southern Arcoona Plateau, South Australia. (b) During the Middle Eocene rivers flowing from the Hamersley Range of northwestern Western Australia cut into the ferruginous capping, detritus from which was deposited in valley floors radiating from the upland. On desiccation the iron-rich debris hardened and protected the valley floors, whereas the adjacent divides were eroded and lowered leaving the one-time valleys in positive relief.

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TIME

SEQUENTIAL DEVELOPMENT - STAGE

The Time factor can be considered in various ways. Davis emphasised sequential development and various stages are apparent in some landscapes, as for instance where the dissection of a caprock and consistent basal attack has induced scarp recession and various plateau forms (figure 13), though as mentioned earlier, water distribution can produce comparable results. But many factors complicate such developments (minor tectonism, isostatic adjustments, structural changes with depth, sea level and baselevel changes, changes in flora). They impede or accelerate the progress or may alter a given mode of development. For instance, scarp recession may succeed a sequence dominated by slope lowering in weak strata if a resistant stratum is uncovered or if a potential duricrust develops in a weathered mantle.

STRATIGRAPHIC CHRONOLOGY

Erosional surfaces develop over time. They have an age-range. In addition, etch surfaces have two ages: the first, denoting the period of differential subsurface weathering, the second, the age of exposure of the weathering front. Similarly, exhumed surfaces can be dated according to when they were buried and when they were re-exposed.

Various numerical dating methods (and especially luminescence procedures) allow some later Cenozoic landforms to be dated within close limits. Numerical methods such as K-Ar ratios date volcanic events and forms. Cosmogenic nuclides provide estimates of recent rates of erosion and for a few youthful landforms, ages. Radiometric datings of rocks provide a solid chronological framework within which landform development can be fitted. Nevertheless, for most landforms, stratigraphy and topography still offer the best chance of obtaining age-range estimates (WATCHMAN & TWIDALE, 2002).

Geological and topographic lines of evidence and argument show or strongly suggest that substantial landscape elements are of considerable antiquity. Some date from the Early Cenozoic, others from the Mesozoic (e. g. TWIDALE, 1994, 2000, 2007c). Determining the stratigraphic age-ranges of these surfaces is not so much the problem as explaining their survival. Several contributary factors have been adduced (TWIDALE, 1976, 2003). Rock composition and structure are of course important. Quartzites, for instance, are physically hard and chemically of low reactivity in most conditions obtaining at the land surface. Low density of open fractures is also a conservative factor.

Most regoliths and other unlithified sediments are friable and readily stripped whereas fresh rock tends to stability. This is the reason for the spatial juxtaposition of recent intense erosion and old land surfaces (TWIDALE, 1999), and also for the wide distribution of etch forms including many of the older palaeoforms so far recognised (HILLS, 1975: 300; TWIDALE, 1994, 2007c).

Figure 13. Silcrete-capped mesas near Innamincka, northeastern South Australia. Note remnant of former debris slope now isolated by dissection of the weathered scarp-foot zone, and also carpet of stones, or gibber, derived from undermining and collapse of silcrete capping.

Figure 14. Two-stage bornhardts and summit bevel of the dacitic Gawler Ranges, South Australia, seen from Spring Hill.

But the distribution of kinetic energy is also significant. Divides persist as old etch surfaces (HILLS, 1975: 300) which, because they imply the former existence of a weathered and reasonably planate surface, carry with them evidence of former even older epigene surfaces. Depositional basins with fining-upward sediments can also imply the former presence of a palaeosurface (TWIDALE, 2000).

In many Gondwanan remnants the end of the Late Palaeozoic glaciations marks the beginning of modern landscape evolution and surfaces of various Cretaceous ages are now recognised from several continents. In Australia, for example, the Gawler Ranges (figure 14), Kakadu, Uluru, the Arcoona Plateau and Flinders Ranges, and parts of the Yilgarn Craton are demonstrably of such great antiquity (TWIDALE, 2007c). A similar age can be attributed to the Drakensberg plateau of southern Africa, parts of West Africa, and the Roraima Plateau of northern South America, as well as parts of the Appalachians, the Californian Sierra Nevada and the Iberian Peninsula (CURTIS *et al.*, 1958; KING, 1962; MICHEL, 1978; PARTRIDGE & MAUD, 1987; POAG & SEVON, 1989; BRICEÑO & SCHUBERT, 1990; TWIDALE & VIDAL ROMANI, 1994a). Some surfaces such as those described from Kangaroo Island, eastern Victoria, the higher domes of Kata Tjuta, central Australia, and the southwest of Western Australia may be as old as Triassic (e. g. JONES, 1931; TWIDALE, 2000). Thus palaeosurfaces of epigene-etch type and of great antiquity have been demonstrated in many parts of the world. Others will surely be located as new dating techniques emerge, and models of landscape evolution must be developed to accommodate them (TWIDALE, 1991), for the antiquity of landscape demonstrated in many parts of the world is incompatible with the continuous change affecting all parts of the surface as postulated by HUTTON (1788) and DAVIS (1899), and implicit in favoured schemes of development.

LINEAGE

Antiquity in another sense is implicit in many landforms that can be shown to have an ancient lineage. An unusual landslip developed in a valley incised in quartzite on the eastern slope of the Hummocks Range, South Australia, in 1974. It again illustrates reinforcement, for whereas the Lochiel Landslip formed during the night of 9-10 August 1974, subsequent enquiries established that a crack running high along the hillslope had developed in the previous May. It allowed runoff from the crestal area to penetrate into the shallow subsurface so that eventually a lobe of blocky quartzite, 11-12 m thick and 200 m wide and 100 m long, slid along bedding planes downslope and almost, but not quite, into the dry valley floor. The Landslip also illustrates the significance of lineage. Quartzite is an unusual material to be involved in a mass movement of this type. The reason for its translocation is that many of the bedding planes were lubricated by thin, attenuated lenses of smectite which originated about 1000 million years ago as clays accumulated in shallow pools when the quartzite now capping the Hummocks Range was deposited as a beach deposit.

Similarly, in the Gawler Ranges, the origin of both sheet fractures and structures and domical hills can be traced back to the period of fracturing. Orthogonal and rhomboidal fractures delineate domical bornhardts shaped in the 1592 million years old Mesoproterozoic dacite and other silicic volcanic rocks. They predate the 1050 million years old doleritic sills intruded along them (CAMPBELL & TWIDALE, 1991). If the interpretation of aligned dolines in the calcarenite of western Eyre Peninsula, already mentioned, is correct then they too have a lineage that can be traced back many millions of years. Thus, while not everlasting (*Genesis*, 49, 26; see also BLISS KNOPF, 1924, p. 667; LINTON, 1957) some hills –and other landforms– nevertheless have a long lineage.

Etch forms are of two-stage origin, for the major stages in their formation are a phase of subsurface weathering followed by one of erosion during which the regolith is stripped and the weathering front exposed. The two phases may occur almost simultaneously as suggested by LEWIS (1955) or they may be separated by an hiatus of millions of years. But whether closely associated or distant in a temporal sense, the many examples of long lineage suggest that many forms are multistage (TWIDALE & VIDAL ROMANI, 1994b; TWIDALE, 2005), as well as two-stage. Factors dating from distant geological epochs may be responsible, for example, for fractures exploited by weathering during the initiation of corestones at the weathering front. But time can negate the impact of structural factors, as for instance where long-continued subsurface weathering controlled by a stable water table has reduced a rock mass, however strongly differentiated, to a planate surface (figure 7b). In any event the two most immediate phases of origin involve subsurface weathering and subsequent erosion of its products and exposure of the weathering front.

DISCUSSION AND CONCLUSIONS

The Davisian triad of structure, process and time remains a sound basis for geomorphological analysis, but, it is suggested, the range of each factor must needs be elaborated. This does not necessarily imply updating, for many concepts now crucial to understanding landscape were already appreciated and published before DAVIS and other geomorphological greats announced their creeds. HASSENFRATZ invoked the etch concept in 1791, LOGAN described reinforcement effects in 1851, and LAPWORTH, BERTRAND, and HOBBS lineaments in 1892 and 1904. TAYLOR implied that some tectonic forms are of recent age as early as 1911, the same year in which FALCONER (1911) interpreted landscapes as of two-stage or etch origin, while JUTSON reached similar conclusions in 1914. Most erosional forms are of etch type. BLISS KNOPF and CRICKMAY signalled unequal activity in 1924 and 1932 (see also CRICKMAY, 1976), respectively, and long-term landscape survival was demonstrated in 1934 by HILLS (also, 1938): not much is new but helpful labels and plausible evidence and argument have been attached to ideas.

Fractures in general and lineaments in particular are basic to the themes pursued here. The lineament concept is not, however, accepted by all, or even most, geologists (see e. g. HOBBS *et al.*, 1976: 267, cited in BATES & JACKSON, 1987: 380). If the value of an idea is judged by the number of features it can explain or by its predictive potential, then one would have thought that, bearing in mind the proven success of lineament theory in mineral exploration, and the number of landforms, major and minor, that are explicable in terms of lineaments or related fractures, it would be widely accepted. But it is not. There appear to be at least two problems. First, faults are the most common representation of lineaments but are not found in every place they ought to be, in terms of the theory. The explanation may be that the implied discontinuities are represented by strain zones or by fractures at depth that have been underprinted on surface forms (TWIDALE & BOURNE, 2007).

The second problem cannot be answered satisfactorily. Though some are overridden in detail by oblique shears at plate junctions lineaments appear to form a global pattern that is common to all continents and to the ocean basins (e. g. KRENKEL, 1925). In terms of plate tectonics, this pattern implies that during phases of plate migration the continents have either maintained their original orientations or that all have rotated through 90 degrees, or a multiple thereof. This calls for much –too much– in the way of coincidence (see also MEYERHOFF & MEYERHOFF, 1974). Have lineament alignments and orientations subconsciously been fitted into a preconceived scheme? Whatever the answer, however, even if the supposed global pattern cannot be sustained, lineaments surely are real.

They are of great antiquity. Not only have they facilitated the passage of upwelling magmas etc, and the infiltration of meteoric waters, they have been planes of dislocation. Shears and strain zones associated with lineaments have been preferentially weathered and eroded in distinctive patterns. Underprinted lineaments also find expression in the landscape, particularly in straight river channels. Subsurface water-related weathering and subsequent regolith stripping to give etch forms is prominent in many areas. Concatenation has developed as unequal erosion has been reinforced, leading to the perpetuation of topographic patterns. Major rivers have maintained their courses despite structural obstacles. Conversely, unequal erosion implies that divides have persisted high and dry in the landscape with little change. Thus very old palaeosurfaces survive in many continents. Their survival poses problems but unequal erosion and reinforcement, allied with the inherent stability of rocks in dry conditions, goes some way to resolving the issue. On the other hand, water in one state or another is a universally significant agent of denudation, so that structural factors, etch forms, and the results of riverine activity are largely azonal. Only selected landforms of the assemblages associated with arid and cold climates can be taken as diagnostic of climatic influences.

It is suggested that the application to landscape analysis of such factors as the etch concept, stress propagation and the possibility of strain-controlled preferential weathering, underprinting, unequal activity and reinforcement, taken together with a more critical consideration of climatic impacts, provides a more realistic understanding of landscape. Water plays a critical role in each of these processes and mechanisms. Without water the Earth's surface would resemble that of the Moon.

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