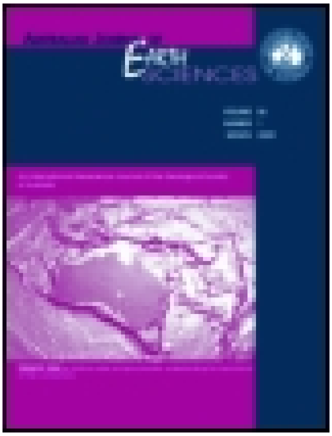

Australian Journal of Earth Sciences: An International Geoscience Journal of the Geological Society of Australia
Publication details, including instructions for authors and subscription information:
http://www.tandfonline.com/loi/taje20

The history of movement on the Henty Fault Zone, western Tasmania: An analysis of fault striations

R. F. Berry [a]
[a] Department of Geology , University of Tasmania , GPO Box 252C, Hobart, Tas., 7001, Australia
Published online: 01 Aug 2007.

Australian Journal of Earth Sciences (1989) **36**, 189–205

The history of movement on the Henty Fault Zone, western Tasmania: An analysis of fault striations

R. F. Berry

Department of Geology, University of Tasmania, GPO Box 252C, Hobart, Tas. 7001, Australia.

The Henty Fault Zone is a major west-dipping structure in the economically important Mount Read Volcanics of western Tasmania. It has been active from the Early Palaeozoic to the Tertiary. Detailed investigations of this fault history were carried out using numerical analysis of fault striations. Five generations of fault movement were recognized. The first generation of movement was east-directed thrusting, which pre-dates Devonian folding. This phase may correlate with Early Ordovician thrusting on the Great Lyell Fault. High angle reverse faulting took place after the Devonian folding and synchronous with granite intrusion. The last Devonian movement was a sinistral displacement of less than 5 km. The structure was reactivated as a sinistral wrench fault, possibly in the Mesozoic, and a normal fault in the Tertiary.

Key words: fault, fault striation, Henty Fault, Mount Read Volcanics, Palaeozoic, Tasmania.

INTRODUCTION

The Henty Fault Zone (Fig. 1) is a major structure within the Cambrian Mount Read Volcanics of western Tasmania. It divides the Central Volcanic Belt into a northwestern section overlain by the Dundas Group and a southeastern section overlain by the Tyndall Group (Corbett 1986a). The Henty Fault Zone is also the locus of Devonian vein deposits rich in Ag, Pb, Zn and Au (Bamford & Green 1986). Despite its regional and economic importance, past studies of this area have been limited to the geometry of the fault. The aim of this paper was to determine the history of movement by detailed investigation of the fault striations within and near the fault zone.

The geology of western Tasmania has been reviewed by Williams (1978), Corbett (1981), Solomon (1981), Cooper and Grindley (1982) and Collins and Williams (1986). Radiometric age constraints were discussed by Adams *et al* (1985). The following summary is derived from those papers except where indicated. All of western and central Tasmania is underlain by multiply deformed metamorphic rocks of Precambrian age. These are overlain by a Late Precambrian–Middle Cambrian continental shelf sequence. In the Middle Cambrian a mafic–ultramafic complex was thrust over most of western Tasmania (Berry & Crawford 1988). During the late Middle and Late Cambrian an extensional phase of tectonism produced the Dundas Trough and filled it with a mainly acid sequence of volcanic rocks and related sediments, including the Farrell Slates, Murchison Volcanics, Murchison Granite and Central Volcanics. At the end of the Cambrian, volcanism ceased and a fanglomerate sequence, the Owen Conglomerate, prograded from the east across part of the area before the onset of platform sedimentation in the Early Ordovician. Substantial faulting took place during deposition of the Owen Conglomerate, with at least 1 km displacement on the Great Lyell Fault (Fig. 2) by the earliest Ordovician (Arnold & Fitzgerald 1986). Strong folding and greenschist facies metamorphism of the Early Palaeozoic sedimentary sequence took place in the Devonian. Williams (1978) suggested the association of north-trending Devonian folds with westward transport direction on the Henty Fault Zone. Granite intrusions were widespread at the end of this orogeny. Since the Devonian, tectonic activity has been limited to minor faulting.

METHODS

Techniques for studying major fault zones have expanded rapidly in the past 15 years. Most of this development has been in the study of ductile shear zones (Ramsay 1980) but substantial development has also taken place in the study of brittle structures (Angelier 1984; Hancock

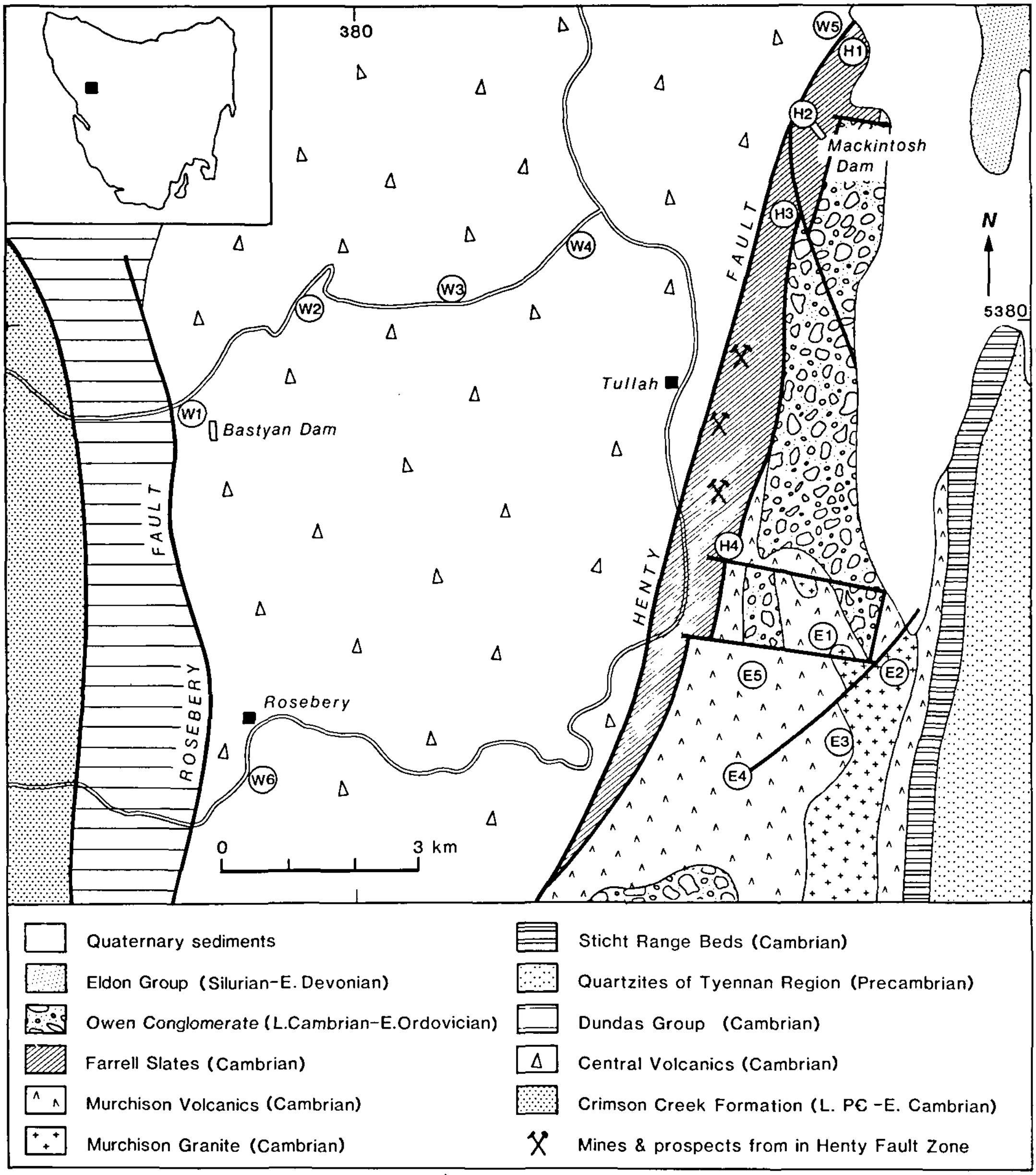

Fig. 1 Location map with geology modified from Corbett (1985). All sites used in numerical analysis are shown: W1–W6 are west of the Henty Fault, H1–H4 are within the fault zone, and sites E1–E5 are east of the Henty Fault. Faults shown as heavy lines, major roads as double lines.

1985). The present study is mainly concerned with brittle structures within the Henty Fault Zone. The most useful structures available are fault striations which are common in freshly exposed sections (i.e. road cuttings and dam sites).

Throughout this work, the criteria summarized by Petit *et al* (1983), and more recently by Petit (1987), were used to determine the sense of displacement on the fault planes. Fibre veins attached to the back of ledges represent the best criterion and were widely available for early

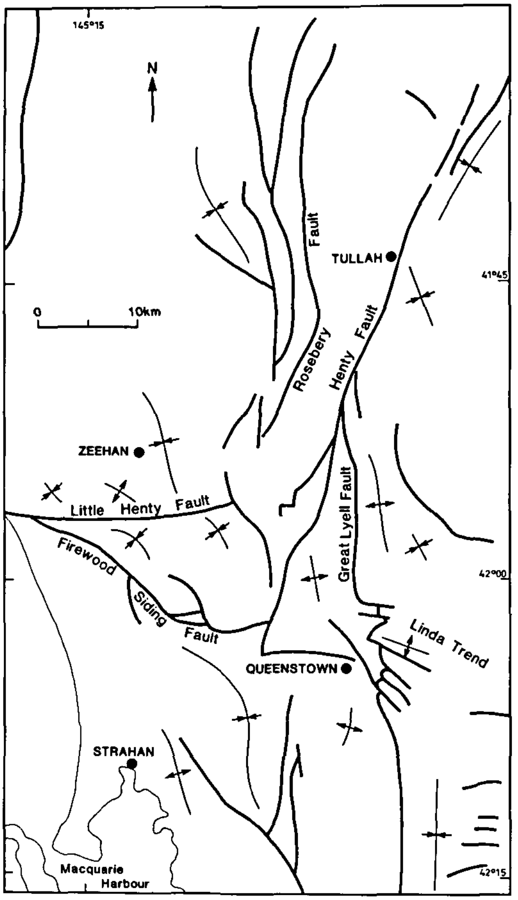

Fig. 2 Map of part of the west coast of Tasmania giving Devonian structural elements referred to in the text. Structures are from fig. 1 of Corbett and Lees (1987).

fault striations (Fig. 3a). The next most common criterion was normal drag of the associated cleavage (Fig. 3b). In several localities gouge was recognized in front of ledges, indicating that they faced the opposing block (Fig. 3c). Lunate fractures and striated Riedel fractures were found on a few striated fault planes (RM criterion of Petit 1987; Fig. 3d). For the last two generations of fault striations the most common displacement sense indicators were deepening grooves associated with asperities and the shadowing of grooves across undulating surfaces (Fig. 3e, f). These are not completely reliable where fault surfaces are imperfectly preserved, but provide a useful indication of sense of displacement. In practice the sense of displacement was directly determined for half of the fault striations, and was inferred from nearby faults of the same orientation and style for the remainder of the cases.

Overprinting relationships of fault striations were used to obtain the history of fault movement. The relative ages of striations were recognizable in three situations: (1) ridges or fibre veins on early polished fault surfaces truncated by grooves of a different orientation (Fig. 3g); (2) grooves on only one side of a broad ridge which parallels another striation, or alternatively fibre veins attached to one side of this ridge (Fig. 3h); and (3) fine grooves on a chloritic surface assumed to be late where chlorite was crystallized in quartz fibre veins parallel to striations on the same plane.

The method of Etchecopar *et al* (1981) was chosen to interpret the fault striations. This method places no restriction on fault plane orientation but assumes the movement on any surface will be parallel to the direction of maximum resolved shear stress on the plane. The direction of maximum resolved shear stress on any plane can be calculated from the directions of the principal compressive stresses (σ_1, σ_2, σ_3) and ratio R ($\sigma_2 - \sigma_3/\sigma_1 - \sigma_3$) which, because the principal stresses are orthogonal, involves only four independent parameters. An initial estimate of the stress is found from random trials, and least squares methods are used to minimize the angular error between the observed striation direction and that predicted from the stress parameters. The ratio of shear stress to normal stress on the plane is not considered.

This model is simplistic as it ignores restrictions placed on fault movement by other intersecting fault surfaces and also effects due to local stress variations such as those producing Riedel shears. It includes in the calculations striations which occur on planes with negligible shear stress. Despite these simplifications, this method of using local fault patterns to model the regional stress field has been successfully applied in a wide range of tectonic environments (Angelier *et al* 1981; Angelier 1984; Bergerat 1987; Frizzell & Zoback 1987). Angelier (1984) discussed the rationale of this technique and argued from a practical basis why errors due to local heterogeneities have little influence on the results. In the case of first order R and P shears, the regional stress field predicts the correct movement direction on these surfaces and there-

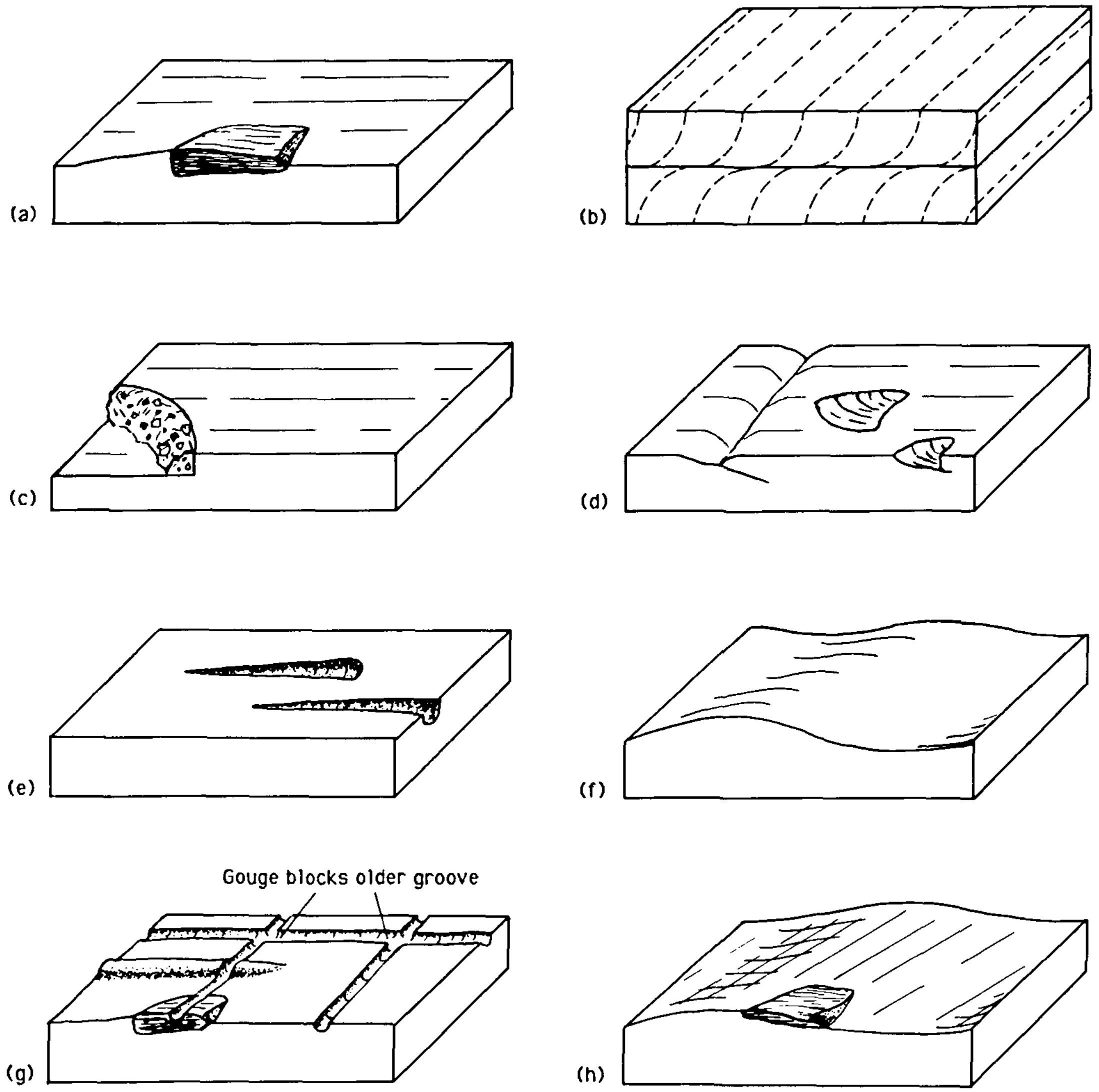

Fig. 3 Criteria used to determine sense of displacement (a–f) and relative age (g, h) from fault striations. All diagrams shown with top displaced to the right. For explanations of the displacement sense criteria see Petit (1987). (a) New minerals crystallized in the lee of a ledge on the fault plane. (b) Drag of cleavage where the cleavage intersects the fault plane at a high angle to the fault striations. (c) Fault gouge collect on ledges facing against the motion of the opposing block. (d) Lunate fractures and striated Riedel Shears. (e) Grooves deepening to the right because of asperities on the opposing face. (f) Striations on the upstream face of an irregular surface. (g) Truncation of grooves, intervening ridges and fibre veins by a later set of grooves indicates relative age. (h) Broad ridges parallel with early striations have been striated on one side only or have fibre veins attached to one side, indicating that striations cutting across the ridges are late.

fore the numerical method of Etchecopar *et al* (1981) is unaffected by their inclusion in the data set. More sophisticated methods which eliminate planes with low resolved shear stress are more seriously degraded by inclusion of Riedel shears.

The major advantages of the numerical method for inversion of fault striation data are that it can handle mixed sets of fault striations, and that it provides a numerical solution to the stress directions along with estimates of the probable error. It can also handle a large range in number of striations from each site and still give directly comparable results. The main limitation to the application of this technique is that the sense of displacement must be known or inferred for all the striations. The numerical methods of Etchecopar *et al* (1981) can separate mixed sets of data, but the realistic limit is that one stress field must produce more than 50% of the striations being considered. The complex assemblage of striations in this area leads to many misclassifications when analysis is based solely on orientation. The results reported here were obtained after the striations were separated into style groups, described below, before attempting numerical modelling. Because of the local stress variations expected in most fault environments, fits to more than 80% of striations are considered successful.

The data collected in this project are mainly from the excellent exposures of the Henty Fault Zone at road cuttings and near dam sites in the Tullah area (Fig. 1). Away from these fresh exposures, few fault striations were found. No attempt was made to study the southern part of the Henty Fault because of the absence of suitable exposures. The results given here are strongly dependent on the 15 localities discussed (Fig. 1), although information collected from many other sites within the same area is compatible with the conclusions.

PREVIOUS WORK

The distribution of lithologies in the Tullah section of the Henty Fault Zone (Fig. 1) has been mapped by Brooks (1962), Polya (1984) and Corbett and McNeill (1986). No major changes to the large scale distribution are inferred from this study and no attempt was made to re-map the lithologies associated with the fault zone. The structure within the Owen Conglomerate, on the Farrell Range and along the Murchison Gorge, was investigated to support re-interpretation of the Henty Fault.

Brooks' (1962) detailed mapping in this area recorded two cleavages: a widely distributed north–northwest-striking cleavage associated with regional folding, and a north–northeast-striking cleavage in a restricted zone within and near the Henty Fault. Brooks recognized that the latter cleavage had a strong down-dip lineation which he referred to as a 'slickenside lineation' but which in modern terminology is a stretching lineation. He also identified zones of steeply plunging non-cylindrical folds in bedding both within the fault and in the Farrell Range which were interpreted as sedimentary in origin. Gentle east–west folds overprint the north–northeast-striking cleavage along the front of the Farrell Range.

McKibben (1968) drew attention to strong ductile deformation of the Farrell ore bodies and proposed that the ore bodies filled north–northwest- to north–northeast-striking fractures of Devonian (Tabberabberan) age. These fractures contained striations indicating oblique slip (dextral-reverse). Rivers (1975) correlated this early reverse motion on the Henty Fault Zone with the Great Lyell Fault. He also suggested that a group of east–west dextral faults was related to the gentle crossfolds identified by Brooks and that these were both the same age as the Linda system of faults at Mt Lyell (Fig. 2). Both Brooks and Rivers suggested substantial Tertiary faulting in the area on the basis of the variable height of river terraces along the Mackintosh River.

FAULT STRIATIONS

Several generations of fault striation were easily determined in the field, based on style and overprinting relations. The earliest striations in each locality are 2–5 mm wide grooves. The fibres in quartz–chlorite fibre veins on early fault planes are sub-parallel to these grooves. *En echelon* arrays of quartz–chlorite–pyrite extension veins are parallel to these early faults and indicate the same sense of displacement. In massive rocks away from the Henty Fault Zone, narrow tabular zones, up to 100 mm wide, near the faults have a slaty cleavage defined by chlorite and white mica. The slaty cleavage forms at a small angle to the fault surface and is 'dragged' into the fault plane, providing a sense of displacement indicator. The second generation striations are also coarse grooves with quartz fibre veins. Chlorite is rarely crystallized in these fibre veins and pyrite is absent. No extension veins are present with orientations compatible with this set of striations. Cataclasite zones up to 1 m wide are present in some of the faults with these second generation striations, but there is no evidence of the development of a new slaty cleavage. The orientation of the second generation striations is at a high angle to the early striations, where they are on the same fault plane, except on steeply dipping northwest-striking planes. On planes striking northwest the movements are subparallel but opposite in sense for these two generations. Where the sense of movement could not be directly determined and the style criteria were ambiguous, these striations were difficult to place in a generation. The two later phases of faulting produced fine striations (<1 mm wide) on the fault planes without any new mineral growth. These striations were always found overprinting earlier striations.

EARLY REVERSE FAULTING

Early reverse faults have many features typical of brittle–ductile shear zones as defined by Ramsay (1980). The faults commonly have ductile deformation of the walls with the production of a slaty cleavage and stretching lineation (Fig. 4a, b). This cleavage does not have the strong rotational fabric of a mylonitic

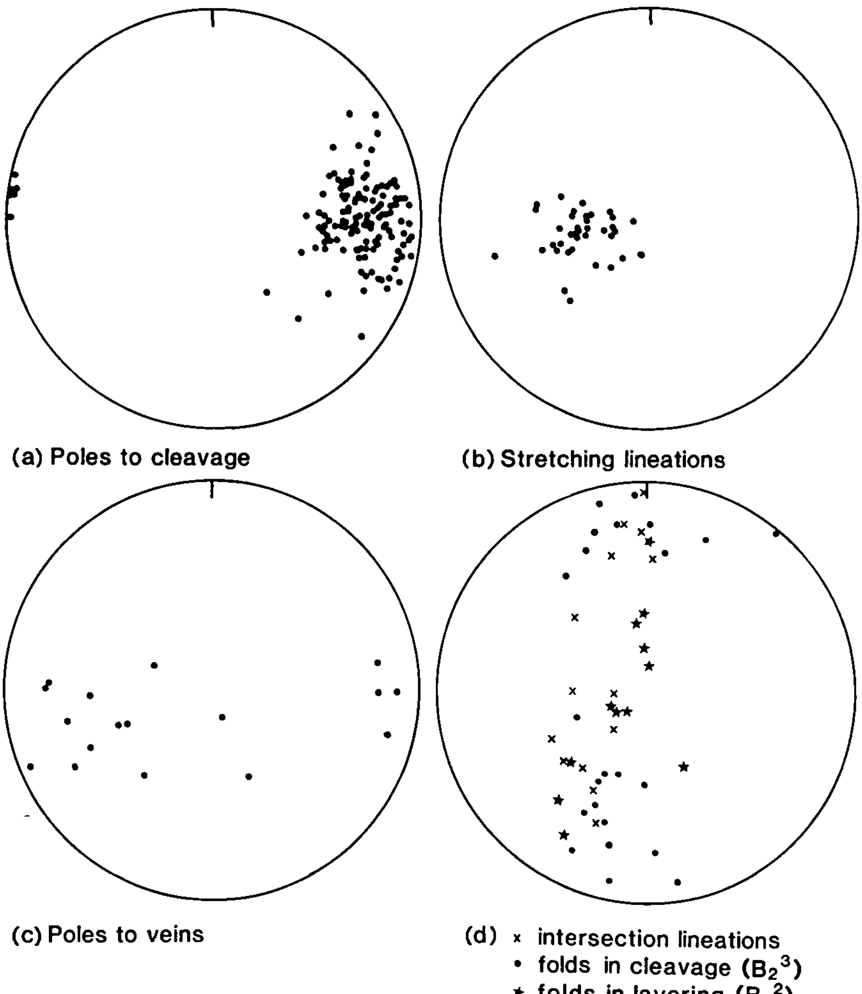

Fig. 4 The orientation of fault-related structures within the Henty Fault Zone shown on equal area lower hemisphere projection. (d) gives three linear features related to deformation on the fault zone. Open folds in the cleavage have shallow plunges with less common steeply plunging tight folds. Tight folds in bedding (B_0^2) and intersection lineations (S_0/S_2) vary as a result of pre-cleavage variations in bedding orientation.

foliation. In small faults the deformed zone ranges from a few millimetres up to 100 mm wide. In the Henty Fault Zone a strong slaty cleavage defined by white mica and chlorite dips steeply west (Fig. 4a). The strong stretching lineation (Fig. 4b) is defined by elongate chlorite- and sericite-rich clasts, and by elongate pressure shadows around quartz and feldspar grains. The slaty cleavage extends tens of metres into the walls of individual reverse faults in the Murchison Gorge but is of less importance in the north. There is little deformation of the fault walls at the Mackintosh Spillway. The increase in cleavage and lineation development to the south has been correlated with high level Devonian granites which probably underlie the southern part of the study area (Solomon 1977; Large 1986; Polya *et al* 1987). The fault striations are subparallel to the stretching lineations and both are approximately perpendicular to the line of intersection of the cleavage and the fault plane. The orientation of the cleavage and stretching lineation (Fig. 4a, b) indicates the maximum shortening direction trends east–west and maximum extension direction plunges steeply west. These orientations are rotated 20° from the stress directions calculated from the early reverse faults (see below).

In the Murchison River section there is a large number of kink bands with shallowly plunging axes accompanied by shallowly plunging bedding-cleavage intersections. At location H3 on the Mackintosh Road (Fig. 1) there is a wide range of kink band orientations. The kink bands grade into chevron folds in the cleavage. These folds and kinks are non-cylindrical with most plunging moderately to shallowly south, but a substantial proportion plunge to the north. There are also reclined folds in the layering (presumed bedding), with the cleavage as an axial plane structure. At the Mackintosh spillway there are many non-cylindrical folds of steep plunge with a slaty cleavage as their axial plane structure. The close association of non-cylindrical folds and a stretching lineation suggests comparisons with ductile shear zones (Bryant & Reed 1969), but the cleavage associated with this deformation does not have a strong rotational fabric and is not mylonitic in character, and the distribution of the steeply plunging folds does not correlate well with the area of strongest cleavage and lineation development. An alternative interpretation for the origin of the steeply plunging folds is that they are caused by interference with the earlier north–northwest-striking folds and fault-bend folds produced by an early phase of reverse faulting (see below).

Veins

En echelon arrays of quartz-dominated extension veins, common throughout the Henty Fault Zone and in the footwall, contain quartz, chlorite and pyrite, with lower abundances of galena and arsenopyrite. K–feldspar is common in these veins within the Murchison Volcanics of the footwall. The veins consistently strike north–south but have a wide range of dips (Fig. 4c). Some veins pre-date the cleavage and are folded but others crosscut the cleavage. The vein arrays are parallel with reverse faults, and quartz fibres within the veins are subparallel with fibre veins in nearby reverse faults. The veins are entirely consistent with the brittle–ductile nature of the faulting but, because of the complex age relationships, a detailed interpretation was not attempted. The broad girdle distribution of poles to veins probably reflects both the initial distribution and folding of early vein arrays.

Striation analysis

All locations investigated in detail along the fault zone, that is H1, H2, H3 and H4 (Fig. 1), are dominated by steeply west-dipping reverse faults. This pattern is least developed at H3 where there is also a large number of northwest-dipping faults with oblique reverse movement (Fig. 5). The calculated stress directions (Table 1; Fig. 6a) for these localities all indicate a near vertical σ_3. Two of the sites have a high value of R, indicating that σ_1 and σ_2 are almost the same, and as a result the direction of σ_1 is poorly defined. Despite this problem the numerical modelling provides strong evidence for compression on a trend of 100°. The generally poor solutions obtained using these early fault striations suggest that some of the basic assumptions of the technique are not met. Two possibilities are that: (1) the faults have been rotated since they formed; or (2) that the reverse faults were produced by a range of stress conditions which cannot be separated on the present data. There is evidence to support both of these possi-

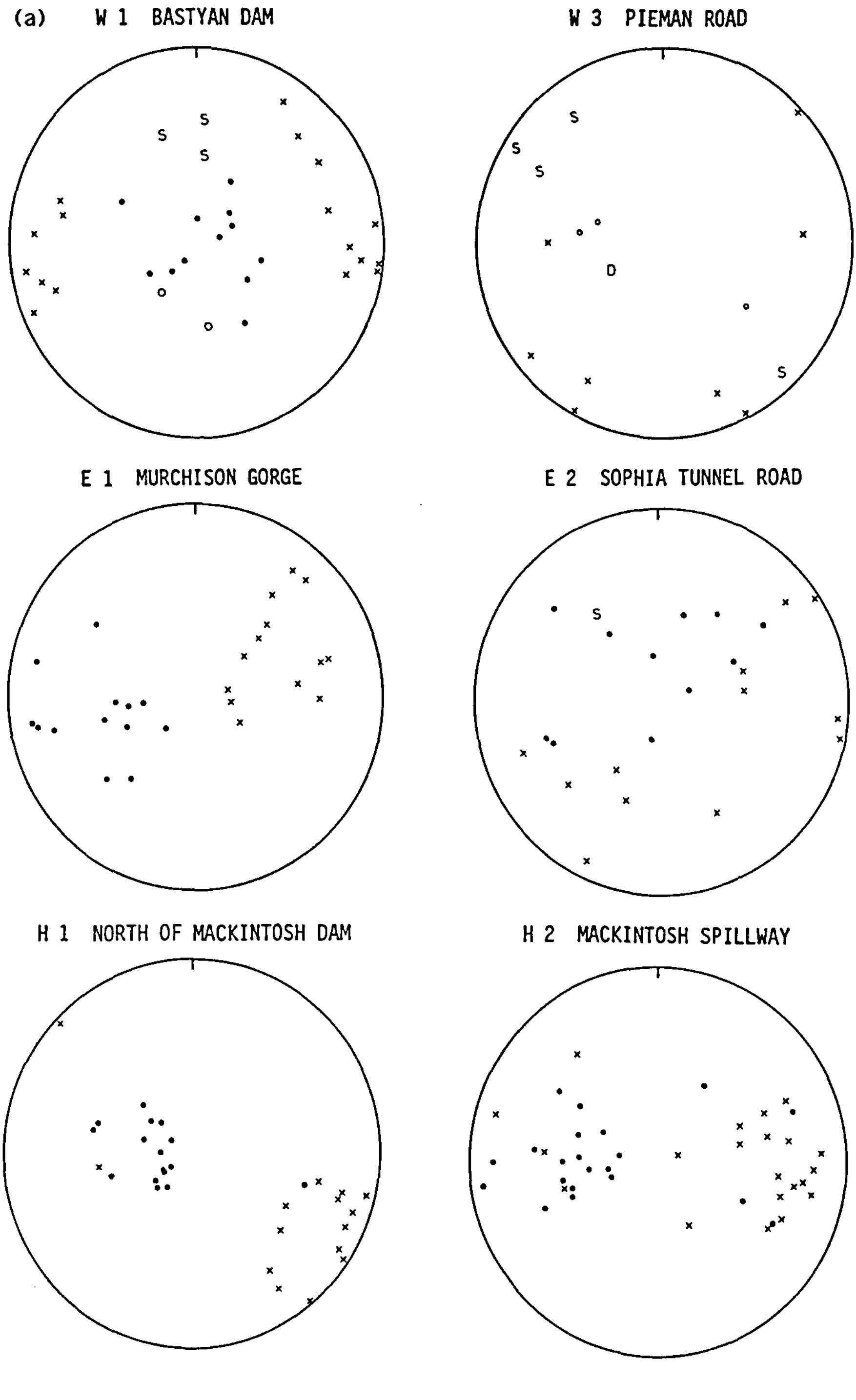

Fig. 5a Lower hemisphere equal area projections of fault striation data from six sites within and near the Henty Fault Zone. Locations of the sites are given in Fig. 1. Interpreted sense of movement is shown for all striations. Symbols as in Fig. 9.

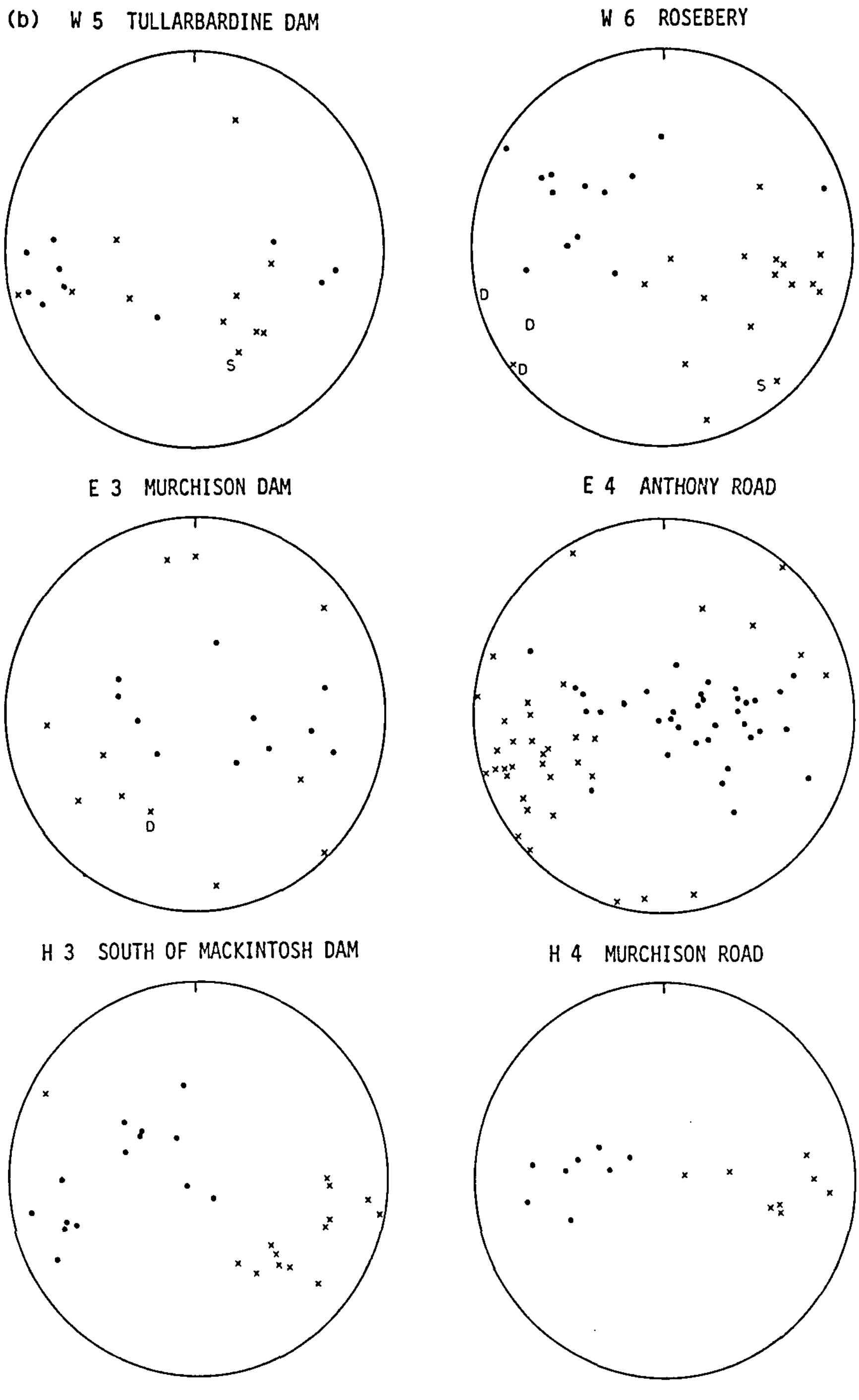

Fig. 5b Lower hemisphere equal area projections of fault striation data from six sites within and near the Henty Fault Zone. Locations of the sites are given in Fig. 1. Interpreted sense of movement shown for all striations. Symbols are given in Fig. 9.

Table 1 Principal stress directions calculated from fault striations.

Location	σ_1 Plunge (°)	σ_1 Trend (°)	σ_2 Plunge (°)	σ_2 Trend (°)	σ_3 Plunge (°)	σ_3 Trend (°)	R	Error (°)	Data no. Fitted	Data no. Total
Early reverse faults										
E1	4 ± 25	064 ± 47	6 ± 15	154 ± 45	83 ± 25	298*	0.86 ± 0.44	9	9	13
E2	3 ± 2	256 ± 12	1 ± 5	346 ± 12	87 ± 2	087*	0.96 ± 0.02	5	10	16
E3	15 ± 4	265 ± 6	6 ± 8	353 ± 6	74 ± 4	107 ± 28	0.73 ± 0.08	6	9	12
E4	2 ± 18	094 ± 24	2 ± 18	184 ± 25	87 ± 8	310*	0.82 ± 0.19	10	23	36
H1	9 ± 17	284 ± 26	12 ± 4	016 ± 26	75 ± 11	157 ± 56	0.89 ± 0.23	5	12	16
H2	3 ± 9	274 ± 8	1 ± 10	184 ± 8	87 ± 9	088*	0.36 ± 0.27	10	17	23
H3	4 ± 15	102 ± 1		†		†	0.14 ± 0.34	13	10	14
H4	6 ± 12	111 ± 54	3 ± 10	021 ± 53	83 ± 14	262 ± 25	0.90 ± 0.33	5	7	12
W1	7 ± 16	171 ± 29	19 ± 9	079 ± 33	70 ± 3	280 ± 25	0.94 ± 0.12	7	11	17
W3	28 ± 10	279 ± 10	17 ± 39	018 ± 19	56 ± 10	136 ± 10	0.22 ± 0.18	13	7	9
W5	3 ± 7	263 ± 9	23 ± 12	354 ± 7	67 ± 12	168 ± 23	0.25 ± 0.21	9	10	11
W6	4 ± 9	091 ± 5		†		†	0.03 ± 0.06	7	10	17
Early wrench faults										
E2, E3, E4	0 ± 11	351 ± 6	84 ± 31	258*	6 ± 31	080 ± 6	0.10 ± 0.16	15	13	23
H2	13 ± 8	358 ± 3		†		†	0.01 ± 0.13	9	13	14
W2, W3, W4	3 ± 7	342 ± 21		†		†	0.00 ± 0.20	11	18	26
Late wrench faults										
H2	9 ± 24	327 ± 32	78 ± 40	103 ± 47	9 ± 33	327 ± 24	0.38 ± 0.51	12	8	11
Late normal faults										
A11	79 ± 10	065*	3 ± 14	170 ± 9	11 ± 9	261 ± 9	0.26 ± 0.24	11	21	29

*Trend not significant because of steep plunge.
†Stress direction not well defined due to error in R.
Data represent mean ± standard error estimate.

bilities. Within the Henty Fault Zone, and especially in the south (H3, H4), the faults are brittle–ductile shears and the numerical technique used here is at the margin of its usefulness. There are several examples of folded faults within the area indicating that the earlier fault surfaces were rotated by the ductile component of the strain, but the vast majority of faults included in this study were apparently syn- to post-cleavage brittle deformation structures. The second possibility is discussed in more detail below.

Early reverse fault striations are recognized over a wide area outside the Henty Fault Zone. They are the most common fault striations throughout the area. Near the Rosebery Fault (W1, Fig. 1) the striations include a wide range of orientations. Steeply dipping faults are most common in the footwall whereas sinistral wrench faults are dominant in the hanging wall. The stress solution from W1 has a similar problem to sites H1 and H4 with σ_1 poorly defined because of a high value for R. There is strong field evidence of drag folding in the footwall where much of the data was collected.

Throughout the Central Volcanic Complex between the Henty and Rosebery faults (e.g. W3, W6) the early faults include a large proportion of wrench faults as well as steep reverse faults (Fig. 5). Numerical analysis of these faults indicates east–west compression but with a low R value (Table 1) indicating that σ_2 in this area was lower. The Central Volcanic Complex occupies an upthrown block between two major reverse faults: the Henty and Rosebery Faults. The stress solution confirms the indication from the increased component of wrench faults that this block was not as strongly constrained on its north and south ends during the early reverse faulting as the downthrown blocks to the east and west.

The early fault striations east of the Henty Fault Zone are dominated by east-dipping reverse faults (Fig. 5), and this trend strengthens towards the southeast. At E4, 75% of the minor faults dip steeply east. This trend suggests a

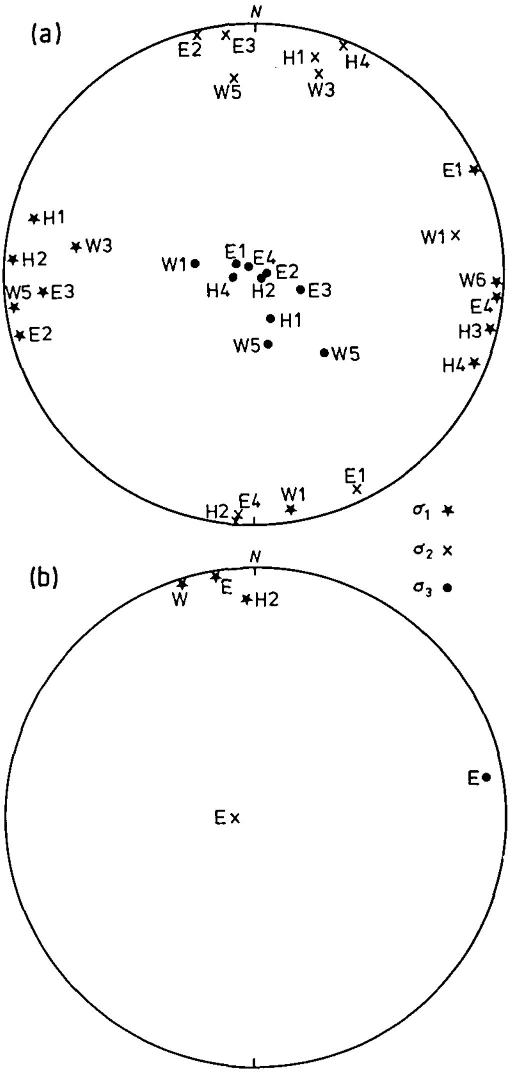

Fig. 6 Lower hemisphere equal area stereographic projections of principal compressive stress directions calculated from striations in: (a) early reverse faults, and (b) early wrench faults. Locality numbers are from Fig. 1. In (b) E indicates E2, E3 and E4, and W indicates W2, W3 and W4.

major reverse fault to the east, which is parallel with the Rosebery Fault. The stress solutions from this area differ from the Henty Fault Zone localities. The faults dip more toward east–northeast than east, and the stress solutions for σ_1 are 10–30° anticlockwise from the solutions at sites farther west (Table 1; Fig. 6a).

Despite the possible complications, an early group of reverse fault striations is clearly developed along the Henty Fault Zone and correlated with a regionally distributed set of minor faults. The systematic variation in fault style suggests that the Rosebery Fault was active at the same time as reverse faulting in the Henty Fault Zone. This event lifted the Central Volcanics with respect to the Murchison Volcanics to the east of the Henty Fault Zone. The maximum compressive stress at this time was trending between 075° and 111°. Within the Henty Fault Zone, the trend of the maximum compressive stress was about 100°. The average strike of the associated cleavage (Fig. 4a) supports this conclusion.

Significance

Several lines of evidence support a Devonian age for the last reverse movement on the Henty Fault Zone. Strong cleavage development over the southern part of the area is related to reverse faulting, and the K/Ar slate age from this area (Adams *et al* 1985) supports a Devonian age. Brooks (1962) recognized a cleavage (S_1) striking 340° in the southeastern part of this area which correlates with regional folds of Devonian age (Williams 1978). This cleavage is overprinted by the north–south-striking cleavage (S_2) of the Henty Fault Zone. The anticline in the Owen Conglomerate along the Murchison Gorge (Fig. 7) trends parallel with the north–northwest-striking cleavage. This fold has interacted with the Henty Fault Zone, producing a complex distribution of lithologies. The syncline along Little Farrell, west of the anticline, is tighter near the fault zone, but the main anticline dies out against this zone (Fig. 7) suggesting it has been unfolded during the reverse faulting.

In addition to this evidence of Devonian movement, there are data supporting an earlier stage of movement on the fault zone. Interpretation of the early reverse faults is complicated by a large range of orientations. In many cases it is impossible to fit more than 60% of the striations to a single stress tensor. This is especially true southeast of the Henty Fault Zone. Many of the reverse faults in the Murchison Gorge strike parallel with the 340° fold trend. The stress solution for these faults is poorly determined, but suggests compression normal to the fold trend (Table 1). These faults may be at least partly related to an older fault event. North–northwest-striking reverse faults are common in

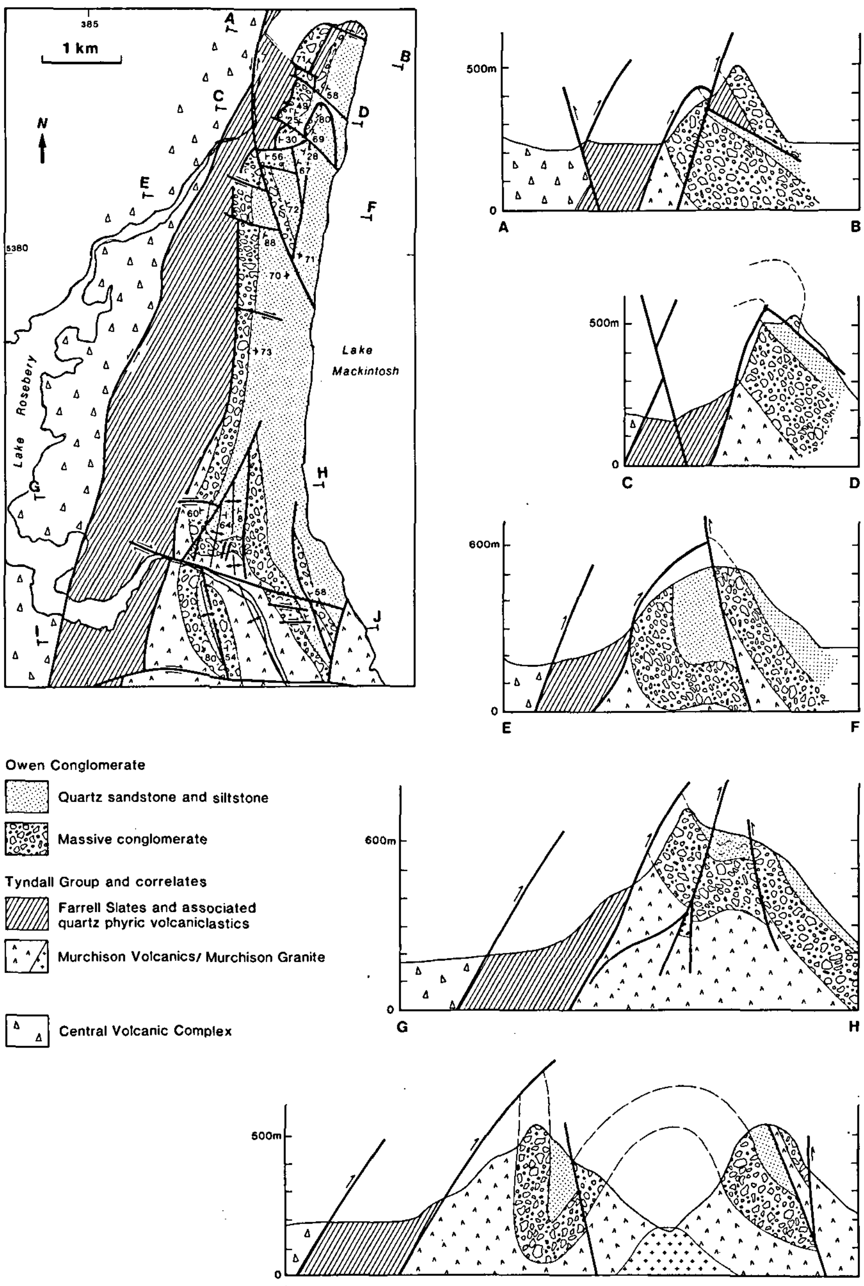

Fig. 7 Cross-sections of the Henty Fault Zone along the Farrell Range. The geological map, modified from Brooks (1962) and Corbett and MacNeill (1986), gives locations of the sections. Sections A–B and C–D indicate the folding of an earlier thrust surface, and the progressive change in fold geometry against the fault is shown in sections I–J, G–H and E–F. The sense of movement on faults is provided for the early reverse faulting on the cross-sections and for the early wrench faulting on the map.

the eastern block (Fig. 5) but evidence for east–northeast compression is equivocal.

Folded thrusts are exposed along the Henty Fault Zone. The most accessible example, in the stream below the Mackintosh spillway, is a flat-lying thrust which is folded from west-dipping to east-dipping over 10 m along the stream. On a larger scale, structures of this type were recognized within the Owen Conglomerate on the Farrell Range. A large scale east-dipping fault with eastward transport direction is exposed at map reference CP 878817 (on section CD in Fig. 7). The fault is associated with quartz-filled tension gashes and local cleavage development. It is overlain by strongly deformed conglomerate. A fault slice of feldspathic sandstone, probably related to the Farrell Slate, has been recognized at the northern end of the Farrell Range (Brooks 1962). Both structures probably originated as a folded thrust (sections AB and CD in Fig. 7) with angular discordances across the fault being caused by fault-bend folds. The probable sequence of events (Fig. 8) begins with a thrust forming a ramp through the Owen Conglomerate. The structural discordance preserved on the Farrell Range and the westward facing of the Farrell Slates, near the Murchison Gorge, are the major pieces of evidence for this stage. The second event folds the earlier thrust and reactivates part of this structure as a high-angle reverse fault. The latter stage produces all of the structures which have been demonstrated to be Devonian in age. The age limits of the early thrust event are Late Cambrian to Devonian.

Rivers (1975) correlated the Henty Fault Zone with the Great Lyell Fault, both faults being essentially along strike from each other (Fig. 2). The faults are the major west-dipping fractures in the Mount Read Volcanics and both form the western boundary of the Owen Conglomerate. Despite these features, no continuity of these structures has been demonstrated. Two stages of reverse movement have been proven on the Great Lyell Fault at Mt Lyell (Arnold & Fitzgerald 1986). The early reverse movement (more than 1 km of dip–slip movement) produced the Haulage Unconformity in the early Ordovician. This early fault was reactivated in the Devonian. There are also Devonian upright north–south folds in the early fault surface, as inferred for the Henty Fault Zone. This largely circumstantial evidence supports correlation between the

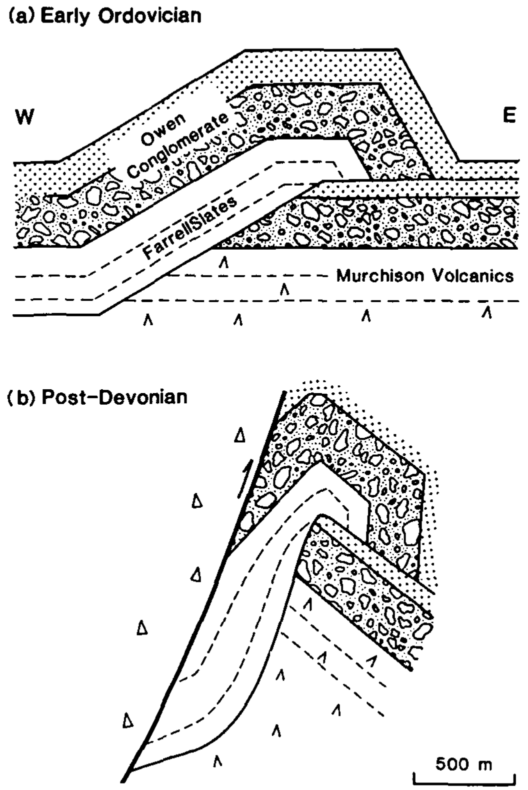

Fig. 8 Interpretation of folded fault on the north end of the Farrell Range. (a) The early thrusting is shown as a ramp through the Owen Conglomerate, with associated fault-bend faults constructed by the method of Suppe (1983). (b) Indicates the result of folding the early fault and reactivating it as a high angle reverse fault in the Devonian. See Fig. 7 for legend.

Henty and Great Lyell Faults. The correlation of the Henty Fault Zone with the Great Lyell Fault is the only evidence that the first stage of thrusting was pre-Devonian.

EARLY WRENCH FAULTS

Striation analysis

Throughout the region, and especially at Mackintosh spillway, are coarse striations (2–5 mm) which overprint early reverse striations, indicating reactivation of the Henty Fault Zone. These striations are associated with quartz fibre-veins containing minor chlorite and white mica in some localities, but no newly crystallized sulfide minerals.

On Mackintosh spillway these faults are exposed as brittle deformation zones, up to 1 m wide, containing cataclasite and strongly kinked and broken material with steeply plunging kink axes. These fault zones form a sinistral set, often parallel to and reactivating the steepest reverse faults in the area, and a northwest-striking dextral set. A common feature of this zone is the presence of Riedel Shears which have a wide range of strikes. For example, at the northwestern part of the upper spillway a sinistral cataclasite zone striking 022° contains R Riedel Shears striking 344–014°. The major sinistral faults strike 020–030° parallel with the Henty Fault Zone, while the major dextral faults strike 330–350° and overlap the orientation of sinistral Riedel Shears. A few P shears striking 040° are exposed at the bottom of the spillway. The stress solution from the early wrench faults at the Mackintosh spillway (H2) gives σ_1 trending 358°, which is 31° clockwise from the best solution for the later phase of wrench faults at this locality (Table 1). Because only a small range of fault orientations is included, the value of R is poorly determined.

Early wrench faults have produced striations over a wide area, although no cataclasite zones have been found away from the Mackintosh Spillway. This may be due to the absence of suitable exposures.

Early wrench faults are common along the Pieman Road. At W4, 95% of the striations indicate wrench faulting, and the early reverse striations are present as faint relics. Three sites along Pieman Road (Fig. 9) have been combined to determine a solution for the stress distribution. The resulting pattern of faults is similar to that observed in Mackintosh spillway. The stress model fits 70% of these striations and indicates compression from the north–northwest but is unstable, probably reflecting variations in the stress tensor between the sites.

Early wrench faults are also common east of the Henty Fault Zone, especially at E2, E3 and E4. The style is similar to the early wrench faults to the west. They overprint the early reverse faults and are overprinted by a set of late normal striations. The stress solution can only explain 60% of the total wrench fault assemblage which suggests that there are other striations mixed in this set. The stress solution (Table 1; Fig. 6b) indicates maximum compression from 351° which

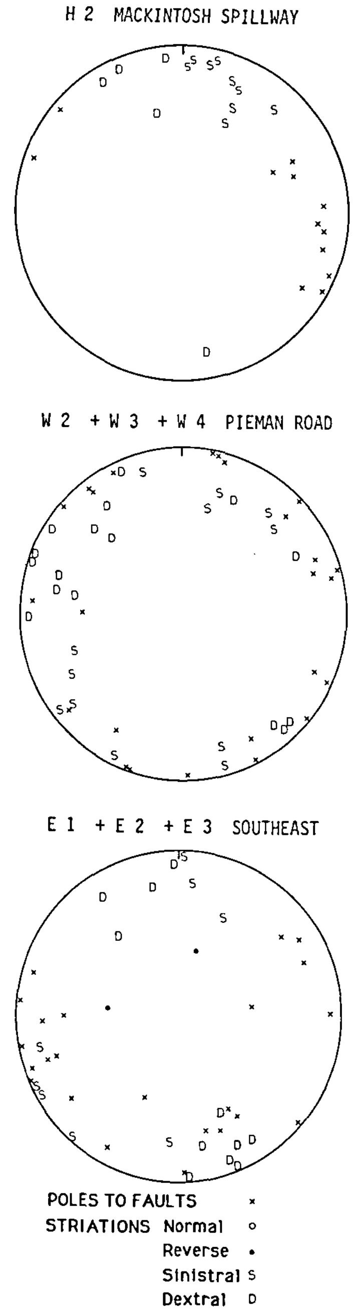

Fig. 9 Lower hemisphere equal area projections of fault striation data related to the early wrench faulting on the Henty Fault. Locations of sites are given in Fig. 1. Interpreted sense of movement is shown for all striations.

is consistent with the results throughout the area.

Significance

The sinistral displacement on the Henty Fault cannot be accurately measured but must be less than 5 km. Vein style mineralization resulted from a granite ridge which intruded across the Henty Fault in the Devonian (Large 1986). The vein deposits are synchronous with the early reverse movement on the Henty Fault and predate the wrench faulting. The distribution of the vein mineralization is given by Green and Bamford (1986). The shape of the northern boundary of the vein province is compatible with an offset of up to 5 km, while the southern boundary suggests a wrench displacement much less than this. The displacement of the western margin of the Central Volcanic Complex in the Howards Road area (Corbett 1986b) is also consistent with an offset less than 5 km.

LATE WRENCH FAULTS

Late movement on many of the wrench faults was demonstrated by a second set of striations. These striations are always fine grooves (<1 mm), without associated fibre growth. They cut the earlier wrench striations and plunge mainly to the south, or more shallowly north than the early wrench striations on the same plane (Figs 9, 10). The striations have only been recognized in the north and are only common along the Henty Fault Zone.

The late wrench faults strike 300–020° and are difficult to determine on many of these planes. The planes striking 000–020° are sinistral and there is weak evidence that faults striking 300–340° are dextral. This distribution has been assumed in calculating the stress solution (Table 1) for these faults. This interpretation gives σ_1 trending 330°, which is anticlockwise from solutions for the early wrench faults.

A Mesozoic phase of wrench faulting has been recognized in eastern Tasmania (Berry & Banks 1985). This faulting event is also found within Middle Jurassic dolerites near Zeehan, indicating it was also active in western Tasmania. Similarities of orientation and style suggest that the late wrench fault activity along the Henty Fault Zone may be a Mesozoic event.

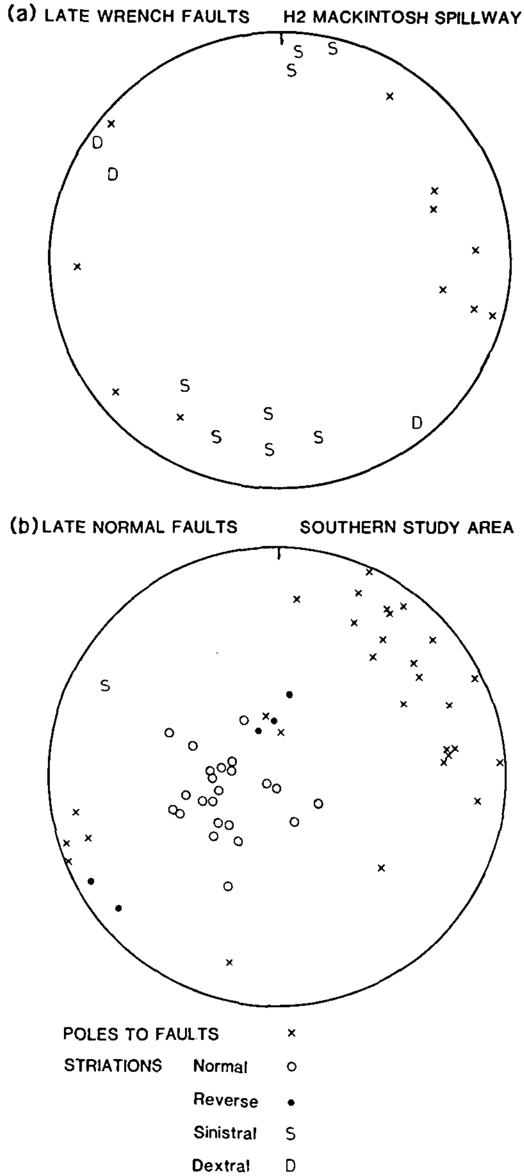

Fig. 10 Lower hemisphere equal area projections of fault striation data related to: (a) the late wrench faulting; and (b) the late normal faulting on the Henty Fault. Locations of sites are given in Fig. 1. Interpreted sense of movement is shown for all striations.

LATE NORMAL FAULTS

In the south, along Murchison Gorge and the Anthony Road, the youngest striations are fine grooves similar in style to those of the late wrench faults in the north. In contrast to the north, these late striations are developed on west- to southwest-dipping normal faults (Fig. 10). No late wrench faults have been recognized in this area.

The late normal faults are most common on Anthony Road (E5). The second generation dextral fault in this locality has been strongly reactivated as a normal fault. In the remainder of the area, normal striations are a minor component of the fabric. There is no direct evidence for reactivation of the Henty Fault Zone during this event although it is likely, considering the orientation of the minor faults that have been reactivated and the observations of possible Tertiary offsets in river terraces, made by Brooks (1962) and Rivers (1975).

The late normal faults form a coherent group, and a good solution has been obtained using all the available data. A single extensional phase with σ_3 trending 260° fits 80% of the striations to better than 20° (Table 1). Normal faulting has been widely recognized within the Tertiary of Tasmania (Spry & Banks 1962) and the geometry of late normal striations recorded here is consistent with the known pattern of this faulting.

CONCLUSIONS

The Henty Fault Zone has had a complex movement history. The earliest recognizable movement is east-directed thrusting which consisted of a ramp through the Owen Conglomerate. This phase was only recognized from folded relicts on the Farrell Range and from the westward-facing of the Farrell Slate. It may correlate with the Early Ordovician movement on the Great Lyell Fault.

The second reverse movement on the Henty Fault Zone uplifted the Central Volcanic Complex against the Farrell Slate and the Owen Conglomerate on a steep west-dipping reverse fault. This phase produced the strong cleavage (S_2) within the fault zone and in the footwall. It post-dated northwest-trending Devonian folds. The stress solutions from the reverse faults within the Henty Fault Zone indicate σ_1 trending 100°. Detailed analysis of fault striations to the east and the west suggests that major east-dipping reverse faults in these localities were formed in the same period. The variation in R across the Central Volcanic Complex is consistent with a pop-up which was less restricted in the north–south direction than the downthrown block to the east of the Henty Fault.

The last Devonian movement was a sinistral wrench displacement of less than 5 km. Stress solutions from striations of this phase indicate nearly uniaxial compression from the north–northwest to north. This stress direction suggests correlation with the late thrusting north of the Tyennan Block (Jennings 1958) and in the Linda Fault Zone (Williams 1978).

Two minor phases of faulting followed: a sinistral wrench movement and normal faulting. These probably correlate with the post-Triassic faulting found throughout Tasmania (Berry & Banks 1985).

ACKNOWLEDGMENTS

The planning for this project arose from discussions with Keith Corbett. Dave Seymour, Andrew MacNeill and Ross Large made many constructive comments on the manuscript. The computer program used for the striation analysis was made available by A. Etchecopar and J.-P. Burg.

REFERENCES

ADAMS C. J., BLACK L. P., CORBETT K. D. & GREEN G. R. 1985. Reconnaissance isotopic studies bearing on the tectonothermal history of Early Palaeozoic and Late Proterozoic sequences in western Tasmania. *Australian Journal of Earth Sciences* **32**, 7–36.

ANGELIER J. 1984. Tectonic analysis of fault slip data sets. *Journal of Geophysical Research* **89**, 5835–5848.

ANGELIER J., COLLETTA B., CHOROWICZ J., ORTLIEB L. & RANGIN C. 1981. Fault tectonics of the Baja California Peninsula and the opening of the Sea of Cortez, Mexico. *Journal of Structural Geology* **3**, 347–357.

ARNOLD G. O. & FITZGERALD F. G. 1986. Mt Lyell: An exploration perspective. *In* Large R. R. ed. *The Mount Read Volcanics and Associated Ore Deposits*, pp. 21–23. Geological Society of Australia, Tasmanian Division, Hobart.

BAMFORD, A. L. & GREEN G. R. 1986. The distribution and nature of mineralisation in the Mount Read Volcanics–Mt Darwin to Hellyer. *In* Large R. R. ed. *The Mount Read Volcanics and Associated Ore Deposits*, pp. 27–29. Geological Society of Australia, Tasmanian Division, Hobart.

BERGERAT F. 1987. Stress fields in the European Platform at the time of Africa–Eurasia collision. *Tectonics* **6**, 99–132.

BERRY R. F. & BANKS M. R. 1985. Striations on minor faults and the structure of the Parmeener Super-Group near Hobart, Tasmania. *Papers and Proceedings of the Royal Society of Tasmania* **119**, 23–29.

BERRY R. F. & CRAWFORD A. J. 1988. The tectonic significance of Cambrian allochthonous mafic–ultramafic complexes in Tasmania. *Australian Journal of Earth Sciences* **35**, 523–533.

BROOKS C. 1962. The geology of the Tullah area. BSc(Hons) thesis, University of Tasmania (unpubl.).

BRYANT B. & REED J. C. 1969. Significance of lineation and minor folds near major thrust faults in the southern Appalachians and the British and Norwegian Caledonides. *Geological Magazine* **106**, 412–429.

COLLINS P. L. F. & WILLIAMS E. 1986. Metallogeny and tectonic development of the Tasman Foldbelt system in Tasmania. *Ore Geology Reviews* **1**, 153–201.

COOPER R. A. & GRINDLEY G. W. eds 1982. Late Proterozoic to Devonian sequences of southeastern Australia, Antarctica and New Zealand and their correlation. *Geological Society of Australia. Special Publication* **9**.

CORBETT K. D. 1981. Stratigraphy and mineralisation in the Mount Read Volcanics, western Tasmania. *Economic Geology* **76**, 209–230.

CORBETT K. D. 1985. Geological compilation map of the Mount Read Volcanics: Que River to Mount Darwin. *Tasmanian Department of Mines, unpublished report* 85/11.

CORBETT K. D. 1986a. The geological setting of mineralization in the Mount Read Volcanics. *In* Large R. R. ed. *The Mount Read Volcanics and Associated Ore Deposits*, pp. 1–10. Geological Society of Australia, Tasmanian Division, Hobart.

CORBETT K. D. 1986b. Geology of the Henty River–Mt Read area. Mount Read Volcanics project, map 3. Department of Mines, Hobart.

CORBETT K. D. & LEES T. C. 1987. Stratigraphic and structural relationships and evidence for Cambrian deformation at the western margin of the Mount Read Volcanics, Tasmania. *Australian Journal of Earth Sciences* **34**, 45–68.

CORBETT K. D. & MACNEILL A. W. 1986. Geology of the Rosebery–Mt Block area. Mount Read Volcanics project, map 2. Department of Mines, Hobart.

ETCHECOPAR A., VASSEUR G. & DAIGNIERES M. 1981. An inverse problem in microtectonics for the determination of stress tensors from fault striation analysis. *Journal of Structural Geology* **3**, 51–65.

FRIZZELL V. A. & ZOBACK M. L. 1987. Stress orientation determined from fault slip data in Hampel Wash Area, Nevada, and its relation to contemporary regional stress field. *Tectonics* **6**, 89–98.

GREEN G. R. & BAMFORD A. 1986. Mineral deposit map: Tullah. Department of Mines, Hobart.

HANCOCK P. L. 1985. Brittle microtectonics: Principles and practise. *Journal of Structural Geology* **7**, 437–457.

JENNINGS I. B. 1958. The Round Mountain district. *Geological Survey of Tasmania, Bulletin* **45**.

LARGE R. R. 1986. Integration of geology and geophysics in the development of exploration models for massive sulphide tin deposits in western Tasmania. *In* IGCP Project 220 Conference on Correlation and Resource Evaluation of Tin/tungsten Granites in South-East Asia and the Western Pacific, Abstract Volume.

MCKIBBEN J. P. 1968. Geology of the Mt Farrell ore bodies. BSc(Hons) thesis, University of Tasmania (unpubl.).

PETIT J.-P. 1987. Criteria for the sense of movement on fault surfaces in brittle rocks. *Journal of Structural Geology* **9**, 597–608.

PETIT J.-P., PROUST F. & TAPPONIER P. 1983. Critères de sens de mouvement sur les miroirs de failles en roches non calcaires. *Bulletin de la Société Géologique de France* **25**, 589–608.

POLYA D. A. 1984. The geology of the Murchison Gorge. BSc(Hons) thesis, University of Tasmania (unpubl.).

POLYA D. A., SOLOMON M., EASTOE C. J. & WALSHE J. L. 1987. The Murchison Gorge, Tasmania — a possible cross-section through a Cambrian massive sulfide system. *Economic Geology* **81**, 1341–1355.

RAMSAY J. G. 1980. Shear zone geometry: A review. *Journal of Structural Geology* **2**, 83–100.

RIVERS W. M. 1975. The geology and geochemistry of the Tullah area. BSc(Hons) thesis, University of Tasmania (unpubl.).

SOLOMON M. 1977. Metallic mineral deposits of the Pieman–Gordon region and the likelihood of new discoveries. *In* Banks M. R. and Kirkpatrick J. B. eds. *Landscape and Man*, pp. 129–146. Royal Society of Tasmania, Hobart.

SOLOMON M. 1981. An introduction to the geology and metallic ore deposits of Tasmania. *Economic Geology* **76**, 194–208.

SPRY A. & BANKS M. R. 1962. The geology of Tasmania. *Journal of the Geological Society of Australia* **9**, 1–362.

SUPPE J. 1983. Geometry and kinematics of fault-bend folding. *American Journal of Science* **283**, 684–721.

WILLIAMS E. R. 1978. Tasman Foldbelt system. *Tectonophysics* **48**, 159–205.

(*Received* 6 *November* 1987; *accepted* 12 *July* 1988)