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REPORT ON THE GEOLOGY OF THE LEONORA AREA, WESTERN AUSTRALIA

Cees W. Passchier

A publication from the National Geoscience Mapping Accord - Eastern Goldfields Project

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Abstract

Deformation in the Archaean greenstone belt and granitoid rocks of the Leonora district comprises at least three phases of deformation. D_1 is a phase of displacement along gently dipping ductile shear zones. A shape fabric developed in the zones, dominantly by N-directed movement of the hanging wall. D_2 is a phase of NE-SW shortening and minor NW-SE transcurrent dextral movement along steeply dipping ductile shear zones. D_2 caused development of upright folds in bedding and S_1. D_3 caused local folding and development of a weak foliation.

Introduction

The Leonora District is situated in the eastern part of the Archaean Yilgarn Craton of Western Australia. The area is characterised by deformed and undeformed granitoid plutons, separated by linear greenschist to amphibolite facies greenstone belts. In the Leonora district, shear zones are common in all lithologic units, and are specifically well-developed along the contact of the granitoid plutons and the greenstone belts. The area around Leonora has been described by Hallberg (1983, 1985), Thom and Barnes (1977), Skwarnecki (1987) and Williams et al (1989). Williams et al (1989) have shown that a complex pattern of shear zones exists in the Leonora area, and that gold mineralisation may be linked to some of these shear zones.

During june-july 1989 an analysis was made of a number of the shear zone structures near Leonora, with the aim to provide a more detailed account of their structural history. This report presents first results of this research project, based on the field data. Work was mainly concentrated in two areas: (1) a narrow strip of deformed quartzite, slate and felsic volcanics between Leonora and Mount Newman, described here as the Mount George zone (Fig. 1) (Mount George shear zone according to Williams et al. 1989); and (2) a shear zone which follows the contact of the Rhaeside granite west of Leonora and the greenstone belt (Fig. 1). Work along this shear zone was meanly concentrated around the Jasper Hills (Fig. 1 & 2).

Geological Setting

The area around Leonora consists of poorly exposed plutons of granodiorite, adammellite and granite, alternating with greenstone belts (Fig. 1). The greenstone belts consist mainly of mafic and felsic metavolcanics, and minor amphibolite, metagabbro, quartzite, banded iron formation (BIF), ultramafics and intrusions of porphyry and dolerite. Rhythmically laminated beds of quartzite, up to 100m thick, occur in the Mount George zone, and adjacent to the Rhaeside granite west of Leonora (Fig. 1, 2). West of the Mount George zone, mafic and ultramafic rocks with occasional strips of slate and thin lenses and layers of ferruginous and siliceous BIF dominate. The quartzite beds in the Mount George zone are bounded on the western side by a strip of slate up to 500m wide. East of the Mount George zone, felsic metavolcanics dominate with minor mafic metavolcanics and quartzite lenses.

Structural analysis was concentrated around the quartzite beds because they crop out well, and allow a single stratigraphic horizon to be followed over a large distance, outlining the large scale structure. In the case of the Mount George zone, a single quartzite horizon could be followed over 65 km.

Deformation sequence

D_1 structures

A weak mica foliation or planar shape fabric (S_1) and associated stretching lineation or mineral lineation (L_1) form the earliest structures in the area. S_1 and L_1 do not occur as penetrative fabric elements throughout the Leonora area; they have sofar only been recognised around Mount Newman, along the contact of the Rhaeside granite

(Fig. 1, 2), and near Mount Malcolm 10 km E of Leonora. In granite and mafic volcanic along the contact of the Rhaeside granite, S_1 and L_1 are only locally developed in shear zones surrounding undeformed lenses. The patchy occurrence of D_1 structures over the area is therefore at least partly an original feature due to localised deformation in shear zones. Later deformation erased or transposed D_1 structures elsewhere. The dramatic decrease in stratigraphic thickness from NW to SE between the quartzite layers in the Mount George zone and along the Rhaeside granite must also be a D_1 effect; the strain intensity of later phases of deformation cannot account for this change in thickness (P. Williams, pers. comm.).

In the Mount Newman area, S_1 is present in slates without an associated stretching lineation (Fig. 2). S_1 is gently N-dipping here, while S_0 dips more steeply to the north (Fig. 1). In the Jasper Hills area, S_1 and L_1 are well developed in all lithologic units. S_1 is best developed at the contact of granite and mafic volcanics (Fig. 3), and in BIF layers. In BIF layers, the L_1 stretching lineation is parallel to isoclinal fold axes. In quartzite, D_1 deformation gave rise to spectacular ellipse shaped aggregates on bedding surfaces, defining a linear and planar shape fabric. L_1 is moderately NNE plunging in the Jasper Hills area (Fig. 4 - cf. Williams et al, 1989).

An interesting feature of the Jasper Hills area is the oblique orientation of S_1 in mafic volcanics and in BIF on two sides of a NW-SE trending D_2 shear zone (Fig. 3); in the west, S_1 is subvertical NS trending; in the E, it is gently N-dipping. This feature is probably an original major D_1 structure, since L_1 orientation is identical on both sides, and the pole to the greatcircle best-fit of S_1 poles coincides with the center of the L_1 orientation cluster (Fig. 4b-4c); it can be interpreted as a mega-scale F_1 sheath fold in the contact zone of mafic volcanics and granite, now transected by D_2 and younger shear zones.

Outside the Jasper Hills area, an S_1 foliation is subparallel to the contact of the Rhaeside granite with the greenstone belt, from the Diorite King mine in the W, to the Sons of Gwalia mine S of Leonora (Fig. 1, 2). Stretching lineations have a variable orientation along this shear zone, as discussed in Williams et al. (1989), and below.

D_2 structures

D_2 is the most prominent phase of deformation in the area. It caused development of open to tight upright folds with subvertical to steeply NE dipping axial planes and a penetrative steeply NE or SW dipping slaty cleavage (S_2) in some areas (Fig. 4d,e; Williams et al, 1989). In the Mount Newman and Jasper Hills areas, open F_2 folds develop in S_1. In the Jasper Hills area and in the Victoria Wells mine, dextral D_2 shear zones transect S_1.

A major NNW-SSE trending shear zone, several kilometres wide (the Keith-Kilkenny tectonic zone of Hallberg 1985) is located to the east of Leonora (Fig. 1, 2). This zone is interpreted as a D_2 structure, since the orientation of the foliation in the zone can be traced into S_2 in adjacent areas where it overprints E-W trending S_1. In the Keith-Kilkenny tectonic zone, S_2 is strong and NW-SE trending (Fig. 4d). An L_2 stretching lineation is present in felsic volcanics in zones of high strain up to 100 m wide. L_2 is gently NW or SE plunging (Fig. 4h). The Keith-Kilkenny tectonic zone is interpreted as the domain in which D_2 structures are most strongly developed, and early fabric elements are transposed.

D_3 structures

Effects of D_3 deformation have been observed only near Mount George, and in the Mount Newman area (Fig. 2). Between Mount George and Station Creek, a large fold (the Station Creek Fold; Fig. 2) is developed in the Mount George zone. It deforms S_2 which locally trends subparallel to S_0 in the quartzite. Axes of F_3 folds, parasitic on the main Station Creek Fold, have a strongly variable orientation depending on the orientation of the fabric element in which they developed (Fig. 4j). Intersection lineations of S_2 and S_3 plunge gently to the NNW or SSE (Fig. 4j). S_3 is locally developed as a crenulation cleavage, especially in the zone up to 5 km N of the Station Creek Fold, and trends NNW-SSE (Fig. 4k). S_3 fans strongly in this area; where the S_2 enveloping surface is steep, S_3 is gently dipping; where S_2 has a shallow dip, S_3 is steep.

Around Mount Newman, a subhorizontal S_3 is locally overprinting a steep S_2. As the dip of S_1 is commonly also gentle, the local structure is difficult to interpret in many outcrops. The presence of three foliations has, however, been confirmed in some outcrops (Fig. 5).

Discussion

Sense of shear during D_1

D_1 shear zones usually lack suitable sense of shear markers in the field; bedding is commonly subparallel to S_1 and must have been near the developing foliation to start with. Where sense of shear can be detected from deflected bedding or foliation planes however, as in some shear zones in the Rhaeside Granite at Jasper Hills and Diorite King mine, and in the Victoria Wells Mine (Fig. 6, 7), movement is normal (upper block to the N). This confirms observations in the Harbour Lights and Sons of Gwalia Mines, where the dominant (D_1) deformation resulted in normal shear zone movement, i.e. uplift of the granite relative to the greenstone belt which lies to the E and NE (Skwarnecki, 1987; Williams et al, 1989). The asymmetry of fibre packets around spherical pyrite aggregates in an outcrop of slate with a gently N-plunging stretching lineation on the Leonora - Malcolm railway, 10 km east of Leonora, also indicates normal movement (Fig.8). This illustrates that early normal movement is not only restricted to the granite-greenstone contact. One should bear in mind, however, that the normal movement on D_1 shear zones only reflects present orientation of the zones, and original orientation may have been different; the D_1 shear zones may even have originated as thrusts with N-directed movement.

orientation of D_1 structures

S_1 in the Leonora area has been recognised where it is overprinted by D_2 fabric elements. Since D_2 structures trend dominantly N-S, S_1 is mainly found in an oblique (E-W) orientation. This does not mean, however, that S_1 was everywhere E-W trending before the onset of D_2 For example, crenulated D_1 fabric elements are absent in most of the Keith-Kilkenny tectonic zone, although a refolded S_1 is present to the east and west. This may mean that D_1 structures were destroyed by strong D_2 deformation, but alternatively D_1 structures may have been N-S trending in this area before the onset of D_2.

sense of shear in the Keith-Kilkenny tectonic zone

In the Keith-Kilkenny tectonic zone several fabric elements indicate that sense of shear is dextral, rather than sinistral as suggested by Williams et al. (1989). This is based on the persistent σ-type asymmetry of feldspar porphyroclasts in felsic volcanics (Passchier & Simpson, 1986), asymmetric boudins and shear band foliation. A dextral shear sense could also be determined in a 30 cm wide D_2 shear zone in mafic metavolcanic rocks in the Victoria Wells mine (Fig. 6). This sense of shear was based on deflection of a D_1 shear zone (Fig. 6), and a shear band cleavage in the D_2 zone. The western limit of the Jasper Hills area is affected by a dextral D_2 shear zone, which has been reactivated by a late transcurrent fault (Fig.3; enlarged domain); S_1 and L_1 stretching lineations have here been deflected by the D_2 shear zone.

significance of the Mount George zone

A strip of lenses of quartzite, slate, quartz-sericite phyllonite and chlorite schist, here described as the Mount George zone, can be followed over 65 km from Mount Newman down to south of Leonora (Fig. 1, 2). Williams et al. (1989) use the term Mount George shear zone for this strip and regard it as a late sinistral transcurrent ductile shear zone which postdates a regional phase of shortening and upright folding (D_2). Their main arguments are:

(1) brittle faults with sinistral shear sense occur in the Mount George Zone SE of Mount Newman (Fig. 1);

(2) gently trending stretching lineations occur in quartzite, slate and quartz-sericite phyllonite in the Mount George zone south of Mount Davis (Fig. 1).

Other fabric elements which seem to indicate sinistral shear sense along the zone are (Williams et al. 1989);

(3) quartz fabric data from the Mount George zone near Leonora;

(4) the flexing of bedding in mafic and felsic volcanic rocks east of Mount George (Fig. 1, 2).
(5) the shape of the Station Creek Fold, which is interpreted as a drag fold in the shear zone.

Detailed work along the entire length of the Mount George zone has shown, however, that the zone cannot be regarded as a shear zone in the sense of a 'zone of high strain, developed by non-coaxial progressive deformation'. The strain intensity in and around the quartzite is in many places not stronger than in mafic volcanics to the west and east. No asymmetric structures which could be associated with non-coaxial flow have been observed along the Mount George zone north of Station Creek. I therefore prefer the term Mount George zone over the term 'Mount George shear zone' used by Williams et al. (1989). The Mount George zone is interpreted as the eastern limb of a 100 km scale F_2 antiform (Figs. 1, 2). S_2, which overprints S_1 in symmetric F_2 folds around Mount Newman, can be followed along the Mount George zone with a consistent vergence of S_2-S_0 down to the Jasper Hills area (Fig. 2). S_2-S_0 intersection lineations (Fig. 4g) and F_2 fold axes plunge dominantly to the NNW. From Station Creek to the south, the structural setting of the Mount George zone changes; S_2 is subparallel to S_0 in this area (Fig. 2), and an L_2 stretching lineation appear on S_2 surfaces. Sheath folds can be found in bedding in the quartzite in this area. An L_2 stretching lineation is also visible in adjacent slates and felsic volcanics, associated with S_2. The rhythmic sedimentary layering in the quartzite, very clear at Mount Newman and still recognisable farther S, is erased by high strain in the section south of Station Creek; also, the quartzite thickness is generally less than in the N. All these features can be attributed to increasing strain from Station creek to the south as an effect of the influence of the major *dextral* D_2 shear zone which lies to the east of Leonora (Keith-Kilkenny tectonic zone).

The arguments used by Williams et al. (1989) for the Mount George zone to be a sinistral shear zone can be accounted for as follows;
(1) the sinistral brittle faults near Mount Newman belong to a late (post-D_2) phase of faulting which is unrelated to the foliation present in the Mount George zone further south; they have not been found elsewhere along the Mount George zone. It is not clear whether these faults are related to D_3 as described above;
(2) the stretching lineation in the Mount George zone near Leonora is an effect of D_2 deformation in the Keith-Kilkenny tectonic zone;

(3) quartz fabrics (Williams et al, 1989) are largely symmetrical and their weak asymmetry may only indicate local flow partitioning or local (small) deviations from bulk near-coaxial flow. In several outcrops of the quartzite along the Mount George zone, quartz veins were found which have been strongly but coaxially flattened and folded; this also gives evidence for near-coaxial deformation in the quartzite during D_2, possibly as an effect of flow partitioning. Further research will be carried out on quartz samples from these outcrops.

(4) the flexing of bedding in mafic and felsic volcanic rocks east of Mount George is an attenuated F_2 fold limb (Fig. 2).

(5) the Station Creek fold, which seems to indicate sinistral shear sense on the map, is younger than S_2 and apparently the result of bulk coaxial shortening. Also, an apparent F_2 fold in dolerite in the Keith-Kilkenny tectonic zone which would be consistent with a sinistral shear sense, intruded along folded bedding *during* D_2 (Fig. 9); it transect S_2, and is largely undeformed in the 'fold closure'. The dolerite apparently intruded parallel to (folded) bedding. A minor dextral D_2 shear zone transects the curved dolerite on its eastern limb (Fig. 9). No interference of this shear zone with foliation in the wall rock is evident, suggesting that the shear zone developed as part of the same phase which formed the transected foliation.

Flow during D_2 in the Keith-Kilkenny zone

An apparent contradiction to the role of the Keith-Kilkenny zone as a dextral shear zone is the fact, that bedding in both limbs of the large F_2 fold east of Mount George (Fig.1, 10a) is stretched, not shortened. This would be easy to explain if these limbs were deformed in pure shear normal to S_2 (Fig. 10b,c), but this does not agree with the numerous asymmetric features found which indicate that D_2 developed by non-coaxial dextral transcurrent flow. Dextral simple shear at a small angle to S_2, however, would lead to shortening of the western limb of the F_2 antiform in Figure 10. Most likely, deformation was by general non-coaxial flow with both pure shear and simple shear components (Fig. 10b, c; centre). Local partitioning of flow into nearly coaxial parts and nearly simple shear parts can explain why some domains show development of 'simple shear' ductile shear zones (e.g. the one transecting the undeformed dolerite NE of Leonora), while elsewhere S_2 seems to have formed in coaxial deformation (most of the Mount George zone between Station Creek and Mount Newman).

The shear zone along the Rhaeside granite contact

Jasper Hills area

Some problems are associated with interpretation of the shear sense in the D_1 shear zone along the contact of the Rhaeside granite at Jasper Hills (Fig. 2). The western domain of the Jasper Hills quartzite near the D_2 shear zone (Fig. 3 inset), shows a very strong linear and planar shape fabric in the quartzite. Williams et al. (1989) measured quartz fabrics in these quartzites (from this site and up to 1 km to the E), which clearly indicate S-directed thrusting of the upper block. They interpreted this deformation as D_1. This creates a regional problem, however, since sense of shear for D_1 elsewhere in the contact shear zone is a N-directed movement of the hanging wall (i.e. relative uplift of the granite). While more measurements of quartz fabrics will have to be made to solve this problem, it is possible that the strong D_2 deformation in the western side of the Jasper Hills quartzite caused deflection of the quartzite from an E-W to a NW-SE trend, and a local strong shape fabric; farther east along the zone, quartzite fabrics are much weaker. In the NW of the Jasper Hills area (Fig. 3, inset), a deflection of the quartzite and local strain increase has been observed near a dextral shear zone; since orientation of lineations in this zone and elsewhere in the quartzite do not coincide, the structure must have formed by two consecutive phases of deformation. As such, it is possible that the thrust-sense measured in crystallographic preferred orientation fabrics in the quartzite is due to D_2 overprint; since S_2 and D_2 shear zones are dominantly E dipping in this area, sense of shear on the D_2 mobile zones was locally dextral thrusting

eastern granite contact

The strongly mineralised domain in the shear zone along the eastern edge of the Rhaeside granite near Leonora shows a complex deformation sequence in which an early foliation (S_1) and stretching lineation (L_1) can be distinguished with steep easterly dip and plunge respectively. Since S_1 trends everywhere parallel to the granite-greenstone contact in the west, and D_2 features increase in importance to the east, the zone along the eastern edge of the granite may be a zone of D_1 and D_2 interference. In Victoria Wells mine, both D_1 and D_2 shear zones are present. In Trump mine (Fig. 1), sense of shear in some pits indicates SSW-directed subhorizontal thrusting, probably an effect of D_2 as well. Nevertheless, no obvious overprint of D_1 features by D_2 occurs in the mines farther south. This can be explained if the original orientation of D_1 structures was such, that they were lying in the instantaneous extension field of D_2 flow, i.e. NW to NNW trending (Fig. 7c); in that case, D_2 would result only in reorientation and further stretching and flattening of existing structures. The steep eastern side of the granite may be be an effect of the major D_2 Keith-Kilkenny tectonic zone, overprinting an originally gently dipping granite-greenstone contact.

possible influence of later deformation

Finally, deformation postdating D_2 may have affected the contact shear zone near Leonora. Williams et al (1989) have shown, that the plunge direction along the contact shear zone of the Rhaeside granite changes from NE plunging in the north (Jasper Hills, Victoria Wells) through E-plunging (Harbour lights) to SE plunging (Sons of Gwalia) in the south. This may be either an original feature (it could be tentatively associated with gneiss doming), or an effect of reorientation in later deformation. It is significant that the plunge of the L_2 stretching lineation in the Mount George zone changes equally near Harbour lights; in Leonora, L_2 is gently south plunging, N of Harbour lights L_2 passes through subhorizontal to a northerly plunge; near the Station creek fold, plunges are 20-35^{o}; further north the plunge of the lineation increases further, although the lineation itself becomes weaker and disappears around Mount Davis. The change in direction of D_1 and D_2 structures near the same site could be coincidental, but the presence of a gentle open fold of post-D_2 age with E-W trending fold axis cannot be excluded

Mineralisation

Williams et al. (1989) have shown, that mineralisation around Leonora is virtually restricted to D_1 shear zones. This does not explain the erratic pattern of mineralisation along the D_1 shear zones, however. In the Victoria Wells mine, mineralisation seems to occur notably at the intersection of solitary D_1 and D_2 shear zones. It will be interesting to see whether it is in fact at the *interference* of D_1 and D_2 shear zones where mineralisation is common; it is remarkable that the most productive mines are situated in a zone of proposed strong D_1 and D_2 interference north of Leonora. Clearly, this possibility warrants further research.

Conclusions

(1) At least three phases of deformation are present in the Leonora area;
(2) D_1 was dominantly a phase of displacement along gently dipping shear zones with movement of the hanging wall towards the north; this is especially obvious in the Jasper Hills and Mount Newman areas. D_1 deformation is mainly concentrated in the contact zone between greenstone belts and granite, and locally in the greenstone belts. Along the contact, both a slaty cleavage (S_1) and a stretching lineation (L_1) are usually present.
(3) D_2 structures are present throughout the area. D_2 caused development of the penetrative regional slaty cleavage S_2. D_2 was a phase of dextral transcurrent non-coaxial deformation with NE-SW trending instantaneous shortening direction and NW-SE tending extensional 'shear plane'. Flow vorticity seems to have varied strongly over the area. Presence of a major D_2 shear zone around and east of Leonora (the Keith-Kilkenny tectonic zone) caused local strong foliation and lineation development, and probably steepening of the E-side of the granite.
(4) The sinistral Mount George 'shear zone' described by Williams et al (1989) does not exist as such: it is a large scale F_2 fold limb in a stratigraphic horizon dominated by quartzite beds; its southern part lies in a D_2 shear zone, but the movement sense on this zone is dextral.

(5) The coincidence of quartzite lenses and layers with shear zones in the area is probably a topographic effect, the result of shear zones transecting relatively flat lying stratigraphy at depth.

Acknowledgements

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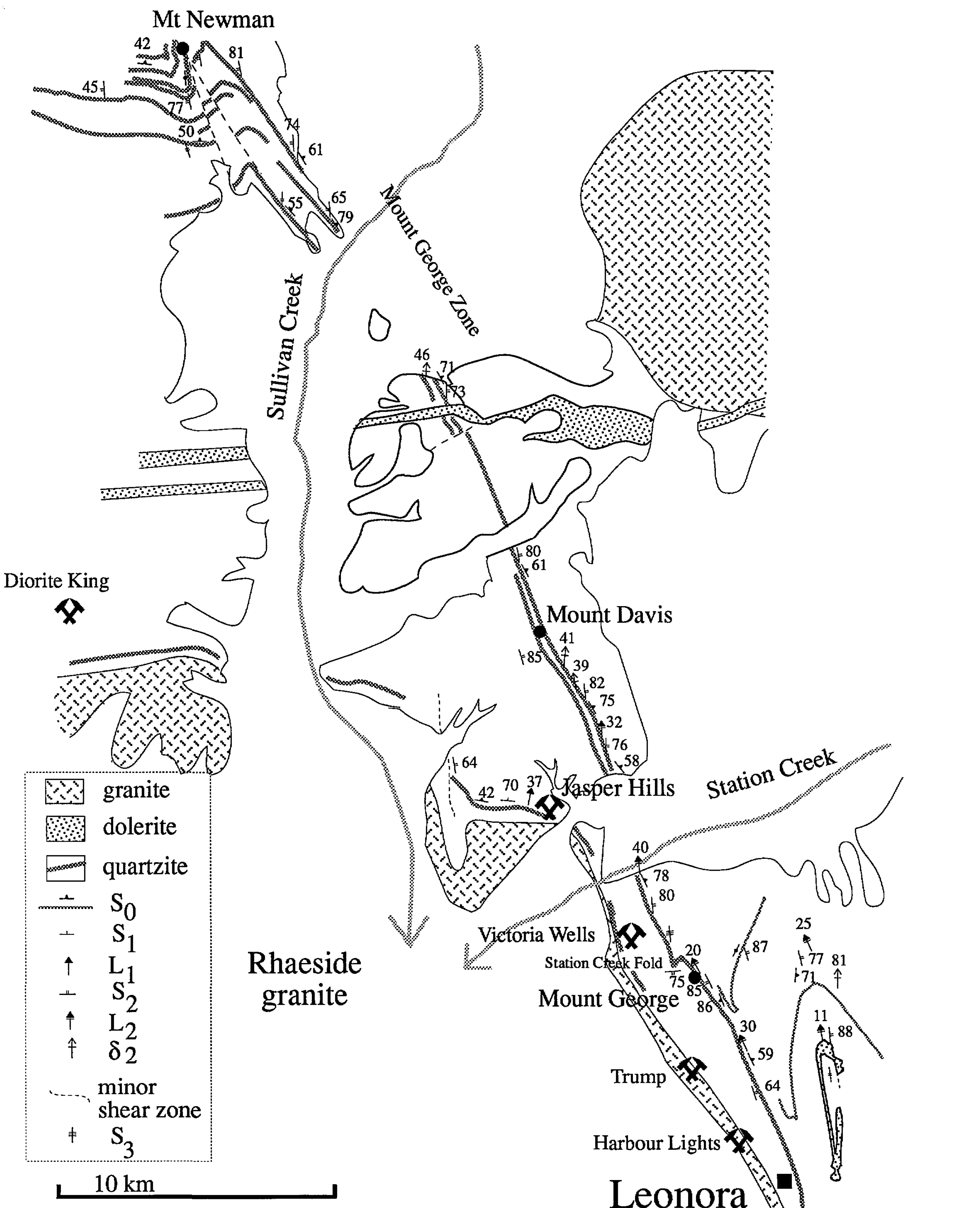


Fig. 1 - Schematic map of the geology NW of Leonora, WA. Lithology details have been omitted from the greenstone belts (white) in order to show detail in structure of quartzite beds.

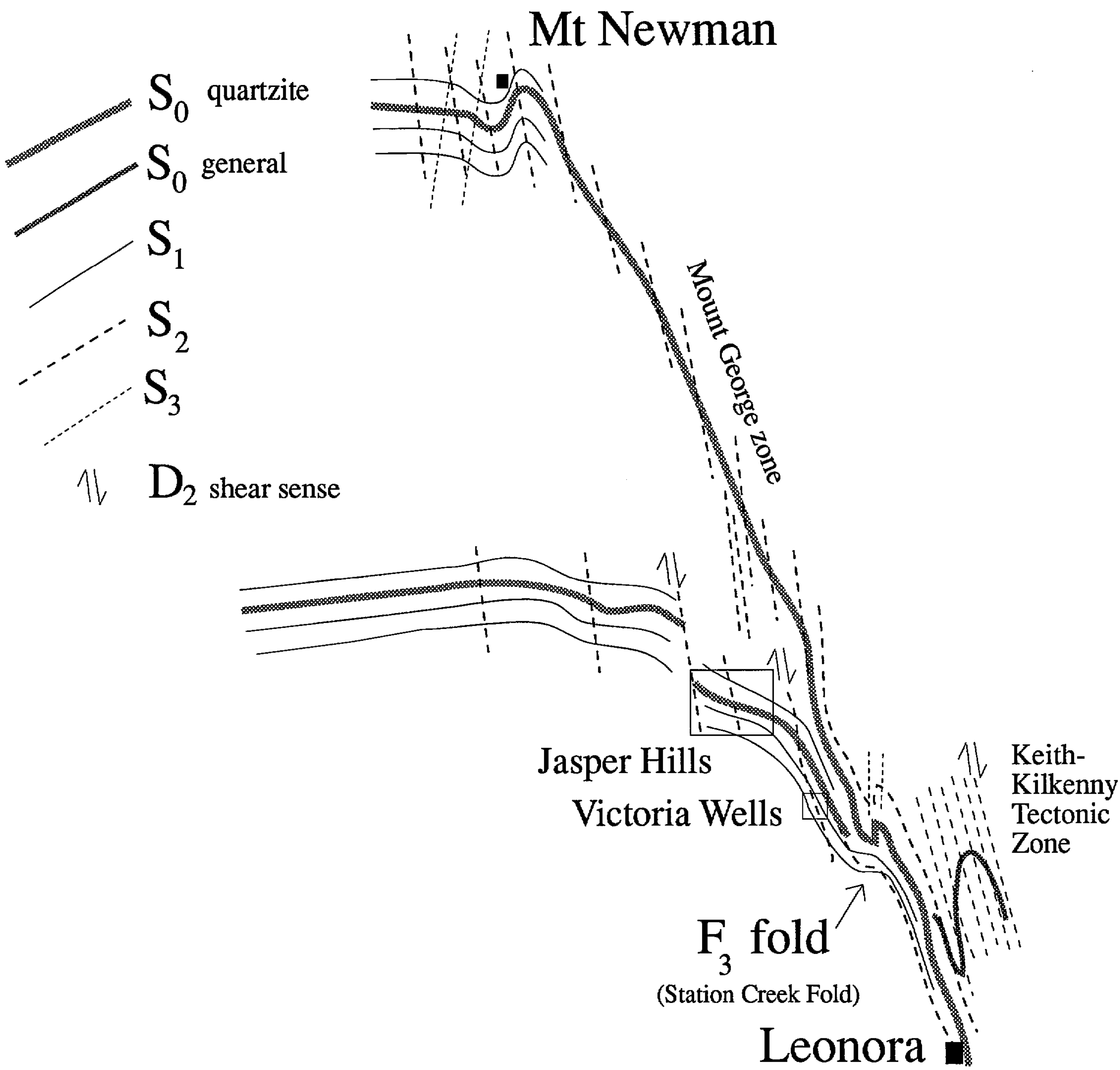


Fig. 2 - Cartoon outlining the large scale structure of the Leonora area

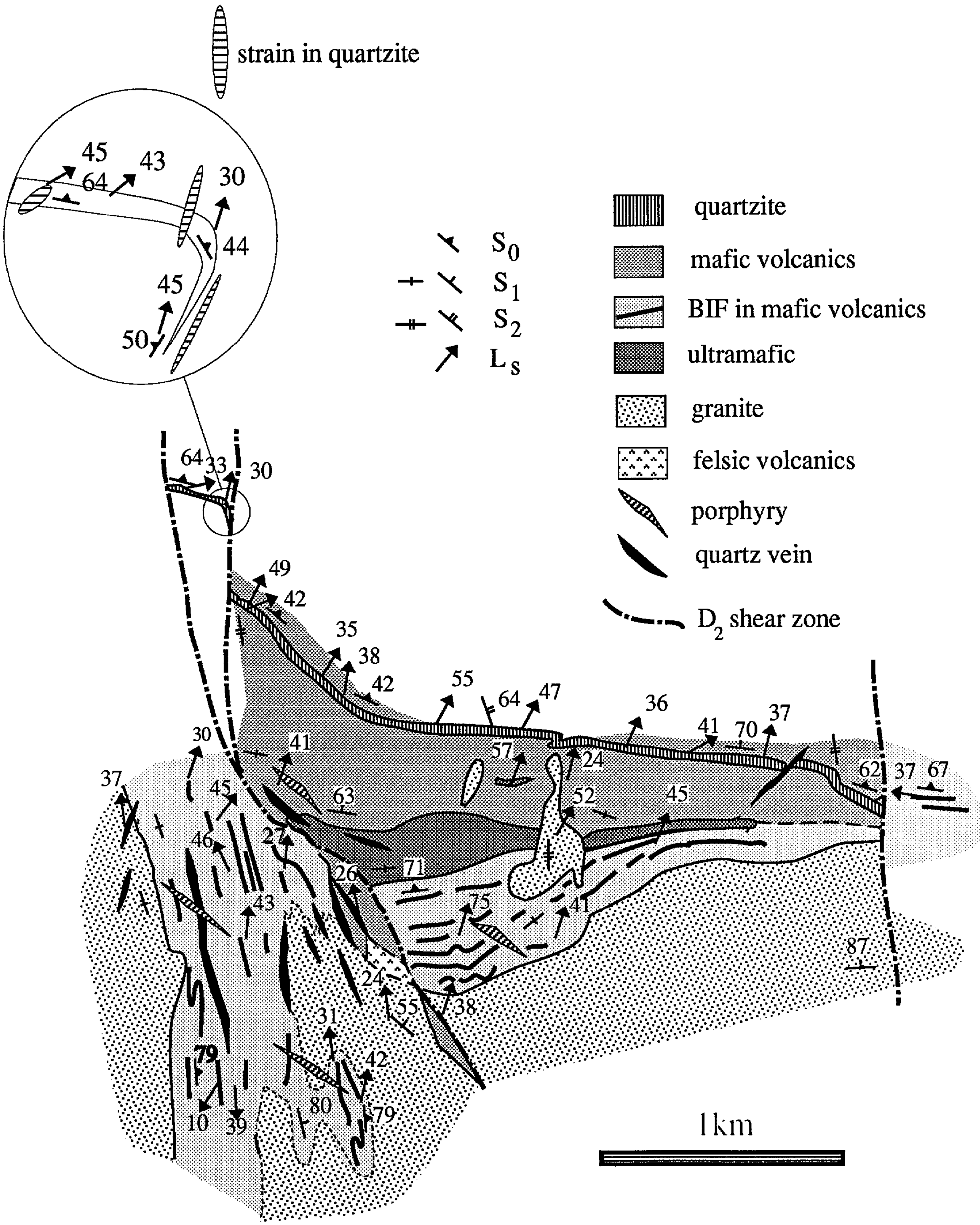


Fig 3 - Map of the Jasper Hills area. Inset shows geology and strain intensity in a quartzite lens
Ls - stretching lineation

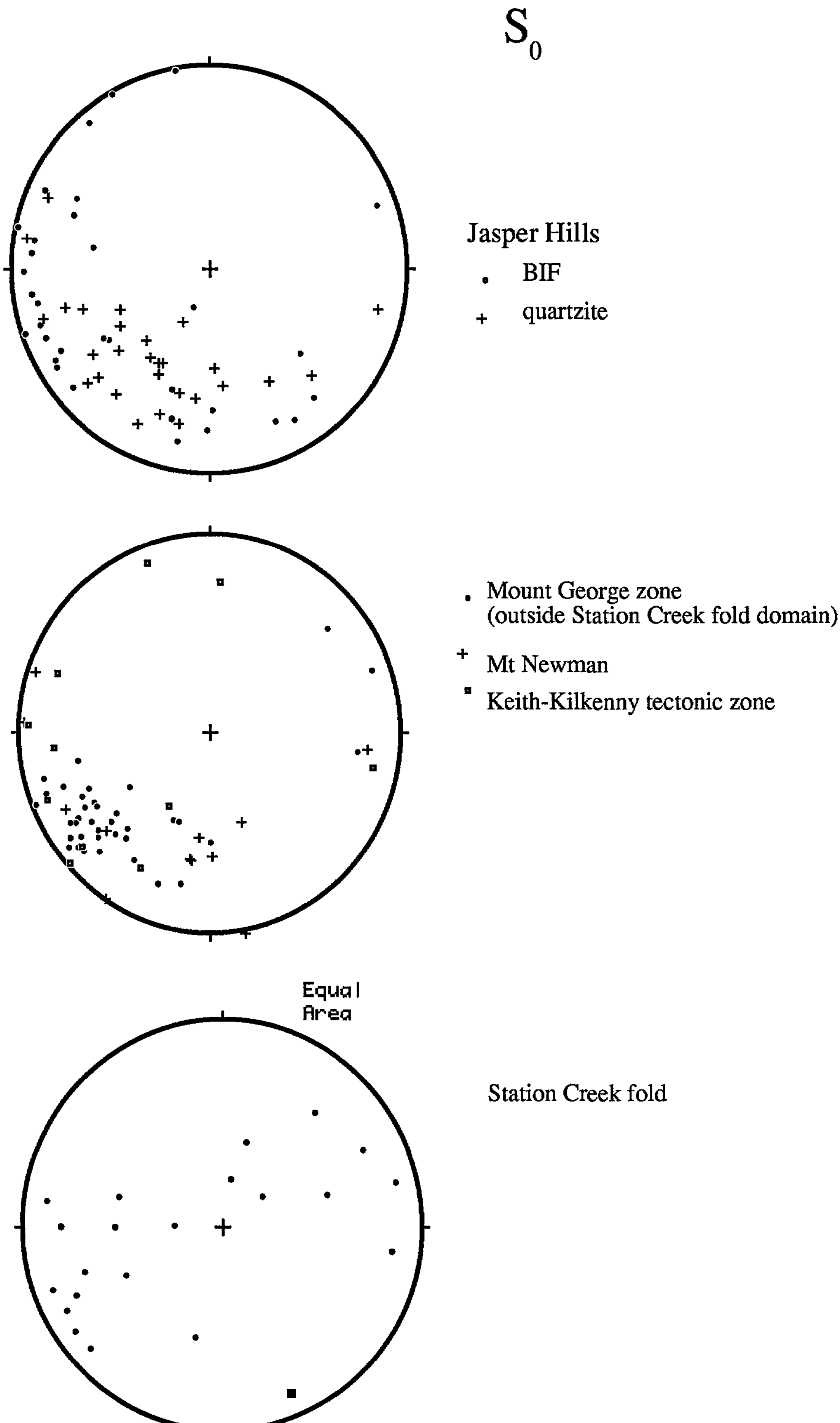


Fig. 4a - bedding

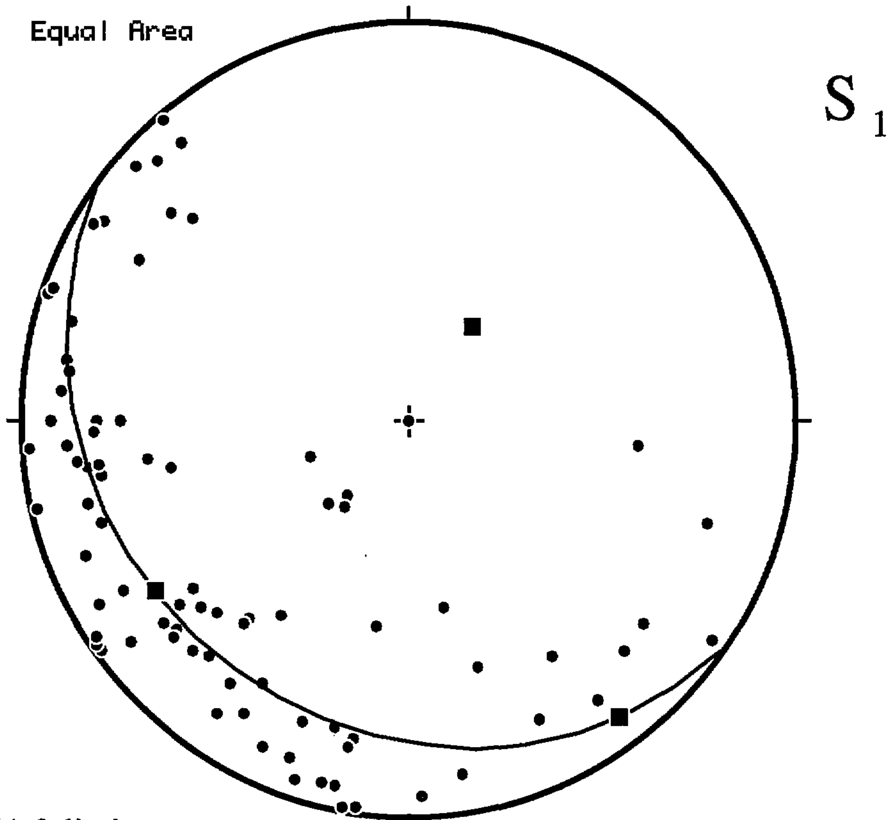


Fig. 4b - S1 foliation

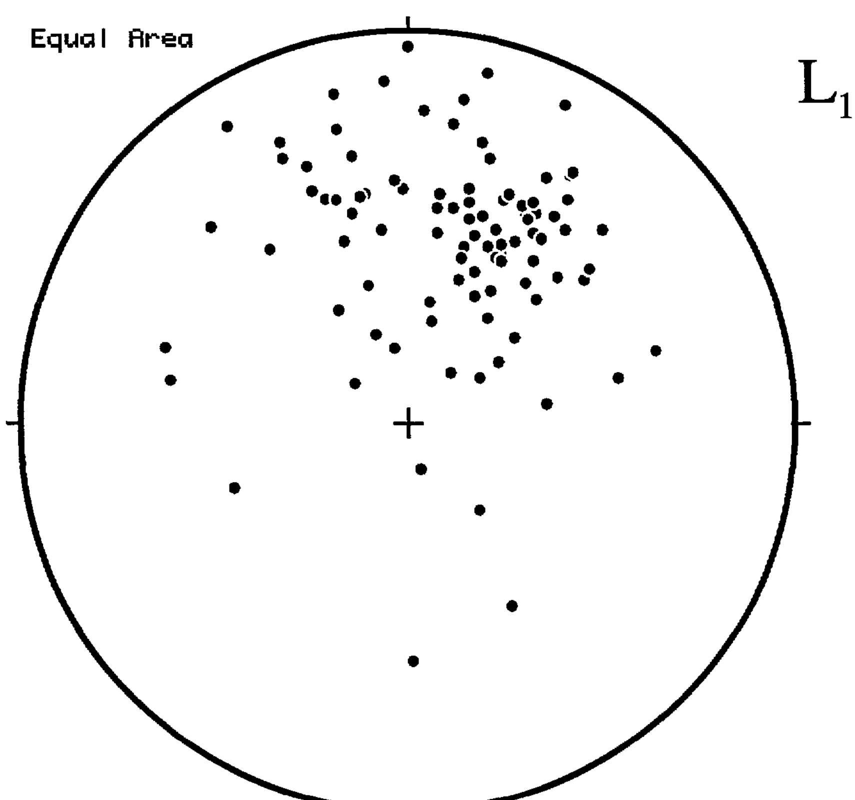


Fig. 4c - L1 stretching lineations

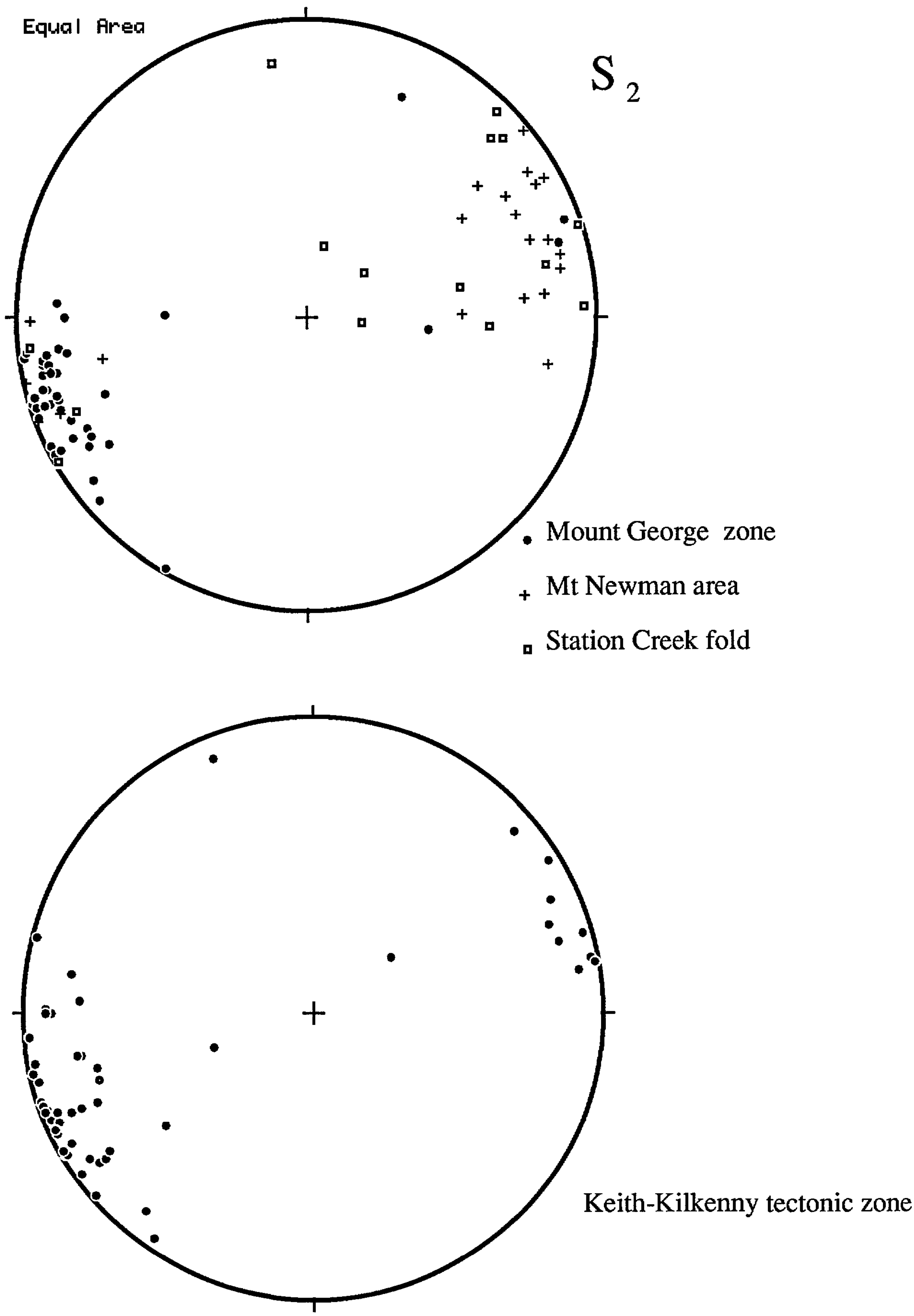
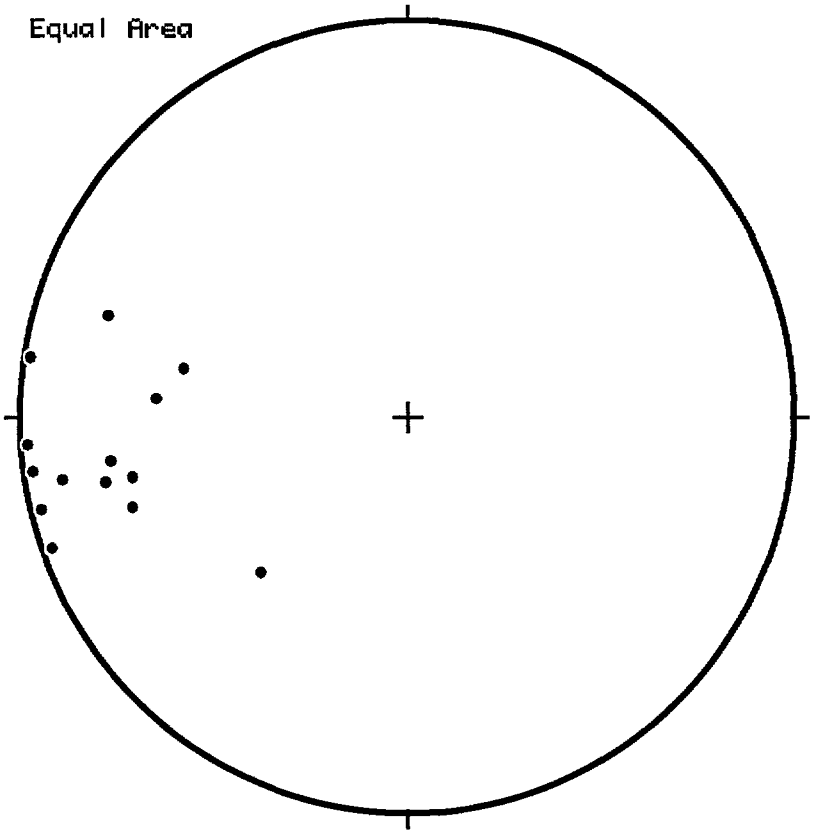
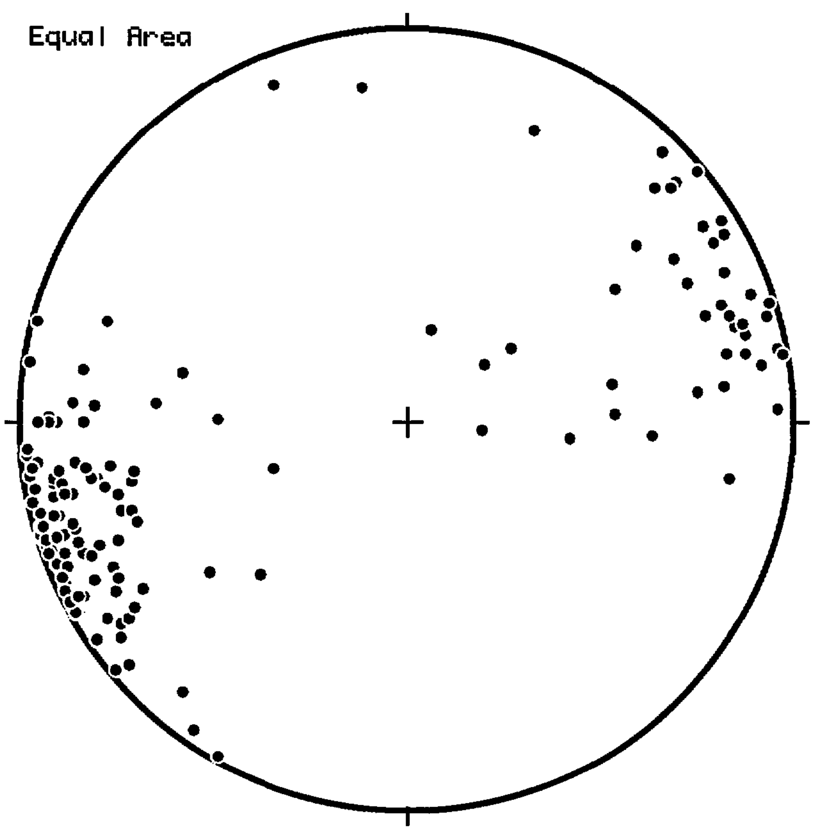


Fig. 4d - S2 foliations



S_2

Jasper Hills



total

Fig. 4 e - S2 foliations

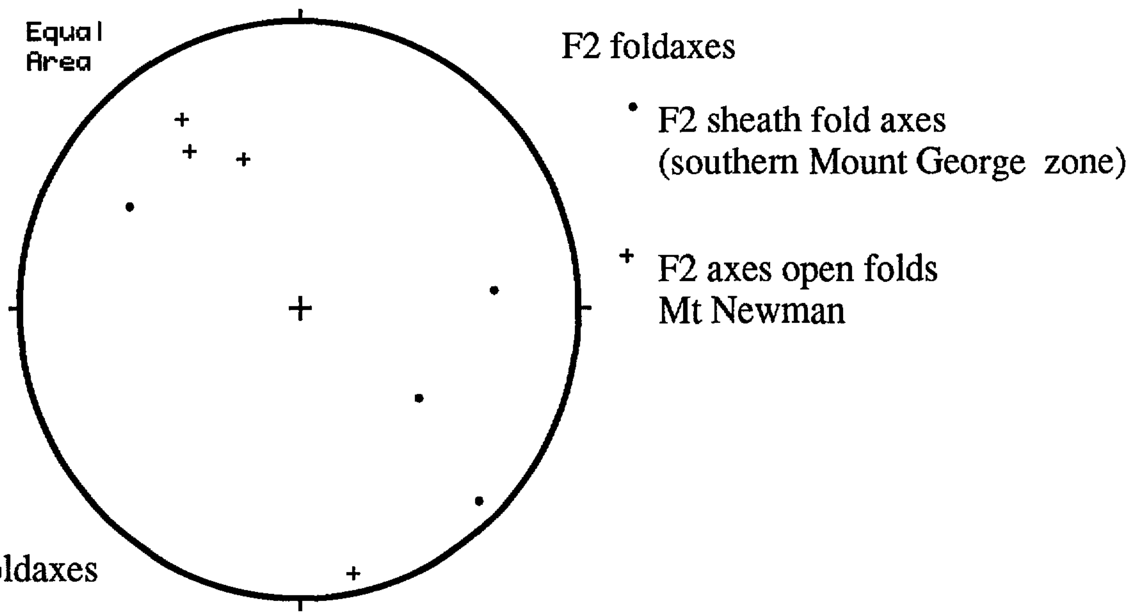


Fig. 4f - F2 foldaxes

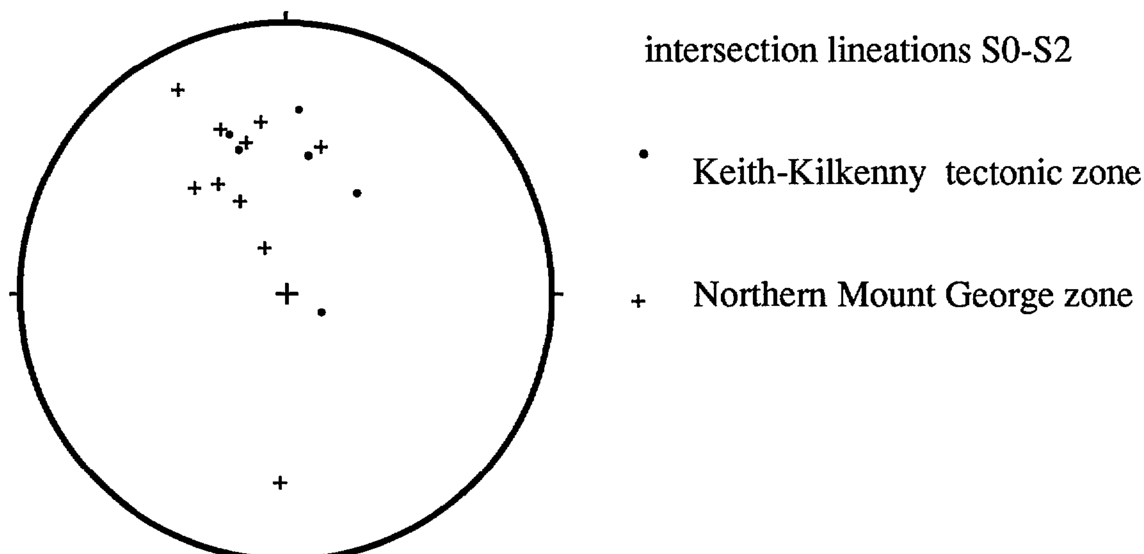


Fig. 4 g - intersection lineations S0-S2

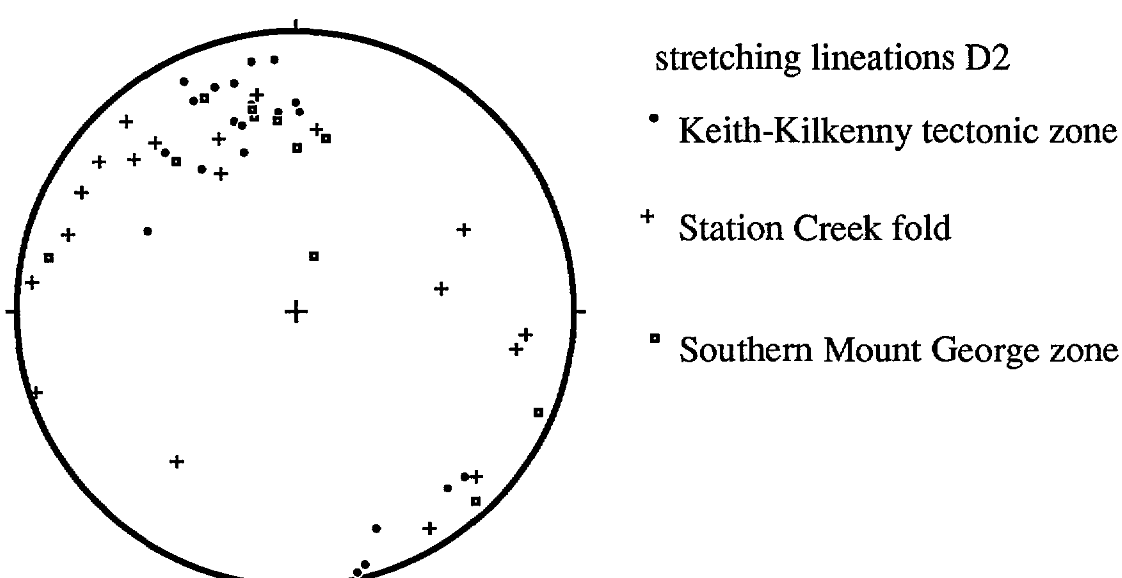


Fig. 4h - L2 stretching lineations

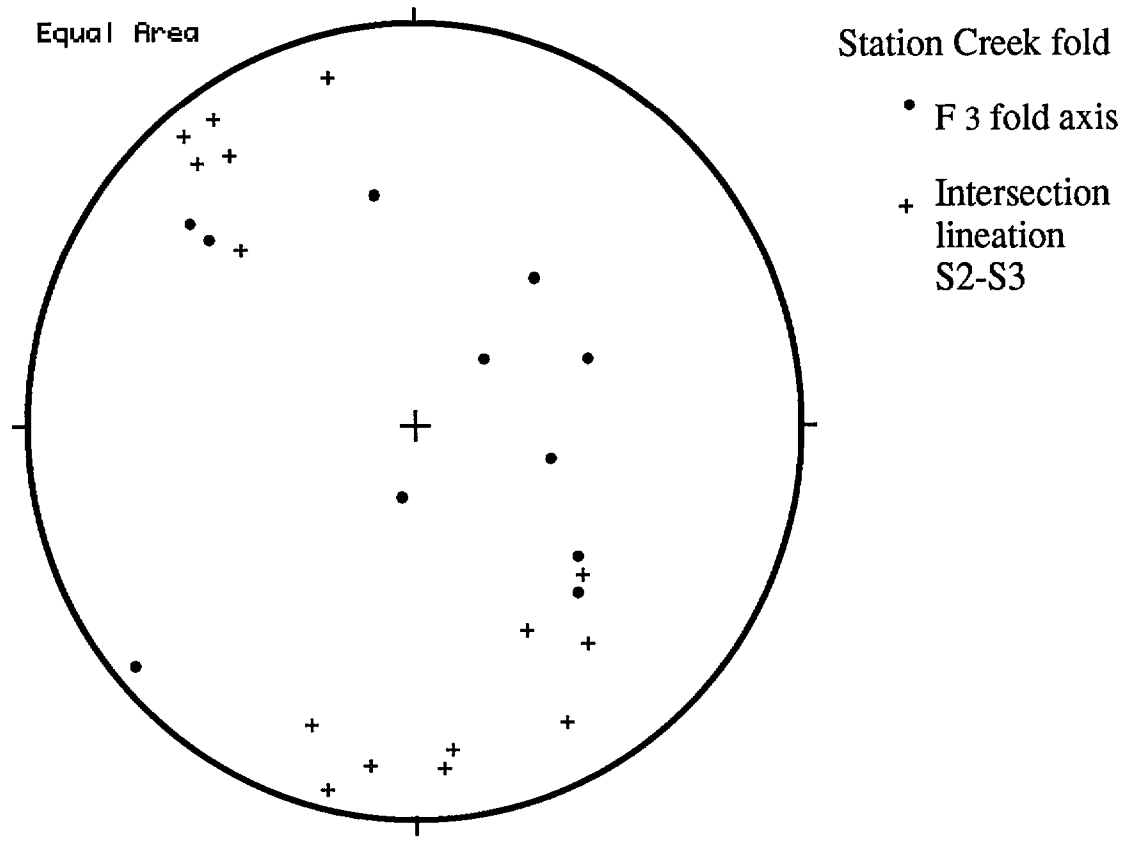


Fig. 4 j - D3 linear structures

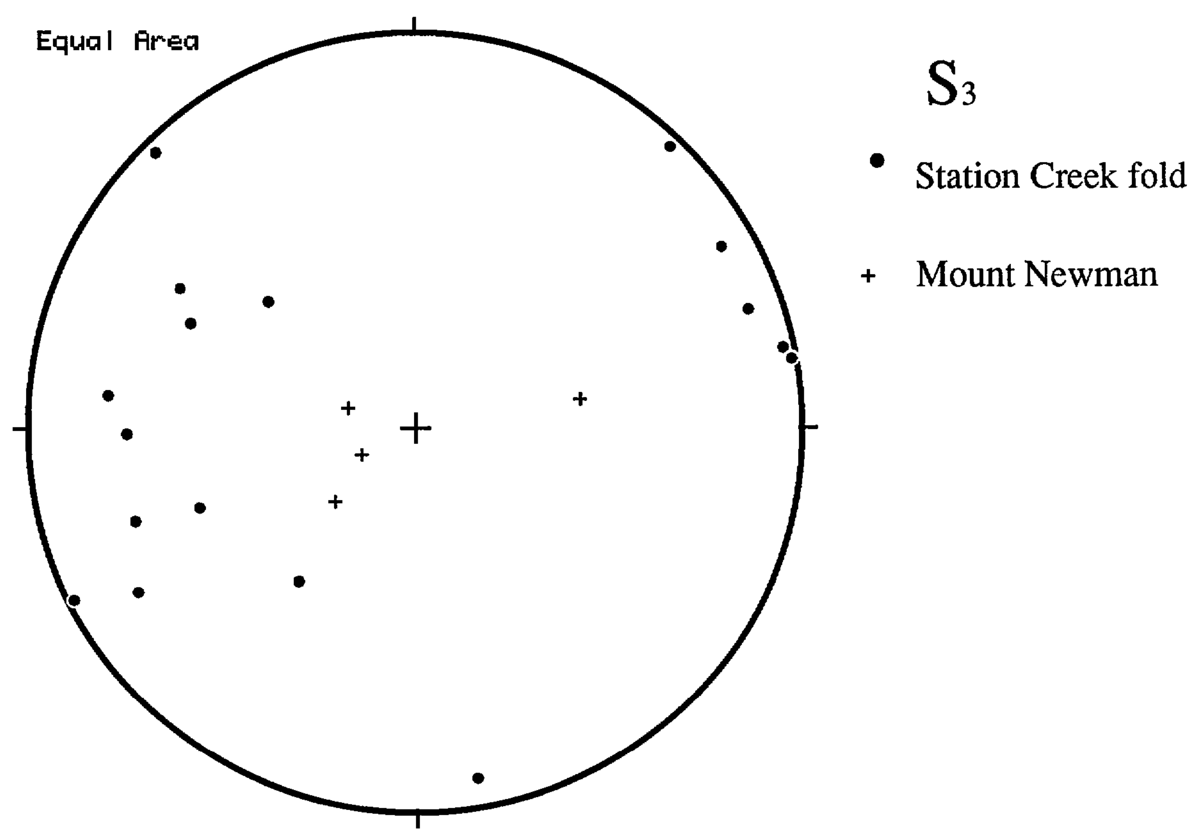


Fig. 4k - S3 foliation

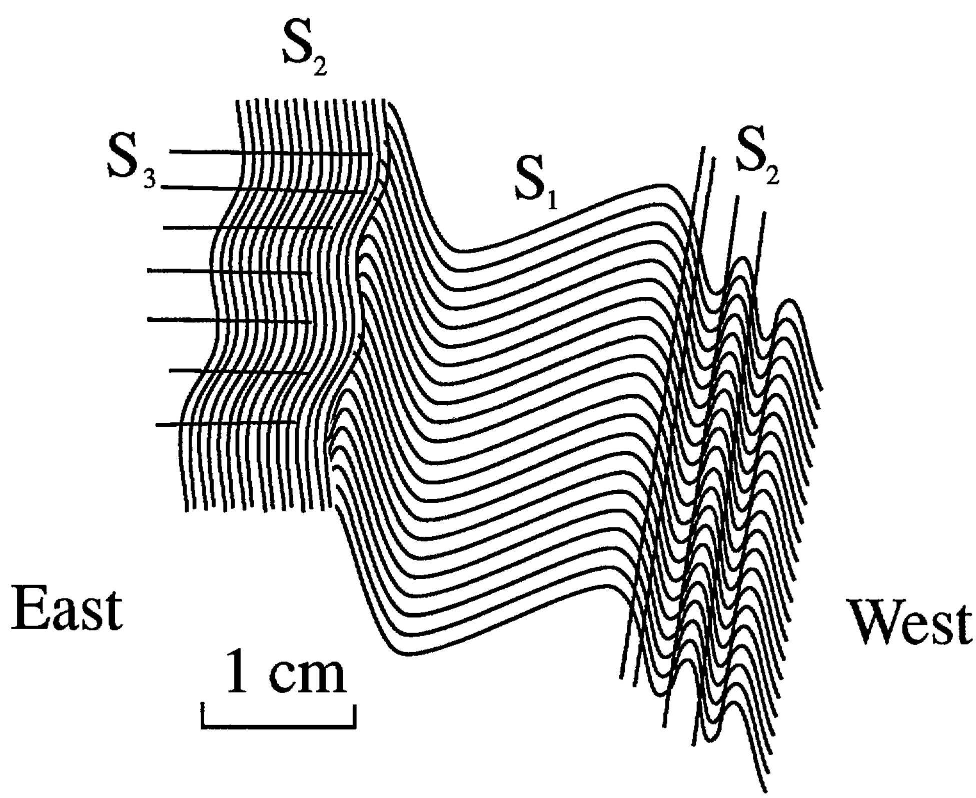


Fig. 5 - Sketch of interference of D1-D2 and D3 structures in an outcrop near Mount Newman.

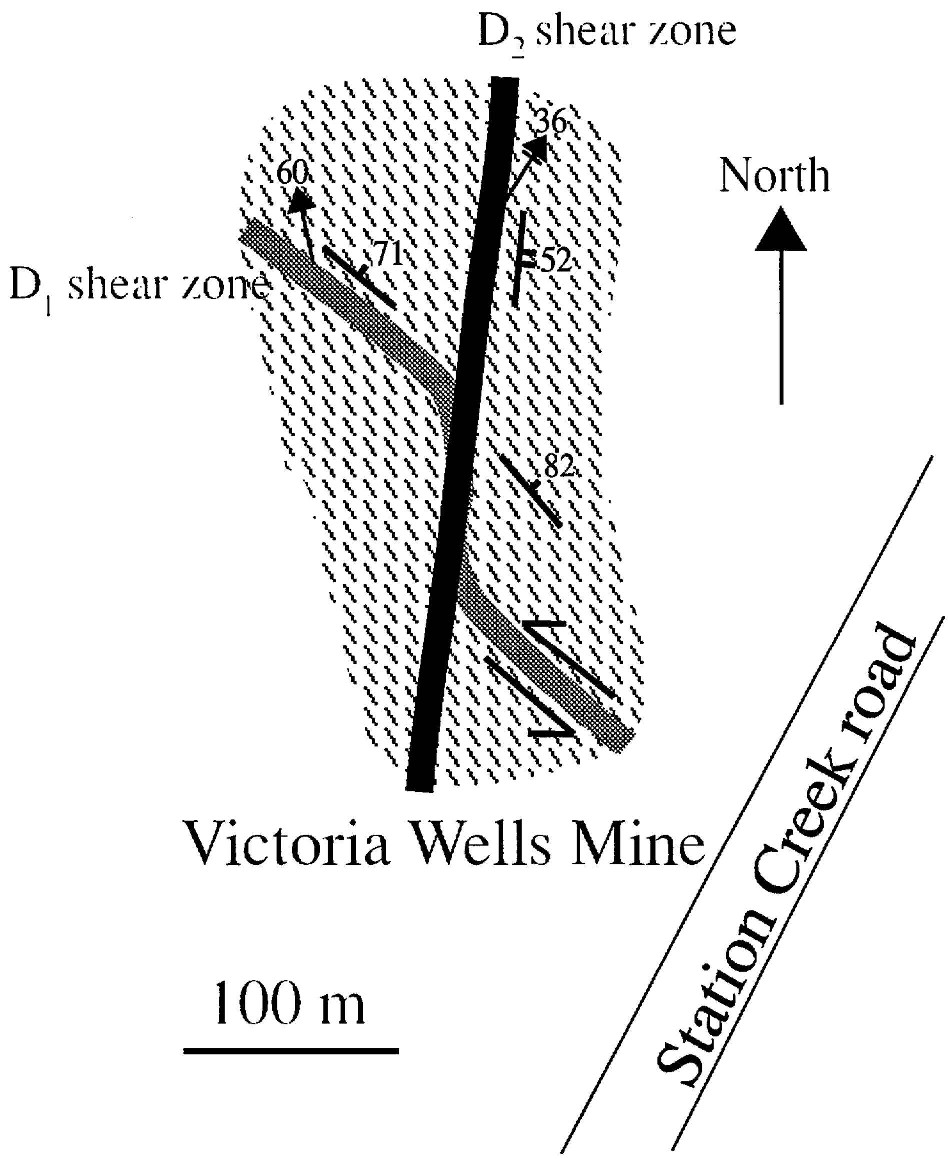
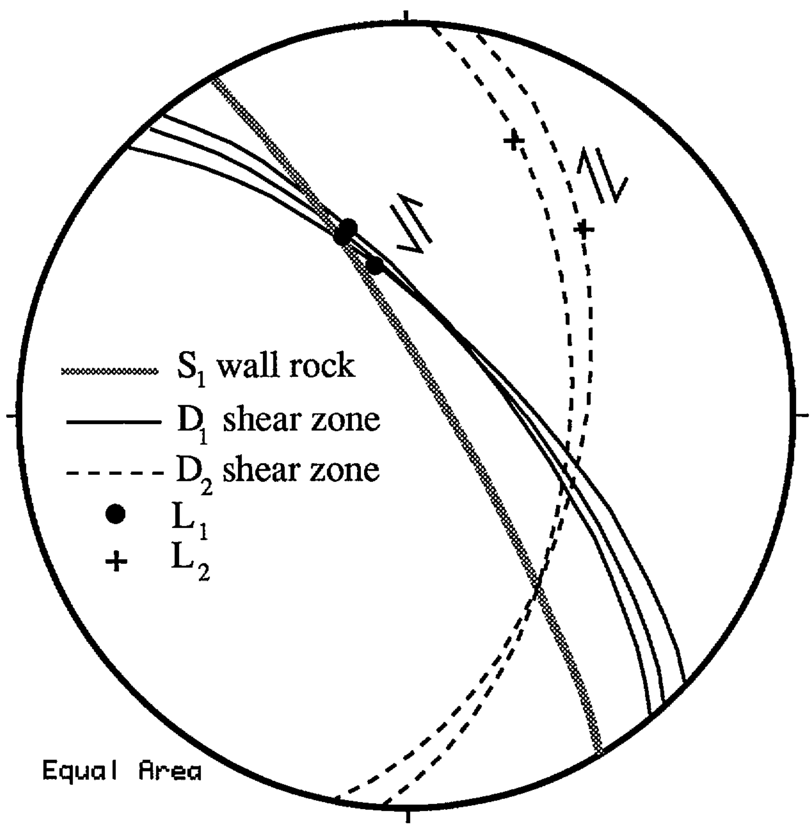


Fig. 6 - Schematic map of the structure in Victoria Wells mine. Ornamentation indicates foliation in the metabasite wall rock.

Victoria Wells Mine



D_1 :sinistral normal
D_2 : dextral thrust

Fig. 7 - Orientation data from the Victoria Wells Mine

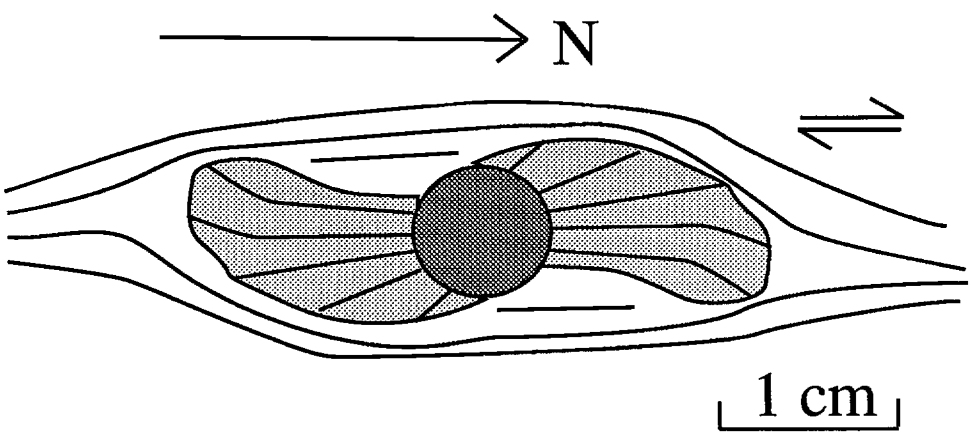


Fig. 8. Fibrous quartz fringes surrounding spherical pyrite aggregate in slate in a section normal to S1 and parallel to an L1 stretching lineation. The geometry of the fringes indicates dextral shear sense. Slate outcrop on railway, 10 km east of Leonora.

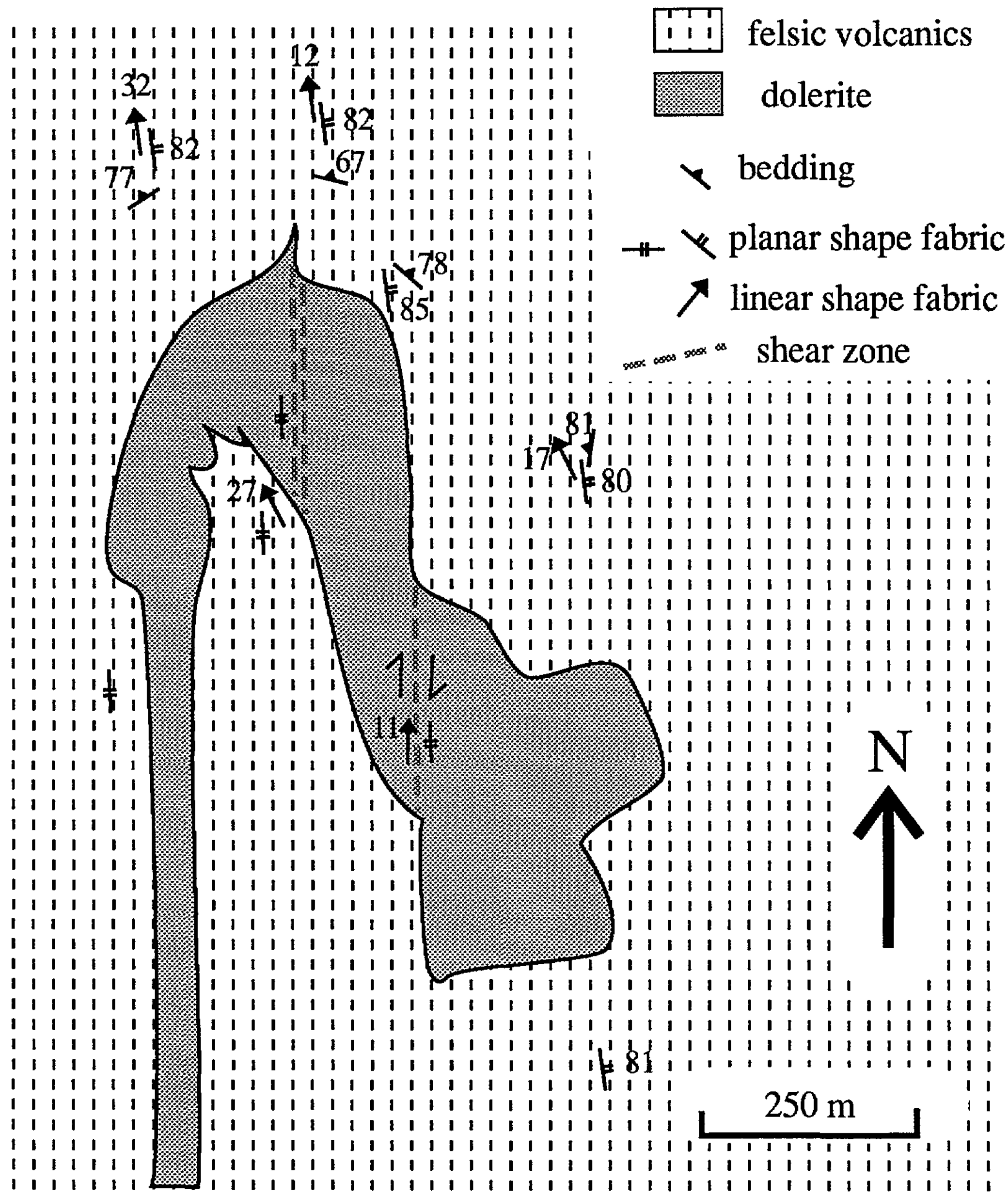


Fig. 9. Dolerite dyke which intruded along D2-folded bedding in felsic volcanics in the Keith -Kilkenny tectonic zone. The undeformed dolerite is transected by dextral D2-shear zones in which the shape fabric elements have the same orientation as in the felsic volcanics.

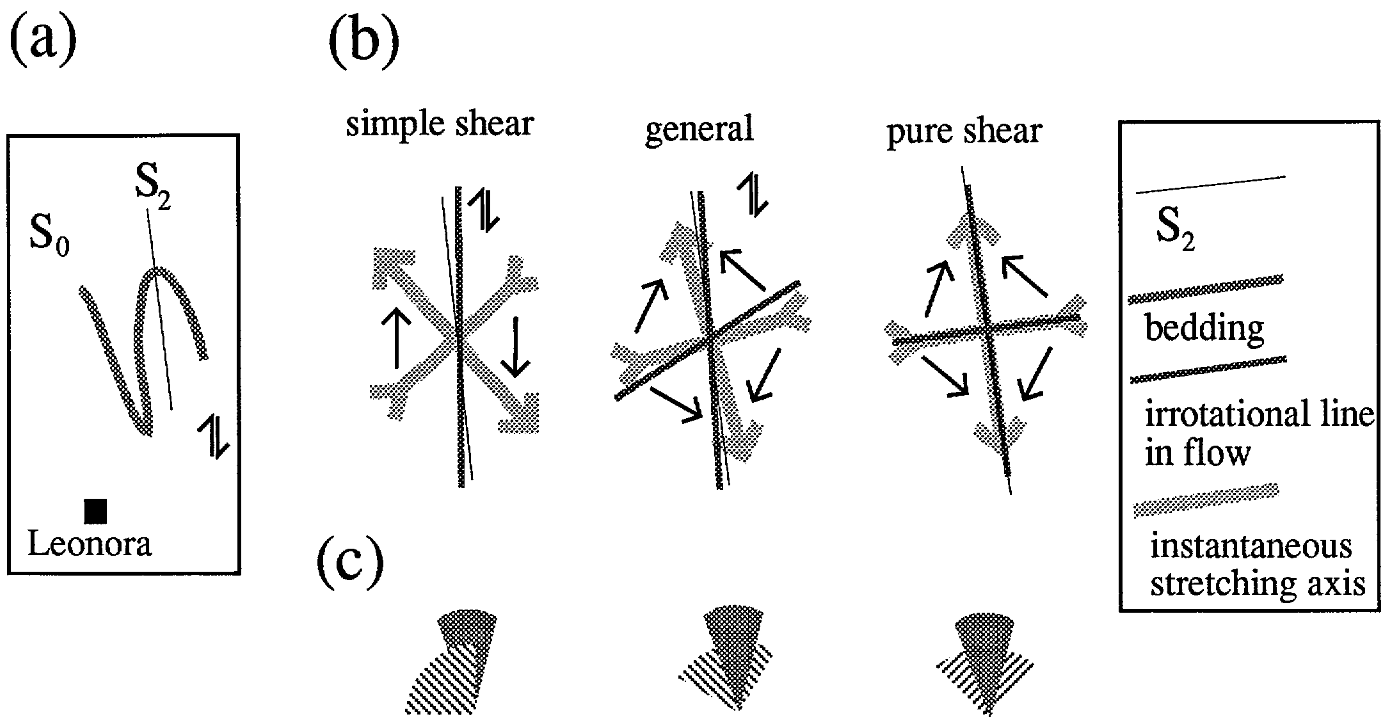


Fig. 10 - explanation for the D2 deformation pattern near Leonora, where both limbs of F2 folds undergo extension in non-coaxial dextral transcurrent deformation;(a) map of bedding and S2 orientation in major F2 folds; (b) different possible flow types for D2; (c) orientational relationship of the domain of shortening (striped) and bedding (grey) for the different flow types.The orientation of bedding and S2 (a) around Leonora is difficult to explain by simple shear (b), since some limbs of F2 folds would undergo shortening (c) during progressive deformation, and rotate dextrally away from the flow plane. The situation could be explained by pure shear (b,c) where both fold limbs are in the extensional domain and rotate towards the principal extension axis. This does not agree with the occurrence of dextral sense of shear markers, however. The situation is best explained by general non-coaxial flow (between pure and simple shear) during D2 deformation: both fold limbs are in the extensional domain and rotate towards the principal irrotational axis; the foliation plane also rotates to this axis.