CENTRE FOR ORE DEPOSIT AND EXPLORATION STUDIES

# STRUCTURE AND MINERALISATION OF WESTERN TASMANIA

**AMIRA PROJECT P.291**

**Report No.1**

September 1990

University of Tasmania

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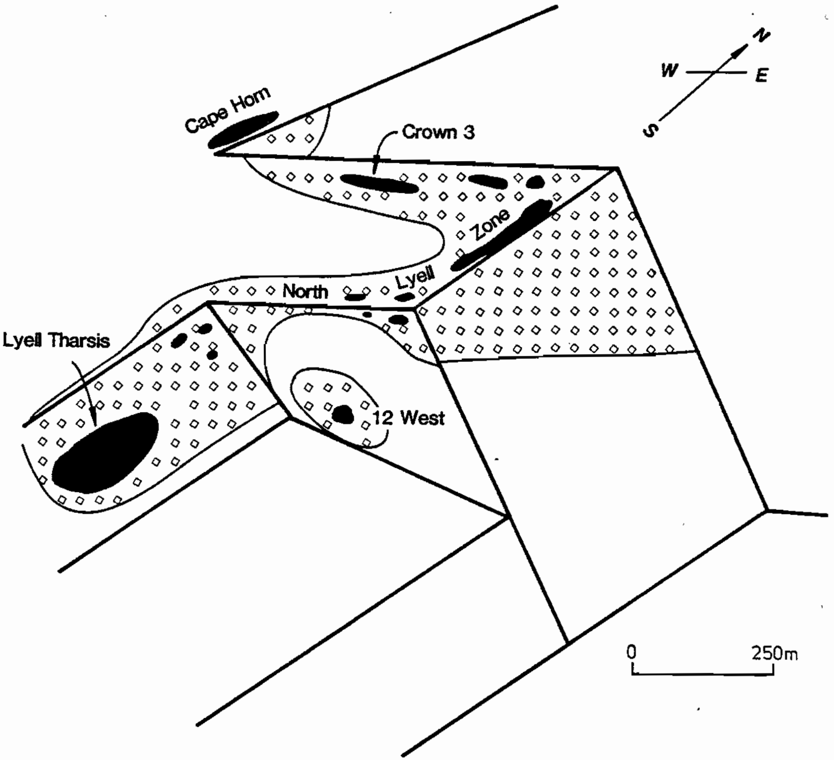

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# CONTENTS

# PALAEOZOIC FAULT KINEMATICS AND A BALANCED CROSS SECTION THROUGH THE HUSKISSON–QUE–HELLYER–MACKINTOSH REGION, WEST COAST, TASMANIA

**Mark S. Rattenbury**
Centre for Ore Deposit and Exploration Studies, University of Tasmania

## SUMMARY

Devonian compressional tectonics in the Huskisson–Que–Hellyer–Mackintosh region have been dominated by north-south and northeast-southwest trending folds and reverse movement of the Rosebery, Mt Charter and Henty Faults. A balanced cross section has been constructed across the region by making assumptions firstly on the structural position of the Gordon Group limestone between the Rosebery and Henty Faults and secondly that the dips of the Rosebery, Mt Charter and Henty Faults have maintained their present east-, east- and west-dipping polarity respectively throughout their movement history. The convergence of the Rosebery and Henty Faults at depth implies local shortening may exceed 50% whereas the overall mid Devonian shortening across the section is about 16%.

The restored section shows major normal fault displacements along the Rosebery and Henty Faults which have resulted in a north–south trending graben. This interpretation is partly based on calculated isopachs of the Dundas Group which show a marked thickening east of the Rosebery Fault, by the apparent confinement of the Central Volcanic Complex between the Rosebery and Henty Faults, and by stratigraphic thickness changes across the Mt Charter Fault. The total extension of the Precambrian–early Cambrian basement need only be around 40% and any further extension would require substantial and improbable crustal thickening through tight folding and thrust imbrication during the Devonian compressional tectonics. The graben containing the Central Volcanic Complex therefore would not have greatly exceeded 20 km width. The three major faults in the Huskisson–Que–Hellyer–Mackintosh region have shown evidence for both Cambro–Ordovician extension and mid Devonian shortening.

Major mines such as Hellyer, Que River and Rosebery, and areas of extensive alteration and mineralisation are confined primarily to zones adjacent to the Rosebery and Henty Faults. The combination of active normal faulting during crustal thinning and volcanism/sedimentation has probably locally elevated the heat flow along these faults and resulted in hydrothermal systems capable of forming volcanogenic massive sulphide deposits.

## INTRODUCTION

The late Precambrian and early Palaeozoic rocks of the West Coast of Tasmania (Fig. 1) form a widely explored and richly mineralised geological province. The province has a great diversity of lithologies dominated by the prospective mid-late Cambrian Mount Read Volcanics, and a virtually continuous geological record from late Precambrian to Devonian despite several major deformational and erosional events. Yet the structural and stratigraphic geology remains problematical in the context of tectonic modelling, particularly the quantification of fault displacements. General fault kinematics of the West Coast are better known through detailed work on complex fault zones such as the Henty Fault (Berry, 1989), and improved understanding of the regional and local stratigraphy. Many plate tectonic settings have been proposed for the region invoking rifting with or without adjacent subduction zones of varying polarity (e.g., Corbett et al., 1972; Crook, 1980; Green, 1984; Large et al., 1987; Corbett & Lees, 1987; Berry & Crawford, 1988; Corbett ,1989). In some cases, dramatic shortening is invoked on geochemical and petrological grounds without serious consideration of the structural consequences.

This study has used the recent 1:25 000 mapping and earlier smaller scale mapping of the Huskisson–Que–Hellyer–Mackintosh region by the Tasmanian Department of Mines. The aim has been to try to constrain the magnitude and kinematics of Palaeozoic faulting, primarily through the application of balanced cross section construction. This study is consequently limited by the information gleaned from the available maps and inferred structural and stratigraphic relationships, although some field investigation of key contact relationships has been undertaken. Structural and stratigraphic interpretations in western Tasmania are inevitably modified by more detailed mapping and fieldwork, and this study will undoubtably require modification with improved mapping and stratigraphic control.

## REGIONAL STRUCTURE AND STRATIGRAPHY

The regional stratigraphy of the Huskisson–Que–Hellyer–Mackintosh region is underlain by Precambrian basement (Figs 1, 2). In the east, the Precambrian basement comprises schists and quartzites of the Tyennan Region. In the west, schistose correlatives of the Oonah Formation of the Rocky Cape Region occur in the core of an anticline in the Huskisson River (Brown 1983). The Oonah Formation is unconformably overlain by the late Precambrian–early Cambrian volcanosedimentary Crimson Creek Formation. Occupying a pseudo-stratigraphic position above the Crimson Creek Formation is a mafic-ultramafic complex (Brown 1983). The complex appears to have been emplaced along shallow dipping thrusts although no consensus on the amount of displacement involved has been reached. Berry & Crawford (1988) have suggested the mafic-ultramafic complex represents the remnants of an allochthonous ophiolite sheet obducted in the early-middle Cambrian. Basal mylonitic amphibolites from several localities have west-directed microstructural kinematic indicators (Berry 1988) implying the mafic-ultramafic complex was thrust over the Tyennan Region. Neither remnants of the mafic-ultramafic complex, nor the underlying Crimson Creek Formation have been found overlying the Tyennan Region however, except possibly in the Adamsfield area where ultramafic rocks are present. The next major stratigraphic unit is the middle-late Cambrian volcanic and sedimentary sequence comprising the Central Volcanic Complex, the Dundas Group, the Tyndall Group and correlative rocks (Figs 1, 2). The sequence occupies a belt through the central part of the Huskisson–Que–Hellyer– Mackintosh region, thinning to nothing towards the east and west. The structural and sedimentary relationships between these groups is not well known due to poor exposure, limited internal stratigraphy and fossil control, and suggestions of rapid lateral facies and thickness changes. In the Huskisson– Que–Hellyer–Mackintosh region the Central Volcanic Complex underlies the Dundas Group with apparent conformity in the Burns Peak–Pinnacles area (Corbett & McNeill 1986) and the Mt Charter area (Corbett & Komyshan 1989). The lower part of the Dundas Group appears to conformably underlie the Tyndall Group in the vicinity of the Cradle Mountain Link Road (Vicary & Pemberton 1988; Corbett & Komyshan 1989). The late Cambrian–early Ordovician Owen Conglomerate overlies the Cambrian volcanosedimentary rocks with local angular unconformable contacts (Figs 1, 2). The conglomerates are regionally overlain by the Gordon Group limestones and a sequence of Silurian–Devonian siliciclastics. Extensive granite intrusion occurred in the middle Devonian such that most of the Huskisson–Que–Hellyer– Mackintosh region has granite 0–10 km below the present erosion surface (Leaman & Richardson 1989).

The structure of the Huskisson–Que–Hellyer–Mackintosh region is dominated by north-south to northeast-southwest trending folds and the Henty, Rosebery and Mt Charter Faults (Figs 1, 2). The Rosebery Fault has undergone major reverse movement, uplifting the Central Volcanic Complex many kilometres against the Dundas Group during the middle Devonian (Corbett & Lees 1987). The Henty Fault has undergone several phases of movement (Berry 1989) including major middle Devonian (pre-granite) reverse faulting, and several kilometres of subsequent, post-granite Devonian(?) strike-slip. Cambrian movement has also been inferred from the localisation of early porphyries and dykes within the Henty Fault zone (Corbett & Lees 1987; Corbett & Komyshan 1989). The Mt Charter Fault marks a dramatic thickening (to the east) of the Que–Hellyer Volcanics and the Que River Shale within the lower Dundas Group, and the fault was active during deposition in the Cambrian (Corbett & Komyshan 1989). The Mt Charter Fault has subsequently undergone minor reverse movement and sinistral strike-slip.

## DEVONIAN COMPRESSIONAL TECTONICS

The middle Devonian period of compressional tectonics in the Huskisson–Que–Hellyer–Mackintosh region has involved shortening about east-west to ESE-WNW axes. In order to quantify the amount of shortening across the region a balanced cross section (Fig. 3) and a restored cross section (Fig. 4) have been constructed along a ESE-WNW trend from near Luina, through the Que River mine to south of Mt Remus, perpendicular to the regional fold trends. In order to balance the cross section, the section must firstly be *admissable* (Elliot 1983), that is, utilising all available geological and structural constraints along and off the section line, and using structural styles of deformation compatible with those observed in the field. The balanced cross section must also be *viable*, that is, able to be restored to a reasonable and realistic

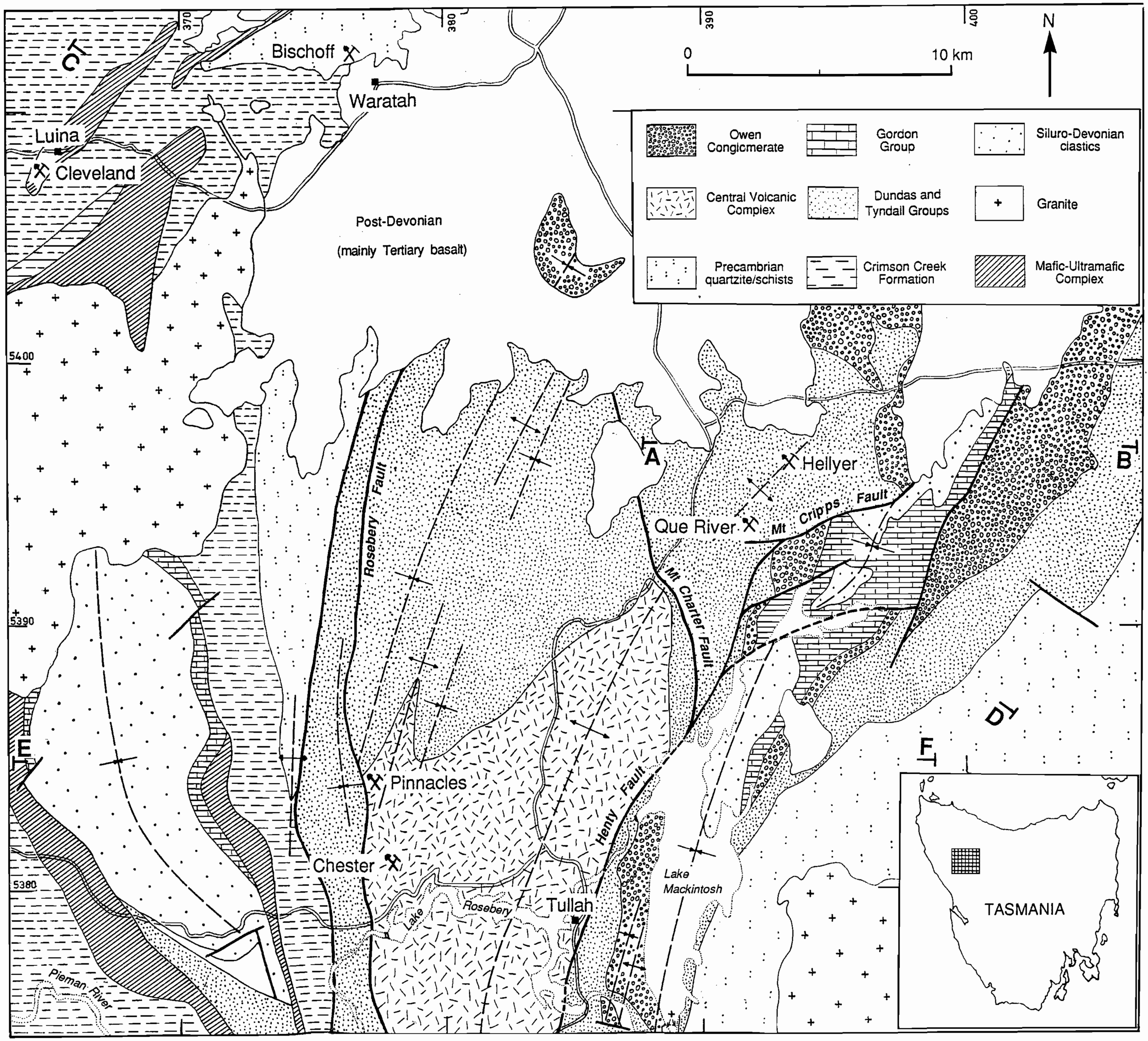

*Fig. 1 Regional structural and stratigraphic elements of the Palaeozoic geology of the West Coast, Tasmania (after Corbett & McNeill 1988).*

pre-deformation state. Classical balanced cross section construction is most successful and least ambiguous in areas with well known and well constrained layer-cake stratigraphy, with a single homogeneous and two-dimensional deformation. The Huskisson–Que–Hellyer–Mackintosh region has neither layer-cake stratigraphy nor strictly homogeneous deformation (such as cylindrical folding). In addition, outcrop is lacking in a number of critical areas, and these problems should be kept in mind when assessing the validity of the balanced cross section. In any event, a balanced cross section is not a unique solution, no matter how well constrained (Woodward et al. 1986). Nevertheless the balanced cross section represents an improvement in the structural knowledge of the area because crucial problems of stratigraphic volume conservation are addressed, and a number of structural possibilities have been effectively ruled out by attempting to balance them.

Construction of this balanced cross section has relied heavily on the position of the base of the Gordon Group limestone because this unit occurs both east and west of the area of interest and has been affected by the Devonian deformation to varying extents (Figs 2,3). The Gordon Group limestone does not occur between the Henty and Rosebery Faults, however, and the structural position of the limestone can only be partly constrained by the occurrence of the underlying Owen Conglomerate at Mt Pearse and by bedding flexures in the Dundas Group (assuming these three units were originally conformable in this area). The inferred folded section length of Gordon Group limestone between the Henty and Rosebery Faults is about 21 km (Fig. 3). To balance the section downwards, the present eastward dip of the Rosebery and Mt Charter Faults, and the westward dip of the Henty Fault has been assumed to have been maintained throughout their respective movement histories. Evidence for rapid changes in stratigraphic thicknesses of the Dundas Group (Fig. 5) across the Rosebery and Mt Charter Faults, and the confinement of the Central Volcanic Complex between the Rosebery and Henty Faults suggests a model of basin thickening towards listric normal faults. The amount of thickening is difficult to assess owing to poor internal stratigraphic control. The Dundas Group was divided into a number of arbitrary stratigraphic intervals of comparable thickness, and the base and top of each of these intervals was kept at a length consistent with the restored section model of steep, listric, east-dipping Rosebery and Mt Charter faults and a steep, listric west-dipping Henty Fault, that is, line lengths decreasing from 21 km down the section profile. Cross sectional area was also maintained in the Dundas Group. The Central Volcanic Complex was treated as a single stratigraphic unit of an arbitrary 3 km thickness, and cross sectional area maintained between deformed and restored cross sections. Because the Henty and Rosebery Faults converge at depth, to maintain line length and cross sectional area (and therefore stratigraphic volume) the folding seen on the surface must become progressively tighter, and the stratigraphy probably imbricated by blind thrusts at depth. Thus while a regional shortening of 16% is apparent, local shortening may exceed 50% at depth (Fig. 3).

Individual faults show large variations in the amount of fault displacement. The Rosebery Fault to the north appears to have undergone only several hundred metres of reverse component displacement (Figs 2,3), although this is dependent on the assumed position of the Gordon Group limestone east of the Rosebery Fault. Farther south the Rosebery Fault has undergone several kilometres of reverse movement (Corbett & Lees 1987). Similarly the Henty Fault has undergone 4 km reverse movement east of the Que River mine (Figs 2,3), whereas the extrapolation of the Henty Fault 6 km northward to the Cradle Mountain Link Road does not require any major truncation of the upper Dundas Group stratigraphy either side. The problem of the Henty Fault extension has not been satisfactorily resolved however. Displacement transfer from the Henty Fault onto the Mt Charter Fault (Fig. 1) is not likely to be significant given the relatively small reverse movement inferred for the Mt Charter Fault. The Mt Charter Fault also appears to be folded south of Mt Charter (Komyshan 1986) which would impede reactivation as a reverse fault. Displacement transfer onto, or truncation by the Mt Cripps Fault is a possibility but the continuity of the Cambro–Ordovician stratigraphy for at least 20 km eastward along the Cradle Mountain Link Road (Vicary & Pemberton 1988) precludes any major reverse fault truncation resulting from the northward extension of the Henty Fault. Another, most likely, alternative is that the shortening associated with the Henty Fault has been accommodated to the north by folding rather than discrete reverse fault displacement. The Dundas Group is steeply east-dipping in this area (Vicary & Pemberton 1988); considerably more so than the Ordovician–Silurian sediments east of the Que River mine (Fig. 2). If folding has taken up the Henty Fault shortening, then the magnitude of shortening probably decreases to the north.

## CAMBRO–ORDOVICIAN EXTENSIONAL TECTONICS

Restoration of this balanced cross section hinges on the Rosebery, Mt Charter and Henty Faults having maintained their present dip polarity. The restoration is partly based on a model of extensional basin development between the Rosebery and Henty Faults, which have localised deposition of the Central Volcanic Complex, the Dundas Group and related rocks. The amount of apparent extension is approximately 40%, which suggests a graben width of about 20 km in the mid Cambrian to early Ordovician. Any larger extension and graben width would require a correspondingly greater component of Devonian shortening for cross section balancing. Increased shortening would be apparent as isoclinal-tight folding and/or significant thrust imbrication resulting in major crustal thickening. None of these features are prominent in the structures currently exposed at the surface, effectively discounting major (>> 20 km) graben development and subsequent closure. Evidence for Cambro–Ordovician extension is based largely on stratigraphic control. Minimum isopachs for the Dundas Group have been calculated (Fig. 5) from small strip sections through areas of relatively planar, well controlled stratigraphy and suggest a dramatic thickening of the Dundas Group east of the Rosebery Fault, possibly reaching in excess of 10 km north of Burns Peak. West of the Rosebery Fault typical minimum thicknesses are around 2–2.5 km but parts of the section may be absent due to erosion, structural truncation or covering over. The consistency of derived thicknesses suggests however that the amount of section absent for these various reasons not significant. A 7 km minimum thickness is apparent to the south and east of Mt Dundas. East of the Henty Fault, the Dundas Group has been estimated to vary from 0.5–2 km thickness. North of Hellyer mine the Dundas Group does not appear to change thickness dramatically across the Henty Fault. The Central Volcanic Complex is apparently confined between the Rosebery and Henty Faults, and the complex is probably at least several kilometres thick, suggesting a major graben structure developed during eruption of the volcanics (Table 1, Fig. 4).

Normal displacement associated with the Henty Fault occurred during deposition of the Central Volcanic Complex and the lower Dundas Group, and movement possibly ceased during deposition of the upper Dundas Group and the Tyndall Group (Fig. 4, Table 1). The Rosebery Fault is inferred to have been an active normal fault throughout deposition of the

Table 1. Palaeozoic fault kinematics of the Huskisson–Que–Hellyer–Mackintosh region.

| | Mid-late Cambrian E–W extension | Mid Devonian E-W shortening | Post-mid Devonian N–S strike-slip |
|---|---|---|---|
| Rosebery Fault | large, >12 km normal near Pinnacles, decreasing rapidly to north, active through mid-late Cambrian | large, >10 km reverse near Pinnacles, decreasing rapidly to north active through mid Devonian | none known |
| Henty Fault | large, <6 km normal, active in mid Cambrian during deposition of the Central Volcanic Complex | large, >3 km reverse, decreasing rapidly north and south, active through mid Devonian | <4 km sinistral |
| Mt Charter Fault | <2 km normal near Sock Creek, active in late Cambrian, particularly during deposition of the Que–Hellyer Volcanics and Que River Shale | <0.5 km reverse, active in early mid Devonian, possibly folded in places | <100 m sinistral |

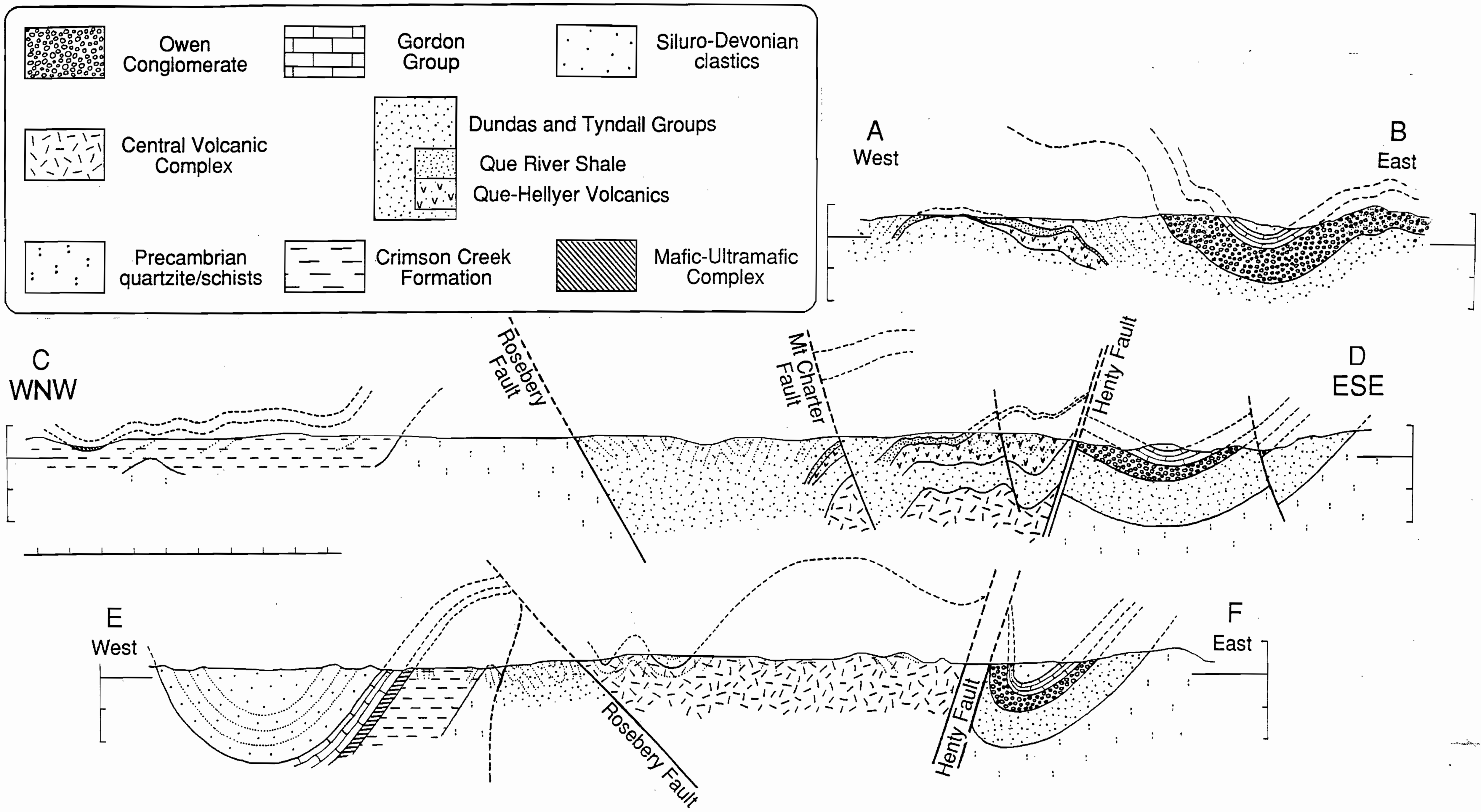

*Fig. 2 Summary conventional cross sections through the Huskisson–Que–Hellyer–Mackintosh region based on geological maps of Barton et al. (1966), Brown (1983, 1984), Corbett & McNeill (1986), Komyshan (1986), and Vicary & Pemberton (1988). Scale ticks at kilometre intervals.*

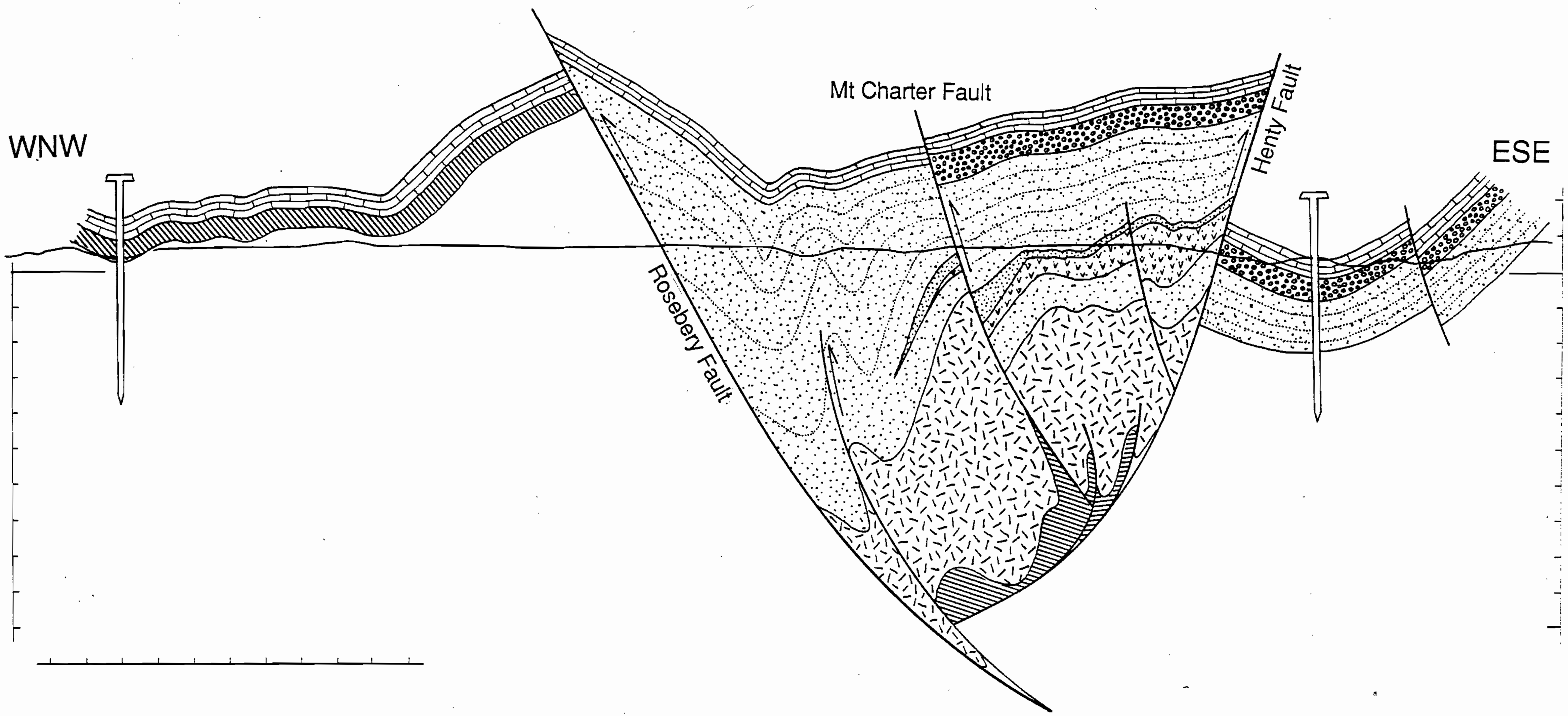

*Fig. 3 Balanced cross section along Luina–Mt Remus section (section C–D) of the Huskisson–Que–Hellyer–Mackintosh region. The combination of rapid variations in stratigraphic thicknesses, poor outcrop, the presence of angular unconformities, and variable fault displacement directions limit the accuracy of the balancing method. Legend as for Fig. 2. Scale ticks at kilometre intervals.*

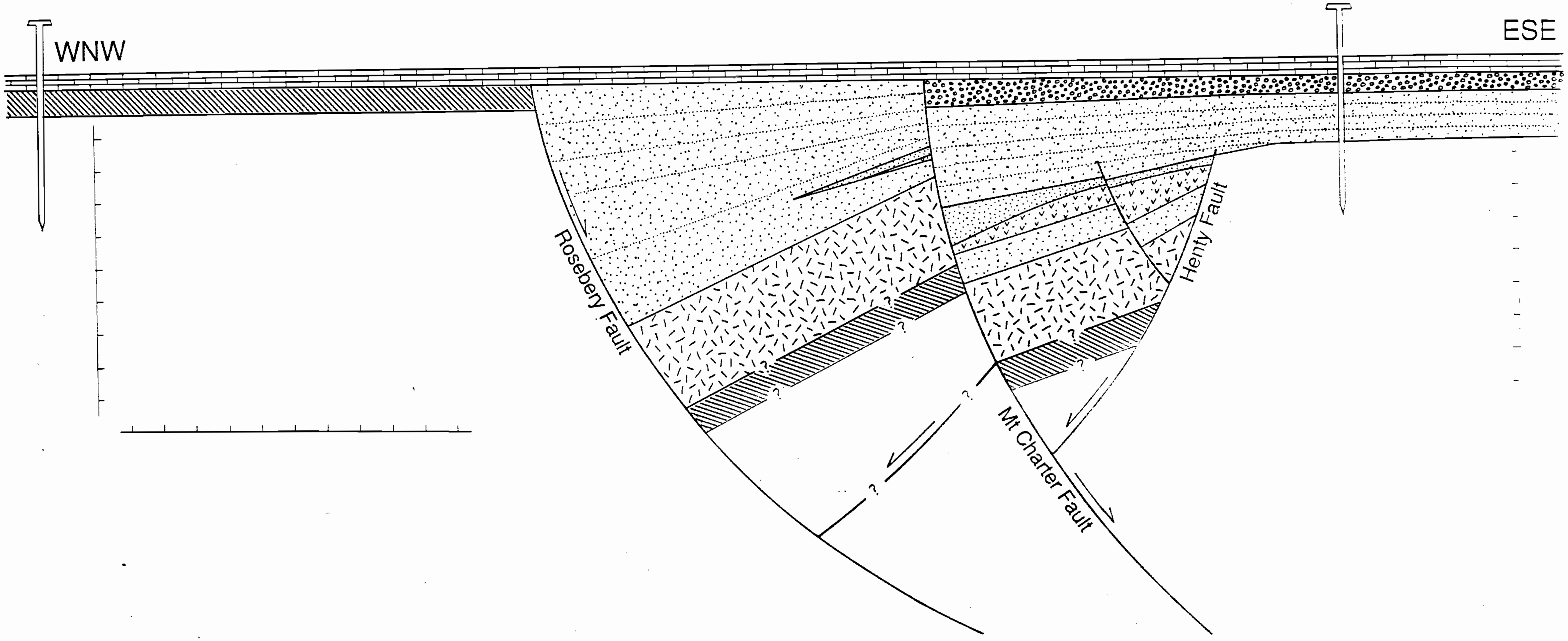

*Fig. 4 Restored cross section along Luina–Mt Remus section (section C–D) of the Huskisson–Que–Hellyer–Mackintosh region. Legend as for Fig. 2. Scale ticks at kilometre intervals.*

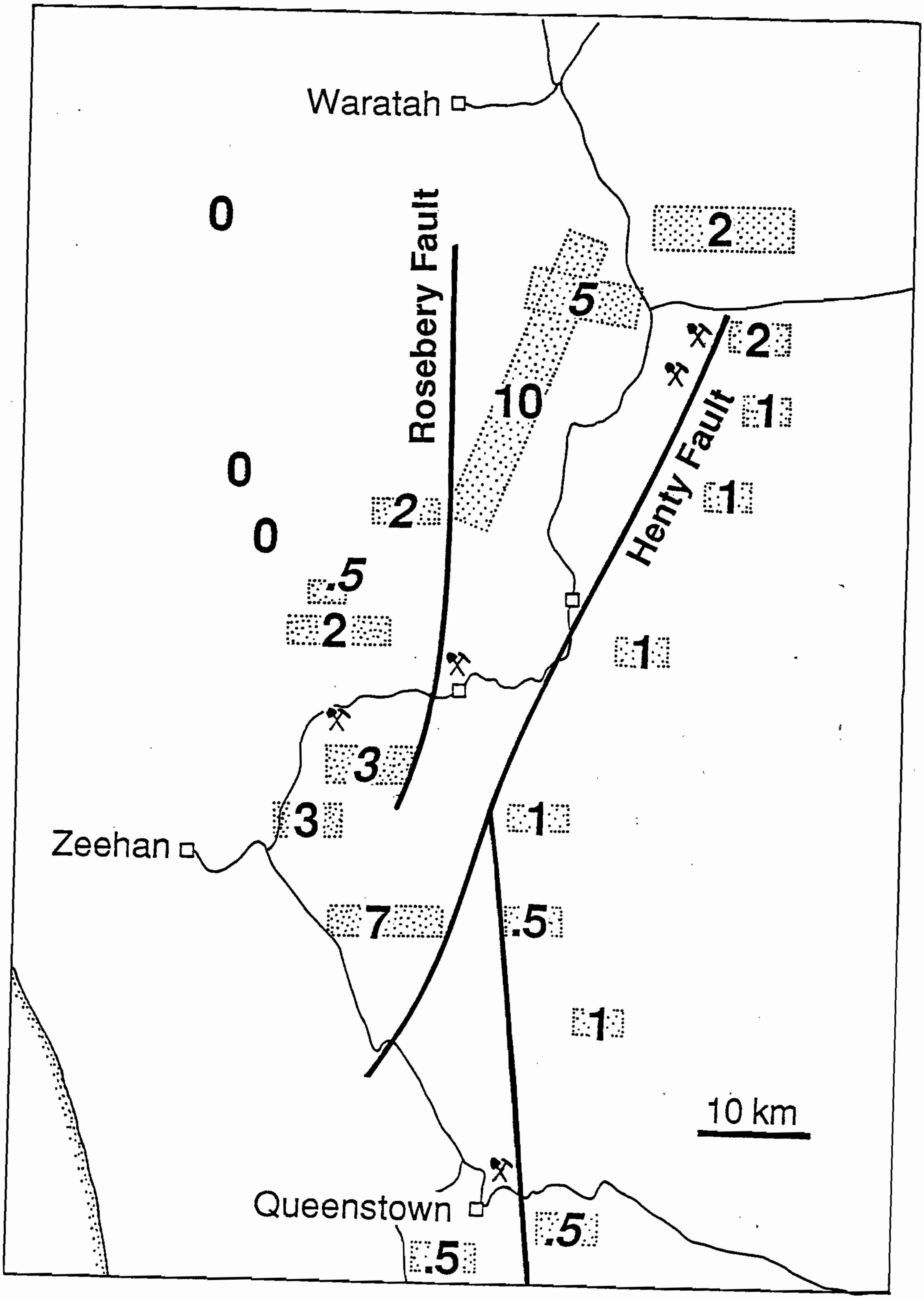

*Figure 5 — Isopachs for the Dundas Group, Tyndall Group and correlative rocks, suggesting a marked thickening between the Rosebery and Henty Faults. Thicknesses were estimated through sections (stippled) of well constrained structure and stratigraphy mapped at 1:63 360 by Barton et al. (1966), and 1:25 000 by Brown (1983), Corbett (1986), Corbett & McNeill (1986), Komyshan (1986), McNeill (1987), Corbett & Jackson (1987), Vicary & Pemberton (1988) and Corbett et al. (1989). Some sections are faulted or have been eroded or obscured and these thicknesses, denoted in italics, should be be regarded as minimum estimates.*

mid-late Cambrian volcanosedimetary succession. The Mt Charter Fault was a relatively late normal fault which resulted in substantial thickness changes within the Dundas Group, notably within the Que River Shale and the Que–Hellyer Volcanics. The Mt Charter Fault projects west of Mt Pearse and may have acted as a western boundary fault to Owen Conglomerate deposition in the late Cambrian–Ordovician (Fig. 4). The Mt Charter Fault probably truncates the early normal Henty Fault system at depth.

## IMPLICATIONS FOR ORE MINERALISATION

Active, syndepositional Cambrian extensional tectonics provides a mechanism for syngenetic ore mineralisation such as the volcanogenic massive sulphide deposits typified by the Hellyer, Que River and Rosebery mines. Active normal faults in regions of crustal thinning have characteristically high heat flows and are therefore likely areas for hydrothermal activity and mineralisation. The occurrence of many hydrothermal alteration systems including the Rosebery, Hercules, Pinnacles and Chester base metal mines, adjacent to the Rosebery Fault suggests relatively high heat flow along the fault during deposition of the Central Volcanic Complex. The high heat flow is compatible with the postulated major normal displacement along the Rosebery Fault. The Hellyer and Que River mines are similarly close to the Henty Fault system. The Hellyer massive sulphide deposit occurs across the Jack Fault, a relatively minor west-dipping fault with early normal movement (McArthur 1986) 1–2 km west of the Henty Fault. Minor normal faults in close proximity to major fault systems must also be considered highly prospective. The implicit two-dimensional nature of the balanced cross section, dominated by north-south trending faults, is too simplistic, and a three-dimensional normal block faulting pattern is considered to be more realistic. Thus north-south trending faults should not be the only prospective extensional structures in terms of Cambrian heat flow anomalies and hydrothermal alteration/mineralisation. Recognition of normal faults will be best achieved through a more detailed understanding of the local stratigraphy, but the faults can often be expected to show reverse reactivation in the mid Devonian.

## CONCLUSIONS

Devonian compressional tectonics in the Huskisson–Que–Hellyer–Mackintosh region have been dominated by north-south and northeast-southwest trending folds and reverse movement of the Rosebery, Mt Charter and Henty Faults. A balanced cross section has been constructed across the region by making two assumptions in the absence of outcrop or good stratigraphic control. Firstly, the structural position of the Gordon Group limestone between the Rosebery and Henty Faults is based on the position of the underlying Owen Conglomerate and the structure within the Dundas Group. This length ultimately controls the amount of shortening between the faults and across the section. Secondly, the dips of the Rosebery, Mt Charter and Henty Faults are assumed to have maintained their present polarity, that is, east-, east- and west-dipping respectively, throughout their movement history. The convergence of the Rosebery and Henty Faults at depth implies local shortening may exceed 50% whereas the overall mid Devonian shortening across the section is about 16%.

The restored section shows major normal fault displacements along the Rosebery and Henty Faults which have resulted in a north-south trending graben. This interpretation is partly based on calculated isopachs of the Dundas Group which show a marked thickening east of the Rosebery Fault, by the apparent confinement of the Central Volcanic Complex between the Rosebery and Henty Faults, and by stratigraphic thickness changes across the Mt Charter Fault. The total extension of the Precambrian–early Cambrian basement need only be around 40% and any further extension would require substantial and improbable crustal thickening through tight folding and thrust imbrication during the Devonian compressional tectonics. Tight folding and thrust imbrication are not well developed at the present erosion level. The graben containing the Central Volcanic Complex therefore would not have greatly exceeded 20 km width. The three major faults in the Huskisson–Que–Hellyer–Mackintosh region have shown evidence for both Cambro–Ordovician extension and mid Devonian shortening.

The major normal movements of both the Rosebery and Henty Faults has implications for the occurrences of ore deposit and mineral exploration. The major VMS orebodies such as Hellyer, Que River and Rosebery, and extensively altered and mineralised zones are confined primarily to zones adjacent to these large faults. The combination of active normal faulting during crustal thinning and volcanism/sedimentation has probably locally elevated the heat flow along these faults. Resulting hydrothermal systems, using the faults as fluid conduits, explains the occurrence of syngenetic deposits such as volcanogenic massive sulphide deposits in such regions. Normal faults active in the mid-late Cambrian are therefore highly prospective structures and their recognition will be best achieved by an increased understanding of the regional and local stratigraphy.

## ACKNOWLEDGEMENTS

This project has been jointly funded by an ARC research grant and AMIRA through participating companies Aberfoyle Resources, Pasminco, and Renison Goldfields. Thanks to Ross Large and Ron Berry for initiating the project and commenting on the manuscript. Especial thanks to the geologists of Aberfoyle Exploration for their help with field aspects of this project.

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# STRUCTURE OF THE ROSEBERY DEPOSIT

**R.F.Berry**
Centre for Ore Deposit and Exploration Studies, University of Tasmania

## SUMMARY

The structure of Rosebery is critical to defining extensions to the ore lenses. The mesoscopic structure indicates a relatively consistent east facing structure with only minor small scale upright folds. The mineralisation and its associated alteration all predate the strong Devonian cleavages in the mine. Most of the chemical, mineralogical, isotopic and structural evidence supports a Cambrian sea-floor origin for the deposit. Previous work in the area suggested that much of the lens repetition was caused by high angle reverse faulting along the cleavage.

The study of Rosebery for the AMIRA project is in its initial stage of checking this earlier work. The first check on faulting within the mine has defined one thrust surface with a movement of 130 m which causes much of the shearing within the G lens. However studies in the north of the mine suggest most of the lens multiplicity is primary. A Cambrian normal fault model is proposed to provide a direction for further work. This model suggests the focus of mineralisation is a series of north dipping minor normal faults which tap larger scale fluid flow in the hanging wall of the Cambrian Rosebery Fault.

## INTRODUCTION

The structural study of Rosebery follows a small, EZ-funded study on the style of the deformation in the deposit and its relationship to the mineralisation. Part of this study was reported at the 10th AGC (Berry 1990). As this study forms the starting point for the project, a relatively complete summary of the relevant aspects are included here. The AMIRA study aims to apply the structural ideas arising out of this work to a detailed assessment of the structural control on the geometry of the Rosebery ore lenses. It is in the initial stage and section 3 represents the state of developments at this time.

## STRUCTURAL SUMMARY

Throughout the host sequence at Rosebery, there is a strong cleavage with associated strong down-dip stretching lineation (Fig. 1). This structure is also evident in the barite lenses and in silicate-rich layers within the high grade ore. Strong reverse faulting occurs throughout the mine and is closely associated with quartz-carbonate veining. The cleavage is strongly developed near the faults and the veins are folded and boudinaged. These relationships indicate that the cleavage, faulting and veining were synchronous. The style of folding and faulting was characteristic of brittle-ductile deformation. All examples of bedding cleavage intersections were relatively shallow in plunge as were most fold axes. Most of the host sequence is east facing and zones of west facing are restricted to minor fold hinges. The host sequence has layering which closely resembles bedding. In two locations grading was found within this layering which confirmed the structural facing of the rocks. The style of deformation within the ore lenses is consistent with a strong component of rotational strain and a mylonitic foliation has been found in sphalerite galena ore from G lens.

The deformation style of Rosebery Mine is shown well in sections between E and G lens (Fig. 2). There is a gradational contact through chlorite pyrite alteration to pyritic ore and then into banded sphalerite rich ore. In 16 mezzanine level at 400N this then changes sharply into a conformable sequence of siliciclastics. A minor fold occurs within this sequence and then it is cut off by a fault with drag folding against the ore horizon. The ore is again conformable overlain by the less altered siliciclastics of the host sequence. Within a few metres the level of deformation in this sequence increases with a zone of fold tightening up against the next major reverse fault which again repeats the ore horizon. Associated with the tightening of fold closures into the fault the fold plunges steepen indicating the rotational nature of

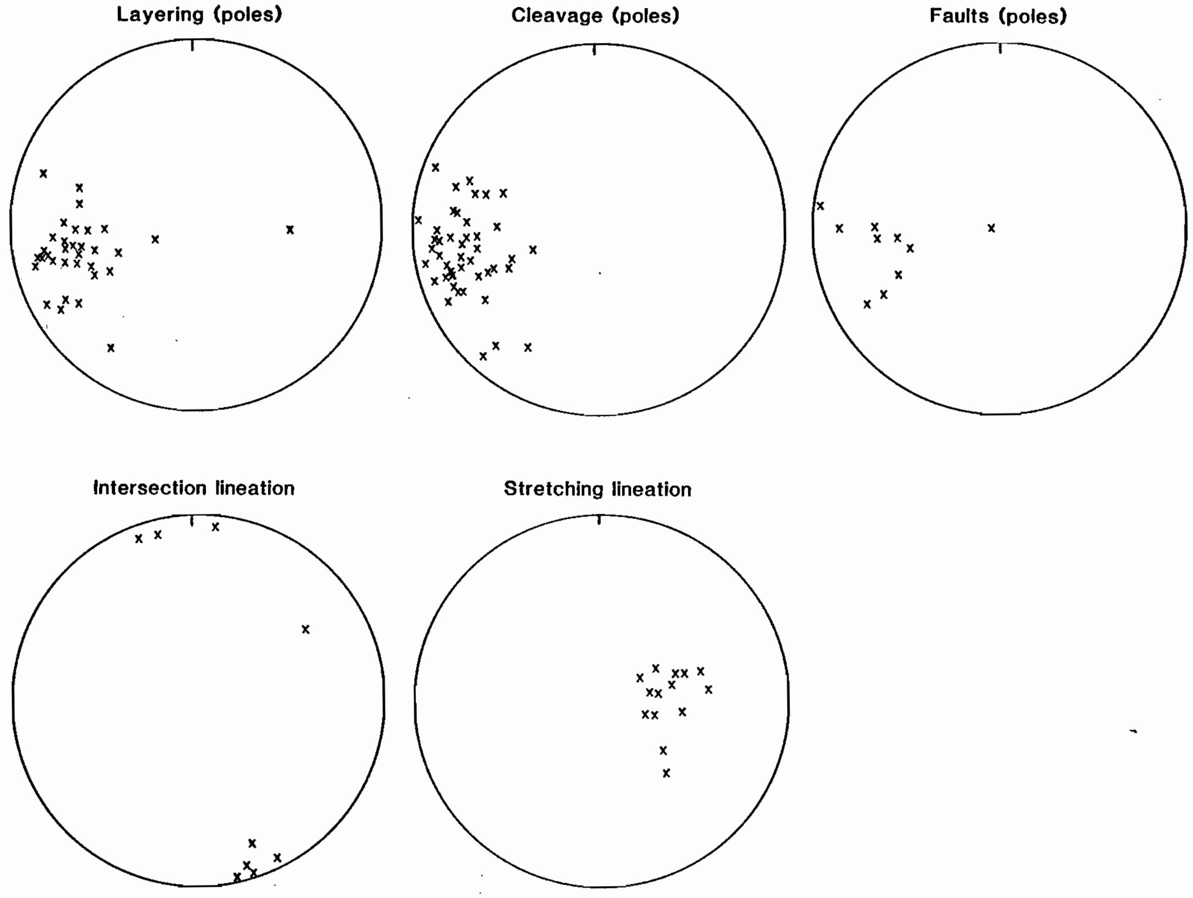

*Figure 1 — Equal area stereographic projections showing the orientations of structures measured in the Rosebery mine.*

deformation on the cleavage in the narrow zones near the fault where strain is concentrated. A very similar style of faults related to stratigraphic repetition is shown in sublevel 15/2 at 500N (Fig. 2). In combination with less well exposed sections, the mesoscopic structures observed in the mine strongly imply the main cause for repetition of the ore horizon is steep reverse faults. No structural evidence was found to support repetition of the ore horizon by folding.

In support of Devonian replacement models for Rosebery, Aerden (1990) has reported the existence of piercement structures across the banded ore. However these stuctures are identical to structures described by Gilligan & Marshall (1987) and interpreted as evidence for local scale tectonic mobilisation. The overwhelming weight of evidence summarised below indicates the ore is pre-tectonic, at least with regard to the commonly visible cleavage ($S_2$ of Aerden 1987) and faulting in the mine. Any relationship to a tectonic structure requires an earlier event for which there is minimal evidence available.

There is widespread evidence that the ore and its alteration halo is pre-cleavage. All the alteration assemblages are cleaved. The silicic alteration has a spaced cleavage. The chlorite-pyrite alteration and quartz sericitic alteration are very strongly cleaved with a downdip stretching lineation. In the latter case the cleavage is partly defined by flattened pyrite. Carbonate alteration has a cleavage wrapping around the carbonate spheres. There is no evidence from within the alteration zones of post cleavage alteration and no obvious evidence for syn- cleavage alteration.

Within the ore lens there is evidence of strong cleavage development. The barite ore is cleaved with a strong down-dip stretching lineation. Where chlorite-pyrite alteration grades into pyritic ore the cleavage is consistent within silicate-rich bands as these become thinner and less common. Within the ore, there are strongly cleaved and folded quartz chlorite lenses that are probable relicts of primary banding in the ore. Pyrite chalcopyrite bands are tightly folded with the cleavage parallel to the axial

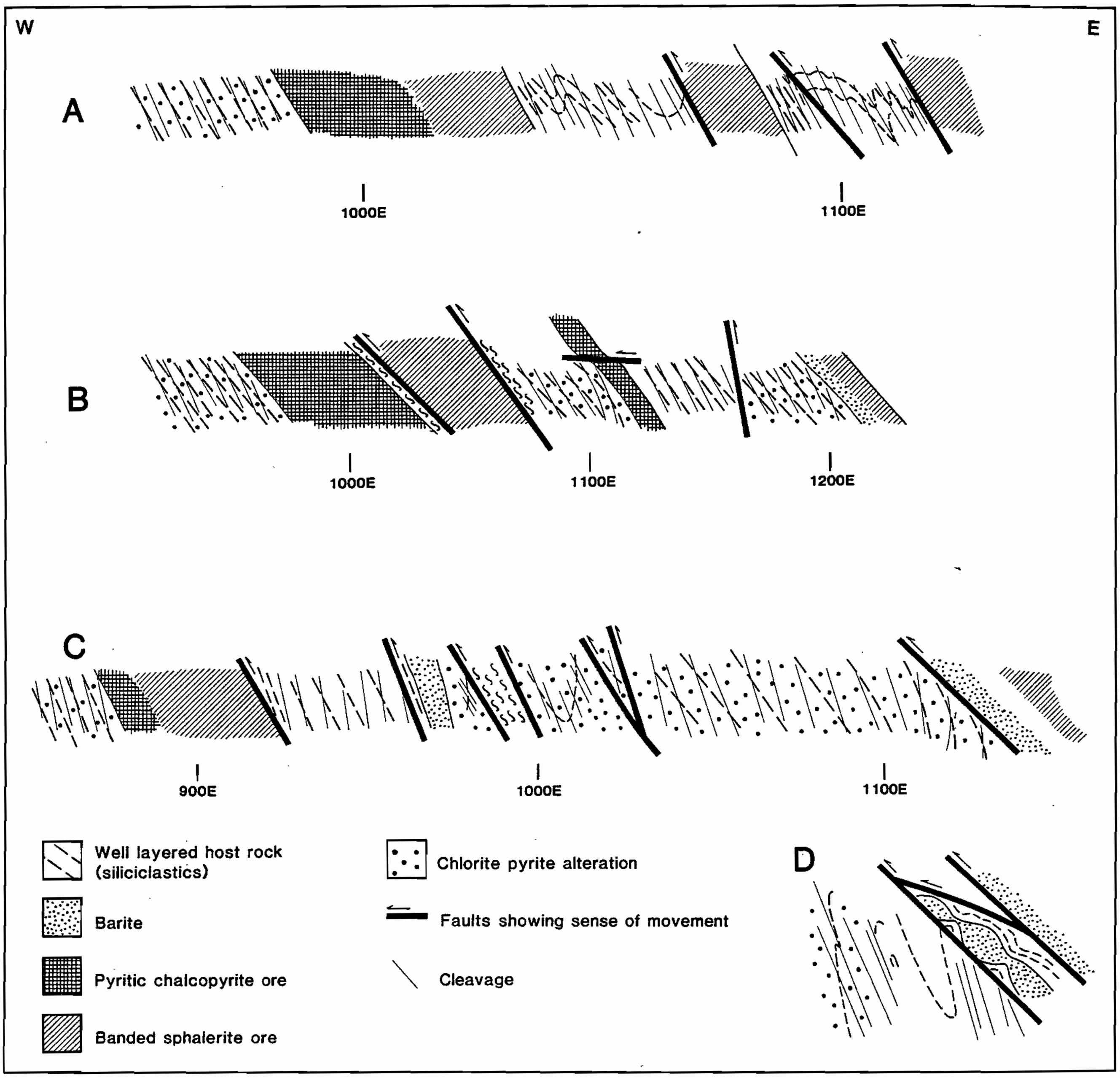

*Figure 2 — Sketches of geology on crosscuts from E to G lens. A, at 16 Mezzanine level 400N (120m N); B, at 16 sublevel 2, 740N (225m N); C, at 15 sublevel 2, 500N (150m N); D, at 15 sublevel 2, 800N (245m N).*

plane. Most of the ore is banded on a scale of 10–50mm. This banding shows gradational contacts to banding in the alteration zone below the ore and is conformable with layered sedimentary rocks above the ore. The overall geometry of the ore lenses is conformable with local stratigraphy. The layering within banded ore shows the same relation to the cleavage as bedding in the least altered host rocks. It is not parallel to the cleavage. The banding is strongly deformed around boudinage structures and syntectonic veins.

A tectonic foliation was recognised from polished slabs of banded ore from G lens. This foliation varies from a dimensional preferred orientation of chlorite to a 0.1–2mm scale layering. It is subparallel to the cm scale banding. The foliation is mylonitic in character. The coarse banding is boudinaged in the area where the mylonitic foliation is strong. Chalcopyrite and galena have been mobilized into extensional fractures during the boudin formation. Pyrite porphyroblasts have asymmetric tails and there are shear bands with a consistent reverse sense of movement. The textures in the ore support a strong rotational deformation overprinting a pre-kinematic coarse pyritic layering. The strong rotational fabric in the ore contrasts with the host sequence and suggests the ore lens has acted as a fault zone, probably because of the ductile nature of sulphides other than pyrite.

The structural evidence supports a three stage process for the evolution of the Rosebery ore: the development of a conformable massive sulphide deposit with widespread subhorizontal pyrite bands, intense rotational deformation of the ore with the development of a fine mylonitic foliation, and a patchy post-kinematic recrystallisation.

Syn-tectonic quartz carbonate veins are common throughout the mine. These are closely related to faults which are oblique to the cleavage and with drag of the cleavage indicating reverse movement. The faults were active during $S_2$ cleavage development as they produced strongly cleaved zones and the veins in the fault zones are folded and boudinaged consistent with continued flattening on the cleavage (Fig. 2D). The vein systems indicate syn-tectonic mobility of silica and carbonate and may suggest remobilisation of the ore. However these veins are variably mineralised depending on their environment. In barren host sequence they have no sulphide phase. In banded sphalerite ore they contain galena and sphalerite. In pyritic ore, they contain chalcopyrite. This is strong evidence that sulphides have not been transported by this fluid movement. In addition the vein systems are a minor component of the ore.

Where the boundaries of the ore lenses are not faulted the asymmetric nature of the alteration is apparent. Gradational contacts to the base of the E lens in 16 level are always into chlorite-pyrite alteration. Where the ore has a continuous sequence into the hanging wall, it is overlain by a relatively unaltered host sequence (Fig. 2).

In summary, while Devonian syn-kinematic fluids have produced quartz- carbonate veins throughout the mine, all the available evidence suggests that they did not introduce significant quantities of metals. Evidence from the southern portion of the mine (e.g. Solomon et al. 1987) suggests they have removed metals from the Rosebery ore lenses. The major mineralisation is pre-kinematic, conformable and has an asymmetric alteration pattern consistent with a syn-genetic origin.

## WORK IN PROGRESS

The primary aim of this project was to extend the structural model suggested by Berry (1989) and provide detailed assessment of its viability .The basic constraints on any structural model are that it:-

- predicts a conformable origin for the ore lenses before the faulting and cleavage development,
- explains the repetition of lenses within the centre of the mine and in general the overlap of minor lenses,
- does not require major fold repetitions, at least in the host sequence, and
- is compatible with the general style of brittle-ductile deformation widespread throughout the mine.

With this in mind the sections in fig. 3 were drawn based only on the geometry of the ore lenses and the interpretation that the most likely structure was a hanging wall duplex to the Rosebery fault. The metal zonation, combined with a knowledge of the distribution of alteration types and host sequence, has the potential for much more accurate reconstruction of the ore lens, including section balancing. Restored sections of the ore lenses would provide a clear guide to exploration below the present limits of the mine. The aim here is to progress this model to the point where individual faults can be identified in the underground development or in core and followed through the sections leading to the production of accurate restorable sections.

The first approach was to consider faults of other easily recognisable boundaries. A major offset of the upper contact of the host sequence has been recognised in the central part of the mine for a long time (e.g. Brathwaite 1974). While this offset has been explained by a number of mechanisms, reverse faulting appears to be the major model applied. On modern sections this offset can be recognised from drill core logs on sections at 300m N to 600m N. Structure contours of the Host sequence / black shale contact were drawn from these sections (Fig. 4) which

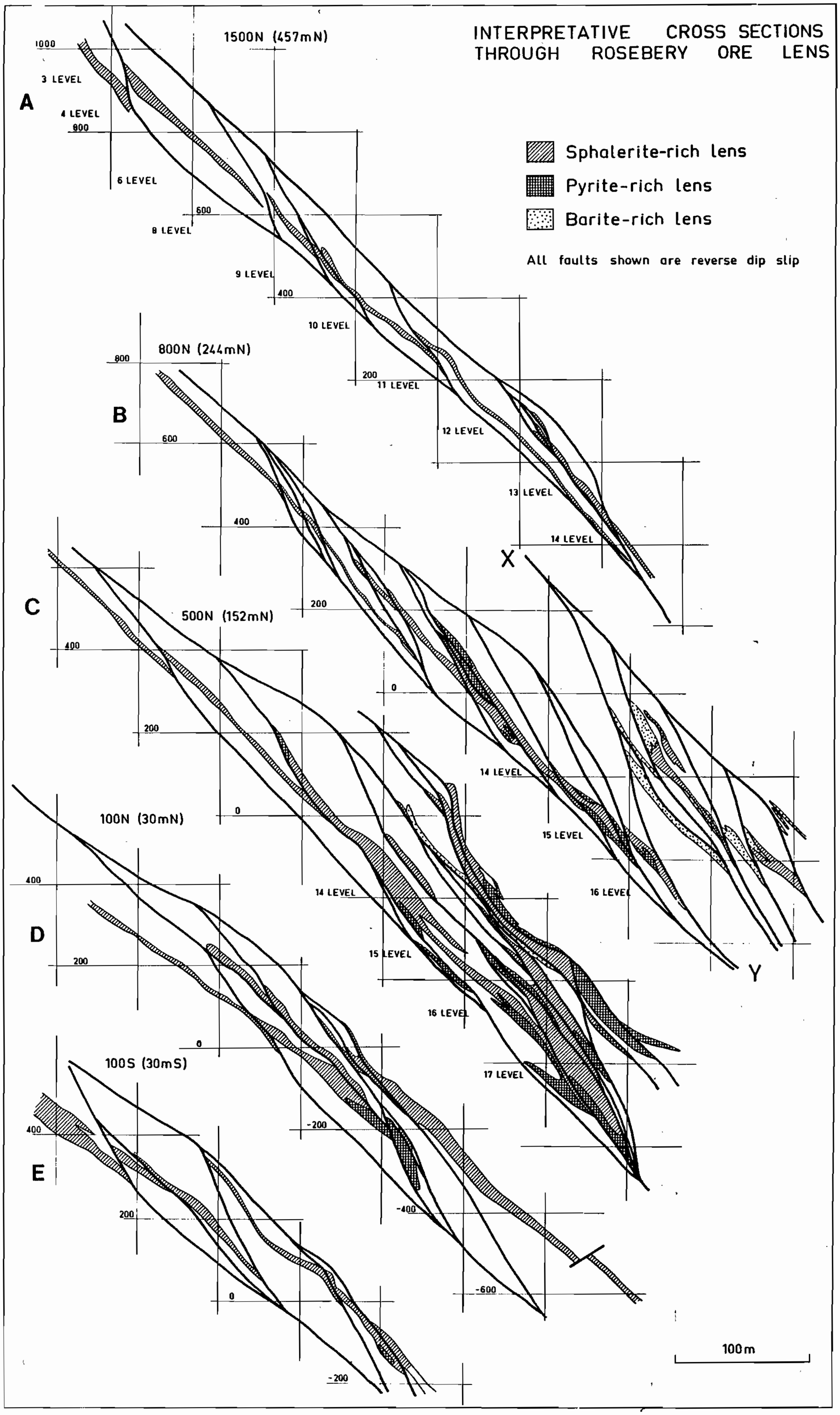

*Figure 3 — Interpreted structure based on ore lens geometry shown on 1:1000 mine sections from Berry (1989). The actual structure is probably simpler with only one major fault (XY in B).*

include exposures of the "fault plane" from 400m N to 500m N the inferred offset of this boundary, assuming dip slip motion, is 130 m. The projection of this structure to the east assuming it has a strike parallel to the cleavage intersects G lens and is clearly consistent with the fault shown as XY in section B of Fig. 3. This fault position is also shown on the 15 level plan (Fig. 4).

A second line of attack was suggested by Mike Quayle. The general shape of the ore lenses as a group in the area of E,F,G,H lens (Fig. 4) is reproduced on a smaller scale in level plans in North Rosebery (Fig. 5). In this area, previous work had failed to show any evidence for strong deformation and the structure appeared very simple. I spent a morning underground looking at all of the contacts relevant to the structure on 3 levels. While there was one reverse fault with intense cleavage development in the area it was not positioned in such a way that it could produce a structural repetition to explain the dramatic thickening and multiplication of the ore lenses at 1100 N as required by the level plans (Fig. 5). I subsequently looked at drill core from holes which pass through the critical areas and none of the critical surfaces showed evidence of intense deformation of the type common in G lens.

In brief, the change in thickness and increase in number of lenses from 1050 N to 1100 N cannot be explained by a duplex structure. The change appears to occur across an east-west sub-vertical fault very obvious on the level shown but very variable in its shape between levels. In the underground development this surface has only very weak fault striations related to Devonian faulting. There is very little evidence of dip slip movement on this surface and the long sections of ore thickness do not show any possible switch to thicker ore on the south side of the structure down dip which would support such a movement. The combination of no offset at the top of the bed and substantial offset at the bottom is the classic evidence for a growth fault. In a restored section (Fig. 6) this plan view is a section across a north dipping normal fault. The massive pyrite and associated low grade semi-massive ore is shown as subsea- floor replacement under an exhalative lens of high grade lead/zinc ore partly covered by a distal barite lens.

A quick overview of the deposit based on level plans, shows three structures like that at 1100 N. In the far south, at 19 level, the F/J lens shows a similar thickening against a near vertical fault. Again, the top of the mineralised section is a near perfect match implying that the fault movement ceased at the end of the mineralising event. The most complex and largest structre is in the 0m N to 400m N range. The relationship here is grossly similar to that at 1100m N but the termination is much more complex and as discussed above there is a substantial amount of evidence for Devonian thrusting. The dip slip movement in this event may not cause a major change to the pattern. If the structure at 300m S and 1100m N is confirmed, it seems likely that the structure in the central part of the mine is a deformed version of a similar growth fault. in this case the only major repetition required is that produced by the fault XY (Fig. 3).

The close association of three asymmetric structures, all interpreted as north dipping normal faults, with three major concentrations of ore within the Rosebery Mine suggests the normal faults have controlled the fluid focussing during mineralisation. At 100m N there is a massive pyrite zone and a general zonation away to more baritic ore especially at upper parts such as H lens and G lens. At 1100m N, massive pyrite is concentrated toowards the bottom and near the fault structure suggestive of a fluid focus. The massive barite forms a cap nearly over the centre of the proposed vent site. A comparison with metal zonation and especially Cu distribution should be useful in testing this hypothesis.

## FURTHER WORK

The result of the initial study of structures in the north and south of the mine, is to remove the requirement of a single lens in the structural interpretation and this vastly reduces the number of thrust faults required to explain the present shape. At this stage only the strong thrust zone through G lens is regarded as well demonstrated. Further work, especially on core, is required to look for other potential thrust zones. In addition, structural and associated metal zonation data will be assessed for each of the 3 zones of asymmetric thickening with a view to testing the hypothesis of north dipping normal faults in the hanging wall of the Cambrian Rosebery Fault controlling the mineralisation (Fig 6).

## ACKNOWLEDGEMENTS

I am indebted to the Pasminco Rosebery staff for the strong support they have given this project. The new ideas appearing in this report arose out of discussions with Mike Quayle and Gerald Purvis. Geoff Illiff provided encouragement and access to a wide range of company information.

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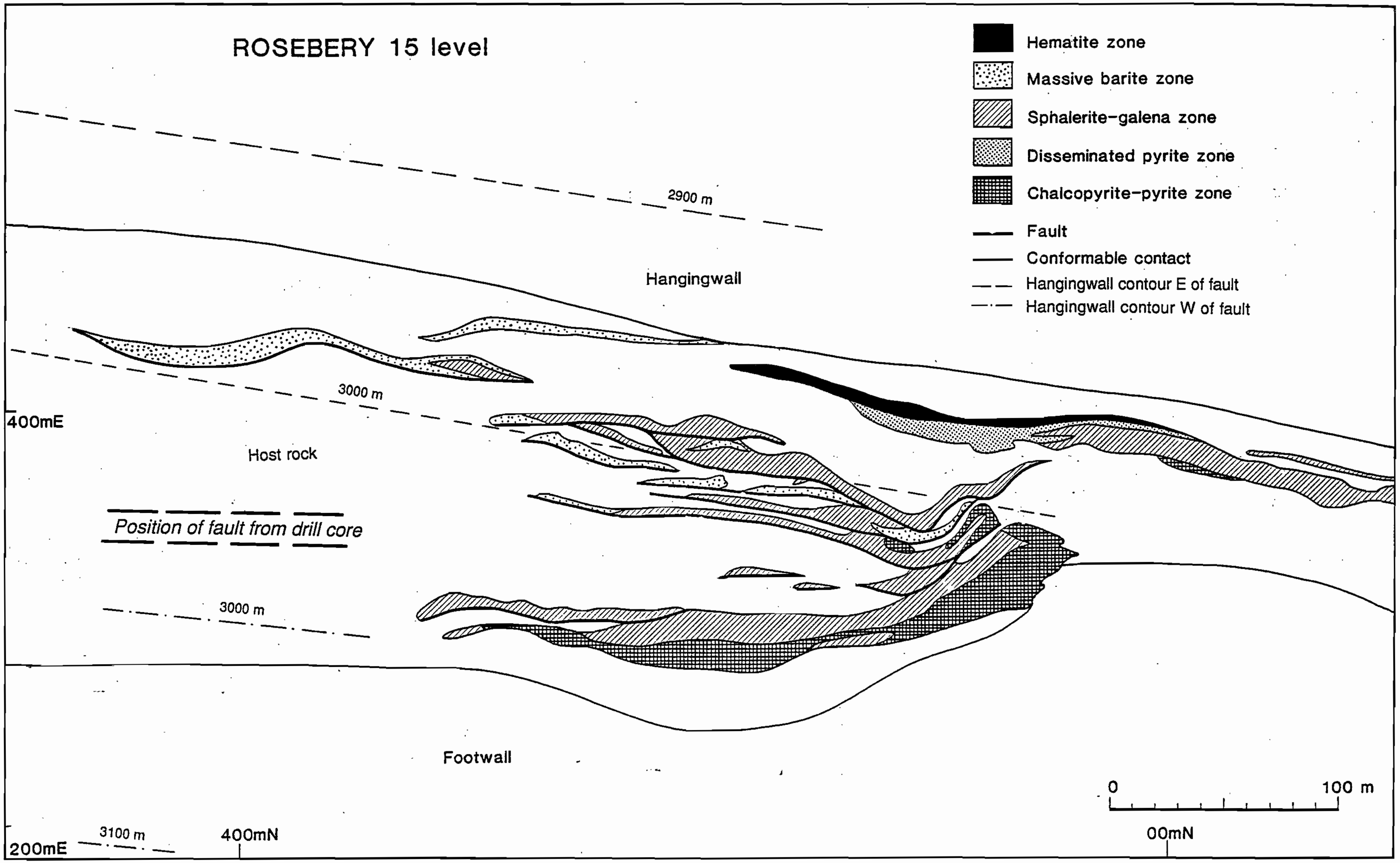


*Figure 4 — Geology of the 15 level showing probable thrust position. Lithologies are based on mine plans. Structure contours for the upper contact of host sequence are shown as is the position of the fault which offsets this structure by about 130m.*

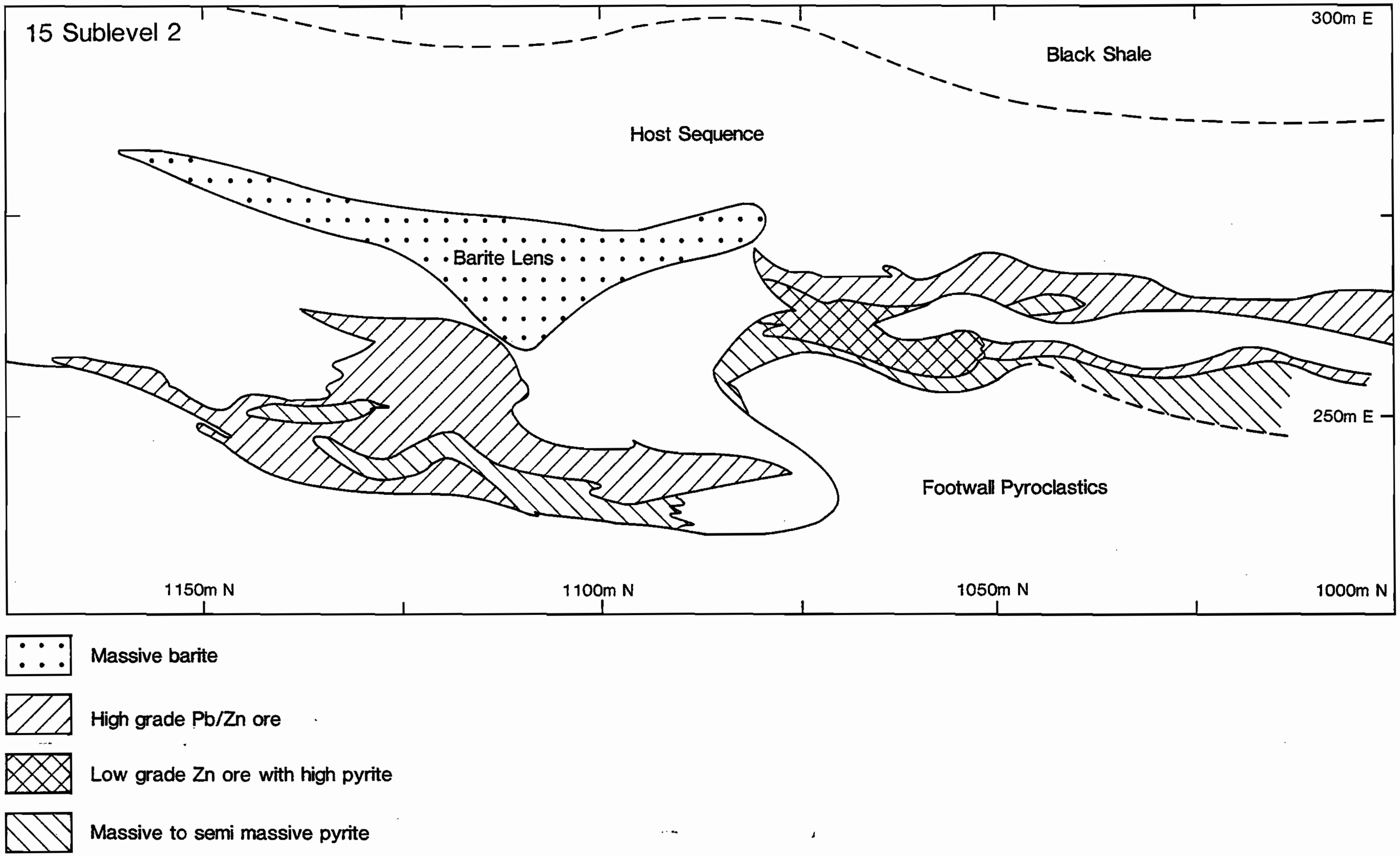


*Figure 5 — Geology of the 15 sublevel 2 plan in North Rosebery. Lithologies based on the mine level plan.*

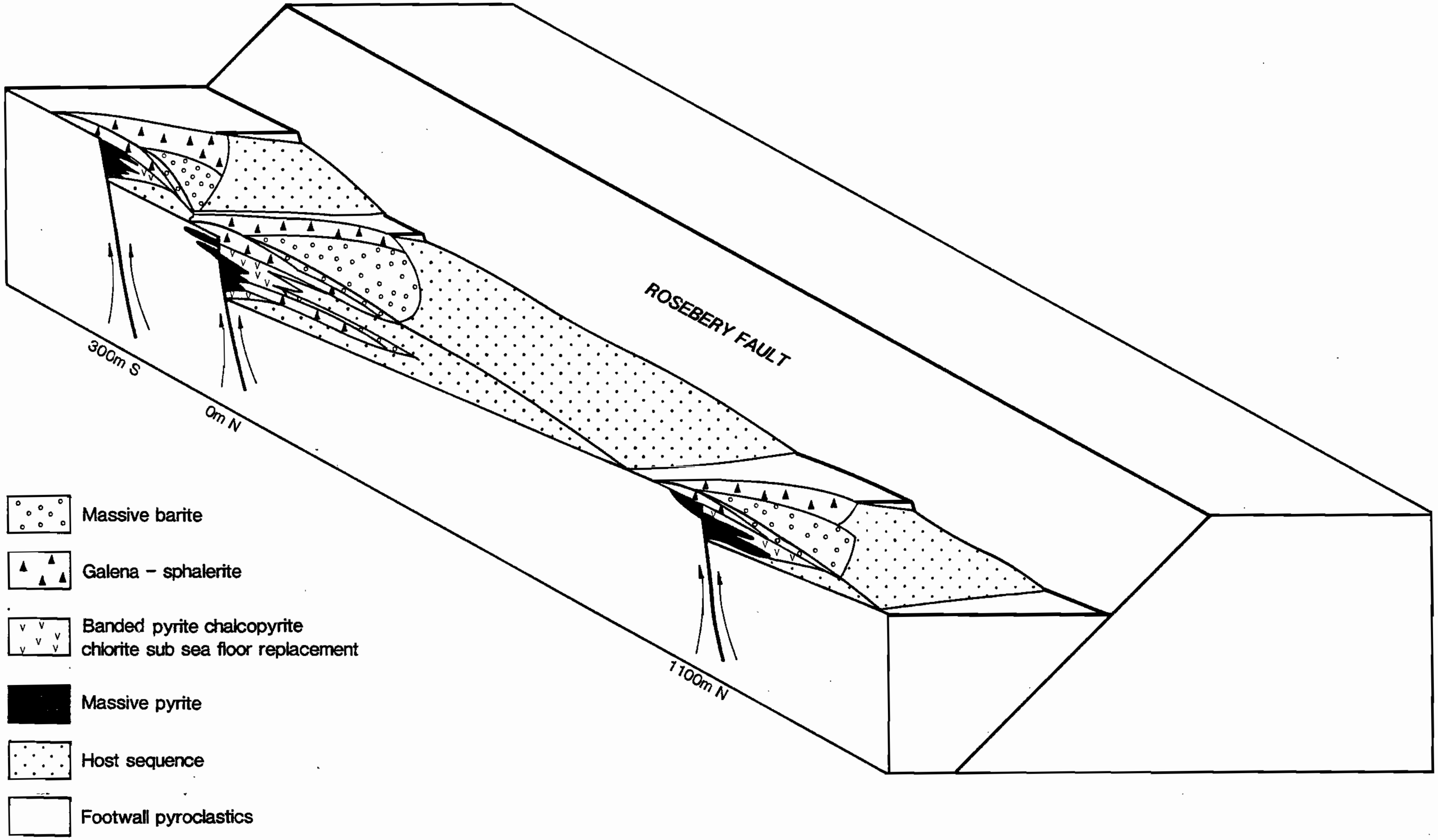


*Figure 6 — Interpretation of the structure of Rosebery during the Late Cambrian mineralisation.*

# STRUCTURE OF THE QUEENSTOWN AREA AND ITS RELATION TO MINERALISATION. INTERIM REPORT

**R.F.Berry**
Key Centre for Ore Deposits and Exploration Studies, University of Tasmania

## SUMMARY

Detailed fault striation studies on the faults in the Queenstown area demonstrated two phases of Devonian faulting consistent with the regional pattern of western Tasmania. The later phase ($D_2$) changes from upright tight folds in the Siluro-Devonian sediments to steep reverse faults in the Central Volcanic Complex with a transitional zone of tight angular synclines and open anticlines in the area of the mill. The early phase ($D_1$) is related to thrusting north and south of the Lyell alteration zone but mainly folding over the mineralised area. Major transfer zones are associated with this change in style.

Unfolding the Devonian structures, suggests there was a Late Cambrian normal fault margin to the basin of Owen Conglomerate deposition which has a complicated shape. The Haulage unconformity appears to be related to normal drag on this fault margin and no evidence was found to support an early Ordovician thrust event. The high grade oxidised ores of the North Lyell area are spatially related to the fault pattern interpreted for the late Cambrian. Field relationships suggest the vast majority of alteration associated with this mineralising event pre-dates the deposition of the Pioneer Sandstone. It certainly pre-dates both phases of Devonian cleavage. The most obvious interpretation for these bodies is that they form where reduced hot mineralised fluids are focussed up along the normal faults at the margin of the Owen basin and react with cooler oxidised connate water resulting from dewatering of the Owen Conglomerate. The result is replacement deposits on or near the Owen/volcanic contact.

## INTRODUCTION

### Aims

The AMIRA structural study of the west coast of Tasmania is an attempt to integrate detailed studies of fault movement history with the already comprehensive data set of lithological distribution and to a lesser extent fold patterns. The resulting structural synthesis will be applied to mineral deposits in the area. In part the emphasis on fault history reflects a major change in emphasis within structural geology in the last 20 years. It is now realised that faults form an intrinsic part of the strain history.

The following report relates to the second transect studied, from Strahan to Victoria Pass but at this stage only the structure in the Queenstown to Gormanston area has been studied. The initial study has concentrated on the complex structure around the Mt. Lyell mineral field. This report represents the half way point in the study of this transect.

### Methods

The geology in the Queenstown area is some of the best mapped on the west coast, partly because of the excellent access and exposure. In contrast the structure of these rocks remains obscure and the topic of controversy. Critical outcrops in the area and especially the "Great Lyell Fault" (GLF) have been checked against the original description. Substantial effort has been made to record fault striation data from previously mapped faults. The distribution of the Pioneer Sandstone on the north and eastern outskirts of Queenstown were remapped as these provide the most reliable evidence for $D_2$ folds across the western part of the area. The remainder of the area has been subject to reconnaisance studies for evidence of cleavage and bedding orientation to test the existing data sets.

A few lithological boundaries within the volcanics were checked but within the aims of this project, it is not possible to remap these. The checking largely supported existing mapping but emphasized the difficulty of reliably recognising rock types within the altered areas.

Finally, a substantial proportion of the effort has gone into assessing the very large existing data base in order to provide an interpretation which is consistent with all the data available to me. At this stage I have not attempted to consider the primary drill logs but have used previous reports to obtain lithological distributions below surface.

The names of major structural elements discussed in the report are shown in Fig. 1. Some of these are informal names which are applied here to aid the discussion and have not been previously defined (e.g. Queen River Detachment, Glen Lyell Fault, East Queenstown Fault). The term "Great Lyell Fault" was first introduced by Gregory (1905 in Arnold 1985) for all the volcanic/conglomerate contacts. While this usage tends to obscure the differences between movement history on the various segments of this contact, I have adhered to this definition. In the text, GLF is used as the abbreviation for these structures.

## Previous Work

The list of previous work in this area is very extensive and includes published papers, unpublished company reports and a number of unpublished theses. This study has been strongly influenced by the recent overview of Arnold (1985). Other important references were Wade & Solomon (1958), Solomon (1964), Cox (1981) and the major maps, both the 1:5000 compilation provided by RGC and the new 1:25000 maps from the Mount Read Mapping Project. With the large range of views previously expressed, almost all ideas proposed here have probably been suggested before. I have attempted to provide references to early workers where I agree with them but since my perusal of the earlier literature was not complete, I apologise to anyone not mentioned.

## DEVONIAN STRUCTURE

The structure of the Lyell Leases has been complicated by a long history of fault reactivation on a variety of trends. The strong Linda Zone fold and fault trend plays a substantial part in the complication and this is a problem that is largely restricted to the Lyell area. Because of this complication it is necessary to unravel the structural history starting from the youngest structures and gradually approach the older structural picture. This report follows this approach. At this stage the structures associated with the Devonian $D_2$ event are the best known and can be defined with a reasonable certainty. The following discussion of the Devonian $D_1$ and Cambrian events are provisional but reflect my present ideas and their significance to the development of the project.

## Fault Movement History

Detailed studies of fault striation data associated with the exposed major faults has been carried out wherever suitable material has been found. These are directly relevant to movements on the nearby major faults and have been grouped in this manner for this discussion.

*Firewood Siding Fault* The Firewood Siding Fault is a major feature within the Mount Read Volcanics. The steep dip and E-W strike are anomalous. The orientation has been used to associate this fault with the Linda Zone by previous workers. While the fault is not well exposed within the area studied, many minor synthetic faults occur near the inferred trace (Location 1 in Fig.2). These faults are consistent with the north south shortening during $D_2$ (Fig.3). The orientation of stress during this phase is not likely to produce major movement on the Firewood Siding Fault and my interpretation is that they reflect minor reactivation of an older structure. The structure across this fault is shown in Fig 4. where the overall character contrasts with the syn-$D_2$ thrusts to the south.

*Glen Lyell* A major NNW striking fault zone cuts through the Glen Lyell area to the west of the major mineralised zone (Fig. 1). This fault zone forms the boundary from apparently east facing lithologies in the east, to the west facing sediments exposed in Conglomerate Creek (Cox 1981, and others). Fault striation data was collected from a broad zone near location 2 in Fig. 2. The fault history is dominated by dextral fault zones (Fig. 5b) which overprint syn- $D_1$ reverse fault striations (Fig.5a). The late movement ($D_2$) is very clear with two active planes of faulting where the fault cuts the Highway but a large number of other fault planes throughout a zone about 1 km wide. This zone forms a major transfer zone with fold and fault style to the east very different to that to the west.

The nature of the early reverse faults is less clear. Both west and east dipping minor fault planes are found in this area but the east-dipping faults are more common. However extension of this zone to the south suggests it should be an east side up fault to lift

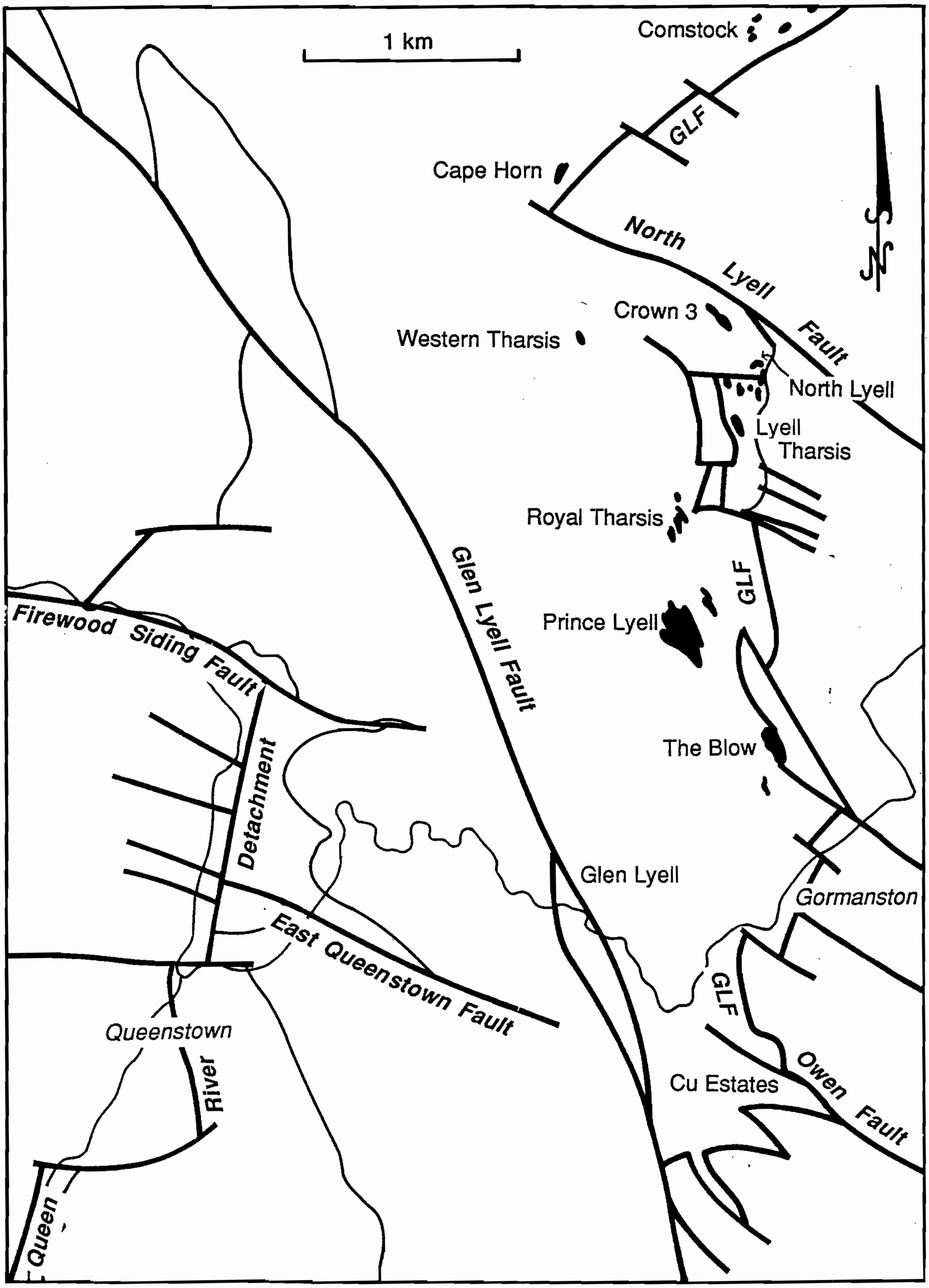


*Figure 1 — Locations of structural features referred to in the text.*

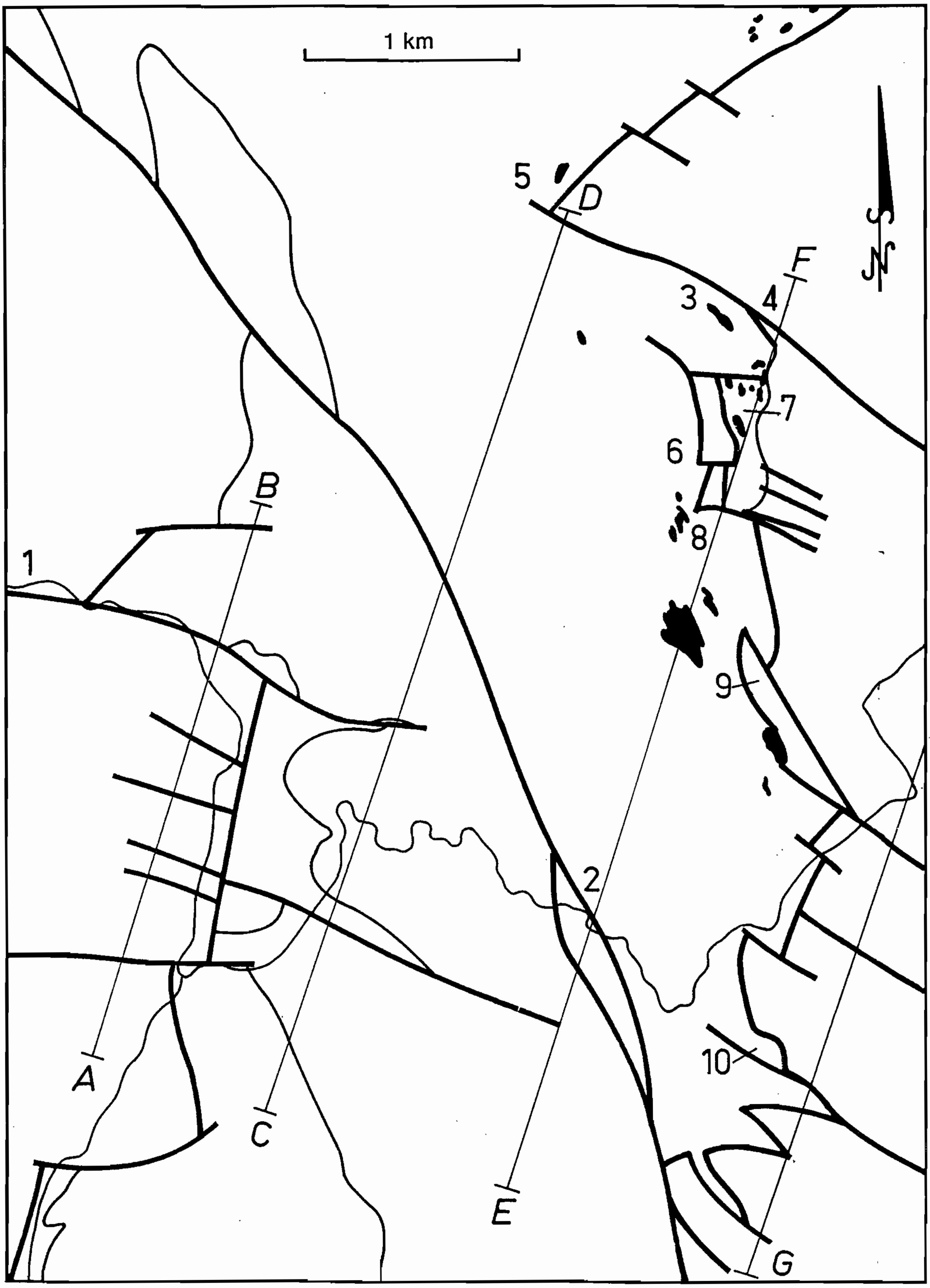


*Figure 2 — Locations of areas from which striation data are reported. Positions of section lines for Fig. 4 are also shown.*

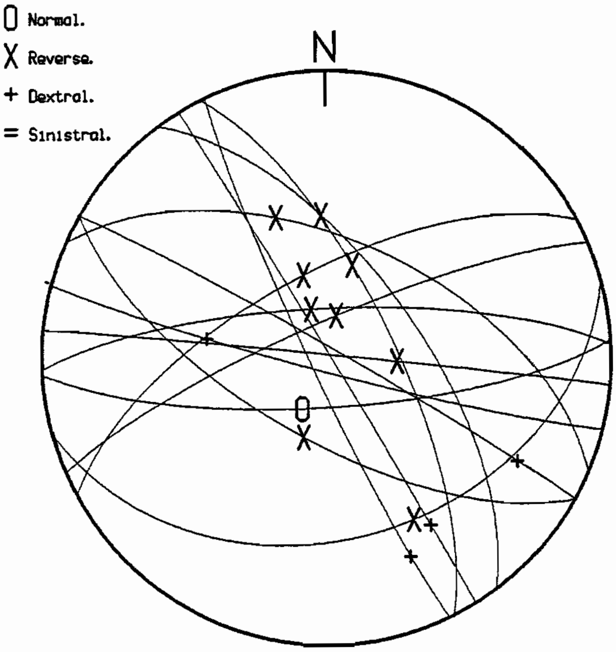


*Figure 3 — Fault planes and striation data for $D_2$ fault movements near the Firewood Siding Fault.*

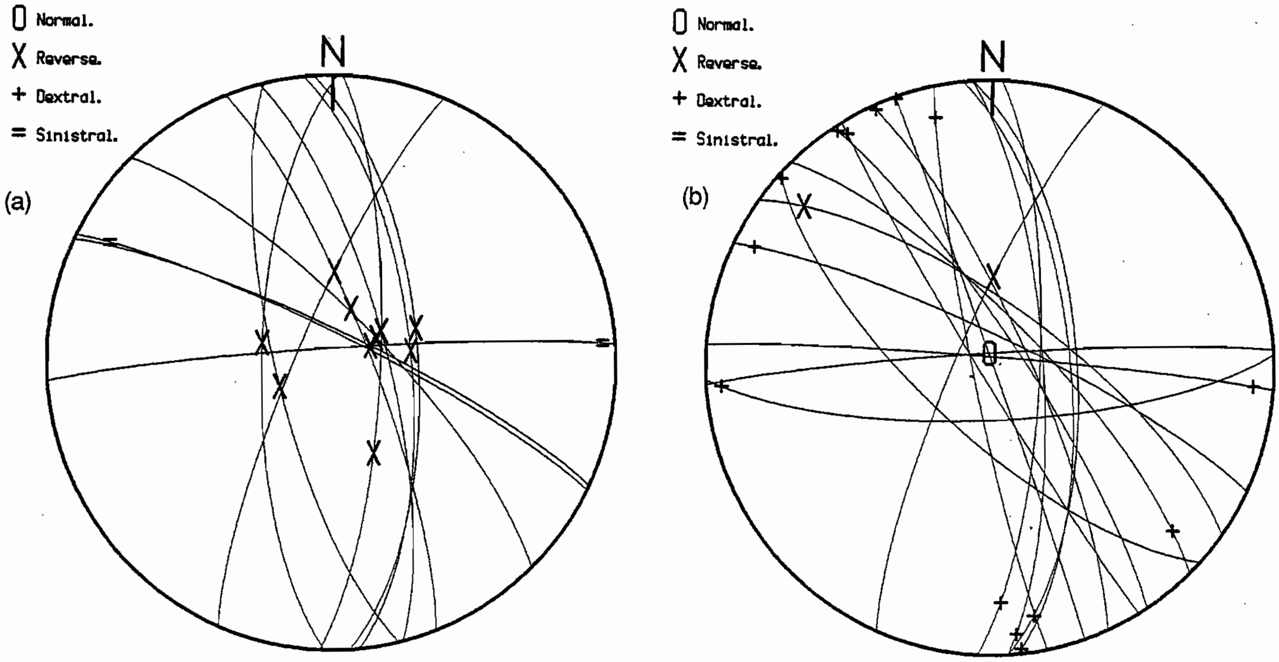


*Figure 5 — Fault planes and striations from the Glen Lyell area. a) $D_1$ fault movements. b) $D_2$ fault movements.*

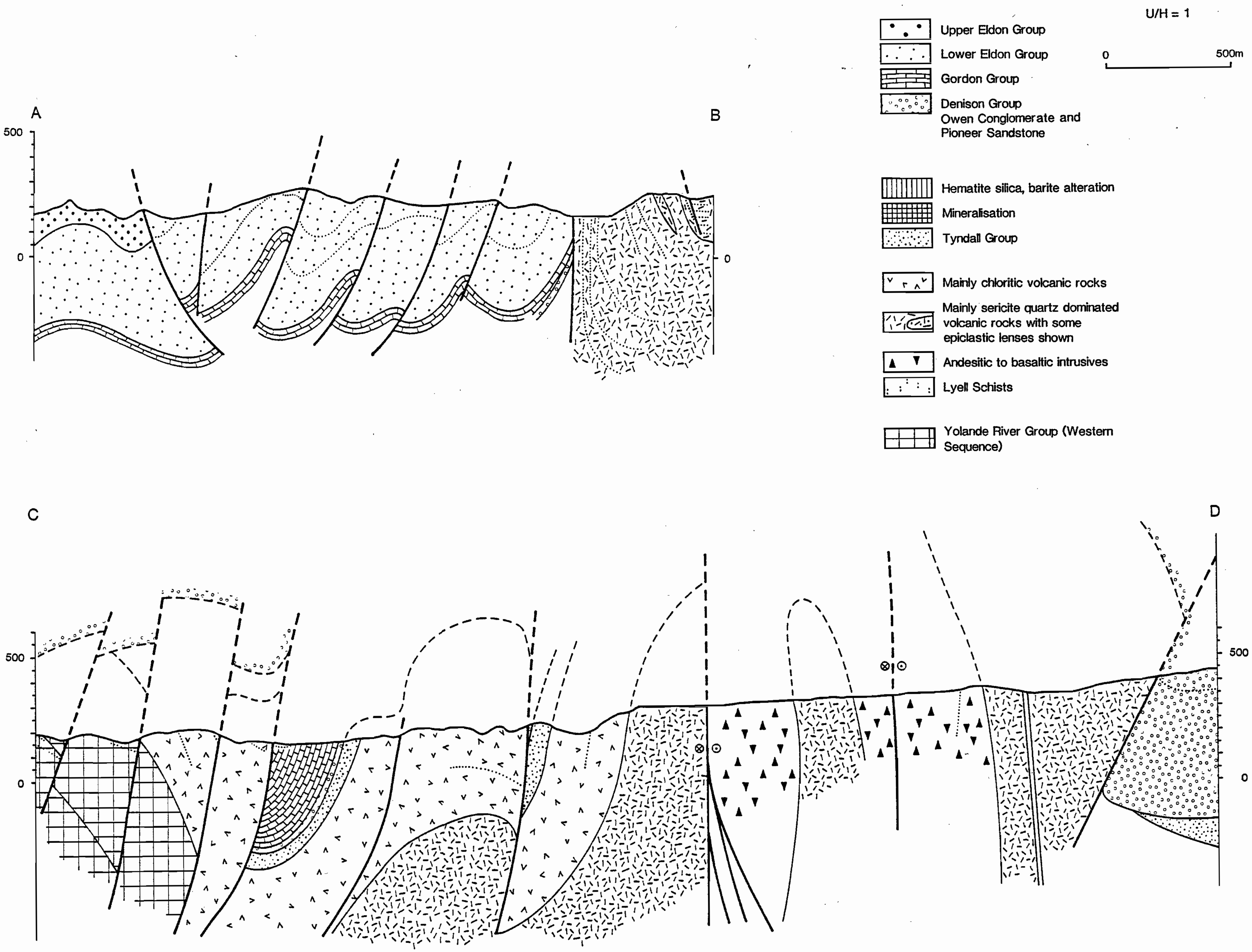
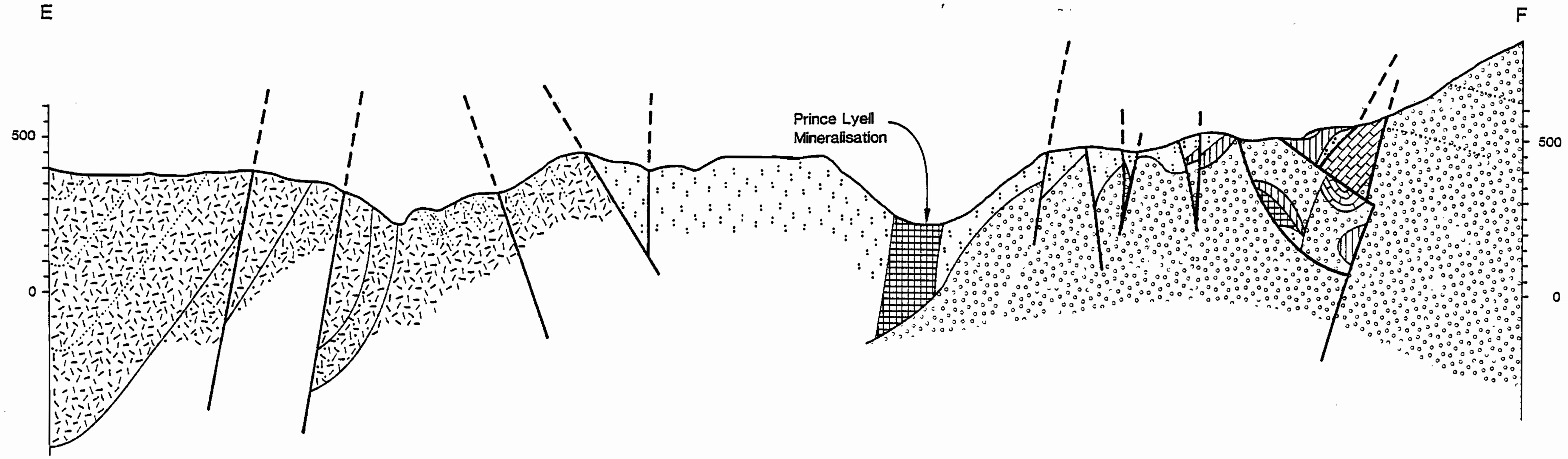


*Figure 4 — 4. Detailed cross-sections of the Mount Lyell area drawn to show D2 structures. The positions of sections are shown in Fig. 2. Sections are based on Gold Fields Explor. 1:5000 series 1986, Corbett et al 1989 and minor additions from this project.*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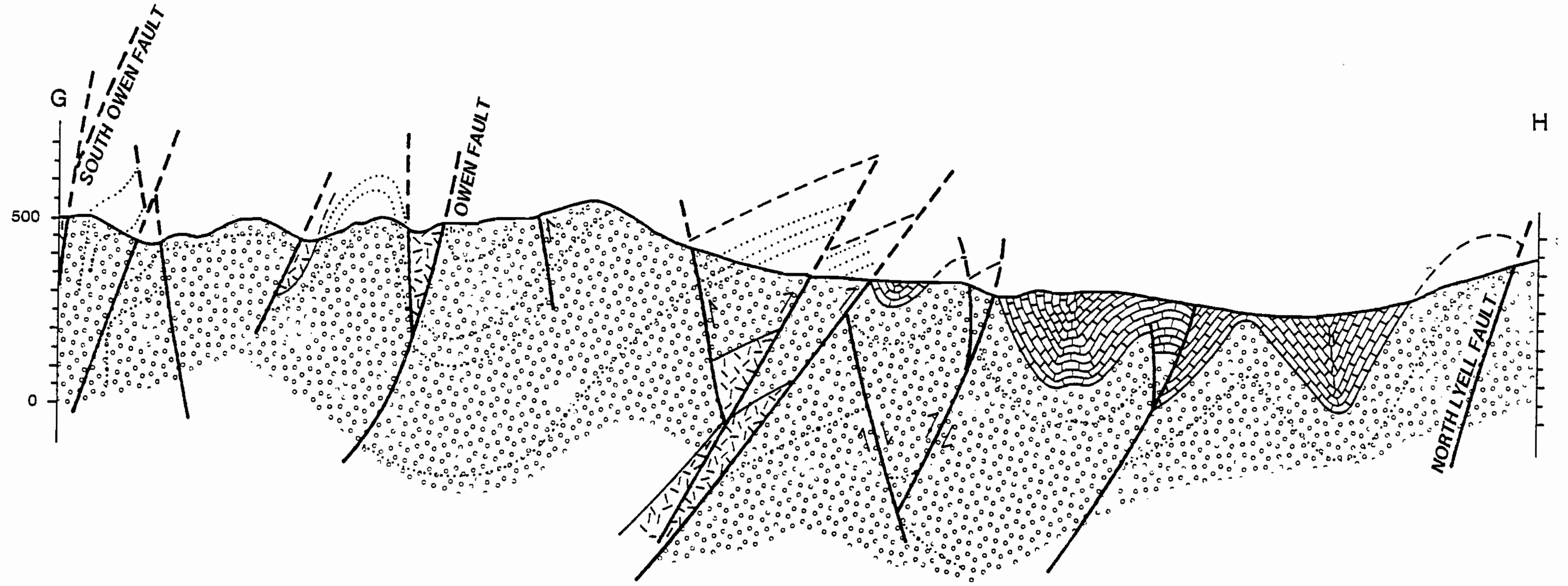
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the Central Volcanic Complex against the Owen Conglomerate. To the north of the Lyell Highway this reverse movement was not identified. My interpretation is that the movement on this fault zone was transferred to a "monoclinal structure" (Cox 1981) over the Lyell mineralised zone (see Fig. 21) and that this transfer zone was a mirror image of the North Lyell Fault at that time. The amount of dextral slip on this zone during $D_2$ can be estimated if the continuation of the Firewood Siding to the east can be correctly identified. While no fault is an exact match, the Owen Fault is the best candidate. It has been a strong fault during $D_2$. There are fault striations typical of a syn- $D_1$ wrench fault striations on the Lyell Highway along the proposed continuation of this fault. The Cu Estates area has extensive alteration suggestive of a long lived feature. While all this is circumstantial, no other fault in this area has any evidence for an early history. Further work is required to substantiate this correlation. The correlation implies a dextral slip of about 1 km on the Glen Lyell Fault during $D_2$.

*Queen River Detachment* The poorly exposed area along the Queen River is interpreted as a detachment zone active throughout the Devonian deformation. So far I have only been able to find fault striations associated with syn-$D_2$ dextral fault movement. These are exposed in sandstone at the Queenstown tip. While this zone has classically been considered an unconformity (e.g. Corbett 1979) it has many features which suggest more affinity with the low angle detachment tentatively recognised by Baillie & Corbett (1985) near Strahan.

Cross-sections across this zone (e.g. Fig. 4) reinforce the visual impact of the geological features of the area. In the section, the Cambrian lithologies are grossly discordant with the post-Cambrian units along this zone. A high angle unconformity is required if this is the original sedimentary contact.

While the mesoscopic structural data are scanty, the only alternatives are that the volcanics of the western sequence were strongly folded in the late Cambrian or that a major detachment surface seperated the older rocks from the Pioneer Formation and younger sediments during $D_1$. Firstly the fold structures in the volcanics which have $S_1$ parallel to their axial planes are tighter and shorter in wavelength than the folds in the immediately overlying rocks giving the appearance of an high angle unconformity. Away from this zone there are only low angle unconformities between these units and this stage there is insufficient evidence to support asymmetric folds in the Cambrian in which one limb remains horizontal. Secondly, the Gordon Group along this zone is highly variable in thickness in a way that cannot be ascribed to facies variation.

Further study of the Queen River Detachment is required to identify the influence of this structure at Mt Lyell.

*North Lyell Fault* The North Lyell Fault must be considered in two segments. The western segment (location 3 in Fig. 2) has a shallower dip and has been strongly reactivated as a reverse fault during $D_2$. The eastern segment (location 4 in Fig. 2) has split into two parts. The northern, and major fault trace is dominated by syn-$D_1$ sinistral wrench faulting (Fig. 6a). This is weakly overprinted by a syn-$D_2$ normal movement. The strong $D_2$ reverse movement (Fig. 6b) carries through on the southern branch and partly as a series of ductile shear zones throughout the North Lyell corridor. This bifurcation leaves the isolated slice of Gordon Group against the main North Lyell fault scarp.

*Cape Horn to Comstock section of GLF* The major fault contact at Cape Horn (location 5 in Fig. 2) is dominated by reverse fault striations with a small dextral component (Fig. 7a). These record stress conditions compatible with syn-$D_1$ movement. The reverse fault striations are overprinted by weak sinistral wrench movement (Fig. 7b) which I correlate with $D_2$ strain. The relative intensity of these structures suggests the GLF in this sector was not strongly reactivated in the $D_2$ event. While studies at Comstock are very preliminary at this stage, they support a syn-$D_1$ oblique dextral movement on this fault plane as the most important Devonian event.

*Western Side of Tharsis Ridge segment of GLF* Most of the western side of Tharsis Ridge (location 6 in Fig. 2) is not strongly faulted. The lithologies on both sides of this contact are sub-parallel to the contact and are in normal stratigraphic order. Thus there is no direct evidence for very large displacement on this surface. Where fault striations are recorded they indicate oblique reverse dextral movement (Fig. 8). The moderate south plunge of the lineations is compatible with the action of this surface as a transfer zone during $D_2$. If this is the case, no syn-$D_1$ striations were seen except near the southern end of Tharsis Ridge.

*Eastern Side of Tharsis Ridge segment of GLF* The surface exposure of the eastern side of Tharsis Ridge (location 7 in Fig. 2) has the appearance of a fault. The surface is a zone of stronger cleavage development and fault striations are common. Only a few striations were recorded very close to the contact. The two that are parallel to the contact both indicate a west side up movement and shallowly dipping fault planes are top to the north. These all match $D_2$ conditions.

In the Tharsis Trough there is a strong fault zone

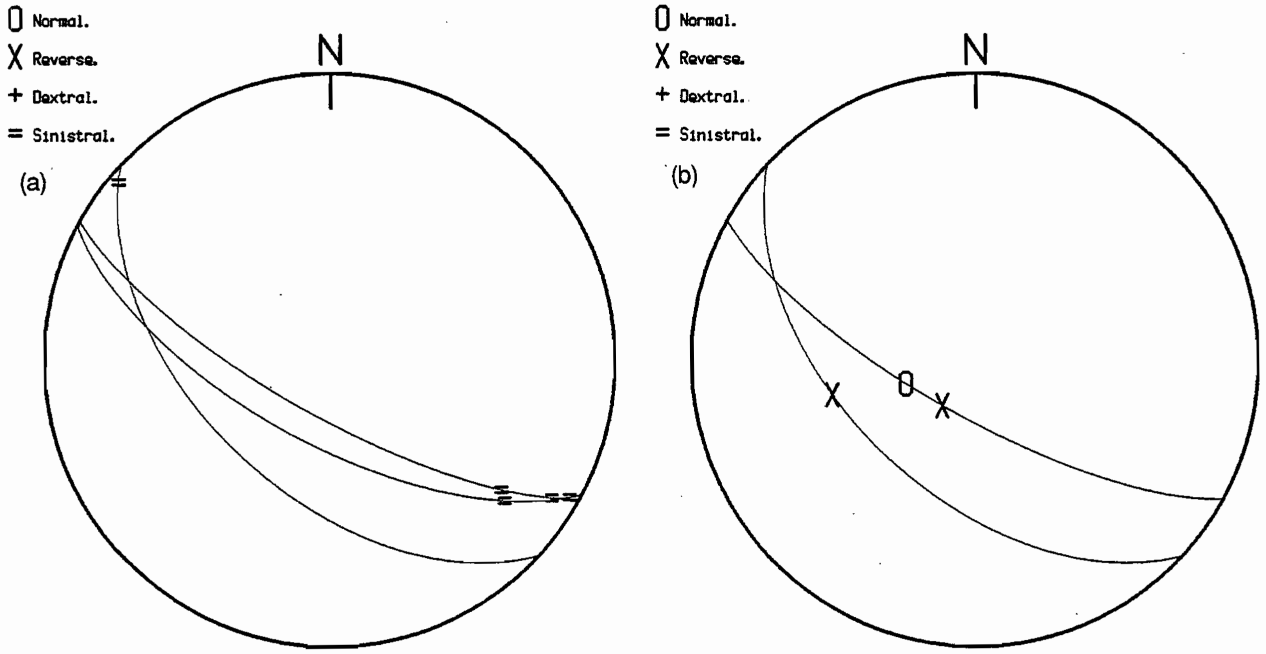

*Figure 6 — Fault planes and striations from the North Lyell area. a) $D_1$ fault movements. b) $D_2$ fault movements.*

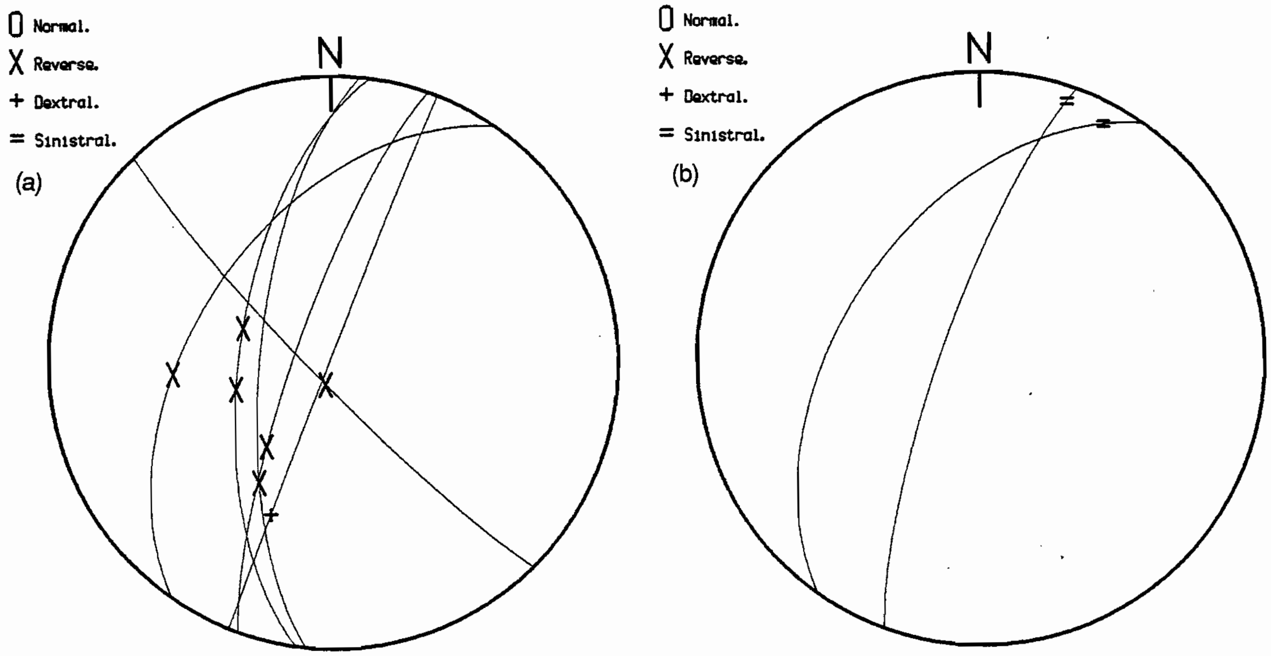

*Figure 7 — Fault planes and striations from the Cape Horn area. a) $D_1$ fault movements. b) $D_2$ fault movements.*

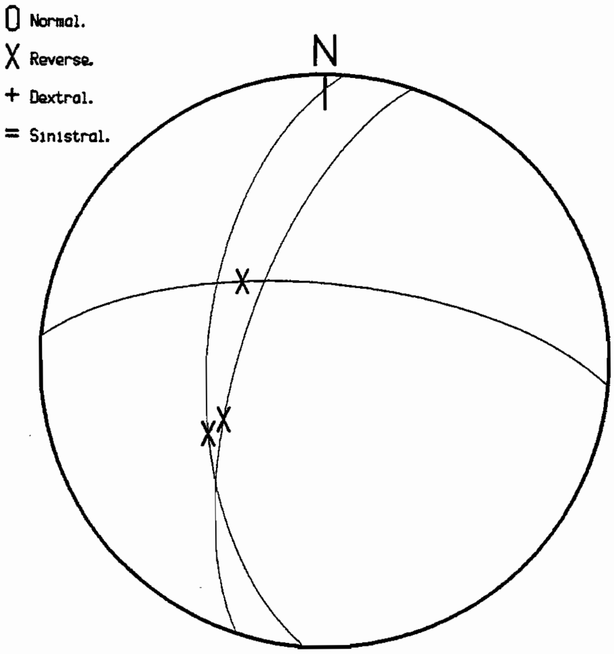

*Figure 8 — Fault planes and striations from the western side of Tharsis Ridge.*

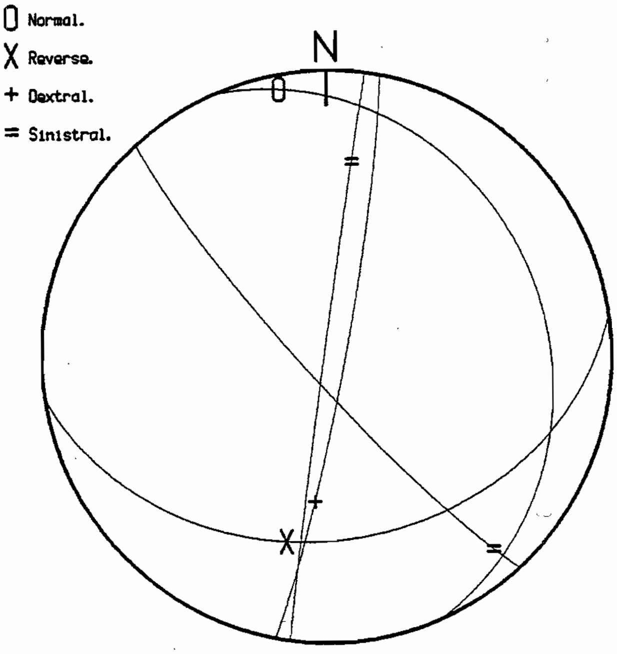

*Figure 9 — Fault planes and striations from the eastern side of Tharsis Ridge.*

within hematitic rocks related to the Lyell Tharsis and North Lyell deposits. The zone is dominate by moderately SW dipping faults. These faults have a series of progressive movements on them which all relate to the $D_2$ deformation. The earliest quartz fibre veins indicate top to the north (Fig. 10) and with time the fibres shift increasingly to more NE and finally E transport directions. The interpretation here is that the earliest fibres reflect regional $D_2$ stress conditions but as the strain increased the relatively flat lying beds to the east shortened by folding while the steeply dipping and very thick Owen Conglomerate to the west could not fold and reacted by a range of faults which include some transport to the east in this zone reflecting its relative uplift along the thrust faults associated with the North Lyell Fault and in the North Lyell Corridor. The whole range of striations in Fig 10 a,b,c are considered to be syn-$D_2$ despite the fact that three distinct directions can be measured on the one surface. The youngest striations are sinistral reactivation of the moderately SSW dipping fault planes. No comparable structures have been observed elsewhere but these appear to post-date $D_2$.

The series of thrust surfaces in this area probably produced the overhang structure on the NE corner of Tharsis Ridge (c.f. Bryant 1975).

*Southern End of Tharsis Ridge* The southern tip of Owen Conglomerate on Tharsis Ridge is exposed on the road at location 8 in Fig. 2. A small area at the east end of the exposure has extremely strong syn $D_1$ fault striations indicating oblique thrusting or that the original steeply west dipping thrust surface has been folded during $D_2$ (Fig. 11a). Most of the fault surfaces here are syn-$D_2$ and there is a very clear overprinting relationship exposed in this cutting. The syn-$D_2$ fault striations (Fig. 11b) are largely south dipping reverse faults but one steep surface has weak west side down movement early, followed by a west side up movement late in $D_2$ reflecting the same change in conditions as recognised in the Tharsis Trough.

*Razorback* In the Razorback area (location 9 in Fig. 2) there are a few relict syn-$D_1$ faults indicating general E-W compression. These are strongly overprint by syn-$D_2$ faults with strong dextral reverse movement (Fig. 12). No evidence was found for east dipping normal faults along the eastern side of the Razorback Ridge although a few dextral faults had a small component of east side down movement. The structure of the Razorback Ridge requires further study.

*Cu Estates* In the Cu Estates area (Location 10 in Fig. 2) the fault striations that have been measured fall clearly into a syn D1 reverse movement on the GLF and a syn-$D_2$ dextral wrench movement (Fig. 13).

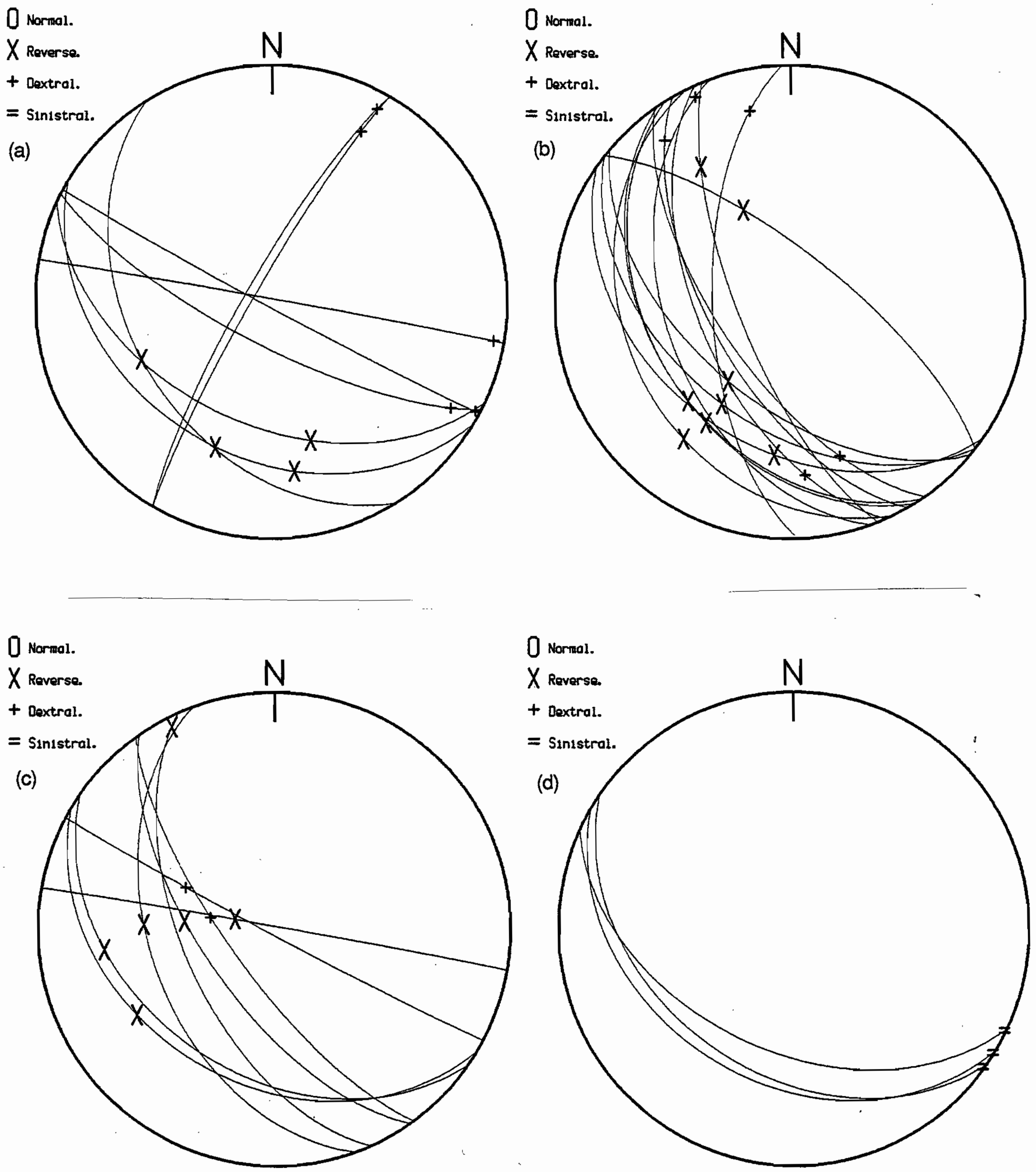

*Figure 10 — Fault planes and striations from the Tharsis Trough near Lyell Tharsis. a),b) and c) sequential movements all within* $D_2$. *d) post* $D_2$ *fault movements.*

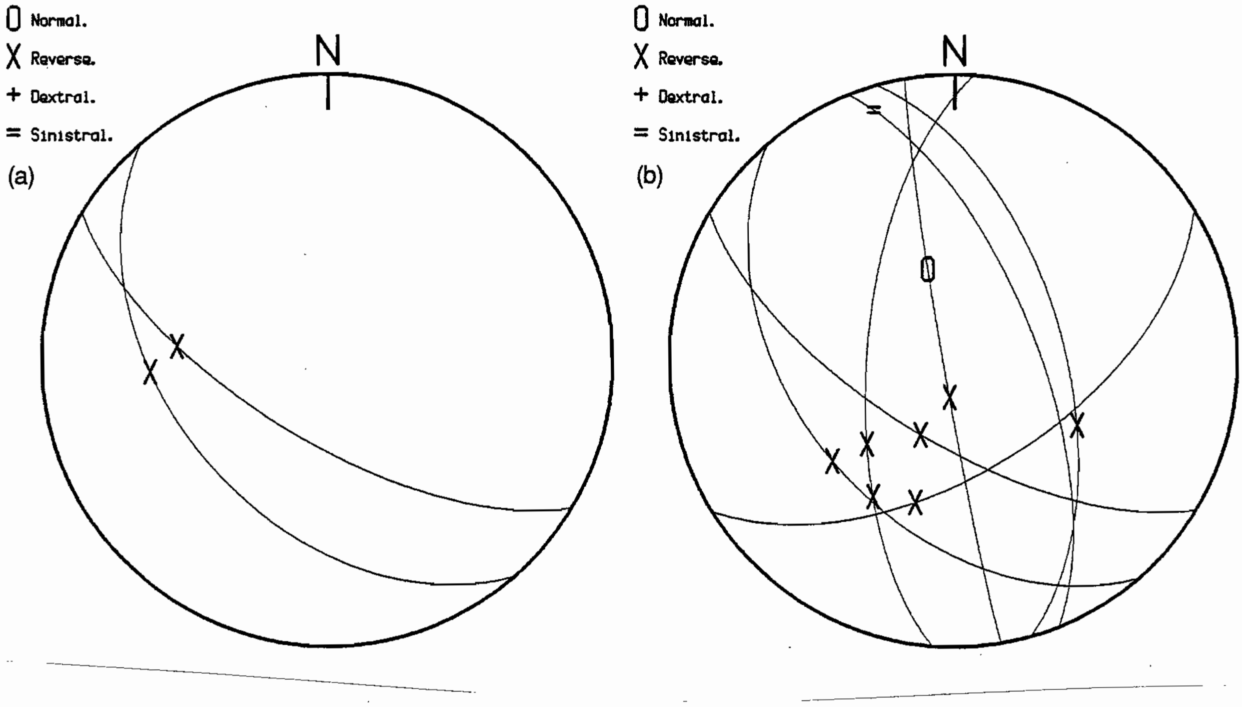

*Figure 11 — Fault planes and striations from the southern end of Tharsis Ridge, a) $D_1$ fault movements. b) $D_2$ fault movements.*

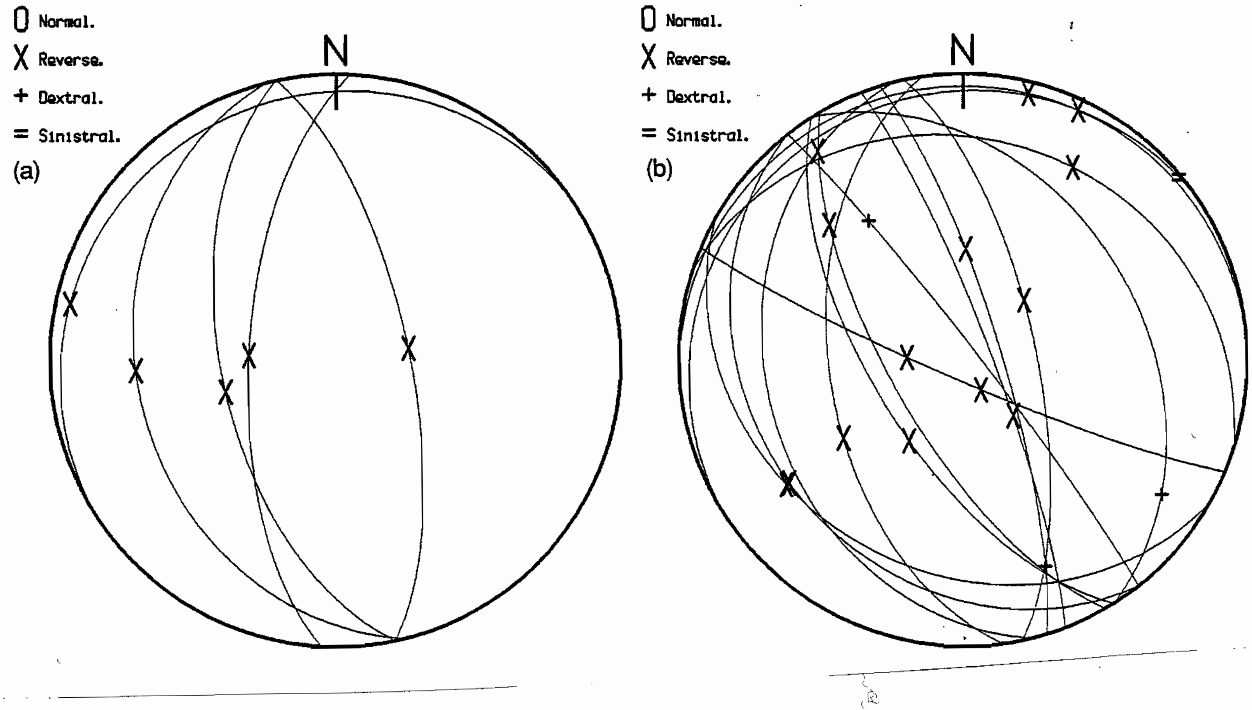

*Figure 12 — Fault planes and striations from the Razorback. a) $D_1$ fault movements. b) $D_2$ fault movements.*

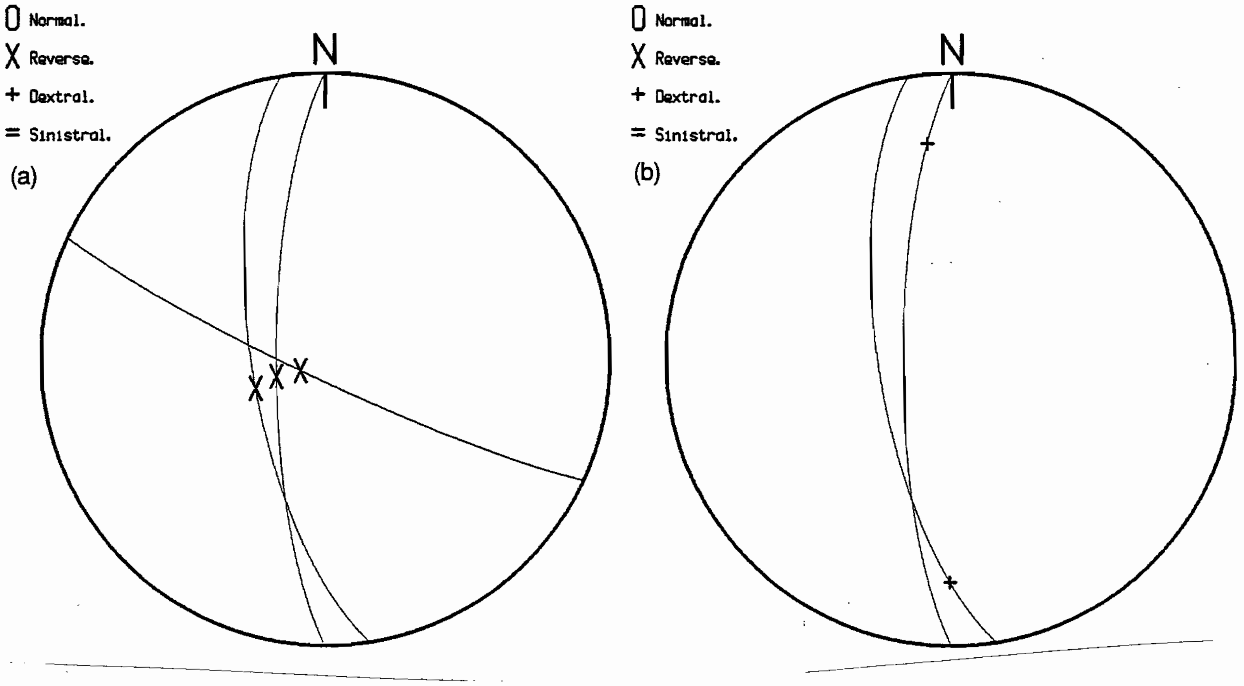

*Figure 13 — Fault planes and striation data from Cu Estates. a) $D_1$ fault movements. b) $D_2$ fault movements.*

## Cleavages

There is a long standing argument about the cleavages developed in this area. Cox (1981) and Williams(1988, in press) have argued that only one cleavage can be recognised over most of the area with the early $S_1$ cleavage very limited in distribution. Williams (in press) has agreed that both cleavages are recognisable along Pioneer Spur. In contrast, Arnold (1985) recognisedtwo cleavages over the whole area.

The Siluro-Devonian sedimentary rocks to the west have a clear record of two cleavages with a NNW striking $S_1$ and a WNW striking $S_2$ (Baillie & Williams 1975). To the east, the $S_1$ cleavage is dominant within the Siluro-Devonian sediments (Calver et al. 1987) except in a narrow zone along the Linda Zone. Thus the absence of two cleavages from the Mount Lyell area would be highly anomalous.

I have found a large number of sites providing convincing support for the conclusions of Arnold (1985) that two cleavages can be found within the Lyell area. In terms of classical cleavage interference, the clearest examples of two cleavages are in the Owen Conglomerate, especially where it is altered to sericite hematite. These samples are not readily studied at microscopic scale as the cleavages are generally weak spaced surfaces enhanced by surface weathering rather than slaty cleavage. One example from the Owen Conglomerate in which two cleavage directions are recognisable in thin section is shown in Fig. 14.

Within the Lyell Schists the relationship is more complex. Individual Syn-$S_2$ reverse faults along the Lyell Highway have substantial zones of W to WNW striking cleavage entirely consistent with the regional orientation of $S_2$. They overprint more widespread weaker cleavage striking NW to NNW which is interpreted here as $S_1$. To the north in the zone from the Razorback to the North Lyell Corridor the major syn-$S_2$ faults strike nearly N in line with the transfer model proposed below. In the area of Tharsis Ridge, the $S_1$ / $S_2$ angle is less than 30°.

The orientation of the cleavages is shown in Fig. 15. The seperation has been based on locations where two cleavages were found (about 40 locations). In a few of these locations the more N-S striking cleavage is demonstrbly older. This N-S striking cleavage is often nearly parallel to the layering. In other exposures the cleavages have been classified from style and orientation. Cleavages of intermediate style and orientation remain unclassified. $S_2$ has an average orientation dipping 82° towards 206°. $S_1$ has an average orientation dipping 80° towards 270°. This average has probably beem skewed by the difficulty of recognising $S_1$ when it is at a low angle to $S_2$. A number of cleavage readings could not be placed definitively in these two groups and these have been included in Fig. 15c. If these are mainly $S_1$ the average orientation is closer to 80°/260°.

Representative orientations of $S_1$ and $S_2$ are shown on Fig. 16. The lowest angle between $S_1$ and $S_2$ occurs close to the GLF along the section from the Razorback to the northern end of Tharsis Ridge. The section from Glen Lyell across Philosphers Ridge to Gormanston Gap has extremely strong $S_2$ cleavage and no $S_1$ relicts were found in this area but west of the Glen Lyell Fault, $S_1$ is common. North of Cape Horn, $S_1$ is the dominant cleavage.

### Folding

The orientation of bedding (Fig. 17) is very complex reflecting the multiple folding. The best fit great circle through the data indicates a near vertical fold axis compatible with refolding of steeply dipping limbs of $F_1$ folds. Since this data is mainly from Owen Conglomerate it can only be used to demonstrate the presence of an anticlinal structure between the Mount Lyell mill and Tharsis Ridge. There may be more than one structure or it could be faulted out. The layering, is mainly fron the Central Volcanic Complex. It is less variable and has apparently been transposed into the cleavage. The lack of shallowly dipping layering reflects the fact that $F_1$ fold hinges have not been recognised in these rocks.

$F_1$ (Devonian) folds are very rare on the Lyell Lease. Along Philosophers Ridge there are a wide range of fold structures in flow banding. Some of these may be $F_1$ folds or composite $F_1$ /$F_2$ folds but the vast majority of these structures are probably primary magmatic bending in the flow banding.

Within the Owen Conglomerate the bedding is clearer and $F_1$ folds can be recognised with more confidence. At Cu Estates, tight upright folds exposed to the south of the waterfall are apparently $F_1$ based on their orientation. A tight fold is exposed in the upper bench at Batchelors Quarry (Location ML81). this fold has been interpreted previously as af Haulage age but the $S_1$ cleavage is axial plane to the fold (Fig. 18). If the fold formed at Haulage time it must have been gentle since the cleavage does not transect the overturned limb, and the fold was then substantially tightened in the Devonian. The discussion in of the Haulage Unconformity below suggests the original interlimb angle could not have been less than 130°.

$F_2$ folds are widespread and can be recognised in a wide range of lithologies. In the Linda Valley $F_2$ folds plunge moderately to the east. West plunging $F_2$ folds are indicated by bedding orientation to the west of the Murchison Highway (Fig. 4 section AB). Along the line of section CD tight folds with thrust out hinges are exposed on the contact between the Pioneer Sandstone and the Central Volcanics Complex. Small scale folds are visible in the syncline in the area east of the Queenstown oval. $F_2$ folds within the volcanics were found in the Conglomerate Creek (ML262 east plunging) and at Cu Estates (east plunging).

### Pattern of Fold and Faulting

The style of large scale $D_2$ structures is demonstrated in sections (Fig. 4). Within the sedimentary units of section AB the $D_2$ event produced upright folds with closely related high angle reverse faults. The next section CD shows the change to very tight syncline and open anticlinal structures typical of basement cover interaction and reflecting the higher effective viscosity of the volcanic rocks. This style of folding requires substantial shortening of the volcanics by reverse faulting. To the east, in section GH, the $D_2$ folding and related reverse faulting is again apparent. The tops of anticlines in the Owen Conglomerate are cut by extensional faults reflecting the stretching on the outside of the massive quartz-dominated units. The synclinal structures are faulted out in many cases and suggest major detachment surfaces occur deeper. In the section EF the $D_2$ structures are reflected by near vertical dextral faults and a number of reverse faults. The major anticline shown is an oblique section through a probable $F_1$ fold.

The plan view of these $D_2$ structures is very informative (Fig. 19). The major faults control the pattern of folding. The dextral Glen Lyell Fault seperates the area into 2 distinct structural provinces. To the west, the faults are largely reverse and strike EW in a regular pattern. To the east in the area of the mineralisation the structure is much more complex probably reflecting the complex distribution of rock units with very different effective viscosities at the time of this event. Reverse faulting on the western segment of the North Lyell Fault transfers through a range of dextral reverse faults both east and west of Tharsis Ridge to the major east west reverse faults (south dipping) through the northern flanks of Mt Owen.

This leads to the zone where $S_1$ and $S_2$ are at a low angle to each other.

The understanding of the structures produced during $D_2$ allow the reconstruction of the structure associated with $D_1$. The sections in Fig. 4 were constructed for this purpose but this work is still in progress and no exact reconstructions are yet available. The following discussion is based on a qualitative assessment of this structure.

The removal of the $D_2$ strain produces the structure shown in Fig. 20. One km of dextral movement was removed from the Glen Lyell Fault to line the Firewood Siding Fault up with the Owen Fault. Approximately 30% shortening was removed across the region in line with the estimates for folding from Fig. 4. The North Lyell corridor is wider as a result of removing the thrust component in this region. The Razorback was moved back into the line of the GLF

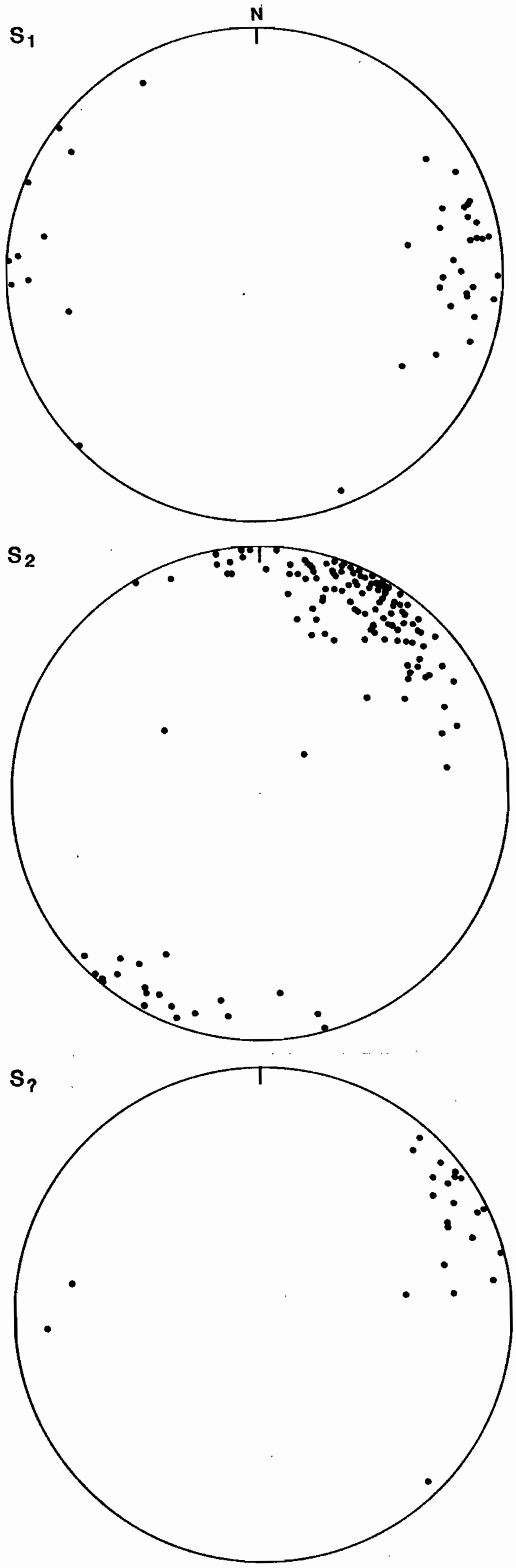

*Figure 15 — Stereographic projection of poles to cleavage. Unclassified foliations are shown in c).*

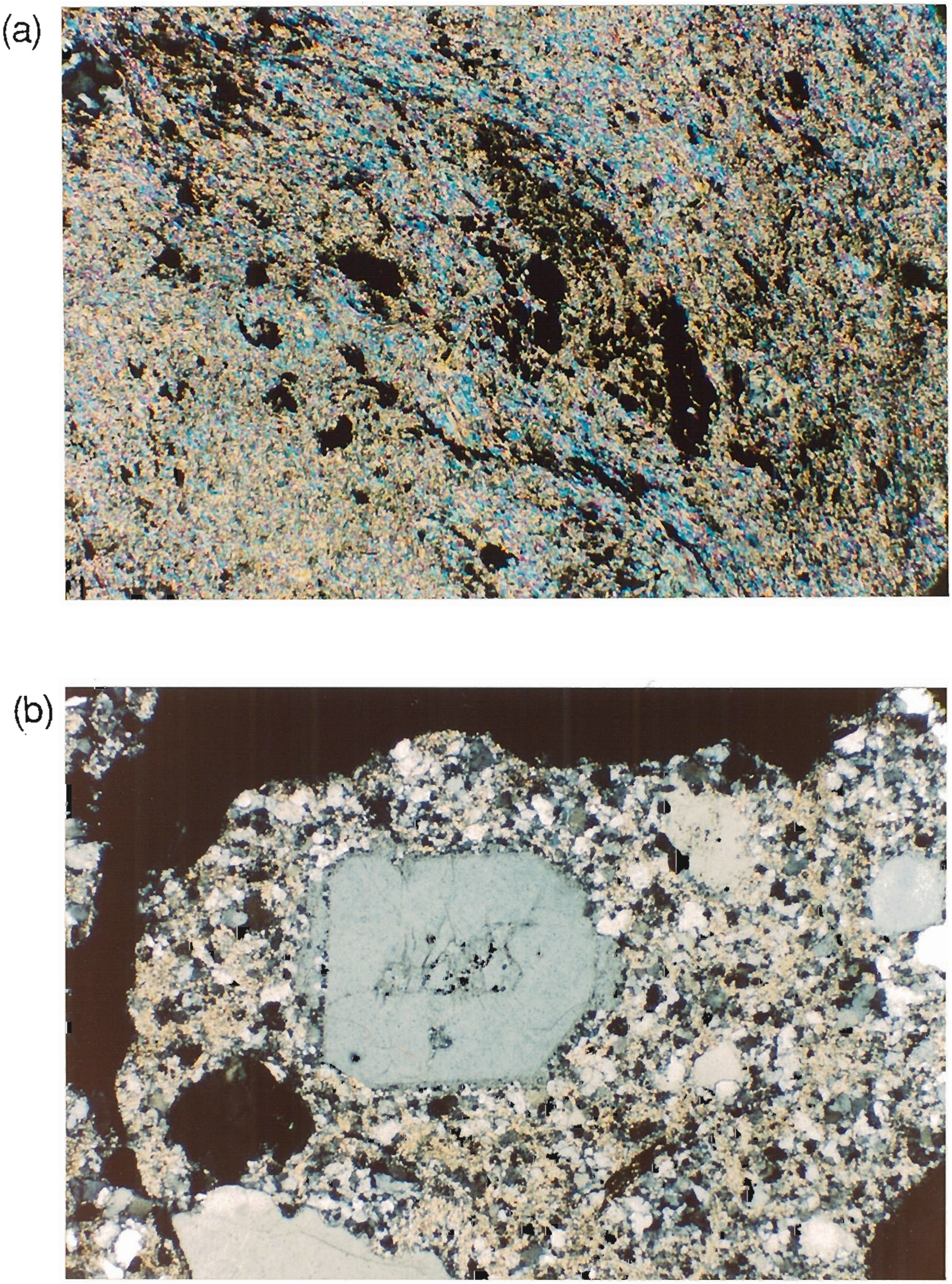

*Figure 14 — (a) Two cleavages developed in sericite altered Owen Conglomerate from Tharsis Ridge. (b) Quartz phyric volcanic clast within Owen Conglomerate on Tharsis Ridge.*

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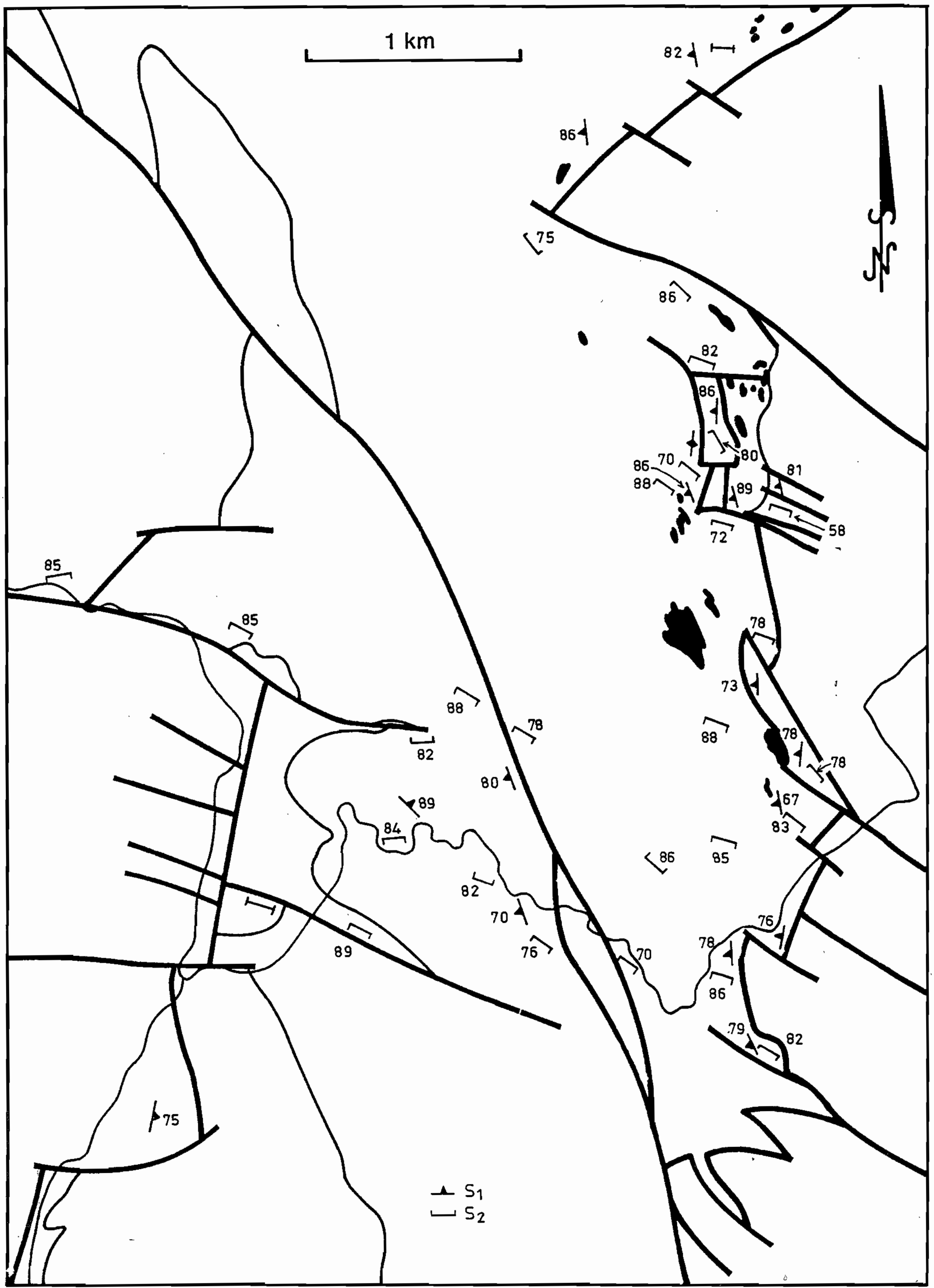


*Figure 16 — Representative $S_1$ and $S_2$ cleavage orientations in the Mt Lyell area.*

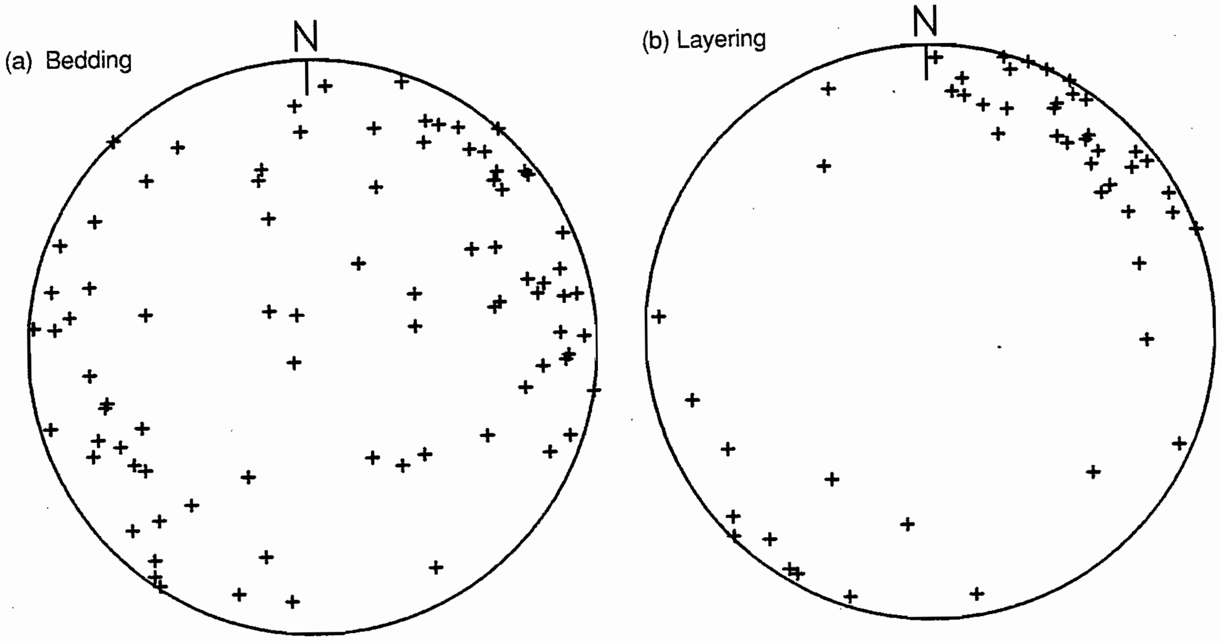
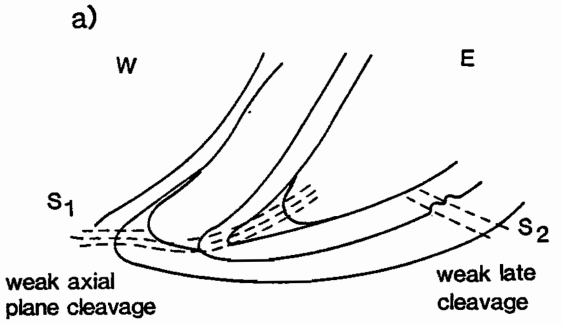


*Figure 17 — Stereographic projection of poles to bedding and layering across the region.*



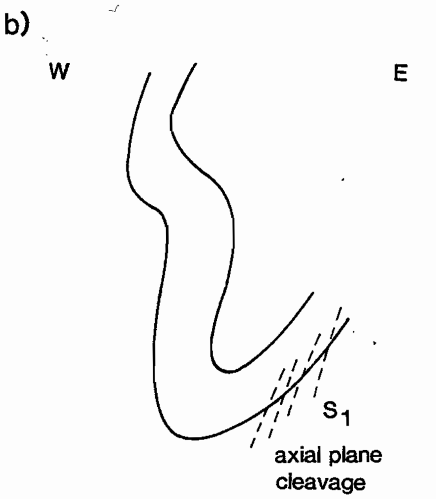


*Figure 18 — Sketches of $F_1$ folds in the Owen Conglomerate showing the relationship to $S_1$. a) from ML68. b) from ML81.*

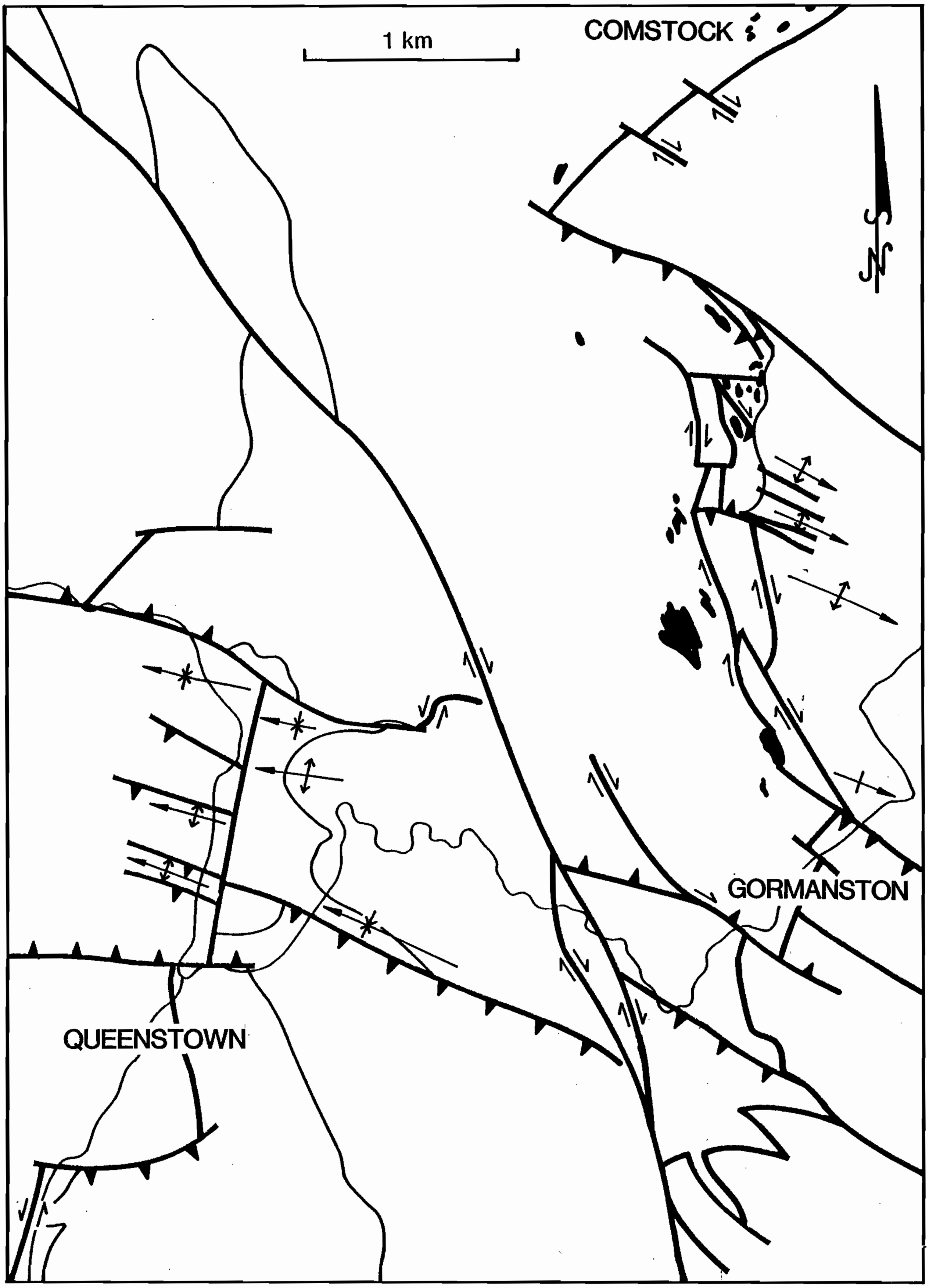


*Figure 19 — Interpretation of large scale $D_2$ structures in the Mt Lyell area.*

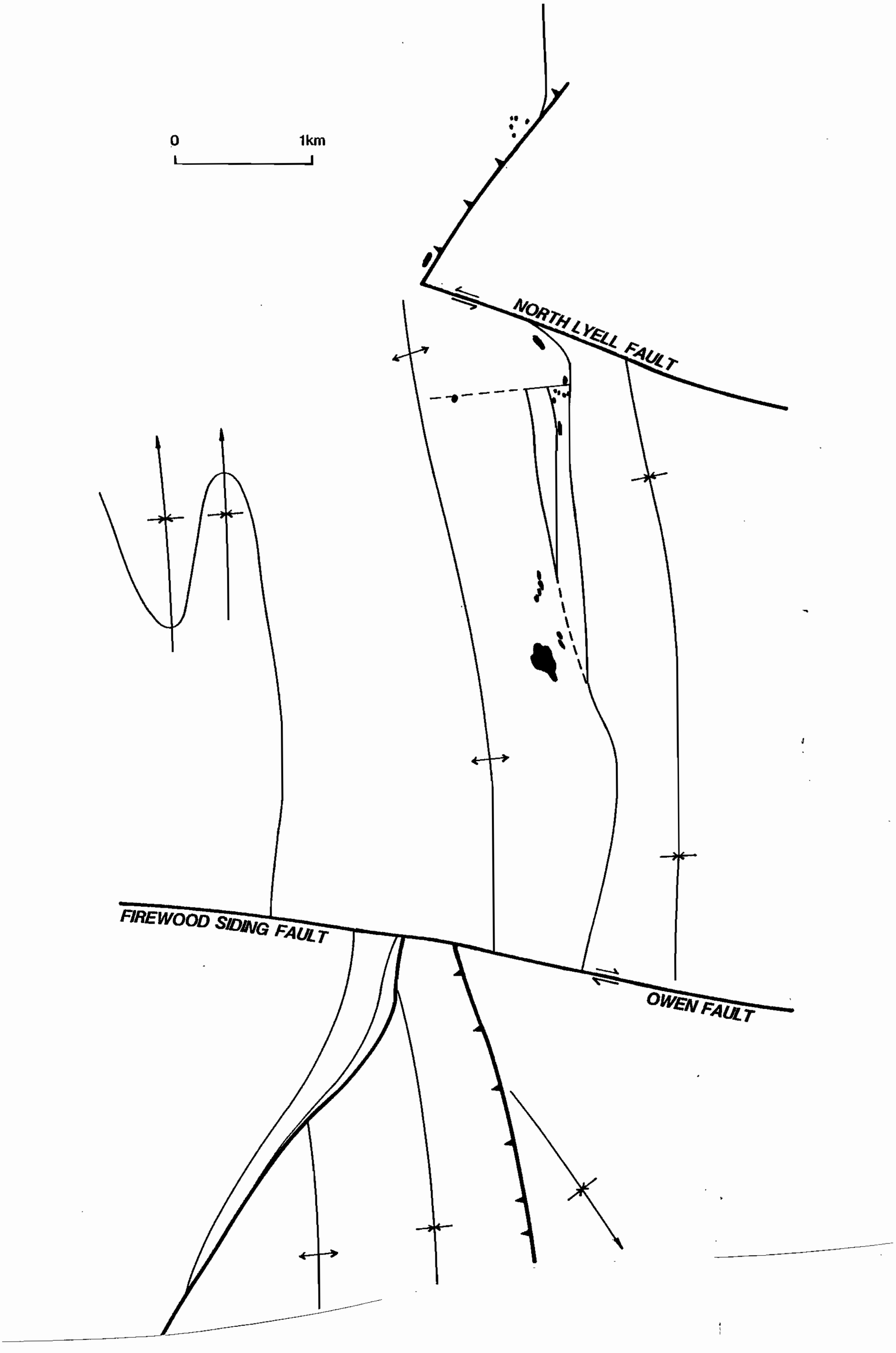


*Figure 20 — Reconstruction of pre-$D_2$ structure based on strain recognised in sections and allignment of Firewood Siding and Owen Faults.*

assuming the main movement was a dextral normal component on the Razorback Fault. The Queen River Detachment was straightened by removal of $D_2$ folds. The position of $F_1$ folds is shown tentatively based on the limited available evidence. The syncline to the east is near Linda, at the end of the east plunging $F_2$ folds presently exposed in this area. The anticline is based on the position shown in section EF on Fig. 4.

In this reconstruction, the Firewood Siding / Owen Fault forms a continous structure defining the south end of the Lyell "monocline" as recognised by Cox (1981). The monocline is limited in the north by the North Lyell Fault. This structure is shown schematically in Fig. 21. To the north and south of this area the western boundary of the Owen Conglomerate occurs at a west dipping high angle reverse fault. These are presently exposed as GLF segments from Cape Horn to Comstock and south of Cu Estates. The faults crosscut the regional NNW trend of $D_1$ folds but this is a common feature for faults on the west coast (e.g. Rosebery and Henty Faults) and potentially implies they are later than the folding (e.g. Green 1984, Berry 1989). The anticline in the Lyell area is replace by a thrust to the south.

### Significance of Reactivation of Older Structures

The $D_1$ style varies dramatically along its length. This variation implies pre-existing structural variations. The presence of the extremely large sericitic alteration zone probably controlled the general variation from a sharp fault to the ductile style over the mineralisation. However, the change from ductile to brittle style occurs very abruptly, at least in the north. This is clear evidence that the North Lyell Fault is an older structure and strongly infers the Firewood Siding Fault is also older. Stratigraphic information supporting this conclusion is discussed below.

## LATE CAMBRIAN STRUCTURE

### Distribution and Thickness of Owen

The distribution of the Owen Conglomerate has long been regarded as a key feature to the Cambro-Ordovician structure of the Lyell mineralisation (e.g. Solomon & Wade 1958). Most recently it has been the subject of a detailed report by Arnold (1985) partly

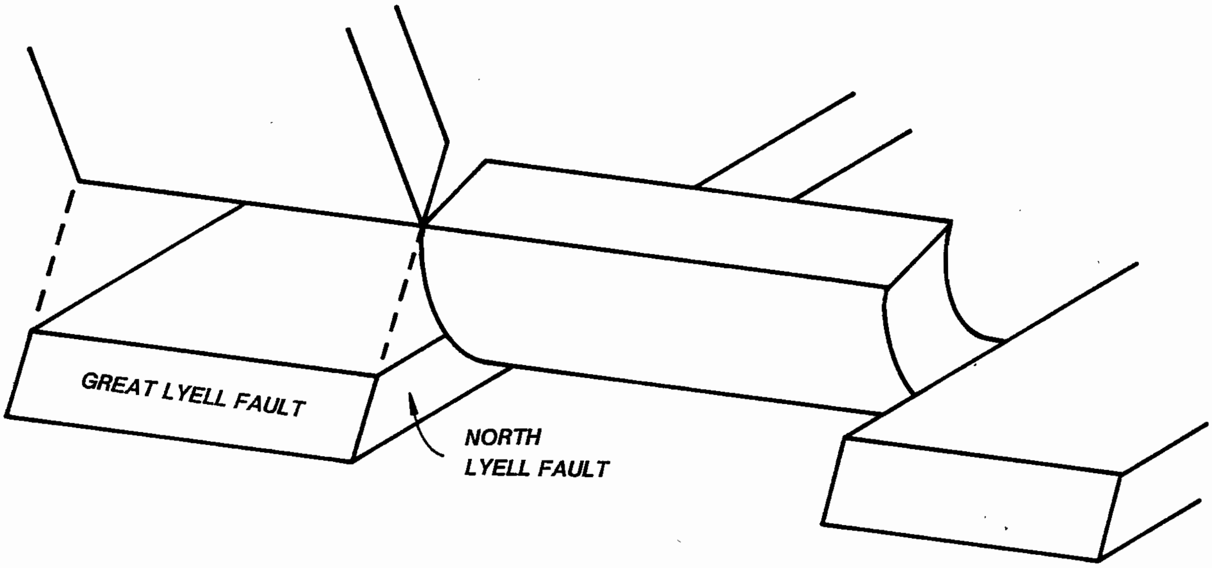


*Figure 21 — Cartoon of the change in $D_1$ style along the Great Lyell Fault.*

summarised in Arnold & Carswell (in press). Recent mapping in the Queenstown area (Corbett et al. 1989) has reinforced the rapid variations in thickness of the Owen Conglomerate and the close relationship of this variation to syn-depositional normal faulting (e.g. Solomon 1957, Wade & Solomon 1958). For example in Fig. 22, the Owen Conglomerate thickens from several hundred metres 6 km east of Cape Horn to about 2 km thick at Cape Horn. Part of this thickening occurs at discrete faults such as (a) on this section but there is also a general thickening especially in the Lower Owen Conglomerate. Yet only 1 km south of this section, the Owen Conglomerate cuts out against the Haulage unconformity across a narrow zone that has been variously interpreted as the basin margin or a large thrust (greater than 1 km movement). The area west of this zone is largely underlain by older rocks but the impression is obtained from the fragmentary record of a large area in which the Owen Conglomerate was either eroded in the Cambrian or was never deposited (Fig. 23).

Assuming that the conglomerate was not deposited in this area implies that a major normal fault boundary occurred in this zone (e.g. Wade & Solomon 1958, Campana & King 1963). The westward increase in thickness and internal unconformities (c.f. Banks & Baillie 1989) suggests this fault had a listric geometry (assuming this thickness variation relates to rollover on the hanging wall side). The position of this fault must lie very close to the present position of the GLF. A reconstructed position is shown in Fig. 24 and the arguments used to construct this figure is given below.

In this situation the mineralised Lyell schists are on the upthrown block and may have been subaerially exposed at least part of the time. Detritus from these rocks is found within the Owen Conglomerate (e.g. Fig. 14) although it is largely overwhelmed by the voluminous metamorphic detritus from the east. Solomon (1957) argued that a consistent onlap stratigraphy could be recognised in this area. The recognition of internal unconformities within the Owen Conglomerate (e.g. on Mt Owen) suggests the basin bounding faults were active during deposition (Banks & Baillie 1989, p.190).

Arnold (1985) argued the structure at Mt Lyell could be better interpreted as a thrust fault active during Owen deposition. While some of the features of the Haulage unconformity and variations in Owen Conglomerate thickness can be explained in this way it has substantial difficulties with lack of evidence for erosion of the upthrown block and the small scale evidence against the geometry indicated (see below).

Since the base of the Owen Conglomerate is considered to be diachronous (Banks & Baillie 1989, p.195), it may overlap substantially with the top of the volcanics nearby although Baillie (1989) was at careful to avoid such a suggestion. It is possible that the Owen Conglomerate was depositing in a fault bounded basin to the east of Mt Lyell while volcanism was still active. Certainly, in the Sheffield area, Mount Read type volcanics intrude Denison Group conglomerates in the Ordovician (Jago et al 1977).

## Haulage Unconformity

The Haulage Unconformity has been the subject of a great deal of debate since Campana & King (1963) first suggested a fault scarp in this locality. Wade & Solomon (1958) first described the structure and Solomon (1967) suggested soft sediment deformation as an explanation for the unconformity. Webby (1978) reinterpreted the structure as evidence of a Delamerian orogeny in Tasmania. Finally Arnold (1985) carried out detailed remapping of the GLF and suggested a detailed thrust model for the structure.

The age of the unconformity is constrained to lie near the Cambro-Ordovician boundary (Arnold & Carswell in press). The classic exposure of the unconformity is in Batchelors Quarry (Fig. 25) but there are a number of other good exposures of which the ones I have studied are shown in Fig. 26 (ML43,44,53,56,64). There are several features that these exposures have in common. Firstly all the contacts show the Owen Conglomerate rotated 40° clockwise (looking north) relative to bedding in the Pioneer Sandstone. Thus on restoring the Pioneer Sandstone to its depositional orientation they indicate a relatively shallow dip (~40°) to the east at all the exposures. This is inconsistent with the suggestions of tight folding (e.g. Solomon & Wade 1958, Arnold 1985). Not only is this angle relatively consistent but close inspection of the termination of individual sandstone beds against the unconformity (Fig. 25) shows no evidence of the strain that would accompany a substantial rotation of the beds below the surface with respect to those above. The beds are cut off at an angle which fits neatly against the overlying surface and there is no evidence of the high strains that would be required to produce this shape tectonically.

The zone of this upturn is up to 400 m wide, and known exposures of the unconformity are limited to a zone 1.5 km long, so the upturn itself can produce very limited thinning and cannot explain the abrupt termination of the Owen Conglomerate. In the model of Arnold (1985) this is not a problem because the base of the Owen is seen as a major thrust fault but since the best available evidence is that this surface dipped 40° E at the relevant time this would need to be a low angle normal fault. At locality ML67 (Fig. 26) the beds of Owen conglomerate terminate against the volcanics on a surface which is at 45° to the bedding (Fig. 27). Rotating these beds back to horizontal suggests this surface dipped 45° E. There is no evidence that major faulting has occurred on this

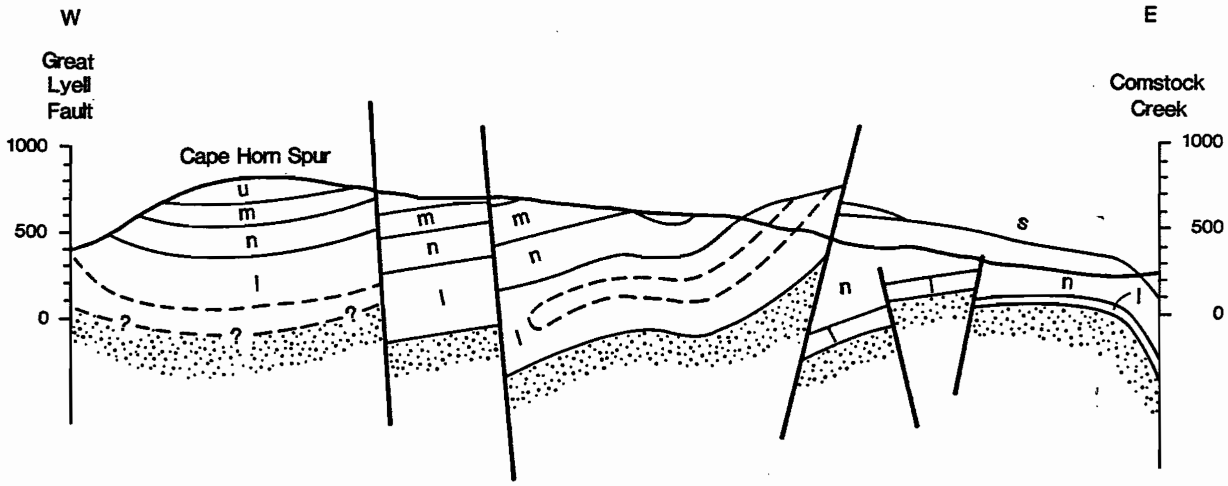


*Figure 22 — Cross-section from Cape Horn to Comstock Creek along 534400N based on Corbett et al. 1989.*

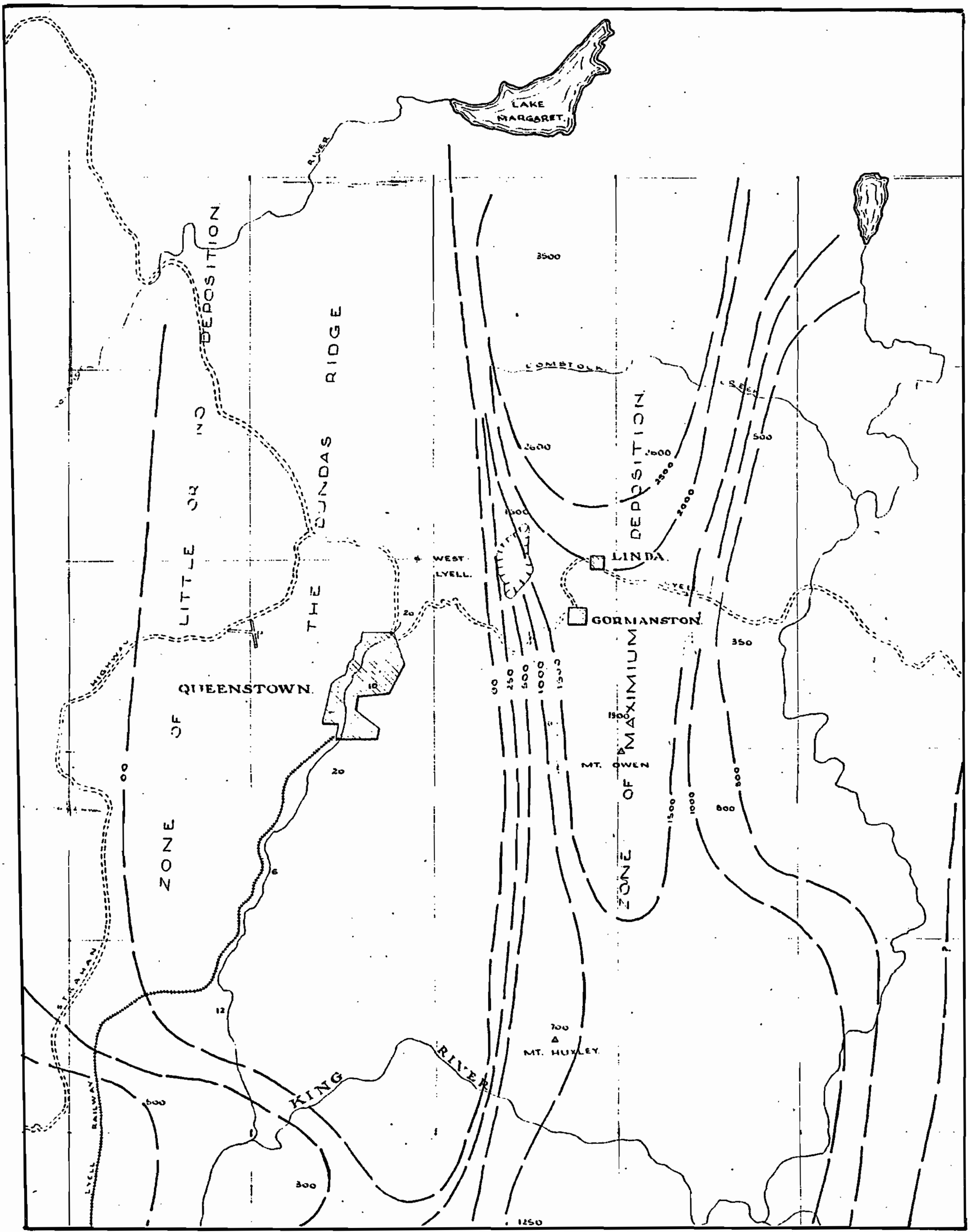


*Figure 23 — Reproduction of part of the map of Solomon (1957) showing contours of thickness (in feet) of the Owen Conglomerate.*

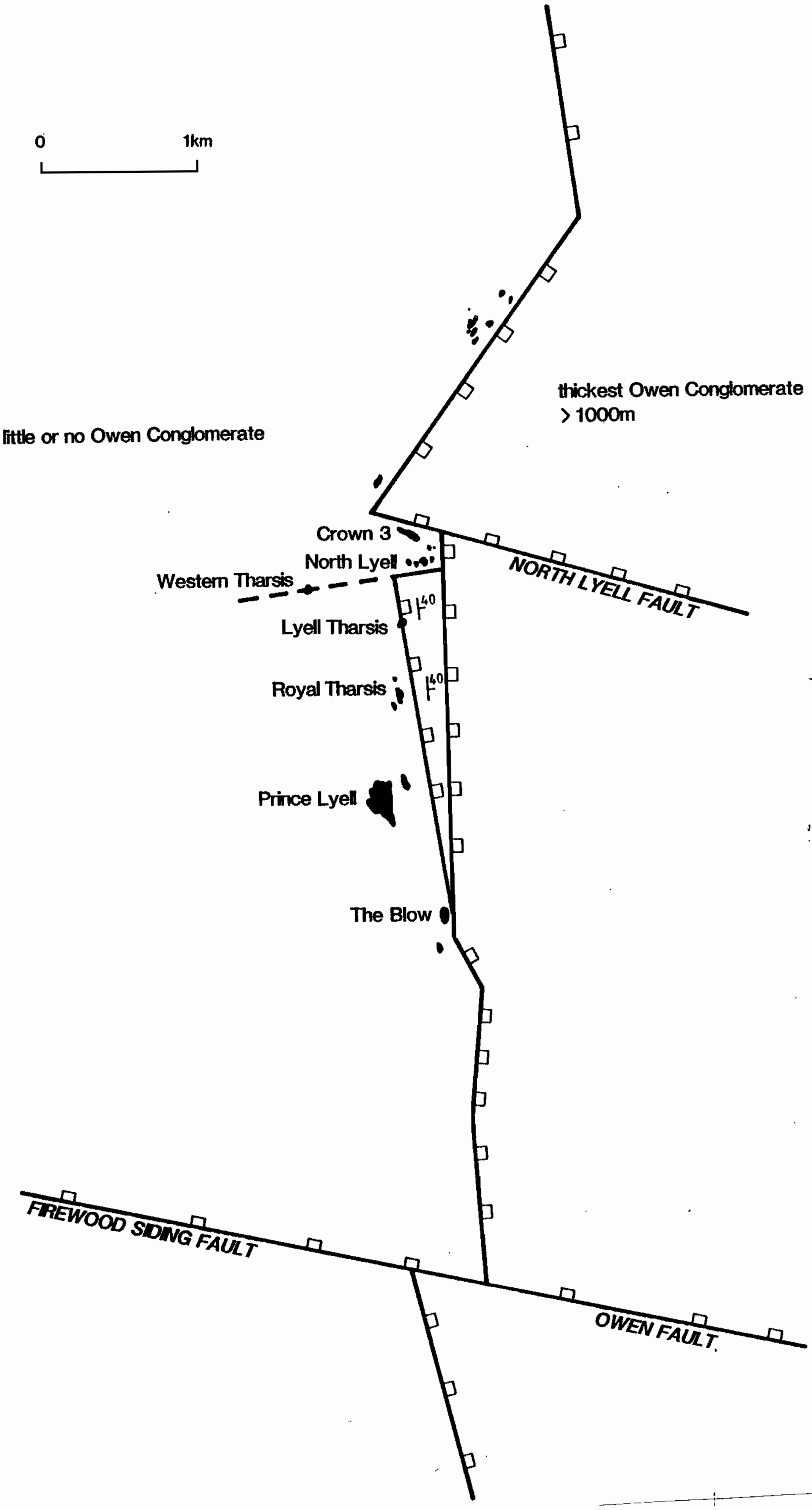


*Figure 24 — Reconstruction of the pattern of Late Cambrian normal faults base on unfolding the $D_1$ structures in Fig. 20. See text for additional assumptions.*

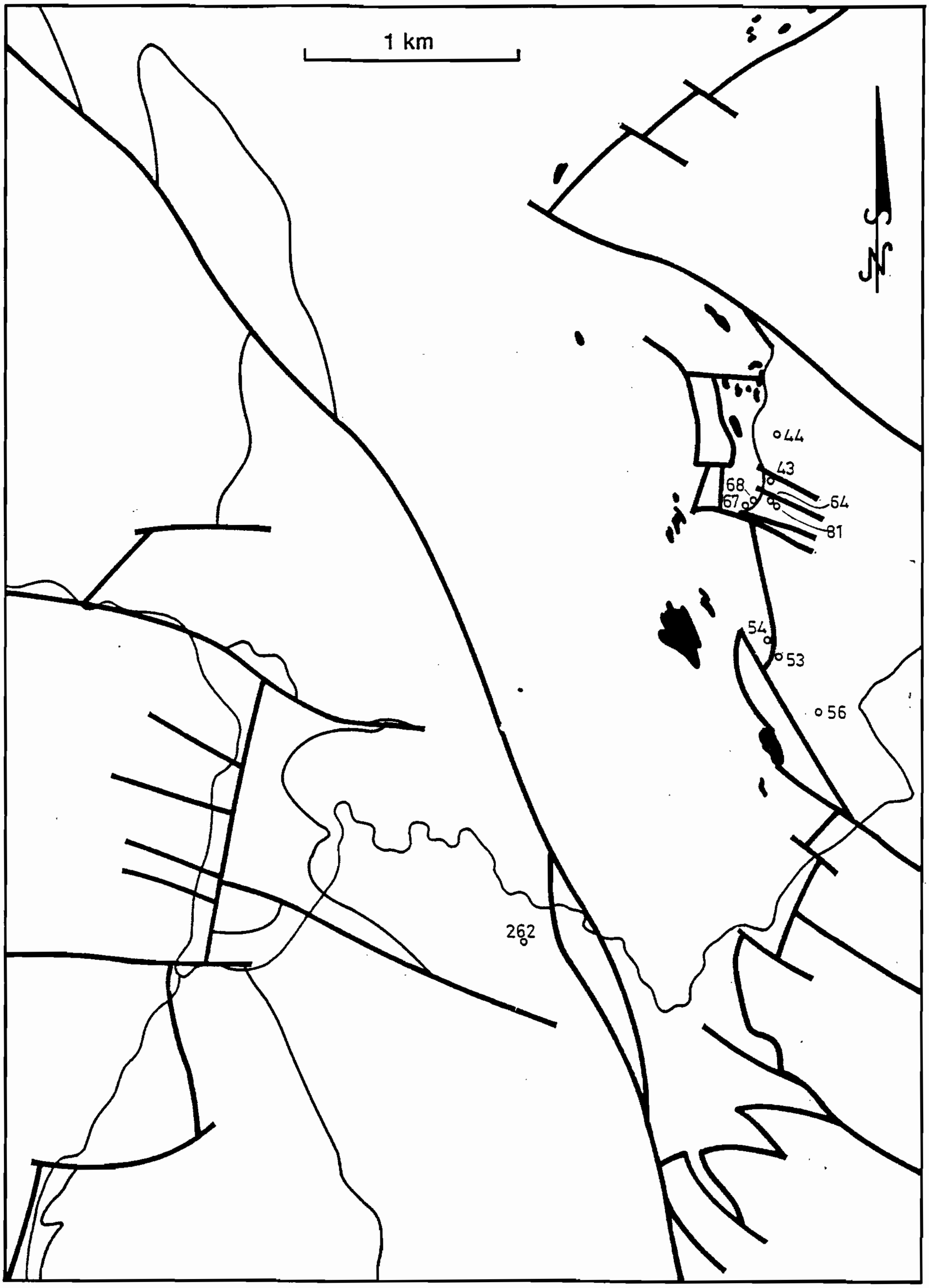


*Figure 26 — Locations of field stations referred to in the text.*

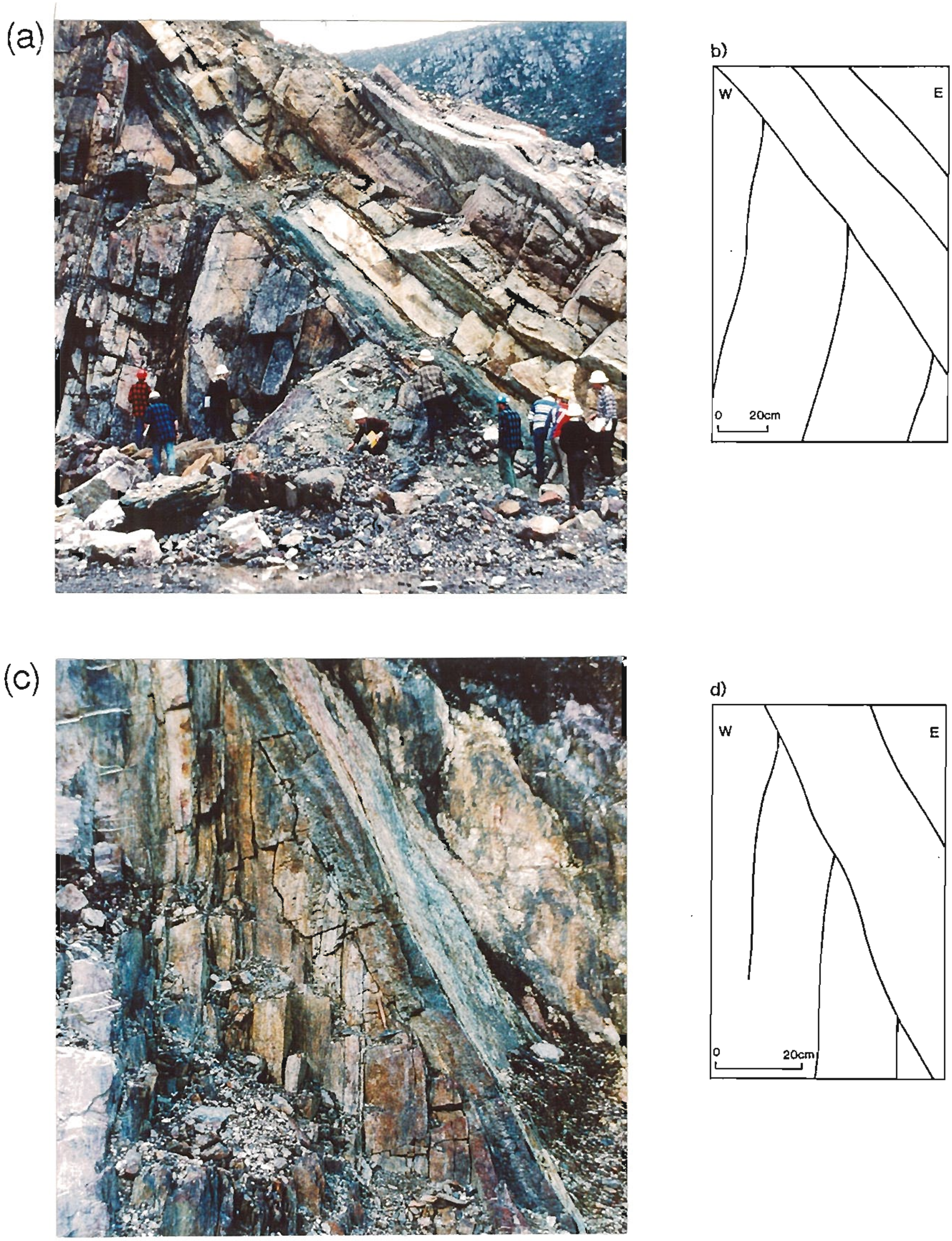


*Figure 25 — (a) Haulage unconformity at Batchelors Quarry. (b) Sketch of detail showing perfect fit of Owen Beds to the angular unconformity. (c) Haulage Unconformity at ML43. (d) Sketch of detail at ML43 confirming the lack of rotation between the beds.*

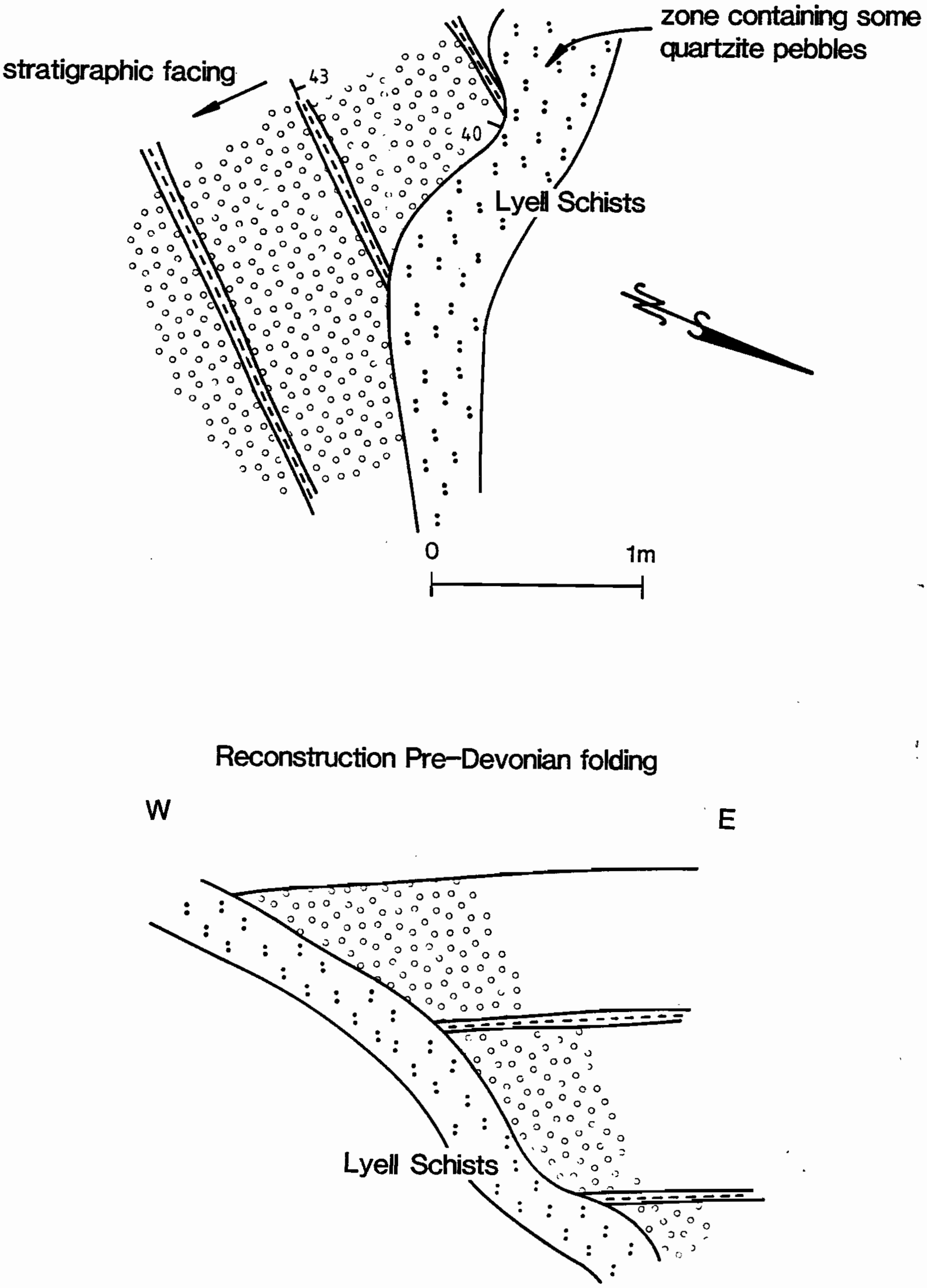


*Figure 27 — Sketch of complex stratigraphic relationships between Owen Conglomerate and CVC at ML67. a) in plan view. b) rotated to demonstrate the interpreted onlap relationship.*

surface and it has none of the features associated with Devonian faults. The obvious interpretations are an onlap relation or a Cambrian normal fault.

The contact of the GLF at location ML54 is particularly well exposed. There is no evidence for Devonian fault movement on this zone. Pebbles project from the base of the basal sandstone and are not truncated. The 5 m of volcanics immediately beneath this surface are blocky and lack distinct bedding. This could be due to Cambrian faulting producing a melange zone in very low grade rocks which have subsequently been deformed at higher metamorphic grade but there is now no structures preserved that are convincing evidence for such and origin. This type of feature along with sandstone dykes was described by Bradley (1956) and Solomon (1957) and were used to argue for an onlapping relationship between the Owen Conglomerate and the Lyell Schists.

I consider the arguments of the early workers in this area are more consistent with the present structure than the thrust model supported by Arnold (1985). This model is consistent with the known distribution of Owen Conglomerate. It explains local areas of relatively steep onlap. Within the context of this interpretation the Haulage Unconformity represents erosion of a drape fold or normal fault drag against the bounding east dipping normal faults (Fig. 28a).

A critical feature of the Haulage Unconformity is its relationship to alteration. Silica sericite hematite barite alteration is closely associated with the North Lyell style mineralisation. This style of alteration replaces Owen Conglomerate in a number of places around Tharsis Ridge and to the east of the North Lyell corridor (Arnold 1985, many early workers). On the Tharsis Ridge both Devonian cleavages were recognised within this alteration (Fig. 14). In 4 of the 5 exposures of the Haulage unconformity studied so far, the Owen Conglomerate below the unconformity is strongly altered. At ML56 the alteration in the Owen is strongly pyritic. At ML53 (Fig. 26) there is extensive hematite veins and large patches of hematite sericite alteration. At Batchelors Quarry (ML64) hematite chlorite alteration is common with minor copper mineralisation. Above the quarry on the road (ML43) there is strong hematite alteration. In all these cases, the alteration stops abruptly at the unconformity surface. At ML44 the alteration appears to continue into the lowest beds above the low angle unconformity but these include only very limited hematite alteration patches. At Batchelors Quarry there is native copper in the basal beds which have been interpreted as a clastic input to the Pioneer Sandstone (Solomon 1967). While Arnold (1985) chose to interpret these relationships as evidence of a compositional control on the alteration it is not clear in what way the Pioneer Sandstones are substantially different in composition from the Owen Conglomerate adjacent to them. Both are quartz arenites derived from metamorphic material. I interpret these relationships to indicate the main phase of mineralisation in the North Lyell field (and the Blow) are synchronous with Owen Conglomerate deposition and pre-date the Pioneer Sandstone. Only the copper clays in the Gordon Group and local vein style remobilisation cannot be explained by Late Cambrian hydrothermal systems reacting with onlapping Owen Conglomerate containing circulating oxidised water.

The alternative view is that all the mineralisation in the North Lyell field is produce during Devonian metamorphism. The relationship to cleavage indicates this is syn- or pre-$D_1$. The distribution of the mineralisation is strongly related to the North Lyell Fault which was active at this time but not all the deposits are close to this fault. Since there is little evidence for strong shearing at the GLF at this time the localising influence for many of these deposits remains enigmatic.

The conclusion here that the North Lyell mineralisation is late Late Cambrian has a significant effect on structural interpretations of the area. Many conglomerate/volcanics boundaries are altered in this way. If the conclusion above is correct, all these boundaries must have existed in the Late Cambrian and while they may have been active in the Devonian the geometry will be influenced by this earlier history. The following discussion implicitly include the assumption that GLF contacts with strong alteration existed in the Late Cambrian.

### Tharsis Ridge

The present distribution of conglomerate at Tharsis Ridge is relatively well known from drill core (e.g. Campbell 1968). A section across the ridge based on this report and modern surface geology is shown in Fig. 30. Since hematite alteration occurs along parts of both the north eastern and south western side of this ridge these surfaces existed in the Cambrian. We have already noted in section 2 that the deformation on the western side during the Devonian did not produce intense fault fabrics. This boundary is in the correct stratigraphic order for a normal stratigraphic contact. The eastern side of the ridge has stronger Devonian faulting, and it has volcanics structurally above the Owen Conglomerate. Since there is hematite alteration on this contact it must be at least partly one of the Cambrian surfaces.

A model has been constructed for the evolution of Tharsis Ridge based on these constraints (Fig. 28). the situation during Pioneer Sandstone deposition is shown at a). The Haulage zone is represented by a dragged section of Owen Conglomerate against the

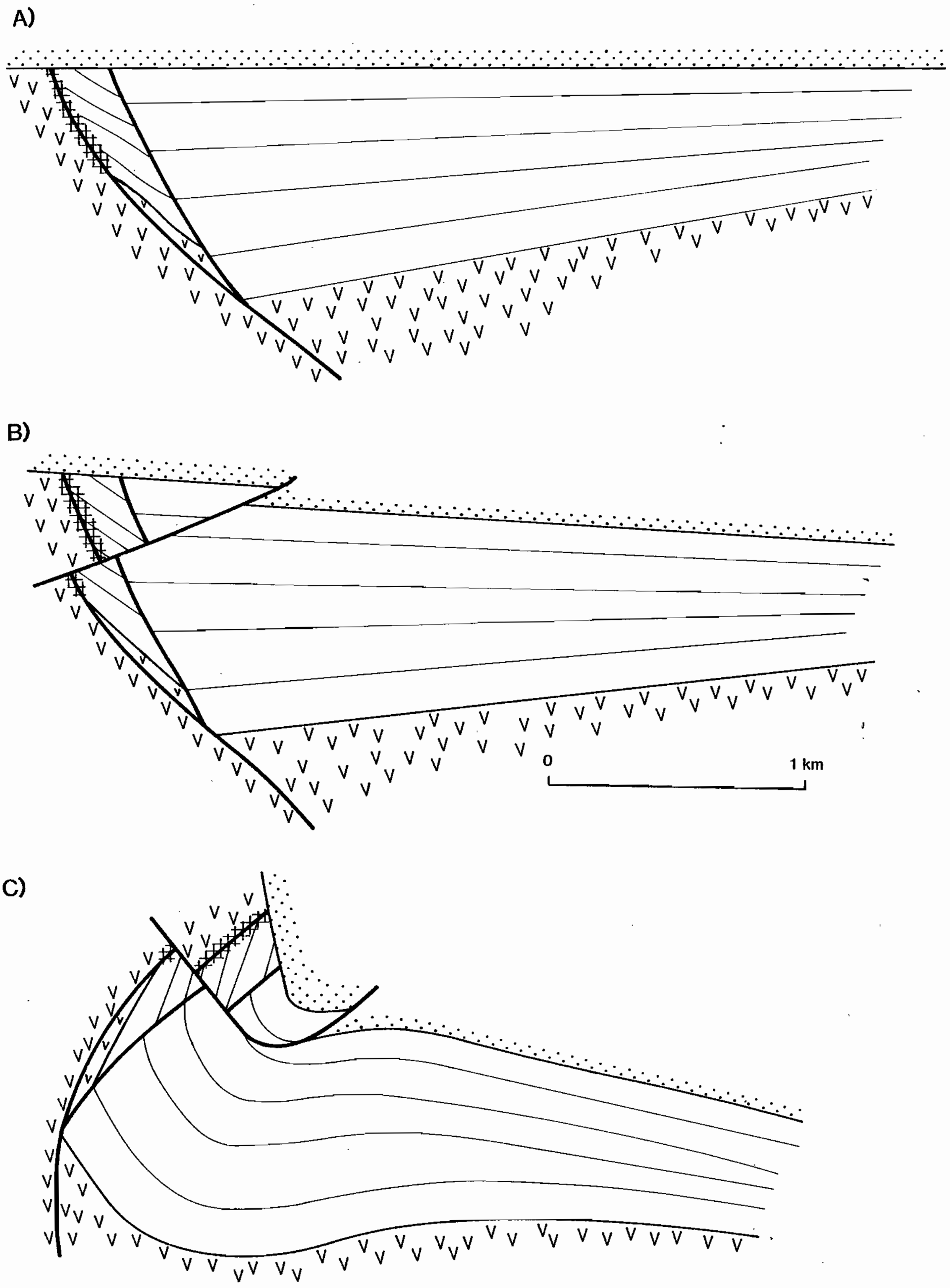


*Figure 28 — Model for the development of the Tharsis Ridge and Trough. (a) the structure at deposition of the Pioneer Sandstone shows two normal faults with a rotated block between them forming the Haulage unconformity. Large scale thickening of Owen Conglomerate towards this structure results from the listric geometry.(b) Thrusting at an early stage of the Devonian offsets these faults. (c) $D_1$ folding produces the Tharsis Ridge and Trough structures.*

*Figure 29 — (a) Hematite matrix restricted to clasts in Pioneer sandstone. (b) Intense hematite sericite alteration 1 m below (a) in Owen conglomerate at ML44.*

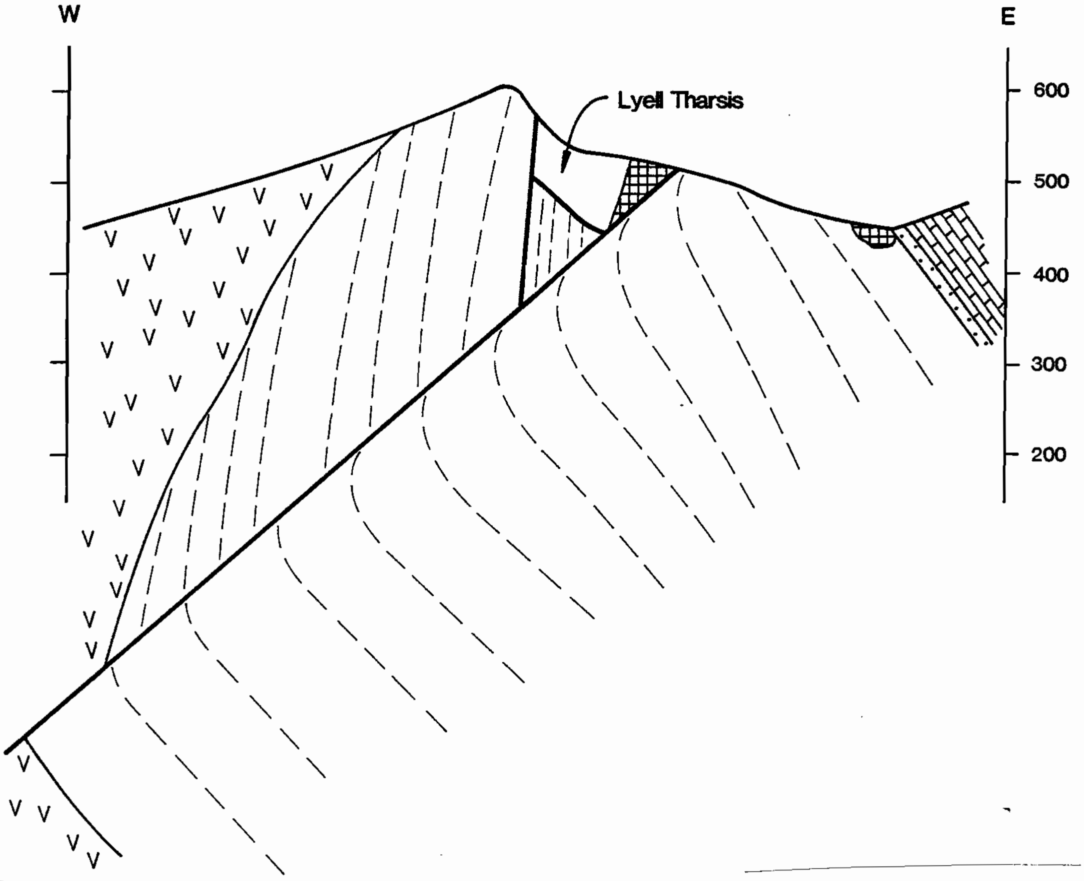


*Figure 30 — Cross-section of Tharsis Ridge based on Solomon (1964), Campbell (1968), Bryant (1975) and surface geology from Arnold (1985). Low angle fault structure is from fault studies in the Tharsis Trough.*

basal normal fault. Mineralisation occurs where faults focused up the margin fault intersect onlapping Owen sediments and can interact with the oxidise connate waters in the clastic sediments. The next event is an early thrust during the Devonian (b) which is folded during $D_1$ folding (c) to produce the Tharsis Trough. Further faulting during $D_2$ complicates this structure. While other solutions are available this is the simplest I have yet found.

North Lyell Corridor

The northern termination of the Owen Conglomerate on Tharsis Ridge has always required very complex structural models. I note here that the presence of the 12 West deposit against this surface strongly suggests it was present as an active fault surface in the Late Cambrian. Similarly, there is alteration on the northern and eastern sides of the corridor.

No Devonian structures were recognised which can explain the lithological distribution in the North Lyell Corridor. Cox (1981) suggested a combination of fault movements which are geometrically possible but the order of these movements does not fit the fault striation data. A section through the corridor was drawn from the level plans (Fig. 31). The resulting shape is shown rotated to make the Owen Conglomerate horizontal in Fig. 31b. The shape is highly suggestive of a normal fault block with Owen Conglomerate onlapping and the North Lyell mineralisation occurring on the top contact of the CVC block. Silicification continues down over the fault surface indicating syn- to post- faulting age for the mineralisation. The pyritic alteration forms a highly suggestive sheath below the mineralisation but this is partly the result of the section chosen and may not reflect the actual shape.

This section provides support for a rotation of the whole North Lyell Corridor area. In removing this $D_1$ folding, the sinistral movement on the North Lyell Fault was included and the amount of slip was adjust on the assumption that the altered section of the fault provided the length of offset of the GLF in the Late Cambrian. The plan view pattern of this restoration is show in Fig. 24. a recontructed shape of the North Lyell corridor is shown in Fig. 32. This reconstruction is very attractive from a number of viewpoints. Firstly the distribution of the mineralisation is closely related to corners in the Cambrian normal fault pattern which have the potential for focussing the fluids. Secondly, it accurately explains the geometry of the corridor. The reconstruction only includes faults and folds

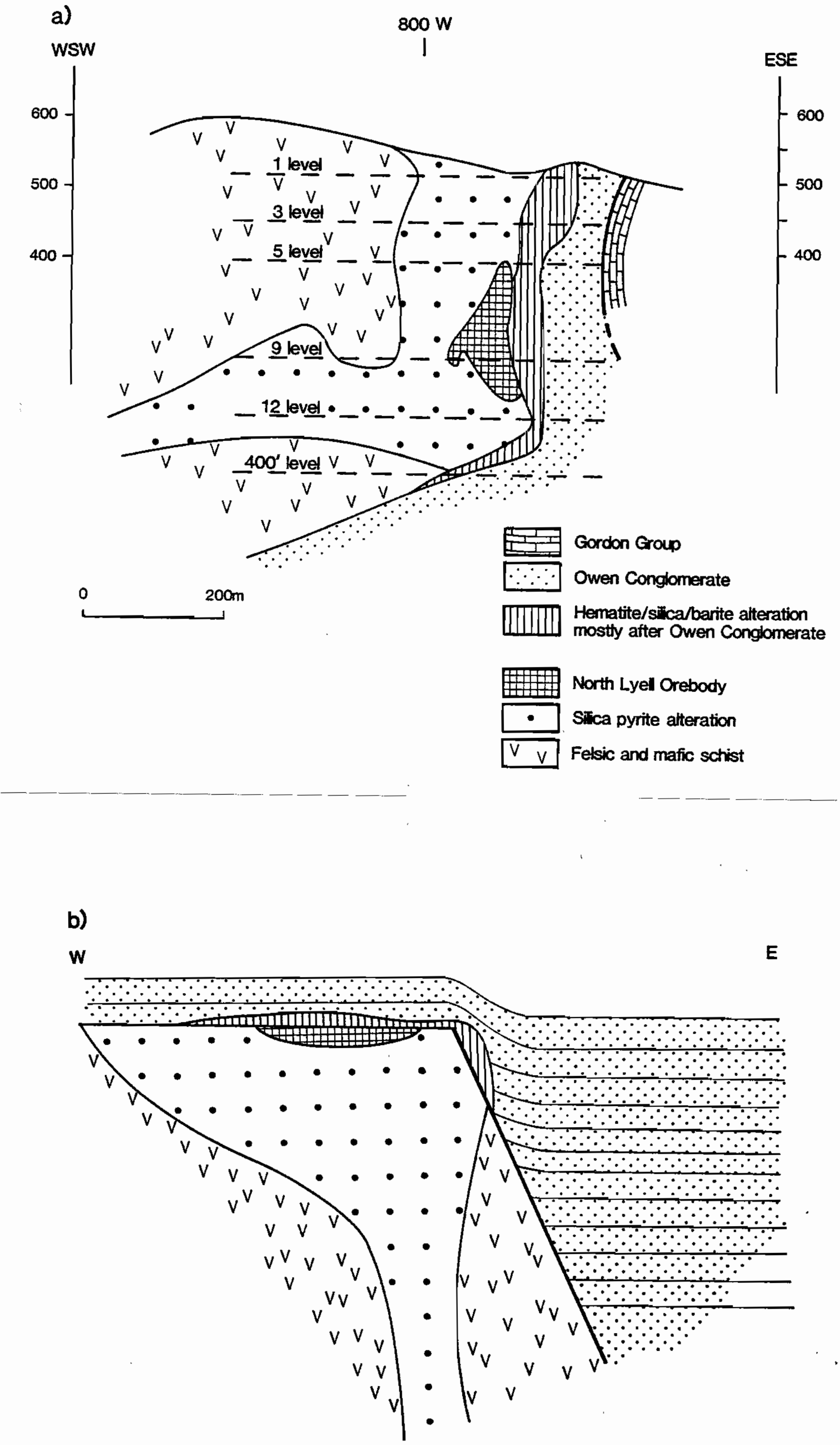


*Figure 31 — Cross-section of the North Lyell Corridor based on Arnold (1985). (a) Present orientation. (b) Rotated to make the Owen Conglomerate horizontal and simplified.*

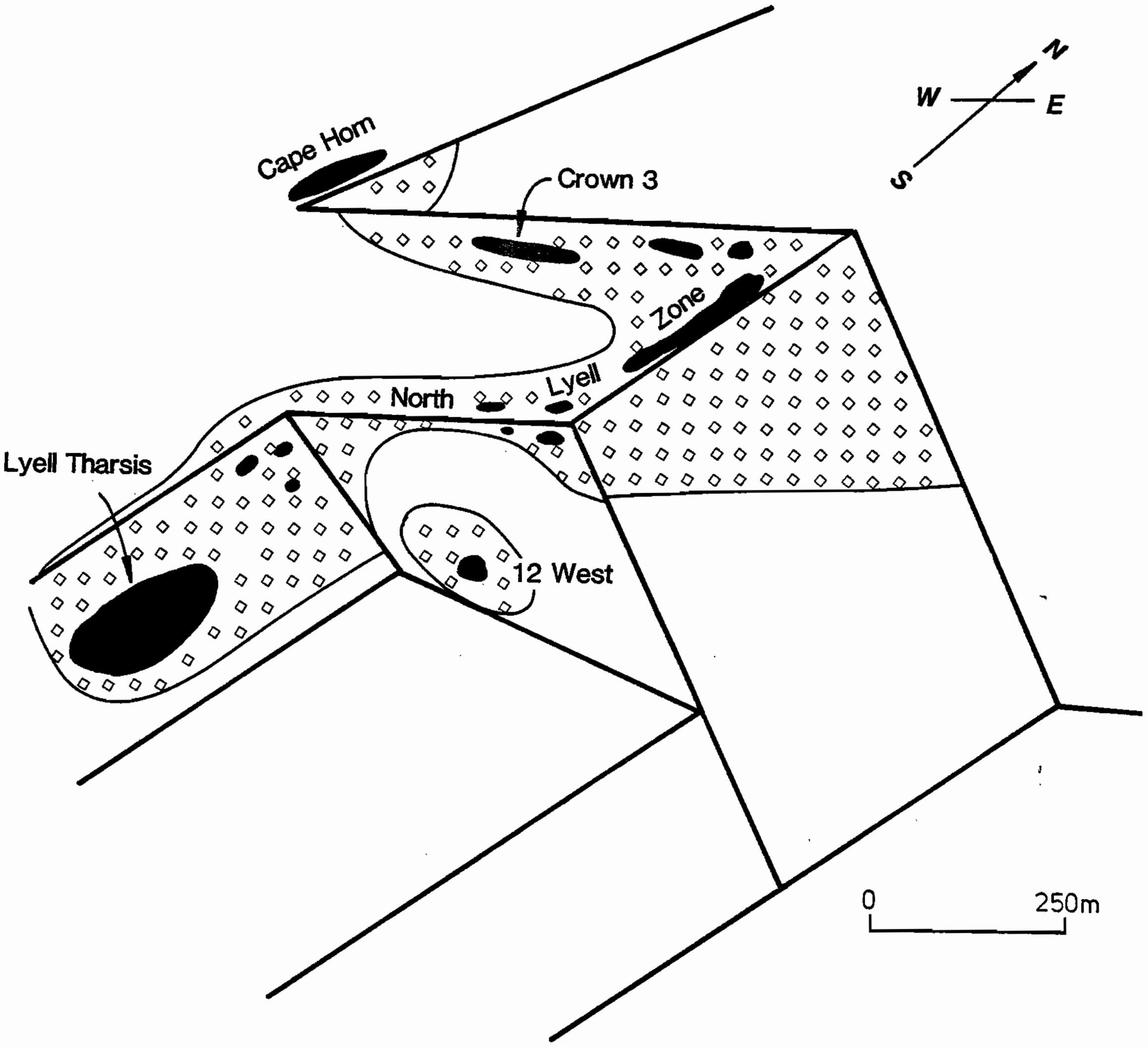


*Figure 32 — Cartoon of the North Lyell structure in the Late Cambrian with the Owen Conglomerate stripped away and showing the approximate position of some of the North Lyell ore bodies.*

which are well known in the area. The Cape Horn deposit is tied into the same pattern rather than being a completely seperate system. The extensive alteration of Owen Conglomerate to the east of the North Lyell mineralisation (Arnold 1985) fits a pattern of mineralising fluid controlled by the North Lyell fault. In this model such an extension is compatible with Cambrian alteration. The very limited zone of Haulage unconformity is explained by the pattern of normal faulting where a transfer fault forms the north end of Tharsis Ridge.

The pattern of faulting suggested here is complex. However normal fault patterns of this type are recognised widely in areas where detailed stratigraphy is possible. For example the normal fault pattern in Fig. 33 is very similar to that proposed for North Lyell. This example, from the Reconcavo Basin, Brazil, is an extensional basin marginal to the South Atlantic (Ghignone & Andrade 1970). The structure of the area has other similarites to the Dundas Trough. It is roughly the same dimensions and has old basement exposed on both sides. On the eastern margin there is a very thick basement derived mass of conglomerate with dimensions similar to the Owen Conglomerate. Similar complexity of faulting is recorded in the Miocene of NorthEast Japan (e.g. Yamiji 1990) although in this volcanic terrane much of the fine detail is lost.

### Razorback Ridge

The general distribution of rocks on the Razorback are similar to the Tharsis Ridge except that the difference in dip between eastern and western contacts is greater. No Devonian normal fault striation were found on the eastern side of the ridge although this has been strongly faulted, mainly as a dextral wrench fault, in the Devonian $D_2$. Thus the Devonian structure does not readily explain the present structure unless the eastern side of the ridge is a reactivated Cambrian Fault. Further work is required to address this problem. The Blow is interpreted here as part of the original onlap surface which has not been remove during reactivation on this surface.

## SUMMARY

The Devonian structure of the Mt Lyell area includes $D_1$ folding and thrusting with reactivation of Cambrian normal faults as both thrusts and transfer faults. The area around Lyell reacted anomalously during this event due to the intense alteration and strong variation in the thickness of the Owen Conglomerate.

During $D_2$ the most intense cleavage development is in a zone across Philosophers Ridge. elsewhere the $S_2$ can be recognised overprinting $S_1$. The major deformations within the Central Volcanic Complex during this phase are reverse faults and the major dextral fault zones through Glen Lyell, and to a lesser extent along the Great Lyell Fault.

A model for the Cambrian is proposed which indicates an irregular fault geometry controlling the distribution of some of the mineralised zones, especially in the North Lyell Field. The Haulage unconformity is related to this fault pattern and a seperate thrusting event in the earliest Ordovician is not required by the data.

Further work is required to extend this data set towards the south and apply it to the area of the Blow and Cu Estates. The model emphasizes the value in using combined structural stratigraphic data to identify potential Cambrian fault structures which may focus mineralising fluids.

## ACKNOWLEDGEMENTS

This report would have not be possible without the access provided by RGC to a wide range of unpublished reports. Many thanks to Gary Arnold and Mark Dufty for their support and encouragement.

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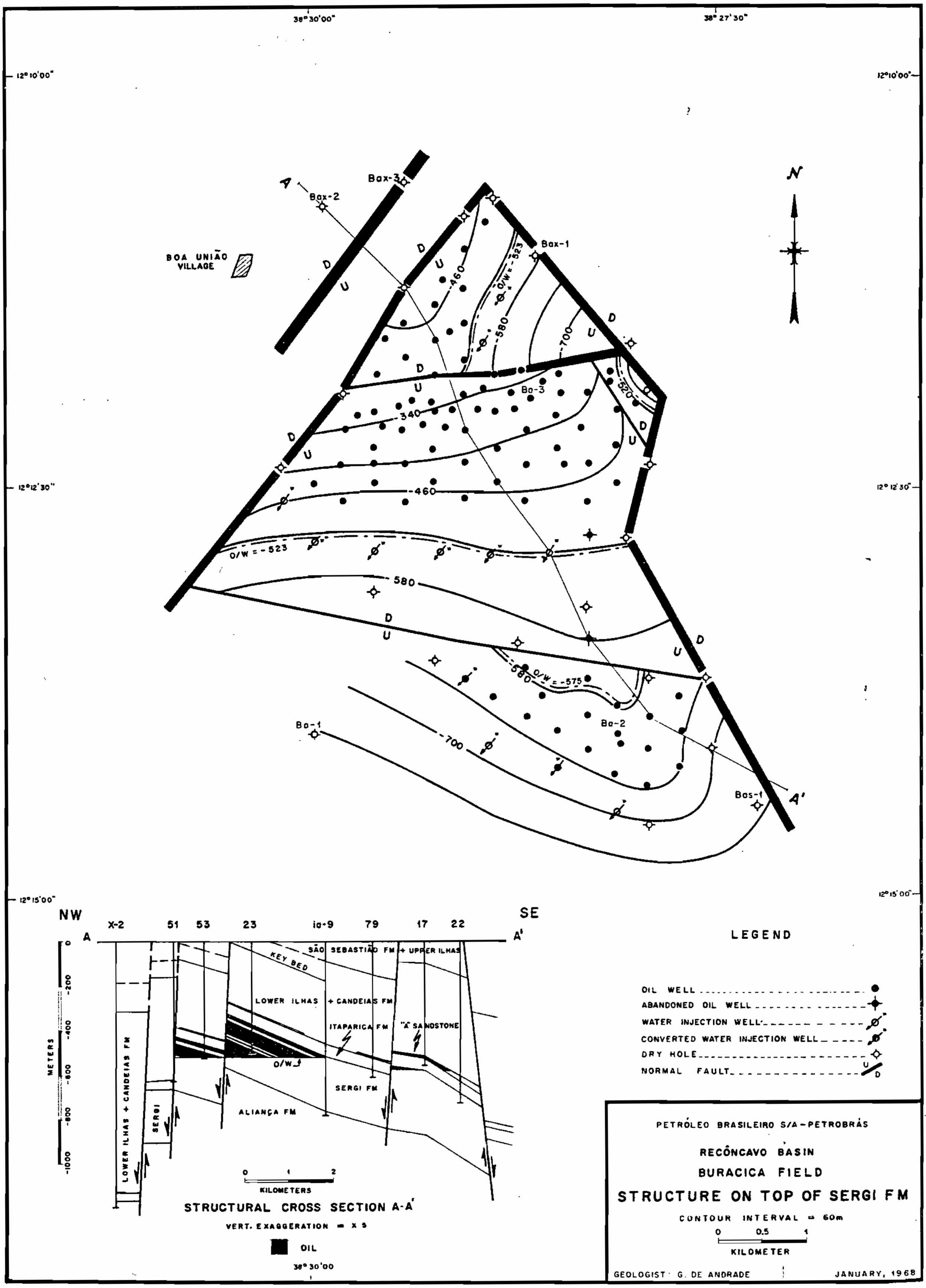

*Figure 33 — Structural map of the Buracica oil field, Reconcavo Basin, Brazil from Ghignone & Andrade (1970) showing its close similarity in shape and dimension to the model for the North Lyell structure.*