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STRUCTURALLY CONTROLLED MINERALIZATION IN AUSTRALIA — HOW SEISMIC PROFILING HELPS FIND MINERALS: RECENT CASE HISTORIES

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ABSTRACT

Mineral systems are defined in terms of a source for mineralizing fluids, migration pathways for the fluids from a source region and a trapping mechanism that causes the fluids to precipitate ore bodies. Three case histories from Australia show how seismic reflection techniques can be applied to the concept of mineral systems models. The refining of the mineral systems models can be used in a number of ways. It can be used to improve regional prospectivity, thereby assisting in area selection ahead of direct mineral exploration, and can also be used to target the regions around ore bodies to define likely limits of mineralization. In two cases, reflector amplitude anomalies at the ore-body scale may be direct alteration and/or mineralization indicators. In this paper, alteration is used to define the process of changing (or altering) part of a rock sequence by some type of fluid, a fluid which may or may not be mineralized.

In the first case history, the crustal structure of the Archean Eastern Goldfields is interpreted in terms of linked crustal fluid pathways capable of channelling large volumes of fluids from deeper within the crust into the overlying greenstone sequences. This model has now been supported by numerical modelling techniques. The second case history, from the Mesoproterozoic Mount Isa Inlier, has taken this development of the seismic technique further by successfully using seismic methods to image faults bounding an ore body and the alteration zone around the ore body. This places a lower limit on the likely depth of mineralization. In the third case history from Paleozoic Tasmania, we show where seismic data suggest that a geologically important structure, possibly with an undiscovered mineral deposit, might have been directly imaged.

The results from these three surveys have resulted in an understanding of fluid flow within the crust and its effects and controls on mineralization, and hence helped generate an improved metallogenic model for each region.

INTRODUCTION

Deep seismic reflection techniques have been applied to basement terranes by various groups from many parts of the world for some time now. These results have proved invaluable in understanding tectonic evolution, and therefore have led indirectly to an improved understanding of the mineral potential of the regions studied. Some recent results, however, have more direct relevance to understanding mineralisation (Drummond and Goleby, 1993; Milkereit *et al.*, 1996; Yeates *et al.*, 1997). This paper presents the results from three studies in Australia. In the first case history, from the Archean Eastern Goldfields region, the focus is on targeting areas of different mineral prospectivity; no attempt is made to link the regional study into local studies at the ore body scale.

The second case history, from the Mesoproterozoic Mount Isa Inlier, does try to link from the regional scale into the ore-body scale. However, the strategy with this study was not to try to image the ore body itself, but rather to target a larger alteration zone that would be characteristic of the environment where mineralisation might occur. This is analogous to the approach used in petroleum exploration where the structure or stratigraphic form of the reservoir is the seismic target, and not the pool

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of oil itself; in petroleum exploration, direct hydrocarbon indicators, whilst becoming more commonplace than in the past, might still be considered a bonus.

The third case history, from Paleozoic Tasmania, also combined regional studies with detailed local studies, and while the environment of ore deposition was once again the target of the detailed study, amplitude anomalies suggest that at least an unexpected alteration zone might also have been detected. The reasons these studies have been so relevant is best demonstrated by looking at the results in terms of mineral systems models.

MINERAL SYSTEMS MODELS

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 basinal brines, for example, 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. Fault systems provide fracture porosity as well as a focussing mechanism; in the case of basinal brines, the general distribution of permeable and impermeable rocks of the basin strata can influence fluid flow and also influence its form. Trapping mechanisms have a variety of forms, and require the superposition of physical barriers to fluid flow, that is, the local structure, stratigraphy and permeability, whether intrinsic or fracture-induced, with the appropriate chemical, thermal and probably paleogeographic settings for the minerals to be deposited. Hence, studies that describe mineral deposits, rather than mineral systems, and have focussed only on the trapping mechanisms, tend to describe the unique combinations of characteristics in the trapping mechanism for each deposit, but may not see all of the underlying unifying characteristics of the mineral system.

Mineral systems are usually initiated 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), mineral systems can be characterised according to either the age of the host rocks or the age of the thermal event that initiated them. Just as a sedimentary basin could have had 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 could have been subjected to several mineral system events.

Mineral systems models are useful for guiding the application of seismic tools in mineral exploration in several ways. Area selection is the first key step in exploration. Mostly this is done by identifying areas that are already mineralised, or areas that are geologically similar to those that are mineralised. For example, most of the known major gold deposits in the Archean Yilgarn Block of Western Australia occur in the Eastern Goldfields Province, and most of those lie in the western part of the province. However, some gold deposits lie outside that region. Does the distribution of known deposits reflect where the first deposits were found, leading explorers to look there, or does a geological reason explain why they are there and not somewhere else?

In the Eastern Goldfields case history below, it will be shown that the broad geological framework is likely to have controlled both the distribution of the fluid sources and their migration pathways. These are key elements in one of the mineral systems models for gold in the region, and point to differing prospectivity across the region. Furthermore, knowing where fluids have moved through a province can further refine the areas of likely high prospectivity; large deposits are unlikely to occur where little or no fluids have been present. Hence, knowing how the broad geological framework has affected the distribution of both fluid sources and migration pathways has a profound effect on defining a region's prospectivity.

Identifying fluid source regions in seismic reflection images can be difficult. The dehydration of a large area of crust will not necessarily leave a significant physical imprint on the rocks that distinguishes that region from any other region, especially in metamorphic rocks where the signatures of metamorphism (higher densities and seismic velocities) may be indistinguishable from those of the dehydration associated with mineralisation. However, Jones and Nur (1984) showed that mylonite zones can be good reflectors. Here, seismic reflectivity results from the constructive interference of reflections from the bands of altered rock along fault zones. Thus, strong reflections can result from faults that have been channels for large volumes of fluids. Subsequently, Drummond and Goleby (1993) interpreted elements of crustal reflectivity within the Eastern Goldfields Greenstone Belt in terms of fluid pathways through the crust.

SEISMIC METHODS

The geology and structure of the three mineralized regions described in the case histories below is complex, with a range of lithologies subjected to at least three deformational and metamorphic events excluding the mineralizing event. In all cases however, the geological control available is good, with information from mining in the region, deep drill holes and detailed surface geological mapping.

The seismic techniques were mostly reflection profiling at different degrees of resolution, and the interpretation of the data was based on the geological control. Explosive charges in 40-m deep drill holes provided the energy sources. The seismic data were collected with a 120-channel acquisition system, 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 40 m for the regional surveys and 10–20 m for the higher resolution surveys. Shot-hole spacings were variable but a nominal stacking fold of between 12 to 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 these types of projects, the two most fundamental problems associated with the data processing sequence are static corrections and velocity variations. A highly variable regolith over all of Australia results in major static anomalies. Detailed and complex refraction static analysis and processing is required to adjust for the effects of the weathering, particularly given the push to higher frequencies needed to achieve the desired resolution in areas with high seismic velocities. Near-surface velocity variations are considerable, varying from around 1000 m/s within parts of the regolith to around 7000 m/s in ultramafic bedrock material within the greenstones of the Eastern Goldfields region.

Reflector continuity is variable but is usually far shorter than that encounted within sedimentary basins. Reflector amplitude, however, is often excellent, and the interpretation strategy is based on identifying regions of similar reflector coherency and dip, and linking reflector geometry and amplitude to the known geology. Gravity modelling, where the geometry is defined by seismic profiling and density is assigned through correlation with surface outcrop or refractor seismic velocity, is generally used to test the seismic interpretation.

CASE HISTORY 1: THE EASTERN GOLDFIELDS OF WESTERN AUSTRALIA

The Archean Yilgarn Block in Western Australia consists of several distinct geological provinces, the Eastern Goldfields Province (Figure 1) being one of the most economically significant mineral provinces in Australia. A regional seismic traverse (Goleby *et al.,* 1993) across the granite-greenstone terrane of the Eastern Goldfields Province (Kalgoorlie and Kurnalpie Terranes) was designed to image the geometry of this terrane, the major faults and shear zones within it, the geometry of granite plutons intruded into the greenstones, and the differences in crustal structure between the Eastern Goldfields Province and the neighbouring Southern Cross Province to the west. The Eastern Goldfields traverse was positioned as an east-west, 213-km long profile (Figure 1) across the general structural strike of the region, running through one of the richest gold regions in the entire Yilgarn Block. The interpreted crustal structure (Figure 2) was used to investigate possible fluid flow models relevant to existing mineralisation models.

The seismic results indicate that the basal greenstone contact is a subhorizontal detachment (Figure 2; Swager *et al.,* 1997), evidenced by large-scale truncations of folded and steeply dipping greenstone strata against a strong reflection zone that is interpreted as the detachment surface. This geometry implies substantial movements, potentially om the order of tens or possibly even hundreds of kilometres, of the greenstone sequences relative to the underlying basement, although there are few direct constraints on directions of movement in or out of the plane of section of the seismic traverse. Surface geological mapping suggests that ENE-WSW shortening (D2) involved crustal-scale folding and stacking of the supracrustal succession above the detachment. Stratigraphic truncations against the basal décollement and against other faults (e.g., Bardoc Shear; Figure 2) suggest that these faults developed after basin formation and greenstone deposition.

Granite emplacement is inferred to be pre- to syn-D2 folding on the basis of regional geometries, and this is supported by evidence from the seismic traverse. The elongate shape and thickness of the plutons (thickness <5 km in those imaged) suggest that they were emplaced above thin feeder dykes into zones of dilation such as anticlinal hinge zones during (early) D2 shortening.

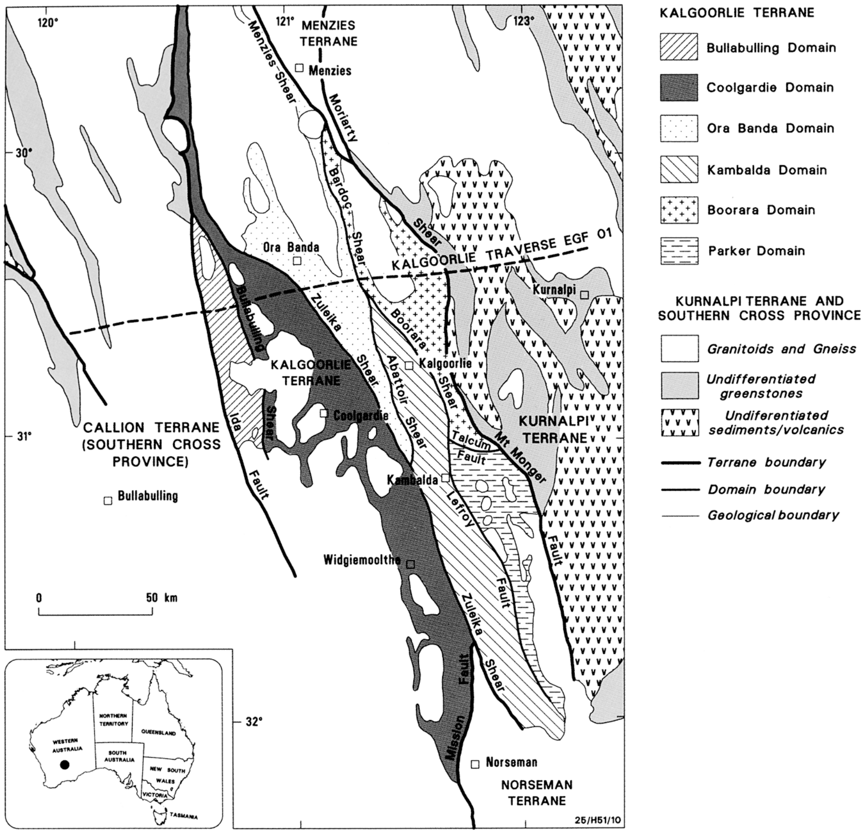

Figure 1: *Geological map of the Eastern Goldfields region, with the major structural sub-divisions shown. The position of the 1991 Eastern Goldfields seismic traverse is shown (modified from Swager and Griffin, 1990).*

Rich gold mineralization districts, such as the Golden Mile (at Kalgoorlie, Figure 1) and the Kambalda-St Ives deposits (near Kambalda, Figure 1) lie in second or higher order splays off the Bardoc Shear and its southward lateral continuation. Samples from the bottoms of shot holes along the seismic traverse show similar alteration patterns from near the Ida Fault and Bardoc Shear (Goleby *et al.,* 1993). This, together with the seismic image indicate that the faults were linked at depth, and that similar or the same fluids moved along both of the faults in the past. In the seismic image, the west-dipping Bardoc Shear (Figure 2) can be traced through and below the basal detachment of the greenstones almost to the east-dipping Ida Fault (the bottom portion seen on the left-hand side of Figure 2).

The model proposed by Drummond and Goleby (1993) refines that of Goleby *et al.* (1993) and proposes mineralizing fluids migrating from the lower crust to higher levels in the greenstones. These fluids followed a path, firstly through east-dipping shear zones within the lower crust, then through west-dipping shear zones in the upper crust, where they deposited ore bodies in the hanging walls of the major shear zones. The region between the Ida Fault and the Bardoc Shear provides the most direct pathways into the upper crust: the Bardoc Shear acted as a scavenger of fluids from several east-dipping shear zones lying beneath it. The fluids from these east-dipping shear zones were focussed into the Bardoc Shear, providing a greater fluid flux along the Bardoc Shear than along other shear zones through the greenstones. Most mineralization could then be concentrated in blind splays off the Bardoc Shear. Some fluids, however, could leak along the detachment and into several of the other faults within the greenstone sequence that splay from the detachment (e.g., Zuleika Shear; Figure 2).

This linked fluid-pathway model was tested and generally supported by numerical modelling of fluid flow within the Eastern Goldfields based on the structures defined by the seismic transect (Figure 3; Upton *et al.,* 1997). The numerical modelling used the geometry of the crustal structure defined by the seismic profile, estimates of likely physical properties of the crust, the relative order of events in the geological history, and quantitative time control from geochronological data, to provide constraints on the development of gold deposits in the region. The modelling predicts an initial, single crustal-scale convection cell in which fluids are driven up the Ida Fault from depth and down the Ida Fault from the surface. These mix and flow up the Bardoc Shear, resulting in a high degree of chemical alteration and hence mineral deposition within the upper crust, particularly within the greenstones (Figure 3). During thermal decay, the single convection cell breaks down into smaller cells which then concentrate the mineral species in the upper crust. The coupled deformation/fluid flow modelling predicts D4 faults in the vicinity of known ore deposits, as mapped, and produces focussed fluid flow into associated east-dipping shear zones (Figure 3).

In summary, regional seismic reflection profiling was used to study the mineral prospectivity of the region by defining the primary structure of the crust in the region of the rich gold deposits. The structure, in turn, was used to constrain fluid flow modelling in the crust. The study

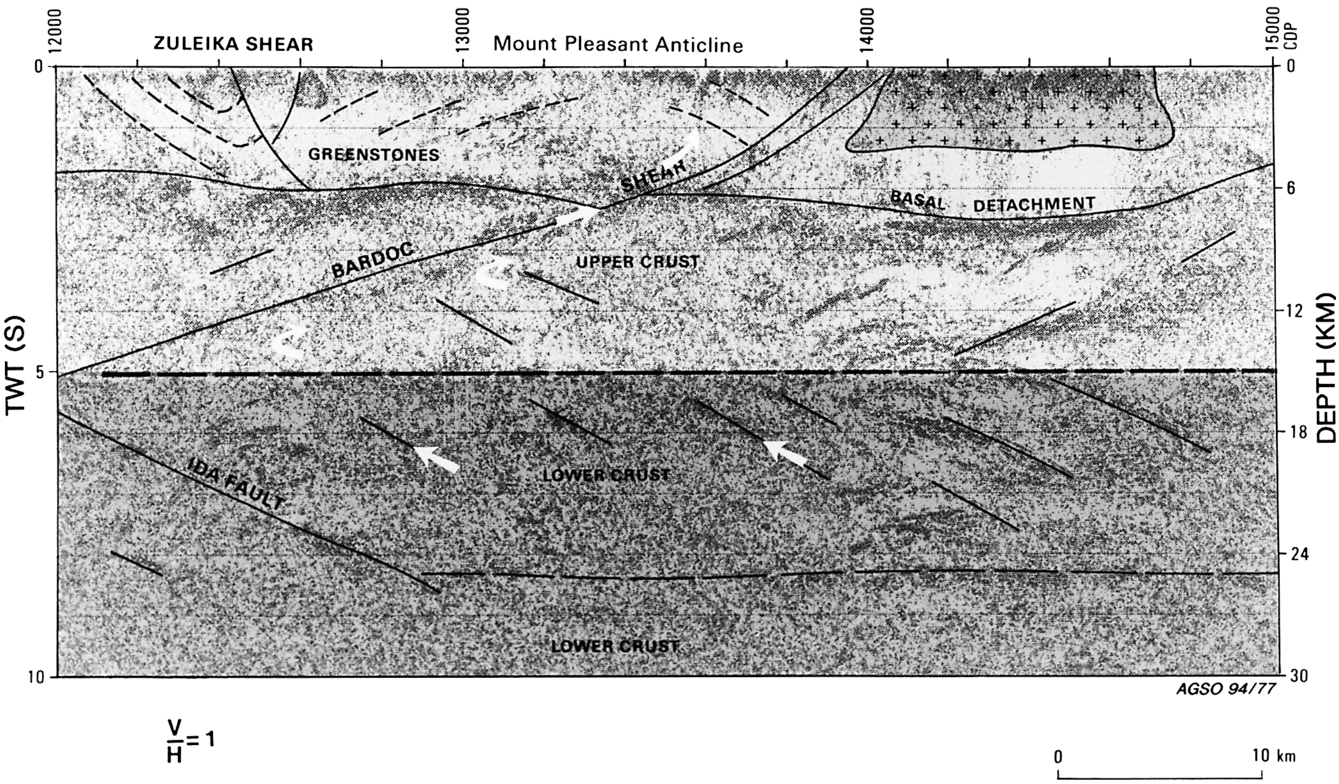

Figure 2: *Portion of the 1991 Eastern Goldfields deep seismic transect recorded within the Archean Yilgarn Block (unmigrated; after Drummond and Goleby, 1993).*

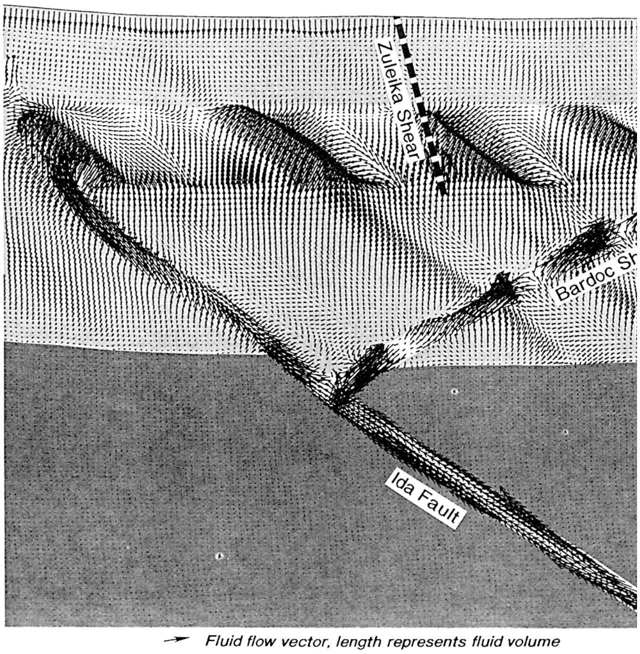

Figure 3: *Fluid flow modelling of the results from the 1991 Eastern Goldfields seismic transect, Yilgarn Block. The arrows represent fluid flow direction, their length representing the volume of fluid flow. This model predicts increased fluid flow within the greenstone along several later structures (after Upton et al., 1997).*

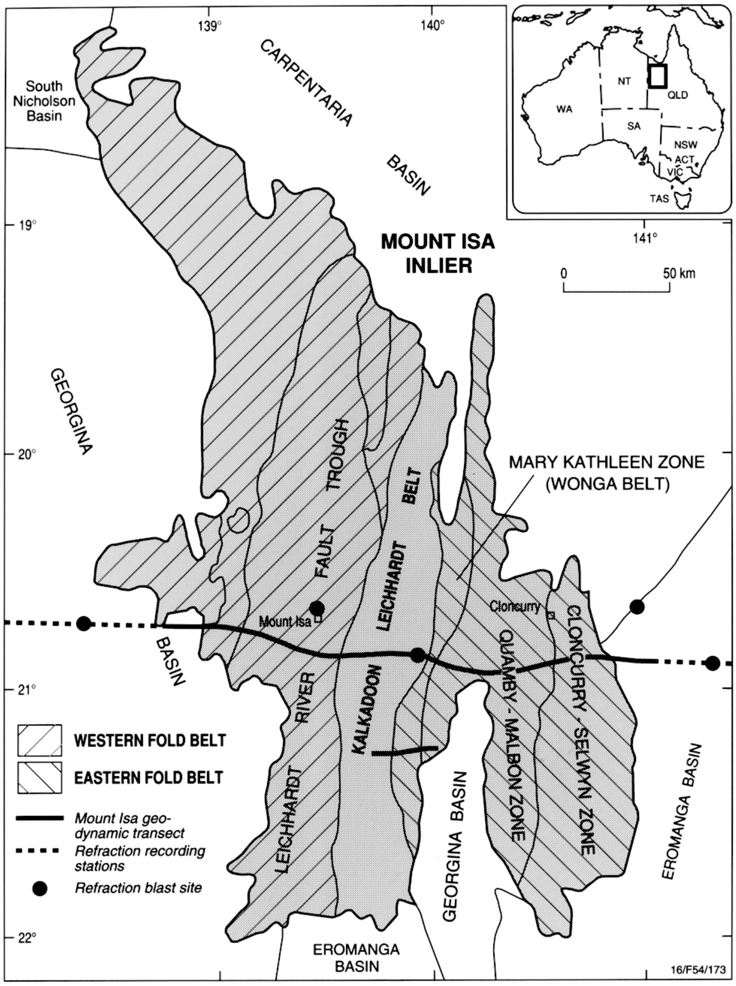

Figure 4: *Tectonic provinces of the Mount Isa Inlier and the locations of both the crustal refraction profile and the deep seismic reflection traverses (after Goleby et al., 1996).*

confirmed the higher prospectivity for gold of the zones along the Bardoc, Zuleika, and to a lesser extent the Ida faults, and probably lower prospectivity along the other regional-scale faults in the region.

CASE HISTORY 2: MOUNT ISA

The Mount Isa Inlier of northern Australia is Mesoproterozoic in age and is renowned for the number of world-class Cu-Au and base metal deposits found within it. The Inlier is subdivided into an Eastern Fold Belt, a Western Fold Belt and a central Kalkadoon-Leichhardt Belt (Figure 4). Most occurrences of Cu and Au occur in the Eastern Fold Belt, although the largest Cu ore body, at Mount Isa in the Western Fold Belt, is an exception. Most identified tonnage of Pb-Zn is in the Western Fold Belt, although small occurrences have been found in the Eastern Fold Belt.

A major east-west deep seismic reflection traverse, 255 km long and located just to the south of Mount Isa (Figure 4), was commissioned by the Australian Geodynamics Cooperative Research Centre (AGCRC). The objectives of the seismic survey were to map the depth extent and internal form of the major structures within the region to provide constraints on the relative importance of compressional thrusting and folding, extensional tectonics and basin formation mechanisms (Drummond *et al.,* 1995). A piggy-backed high-resolution seismic reflection survey near the Mount Isa mine, commissioned by MIM Exploration Pty Ltd., aimed to improve the understanding of the mineral systems at the local scale by placing the major Cu and Pb-Zn ore bodies in a regional three-dimensional context.

Key features of the regional seismic reflection section include a marked difference in the styles of the structures of the top 5–10 km between the Eastern Fold Belt and the Western Fold Belt, the imaging of several major fault systems that cut through the crust, and the identification of several faults that appear linked to the mineralization.

Much of the Eastern Fold Belt is underlain by a prominent subhorizontal to gently dipping reflector (at 2-2.5 sec TWT; Figure 5) that is interpreted as a regional detachment surface. The detachment surface allowed the supracrustal rocks of the Eastern Fold Belt to be thrust to the west over basement. The detachment, in turn, is cut by a number of more steeply dipping faults (e.g., Figure 5), some of which correlate with mapped faults. Many of these faults are identified in the seismic section because they offset both the reflector attributed to the detachment surface and the patterns of reflectivity above the detachment that are attributed to the supracrustal rocks of the Eastern Fold Belt. One of these faults (just to the west of centre in Figure 5) does not correlate with any previously mapped faults. Unlike other faults that are non-reflective, this fault (hereafter called the Marimo Structure) has an associated zone of reflectors that projects to the surface. Although no fault has been mapped in the vicinity of the seismic traverse, an east-dipping, 200-m wide zone of alteration has been identified in outcrop, and hence we

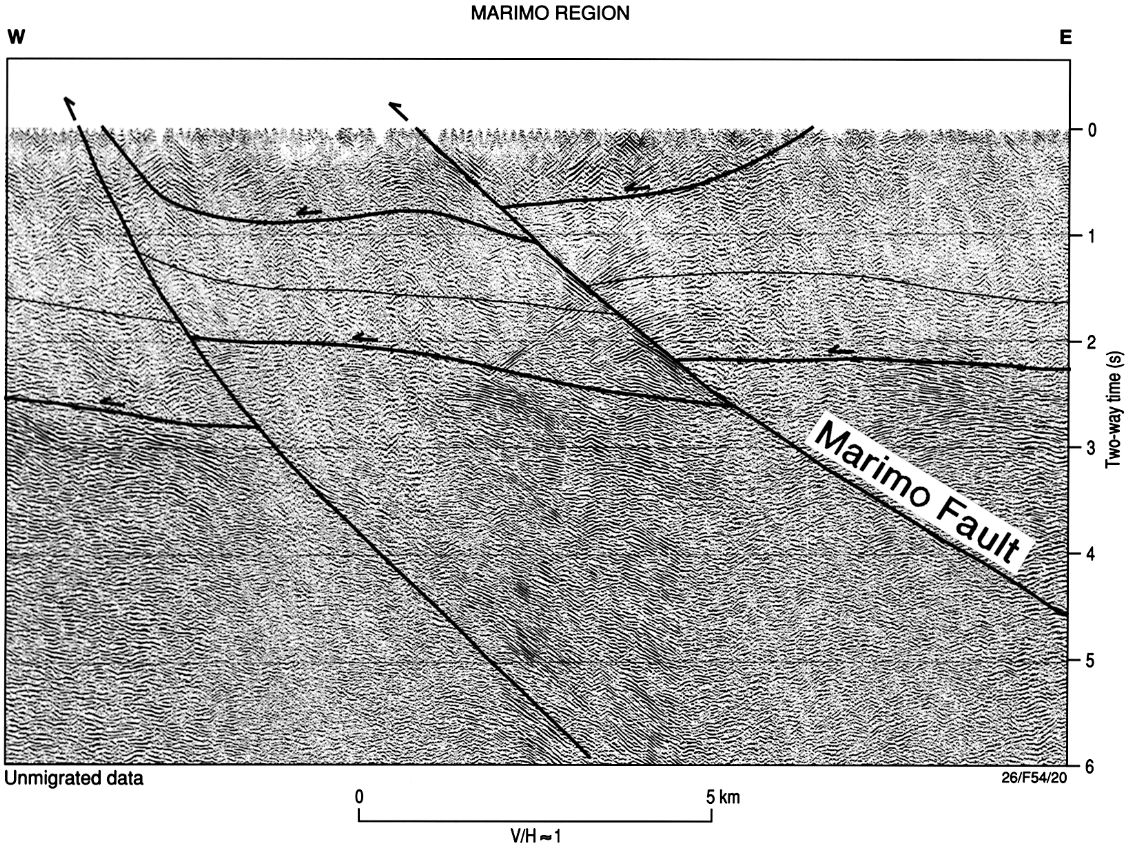

Figure 5: *Portion of an unmigrated seismic section from the Eastern Fold Belt, Mount Isa Inlier showing the earlier shallow detachment cut by later steeper faults imaged within the Marimo region (after Goleby et al., 1996).*

infer that the high reflectivity seen is due to a hydrothermal alteration event along a previously unmapped fault. This observation is further supported by the presence of a Cu-Au mine (Mount McNamara) close to the surface projection of this zone of reflections to the north.

Further evidence that this fault acted as a fluid pathway comes from its spatial relationship to other deposits in the region. This unmapped fault links up with a series of documented, north-south faults which are linked together to create a 100-km long fault system. Southwards, in the direction of the fault trace, a series of significant operating Cu-Au mines (e.g., Hampden, Mount Dore, Selwyn, and Osborne) suggests that this fault system played a major role either as a simple migration pathway for fluids from their source to their final reservoir, or as a control on the position and style of fluid convection cells in the crust. The role that the basal detachment surface played in the mineralization, relative to the younger, steeper east-dipping faults, is as yet unclear and fluid flow modelling is currently being undertaken. However, all the faults are linked, indicating the presence of paths to facilitate fluid flow from the middle crust and focus these fluids directly into late deformational structures near the surface (Figure 5).

Further west, the seismic transect over the Western Fold Belt also crosses the major Mount Isa mineral field. This section images a sequence of west-dipping reflectors representing sequences of the Leichhardt River Fault Trough (Figure 6; MacCready *et al.,* 1997). All faults imaged on the regional seismic profile within this trough dip to the west. The main fault identified in outcrop is the Mount Isa Fault. This fault is westerly dipping and extends well into the middle crust at around 70° (Figure 6). This dip is in general agreement with published geological cross-section models of the Mount Isa Fault (e.g., Fallon and Busuttil, 1992; Figure 7). The Mount Isa Fault is part of a complex series of north-south-trending faults of various generations. Three major Pb-Zn deposits and a major Cu deposit are located close to this structural zone along strike from the seismic transect. An unexpected outcome of this seismic survey is the importance that the Adelheid Fault played in focussing fluid flow within the region. The Adelheid Fault is highly reflective; this is interpreted to be the result of hydrothermal alteration similar to the that seen in the Marimo area, Eastern Fold Belt. The model, largely based on Heinrich *et al.* (1995), is one where fluids circulating at shallow crustal levels are responsible for both the Cu and Pb-Zn deposits. The seismic data, however, suggest that the Adelheid Fault and not the Mount Isa Fault acted as the focussing mechanism for convection cells within the Mount Isa Valley.

We conclude that there is a fundamental relationship between the larger deposits in the Mount Isa Inlier and the more significant faults as imaged by the seismic data. Most of the major structures associated with mineralisation that are visible in the seismic data are inclined and terminate in the mid-crust. In contrast, other younger major vertical structures imaged in the seismic section are not hosts to any significant known mineralisation, even though they appear to penetrate through to the middle crust. This could imply that major movement on these vertical structures postdated any significant hydrothermal activity, and it is possible that these faults relate to Paleozoic and younger events.

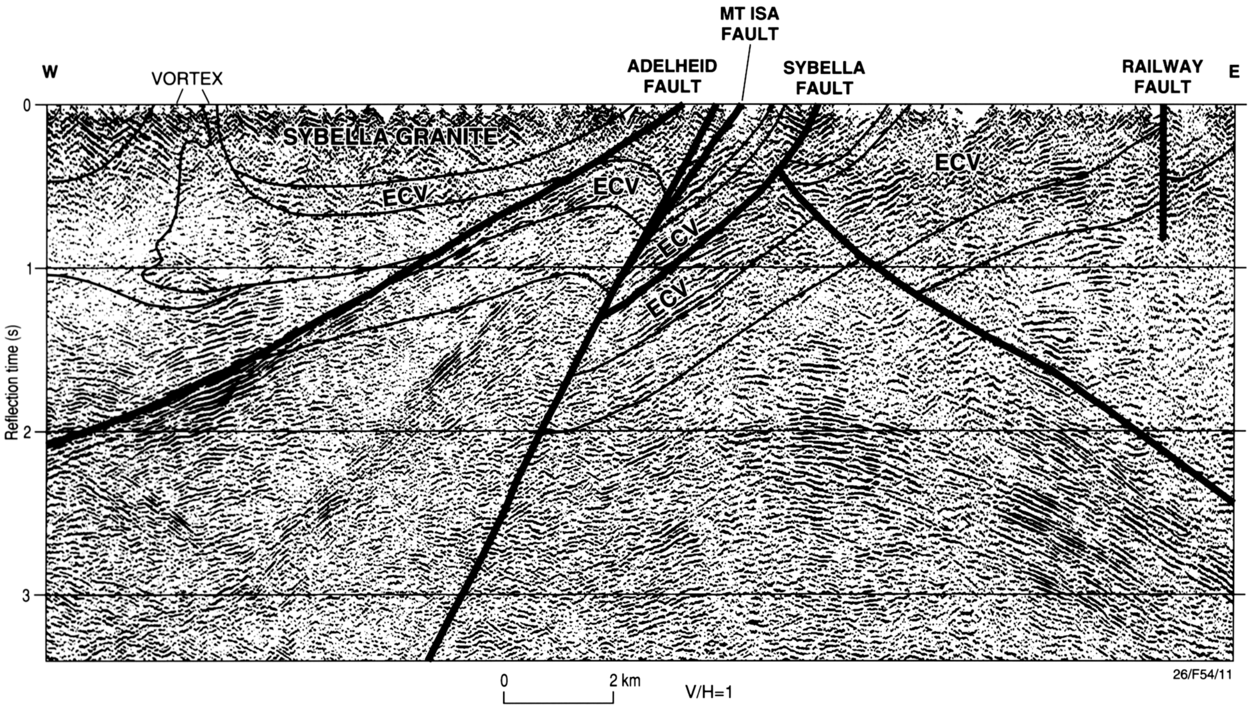

Figure 6: *Portion of an unmigrated seismic section from the Western Fold Belt, Mount Isa Inlier showing the Mount Isa Fault, Adelheid Fault and structure within the Leichhardt River Fault Trough (after Goleby et al., 1996). The westerly dipping linear reflectors halfway between the Mount Isa Fault and the Adelheid Fault are S-wave reflections off the Adelheid Fault.*

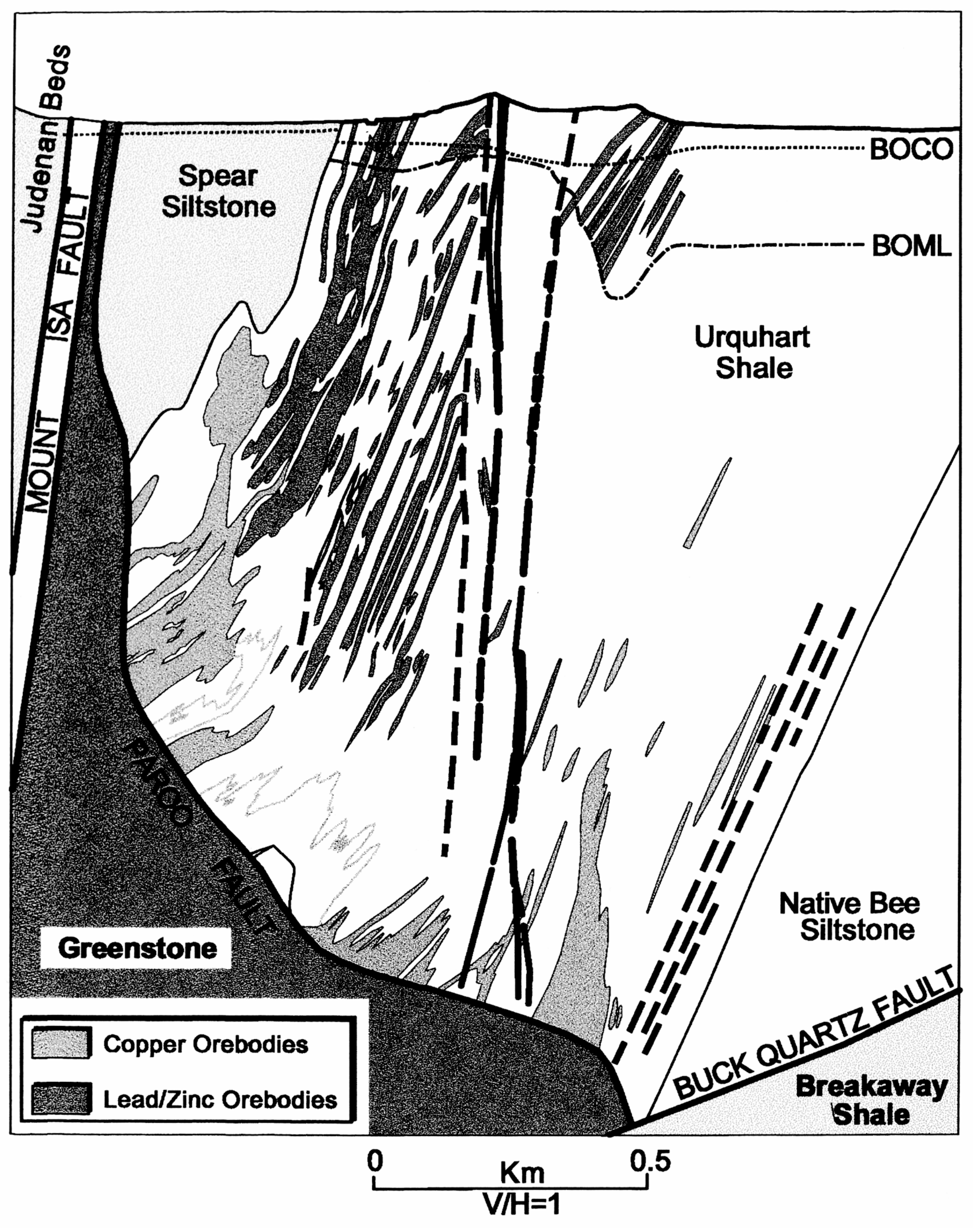

Figure 7: *Schematic cross section across the Mount Isa Valley Pb-Zn and Cu Mineral Field showing the geological structure around and within the ore body (after Fallon et al., 1997).*

At the mine-scale near Mount Isa, both the Cu and Pb-Zn mineralization deposits are located above the Paroo Fault (Figure 7). The Paroo Fault lies just to the east of the Mount Isa Fault and dips steeply east. At depth, it becomes more shallowly east-dipping. The ore bodies, particularly the Pb-Zn ore body, lie in steeply west-dipping lenses within a broad alteration halo. A schematic cross-section through the Cu and Pb-Zn ore bodies based on surface geology, drill holes and gravity modelling (Figure 7) shows the main mineralization sitting above a major fault separating west-dipping mineralized sediments from basalts (Eastern Creek Volcanics). A high resolution seismic reflection strike line and three dip lines as well as a small-scale 3-D seismic survey were recorded between two mines (Mount Isa Mine and Hilton Mine) to image the Mount Isa and Paroo fault systems. Because known mineralization lies only above the Paroo Fault, one objective was to image the faults away from the mineralisation in order to define the maximum depth of prospective rocks in the area. The dip lines were positioned to image the westerly dipping Mount Isa Group in regions of known geology. The strike line was positioned to carry known mine-site geology to the north to create a tie with the dip lines. There are two areas where the density contrasts were likely to produce reflections: the Paroo Fault itself which juxtaposes different rock types, and the broad halo of alteration around the ore body as the combination of altered and mineralized sediments and volcanics have a dramatically increased density over the non-altered sediments and volcanics.

The seismic section from one of the migrated dip lines is shown in Figure 8. The Paroo Fault is not imaged directly but is inferred by projection from its known surface position downwards, and by the sudden termination of reflections from the west-dipping Mount Isa Group in the upper right of the section (Figure 8). Although the Mount Isa Group sequence is steeply dipping, the seismic profile has only imaged a small part of this dipping sequence, particularly in the regions inferred to contain Pb-Zn mineralization. In particular, a zone of especially high-amplitude reflections within the Mount Isa Group at around 0.35 sec TWT beneath CDP 6100, is postulated to be due to very intense alteration. Whether this zone is altered and whether it contains economic mineralization have to be tested by drilling. The zone of strong, subhorizontal reflections seen at 0.9 sec TWT (Figure 8; this zone extends downwards to 3 sec TWT) can be correlated with a similar reflective band imaged on the regional traverse to the east of the Mount Isa Fault

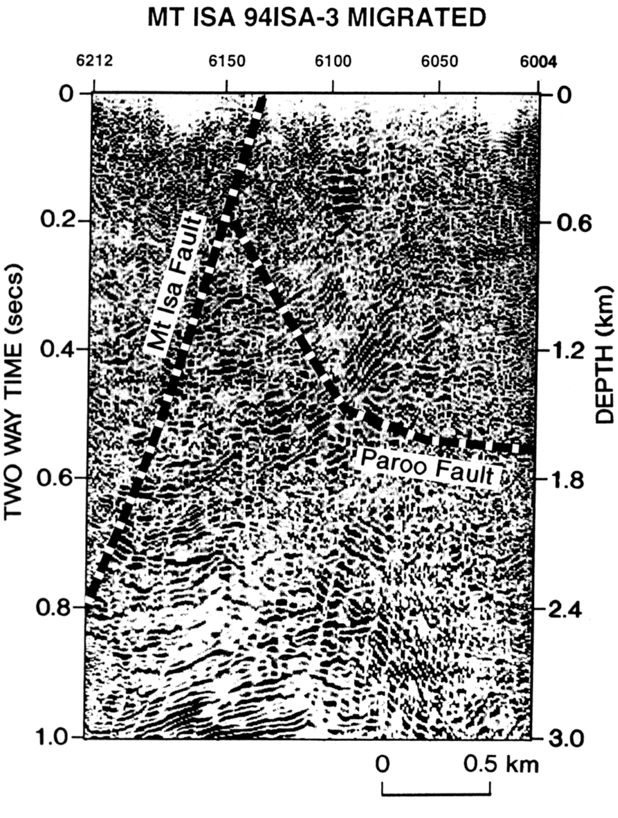

Figure 8: *Portion of a migrated seismic section from the Mount Isa Pb-Zn and Cu Mineral Field, Western Fold Belt, Mount Isa Inlier, showing the Paroo Fault location and west-dipping sediments of the Mount Isa Group.*

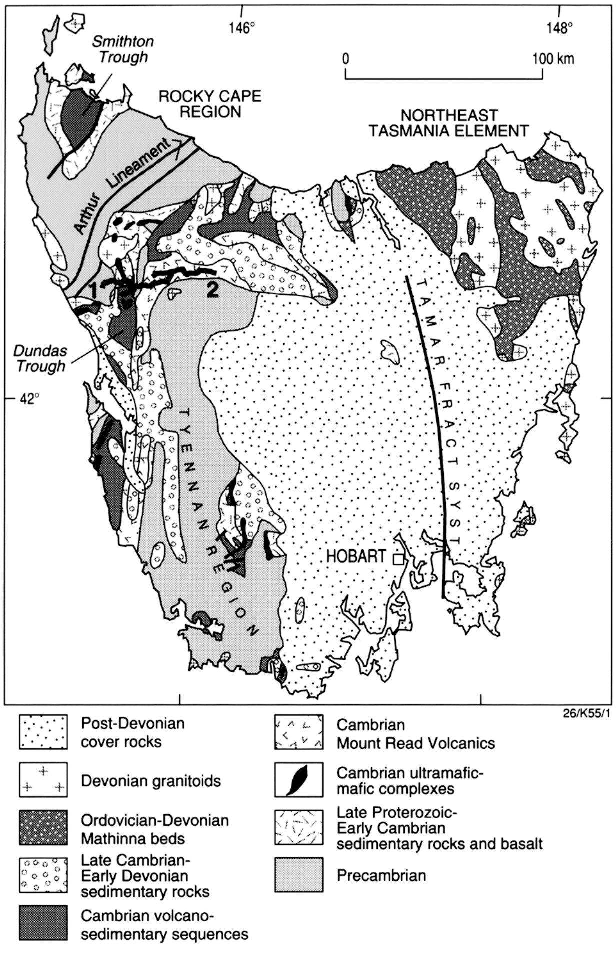

Figure 9: *Onshore geology of Tasmania and the locations of seismic lines 1 and 2 within the Mount Read Volcanics region, northwest Tasmania (after Drummond et al., 1996).*

(Figure 6). This reflective band is interpreted either as original Mount Isa Inlier basement material or as representing a change in metamorphic grade across the fault system.

In this case history, the seismic method has clearly demonstrated a difference in the structural styles between the Eastern and Western fold belts, with the thin-skinned detachment-controlled tectonics in the east and the thick-skinned tectonics (latest movements) in the west. The difference probably underpins the apparent zonation of Cu-Au and Pb-Zn mineralization into the east and west, respectively. In both the east and west, mineralisation has a close spatial relationship to major faults. This implies that these faults have been instrumental in focussing mineralising fluids and enhancing reflectivity of some faults relative to others. There is enhanced mineral prospectivity along and adjacent to these faults. High resolution profiling near the ore bodies at Mount Isa has successfully imaged the Paroo Fault and defined the maximum likely depth of mineralization in the area. Unexpectedly large amplitude reflections within the Mount Isa Group are attributed to zones of alteration.

CASE HISTORY 3: TASMANIA

Northwest Tasmania consists of several distinct Precambrian and Paleozoic geological elements (Figure 9). A survey across several of the major geological provinces was undertaken in 1995 and included

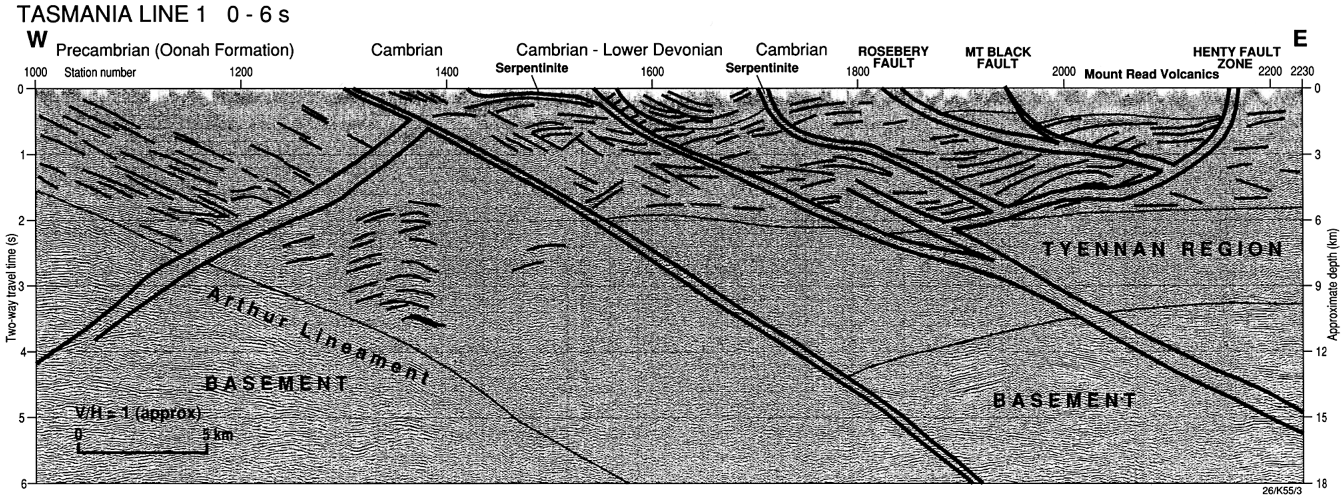

Figure 10: *Seismic section of the upper crust along Tasmanian Line 1. The structural complexity within the Mount Read Volcanics region is illustrated (unmigrated; after Drummond et al., 1996).*

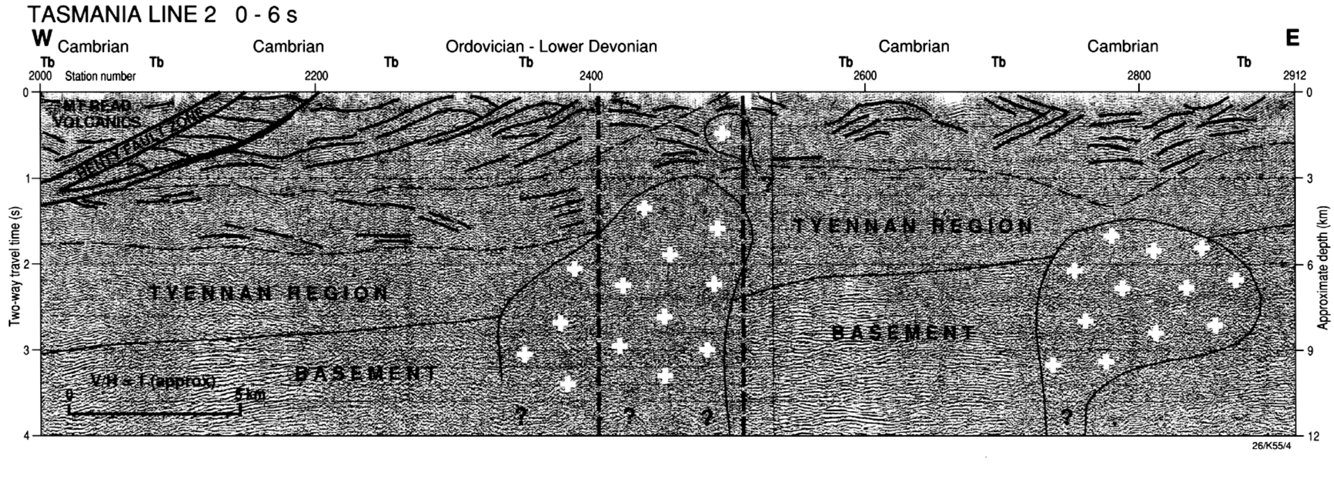

Figure 11: *Seismic section of the upper crust along Tasmanian Line 2. The Henty Fault Zone provides a marker between this figure and Figure 10. The two vertical dashed lines define sections where the seismic line takes a major bend (unmigrated; after Drummond et al., 1996).*

regional deep seismic profiles both onshore and offshore close to the coast, as well as a short high-resolution survey imaging a portion of the prospective Cambrian Mount Read Volcanics. This unit contains world-class high-grade VHMS-style mineral deposits (Large, 1992).

The seismic data from the regional onshore traverses (Lines 1 and 2, Figures 10 and 11) have imaged the main structures of this province (Drummond *et al.,* 1996). The most distinctive reflections imaged within the crust are attributed to the Arthur Lineament. This lineament is imaged as a planar feature dipping east at approximately 30° from the surface to depths of at least 20 km beneath the Tyennan Block. The Henty Fault System dips west and links with other faults including the Rosebery Fault, and with faults bounding ultramafic bodies to form a crustal-scale flower structure which roots into basement at about 10 km depth under the western edge of the Tyennan Block (Drummond *et al.,* 1996). The Paleozoic section is imaged as a highly folded and faulted succession above a non-reflective basement, with a total thickness of at least 5-6 km. Individual stratigraphic units within the Paleozoic section are generally not differentiated in the regional profiles, due mainly to their highly deformed nature and the low reflection impedance contrasts between the units (Drummond *et al.,* 1996).

In addition to the above regional traverses, a short, high resolution seismic reflection profile was recorded within the northern portion of the Mount Read VHMS district along trend from the Que River and Hellyer base metal mines (Yeates *et al.,* 1997). It was coincident with part of regional seismic Line 2 (Figure 11), and in a structural position close to the Henty Fault Zone (Figure 10). Geological control is lacking below about 500 m. This high resolution profile defined the internal geometry of a section interpreted as Que River Shales and underlying basalts of the Que-Hellyer Volcanics. The migrated seismic data show the lavas thickening into a lens with overlying high-amplitude anomalies (Figure 12).

Reflectors at about 900 m and 1150 m depth are interpreted as the top and base of the Que River Shale. This unit overlies the Que-Hellyer Volcanics whose base is interpreted as the reflector at about 1500 m (Figure 12). In this area, there is a notable bulge in the thickness of the Que-Hellyer Volcanics, with a corresponding coincident gravity anomaly (Yeates *et al.,* 1997). Reflections are weaker in the bulge and Yeates *et al.* (1997) suggested this may represent a zone of strong alteration. The strong reflectors imaged above this zone, at 1150 m (Figure 12) suggest the presence of high-velocity rocks. This feature is similar to textbook descriptions of volcanic-hosted massive sulphide deposits in the region (Large, 1992) and we infer from the geometry of the reflectors and their amplitudes that these rocks could be carbonates, *dolerite* (diabase) or massive sulphides(?).

DISCUSSION

The above three case histories illustrate that seismic reflection studies undertaken within several Australian mineral provinces have significantly contributed to an understanding of fluid flow within the crust, its effects and controls on mineralization, and hence an improved metallogenic model for each region. These seismic reflection studies demonstrate how regional and local-scale seismics in mineral provinces can assist the understanding of the structural controls and the source-pathway-reservoir schematics of mineral systems.

In most cases, the approach has been to image the main controlling structures that either control the ore body itself or bound the mineralization field. In these hard-rock regions, the strongest reflections result from within shear zones or on either side of fault zones. This is consistent with the observations of Jones and Nur (1984). We infer that the enhanced reflectivity of a fault plane is an indicator of enhanced fluid flow along the fault (e.g., Marimo Structure, Mount Isa, Figure 5). The increased reflectivity is therefore a potential indicator of past fluid flow. In several cases, we have also observed either increased or decreased reflectivity associated with alteration around an ore body; the reflectivity change is dependent on the host rock and the style of alteration. In the Mount Read Volcanics, Tasmania, we have inferred an increase in reflectivity above and within a bulge of the interpreted Que-Hellyer Volcanics, whereas in Mount Isa we infer an increase in reflectivity around a potential ore body.

In all cases, linked fault systems play an important part in establishing and connecting pathways from the lower crustal source areas to the

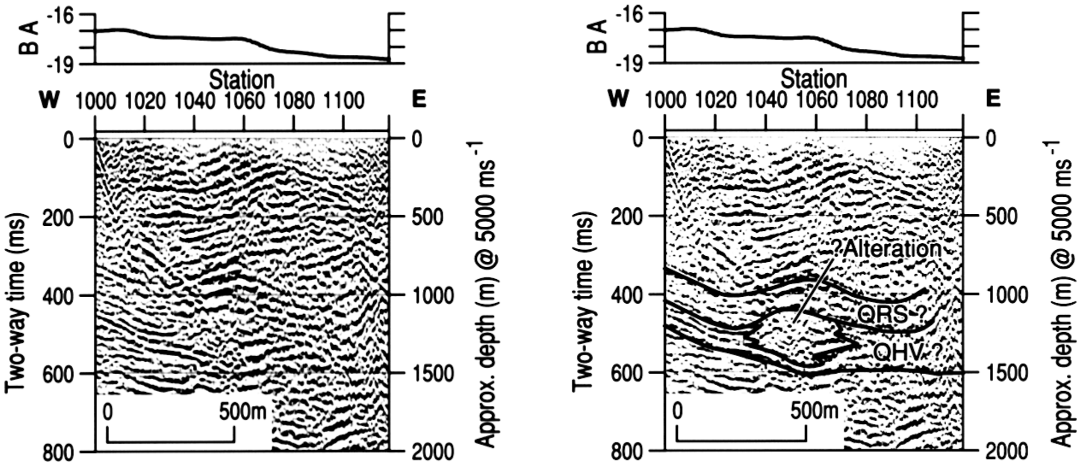

Figure 12: *High resolution portion of Tasmania Line 2 seismic section recorded within the northern Mount Read VHMS district, northwestern Tasmania, showing thickening of the interpreted Que-Hellyer Volcanics and weaker reflectors in the bulge, suggesting alteration. High amplitude reflectors above the bulge could represent dense rocks, perhaps carbonate, dolerite or massive sulphides (?) (migrated; after Yeates et al., 1997).*

site of deposition. Fluid flow modelling shows that the overall structure controls the scale and style of fluid flow flux through the crust.

We have therefore concentrated on developing our seismic techniques to directly image the main fault systems, in particular focussing on dipping shear zones which are likely to provide a greater fluid flux into the upper crust.

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