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# The Nature of High-strain Zones in the Laverton—Leonora Area, Western Australia
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***Minerals and Land Use Program***



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# Abstract

Four high-strain zones from the Laverton—Leonora area in the NE-Yilgarn craton were investigated to determine the nature of local deformation. These are from east to west: the Mt Admiral-, Windarra-, Keith-Kilkenny- and Sons of Gwalia High-strain zones. The Mt Admiral High-strain Zone east of Laverton is not a shear zone, but a zone of dominant coaxial flattening and tight folding. The Windarra High-strain Zone west of Laverton is a major sinistral shear zone; the Keith—Kilkenny High-strain Zone east of Leonora shows evidence of two major tectonic events; a phase of N-directed nappe-type transport, followed by dextral transpressional movement. The Sons of Gwalia High-strain Zone was investigated in the Diorite King area. In this area, it is a complex structure involving early N-directed nappe transport, followed by minor E-W shortening

In the Leonora area, the early N-directed normal shear zones in the Keith—Kilkenny High-strain Zone and the Diorite King area of the Sons of Gwalia High-strain Zone may belong to the same early phase of deformation, probably regional extension ($D_1$). Dextral shear zone activity in the Keith—Kilkenny High-strain Zone is contemporaneous with open folding in the Diorite King area after this early nappe-type deformation event ($D_2$). The main deformation phase in the Mt Admiral and Windarra High-strain Zones is probably $D_2$. The difference in nature of $D_2$ deformation at both sites can be explained by the presence of a granite pluton just west of the Windarra High-Strain Zone.

# Rationale

This research forms part of the Eastern Goldfields NGMA project undertaken jointly by the Australian Geological Survey Organisation and the Geological Survey of Western Australia. The National Geoscience Mapping Accord, endorsed by the Australian (now Australian and New Zealand) Minerals and Energy Council in August 1990 is a joint Commonwealth/State/Territory initiative to produce, using modern technology, a new generation of geoscientific maps, data sets, and other information of stategically important regions of Australia over the next 20 years.

The Leonora—Laverton District is situated in the Eastern Goldfields Province (EGP) in the eastern part of the Archaean Yilgarn Craton of Western Australia (Fig. 1). The area is characterised by deformed and undeformed granitoid plutons, separated by linear greenschist- to amphibolite facies greenstone belts. High-strain zones are common in all lithologic units, and are especially well-developed along the contact of the granitoid plutons and the greenstone belts. The Norseman—Wiluna Belt on the western edge of the EGP is the most richly mineralised greenstone belt in Western Australia with a total production of 1900t of gold (Hallberg, 1986; Barley et al, 1989). Gold deposits seem to be locally associated with reactivation of high-strain zones (Vearncombe et al, 1989). It is therefore important to understand deformation in the high-strain zones in detail.

During June-July 1990 an analysis was made of a number of the high-strain zones near Leonora and Laverton with the aim to provide a more detailed account of their structural history. This report presents the results of this study. A similar investigation of other high-strain zones in the Leonora area in 1989 was published as BMR Record 1990/59 (Passchier, 1990).

This report deals with two high-strain zones near Laverton, the Mt Admiral and Windarra High-strain Zones, and with two high-strain zones near Leonora, the Keith—Kilkenny High-strain Zone near Mt Malcolm, and the Sons of Gwalia High-strain Zone near the Diorite King mine (Fig.1).

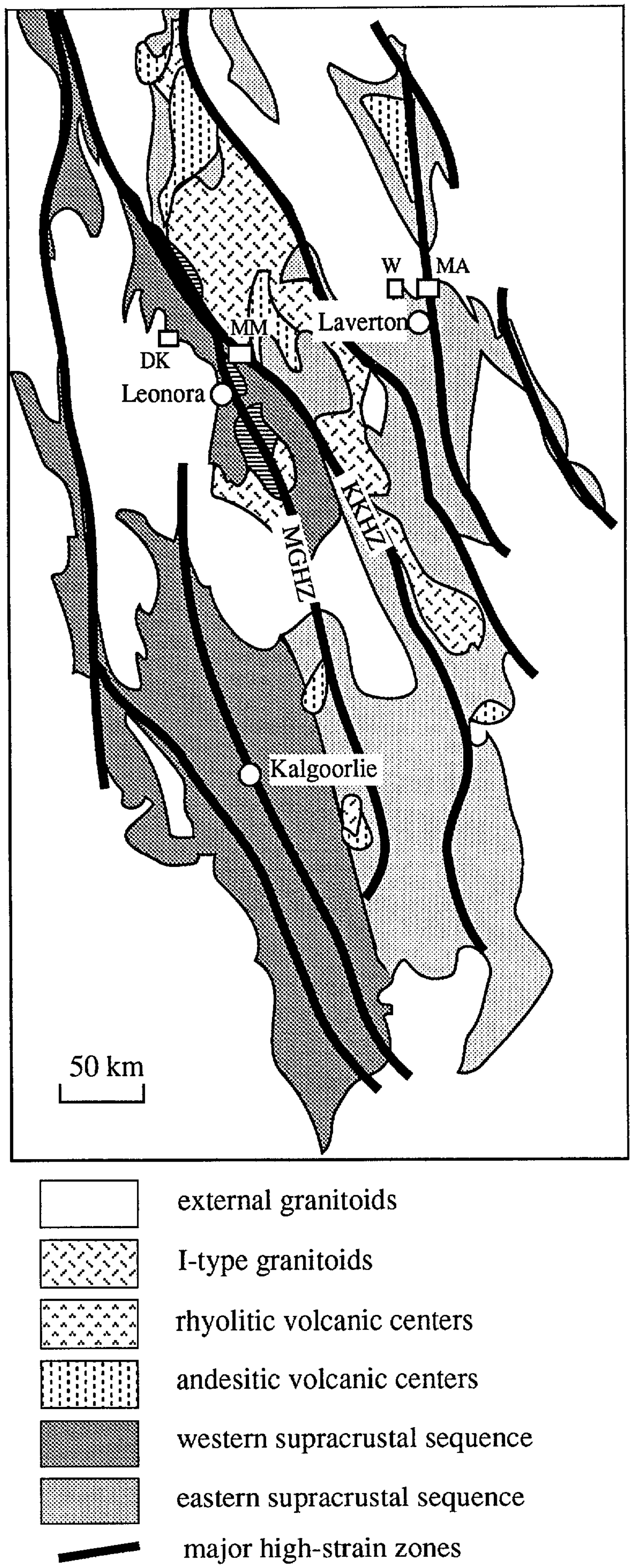


**Fig. 1. Schematic map of the Norseman—Wiluna Belt in the Eastern Goldfields Province, after Barley et al (1989). Mapped areas are indicated as squares: MA – Mt Admiral; W – Windarra; mm – Mt Malcolm; DK – Diorite King. MGHZ – Mt George High-strain Zone; KKHZ – Keith—Kilkenny High-strain Zone. The Norseman—Wiluna Belt lies west of the KKHZ following Hallberg (1986).**

## Geological Setting

The area between Leonora and Laverton covers the northeastern sector of the EGP (Williams, 1974; Hallberg, 1986). The western part of the area belongs to the Norseman—Wiluna Belt (Fig. 1). The Norseman—Wiluna Belt is 800 km long and up to 150 km wide, comprising a ~2.7 Ga old greenstone sequences surrounded by poorly exposed plutons of granodiorite, adamellite and granite (Fig. 1). The belt contains abundant tholeiites, komatiites and deep-water sulphidic shales (Hallberg, 1986; Barley et al, 1989). To the east of the Norseman—Wiluna belt, tholeiites with calc-alkaline volcanic rocks and related sediments dominate (Barley et al, 1989). The calc-alkaline volcanic sequences range in composition from basalt to rhyolite (with andesite and dacite dominant) and were mainly erupted from subaerial volcanic centres (Barley et al, 1989). In distal environments, pyroclastics and feldspathic sedimentary rocks are interlayered with tholeiitic basalts and sulphidic shales (Barley et al, 1989). In the Norseman—Wiluna Belt basalts are commonly pillowed, interlayered with sulphidic shales and comagmatic layered sills, and overlain by intermediate to silicic pyroclastics and associated sediments that are similar to those in the east of the belt. According to Barley et al (1989) and Barley & Groves (1990), the eastern succession is comparable with modern ensialic volcanic arcs, while the lower part of the western association is comparable to crust in younger submarine extensional basins in back-arc settings. In both tectonostratigraphic units, minor amphibolite, metagabbro, quartzite, banded iron formation (BIF), and intrusions of porphyry and dolerite occur. Overall, the greenstones seem to be representative of shallow water deposits with minor influence of terrigenous material.

The two domains distinguished by Hallberg (1985), Barley et al. (1989) and Barley & Groves (1990) in the greenstone belt are separated by a major high-strain zone, the Keith—Kilkenny High-strain Zone (KKHZ). Barley et al. (1989) and Barley & Groves (1990) interpret the Norseman—Wiluna Belt as being the result of a complex history of subduction-related volcanism, crustal extension, crustal shortening and terrane assembly similar to that in obliquely convergent Phanerozoic continental margins. The KKHZ would be a major strike-slip zone in this model.

Granitoids have been divided into internal and external suites (Sofoulis, 1963). Granitoids to the west of the Norseman—Wiluna belt belong to the external granitoids, which are dominantly biotite-bearing monzogranites derived by partial melting and remobilisation of older sialic crust (Barley et al, 1989). Emplacement of external granitoids was broadly synchronous with deformation and metamorphism of the greenstone sequences, with zones of high-grade metamorphism adjacent to regional granitoid-greenstone contacts. In the eastern sequence lie internal granitoids, which are more compositionally diverse than external ones, and include I- and A-type syn- to post-kinematic plutons. The I-type granitoids have geochemical signature (LILE-enrichment and Nb depletion) typical of magmatism at Phanerozoic convergent margins (Barley & Groves, 1990). Metamorphism was in greenschist facies, except near syn-kinematic granitoids where high-grade assemblages have been found (Binns et al, 1976).

Komatiite volcanism at Kambalda, in the southern part of the Norseman—Wiluna Belt has been dated at 2690 Ma (Claoue-Long et al, 1988). An age of 2662 ± 6 Ma for a synkinematic granitoid at Kambalda (Claoue-Long et al, 1988) has been taken to indicate that strike slip and thrusting deformation started within 30 Ma of komatiite volcanism. A postkinematic granite, near Coolgardie in the south of the Norseman—Wiluna Belt has been dated at 2610 Ma (Hills and Compston, 1986). According to Barley et al (1989) and Barley & Groves (1990), deformation is monophase around ~2.66-2.63 Ga and characterised by regional oblique compression, resulting in the generation of craton-scale oblique-slip fault zones, upright folding and local thrusting. Others (Martyn, 1987; Williams et al, 1989; Swager & Griffin, 1990) have advocated polyphase deformation, with an early phase of nappe like-transport, followed by several phases of upright folding and of ductile and brittle strike-slip deformation.

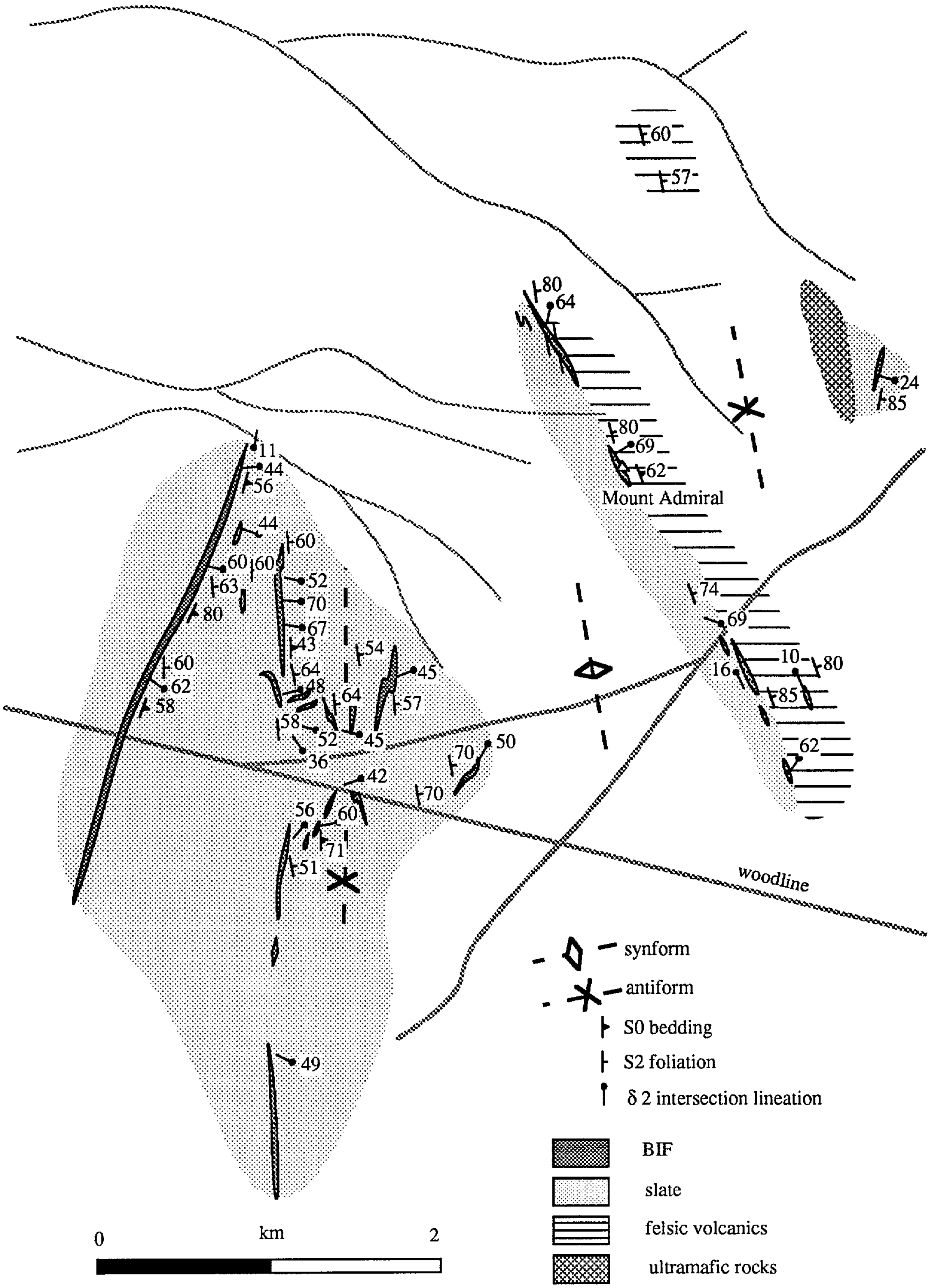


**Fig. 2. Schematic map of the Mt Admiral area, NE of Laverton.**

# Part 1 — Laverton area

## Mt Admiral High-strain Zone

Approximately 20 km east of Laverton lies a N-S trending belt of strongly foliated rocks, known as the Mt Admiral High-strain Zone (Fig. 2). The nature of this deformed zone was investigated in the vicinity of Mt Admiral, a prominent quartzite outcrop. The area west of Mt Admiral is mainly composed of slates and siltstones with minor BIF horizons, up to 20 m wide. East of Mt Admiral, N-S trending lenses of felsic volcanics, slate, metabasalts and ultramafic rocks alternate (Fig. 2).

### Structure

In the Mt Admiral area, evidence exists for three phases of deformation. The main foliation in the area is a steeply E-dipping slaty cleavage ($S_2$) developed in all lithologic units (Fig. 3). Bedding in BIF horizons and in slates is tightly to isoclinally folded with this main foliation as an axial planar cleavage. Throughout the area, the vergence of bedding and cleavage can be used to reconstruct the geometry of major $D_2$ folds. $D_2$ folds occur on a dm to km scale (Fig. 2). Foldaxes and $\delta_2$-lineations are steeply E- to NE plunging, but orientation is strongly variable, even within a single outcrop (Figs. 2, 3). Such a spread in orientation of δ-lineations can result from a non-planar bedding prior to $D_2$ folding, or to post-$D_2$ folding. In two outcrops, open chevron folding of $S_2$ was observed with steep axial planes and gently SW plunging foldaxes, but this $D_3$ folding seems to be regionally unimportant. In several locations, $S_2$ was seen to transect folds in BIF layering and a number of refolded folds were observed, cut by $S_2$ (Fig.4). This implies, that a phase of deformation predates $S_2$. The spread in $\delta_2$-lineations is therefore probably a result of large-scale $D_1$-folding of bedding. The nature of the $D_1$ event is not clear because of the small number of early structures observed in the limited outcrop available.

Although the $D_2$ fabric (expressed as $S_2$ and $D_2$ folding) is strongly developed in the Mt Admiral High-strain Zone, the zone cannot be classified as a shear zone. No evidence was found for a non-coaxial progressive deformation history which is typical for shear zones. Stretching lineations are absent, and the structure in the area can be fully explained by dominantly coaxial E-W shortening during $D_2$. No structures interpretable as sense of shear markers were observed in the area.

## Windarra High-strain Zone

The Windarra Nickel-mine west of Laverton lies in the Windarra High-strain Zone. A relatively well-exposed section through this high-strain zone around the turnoff to Windarra from the Leonora—Laverton road was investigated in some detail (Fig. 5). Lithologically, the area consists of a major quartzite horizon in the west, and alternating lenses of ultramafic rocks, metabasalt and felsic volcanics to the east of the quartzite (Fig. 5). The quartzite horizon contains lensoid bodies of polymict conglomerate. A major unexposed granite pluton lies to the west of the quartzite ridge.

### Structure

In felsic volcanics and metabasalt, a strong subvertical NW-SE trending foliation is present. In metabasalt, this foliation is defined by a preferred orientation of amphiboles, in felsic volcanics by flattened aggregates of quartz and feldspar. A strong stretching lineation is present in all units, plunging gently to the SE or E (Fig. 5). On horizontal outcrop surfaces and in thin section, asymmetric feldspar porphyroclasts (Passchier & Simpson, 1986) indicate a sinistral sense of

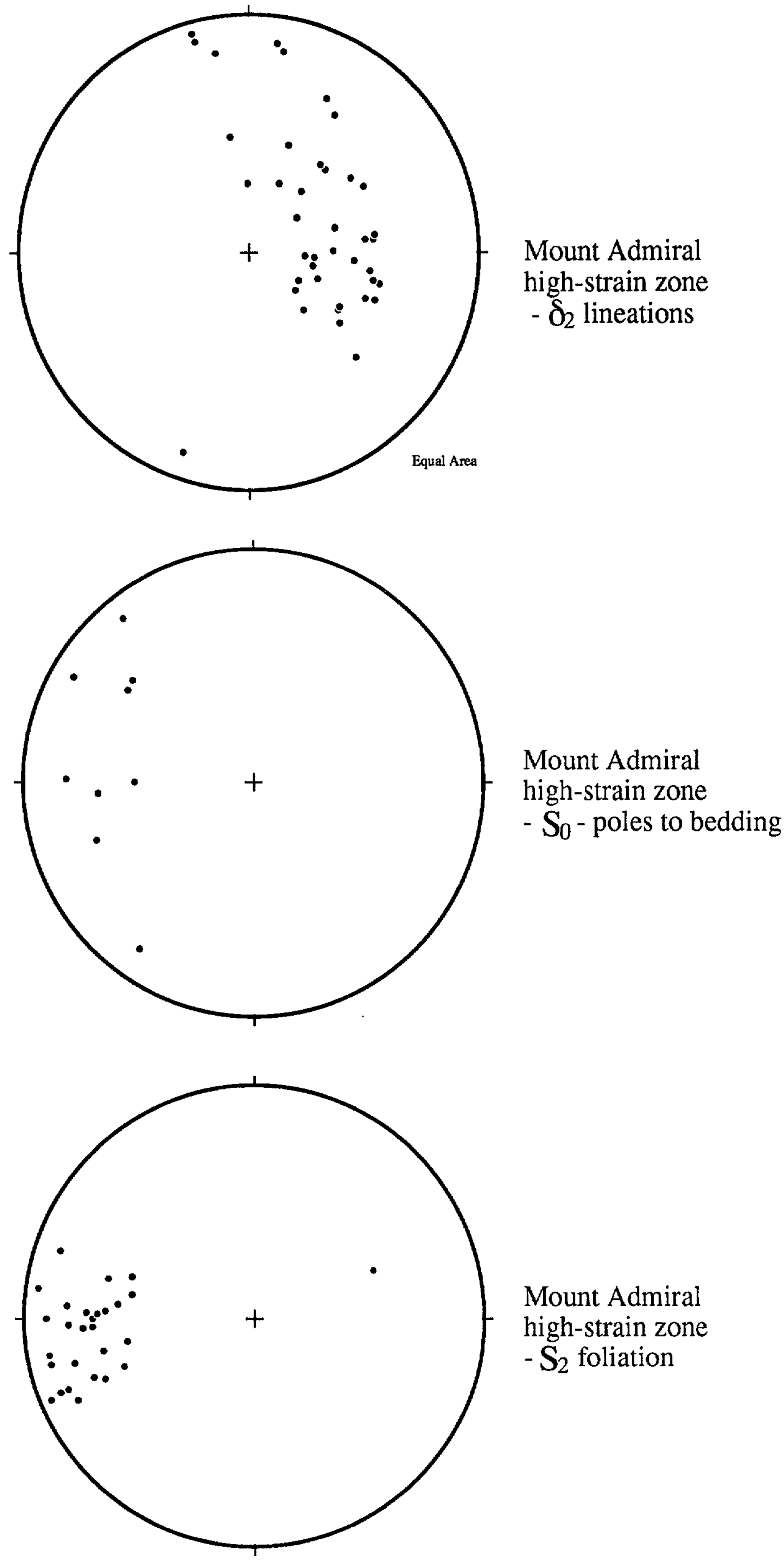


**Fig. 3. Orientation data of the deformation fabric in the Mt Admiral High-strain Zone.**

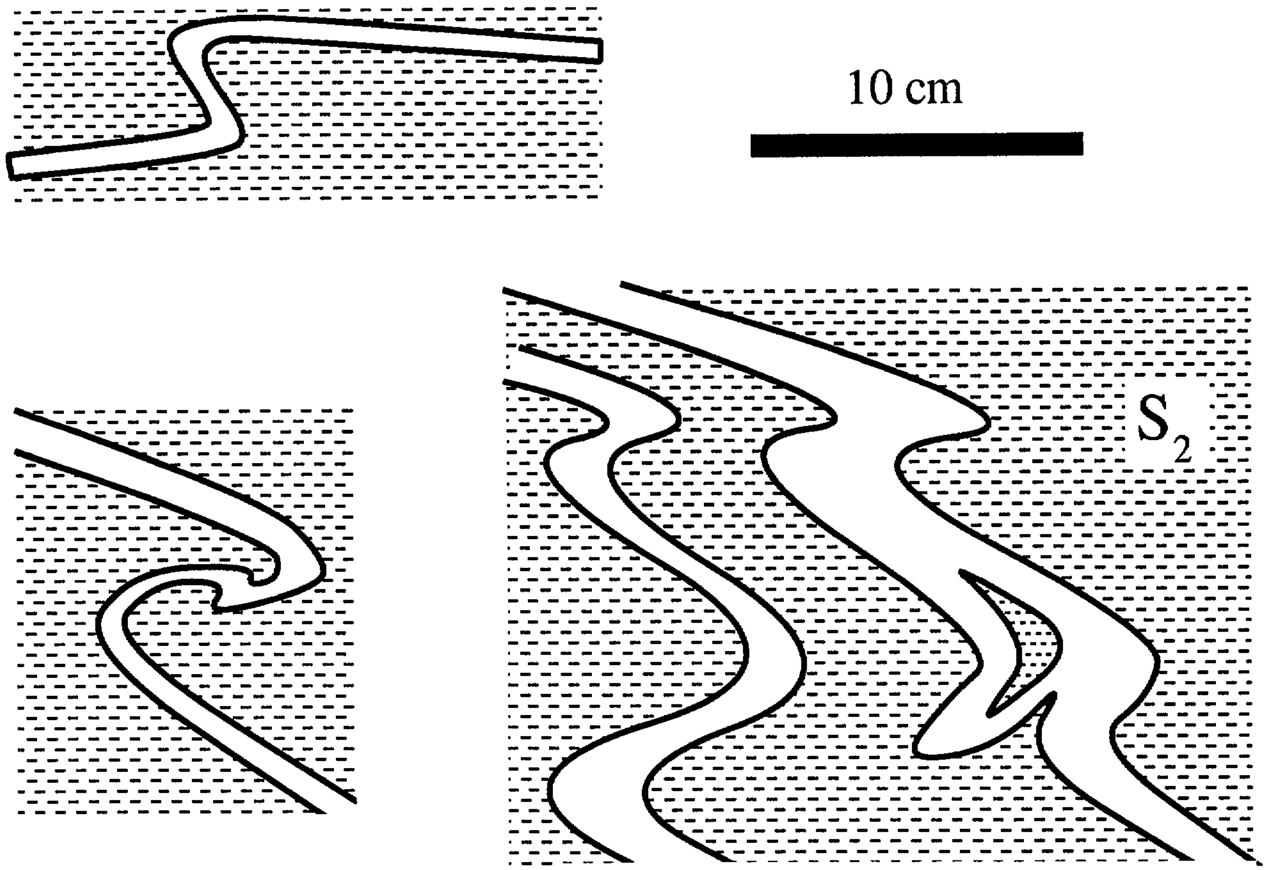


**Fig. 4. Sketches of minor folds in bedding in the Mt Admiral High-strain Zone. The fold geometry gives evidence for the presence of early folds, overprinted by the $D_2$ fabric. $S_2$ is indicated by horizontal striping.**

movement in the high-strain zone. Where bedding is present in the felsic volcanics, this is commonly isoclinally folded with the main foliation as axial planar foliation and with foldaxes parallel to the stretching lineation. In metabasalt, actinolite locally recrystallised postkinematically to undeformed needles which weaken the foliation and lineation in the rock. Locally, the foliation is affected by minor dm-scale chevron folding. The stretching lineation is also deformed by these folds. Axial planes of the chevron folds are subvertical and N-S trending. Foldaxes of chevron folds are steep.

Bedding in the quartzite horizon is tightly to isoclinally folded, and transected by a strong slaty cleavage. The vergence of bedding and cleavage indicates an antiform to the east (Fig. 5). In the northwestern part of the quartzite horizon, the quartzite is offset by spectacular minor sinistral shear zones, parallel to the trend of the main foliation in the surrounding slates (Fig. 5). The stretching lineation is particularly strongly developed in these minor shear zones. Pebbles in the conglomerate are deformed to a prolate shape and oriented parallel to the stretching lineation in the surrounding fine-grained rocks. The occurrence of these minor shear zones confirms the sinistral shear sense in this high-strain zone.

# Conclusions

The Mt. Admiral High-strain Zone is not a shear zone. It contains evidence of a first phase of deformation ($D_1$), overprinted by a main phase of coaxial E-W shortening ($D_2$). Minor refolding of the main foliation has been locally observed. The Windarra High-strain Zone is a major transcurrent shear zone with sinistral sense of shear and a significant component of WNW directed thrusting. The main foliation in the shear zone is affected by late folding indicative of E-W shortening.

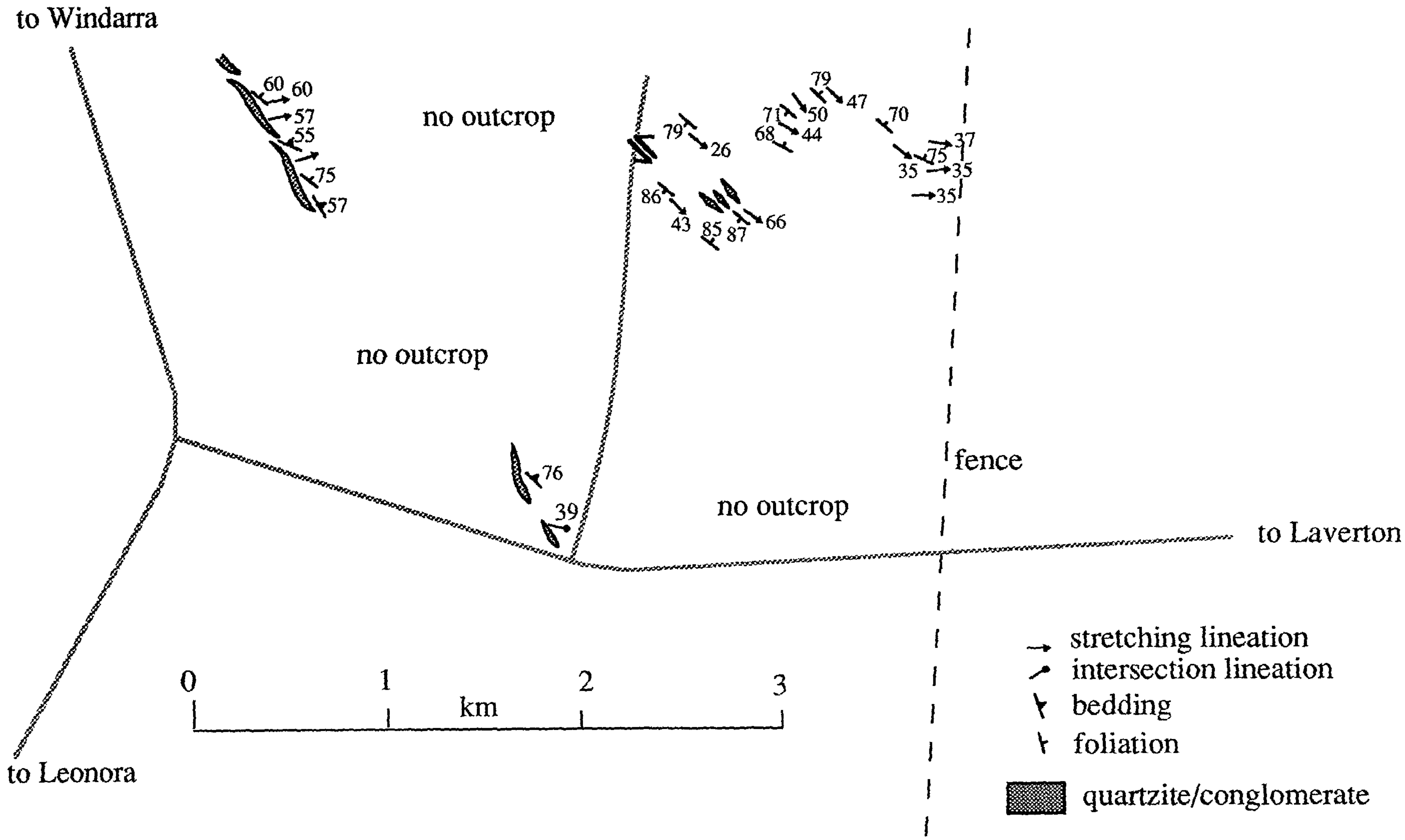


Fig. 5. Structural map of the area around the Windarra turn off, Laverton. Details of lithology have been omitted.

Interpretation of the relationship of high-strain zones at Laverton is hampered by lack of outcrop. The most likely interpretation of the local structure is that of dominant $D_2$ deformation in both high-strain zones. The absence of $D_1$ structures and the non-coaxial nature of progressive deformation in the Windarra Zone, compared with coaxial progressive deformation at Mt Admiral, can be explained by the presence of a major pluton west of the Windarra Zone. In an overall E-W $D_2$-shortening field the presence of a granite pluton may have caused local intense, non-coaxial progressive deformation at the granite margin leading to destruction of $D_1$ structures, and coaxial deformation further east. Late folding in the high strain zones near Laverton may be a later ($D_3$) phase of E-W shortening similar to that in the Norseman—Wiluna Belt (Passchier, 1990; Swager & Griffin, 1990).

# Part 2 — Leonora area

## Keith—Kilkenny High-strain Zone

The Keith—Kilkenny High-strain Zone of Hallberg (1985) (KKHZ; Fig. 1) is a zone of deformed rocks up to 20 km wide which trends NW-SE along the length of the Norseman—Wiluna Belt (Fig. 1). In the Leonora area, the KKHZ lies east of Leonora in a domain dominated by felsic volcanics, slates, metabasalts and minor quartzite and BIF layers (Fig. 6). West of Mt Malcolm in the KKHZ, rhyolitic rocks are dominant (Fig. 6) while around Mt Malcolm, calc-alkaline felsic volcanics dominate (Hallberg & Giles, 1986). Rhyolitic rocks of this type, usually LILE-enriched, are restricted in occurrence to the KKHZ (Hallberg & Giles, 1986). The KKHZ separates domains of distinctly different lithostratigraphic associations, as outlined in the introduction (Hallberg, 1985). Quartzite and BIF horizons allow recognition of bedding, and provide useful outcrop to unravel the local high-strain history.

## Structure

### $D_1$

Within the KKHZ, at least two phases of penetrative ductile deformation can be recognised. A fabric belonging to the second phase of deformation is dominant in most of the KKHZ (Fig. 12)(Passchier, 1990). However, strain intensity varies over the KKHZ and some low strain areas allow recognition of fabric elements which belong to a first phase of deformation in the zone. The most notable is a zone of gently well-bedded N-dipping quartzite lenses, up to 10 m wide west of Mt Malcolm (Fig. 7, 8). In this area, quartzite beds are folded by two separate fold sets that can be distinguished by style and orientation. A first set of folds ($D_1$ folds) is isoclinal and similar, and occurs usually as intrafolial folds in quartzite, with an axial plane parallel to bedding (Fig. 8). The orientation of fold axes is strongly variable, and the folds are probably non-cylindrical. In quartzite the folds lack an axial planar cleavage but in slate adjacent to the quartzite beds, a slaty cleavage ($S_1$) is developed parallel to bedding in the quartzite (Fig. 9). $D_1$ folds in quartzite layering are refolded by open, chevron type upright folds ($D_2$ folds) which commonly have a weak axial planar cleavage ($S_2$ – Fig. 9). The folds are roughly cylindrical in outcrop. $S_2$ can be traced into adjacent slates, where it can be seen to overprint $S_1$ as a crenulation cleavage. The $D_1$ fabric is also preserved in felsic volcanics near Lookout Hill and in an outcrop south of the railway (Fig. 7).

#### Quartz fringes

In one of the quartzite layers in the Mt Malcolm area, framboidal pyrite spheres are mantled by asymmetric fibrous quartz pressure fringes (Fig. 11; Williams et al, 1989). In this locality, bedding and $S_1$ are gently N-dipping, and a well developed stretching lineation is present on the bedding planes. The quartz fringes are rod-shaped and lie parallel to this lineation. Internally, the fringes have

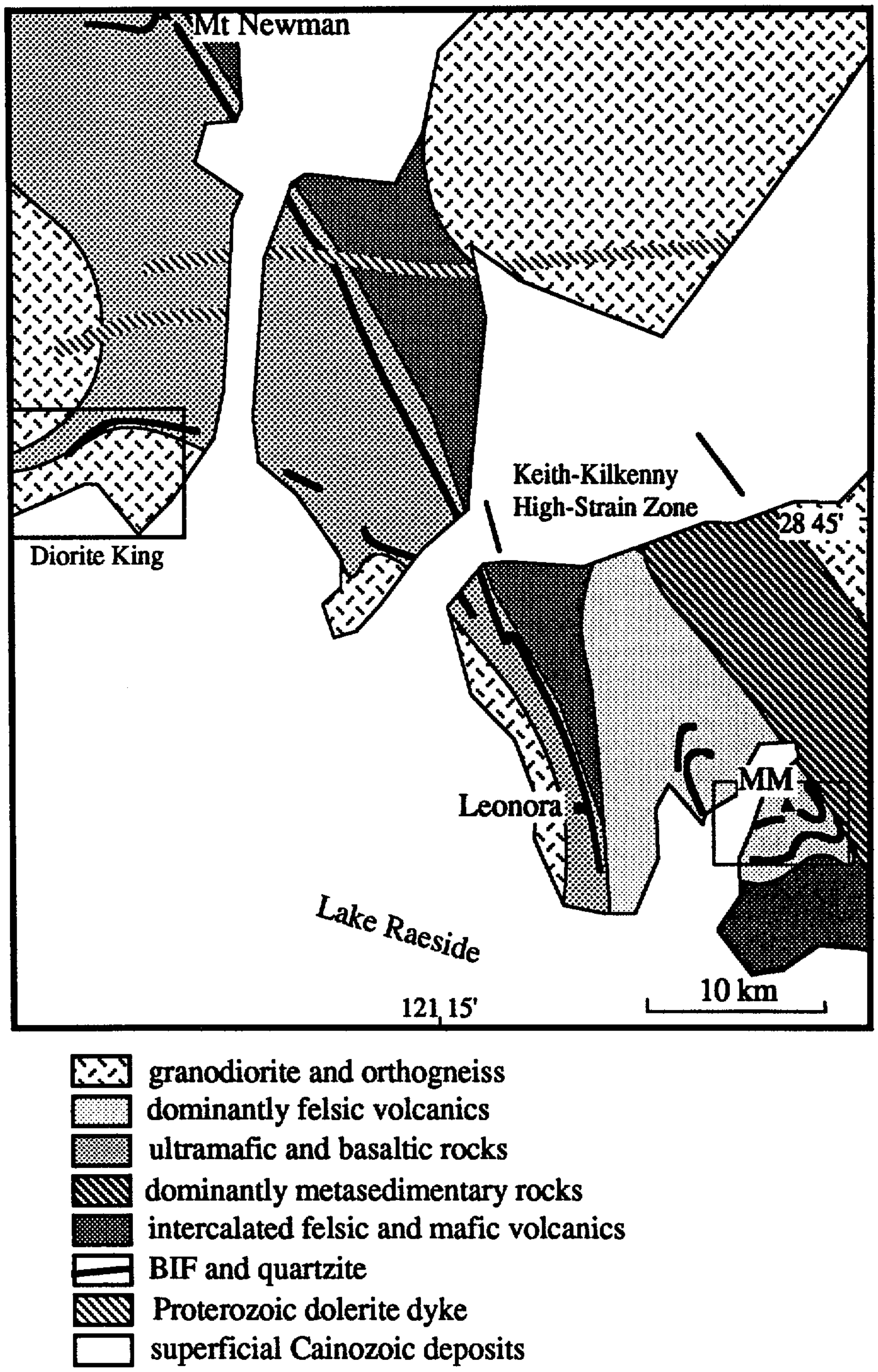


**Fig. 6. Simplified map of the geology around Leonora, after Williams et al (1989). Mt Malcolm (MM) and Diorite King areas are indicated.**

a monoclinic shape symmetry with the symmetry axis normal to the lineation and in the plane of the bedding. Comparison of the shape of these fringes with those described and modelled by Etchecopar & Malavieille (1987) indicates that they developed during non-coaxial progressive deformation in the quartzite with the upper block moving towards the north (Williams et al, 1989). Fig. 11 shows a tentative reconstruction of the development of the quartz fringes after the model by Etchecopar & Malavieille (1987).

## $D_2$

Most of the KKHZ is characterised by the presence of a well developed, steeply NE-dipping main $S_2$ foliation ($S_2$; Fig. 9) and a gently N-plunging stretching lineation ($L_2$; Fig. 7, 10). These structures are

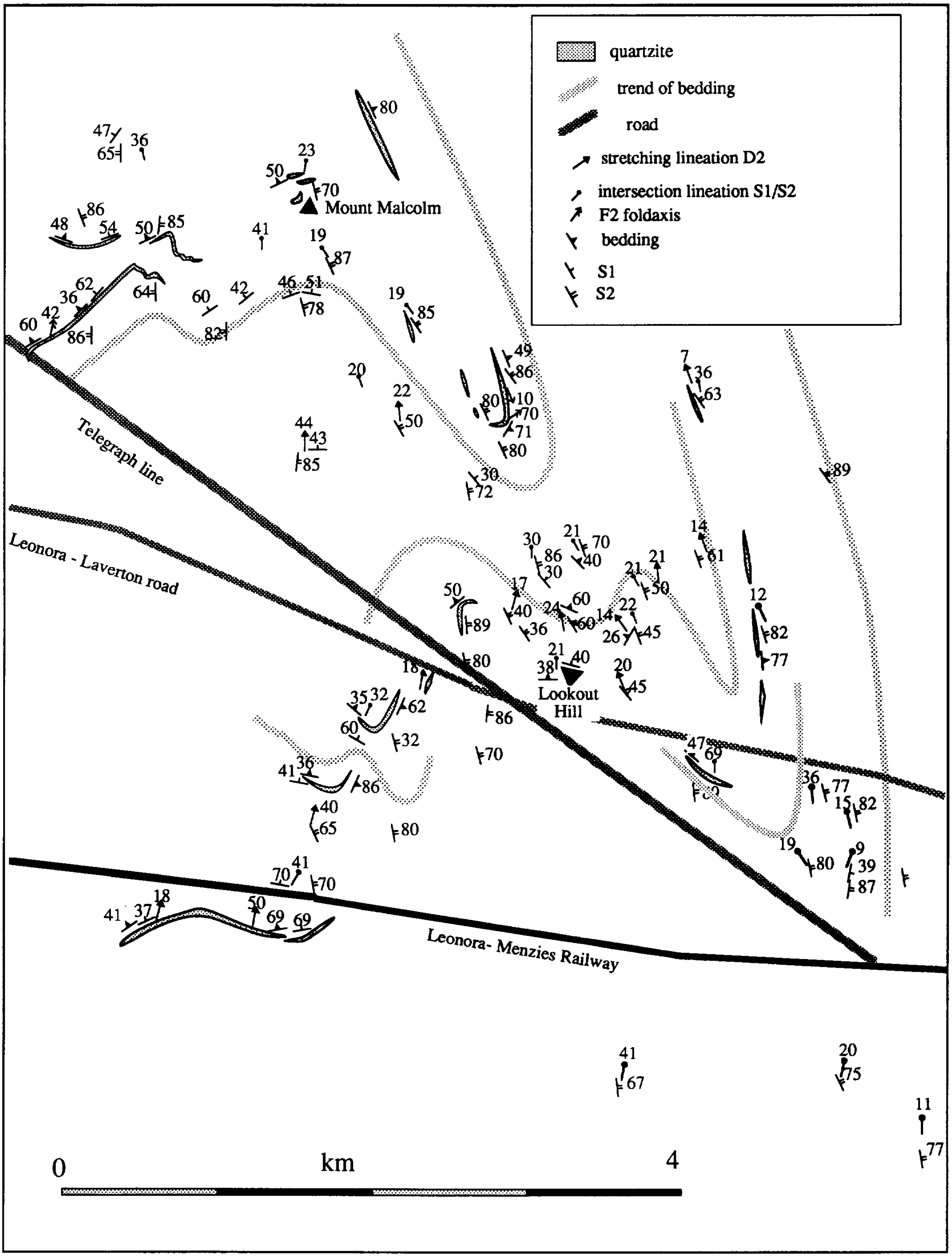


**Fig. 7. Structural map of the Mt Malcolm area. Grey bands indicate local trend of bedding.**

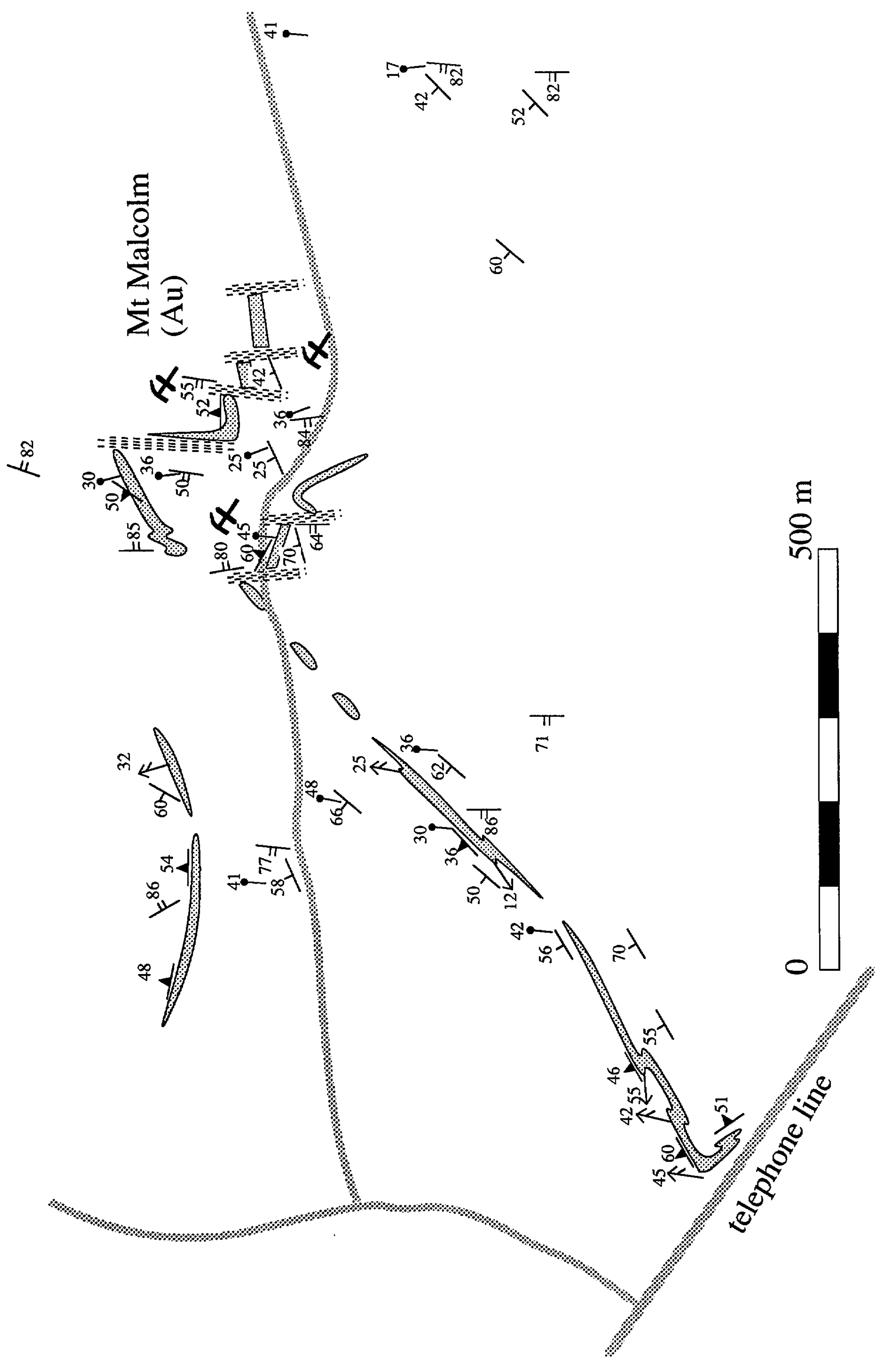


Fig. 8. Structural detailed map of the area around the Mt Malcolm mine site, in the NW corner of Fig. 7. Ornamentation as in Fig. 7. Striped zones near the mine are dextral $D_2$-shear zones.

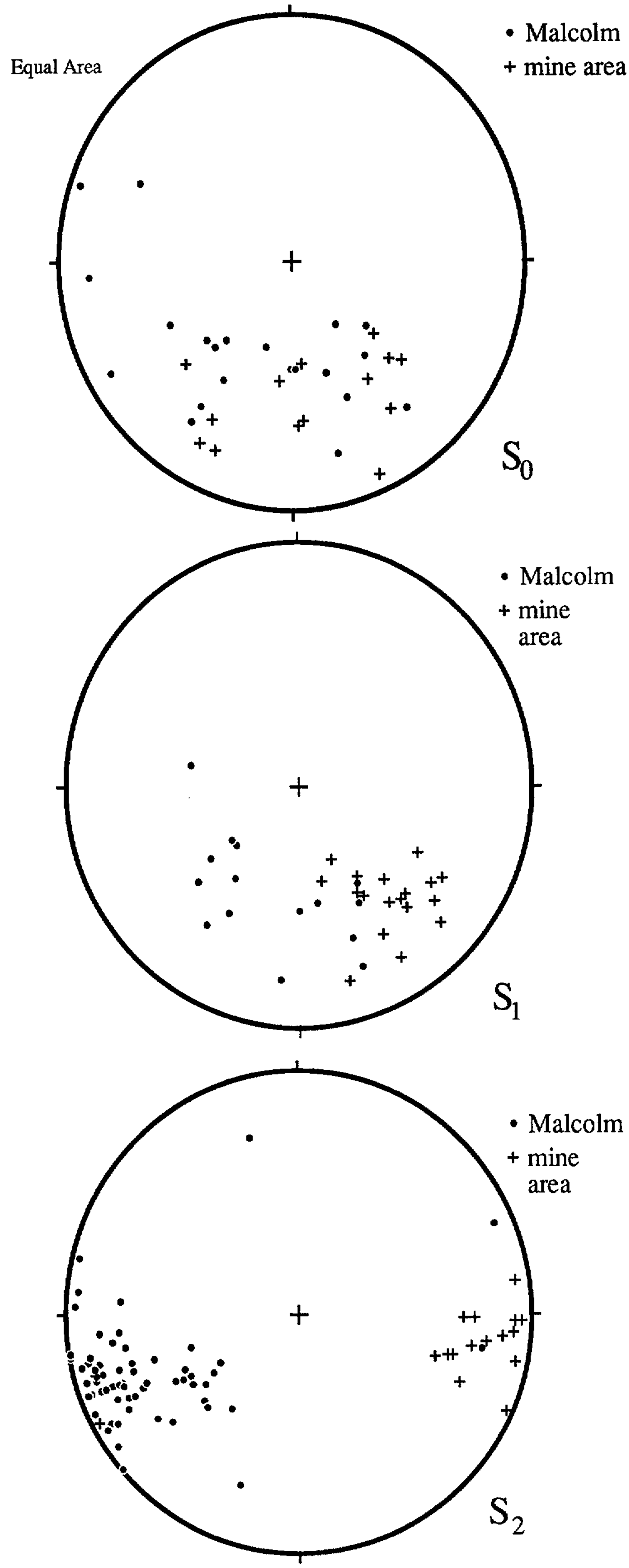


**Fig. 9. Orientation data of bedding and foliation elements in the Mt Malcolm area of the Keith—Kilkenny High-strain Zone.**

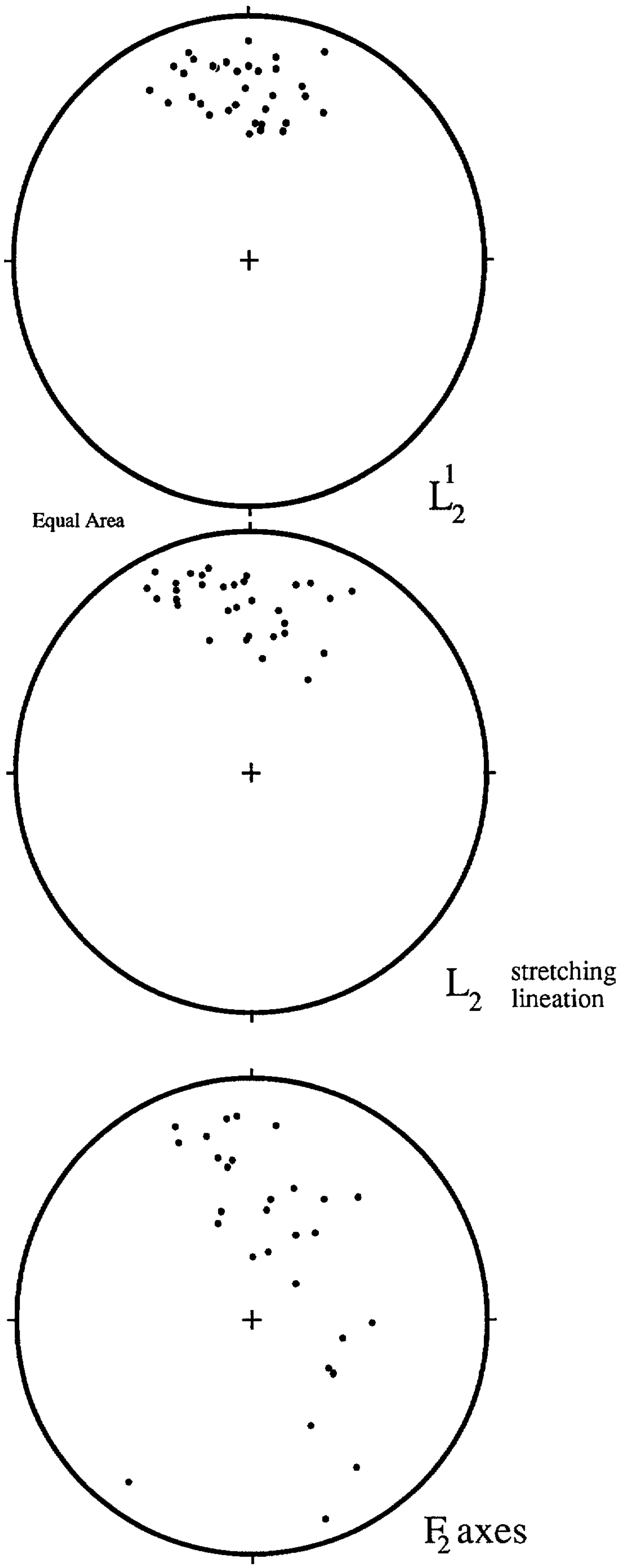


**Fig. 10. Orientation data of lineations and fold axes in the Mt Malcolm area of the Keith—Kilkenny High-strain Zone.**

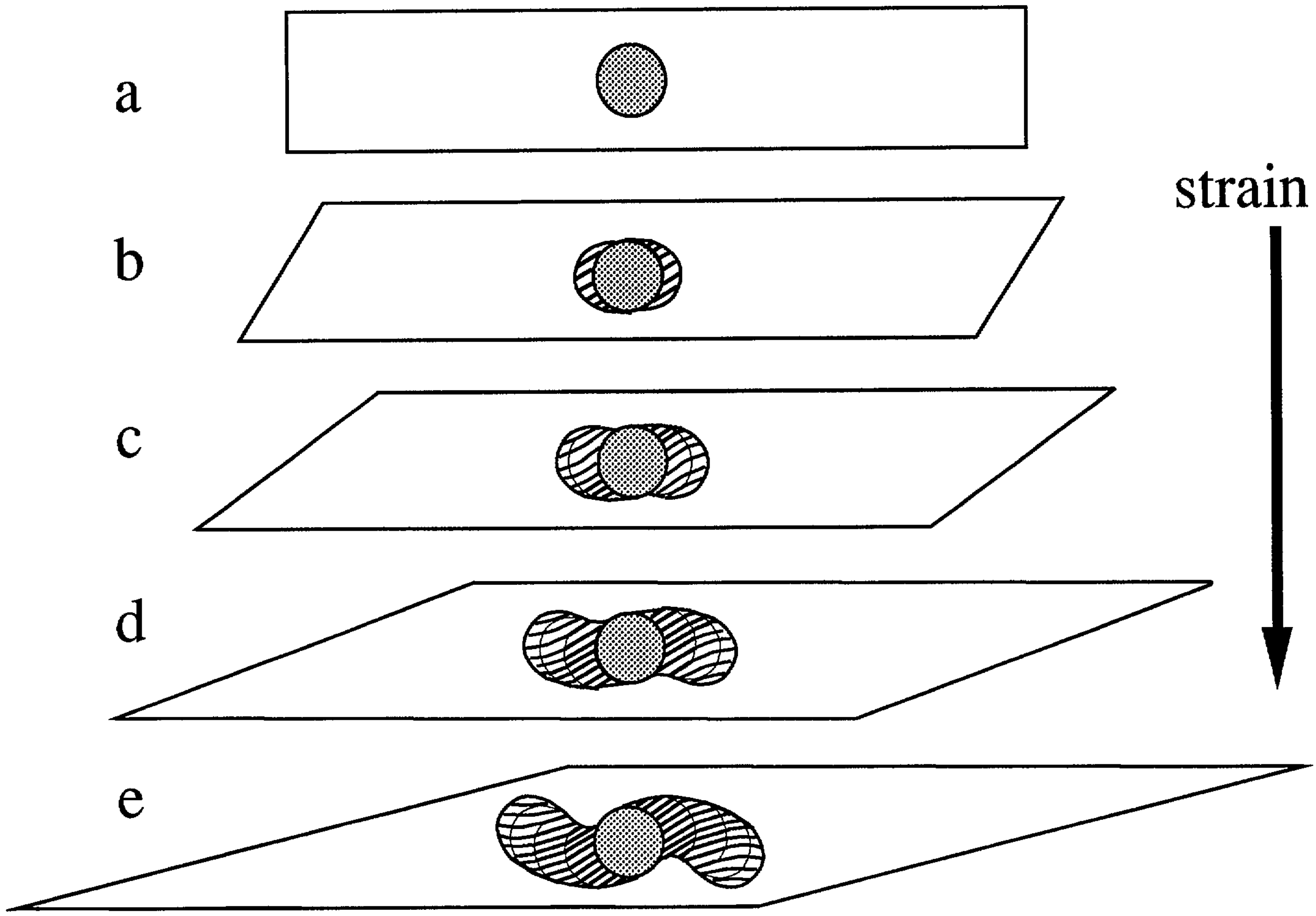


**Fig. 11. Schematic representation of the development of pressure fringes around spherical pyrite framboids as observed in the Mt Malcolm area. Quartz fibres develop in the direction of the instantaneous extension axes of the flow (b) but are rotated away from the pyrite framboid with progressive non-coaxial deformation (c-e) while new fibre segments are formed adjacent to the pyrite. Deformed square indicates deformation in the matrix. Sense of shear is dextral.**

developed in all lithologic units; in slates, $S_2$ is developed as a slaty cleavage; in felsic volcanics as a planar shape fabric. Associated with $S_2$ are tight to isoclinal folds in bedding, to which $S_2$ is axial planar. Bedding lies usually at a small angle to $S_2$ in limbs of major $D_2$-folds. In quartzite and BIF, $S_2$ shows a marked refraction in such fold limbs. The intensity of $D_2$ folding and $S_2$ is highly variable over the area. In areas of high $D_2$ strain, $D_1$ structures are almost completely erased; only $S_2$ is present in slates, and $D_2$ folds in bedding are tight to isoclinal. In such zones of high $D_2$ strain a strong lineation is usually present. In coarse-grained felsic volcanics with large feldspar phenocrysts (up to 5mm in diameter) the $L_2$ stretching lineation is defined by rod-shaped aggregates of recrystallised feldspar. Such a stretching lineation can also be seen in some of the more strongly deformed quartzite beds. $L_2$ is gently N-plunging with an identical orientation as the intersection lineation $L_{1/2}$ of $S_1$ and $S_2$ (Fig. 10). Because of this coincidence, outcrops in the KKHZ were carefully investigated to see if the shape lineation could be some deviant type of $S_1$-$S_2$ intersection structure. However, several outcrops have been found in which two lineations are present; a stretching lineation, and an intersection lineation. Apparently, $L_{1/2}$ coincides with $L_2$ at high $D_2$ strain values. In areas where $D_2$ deformation is strong, several fabric elements indicate that deformation in the high-strain zone was non-coaxial with a dextral sense of shear. This implies, that the KKHZ is a dextral transcurrent shear zone with a thrust component towards the south. The following evidence was found for dextral shear sense;

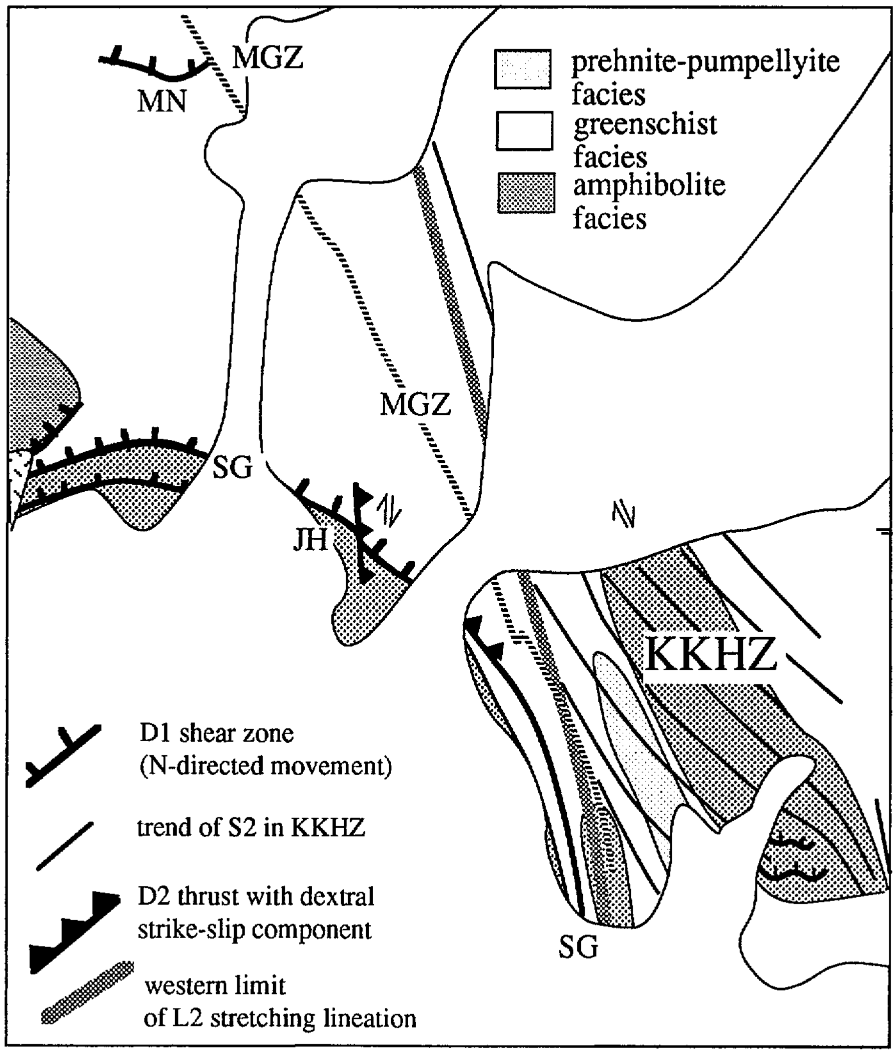


**Fig. 12. Interpretation of the main deformation structures in the Leonora area. SG — Sons of Gwalia High-strain Zone; MGZ — Mt George Zone; MN — Mt Newman; JH — Jasper Hills. KKHZ — Keith—Kilkenny High-strain Zone. $D_1$ structures are commonly found in domains of locally highest grade of metamorphism. $D_2$ structures are weakly developed except in the KKHZ, whose western boundary is taken to lie where $L_2$ stretching lineations disappear.**

- (1) asymmetric δ-type feldspar porphyroclasts (Passchier & Simpson, 1986) and asymmetric boudins in felsic metavolcanics, mainly in the western part of the KKHZ near Leonora (Passchier, 1990);
- (2) displacement of quartzite beds over zones of high $D_2$ strain in the Mt Malcolm area (Fig. 8);
- (3) a shear band cleavage in minor high strain zones in metabasalt; this type of foliation only develops where the metabasalt has been deformed to a strongly fissile mafic schist (Passchier, 1990);
- (4) variation in orientation of $S_2$ over the KKHZ (Fig. 12). Mapping in the KKHZ has shown that a relation exists between the orientation of $S_2$ and the strain intensity; in high strain areas, the foliation is E dipping; in low strain areas, it is NE dipping. This systematic difference in orientation can be explained as an effect of $S_2$ the high-strain cores of shear zones.

## $D_2$ outside the KKHZ

Outside the KKHZ, deformation intensity of $D_2$ gradually decreases. $S_2$ is only locally developed west of the KKHZ as a penetrative steeply NE or SW dipping slaty cleavage ($S_2$). The $L_2$ stretching lineation is absent outside the KKHZ except in minor, 10m scale dextral shear zones (Fig. 12). Such minor $D_2$ shear zones were found in mafic metavolcanic rocks in the Victoria Wells mine 10 km NW of Leonora, and in the Jasper Hills area (Fig. 6, 12)(Passchier, 1990). $D_2$ caused development of open to tight upright folds with subvertical to steeply NE dipping axial planes throughout the area. In the Mt Newman and Jasper Hills areas, open $F_2$ folds develop in $S_1$ (Fig. 12) (Passchier, 1990).

# Sons of Gwalia High-strain Zone

The Sons of Gwalia High-strain Zone is a zone of deformed rocks which follows the contact of the Raeside granite west of Leonora (Williams et al, 1989; Passchier, 1990). Some of the major gold mines in the area (Sons of Gwalia, Harbour Lights, Trump, Diorite King) are situated on this high-strain zone. The structure in the zone is complex; an early phase of extension with relative uplift of the granite with respect to the greenstones was followed by $D_2$ overprint, which produced dextral shear zones with a thrust component to the south, and refolding of the early structures outside the shear zones (Passchier, 1990). The $D_2$ overprint seems to increase in importance towards the east. In order to study part of the high-strain zone where the influence of $D_2$ is less, a small area near Diorite King gold mine (Fig. 1) has been mapped.

## Diorite King area

The diorite King area discussed here lies to the south of the Old Agnew Road, 35 km NW of Leonora, on the northern edge of the Raeside granite body (Fig. 6). It is named after the abandoned Diorite King gold mine. A prominent feature of the area is the telephone repeater adjacent to the mine site.

Lithologically, the Diorite King area consists of metabasalts and minor talc-chlorite schists, BIF layers and slate between major granite plutons (Fig. 13). A horizon of BIF and slate follows the contact of the Raeside granite and may link up with a similar BIF horizon in the Jasper hills area to the east (Passchier, 1990). The BIF horizon is cut off by the Raeside granite in the west of the Diorite King area. Three types of granite occur in the area; the Raeside granite; a deformed monzogranite in the north; and a minor body of undeformed leucogranite in the west (Fig. 13).

## Structure

### Southern shear zone

Development of a weak foliation in metabasalts was followed by intrusion of the Raeside granite. This again was followed by development of an extensional shear zone along the contact, deforming all lithologic units (Fig. 13). In this shear zone, a gently dipping foliation and N- or NW plunging stretching lineation developed (Fig. 14). The intensity of fabric development does not vary much over the Raeside granite, but decreases rapidly north of the contact with the metabasites. An oblique shape fabric in deformed quartz veins in the Raeside granite, and en-echelon sets of quartz-filled tension gashes indicate that the southern shear zone is a zone of normal movement, top block being displaced towards the north. Locally, N-S trending granite veins were activated as dextral transcurrent deformation zones, probably during the main movement. Bedding in BIF is folded isoclinally in association with the shear zone fabric.

The main shear zone is cut in the contact zone of the granite by undeformed biotite-porphyry veins. These veins are found in the greenstones and in the Raeside granite up to 20 m away from the contact, but not in the more internal parts of the granite. Some offshoots of these veins are parallel to the main foliation, but most veins are oblique. On the west side of the area near the major undeformed granite body, undeformed leucogranite veins crosscut the main foliation.

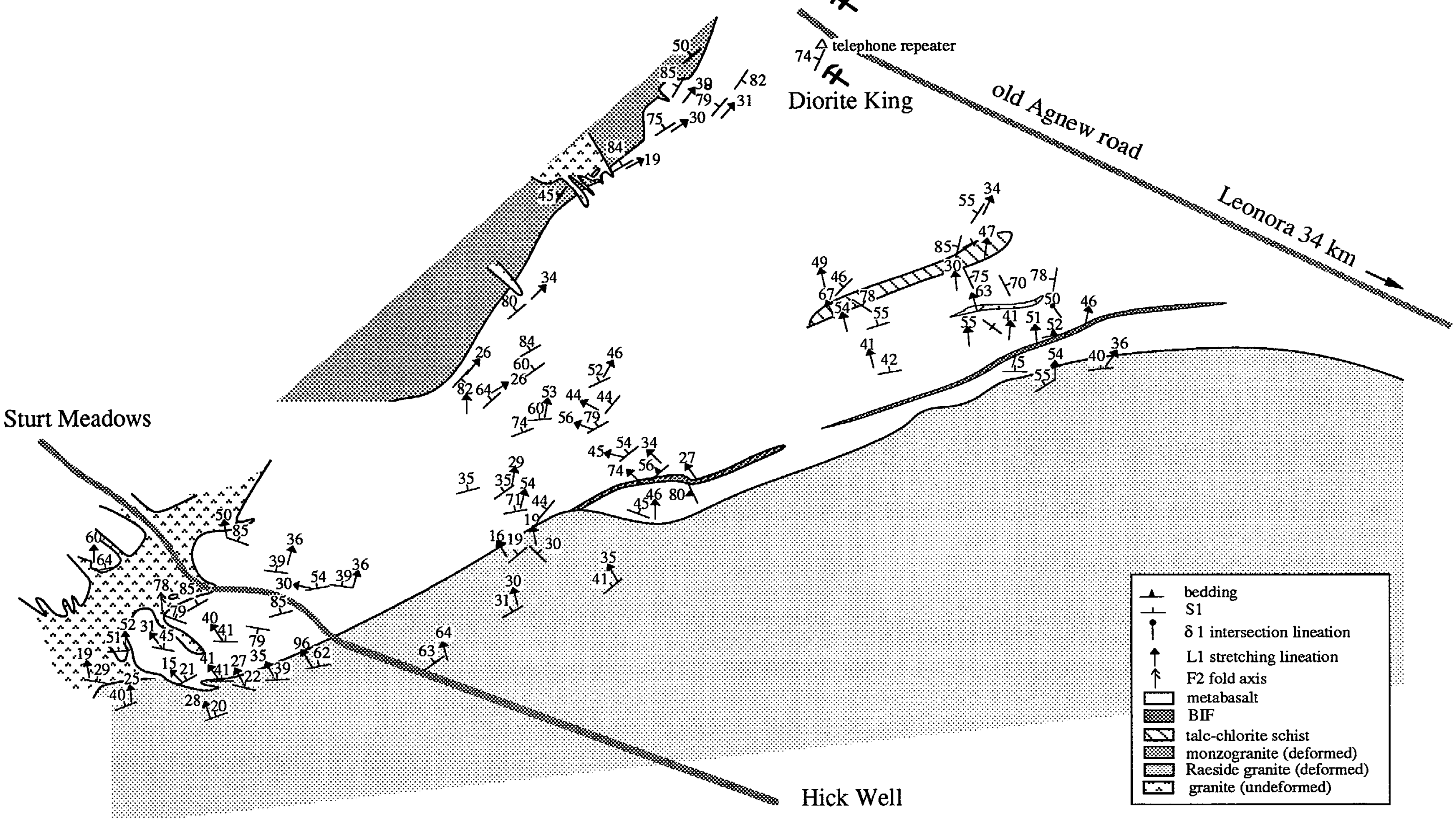


**Fig. 13. Geological map of the Diorite King area.**

## Northern shear zone

In the northern structural domain, a strong $S_1$ foliation is developed in both the monzogranite and amphibolite in anastomosing shear zones (Fig. 13). The foliation is steeply NW dipping and a stretching lineation is gently NE plunging (Fig. 14). Sense of shear is clearly dextral with a significant component of NE-directed normal movement. This is indicated by extensional crenulation cleavage and asymmetric feldspar aggregates in monzogranite, and by deflection of quartz veins and the main foliation due to strain gradients in the metabasites. The deformation fabric is best developed along the contact of the monzogranite with the metabasites, and decreases in strength to the south.

Numerous N-S trending vertical veins of undeformed leucogranite cut the deformation fabric along the length of the contact zone. In the deformed monzogranite, these veins are locally transected by minor ductile shear zones, up to 2 cm wide and several tens of metres in length. These shear zones are subparallel to the main fabric in the monzogranite and apparently have dextral sense of shear. Since these late shear zones have only been observed on a pavement outcrop, the dip-slip component is unknown.

Throughout the Diorite King area in all lithologic units, the main foliation is affected by open folding with steep N-S trending axial planes. In BIF, isoclinal $D_1$ folds are overprinted by $F_2$ open folding. No $S_2$ foliation is developed in any of the lithologies in the Diorite King area; in slates a pencil cleavage is locally developed due to interference of $S_1$ and $D_2$ folding. The relative age of $D_2$ to intrusion of the undeformed granite veins in the area is unknown; the small amount of strain responsible for the folding would not be easily recognised in the coarse grained granite. Comparison with the deformation pattern in other parts of the Leonora area suggests, that the open folds are part of the regional $D_2$ phase which is also responsible for dextral movement in the KKHZ (Passchier, 1990). Throughout the Leonora area, the intensity of $D_2$ deformation seems to decrease towards the west; $L_2$ stretching lineations and $S_2$ disappear towards the west, and $D_2$ folding becomes gradually more open in that direction.

## Relation of the northern and southern shear zones

In the eastern, wider part of the metabasite wedge in the Diorite king area (Fig. 13), a zone of weakly foliated and non-lineated metabasite exists between the southern and the northern shear zones. In the west, there seems to be a gradual transition between both shear zones, but unfortunately the fabric is obscured here by postkinematic recrystallisation of amphibolite due to intrusion of the undeformed granite. It is likely that both shear zones were active at the same time, and that the difference in orientation of fabric elements is simply due to a different orientation of granite-metabasite contacts in the north and south at the onset of deformation; the shortening fields of both shear zones show an overlap, indicating that they may have been active contemporaneously. Both shear zones definitely predate intrusion of the undeformed western granite. The minor shear zones which affect undeformed granite veins in the northern shear zone may represent a more low grade phase of minor deformation after considerable uplift of the whole assemblage.

The general impression of the Diorite King area is, that a first weak phase of deformation in metabasites was followed by intrusion of the granite and monzogranite plutons. This was followed by (or partly contemporaneous with) a major phase ($D_1$) of N-S or NE-SW directed extension. The $D_1$ fabric is transected by a small granite pluton in the west and by leucogranite and porphyry veins along the major shear zones. Minor E-W $D_2$ constriction affects the $D_1$ fabric, but the age relation with undeformed granite veins is not clear.

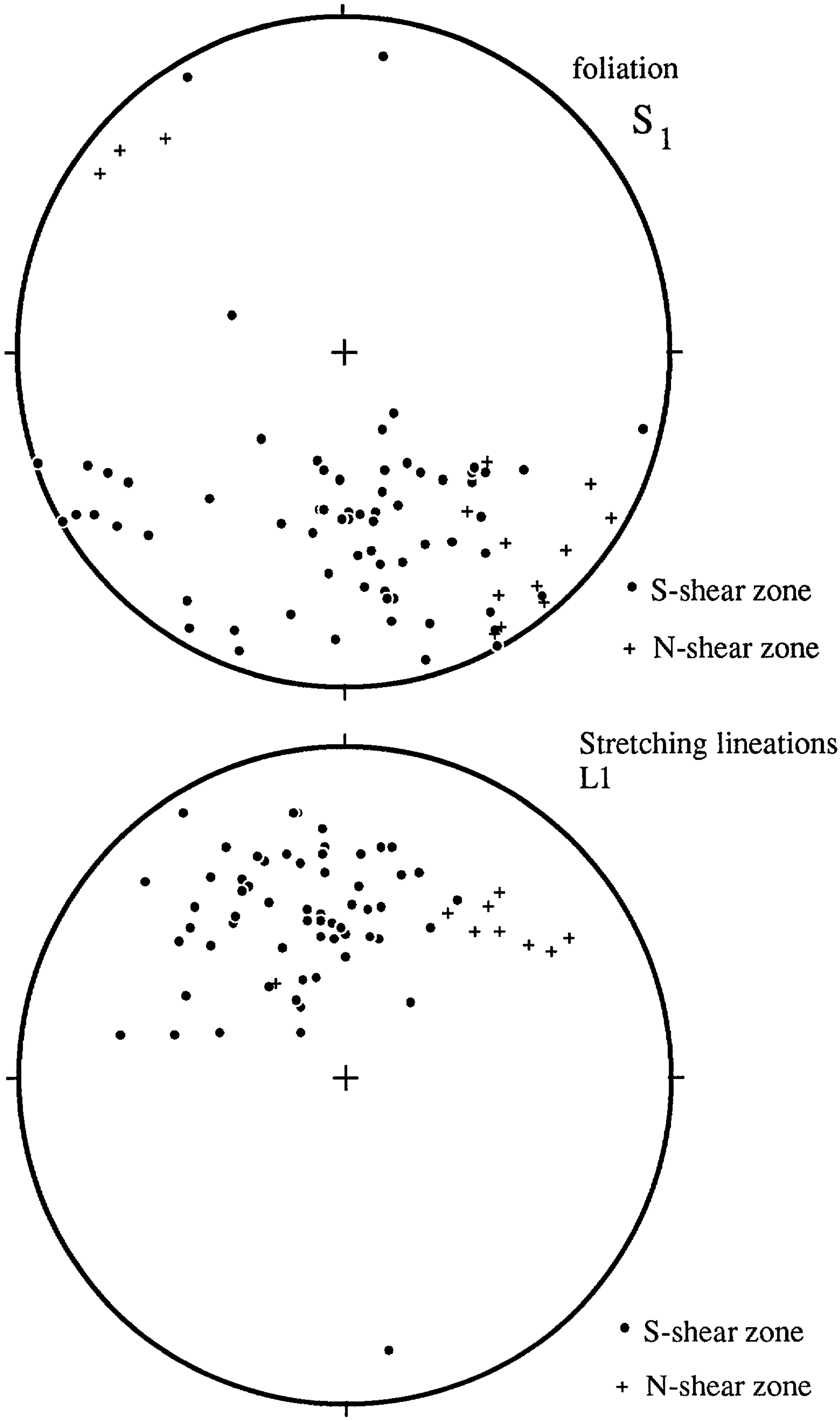


**Fig. 14. Orientation data for the Diorite King area, separated for the northern and southern shear zone domains.**

# Discussion

## $D_1$ structures

$D_1$ structures similar to those described from the Mt Malcolm and Diorite King areas have also been observed elsewhere in the Leonora area. A gently dipping mica foliation or planar shape fabric associated with a stretching lineation or mineral lineation commonly predates $D_2$ fabric elements. $D_1$ structures have so far been recognised around Mt Newman, and along the northern and eastern contact of the Raeside granite (Fig. 6, 12)(Williams et al, 1989; Passchier, 1990).

In the Mt Newman area (Fig. 12), a foliation predating $D_2$. folding is present in slates without an associated stretching lineation (Fig. 12; Passchier, 1990). This foliation is gently N-dipping here, while bedding dips more steeply to the north. In the Jasper Hills area of the Sons of Gwalia High-strain Zone (Fig. 12), a gently N-dipping planar $D_1$ shape fabric with a NE-plunging stretching lineation is well developed at the contact of granite and mafic volcanics and in BIF layers (Passchier, 1990). As in the Diorite King area, undeformed porphyry veins cut the early fabric in the Jasper Hills area. The gently dipping planar fabric is deflected by steeply E-dipping $D_2$ dextral reverse shear zones with a N or NW plunging stretching lineation. The $D_1$ fabric is similar to that in the Diorite King area, but $D_2$ overprint is stronger in the Jasper Hills area. Analysis of quartz fabrics from the BIF horizons in the Jasper Hills area was reported to indicate $D_1$ thrusting towards the south (Williams et al, 1989). However, resampling and analyses of more quartz fabrics has shown, that the $D_1$ fabric formed by north-directed normal movement, and that thrusting towards the south is only indicated by fabrics which have a strong $D_2$ overprint (Passchier, in prep). The south-directed thrusting reported by Williams et al (1989) is therefore probably a $D_2$ effect (Passchier, 1990; in prep).

In the eastern contact zone of the Raeside pluton in the Harbour Lights and Sons of Gwalia gold mines, foliations dip steeply to the east, and stretching lineations are to the east or southeast respectively (Williams et al, 1989; Passchier, 1990). Sense of shear markers indicate normal movement to the east and southeast (Williams et al, 1989; Vearncombe et al, 1989). $D_2$ overprint may have altered the orientation of early structures considerably in this area (Passchier, 1990).

## Nature of $D_1$

One possible interpretation of $D_1$ structures would be as an early phase of the main deformation $D_2$. However, the common observation of N-directed movement of the upper block in $D_1$ shear zones implies, that it cannot have formed in the same kinematic frame as $D_2$ (Passchier, 1990). $S_1$ is inferred to have been gently dipping prior to the $D_2$ upright folding event, because extensive gently dipping and subhorizontal cleavage is present which is not consistent with refolding of an earlier upright or steeply dipping surface (Williams et al, 1989).

With the presently available incomplete data on the nature of $D_1$ fabric elements around Leonora, it is not possible to give a definite account of the significance of early deformation in the area. In the Mt Newman and Diorite King areas, the influence of $D_2$ seems to be restricted to open folding of the early foliation and lineations, and the transport directions may not have suffered much modification. In the Jasper Hills area and in the mines near Leonora, however, the influence of $D_2$ is clearly stronger: $D_2$ shear zones appear. In the Trump mine 5 km north of Leonora, sense of shear in some pits indicates SSW-directed subhorizontal thrusting, probably an effect of $D_2$ as well. Finally, in the Harbour Lights and Sons of Gwalia gold mines, the influence of $D_2$ is strong as attested by overprinting of the early mylonitic fabric by $D_2$ folds, and the present orientation of early fabric elements may have been modified by $D_2$. Thus, the steeply east-dipping geometry of the Raeside pluton may be be an effect of the major $D_2$ Keith-Kilkenny High-strain Zone, overprinting an originally gently dipping granite-greenstone contact (Fig. 12).

Skwarnecki (1987) suggested that the early shear zones are related to gneissic doming of the major granitoid plutons, but this seems uncertain in the light of present data. $D_1$ structures near Mt Newman and Mt Malcolm are not obviously related to granitoid plutons, and the well exposed structures in the Diorite King area show that the monzogranite north of Diorite King mine was descending instead of rising with respect to the greenstones. The gently dipping $D_1$ foliations are due to early regional low angle nappe-style tectonics, not necessarily related to granitoid emplacement.

The areas least affected by $D_2$ overprint in the Mt Malcolm, Mt Newman and Diorite King areas give dominant northward directed movement of the hanging wall (BMR 1990). In the present orientation of the shear zones, this implies normal (extensional) movement. Not all $D_1$structures need have been E-W trending, however; originally N-S trending structures would be difficult to recognise and could be preferably overprinted by $D_2$ shear zones. The existence of such structures is suggested by the observation in the mines in the eastern side of the Raeside pluton, and by a west-dipping shear zone with west-directed normal movement near Tarmoola, between Jasper Hills and Diorite King in an area of low $D_2$ strain. Obviously, 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 might even have originated as thrusts. However, observations in the northern Raeside pluton contact (Williams et al, 1989) and in a deep borehole near the eastern contact of the Raeside granite (BMR, 1990) suggest that an abnormally high geothermal gradient existed over early shear zones in this position. Although available outcrop does not allow a detailed analysis, the area where $D_1$ structures were found near Mt Malcolm (Fig. 4) lies in a domain of amphibolite grade assemblages, surrounded by greenschist and prehnite-pumpellyite facies domains. The local metamorphic gradients seem unusually steep, and could be explained as a result of crustal extension. Observations in the Mt Malcolm area suggest that early fabric elements are syn-peak metamorphic conditions; Williams et al (1989) report growth of andalusite porphyroblasts syn-$D_1$ and pre-$D_2$ at Mt Malcolm, and chloritoid porphyroblasts in outcrops near Mt Malcolm mine found during this study have the same relative age. In the Diorite King area, $D_1$ shear zones are transected by granite intrusion.

In conclusion, the presently available data suggest that $D_1$ was a phase of crustal extension. According to Hallberg & Giles (1986), the bimodal rhyolite-basalt associations in the KKHZ are due to increased rates of crustal extension and Barley et al, (1989) proposed a regional tectonic model with extension in the Norseman—Wiluna Belt. In fact, no $D_1$ fabrics have to date been found in the rhyolitic part of the KKHZ, only in the apparently underlying BIF horizons near Mt Malcolm. This could mean that the bimodal rhyolite-basalt association formed at the end of local $D_1$-extension.

## Nature of $D_2$

$D_2$ deformation is strongly partitioned over the Leonora area in terms of strain and vorticity. $D_2$ structures include both dextral reverse shear zones, and upright folding in domains between shear zones with fabrics indicative of coaxial progressive deformation. Shear zones and fabrics indicative of non-coaxial flow occur mainly in the KKHZ east of Leonora. In this domain, axial planes of $D_2$ folds are parallel to the shear zones. Since bedding planes which trend west and east of the symmetry axis of the shear zone are both extending (Passchier, 1990), $D_2$ is manifested by transpression here; $D_2$ deformation is mainly by dextral strike slip, but there is a considerable component of E-W shortening in the wall rock of shear zones, with vertical thickening of the sequence and probably also a N-S stretching component (Passchier, 1990). This N-S stretching component should not be confused with $D_1$ north-directed nappe transport, which is contemporaneous with the local peak of metamorphism and which is clearly overprinted by $D_2$ structures.

## Post-$D_2$ structures

Effects of post $D_2$ deformation have been observed locally throughout the Leonora area (Passchier, 1990), but they do not seem to have contributed much to the large-scale structure. Most common are locally developed shallowly N-dipping slaty cleavage planes which overprint a steep $S_2$. West of the Mt George quartzite (Fig. 12), brittle sinistral transcurrent faults occur (Williams et al, 1989).

# Conclusions

In the Leonora area, evidence exists of an older ($D_1$) phase of deformation, which led to development of gently dipping foliations and generally N or S-plunging stretching lineations. $D_1$ shear zones give evidence for dominant movement of the upper block to the north, apparently due to extension. $D_1$ shear zones with other movement directions may have been present but are difficult to recognise due to overprint by $D_2$. $D_2$ structures are strongly variable over the Leonora area, both in strain intensity and in fabric symmetry. The main structural feature in the area is a $D_2$ high-strain domain with dextral $D_2$ shear zones in the KKHZ east of Leonora. $D_2$ deformation outside the KKHZ is mainly by upright folding with evidence of coaxial progressive deformation. Post-$D_2$ deformation in the area includes local crenulation of earlier fabrics, and brittle faulting.

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