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An example of the use of veins to establish a cover fold history—Irregully Formation, Western Australia

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Abstract—Structural correlation using fold overprinting and style, plus the timing and orientation of possible syntectonic veins, are used to interpret three minor folding events in part of the Irregully Formation. The formation lies near the base of the Middle Proterozoic Bangemall Group in the Bangemall Basin of Western Australia. It comprises interbedded well-laminated dolostones and orthoquartzites, metamorphosed under lower greenschist-facies conditions. Bedding in the formation is folded about a gently NW-plunging axis. Most mesofolds are consistent with the bedding distribution, exhibiting a fold-axis maximum plunging gently NW and vertical axial planes. Folds with NE-, E- and NNE-trending axial planes are common in the area, but most cannot be explained by reorientation of the dominant NW-trending folds.

A deformation history accounting for different fold geometries is established using fold overprinting in conjunction with dilational offsets between fold-related quartz and dolomite veins. A number of approaches to determine the history of folding are possible. Fold overprinting is the most valuable criterion, but in weakly deformed terrains it may not be easily recognised, so that alternative methods should be examined. Fold directions in the Irregully Formation are parallel to trends in the underlying Ashburton Formation, suggesting a degree of basement reactivation. As a fold chronology in the cover has been established accounting for mesofolds and macrofolds, the interpreted reactivation is believed to have involved compression rather than passive drape over earlier structures. In the Irregully Formation differently oriented folds probably developed through a degree of cover shortening, associated with reactivation of basement faults or folds.

INTRODUCTION

IN COVER regions drape or forced folds (e.g. Stearns 1971, Stearns & Weinberg 1975, Matthews 1978) may develop by basement reactivation. Commonly in weakly folded areas where gently dipping sediments overlie more intensely deformed basement, poor exposure or lack of mesoscopic features may hinder determination of the fold history in the cover. In these terrains interpretations are usually based on limited seismic or drill-core data and may not be satisfactory. Basement is commonly reactivated under these areas, producing either normal or reverse faulting and/or fold tightening.

'Passive' basement reactivation, where blocks readjust without any associated compressive influence, is a feature of many drape-folded regions, particularly those under tension. In these areas cover blocks may move in response to thermal changes in the underlying material or as part of a residual stress release. Although the drape folds produced may not be entirely random, there probably will not be any means of establishing their relative ages, and they may be synchronous. In areas where wrench or block faulting is significant, readjusting basement blocks could develop cover structures with several orientations at the same time. However in other areas an event sequence may exist if horizontal compressional stresses were active at different times and in different directions. The effect of horizontal stresses at different times on a basement in which folds or faults have variable trends might cause drape folds in the cover to form with differing orientations. Horizontal stresses near the earth's surface (e.g. related to plate motion, Currie 1983) could reactivate basement faults and produce distant crustal shortening and extension. A review of mechanisms accounting for drape folds is given by Davis in Matthews (1978, pp. 216–217).

This study of the folding history in a cover area was undertaken in order to examine the proposition that 'active' as opposed to 'passive' basement reactivation could produce drape folds and shortening. The Irregully Formation in Irregully Gorge (Fig. 1) lies on the NW margin of the gently folded, intracratonic, Bangemall Basin, Western Australia. The gorge extends through the Irregully Formation near the base of the Middle Proterozoic Bangemall Group (Gee 1979), in a section normal to strike, and it provides an ideal area for evaluation of basement reactivation.

The Irregully Formation comprises about 1300 m of well-bedded, finely laminated (commonly at mm scale), microcrystalline dolostone, interbedded with orthoquartzite, conglomerate, shale, siltstone and silicified carbonate. Desiccation cracks and wave-ripple marks suggest a shallow-marine depositional environment, with a terrigenous input reflected by siliceous sand and conglomerate. A section of the formation is well exposed in the gorge, enabling meso- and microdeformation responses, incorporating pressure solution, shear, buckling, dilation and cataclasis, to be related to the macrostructure. Carbonates readily respond to stress under low-temperature conditions (<250°C) (Logan 1984), such as those experienced in the Irregully Formation, where the highest grade of metamorphism was that of the lower chlorite zone of the greenschist facies. The deformation intensity and metamorphic grade vary

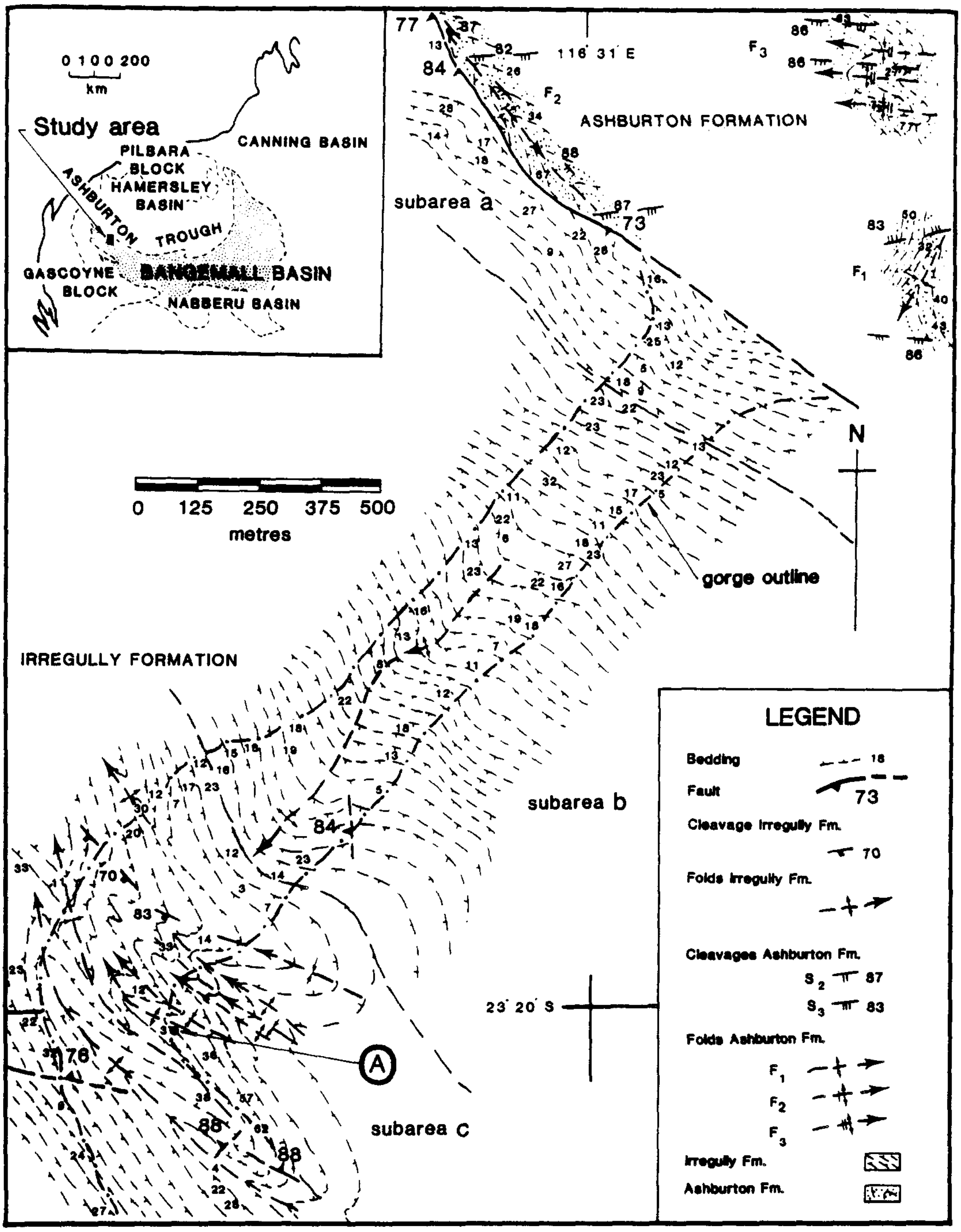


Fig. 1. Interpreted bedding trends through part of Irregully Gorge (containing subareas a, b & c and position A). Inset map shows relation of gorge (i.e. study area) to the Bangemall Basin.

through the Bangemall Basin (Muhling *et al.* 1985), the gorge being less deformed than in the southern portions of the basin.

Previous studies of macrofolds in the basin have revealed mainly NE–SW and NW–SE trends, although in the study area (Fig. 1) only NW folds were identified (e.g. Muhling *et al.* 1985). Fold changes across the basin may reflect variable basement directions (Brakel & Muhling 1975). Daniels (1966), Gee (1979) and Muhling *et al.* (1985) believe fold trends throughout the area are controlled by synchronously, but independently moving, basement structures (here referred to as 'passively' reactivated basement). 'Active' reactivation of basement is taken as nonsynchronous movement of basement structures associated with a degree of reactivation of compressive forces. Muhling *et al.* (1985) suggest the following features support the idea that in the Bangemall Basin structures reflect basement reactivation: (1) parallel fold-trends in cover and basement; (2) parallel structural boundaries in cover and basement; (3) synchronous folding of basement and cover; and (4) high strain areas in the cover that reflect intensely deformed basement zones.

The Irregully Formation in the northern part of the study area unconformably abuts the Lower Proterozoic Ashburton Formation. The latter formation, which is more intensely deformed and metamorphosed, was deposited in the Ashburton Trough (Fig. 1, inset), which

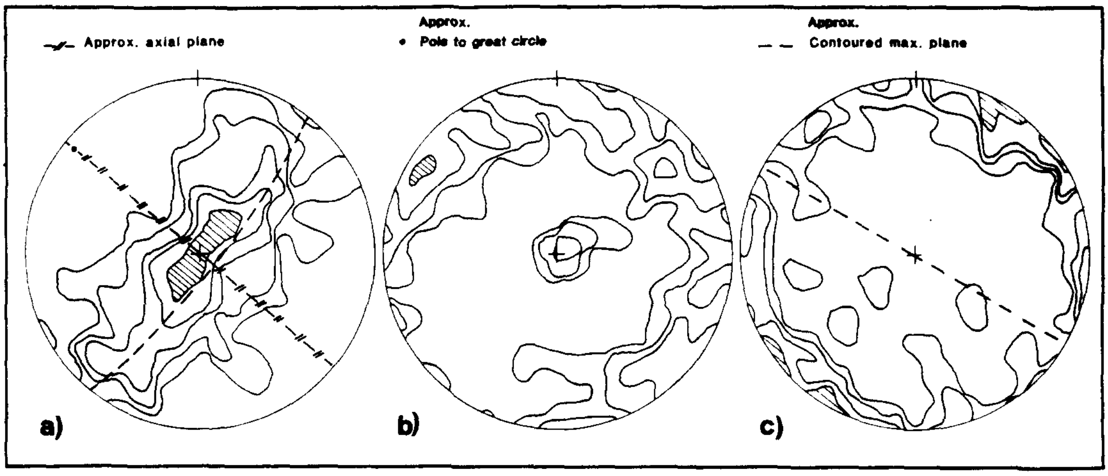


Fig. 2(a). 244 contoured bedding poles, Irregully Formation. Contour interval 0.41, 0.82, 1.64, 3.28, 6.56%, approximate fold axis 040/08°W, approximate axial plane 130/90°W.

(b). 120 contoured mesofold axes, Irregully Formation. Contour interval 0.85, 1.69, 3.39, 6.78%, maximum 8.47%. Contour maximum 035/10°W.

(c). 120 contoured poles to mesofold axial planes, Irregully Formation. Contour interval 0.85, 1.69, 3.39, 6.78%, maximum 11.86%. Contour maximum 120/90°W.

forms part of the Ashburton Fold Belt (Gee 1979). The contact between the two formations in the study area (Fig. 1) is a steep SW-dipping fault which is partly filled with massive quartz.

Three folding episodes (NW-trending F_1, NNE-trending F_2 and E-trending F_3) preceded a set of NW-trending folds in the Ashburton Formation near the gorge, according to Daniels (1966). Fold overprinting was considered responsible for cross folds and for large-scale dome and basin structures. Notably in the Ashburton Formation adjacent to the gorge, F_1 folds (using the terminology of Bell & Duncan 1978) trend NE because of refolding. Each folding event in the Ashburton Formation has an associated cleavage (S_1: slaty cleavage; S_2 & S_3: local crenulation or penetrative cleavages). North-E-trending structures in the Ashburton Formation near the gorge are believed by Gee (1975) to have influenced deposition of the Irregully Formation. Local unconformities in the formation are considered by Daniels (unpublished explanatory notes on the Edmund 1 : 250,000 Geological Sheet, 1969) to be due to reactivation of NE-trending folds in the Ashburton Formation.

The macrostructure through the Irregully Formation in the gorge is defined and interpreted in terms of mesoscopic features, including veins of probable tectonic origin. Studies of vein orientation and relative timing may help decipher histories in other weakly deformed areas.

STRUCTURE IN THE IRREGULLY FORMATION

Macrostructure

The macrostructure through the Irregully Formation in Irregully Gorge, based on interpreted bedding data from the sides of the gorge, is shown in Fig. 1. In the northern part where there is no macrofolding, bedding dips about 20°SW. Further south, an open NE-trending, SW-plunging (i.e. normal to bedding strike) flexure is present. The thickness of sediments through which this flexure is developed is about 1 km, which together with the inferred shallow-water depositional environment suggest the flexure developed after sedimentation. Near location A (Fig. 1), there is an increase in macrofolds trending NW to NNW and plunging less than 20°NW. These folds are symmetrical to slightly asymmetrical upright gently-plunging buckles. Synclines range from broad open to small tight types, rarely with a penetrative axial-plane cleavage. Along some axial planes or subparallel to them a degree of faulting is evident (i.e. minor faults trending E to NW in the southern part of Fig. 1). Movement along a fault dipping 76°N near location A (Fig. 1) may be due to further shortening of the adjacent anticline or variation in principal stress orientation. Contoured bedding poles (Fig. 2a) in the formation reveal symmetrical folding about a gently NW-plunging axis (040/08°W). Variability in axial-plane orientation of the dominant macrofolds may be due to refolding or inhomogeneity in one event.

The Irregully Formation (Fig. 1) maintains a near constant bedding orientation throughout a large portion of the gorge and then over a short distance (near location A) exhibits macrofolds. The following interrelated factors could be considered responsible: (1) lithological variation causing differing response to stress; (2) spatial changes in strain intensity; and (3) cover draped over an underlying reactivated weakness.

The idea that lithological differences may account for changes in degree of macrofolding is not supported by sequence variations. The formation is more quartzose in the earliest deposited horizons, which probably responded to stress by buckling, while a quartz-poor dolostone up-section would more readily undergo pressure dissolution. In the northern part of the gorge where the metasediments are rich in quartzose material there are few macrofolds, suggesting that lithological variations are not responsible for their distribution.

The strain intensity is clearly higher in the region of prominent macrofolding, but the reason for this localised higher strain is probably related to an underlying basement influence. That the cover trends reflect those in the basement accords with the commonly held view (e.g. Muhling *et al.* 1985, Gee 1979) that underlying structures have been reactivated.

Mesostructure

Folds. Mesofolds are abundant in the Irregully Formation through the gorge (Fig. 1). Three subareas can be assigned: (a) close to the contact with the Ashburton Formation and (b) the area of near-constant dip extending south to (c), the folded region near location A. Of 120 mesofolds, 15 are in subarea (a), 49 in (b), and 56 in (c). As subarea boundaries are subparallel to strike, each should contain about the same number of folds with respect to bedding geometry if they have the same area. Subarea (c) is smaller than (b) and for this reason may contain less folds, but many are related to the locally prominent macrofolding.

Mesofolds display considerable variation in geometry and style, but most are of 'similar' type (e.g. Ramsay 1962a), with no apparent change in tightness through the area. Geometrical analysis indicates that some tight folds are congruent with NW-plunging macrofolds, whereas others are incongruent. Interlimb angles vary from 22 to 146° and wavelengths range from 1.5 cm to 20 m. Anticlines are by far the more noticeable mesofolds: synclines are usually open and weakly developed (i.e. of 120 mesofolds noted, 74% were anticlines). Although any two anticlines that are spatially related and make up a continuous wave form must be separated by a syncline, many synclines are not easily analysed as their interlimb angles are commonly near 180°. Evidence of tight meso-anticlines flanked by open synclines could be a response to the relative ease with which buckling may occur upwards into areas undergoing less pressure solution, rather than downwards into material having more volume reduction via pressure solution through greater overburden pressure. Anticlines that are tighter than synclines can be expected in terrains such as that under examination, as deformation is not intense and depth of burial was probably not great (i.e. <10 km as indicated by the very localised development of lower greenschist-facies metamorphic minerals).

The orientation of 120 mesofold axes and corresponding axial planes (Figs. 2b & c) reveals a fold axis maximum coinciding with the great-circle pole about which bedding is folded. Most mesofolds are clearly consistent with the dominant NW-macrofolding (Fig. 1). Other folds plunge to the NE, while a few are E or W plunging. Significantly, folds with particular orientations are not localised or spatially grouped in the gorge, but occur throughout (i.e. folds plunging 90° to each other are present at the same location). For this reason no advantage is obtained by plotting the limited data in subareas, although the number of folds in subareas distinctly striking NW or NE is shown in Table 1.

Table 1. Number of distinctly striking folds in subareas

Subarea	No. of NW-striking folds	No. of NE-striking folds
a	4	3
b	32	8
c	33	10

Inteference patterns (e.g. Turner & Weiss 1963, Ramsay 1967, Hobbs *et al.* 1976) are not easily identified between folds with different orientations in the Irregully Formation (Figs. 2b & c). Some incongruent folds are present on NW-plunging fold limbs, but care in interpretation is required as the former might be overburden pressure effects or prelithified 'soft' sediment (syn-sedimentary) folds (e.g. Maltman 1984). The effect of overburden pressure (de Sitter 1964) might create incongruent mesofolds on macrofold limbs, which may be incorrectly assigned to an early folding phase. In most moderately deformed terrains overburden pressure is not considered responsible for any significant deformation effect: however, carbonates readily pressure-solve even under small loads.

Veins and joints. Quartz and dolomite veins, and joints, are common in the Irregully Formation, suggesting a degree of tension during deformation and that fluid pressure was locally greater than σ_3.

Quartz veins. Straight fibres fill most quartz veins and are subnormal to vein walls in all but two veins. Veins vary in thickness from a few mm to about 5 cm, most having widths towards the lower end of the range. The orientation of 50 veins indicates two main sets, one about horizontal and another near-vertical and NW-trending (Fig. 2a).

The two sets may be related to the prominent NW-trending folds. The near-vertical veins are subparallel to the axial planes and may have formed in response to compressional force relaxation (e.g. Mitra 1979, Winsor 1983).

The horizontal veins (Fig. 3a) are generally bedding parallel, but where bedding is not horizontal, subhorizontal fibrous veins have been noted. The veins with near-vertical fibres may be related to NW meso- and macrofolds and have fibres coinciding with the maximum principal strain (X) of a deformation (e.g. Mitra 1979, Winsor 1983). Unlike the situation described by Winsor (1983), where a relationship could be established between veins and the strain ellipsoid of two deformations, in the Irregully Formation cleavage development is weak (i.e. only recognised at two locations, with no mineral lineation identified), so no independent criterion is available to define the orientation of the strain ellipsoid. However, the fibrous vein nature and consistent orientation points to a syntectonic origin (Durney & Ramsay 1973). Assumptions made in this interpreta-

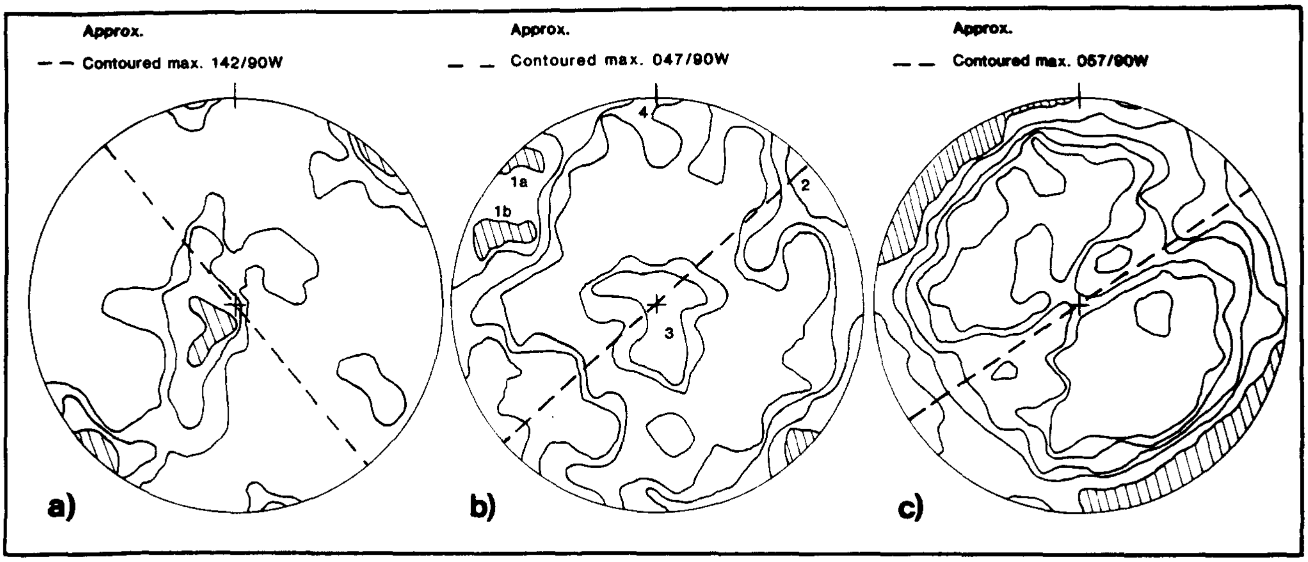


Fig. 3(a). 50 contoured poles to quartz veins. Irregully Formation. Contour interval 2, 4, 8%, maximum 14%. Contour maximum 142/90°W.

(b). 166 contoured poles to dolomite vein, Irregully Formation (sets 1–4). Contour interval 0.62, 1.23, 2.47, 4.95%, maximum 6.79%. Contour maximum 047/90°W.

(c). 943 contoured poles to joints, Irregully Formation. Contour interval 0.11, 0.21, 0.42, 0.85%. Approximate contour maximum 057/90°W.

tion are (1) that veins are extensional, generally related to the NW-trending folds, and (2) fibres in most veins are parallel to either X or Z of a strain ellipsoid, where the observed cleavage and mean axial plane define the XY plane.

Dolomite veins. Veins filled with equant to fibrous dolomite, from a few mm to about 4 cm wide, are prominent in the Irregully Formation. Fibres are commonly present, but are more weakly defined than those in quartz veins. The fibres are commonly normal to vein walls, which, together with the fact that veins appear to be geometrically related to folds, suggests syntectonic dilation via hydraulic fracturing (e.g. Hubbert & Willis 1957, Phillips 1972, Pollard 1976).

Dolomite veins range widely in orientation, but four major sets are recognised (Fig. 3b). Set 1, striking NE to NNE, can be divided into two subsets, 1a vertical, striking NE and 1b steeply E-dipping, striking NNE. Set 2, with veins striking NW, has moderate to steep NE or SW dips, and set 3 has horizontal veins. Set 4 has near-vertical veins striking E, but there is some variation in orientation, either due to folding or to local variations in initial orientation. Figure 3(b) displays all veins recorded in the Irregully Formation; variations in orientation could be attributed to local folding, but veins of all sets are present in each subarea. As all the major sets are present in subareas (a) and (b), where there is only minor macrofolding, the sets are considered real and not a consequence of folding. Table 2 shows vein numbers, which can be readily assigned to a particular set in each subarea.

Individual veins of each set have been observed to have a fibrous filling, which suggests a syntectonic origin if the veins are geometrically related to folds. Of the veins noted many are apparently related to either the NW- or NE-plunging folds, where the locally observed cleavage and fold axis orientation can be approximately used to infer the principle axes of strain related to folding. The veins sets observed may then be geometrically related to fold elements.

Sets 1a and 1b veins are roughly oriented in the inferred XZ plane of NW folding (i.e. poles to veins coincide with the dominant mesofold axes, taken as the Y direction).

Set 2 veins are subparallel to the axial planes of the prominent macro- and mesofolds, and a set of near vertical NW-striking quartz veins (i.e. poles to veins are normal to the mesofold axes, parallel to Z). There is an apparent variation in dip of veins of this set, which may be because some are normal or parallel to bedding, and thus follow variations in bedding orientations.

Set 3 veins are subhorizontal, with the same geometry as a number of quartz veins (i.e. poles to veins are interpreted to plot in the X direction). Some veins are parallel to bedding, whereas others may have formed in response to tectonic uplift or have geometries controlled by regional (NW) folding.

Set 4 veins strike E (Fig. 3b).

Table 2. Number of veins in a geometrical set in subareas

Subarea (Fig. 1)	Vein sets (with no. of veins recognised) 1a	1b	2	3	4
a	1	3	5	2	1
b	1	4	10	2	6
c	28	22	38	7	5

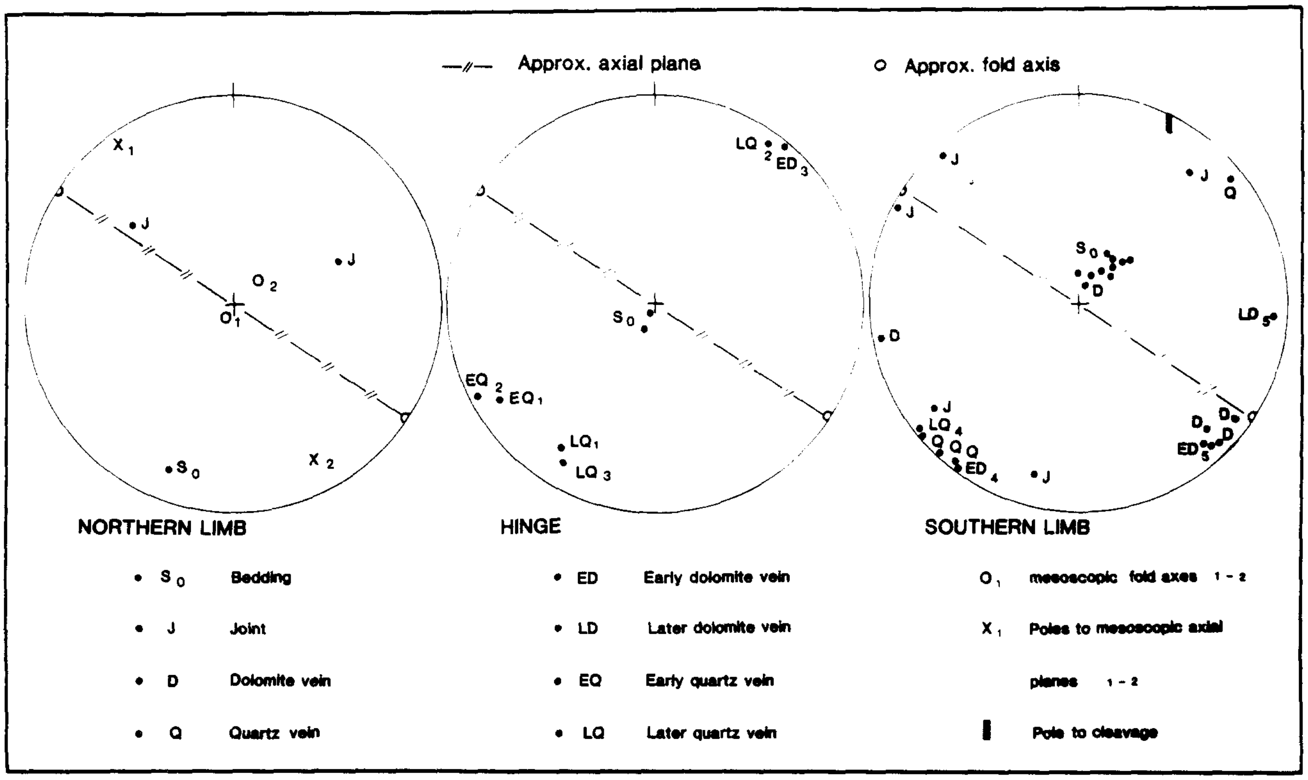


Fig. 4. Orientations of bedding, joints, veins and folds at positions across a NW-trending macrofold, location A (Fig. 1).

Joints. Joints are prominent mesofeatures in the Irregully Formation, implying intervals of folding and faulting. Some joints have a 'late' stage carbonate filling, although absence in most suggests development after folding, perhaps during uplift. However, the presence of fibrous dolomite and quartz veins related to, and probably forming during, folding indicates a degree of fracturing during folding.

The orientations (Fig. 3c) of most joints are controlled by NW-trending folds, most being bedding-normal and related to stress directions during folding. Although joints have a large spread in orientations, the contoured maximum is consistent with tensional *ac* fractures (Hancock 1985), while NW-striking joints could correspond to tensional *bc* joints. Minor 'late' stage faulting on either a meso or macroscale is evident along some joints (e.g. the NE-striking steeply-dipping fault south of location A may follow an *ac* joint orientation).

Interpretation of fold overprinting relationships

Fold overprinting and vein offsets are recognised in the Irregully Formation. At any particular location, a dilational offset defines the relative time of vein dilation. This will be unique unless evidence is available at a locality that two veins of the same orientation and infilling dilationally displaced another vein with a different orientation at different times. This could occur during synchronous extension along X and Y during a related folding event (Winsor 1983).

Although the number of fold overprints and dilational offsets is not large, at location A data are available from which an interpretation can be developed. Location A (Fig. 1) encompasses the northern and southern limbs and hinge of an asymmetrical (i.e. steeper northern limb) non-plunging SE-striking macrofold. Across the fold, mesofolds are identified that are incongruent to the larger-scale fold, and some fibrous quartz plus dolomite veins display dilational relations. The macrofold has an axial-planar slaty cleavage and a number of possibly related joints.

Figure 4 displays data across the macrofold at location A, showing that two tight to moderately open incongruent mesofolds are developed on the northern limb (e.g. Fig. 5a). In the hinge dilational offsets are observed between fibrous quartz and dolomite veins, while elsewhere quartz veins offset one another. Figure 4 shows quartz veins subparallel to the axial plane, which displace earlier veins. Two veins EQ_1 and LQ_1 (Fig. 4) are also noted, with the latter being a thick fibrous vein (fibres plunging 133/18°W) subparallel to the axial plane of the large-scale fold. A thinner vein (fibres plunging 147/08°W), is truncated (in Fig. 5b) by the later vein. Figure 5(c) illustrates two thin non-fibrous quartz veins displaying evidence of dilational offsets, with the later vein subparallel to the axial plane of the large-scale fold. An offset between an irregular dolomite vein subparallel to the axial plane and a fibrous quartz vein is shown in Fig. 5(d). On the southern limb an early irregular dolomite vein (ED_4, subparallel to the axial plane) is displaced by a fibrous quartz vein (LQ_4), also related to the axial plane (see Fig. 5e). In Fig. 5(f) a dolomite vein (ED_5) normal to the axial plane (i.e. possibly normal to Y, if the XY plane is parallel to the axial plane or cleavage), is deformed in a minor shear zone into the orientation LD_5 (Fig. 4).

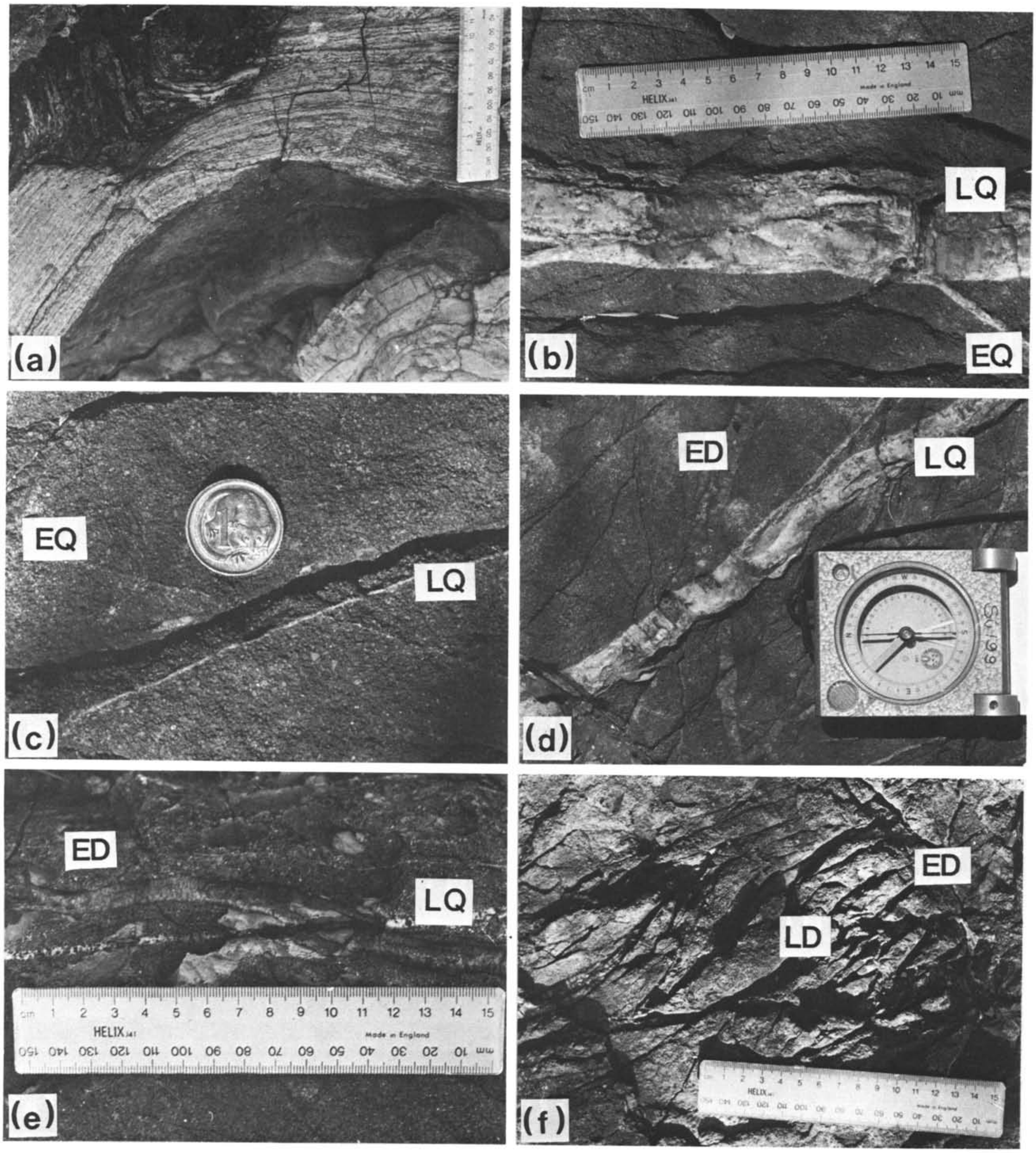


Fig. 5(a). Incongruent mesofold (fold I in Fig. 4) on northern limb of a NW-trending macrofold at location A. Axial plane of mesofold 061/88°W, fold axis 136/66°W.

(b). Fibrous quartz vein LQ_1 (Fig. 4), subparallel to axial plane of NW-trending macrofold at location A, truncates an earlier fibrous quartz vein EQ_1.

(c). A thin quartz vein (EQ_2) is offset by a later quartz vein (LQ_2), subparallel to the NW macrofold at location A.

(d). An early fibrous dolomite vein (ED_3) is displaced by a dilational fibrous quartz vein (LQ_3).

(e). On the southern limb an early dolomite vein (ED_4) is displaced by a fibrous quartz vein (LQ_4).

(f). Dolomite vein (ED_5) subnormal to macroaxial plane is deformed in a minor shear zone. Veins (LD_5) in the shear zone at oriented 004/74°W.

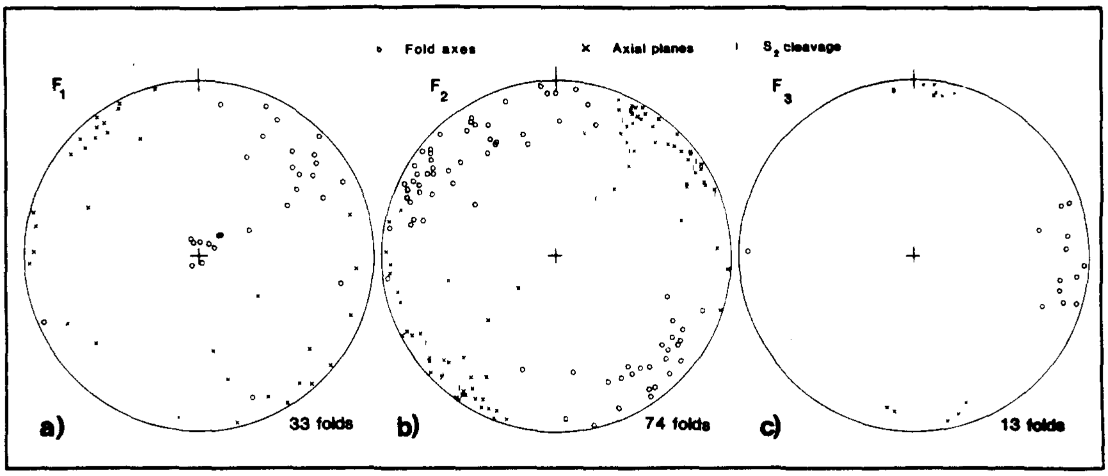


Fig. 6. Interpreted F_1, F_2 & F_3 folds and axial planes, Irregully Formation. (a) F_1 fold axes and axial planes. (b) F_2 fold axes and axial planes, plus cleavage S_2. (c) F_3 fold axes and axial planes.

Interpretations drawn from Figs. 4 and 5 are: (1) at location A incongruent mesofolds are present; (2) dolomite and quartz veins are parallel to the NW-trending axial plane of the large-scale fold; (3) some dolomite veins are subnormal to the axial plane; (4) dilation indicated by quartz veins (i.e. EQ_1 & EQ_2) occurred at about 70° to the axial plane; and (5) some dolomite veins related to the macrofold are deformed in minor shear zones into a N-striking orientation.

That veins and mesofolds at location A are inconsistent with NW macrofolding has implications for structural interpretations of the area. Using the method outlined by Ramsay (1961), NW-trending folding effects can be removed from incongruent folds, producing shallow NE-plunging (F_1) folds with NE-trending axial planes (i.e. fold 1 plunges 114/20°E, and fold 2 plunges 119/06°E). The incongruent folds demonstrate folding (F_1) about a shallow NE to NNE axis, before the NW (F_2) folding. Early quartz and dolomite veins apparently unrelated to the macrofold are also undeformed, providing evidence for a period of dilation along steeply dipping veins striking NNW. The undeformed veins trend about 30° to the inferred F_1 fold axis, so caution is necessary in using them to define the orientation of first event folds. As they make a low angle to F_1 folds, they could have developed as hydraulic fractures or as oblique extensional veins during D_1 or earlier. Although the vein data are inconclusive, the evidence of folding about a NE-trending axis prior to the NW-trending folds means that with care, folds can be assigned to F_1 or F_2. At a number of other locations in the gorge, fold overprinting and vein offsets are observed consistent with the interpretation developed at location A.

A weak third folding event may account for localised gently plunging, E-striking mesofolds (Fig. 2b). The relative timing and geometry of F_3 is suggested by the following: (1) evidence for shearing along F_2 axial planes (e.g. ENE-striking fault, south of location A); (2) deformation of D_2 veins in minor shear zones into a N-striking orientation (i.e. normal to speculated F_3 axial planes, a direction along which extension could occur during D_3); and (3) observations that N- and E-striking veins transect F_2 mesofolds.

Assignment of folds to a deformation event

Folds in the Irregully Formation can be assigned to a fold event, using the following criteria: (1) the geometry and vergence of macro/mesofolds; (2) the relationship between veins and folds; (3) relative vein timing; and (4) geometry of unfolded early veins not related to the NW-trending folds. Folds assigned to events are displayed in Fig. 6, revealing a high variability of F_1 and F_2 but restricted F_3 orientation. Table 3 shows the number of folds designated to a particular generation in each subarea, and indicates that the highest proportion are F_2 folds in subareas (b) and (c).

Following assignment, other criteria can be examined to see if they support the interpretation. These include the following. (1) The interlimb angle measured in the profile plane indicates the tightness (F_1 folds probably were effected by later events and on average should be tighter). (2) The amount of shortening can be estimated by comparing fold arc and straight line length (e.g. Hudleston 1973), which assumes folding entirely by buckling. Although not completely valid (as there is evidence of pressure solution during folding), older generation folds on average should be tighter.

A comparison of F_1, F_2 and F_3 folds reveals the following facts. For 31 F_1 folds the mean interlimb angle is 68°, the wavelength range is 3 cm to 15 cm, and mean shortening for 4 folds is 74%. For 88 F_2 folds the mean interlimb angle is 87°, the wavelength range is 1.5 m to 20 m, and mean shortening for 20 folds is 51%. For 21 F_3 folds the mean interlimb angle is 103°, the wavelength

Table 3. Number of folds in a given generation in subareas

Subarea	F_1	F_2	F_3
a	6	7	2
b	8	32	9
c	19	35	2

range is 1.5 m to 3 m, and mean shortening for 2 folds is 31%. These differences support the proposed history, as F_1 folds are generally tighter and have undergone greater shortening than F_2.

It is difficult to determine whether folding was in discrete events (F_1, F_2 and F_3), or corresponded to one event with progressively changing principal strain axes. To produce the range of fold orientation in areas of no macroscopic refolding i.e. subareas (a) and (b), in a time sequence, implies varying strain directions. Within each folding event deformation is likely to have been progressive as indicated by the fibrous nature of the vein-filling material, but between folding events there is no evidence to support the notion of continuous deformation. In particular there is little evidence of vein-fibre curvature to suggest progressive deformation between the three folding episodes.

DISCUSSION

Criteria for distinguishing fold generations

To determine the history of folding, a variety of approaches are possible, depending on the exposure and availability of suitable 3-dimensional mesofeatures (e.g. cleavage related to folds). A number of methods can be designated at levels 1–5 (Fig. 7), related to the degree of certainty a particular level has (i.e. at level 1, overprinting establishes a unique chronology, while at level 5 a greater degree of caution is required). If two fold orientations are present, the first criterion (level 1) to examine is macro or mesofold refolding (e.g. Ramsay 1962b, Turner & Weiss 1963, Hobbs *et al.* 1976, Thiessen & Means 1980). In a given area this should give unique results, unless differently oriented folds developed synchronously or refolding occurs in one event (e.g. Jacobson 1984). Caution is also necessary if incongruent folds could be products of overburden (lithostatic) pressure effects, but this may only be a problem for material that readily responds to low or moderate pressure in areas close to the Earth's surface. For macrofolds with about the same orientation macro-overprinting may be difficult to observe, but if a time sequence exists, it might be recognised using meso and microfold refolding.

If fold overprinting at any scale is not recognised, other criteria should be sought. In some regions where there is no apparent refolding the metamorphic grade may be such that one or more fold groups have an associated cleavage. Initially it is necessary to determine whether cleavage and folds are related. If this can be established, cleavage/fold overprinting (i.e. levels 2a and 2b; Fig. 7) can be used to assign generations. Notably in some areas a cleavage considered part of a folding event may transect folds of the event (e.g. Stringer 1975, Borradaile 1978, Duncan 1985), suggesting development late during folding.

In some terrains cleavage/fold relations are not easily observed, so other criteria should be examined. If both fold groups have genetically and geometrically related cleavages, timing relationships may be recognisable between cleavages (i.e. level 3). Very mildly deformed areas often lack observable cleavage, but fortunately in areas near the Earth's surface, fracturing, dilation and precipitation may accompany folding (i.e. syntectonic veins can develop). If for these veins the geometrical relations and the nature of the vein filling indicates development during folding, fold/vein overprinting (levels 4a & 4b) or dilational offsets (level 5, e.g. Winsor 1983) may help establish a folding sequence.

In all cases where mesoscopic features are used, it is crucial that they be related to larger-scale folding. Where fold overprinting is present this should be used, and as cleavages are pervasive and more likely to be related to folds, an attempt should be made to use cleavage overprinting before vein timing. In the present example, levels 1, 4a and 5 are used to help date folds in the Irregully Formation. After the relative timing of folds has been preliminarily determined, other differences (i.e. style, interlimb angle and percentage shortening) can be examined to see if they support the proposed history.

Basement/cover relations

The current interpretation indicates that three folding phases, each involving shortening, revealed by meso/macrofolds, and extension indicated by probable syntectonic veins, have affected the Irregully Formation. A comparison of Figs. 1 and 6 suggests that folds in the Irregully Formation mimic Ashburton Formation trends (i.e. F_1 is NNE, F_2 is NW and F_3 is E). Folds in the Ashburton Formation very likely persist below the Irregully Formation through the gorge, so basement reactivation may have given rise to Irregully Formation folds. As a fold chronology has been developed to account for macro and mesofolds in the cover, the suggested basement reactivation was probably 'active' (i.e. involving cover compression and extension); rather than 'passive' with synchronous readjustment. It seems unlikely that mesofolds could be produced within a time sequence through synchronous 'passive' reactivation. That 'active' reactivation probably took place, has implications for other regions where basement fault/fold reactivation could occur.

Often when basement reactivation has been suggested (e.g., Prucha *et al.* 1965, Stearns 1971, Stearns of Weinberg 1975, Matthews 1978), studies have dealt with the nature and morphology of drape folds in the cover, the reactivation mechanism and the nature of the basement. Many investigations (e.g. in Matthews 1978) conclude that drape folds are primarily a response to subvertical movement on basement faults (due to the crystalline and hence brittle nature of the basement). Stearns (in Matthews 1978, pp. 10–21) examined reasons why either vertical or horizontal movement may produce drape folds and concluded that vertical adjustment is the major cause of such folds. Results of experimental modelling (e.g. Friedman *et al.* 1976) also support the idea that drape-fold nature is primarily dependant on the type of

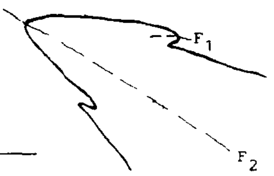
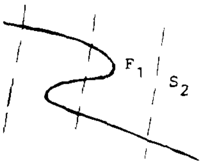
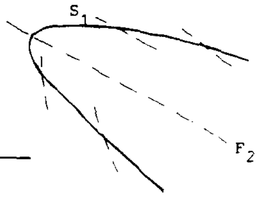
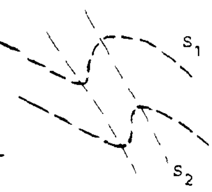
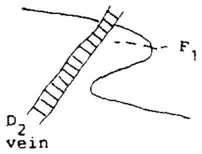
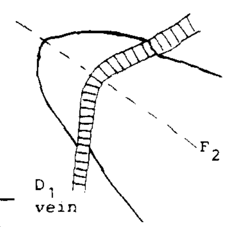
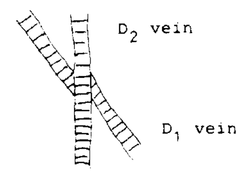
Level	Scale	D_1	D_2	Overprinting
1	macro/ meso.	F_1 fold	F_2 fold	F_1 refolded by F_2 
2a	macro/ meso.	F_1 fold	S_2 cleavage	S_2 transects F_1 
2b	macro/ meso.	S_1 cleavage	F_2 fold	S_1 folded by F_2 
3	meso/ micro.	S_1 cleavage	S_2 cleavage	S_1 crenulated by S_2 
4a	meso/ micro.	F_1 fold	D_2 veins	D_2 extension veins transect F_1 
4b	meso/ micro.	D_1 veins	F_2 fold	D_1 extension veins folded by F_2 (deformed fibres) 
5	meso/ micro.	D_1 veins fibres in X, Y & Z	D_2 veins fibres in X, Y & Z	D_1 veins displaced by D_2 extensional veins 

Fig. 7. Levels of overprinting using folds, cleavages and veins.

basement response. Stein & Wickham (1980), however, suggest that experimental results are too simplistic to account for natural drape folds, which probably involve layer-parallel compression or extension. Horizontal compression ('manifestations of earlier deformations') is interpreted (Kelley 1955) as being important in the development of large monoclines. A comment by Reches & Johnson in Matthews (1978, p. 300) is relevant, as they suggest that "shortening must be incorporated in a general model of monocline formation". Matthews & Work in Matthews (1978, pp. 101–124) and Prucha *et al.* (1965) have interpreted cover folds in terms of horizontal compression, the folds being related either to localised upthrust faulting or to disoriented blocks. Such mechanisms may not account for folds in the Irregully Formation in view of their widespread occurrence.

In the literature little investigation has been made concerning the possibility that underlying faults with different orientations can be independently reactivated at different times, producing a history of cover folding. The possibility that differently oriented folds in the basement may be tightened is also rarely considered.

The basement type obviously has considerable influence on the form of cover structures. Whereas previous investigations largely considered crystalline ('brittle') basement, in the Bangemall Basin the 'basement' may well have responded in a ductile manner after cover deposition. This is suggested by the earlier ductile nature of the Ashburton Formation and the conclusion (Muhling *et al.* 1985) that pre-Bangemall Group sediments were folded during the NW (F_2) folding event affecting the Bangemall Basin.

Basement reactivation may have occurred during sedimentation of the Bangemall Group, as a number of inhomogeneous F_1 NE-trending mesofolds in the Irregully Formation (study area, Fig. 1) could be a result of synsedimentary folding. However, the presence of a NE-trending macrofold extending through a 1 km thick stratigraphic unit, in conjunction with the observation of related mesofolds and associated extension veins, indicates that reactivation and associated compression and extension continued after cover deposition.

CONCLUSIONS

A history accounting for differently oriented folds in the Irregully Formation of the Lower Proterozoic Bangemall Basin has been constructed using mesofold overprinting and vein relations. Based on vein orientation and nature of filling it is inferred that many of the veins developed during folding. In weakly folded terrains lacking strong cleavage and few or speculative fold overprints, relations between dilational veins could be a useful tool in establishing a fold chronology. Other evidence supporting the deformation sequence includes variations in dihedral angle and shortening percentage between fold generations. Fold directions in the Irregully Formation appear to follow underlying Ashburton Formation ('basement') fold trends. Contrary to previous interpretations, the inferred basement reactivation has been 'active' resulting in a history of cover folding in association with compression and related localised extension.

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