Structural controls on the orientation of erosion gullies in mid-western New South Wales, Australia

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Abstract

The role of geology in determining the drainage network of gullying has been evaluated by quantitative methods of analysis. At gully erosion sites in New South Wales, field evidence suggests that soil cracks are sites of preferential flow and erosion at both the surface and subsurface. Soil fabric and rock structure and weathering studies were undertaken to establish the inheritance of soil cracks from the underlying parent material. Gully orientation was correlated with the strike of joints and bedding planes in a range of rock materials, including sedimentary, intrusive and extrusive igneous, and thermal and regional metamorphic rocks. These units vary not only in terms of mineralogy but also in degree of weathering. However, all are steeply dipping structures (usually exceeding 60°). Correlations exist between gully orientation and joints in the underlying material, but the strength of the relationship varies according to the parent material. In the Ordovician hornfels, where no correlation between joints and gully orientation occurred, the evidence showed that gullying was controlled by faulting along the hornfels–granite boundary. These relationships support the view that throughflow processes are dominant in the development of gullies, since convergence of runoff would not be expected to align with subsurface soil discontinuities. © 2000 Elsevier Science B.V. All rights reserved.

Keywords: erosion gullies; throughflow; soil cracking; gully orientation; joints; bedding; faulting

1. Introduction

Discontinuous gullies are a feature of accelerated erosion which has been recognised in climatically diverse regions including England, Spain, Italy, Russia, southern Africa, the United States of America, the western Canadian Arctic, New Zealand, Australia and Central and South America. The current domi-

nant hypothesis is that erosion gullies are initiated when the force of flows is greater than the critical soil shear stress, allowing scouring or tunnelling to take place (Dietrich et al., 1993). At a broad scale, it is apparent that discontinuous gullies are most likely to develop on the shallow, dispersible soils of cleared slopes. Areas with mean annual rainfall in the range 600–800 mm are particularly vulnerable because of the impact of highly variable rainfall on surface cover.

The literature reviewing this form of land degradation has been prodigious. Because of the threats

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posed by gullyling to sustainable land management and water quality, considerable effort has been spent in further understanding and quantifying gully initiation and development, in terms of either processes (Swanson et al., 1989; Harvey, 1992; Prosser and Winchester, 1996) or the factors of climate, land-use, and/or topography (Moore et al., 1988; De Oliveira, 1990; Radoane et al., 1995; Vandaele and Poesen, 1995; Prosser and Winchester, 1996; Gutierrez et al., 1997). In contrast, although the role of geology, in terms of lithology (Williams, 1981; Verstappen, 1983) and palaeo- and neotectonics (Egboka et al., 1990), has been accepted as contributing to this erosional feature, no quantitative work has been published on the relationship between erosion gullyling and structure of the underlying parent material, although recent work suggests a structural role in the development of piping (Farifteh and Soeters, 1999). In mid-western New South Wales, Australia, the influence of geology on erosion is complex (Beavis, 1991). In its simplest form, the relationship can be thus described: structure determines the location of erosion within the landscape, while lithology and texture, by controlling mineralogy and particle size, determine the severity of erosion.

Previous studies of drainage networks have demonstrated a correlation between stream orientation and joints in parent material in arid zones with low relief, moderate structure, and an extensive mantle of soil overlying chalk (Polishook and Flexor, 1983) and in sandstone lithologies characterised by mildly folded, deeply dissected plateaux (Everette Bannister, 1980). In these studies, joint orientation was found to be a major contributing factor in stream network orientations, with hydraulic gradients being increasingly important in areas with steeply dipping strata. Since these studies, together with work in the study area considered here (Beavis, 1991), indicate that stream networks adjust to the underlying geological structure during dissection, the question whether similar adjustments are made by erosion gullies arises.

Field observations indicated that major soil cracks in the sidewalls and headcuts of gullies were sites for preferential erosion in subsoils by throughflow processes and piping (Beavis, 1991). These cracks are also sites of erosion initiation and development. If these sites are controlled by geological factors, then

it could be expected that similar controls will determine the orientation of gully systems. This study comprises two components: an investigation of the orientation of soil cracks, with reference to the horizontal, to determine whether sites of preferential erosion are controlled by discontinuities in the underlying rock; and, an investigation into the relationship between gully and joint/bedding orientation. Hence, the present work specifically explores the relationship between geological structure — in terms of joint systems, bedding and faulting — and soil macrofabric and gully orientation. The study examines a wide range of lithologies in mid-western New South Wales, Australia, which vary in terms of mineralogy and weathering. All units, however, are characterised by steeply dipping structures usually exceeding 60°.

2. Regional setting

The study area was selected because of its significant gully density, erosion risk, highly variable geology and agricultural productivity. The area, of approximately 1500 km², is located in mid-western New South Wales, Australia, and includes the small township of Grenfell (Fig. 1). The topography comprises: precipitous slopes and rough terrain in association with the Devonian sedimentary belt, with slopes generally > 15° in the eastern and northeastern sections of the area; rolling terrain in the central area; and, gently undulating to flat terrain in the western section associated with the alluvial aprons of the granites and deep alluvial plains at the western boundary. Relief ranges from ~ 280 m in the Devonian sedimentary belt, through 100–180 m in the central region associated with the granites and hornfels, to 20 m in the depositional areas to the west. Rainfall appears to be quite uniform, spatially, with a long term mean annual rainfall of 609 mm in the north at Gooloogong, and 629 mm at Grenfell in the south.

2.1. Erosion

The study area is located within the wheat belt of central New South Wales, where intensive agricultural expansion and development has occurred since European settlement last century. Extensive clearing

Fig. 1. Location of study area.

of native vegetation, and reduction of groundcover through grazing and cropping systems has exposed soils to erosion. In addition, gold, tin–bismuth, and manganese mining, which operated from the middle of last century until the 1960s, has provided a set of conditions conducive to the development of erosion at a local scale. In the area, gully erosion is a major form of land degradation causing accelerated soil loss, downstream turbidity and sedimentation and reduced farm access. While severe gully erosion occurs in association with agriculture, actively eroding gullies have also been observed in undisturbed forest, suggesting that this landscape is inherently, erosionally unstable.

2.2. Geology

The geology of the area is shown in Fig. 2. The area lies within the Cowra Trough of the Lachlan Fold Belt (Fig. 3). Interpretations of the tectonic development of the Lachlan Fold Belt differ; how-

ever, four orogenic episodes have defined the deformational history of the area. In the Late Ordovician, deformation and regional metamorphism occurred in response to the Benambran Orogeny. According to Cas (1983), the peak of facies diversity, and of granitoid intrusions, can be correlated with the later Bowring Orogeny, in the latest Silurian to Early Devonian. During this orogenic episode, sedimentation, vulcanism and plutonism, together with crustal deformation, were occurring concurrently (Gilligan and Scheibner, 1978; Cas, 1983). In the Late Middle Devonian, the Tabberaberan Orogeny caused major deformation, folding and uplift in the Cowra Trough. During the Carboniferous, Late Devonian sediments were deformed by the ‘weak’ Kanimblan Orogeny.

Within the area, field observations and structural data indicate that the pre-Late Devonian rocks are typically highly deformed with complex folding and fracturing, including several generations of deformation in the Ordovician metasediments and Silurian tuffaceous sediments. In contrast, this complexity of

folding and intense deformation does not occur in the Late Devonian sequences.

The stratigraphic sequence of the rocks of the area are summarised in Table 1.

Fig. 3. Geological setting of study area.

2.3. Soils

Sites selected for study were located where rock occurred in erosion gully floors and/or adjacent to gully systems. Soils are typically shallow, ranging 1–2 m in depth. The contribution of parent material to soil genesis was assessed on the basis of texture, and by comparison of the mineral composition of the parent rock with that of the soils. The soils formed from the differing lithologies are quite distinct and are summarised below.

2.3.1. Ordovician metasediments

These soils are characterised by a strong textural contrast between the surface and sub-soils, with fine sandy loam surface soils with A2 horizons overlying sandy clay loams to sandy clay subsoils. Abundant gravel comprising metasedimentary material occurs throughout the profile.

2.3.2. Ordovician hornfels

These soils are black, self mulching cracking clays with abundant lithic fragments of weakly weathered hornfels throughout the profile.

Table 1
Stratigraphic sequence of rocks in the study area

Age	Lithology
Quaternary	Alluvium
Tertiary	Non-marine alluvial and lacustrine sediments
Late Devonian	Grenfell–Gooloogong Mandagery Sandstone Hunter Siltstone Peaks Sandstone Mogongong Conglomerate Member Weddin Mountain Weddin Sandstone Bogan Gate Sandstone
Middle Devonian	Grenfell Granite Eugowra Adamellite
Late Silurian	Young Granodiorite Illunie Rhyolite — rhyolite, dacite, andesite, tuffs, tuffaceous sediments and rhyodacitic ignimbrite
Late Ordovician	Phyllite, greywacke, jasper and hornfels

2.3.3. Illunie rhyolite: rhyolite, tuffaceous sediments

The majority of soils are kraznozems and structured plastic clays with hardsetting apedal surface soils grading from sandy to light medium clays. Fragments of igneous parent material are abundant, increasing downprofile.

2.3.4. Granitic soils

The soils developed on the Young Granodiorite, Grenfell Granite and Eugowra Adamellite range from shallow structured sands/lithosols to yellow podzolics. The yellow podzolics are characterised by an apedal, hardsetting sandy loam surface soil overlying a coarse textured, sandy clay.

2.3.5. Peaks Sandstone

Hard pedal red texture contrast soils are representative of this unit, comprising a hardsetting fine sandy loam overlying sandy clays with weakly weathered lithic fragments of sandstone and soft nodules of iron.

Fig. 2. Geology of the area: (19) alluvium, (18) Bumberry Formation, (17) Mandagery Sandstone, (16) Hunter Siltstone, (15) Peaks Sandstone, (14) Mogongong Conglomerate Member, (13) Weddin Sandstone, (12) Bogan Gate Sandstone, (11) aplite, (10) Grenfell Granite, (9) Eugowra Adamellite, (8) Young Granodiorite, (7) Young Granodiorite — pegmatite, (6) Illunie Rhyolite — rhyolite, dacite, andesite, tuffs, tuffaceous sediments, (5) Illunie Rhyolite — rhyodacitic ignimbrite, (4) Bumbaldry Limestone, (3) jasper, (2) hornfels, (1) metasediments — phyllite, greywacke, metasiltstone.

3. Methods of analysis

Given the paucity of good outcrop in the study area, suitable localities for strike measurement were limited. However, in most lithological units, three sites (referred to here as ‘primary sites’) were selected for measurement of joint strike (and bedding plane where applicable). In the case of Young Granodiorite, where exposure was extremely limited, one primary site was selected, and in the Eugowra Adamellite and Hunter Siltstone, data from two primary sites were analysed. The orientation of gully segments for each of the lithological units was measured within a 5-km radius of these primary sites. The gullies incised soil material developed on the same parent material as that at the primary site. The soils are polygenetic, in the sense that they contain elements of the weathered rocks and of colluvium (derived from the same parent materials) moving downslope. Mineralogical, textural and chemical evidence suggested that aeolian accretions did not play a significant role in soil genesis in the area (Beavis, 1991). This was confirmed by the results of scanning electron microscopy analyses which indicated that there was a total absence of features suggestive of aeolian environments or of high energy chemical environments (Beavis, 1991).

Sites of macro-fabric studies were also located within this 5-km radius, and were characterised by having similar slope gradients (3–5%), landuse (native pasture), drainage basin area (> 8 ha < 25 ha), dominant soil type for each given lithology, and, by having rock outcrops on the gully floor, headcut and/or lower sidewalls. Soil cracks, with the exception of the hornfels site, were not expressed at the ground surface.

3.1. Soil fabric

Field observation of sites where preferential infiltration along inherited fracture planes and piping occurred indicated that vertical cracking was important. Soil macrofabric studies of subsoils using crack orientation analyses were undertaken on undisturbed

soils exposed at gully sidewalls adjacent to headcuts. These analyses were done for soils developed on: Peaks Sandstone; Grenfell Granite; Young Granodiorite; Illunie Rhyolite, rhyolite and tuffaceous sediments; and the Ordovician hornfels and metasediments. The analyses were carried out to determine the degree of inheritance from joint fractures, and bedding planes where applicable, of the underlying rocks. The dip angle is considered a reliable parameter (Hart et al., 1985) for determining correlations between soil cracks, and joints in the underlying rocks. Orientation of the cracks was measured in a clockwise direction with reference to the horizontal, and recorded as degrees inclination from the horizontal from 0° to 179° . The measured inclinations were then grouped into 10° classes ($0-9^\circ$, $10-19^\circ$, ..., $170-179^\circ$), and the number in each class expressed as a percentage of the total number measured. The percentage for each class was then plotted at a point at the class midpoint (4.5° , 14.5° , ..., 174.5°) and a rosette was constructed (see Fig. 4).

Soil crack density was also determined, and this parameter was expressed as length of cracks per square metre (Evans, 1978). The method used was to measure the length of cracks within several areas, each being from 0.50 to 0.75 m², and extrapolating to length in m/m².

In order to determine the degree of correlation between structural elements in the parent material and the overlying soil, fracture spacing index (I_f) (Beavis, 1985) was measured of discontinuities in rocks outcropping in and/or immediately adjacent to the gully systems where macrovoid studies had been undertaken. Fracture spacing was determined by counting the number of joints which cut a selected length of traverse line. Traverse lines were set out at right angles to each of the joint sets present, which ensured that at each primary site, at least four traverse lines approximately 30–50 m in length were measured. Spacing was expressed in terms of the average distance between the fractures. All primary sites, with one exception (incising hornfels) are characterised by relatively good outcrops, providing adequate lengths of transects in more than one direction.

Fig. 4. Soil crack orientation rosettes for soils developed on (a) metasediments; (b) hornfels; (c) Illunie Rhyolite, tuffaceous sediments; (d) Illunie Rhyolite, rhyolite; (e) Young Granodiorite; (f) Grenfell Granite; Peaks Sandstone.

(a) Ordovician metasediments

(b) Ordovician hornfels

(c) Illunite Rhyolite: tuffaceous sediments

(d) Illunite Rhyolite: rhyolite

(e) Young Granodiorite

(f) Grenfell Granite

(g)

In the case of the hornfels site, measurement of I_f was taken at an adjacent location approximately 150 m upslope. It should be noted that although massive rocks were also sampled (Grenfell Granite and Young Granodiorite), the sites studied were located either on, or adjacent to, major faults, or the parent material represented highly fractured marginal phases.

3.2. Gully orientation

Primary sites for Hunter Siltstone, Peaks Sandstone, Grenfell Granite, Eugowra Adamellite, Young Granodiorite, Illunie Rhyolite (rhyolite and tuffaceous sediments) and the Ordovician hornfels and metasediments were selected for measurement of joint strike, and bedding plane strike where applicable.

In the early stages of data design, when measurement of gully segment orientation was undertaken further than 10 km from the primary site, no relationship between joint and gully orientation occurred. This emphasises that the structural controls on gully orientation are local rather than regional.

Aerial photographs were interpreted and mapped to record the location and orientation of the gully erosion network. Information from the contact prints was copied directly onto clear overlays to form a mosaic, which took into account peripheral distortion. Field checks were undertaken to verify the accuracy of interpretation of the photography. Strike of joints, and bedding planes, was measured using a modified universal clinometer. All joints (and where appropriate, bedding planes) and gully segment orientations were measured at each site. Gully segment orientation, and the strike of joints and bedding planes, were all collated into 20° categories. These directional categories were then analysed to obtain correlation coefficients between gully orientation and joint/bedding orientation.

In addition, weathering studies of the rock mass and material for each lithological unit were used to interpret the results of the statistical analyses. Description of the rock mass and material, including fabric and colour, and the rock:soil ratio were based on field observations. Depth of weathering was determined from bore data. I_f of the rock mass was measured using the method described in Section 3.1. The spacing of fractures tends to decrease with

increased weathering, so the index can be used as a guide to the grade of weathering for a particular rock mass (Beavis, 1985). The micropetrographic index (I_{mp}) (Beavis, 1985) is defined as:

$$I_{mp} = \frac{\text{percentage sound constituents}}{\text{percentage unsound constituents}}$$

The 'sound' constituents are the primary minerals and the 'unsound' constituents are secondary minerals, produced by weathering, such as sericite, clays and iron oxides together with microcracks and voids resulting from weathering. Results of these analyses were used to define the grade of weathering.

4. Results

4.1. Soil fabric

Soil crack density results indicate that there is a large range of values (Table 2), with some general trends according to parent material associations. Statistical analysis indicates a relationship between crack density and linear shrinkage (correlation coefficient = 0.718), which demonstrates the role of shrinkage behaviour of soils (a function of clay mineralogy) in determining the cracking density. This result is to be expected. However, analysis of soil crack density and I_f of the underlying rock provides a correlation coefficient of -0.842 . Thus, soils which are characterised by high crack densities can be expected to be associated with highly fractured parent material, while soils with low crack densities overlie rocks in which the spacing between discontinuities is greater. Measurements of crack orientations (dip angles) demonstrate maxima and sub maxima (Table 3), which also vary according to parent material.

Table 2
Soil crack density values according to associated parent material

Lithology	Crack density (m m^{-2})
Peaks Sandstone	40.3
Grenfell Granite	47.7
Young Granodiorite	37.21
Illunie Rhyolite: rhyolite	60.7
Illunie Rhyolite: tuffaceous sediments	61.5
Ordovician hornfels	84.7
Ordovician metasediments	53.7

Table 3

Maxima and sub-maxima of soil crack orientations according to lithological association

Lithology	Soil crack orientation maxima and sub maxima	Correlated joint set(s) in parent material
Peaks Sandstone	80–99° 30–39°; 110–119°	ac joints ^a <i>h0l</i> joints ^b ; ac joints
Grenfell Granite	110–119°	tension joints
Young Granodiorite	140–149°	tension joints
Illunie Rhyolite: rhyolite	80–89° 0–9°	Tensional release at unconfining boundary of the ground surface
Illunie Rhyolite: tuffaceous sediments	80–89°; 90–109° 90–99°	ac joints ac joints
Hornfels	150–159°; 50–59° 90–99°	<i>h0l</i> joints ac joints
Metasediments	40–49°; 130–139° 90–99° 80–89°; 100–109°	<i>h0l</i> joints ac joints ac joints

^aac joints (perpendicular to the fold axis).^b*h0l* or radial joints (parallel to fold axes and approximately perpendicular to layering); *hkl* joints (shear joints).

The distribution of soil cracks is apparent in crack orientation rosettes for each lithology (Fig. 4a–g). The results of macrovoid fabric studies demonstrate two components of crack patterns: shrinkage cracks (a response of expansive clays to cycles of wetting and drying), and those inherited from joints in the underlying parent rock. Superimposed on these patterns are the subhorizontal cracks aligned parallel to the gradient of the hillslope, which relate to the tensional release at the confining boundary of the ground surface. Furthermore, major continuous cracks in soils developed on intensely fractured and

finely bedded material can be correlated with fracture spacing in the parent material, so these are inherited features. This relationship is important to erosion studies, given the preferential infiltration and consequent erosion, including piping, associated with these cracks. There is a similar correlation between soil crack spacing and I_f of silcrete, where this occurs as a discontinuous indurated pan underlying the B1 horizon of soils developed on the Grenfell Granite. This relationship does not occur with soils developed on massive lithospheric material (granite, granodiorite and adamellite).

Table 4

Correlation coefficients (R_s) of joint/gully orientation and bedding plane/gully orientation, classified according to associated lithological units

Lithological unit	Strike of joints/gully orientation	Strike of bedding/gully orientation
Hunter Siltstone	0.901	
Peaks Sandstone	0.787	0.505
Grenfell Granite	0.792	
Eugowra Adamellite	0.066 (not significant)	
Young Granodiorite	0.834	
Illunie Rhyolite: tuffaceous sediments	0.840	0.588
Illunie Rhyolite: rhyolite	0.616	–0.585
Hornfels	–0.502	
Metasediments	0.949	–0.481

Fig. 5. Frequency distribution of gully segment and joint orientation, Hunter Siltstone, showing maxima of joint sets.

4.2. Gully orientation

Statistical analyses of the orientation of gully segments and the strike of joints and bedding in Table 4 indicate that underlying rock structure exerts a significant control on gully systems.

Joint systems exert the strongest control on gully orientations, with most lithologies recording significant correlations above $R_s = 0.500$. Plotting of frequency diagrams for both joints and gully orientation provides some clarification on the correlations between these variables (Figs. 5–13). In each frequency data set, it is clear that maxima of specific joint sets coincide with maxima of gully orientations.

Fig. 6. Frequency distribution of gully segment and joint orientation, Peaks Sandstone, showing maxima of joint sets.

Fig. 7. Frequency distribution of gully and joint orientation, Grenfell Granite, showing maxima of tension joints (T).

However, as would be expected from the statistical analyses, the degree of coincidence varies according to parent materials. This variation is, to some degree, a function of the nature of the joint systems: for example, their openness and spacing, and the number of dominant joint sets.

In terms of sedimentary or folded rocks, ac joints (perpendicular to the fold axis) and *h0l* or radial joints (parallel to fold axes and approximately perpendicular to layering) are particularly significant. From a theoretical point of view, it could be expected that these types of tension joints would be open, relative to the *hkl* shear joints, and that gullies

Fig. 8. Frequency distribution of gully and joint orientation, Eugowra Adamellite, showing maxima of tension joints (T). Correlation not significant.

Fig. 9. Frequency distribution of gully and joint orientation, Young Granodiorite, showing maxima of tension joints (*T*).

Fig. 11. Frequency distribution of gully and joint orientation, Illunite Rhyolite (rhyolite), showing maxima of joint sets.

would develop preferentially on them. The frequency diagrams confirm this to a degree: in the majority of cases, *ac* joints represent a dominant joint set which is coincident with a maxima of gully segment orientations. However, in the Ordovician metasediments, and the Devonian Peaks Sandstone and Hunter Siltstone, certain gully orientation maxima are coincident with subdominant *hkl* joint sets.

The variation in the strength of correlations between gully segment and joint orientation can be explained in terms of degree of weathering and the

physical and mechanical characteristics of the joint systems, specifically, their spacing in two dimensions and the degree of openness. Comparison of the different rock types shows that the strongest positive correlations between joint and gully orientations tend to coincide with highly weathered material (as defined by a qualitative assessment of fabric and colour of the rock mass and material including the openness of joints; and quantitative analyses of depth of weathering; rock to soil ratio — applicable to crystalline rocks only; fracture spacing index; and micropetrographic index, I_{mp}). Table 5 provides an

Fig. 10. Frequency distribution of gully and joint orientation, Illunite Rhyolite (tuffaceous sediments), showing maxima of joint sets.

Fig. 12. Frequency distribution of gully and joint orientation, hornfels, showing maxima of joint sets.

Fig. 13. Frequency distribution of gully and joint orientation, metasediments, showing maxima of joint sets.

overview of the quantitative analyses on which weathering grade was partly based, and joint/gully orientation correlations. Qualitative descriptions are not shown.

Where weak relationships occur, other structural controls or surface modifications may override the influence of jointing on gully segment trend. Intrusion of the Grenfell Granite resulted in the imposition of a thermal metamorphism on the Ordovician

metasedimentary rocks. The thermal metamorphic rocks are extremely hard, durable hornfels. The hornfels occur as a well-defined ridge with steep sided slopes. Subsequent faulting along the boundaries with the granite is evident with outcrops of mylonite and fault breccia, and the development of lineaments. Erosion gullies either align with these faults, or are associated with groundwater discharge from the highly fractured fault rock as shown in Fig. 14. The dominant structural influence on the orientation of gullies incising soils associated with the hornfels is clearly faulting.

The Eugowra Adamellite occurs in the central northern section of the area as a massive, and essentially continuous outcrop, representing the southernmost part of a granitic complex which extends 44 km to the north. The rock outcrops as continuous sheets and tors on crestal slopes, with gently sloping colluvium and alluvial toeslopes. Soils are structured sands and yellow podzolics, with low fertility and poor aggregate stability. Agricultural development of this area has included cropping and grazing of what is essentially marginal land, with consequent degradation of soils. In response to this, soil conservation programs have been in operation over an extended period, and include surface structural modifications (graded banks, grassed waterways) and gully fill. The impact of these restoration works may explain

Table 5

Gully joint orientation correlations and weathering characteristics of lithological units

CW = completely weathered; MW = moderately weathered; SW = slightly weathered.

Lithological unit	Joint/gully orientation correlation	Depth of weathering (m)	I_{mp}	I_f	Rock: soil ratio	Degree of weathering ^a
Hunter Siltstone	0.901	99	4	0.769	n.a.	HW
Peaks Sandstone	0.787	69	6.0	0.48	n.a.	MW
Grenfell Granite	0.792	40	5.6	1.098	80%	MW
		70 ^b	2.0 ^b	nd	50%	CW ^b
Eugowra Adamellite	0.066	27	7.3	0.80	90%	SW
Young Granodiorite	0.834	39	5.6	0.43	80%	MW
Illunie Rhyolite (rhyolite)	0.616	32	9	0.19	95%	SW
Illunie Rhyolite (tuffaceous sediments)	0.840	49	5.6	0.15	n.a.	MW
Hornfels	-0.502	45 ^c	11.5	0.16	90–95%	SW
Metasediments	0.949	102	3	0.083	n.a.	HW

^aBased on weathering classifications by Irfan and Dearman (1978) and Beavis (1985).

^bFaulted and sheared.

^cMine shaft.

Fig. 14. Groundwater discharge sites (associated with gullyng) and major discontinuities in the hornfels and the Grenfell Granite.

the statistically insignificant correlation, where $R_s = 0.066$.

5. Conclusions

Four orogenic episodes have defined the geologic deformational history of the area. As a consequence, the warping, folding, jointing and faulting of the rocks are complex with several generations of fold and fracture structures. This has had a profound effect on rock mass weathering, slope morphology and drainage characteristics, all of which are, to some degree, defined by structural discontinuities in the rock mass. Structural analyses of discontinuities in the parent rock, and in the overlying soil, suggest a high degree of inheritance of discontinuities by the

soils from the rock mass. It is along these structural discontinuities that water flows preferentially.

It has been established that there is significant correlation between the cracks of the soils and the fracture fabric, especially joint patterns, in the underlying rock. It is interesting to note that this relationship between soil cracks and parent rock fractures has persisted through a very large number of soil wetting and drying cycles. This work has also demonstrated a significant correlation between joint orientation and gully orientation in the parent rock as well as the alignment of gully systems along faults. The evidence presented herein strongly suggests that the discontinuities in underlying rock have a very strong influence both on the development of gully systems and on the orientation of gully segments in areas where the soil is formed by in situ weathering. This supports the view that throughflow processes are dominant in the development of gullies (Beavis, 1991) in contrast to runoff processes where no correlation with underlying structure would necessarily be expected.

Finally, the lack of correlation found for the Eugowra Adamellite on which soil conservation works have been carried out, suggests that these erosion control works are effective in modifying erosion systems, at a level previously not recognised.

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