SEISMIC REFLECTION IMAGING OF MINERAL SYSTEMS;

THREE CASE HISTORIES.

by

B.J. Drummond[1], B.R. Goleby[1], A.J. Owen[1], A.N. Yeates[1], C. Swager[2],

Y. Zhang[3] and J.C. Jackson[4]

1   Australian Geological Survey Organisation, P.O. Box 378, Canberra, A.C.T., 2601,

Australia.

2   Geological Survey of Western Australia, 100 Plain Street, Perth, W.A., 6000, presently at

North Ltd, PO Box 231, Cloverdale, W.A., 6105

3   CSIRO, Division of Exploration and Mining, Nedlands, W.A., 6009, Australia

4   Mount Isa Mines Exploration, presently at Sons of Gwalia, 16 Parliament Place, West

Perth, W.A., 6005, Australia.

ABSTRACT

Mineral deposits can be described in terms of their mineral systems, ie., fluid source, migration pathway and trap. Source regions are difficult to recognise in seismic images. Many orebodies lie on or adjacent to major fault systems, suggesting that the faults acted as fluid migration pathways through the crust. Large faults often have broad internal zones of deformation fabric, which is anisotropic, and this, coupled with the metasomatic effects of fluids moving along faults while they are active, can make the faults seismically reflective. For example, major gold deposits in the Archaean Eastern Goldfields Province of Western Australia lie in the hanging wall block of regional-scale faults that differ from other faults nearby by being highly reflective and penetrating to greater depths in the lower crust. Coupled thermal, mechanical and fluid flow modelling supports the theory that these faults were fluid migration pathways from the lower to the upper crust. Strong reflections are also recorded from two deeply penetrating faults in the Proterozoic Mt Isa Province in northeast Australia. Both are closely related spatially to Cu and Cu-Au deposits, and one, the Adelheid Fault, is also adjacent to the large Mt Isa Ag-Pb-Zn deposit. In contrast, other deeply penetrating faults that are not intrinsically reflective, but are mapped in the seismic section on the basis of truncating reflections, have no known mineralisation. Regional seismic profiles can therefore be applied in the pre-competitive area-selection stage of exploration. Applying seismic techniques at the orebody scale can be difficult. Orebodies often have complex shapes and reflecting surfaces that are small compared to the diameter of the Fresnel Zone for practical seismic frequencies. However, if the structures and alteration haloes around the orebodies are targeted, rather than the orebodies, seismic techniques may be more successful. Strong bedding-parallel reflections were observed from the region of alteration around the Mt Isa Ag-Pb-Zn orebodies using high resolution profiling, and a profile in Tasmania imaged an internally non-reflective bulge within the Que Hellyer Volcanics suggesting a good location to explore for a Volcanic Hosted Massive Sulphide deposit. These case studies provide a pointer to how seismic

techniques could be applied during mineral exploration, especially at depths greater than those being explored with other techniques.

INTRODUCTION

Deep seismic reflection programs around the world are mostly directed to understanding the tectonic evolution of the regions studied, and therefore have often led only indirectly to an improved understanding of their mineral potential. In contrast, a seismic transect of the Mount Isa Inlier of northeast Australia sponsored by the Australian Geodynamics Cooperative Research Centre was deliberately designed to place major orebodies in the inlier into their regional geodynamic framework (Drummond et al, 1997).

The results from the Mt Isa transect, together with the findings of Drummond and Goleby (1993) from the Eastern Goldfields Province of Western Australia, suggest that the seismic profiling technique could be imaging fluid migration pathways within the crust. Higher resolution studies (eg., Milkereit et al., 1996, Yeates et al., 1996, and Goleby, et al., 1997) suggest that seismic techniques can also be successful at the orebody scale, especially if they are used to image the structures and alteration zones around the orebody, rather than the orebody itself.

In this paper, we place the seismic results from three unrelated and widely separated terranes of different ages, ie the Eastern Goldfields Province (Drummond and Goleby, 1993), the Mount Isa Inlier (Drummond et al., 1997) and Tasmania (Yeates et al., 1996), into a mineral system framework. Although the mineral deposits studied are different in many ways, the simplifying mineral systems approach provides pointers to how seismic techniques can be effective in both the pre-competitive area selection stage and in direct exploration.

MINERAL SYSTEMS

Mineral systems are analogous to petroleum systems, which describe the genetic relationship between a petroleum source rock and an accumulation (Magoon and Dow, 1991). Using this definition, a mineral system can be described in its simplest form as a fluid source, a migration pathway, and a trapping mechanism that scavenges the minerals from the fluids. The fluid source could be basin brines in the case of strata-bound deposits, or more deep-seated lower crustal or even upper mantle hydrated rocks in the case of other deposits.

Migration pathways are needed to focus the fluids from their source into the trap. Many mineral deposits lie on, or adjacent to, major fault zones, suggesting a causal relationship. Fault systems provide fracture porosity as well as a focussing mechanism. In the case of basin brines, the general distribution of permeable and impermeable rocks of the basin strata also allows fluid flow and influences its form.

Trapping mechanisms take a variety of forms, and require the superposition of physical barriers to fluid flow, eg., local structure, stratigraphy and permeability, whether intrinsic or fracture induced, with the appropriate chemical, thermal and probably palaeogeographic settings for the minerals to be deposited. Hence studies that describe mineral deposits, rather than mineral systems, and which focus mainly on the trapping mechanisms, tend towards descriptions of the unique and often complex combinations of elements in the trapping mechanism for each deposit, and do not see the underlying unifying elements of the mineral system.

Mineral systems are usually triggered by a thermal pulse, which in turn can often be related to intraplate tectonics resulting from interplate activity (Loutit et al., 1994). Whereas petroleum systems are usually characterised according to the age and type of the source rocks (the fluid source) (Bradshaw, 1993), the ages of mineral deposits are often less certain. Mineral systems may be characterised either according to the age of the host rocks or the age of the thermal event that triggered them. Just as a sedimentary basin can have several superimposed petroleum systems reflecting the maturing through time of a number of stacked source rocks and their associated fluid pathways and traps, a mineral province can be host to several mineral systems.

Identifying fluid source regions in seismic images may be difficult. The dehydration of a large area of crust to create mineralising fluids will not necessarily leave an observable physical imprint on the rocks that distinguishes that region from any other region, especially in metamorphic rocks. This is because the physical effects of dehydration may be similar to those of metamorphism (higher densities and seismic velocities).

Large volumes of rock can be effectively dehydrated over time by relatively low fluid flux rates, but if the fluids are concentrated into fracture induced permeability zones along faults, higher flux rates will occur along the faults. This can lead to wide alteration haloes along faults and metasomatism within the fault zone. Where the fault zone is the focus of high strain, mylonite zones develop. They characteristically have a well-developed fabric which is anisotropic (e.g., Jones and Nur, 1984; Siegesmund and Kern, 1990). Mylonite zones can be good reflectors (Jones and Nur, 1984; Goodwin and Thompson, 1988). The seismic reflectivity results from the constructive interference of reflections from the bands of altered and strained anisotropic rock within the mylonite zones. Subsequently, Drummond and Goleby (1993) interpreted some elements of crustal reflectivity in the Archaean Eastern Goldfields Province of Western Australia in terms of fluid pathways through the crust based on the geometry of the fault zones and their spatial relationship to known mineralisation. This was a regional study and no attempt was made to link it with local studies at the orebody scale.

The second case history, at Mount Isa, did try to link from the regional scale into the orebody scale. Salisbury et al. (1996) demonstrated that many of the sulphide minerals that typically make up the bulk of mineralisation constituting orebodies have seismic velocities similar to felsic and mafic igneous rocks, and also some sedimentary rocks, but they have much higher densities. Pyrite has both higher density and higher seismic velocity. Therefore, in many cases, the orebody should have a significant impedance contrast with country rock of most compositions. However, orebodies can have very complex shapes, and often lie in complexly folded or deformed host rocks. Orebody reflections may be lost amongst the reflections and interference signals from the surrounding host

material. Orebodies are often very small in size compared to the wavelength of seismic energy returned from the earth. Therefore, to maximise the chance of success in using seismic methods at the trap or orebody part of the mineral system, we recommend targeting the controlling structures around the trap, and perhaps the broader alteration haloes around the orebodies.

Therefore, in the Mount Isa study, the strategy was not to try to image the orebody itself, but rather to target a known larger alteration zone that would be characteristic of the environment where mineralisation might occur. That is, it focussed on the fluid migration pathways adjacent to the orebody, and the structure of the trap. This is analogous to the approach used in petroleum exploration where the structure of the reservoir would be the seismic target, rather than the pool of oil it may contain.

The third case history, in Tasmania, studied a totally different style of ore environment and demonstrates that by targeting the mineral system rather than the orebody, seismic methods can be successfully applied in a range of environments.

SEISMIC METHODOLOGY CONSIDERATIONS

Typically, the geology and structure of the three mineralized regions described in these case histories is complex, with a range of lithologies subjected to at least three deformational and/or metamorphic events prior to the mineralizing event. However, in all cases the available geological control is good, with information from mining in the region, deep drill holes and detailed surface geological mapping. Two-dimensional and some low fold 3D seismic reflection, and 2D and 3D crustal scale refraction techniques were used. However, only seismic reflection results are presented here.

The case studies used regional transects that were focussed on structure within the middle to upper crust, and higher resolution seismic surveys of mine-scale structures.

Explosive charges in deep drill holes provided the energy sources. The seismic data were

collected with 96 or 120 channels, and quality control was primarily through field monitors and in-field data processing to at least brute stack stage, especially for the high resolution data. Typically, the station spacing was 40m for the regional surveys and 10-20m for the higher resolution surveys. Shot-hole spacings were variable but a nominal stacking fold of between 12 and 24 was achieved. Symmetrical split-spread geometries were used, which resulted in a maximum shot-to-receiver offset of 2400 m for the regional surveys.

In this type of project, the main data processing problems result from difficult static corrections and large velocity variations. Detailed refraction static analysis is required to adjust for the effects of a highly variable regolith in most parts of Australia, especially with the higher frequencies needed in high resolution studies. Near-surface velocity variations are high, ranging from around 1000 $m.s^{-1}$ within parts of the regolith up to 7000 $m.s^{-1}$ in metamorphosed ultramafic bedrock in the Eastern Goldfields Province.

The rocks are mostly highly deformed, so reflector continuity, although variable, is usually far shorter that that encountered within sedimentary basins. The amplitudes of reflections are often excellent, but they may not be primary reflections. We have adopted a strategy in which we identify regions of similar reflector coherency and dip. We correlate those regions with the surface geology, or with seismic velocities from crustal scale refraction or tomography studies in order to assign rock type, and use the geometry and spatial relationships of regions of similar reflection character to infer tectonic processes. Interpretations are usually confirmed with both qualitative and quantitative interpretation of gravity and magnetic data, supplemented with available geological evidence.

CASE HISTORY 1: THE EASTERN GOLDFIELDS OF WESTERN AUSTRALIA

The Yilgarn Craton in Western Australia (Figure. 1) consists of several geological provinces. Gneissic granitoid, with granitoid plutons and greenstone supracrustal rocks are common in all provinces. Each province can be divided into a number of terranes, each defined by the distinct

stratigraphy of its volcanic and sedimentary supracrustal rocks. The Eastern Goldfields Province is host to much of the region's known gold deposits, most of which occur in the west of the province. The Ida Fault separates it from the Southern Cross Province to the west.

A regional scale, 213 km-long seismic reflection traverse was positioned east-west across the regional strike (Figure 1) (Goleby et al., 1993). The interpretation of the shallow part of the seismic data was given by Swager et al., (1997). The greenstone supracrustal rocks lie above a subhorizontal detachment between 1.5 and 2.5 s (4.5 and 7.5 km), and therefore have a tectonic boundary with the underlying, presumably felsic gneissic basement (Figure 2). Many of the faults in the greenstones, eg., the Zuleika Shear (Figure 2) are not reflective and are interpreted by their truncations of greenstone stratigraphy. These faults can be mapped laterally over considerable distances within the greenstones, but they are not deeply penetrating and sole on the detachment surface.

However, several faults penetrate the detachment. These faults are often reflective. Within the seismic section, the Ida Fault and the Bardoc Shear are the prominent examples (Figure 2). The Ida Fault dips approximately 30° to the east and extends to 25-30 km depth. The Bardoc Shear dips west, penetrates the detachment surface, and truncates against the Ida Fault at about 15 km depth. Bottom hole cuttings from the shot holes along the traverse were chemically analysed. Those from near the Ida Fault and Bardoc Shear have comparable alteration patterns, indicating that similar or the same fluids moved along both of the faults in the past. This supports the seismic observation that the faults are probably linked at depth (Goleby et al., 1993).

Many of the faults in the region, including those that do not penetrate the detachment, can be associated spatially with gold deposits. However, the Bardoc Shear and its southern extension (Boorara Shear near Kalgoorlie, Lefroy Fault near Kambalda) are associated spatially with major gold districts, including the Golden Mile at Kalgoorlie and the Kamdalda-St Ives deposits. Many of the gold deposits lie to the west of the shear, i.e., in the hanging wall block.

Based on near-surface fluid flow patterns suggested by Goleby et al. (1993), Drummond and

Goleby (1993) proposed that mineralizing fluids migrating from the lower crust to higher levels in the greenstones followed a path, firstly into and along east-dipping shear zones within the lower crust, then into the Bardoc Shear. From there they were able to percolate into the hanging wall block (arrows in Figure 2). Some would leak along the detachment and into other faults within the greenstone sequence that splay from the detachment (e.g., Zuleika Shear; Figure 2), but most would concentrate in the greenstones, immediately above and to the west of the Bardoc Shear.

Numerical modelling of fluid flow within the Eastern Goldfields Province supports this linked fluid-pathway model (Figure 3) (Upton et al., 1997). The numerical modelling used the crustal structure defined by the seismic profiling; other physical properties of the crust were assumed. The order of deformational and thermal events was derived from the geological record. The modelling predicted an initial, single crustal-scale convection cell in which fluids were driven up the Ida Fault from depth and down the Ida Fault from the surface. These mixed and flowed up the Bardoc Shear, resulting in a high degree of chemical alteration and hence mineral deposition within the upper crust, particularly within the greenstones. As temperatures dropped, the single convection cell broke down into smaller cells within the upper crust. These concentrated the mineral species in the upper crust. The coupled deformation, thermal and fluid flow modelling predicted east-dipping faults within the crust, as seen in the seismic data, and in the vicinity of known ore deposits. It also predicted focussed fluid flow into the east-dipping shear zones.

CASE HISTORY 2: MOUNT ISA

The Proterozoic Mount Isa Inlier of northern Australia is recognised for its world-class Ag-Pb-Zn and Cu-Au ore deposits. The inlier consists of an Eastern Fold Belt, a Western Fold Belt and the central Kalkadoon Block (Figure 4). A major east-west deep seismic traverse 255 km long was recorded just to the south of Mount Isa (Figure 4). The seismic reflection section shows a marked difference in the structure of the top 5-10 km between the Eastern Fold Belt and the Western Fold

Belt (MacCready et al., 1999; Drummond et al., 1997).

Seismic data from the Marimo region (Figure 5) combined with detailed structural mapping show that the sediments of the Eastern Fold Belt were emplaced by thin-skinned thrusting from the east along several stacked and probably contemporaneous sub-horizontal thrusts. Further shortening then occurred along steeper east-dipping reverse faults. They are mostly recognised in the seismic data by the offset they created on the reflective lowermost thrust detachment (MacCready et al., 1999) and extend to depths of 15-18 km where they intersect a region of high seismic velocities, probably mafic in composition (Drummond et al., 1997).

The Marimo Fault ('M', Figure 5) is intrinsically reflective in the upper 6 km (2 s two way time). Prior to the seismic survey, no fault had been mapped in this region. Structural mapping undertaken to support the interpretation of the seismic data found an east-dipping, 200 m wide zone of hydrothermal alteration. The reflectivity of the fault is believed to result from the broad zone of alteration. The spatial relationship of this fault to mineral deposits in the region is seen as further evidence that this fault acted as a fluid pathway. The Mount McNamara Cu-Au mine lies near the transect, and the Hampden, Mount Dore, Selwyn, and Osborne Cu-Au mines lie on a linear trend to the south (Figure 4).

Farther west, the seismic transect imaged a sequence of folded and faulted reflectors representing sequences within the Leichhardt River Fault Trough of the Western Fold Belt. Those of the Eastern Creek Volcanics (ECV) are marked in Figure 6 (MacCready et al., 1997). The Mount Isa, Adelheid and Sybella Faults, and a number of other minor faults, form part of an anastomosing fault system that extends for many tens of kilometres along the western side of the Leichhardt River Fault Trough.

To the north of the transect, four major Pb-Zn (-Ag) and Cu deposits lie close to the Mount Isa Fault. The fault dips west at 70° and extends into the upper to middle crust (Figure 6). However, it is not reflective. Its surface outcrop is less than a kilometre to the east of the Adelheid fault. The data in Figure 6 are not migrated and show that the Adelheid Fault not only has strong P-wave

reflections, which are interpreted in the figure, but also S-wave reflections which are unmarked and lie between the Adelheid and Mt Isa faults. The strongest reflections in this pseudo- true amplitude section are seen on the fault below the word "vortex" at the top of the figure. Heinrich et al. (1995) proposed that the Pb-Zn deposits in the region formed from brines circulating within the Leichhardt River Fault Trough. The seismic data indicate that the Adelheid Fault probably acted to focus these brines into the anastomosing fault set near the present day surface.

Two and 3-dimensional high resolution seismic data were recorded between the Mount Isa and Hilton Mines (1-2 km N of Mt Isa, Figure 4). They were designed to test predicted cross sections just north of the Cu and Pb-Zn orebodies (Figure 7) (Neudert and Russell, 1982). Locally, Pb-Zn mineralisation tends to be in steeply west-dipping lenses parallel to bedding within the Urquhart Shale. Copper mineralisation lies deeper. Both the Pb-Zn and Cu mineralisation lie above the Paroo Fault.

The Paroo Fault and alteration haloes above the copper deposits were the targets for the high resolution survey; the Urquhart Shale was expected to have strong impedance contrast with the underlying basement of Eastern Creek Volcanics. A two-dimensional data section is shown in Figure 8. Reflections were recorded from the sub-horizontal part of the Paroo Fault in the east of the section; farther west it is mapped using truncations of the reflections from the Urquhart Shale. The data also show unexpectedly strong, west-dipping reflections from within the Urquhart Shale; they are parallel to bedding and correspond to predicted zones of alteration and sulphide mineral enrichment.

CASE HISTORY 3: TASMANIA

The Dundas Trough and its constituent Mount Read Volcanics in Tasmania (Figure 9) are host to a number of world class mineral deposits (Large, 1992). A seismic reflection survey across the region in 1995 included both regional deep and shallow high-resolution seismic profiles.

Drummond et al. (1996) summarised the results of the regional profiles. They show the Palaeozoic section of the Dundas Trough and Mount Read Volcanics to be a highly folded and faulted succession with a total thickness of at least 4 km. Individual stratigraphic units within the Dundas Group and Mount Read Volcanics are generally not differentiated in the regional profiles, due probably to their highly deformed nature and the low impedance contrasts between the units.

The high resolution data were expected to overcome these problems. They were interpreted using drill hole control (Jovan Silic, Andrew McNeill and Steve Richardson, Aberfoyle Pty Ltd, *pers. comm*, 1996) (Figure 10 and Yeates et al., 1997). Reflectors at about 900 m and 1150 m below shot point 1055 are interpreted as the top and base of the Que River Shale. This unit overlies the Que-Hellyer Volcanics. The base of the volcanics is interpreted as the reflector at about 1500 m. The Que-Hellyer Volcanics therefore have a noticeable bulge, similar in geometry to the mound-type Zn-Pb-Cu (Ag, Au) Hellyer deposit (Large, 1992) within the Que-Hellyer Volcanics several kilometres to the south. From the known lithologies in the area, the strong reflections above this zone, at 1150 m, infer the presence of carbonates, dolerite or massive sulphides. Reflections within the bulge are weak, inferring a zone of strong alteration that produced homogeneity within the volcanics in the bulge.

DISCUSSION

The relation of fault reflectivity to anisotropy within fault zones and alteration caused by fluids is both observationally based and supported by modelling. In the Eastern Goldfields Province, some faults are reflective and others are not. Those that are reflective penetrate to greater depths. The surface outcrop of the Bardoc Shear is hundreds of metres wide and shows high strain (Swager and Griffin, 1990). It has several gold deposits in its hanging wall in the region of the transect. The geochemical alteration signatures from shot hole samples support the seismic interpretation that it links in the crust with the Ida Fault. The surface outcrop of the Marimo Fault in

the Eastern Fold Belt of the Mount Isa Inlier has extensive hydrothermal alteration, and lies along strike from operating Cu-Au mines. In NW Tasmania, the loss of reflectors in the bulge of the Que-Hellyer Volcanics would infer alteration.

The physical model of shear zones of Jones and Nur (1984) suggested that anisotropy is the primary cause of the reflectivity from two crustal scale shear zones. Their model was based on measurements of the physical properties of samples collected from surface outcrops of mylonite zones. It consisted of anisotropic rock with low impedance normal to the shear zone, interlayered with isotropic rock with impedance similar to the protolith either side of the shear zone. Their modelling required constructive interference to create amplitudes comparable to those observed. To do this, they required the layers to be 110 - 150 m thick. Goodwin and Thompson (1988) also discussed the reflectivity due to mylonite zones. Their physical models were based on logs from a conveniently located well, and had layers that were much thinner (about 30 m). They also found that tuning of the layer thickness was important to achieve the observed amplitudes, but that lateral variations in layer velocity and/or thickness over distances of about 100 m were also important.

Neither of these studies compared the relative effects of anisotropy resulting from strain, and alteration caused by metasomatism. Siegesmund and Kern (1990) found that reflectivity due to anisotropy cannot account for the amplitudes of all observed lower crustal reflections. Klemperer et al. (1986) studied the Outer Isles Thrust in Britain, and found that metasomatism was more important than anisotropy in causing impedance contrasts. Anisotropy, although present, was disorganised at scales of 100m. Whereas Jones and Nur (1984) found that the bulk physical properties of anisotropic rock were near those of the protolith, Jones (1986) found that both velocity and density increased from protolith through mylonite to ultramylonite, accompanying a reduction in Si and an increase in Fe, Ca and Mg.

The details of the physical properties on which these models are based differ from study to study, and from fault to fault, indicating that local factors are important. However, the principles established by these studies are that on a regional, deep crustal scale, fault zone reflectivity can be

related to strain induced anisotropy and changes in bulk physical properties resulting from alteration. These principles also apply to structures and alteration at the mine scale.

However, the alteration products may be different because they are formed at the end of the fluid migration pathway. For example, the alteration haloes around the Cu orebody at Mount Isa contain significant amounts of pyrite whereas the Pb-Zn orebodies at Mount Isa lie within an altered zone containing lesser pyrite. Salisbury et al. (1996) found that massive sulphide deposits can have impedances much higher than most common host rocks, and Milkereit et al. (1986) confirmed that massive sulphide orebodies, if thick enough, can be good reflectors. Pyrite, in particular, has a higher density than the host rocks of the Mount Isa orebodies, and if present in sufficient quantities in the alteration haloes, will result in an impedance contrast between the host rocks and the alteration zone. This is probably what caused the high amplitude reflections in Figure 8, and possibly also over the bulge in the data from northwest Tasmania (Figure 10).

Not all strong reflections in the seismic sections are from fault zones. The identification of fault zones often depends on whether they link with surface outcrop, and, in the case of reflectors which do not reach the surface, whether the structure mapped at depth in the seismic section makes structural sense if the reflectors are or are not interpreted as faults.

We believe that reflectivity of faults is one parameter that could be used to indicate where fluids have fluxed from the deeper crust. In our studies, the seismic methodology was used to image the main structures that either control the orebody itself or bound the extent of mineralisation. In our experiences, in fold belt terrains the strongest and most laterally continuous reflection zones often can be interpreted as faults and shear zones. In the few occasions where we applied this principle at the mine scale, our results were encouraging.

Many tens of thousands of kilometres of high quality, deep seismic profiles now exist for a wide range of tectonic environments around the world. Most are in the public domain, and in almost all cases, the data have not been examined extensively for pointers to areas of enhanced prospectivity.

ACKNOWLEDGMENTS

REFERENCES

Drummond, B.J., and Goleby, B.R., 1993, Seismic reflection images of major ore-controlling structures in the Eastern Goldfields, Western Australia: Exploration Geophysics, **24**, 473-478.

Drummond, B.J., Goleby, B.R., Goncharov, A.G., Wyborn, L.A.I., Collins, C.D.N., and MacCready, T., 1997, Crustal-scale structures in the Proterozoic Mount Isa Inlier of north Australia: their seismic response and influence on mineralisation: Tectonophysics, **288**, 43-56.

Drummond, B.J., MacCready, T., Lister, G.S., Goncharov, A., Goleby, B.R., Page, R., and Wyborn, L.A.I., 1995, AGCRC Mount Isa Transect: AGCRC Mt Isa Transect Workshop Publication, AGCRC Perth.

Drummond, B.J., Korsch, R.J., Barton, T.J., and Yeates, A.V., 1996, Crustal Architure in northwest Tasmania revealed by deep seismic reflection profiling: Australian Geological Survey Organisation, Research Newsletter, **25**, 17-19.

Fallon, G.N., and Busittil, S., 1992, An appraisal of the geophysical effects of the Mount Isa

orebodies: Exploration Geophysics, **23**, 133-140.

Fallon, G.N., Andrews, P., Bartrop, S., and Jackson, J., 1997, Drillhole electromagnetic surveying in the mine environment: Exploration Geophysics, **27**, 67-75.

Goleby, B.R., Drummond, B.J., Owen, A.J., Yeates, A.N., Jackson, J., Swager, C., and Upton, P., 1997, Structurally controlled mineralisation in Australia - how seismic profiling helps find minerals: recent case histories, *in* A.G. Gubins (Ed.) Proceedings of Exploration' 97: Fourth Decennial International Conference on Mineral Exploration, Toronto, 409-420.

Goleby, B.R., Rattenbury, M.S., Swager, C.P., Drummond, B.J., Williams, P.R., Sheraton, J.W., and Heinrich, C.A., 1993, Archaean crustal structure from seismic reflection profiling, Eastern Goldfields, Western Australia: Australian Geological Survey Organisation, Record 1993/15.

Goodwin, E.B., and Thompson, G.A., 1988, The seismically reflective crust beneath highly extended terranes: Evidence for its origin in extension: Geological Society of America Bulletin, **100**, 1616-1626.

Heinrich, C.A., Henley, R.W., and Seward, T.M., 1989, Hydrothermal Systems: Australian Mineral Foundation, Adelaide.

Jones, R., 1986, Seismic reflections from major faults: PhD Thesis, Cambridge University.

Jones, T., and Nur, A., 1984, The nature of seismic reflections from deep crustal fault zones: Journal of Geophysical Research, **89**, 3153-3171.

Klemperer, S., and the BIRPS Group, 1986, Progress in understanding the origin of crustal reflections: Second International Symposium on Deep Seismic Profiling of the Continental Lithosphere, Cambridge, Abstracts, 19.

Large, R.R., 1992, Australian VHMS deposits: features, styles, genetic models: Economic Geology, **87**, 471-510.

Loutit, T.S., Wyborn, L.A.I., Hinman, M.C., and Idnurm, M., 1994, Palaeomagnetic, tectonic, magmatic and mineralisation events in the Proterozoic of northern Australia: Australasian

Institute of Mining and Metallurgy Annual Conference, Proceedings, 123-128.

MacCready, T., Goleby, B.R., Goncharov, A., Drummond, B.J., and Lister, G.S., 1999, A framework of overprinting orogens based on interpretation of the Mount Isa deep seismic transect: Economic Geology, **93**, 1422-1434.

MacCready, T. Goleby, B.R., Goncharov, A., Lister, G.S., and Drummond, B.J., 1997, An Evolutionary Framework for the Isan Orogeny Proterozoic Terranes: Geodynamics and Ore Deposits Conference, Australian Geodynamics Cooperative Research Centre, Ballarat, Victoria, Abstract, 42-45.

Magoon, L.B., and Dow, W.G., 1991, The petroleum system - from source to trap: American Association of Petroleum Geologists, Bulletin, **75(3)**, 627.

Milkereit, B., Eaton, D., Wu, J., Perron, G., and Salisbury, M., 1996, Seismic Imaging of Massive Sulfide Deposits: Part II. Reflection Seismic Profiling: Economic Geology, **91**, 829-834.

Neudert, M.K., and Russell, R.E., 1981, Shallow water and hypersaline features from the Middle Proterozoic Mount Isa sequence: Nature, **293**, 284-286.

Salisbury, M.H., Milkereit, B., and Bleeker, W., 1996, Seismic imaging of massive sulfide deposits: Part I. Rock Properties: Economic Geology, **91**, 821-828.

Siegesmund, S., and Kern, H., 1990, Velocity anisotropy and shear-wave splitting in rocks from the mylonite belt along the Insubric Line (Ivrea Zone, Italy): Earth and Planetary Science Letters, **99**, 29-47.

Swager, C.P., Goleby, B.R., Drummond, B.J. Rattenbury, M.S., and Williams, P.R., 1997, Crustal structure of granite-greenstone terranes in the Eastern Goldfields, Yilgarn Craton, as revealed by seismic reflection profiling: Precambrian Research, **83(1-3)**, 43-56.

Swager, C., and Griffin, T., 1990, Geology of the Archaean Kalgoorlie Terrane, Northern and Southern Sheets, 1:250,000: Geological Survey of Western Australia.

Yeates, A., McNeill, A., Richardson, S., Barton, T.J., Drummond, B.J., and Richardson, R.G., 1997, High-resolution reflection seismic in the Hellyer Ore Environment: New Developments in

Research for Ore Deposit Exploration, Third National Conference, January 1997, Geological Society of Australia, Abstracts, 78.

Upton, P., Hobbs, B., Ord, A., Zhang, Y., Drummond, B., and Archibald, N., 1997, Thermal and deformation modelling of the Yilgarn Deep Seismic Transect: Geodynamics and Ore Deposits Conference, Australian Geodynamics Cooperative Research Centre, Ballarat, Victoria, Abstract, 22-25.
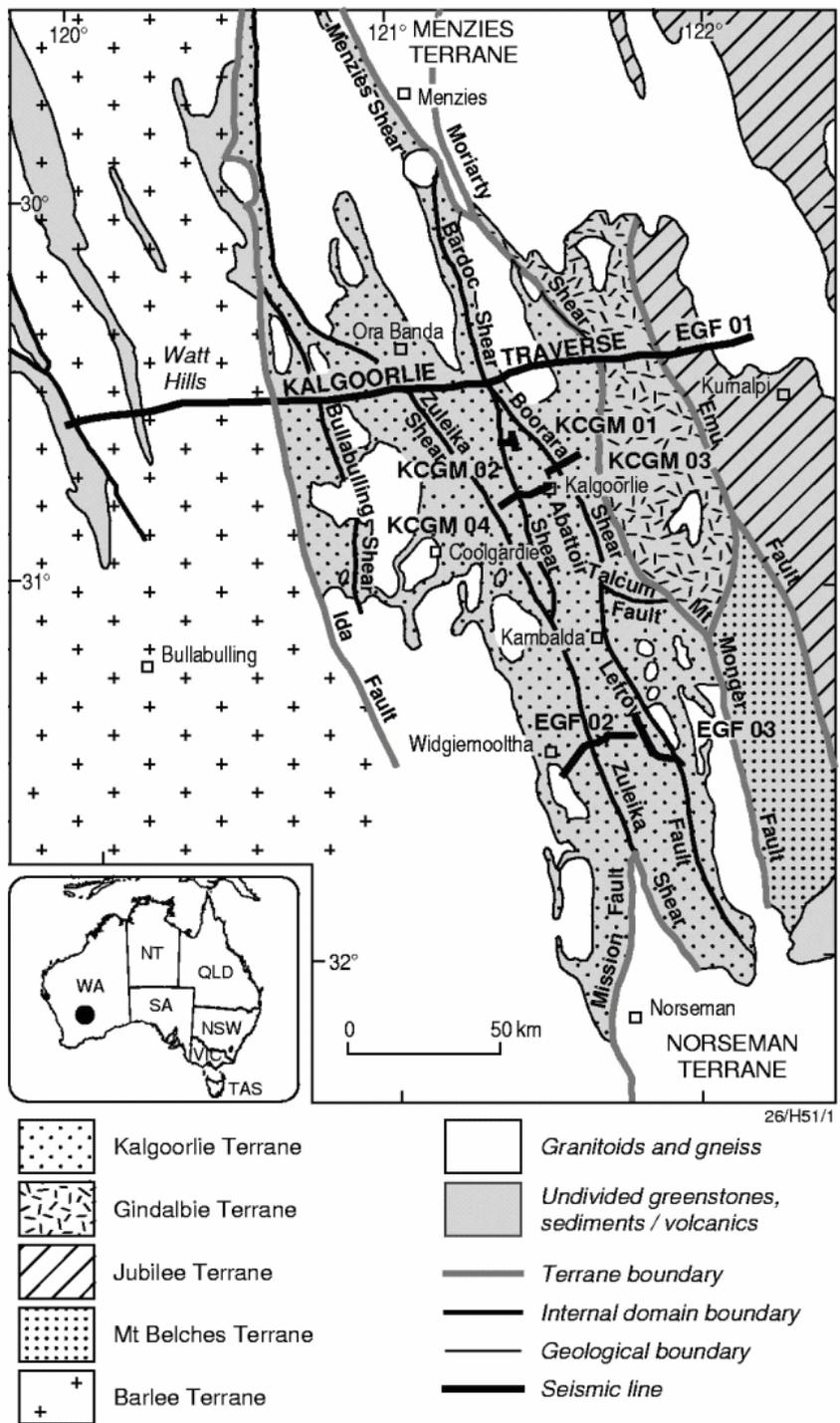
FIG. 1. Major structural subdivisions of the southern Eastern Goldfields Province, Yilgarn Block, Western Australia. Position of 1991 seismic transect is also shown. (modified from Swager and Griffin, 1990).
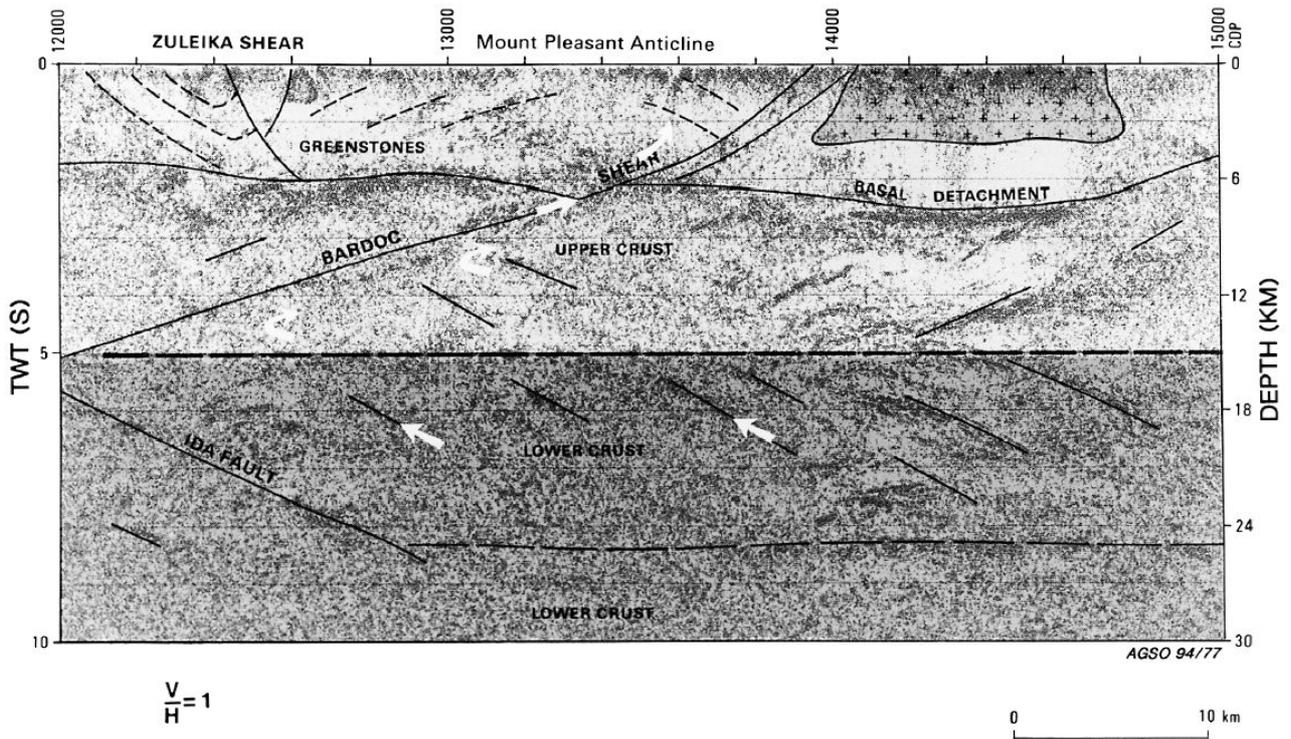
FIG. 2. Portion of the 1991 deep seismic transect recorded within the Archaean Yilgarn Block. Arrows indicate fluid flow directions predicted by Drummond and Goleby (1993). D = Diffraction, S = Sill. Detailed images of the interpretation, particularly the top 2 seconds can be found in Goleby et al. (1993) and Swager et al. (1997).
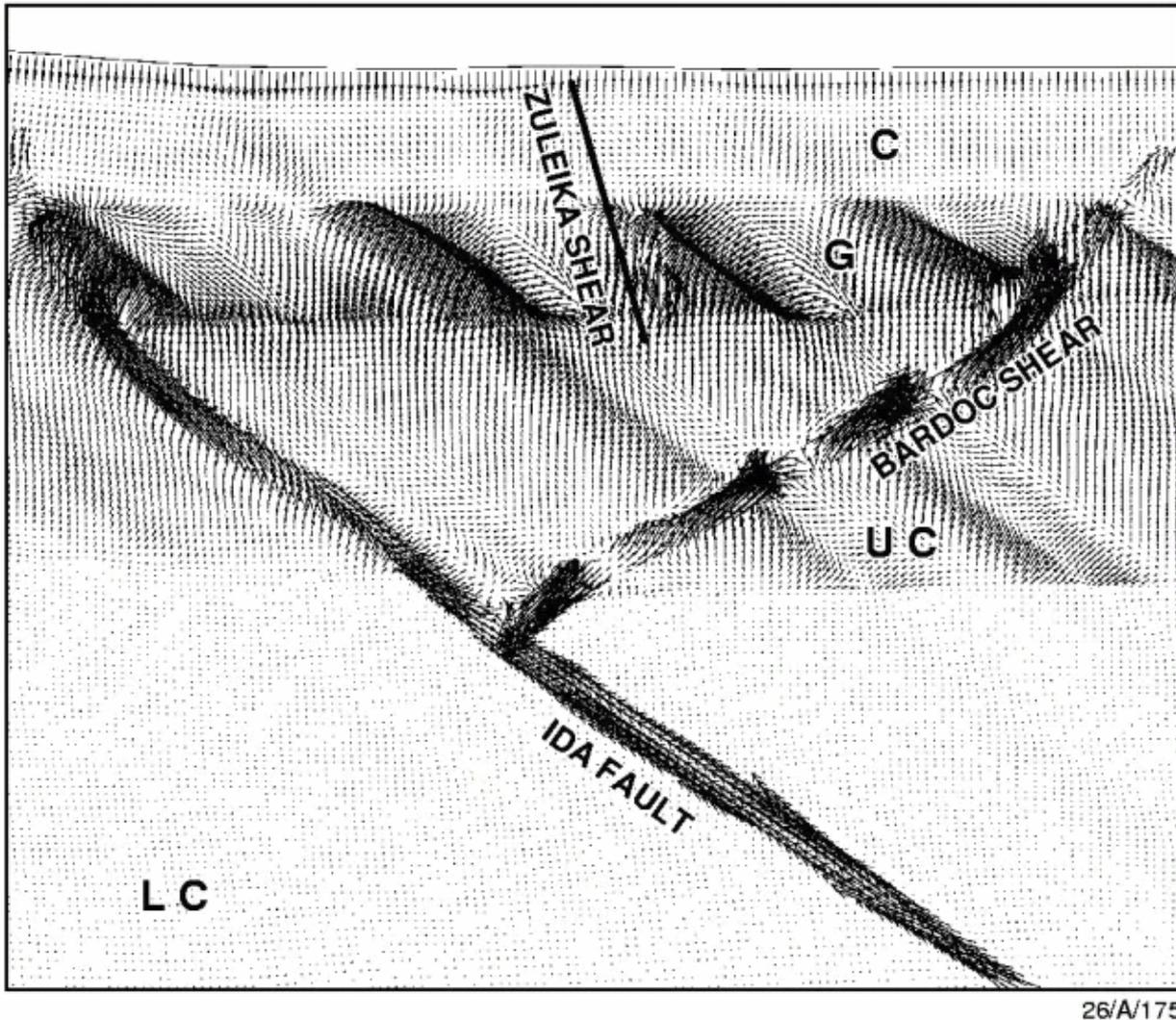
26/A/175

FIG. 3. Fluid Flow modelling of the Yilgarn. The fault geometry is derived from the seismic data. Crustal layering is implied from reflectivity patterns along the profile. The top-most layer was added to account for crust removed by erosion since the ore deposits were formed. Arrows represent fluid flow vectors. East dipping zones of longer vectors in the greenstones and basement are predicted by the modelling and coincide with weak reflections in the seismic data. LC = Lower Crust, UC = Upper Crust, G = Greenstones, C = Crust removed by erosion.
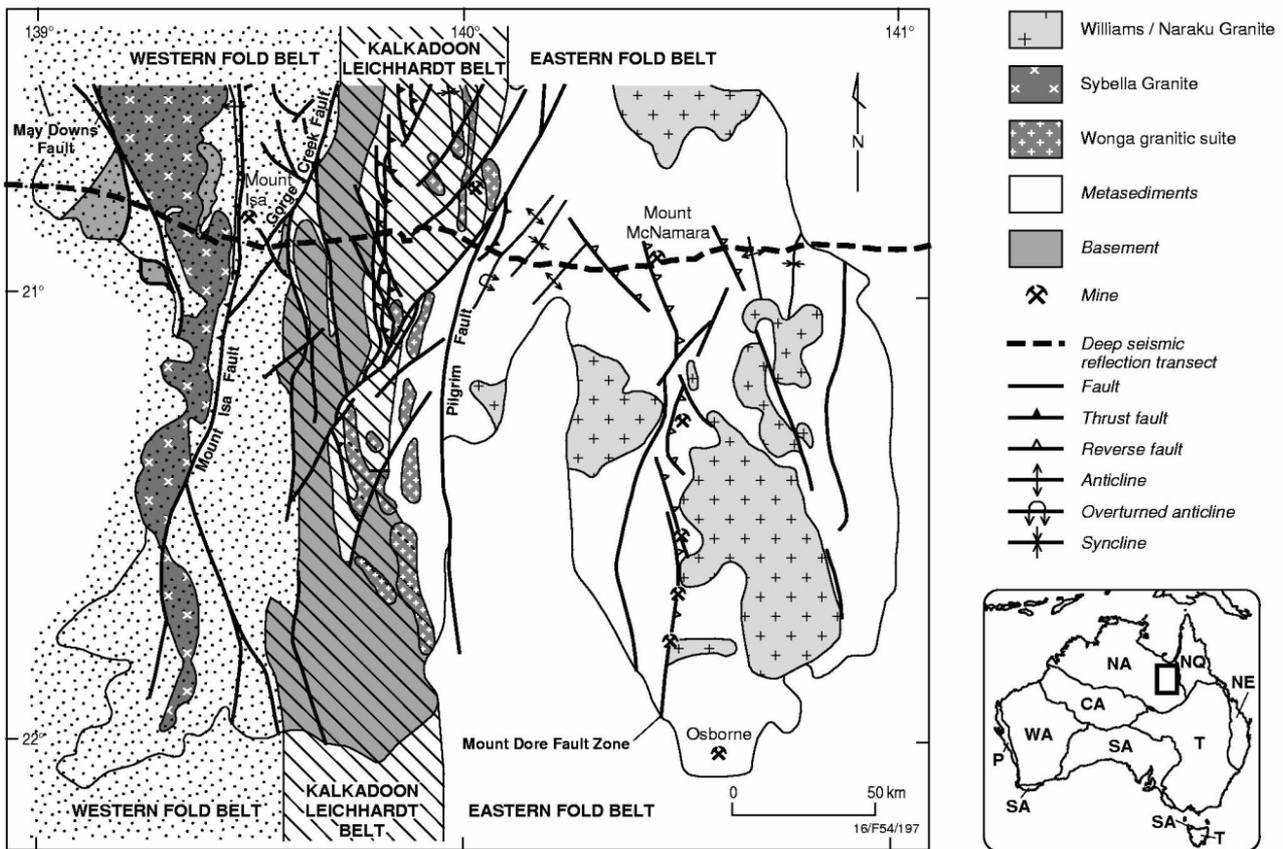
FIG. 4. Tectonic provinces of the Mount Isa Inlier and the location of the seismic transect.
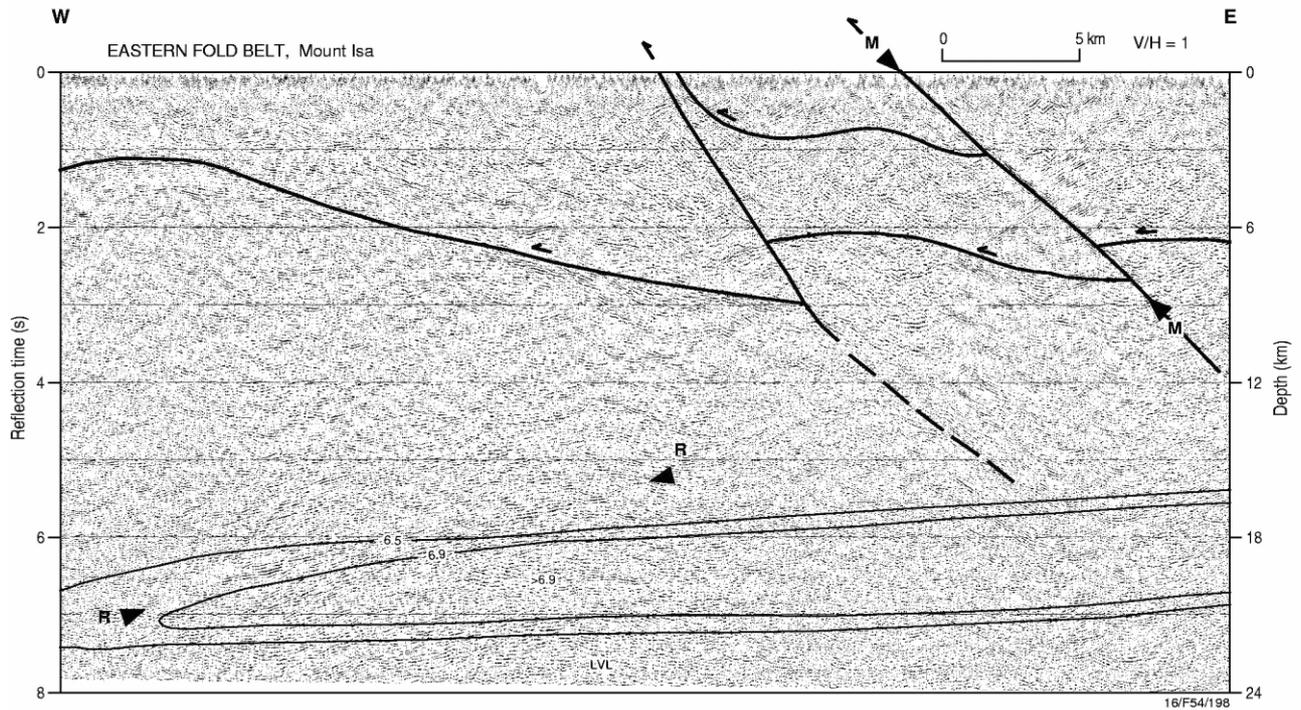
FIG. 5. Portion of migrated seismic data from the Eastern Fold Belt, Mount Isa Inlier showing the earlier shallow detachment cut by later steeper faults imaged within the Marimo Region. Contours (km.s^{-1}) show position of high velocity body in mid crust. R = Reflections from high velocity body. LVL = Low Velocity Layer. M= Marimo Fault. (from Drummond et al., 1997).
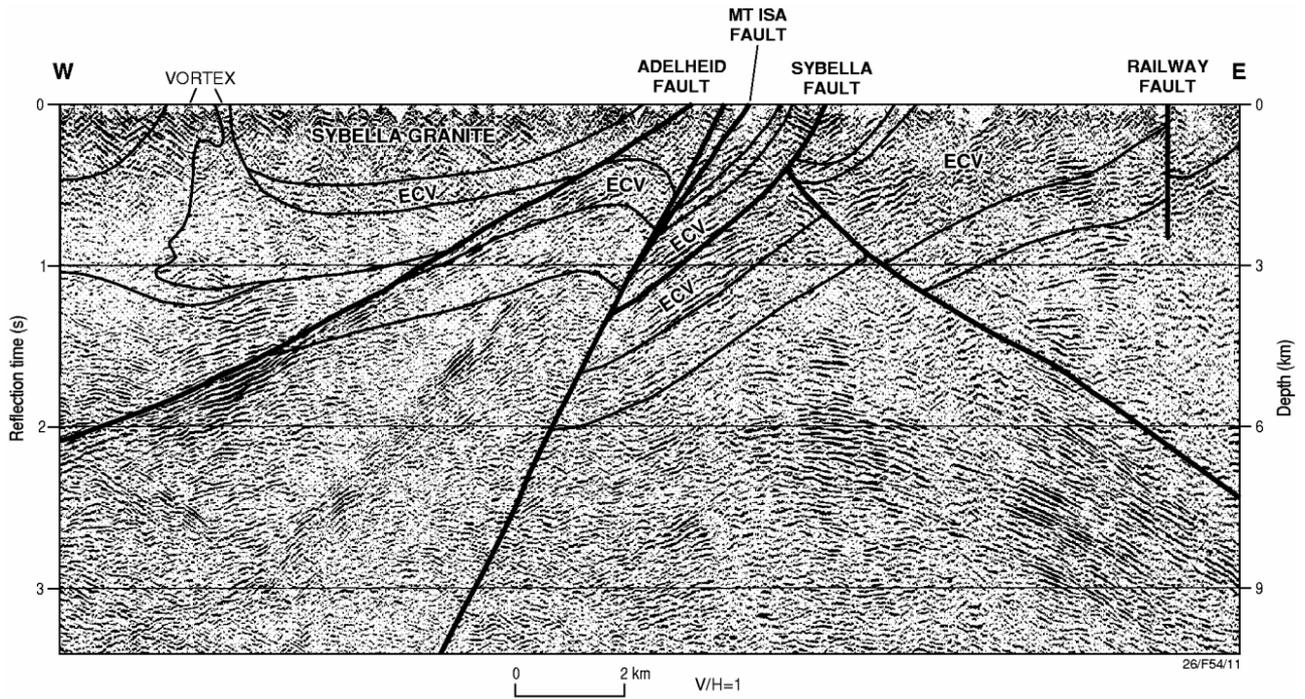
FIG. 6. Portion of seismic line from the Western Fold Belt, Mount Isa Inlier showing the

interpretation of MacCready, et al. (1999). Note that the Adelheid Fault is highly reflective

but other faults are not. Reflections between the Adelheid and Mount Isa Fault are

interpreted as S-wave reflections from the Adelheid fault. (from Drummond et al, 1997).
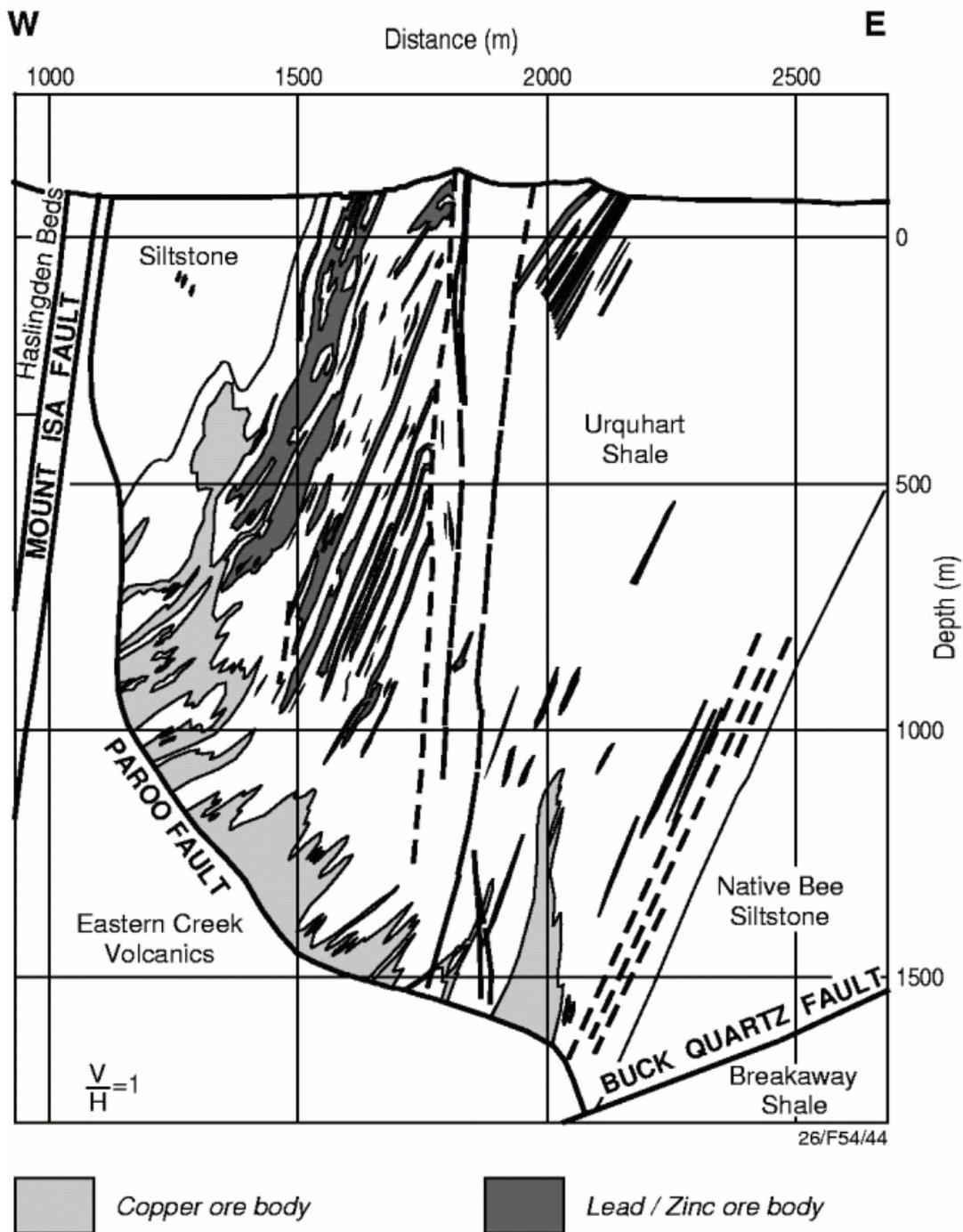
ECV = Eastern Creek Volcanics.

FIG. 7. Schematic section across the Mount Isa valley Pb-Zn and Cu mineral field showing the geological structure around and within the orebody (after Fallon et al., 1997).
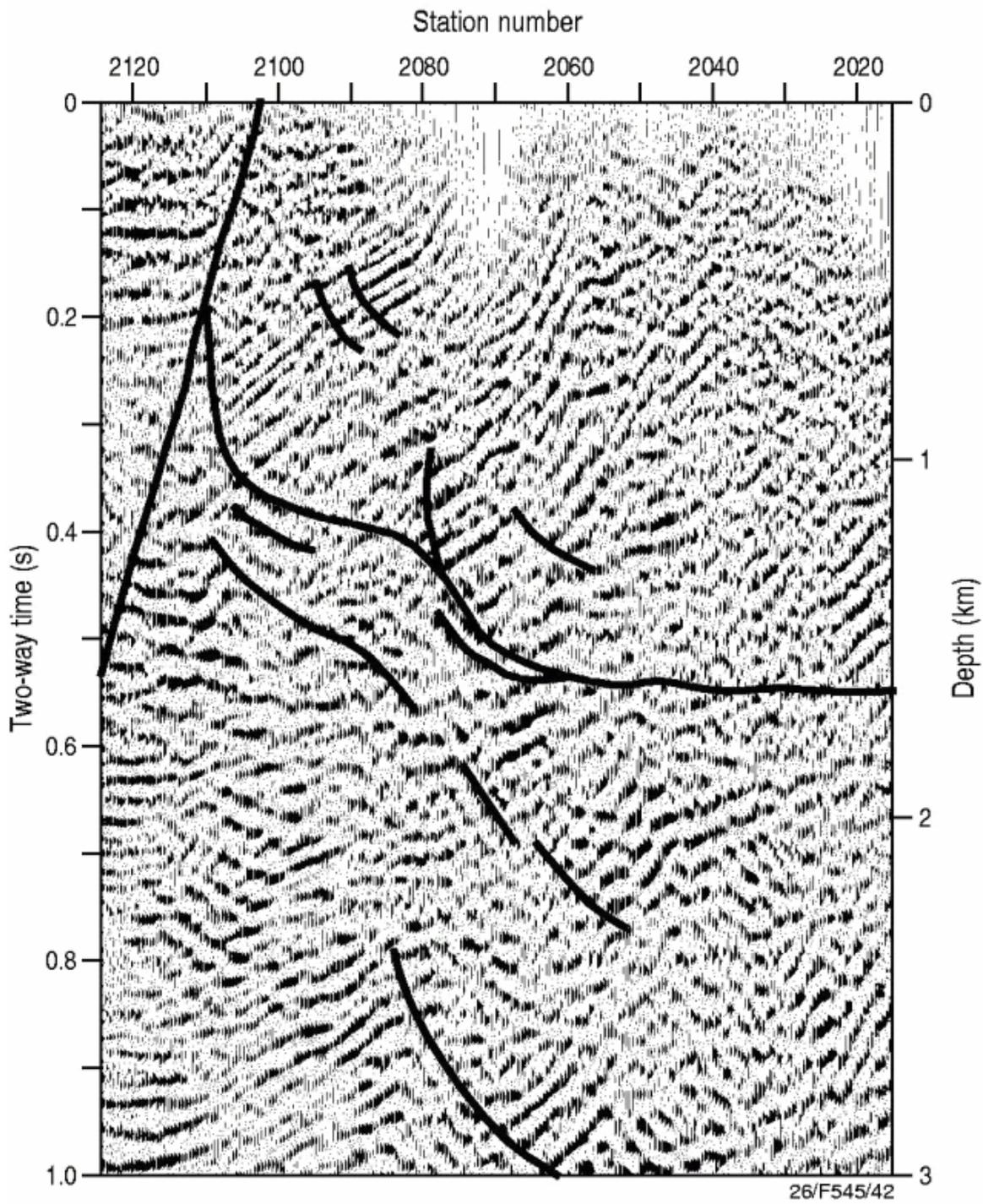
FIG. 8. Migrated high resolution seismic data from the Mount Isa valley, with interpreted positions of the Mount Isa and Paroo Faults.
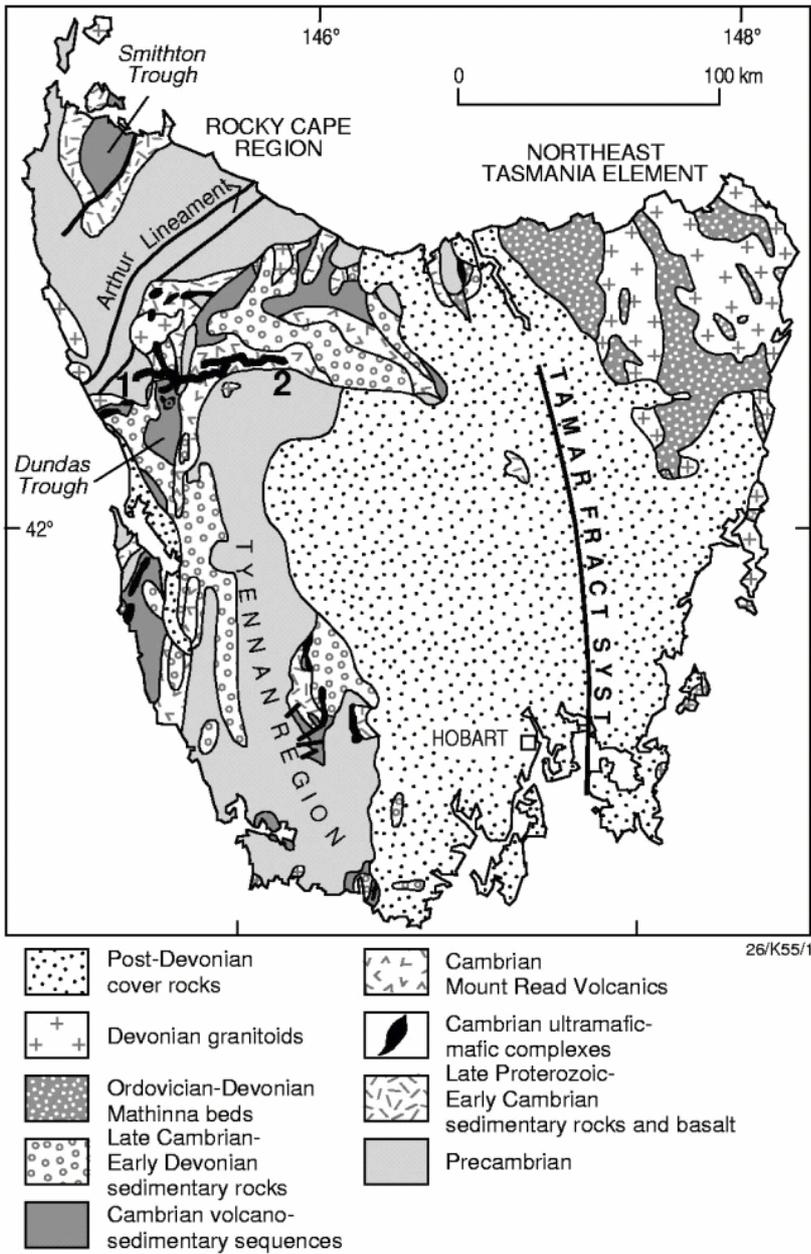
FIG. 9. Geology of Tasmania and the locations of two deep seismic transects. The high resolution

seismic line in Fig. 10 is coincident with and just to the west of the bend in Line 2. (after
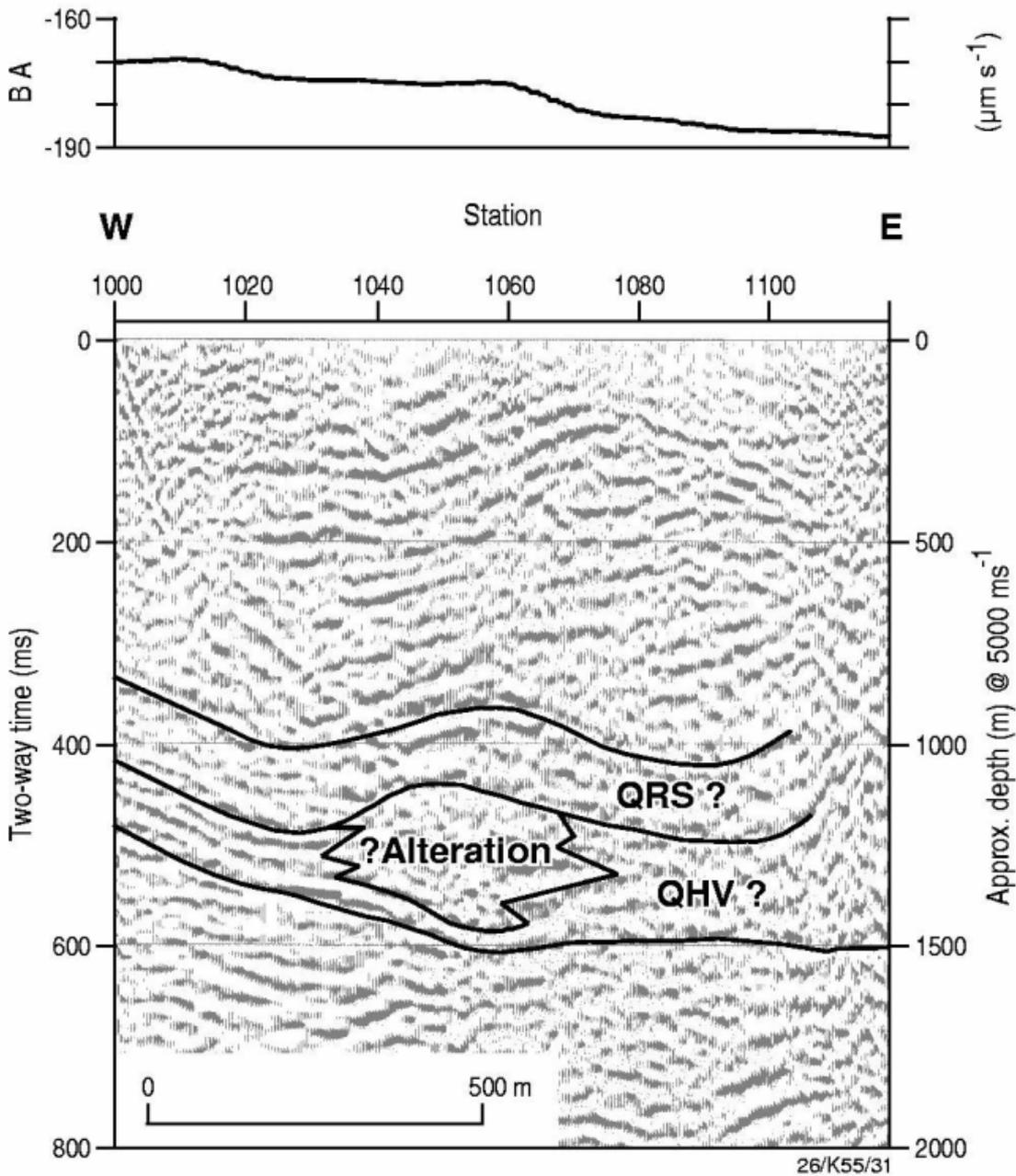
Drummond et al., 1996)

FIG. 10. Portion of the 1995 high resolution seismic section recorded within the northern Mount Read VHMS district. The data show a bulge in the Que Hellyer Volcanics (QHV) and weaker reflections in the bulge, suggesting alteration. High amplitude reflectors above the bulge could represent dense rocks, perhaps carbonate, dolerite or perhaps massive sulphides. QRS = Que River Shale. BA = Bouguer Anomaly gravity values in μm.s^{-2} (after Yeates et al., 1997).