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Seismic reflection imaging of mineral systems: Three case histories

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ABSTRACT

Mineral deposits can be described in terms of their mineral systems, i.e., fluid source, migration pathway, and trap. Source regions are difficult to recognize 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. 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 hangingwall block of regional-scale faults that differ from other nearby faults by being highly reflective and penetrating to greater depths in the lower crust. Coupled thermal, mechanical, and fluid-flow modeling 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 northeastern Australia. Both are closely related spatially to copper and copper–gold deposits. One, the Adelheid fault, is also adjacent to the large Mt. Isa silver–lead–zinc 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 mineralization. Regional seismic profiles can therefore be applied in the precompetitive 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 themselves, seismic techniques may be more successful. Strong bedding-parallel reflections were observed from the region of alteration around the Mt. Isa silver–lead–zinc orebodies using high-resolution profiling. In addition, a profile in Tasmania imaged an internally nonreflective bulge within the Que Hellyer volcanics, suggesting a good location to explore for a volcanic hosted massive sulfide 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 toward 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 Mt. Isa inlier of northeastern 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 (e.g., Milkereit et al., 1996; Yeates et al., 1997; and Goleby et al., 1997) suggest that seismic techniques can also be successful at the orebody

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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, i.e., the Eastern Goldfields province (Drummond and Goleby, 1993), the Mt. Isa Inlier (Drummond et al., 1997) and Tasmania (Yeates et al., 1997), into a mineral system framework. Although the mineral deposits studied differ in many ways, the approach of simplifying mineral systems provides pointers on how seismic techniques can be effective in the precompetitive 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 it could be 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 focusing 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, e.g., 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 that focus mainly on the trapping mechanisms tend to describe the unique and often complex combinations of elements in the trapping mechanism for each deposit but 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 characterized according to the age and type of source rock (the fluid source) (Bradshaw, 1993), the ages of mineral deposits are often less certain. Mineral systems may be characterized 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, so also can a mineral province 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 mineralizing 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 anisotropic fabric (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. The case histories presented in this paper describe the seismic effect of the mineral system in terms of migration pathway and trapping mechanism.

In the first case history, the crustal structure of the Eastern Goldfields is interpreted in terms of linked fluid pathways. Drummond and Goleby (1993) interpret 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 mineralization. They make no attempt to link this regional study with local studies at the orebody scale.

The second case history, at Mt. Isa, tries to link from the regional scale into the orebody scale. Salisbury et al. (1996) demonstrat that many of the sulfide minerals that typically make up the bulk of mineralization constituting orebodies have seismic velocities similar to felsic and mafic igneous rocks, and also some sedimentary rocks, but 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 among 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 maximize 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.

In the Mt. Isa study, the strategy was not to try to image the orebody itself but rather to target a known larger alteration zone characteristic of the environment where mineralization might occur—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 might contain.

The third case history, in Tasmania, studies a totally different style of ore environment and demonstrates that by targeting the mineral system rather than the orebody, seismic methods can be applied successfully 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 drillholes, and detailed surface geological mapping. Two-dimensional and some low-fold 3-D seismic reflection as well as 2-D and 3-D crustal-scale refraction techniques were used. However, only seismic reflection results are presented here.

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

Explosive charges in deep drillholes 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 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 and 24 was achieved. Symmetrical split-spread geometries were used, which resulted in a maximum shot–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 within parts of the regolith up to 7000 m/s 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 adopted a strategy of identifying regions of similar reflector coherency and dip. We correlated those regions with the surface geology or with seismic velocities from crustal-scale refraction or tomography studies to assign rock type. Then we 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 by 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 is 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, e.g., 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. Bottomhole cuttings from the shot holes along the traverse were chemically analyzed. Those from near the Ida fault and Bardoc shear have comparable alteration

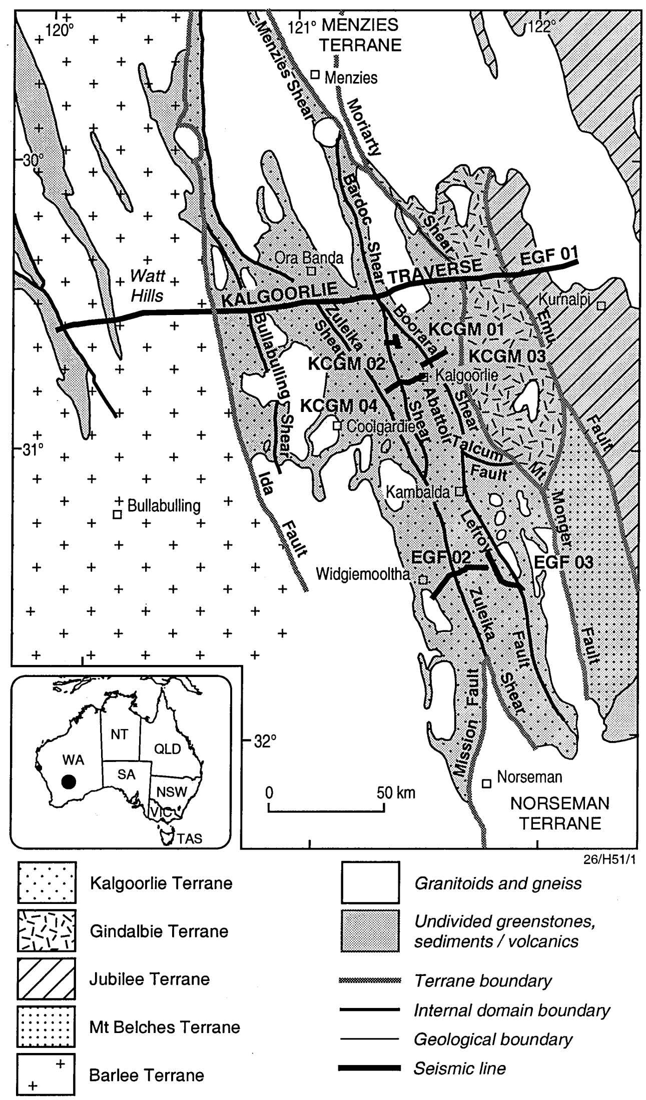

FIG. 1. Major structural subdivisions of the southern Eastern Goldfields province, Yilgarn block, Western Australia. Position of 1991 seismic transect is also shown (modified from Swager and Griffin, 1990).

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—first into and along

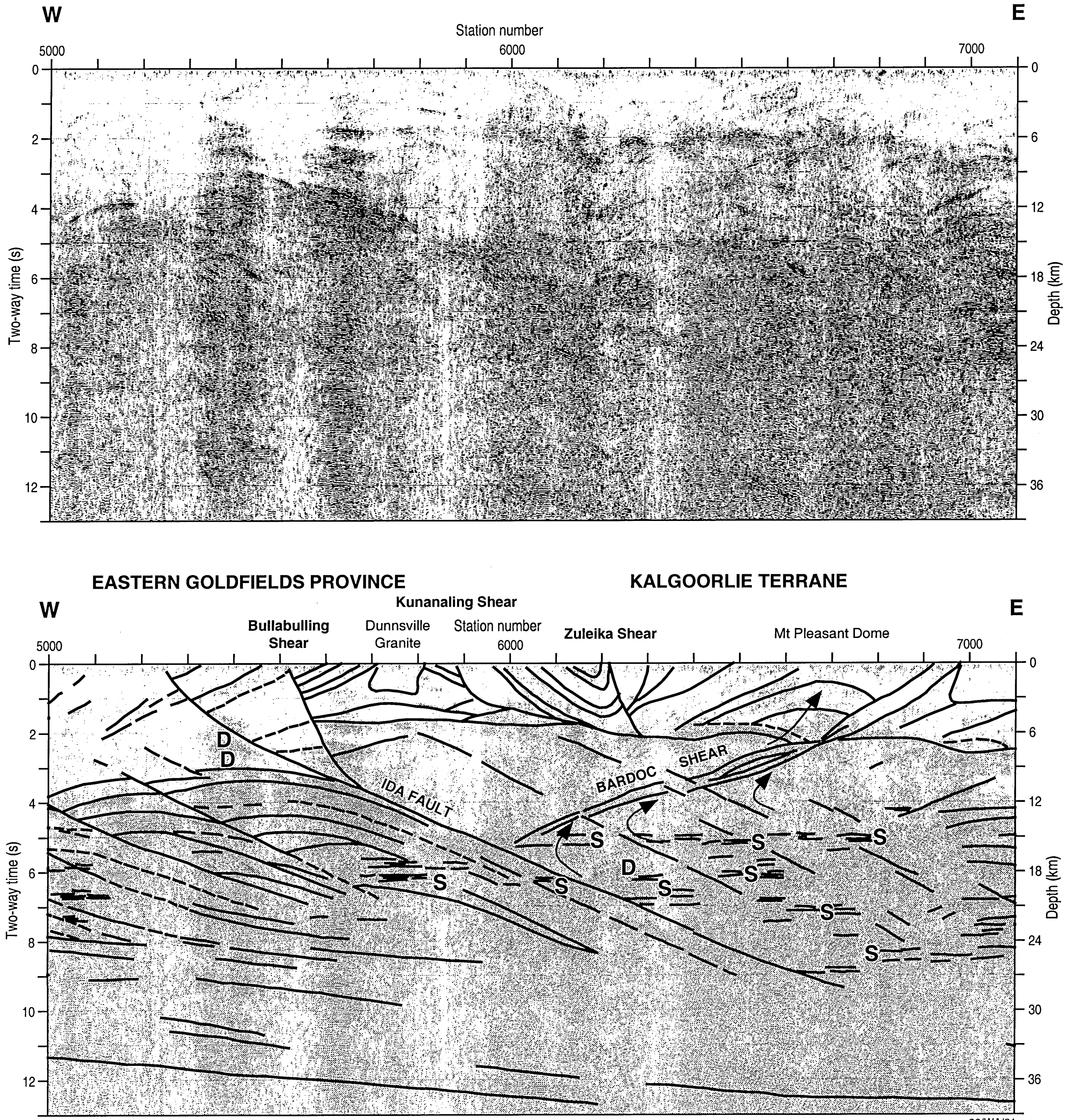

FIG. 2. Portion of the 1991 deep seismic transect recorded within the Archaean Yilgarn block. Arrows indicate fluid-flow directions predicted by Drummond and Goleby (1993). D = diffraction, S = sill. Detailed images of the interpretation, particularly the top 2 s, are found in Goleby et al. (1993) and Swager et al. (1997).

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, Figure 2). Some leaked along the detachment and into other faults within the greenstone sequence that splay from the detachment (e.g., Zuleika shear; Figure 2), but most concentrated in the greenstones immediately above and to the west of the Bardoc shear.

Numerical modeling of fluid flow within the Eastern Goldfields province supports this linked fluid-pathway model (Figure 3) (Upton et al., 1997). The numerical modeling 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 modeling 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. Coupled deformation-fluid flow modeling predicted the occurrance of east-dipping faults within the crust. These were seen in the seismic data. The model also predicted focused fluid flow into the east-dipping shear zones.

CASE HISTORY 2: MT. ISA

The Proterozoic Mt. Isa inlier of northern Australia is recognized for its world-class silver–lead–zinc and copper–gold 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 Mt. 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 (Drummond et al., 1997; MacCready et al., 1999).

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 subhorizontal thrusts. Further shortening then occurred along steeper east-dipping reverse faults. They are mostly recognized 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 to 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

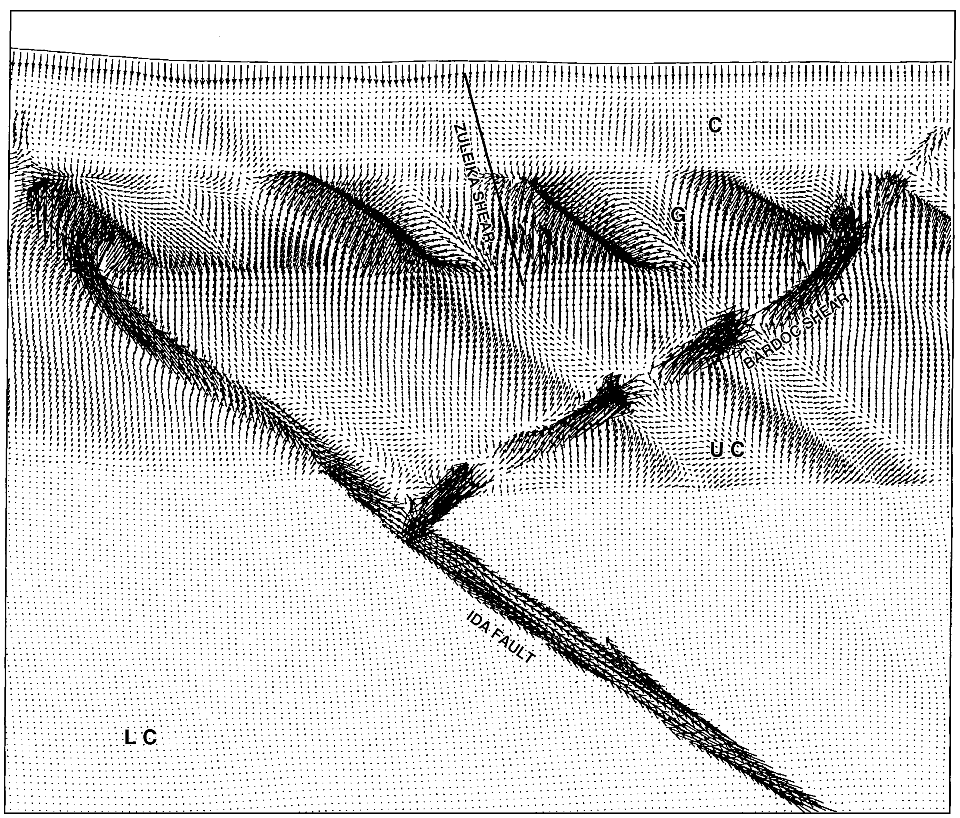

FIG. 3. Fluid-flow modeling of the Yilgarn block. The fault geometry is derived from the seismic data. Crustal layering is implied from reflectivity patterns along the profile. The topmost layer was added to account for crust removed by erosion since the ore deposits were formed. Arrows represent fluid-flow vectors. East-dipping zones of longer vectors in the greenstones and basement are predicted by the modeling and coincide with weak reflections in the seismic data. LC = lower crust, UC = upper crust, G = greenstones, C = crust removed by erosion.

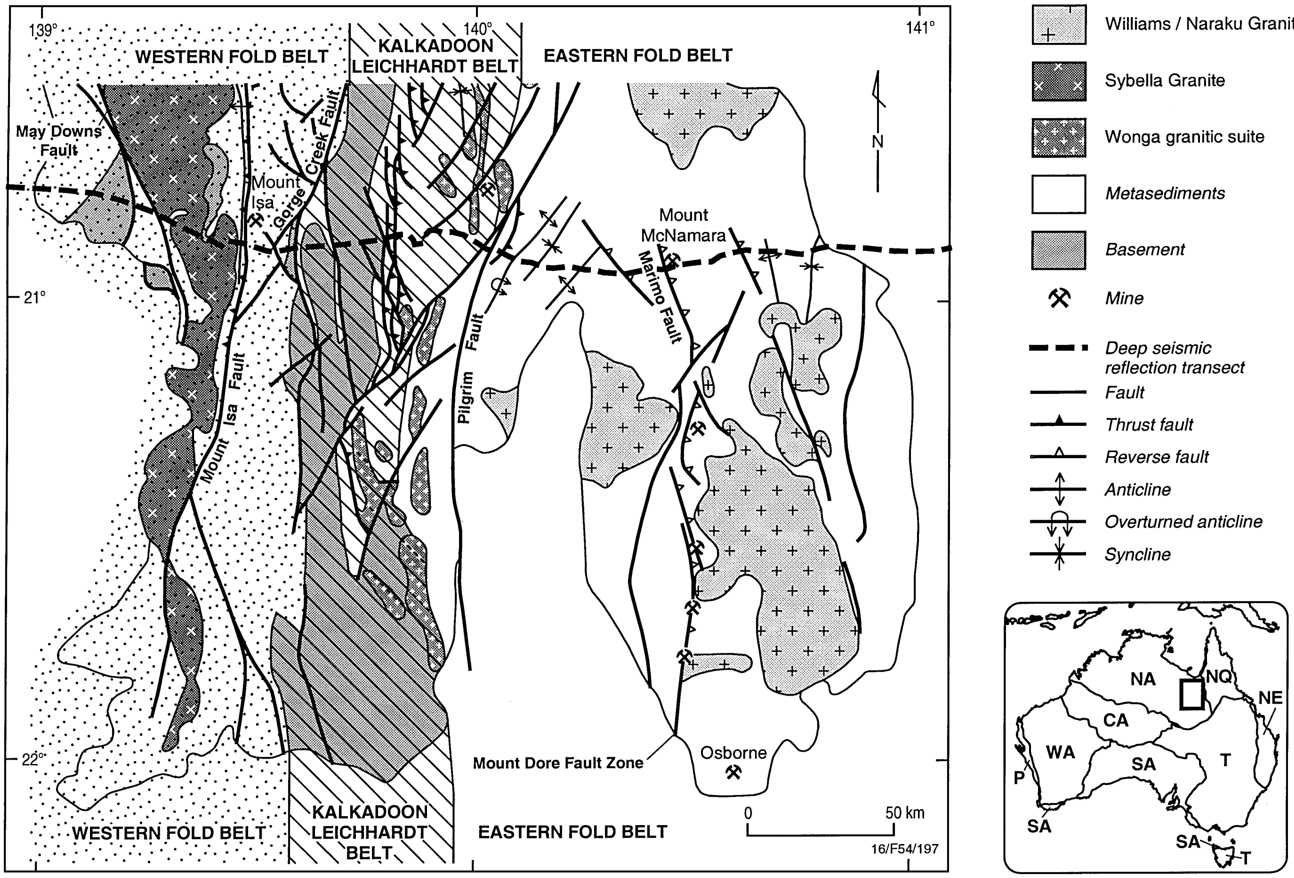

FIG. 4. Tectonic provinces of the Mt. Isa Inlier and the location of the seismic transect.

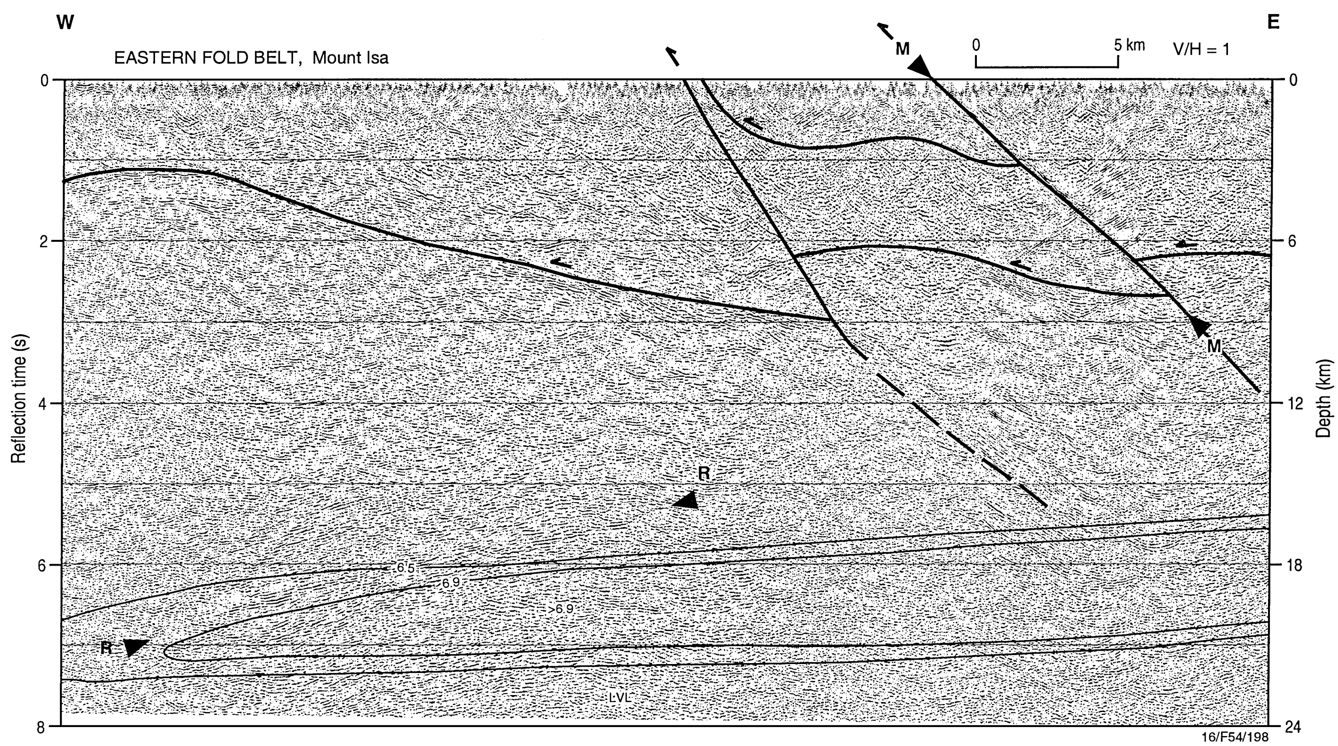

FIG. 5. Portion of migrated seismic data from the Eastern fold belt, Mt. Isa inlier, showing the earlier shallow detachment cut by later steeper faults imaged within the Marimo region. Contours (in kilometers per second) show position of high-velocity body in midcrust. R = reflections from high-velocity body; LVL = low-velocity layer; M = Marimo fault (from Drummond et al., 1997).

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 copper–gold mine lies near the transect, and the Hampden, Mount Dore, Selwyn, and Osborne copper–gold 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 Mt. 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 kilometers along the western side of the Leichhardt River fault trough.

To the north of the transect, four major lead–zinc(–silver) and copper deposits lie close to the Mt. 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 <1 kilometer 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 pseudotrue-amplitude section are seen on the fault below the word vortex at the top of the figure. Heinrich et al. (1989) propose that the lead–zinc 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.

Both 2-D and 3-D high-resolution seismic data were recorded between the Mt. Isa and Hilton mines (1–2 km north of Mt. Isa, Figure 4). They were designed to test predicted cross-sections just north of the copper and lead–zinc orebodies (Figure 7) (Neudert and Russell, 1981). Locally, lead–zinc mineralization tends to be in steeply west-dipping lenses parallel to bedding within the Urquhart Shale. Copper mineralization lies deeper. Both the lead–zinc and copper mineralization 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 2-D data section is shown in Figure 8. Reflections were recorded from the subhorizontal 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 sulfide 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) summarize the results of the regional profiles. They show the Paleozoic section of the Dundas trough and Mount Read volcanics to be a highly folded and faulted succession with a

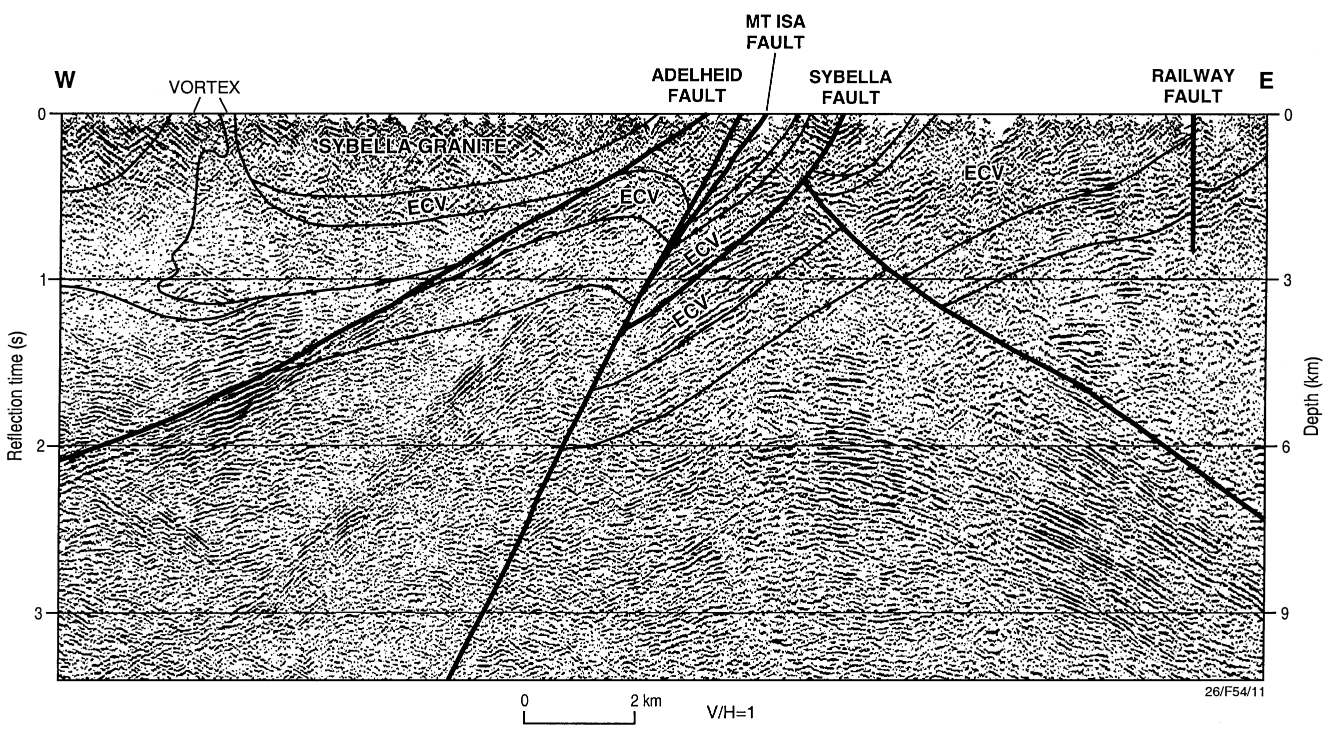

FIG. 6. Portion of seismic line from the Western fold belt, Mt. Isa inlier, showing the interpretation of MacCready et al. (1999). The Adelheid fault is highly reflective, but other faults are not. Reflections between the Adelheid and Mt. Isa fault are interpreted as *S*-wave reflections from the Adelheid fault. ECV = Eastern Creek volcanics (from Drummond et al., 1997).

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, probably because of 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 drillhole control (J. Silic, A. McNeill, and S. Richardson, Aberfoyle Pty. Ltd., personal communication, 1996) (Figure 10 and Yeates et al., 1997). Reflectors at about 900 and 1150 m below shotpoint 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 zinc–lead–copper (silver, gold) Hellyer deposit (Large, 1992) within the Que-Hellyer volcanics several kilometers 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 sulfides. 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 modeling. 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 meters 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 Mt. Isa Inlier has extensive hydrothermal alteration and lies along strike from operating copper–gold mines. In northwestern 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) suggests that anisotropy is the primary cause of the reflectivity from two crustal-scale shear zones. The model is based on measurements of the physical properties of samples collected from surface outcrops of mylonite zones. It consists of anisotropic rock with low impedance normal to the shear zone, interlayered with isotropic rock with impedance similar to the protolith on either side of the shear zone. The model required constructive interference to create amplitudes comparable to those observed. To do this, the layers had to be 110–150 m thick. Goodwin and Thompson (1988) also discuss reflectivity attributable to mylonite zones. Their physical models are based on logs from a conveniently located well, and their layers are much thinner (about 30 m). They also note tuning of the layer thickness is important to achieve the observed amplitudes, but that lateral variations in layer velocity and/or thickness over distances of about 100 m are also important.

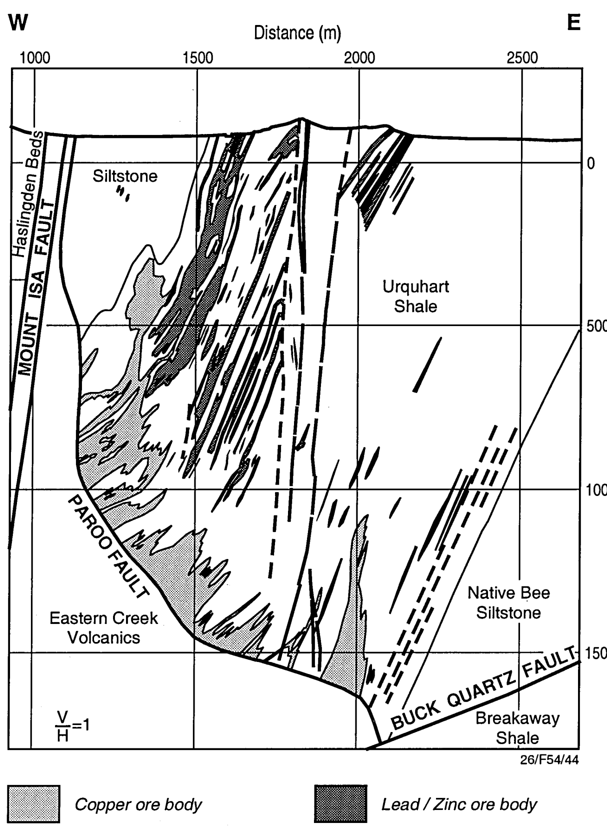

FIG. 7. Schematic section across the Mt. Isa Valley lead–zinc and copper mineral field, showing the geological structure around and within the orebody (after Fallon et al., 1997).

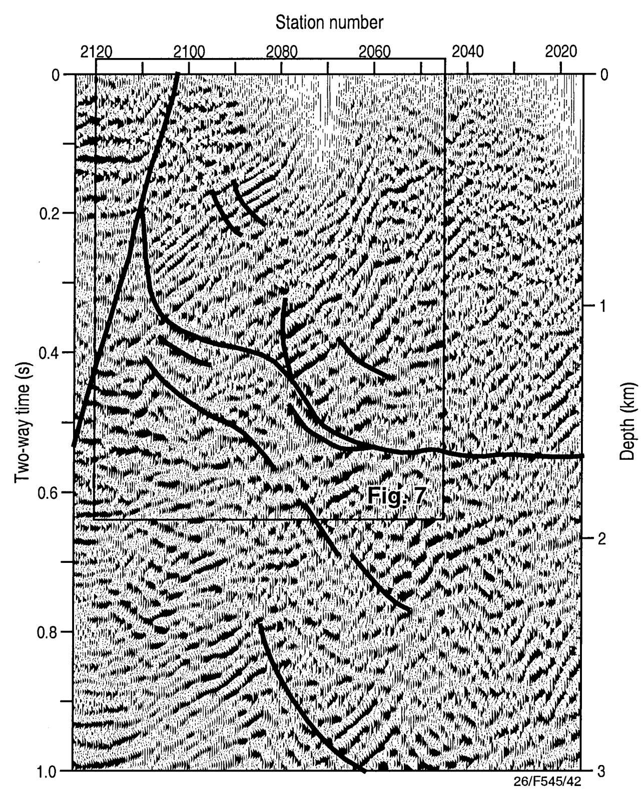

FIG. 8. Migrated high-resolution seismic data from the Mt. Isa Valley, with interpreted positions of the Mt. Isa and Paroo faults.

Neither of these studies compares the relative effects of anisotropy resulting from strain and alteration caused by metasomatism. Siegesmund and Kern (1990) find that reflectivity as a result of anisotropy cannot account for the amplitudes of all observed lower crustal reflections. Klemperer and BIRPS (1986) study the Outer Isles thrust in Britain, and find that metasomatism is more important than anisotropy in causing impedance contrasts. Anisotropy, although present, is disorganized at scales of 100 m. Whereas Jones and Nur (1984) find that the bulk physical properties of anisotropic rock are near those of the protolith, Jones (1986) finds that both velocity and density increase from protolith through mylonite to ultramylonite, accompanying a reduction in silicon and an increase in iron, calcium, and magnesium.

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.

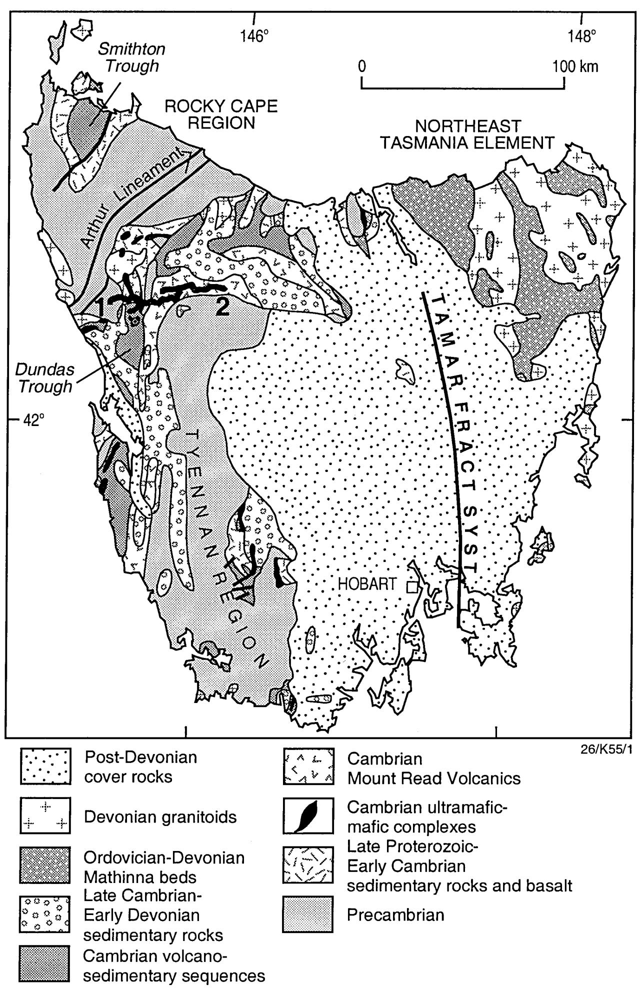

FIG. 9. Geology of Tasmania and the locations of two deep seismic transects. The high-resolution seismic line in Figure 10 is coincident with and just to the west of the bend in line 2 (after Drummond et al., 1996).

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 copper orebody at Mt. Isa contain significant amounts of pyrite, whereas the lead–zinc orebodies at Mt. Isa lie within an altered zone containing less pyrite. Salisbury et al. (1996) find that massive sulfide deposits can have impedances much higher than most common host rocks, and Milkereit et al. (1986) confirm that massive sulfide orebodies, if thick enough, can be good reflectors. Pyrite, in particular, has a higher density than the host rocks of the Mt. Isa orebodies. If present in sufficient quantities in the alteration haloes, it 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 northwestern Tasmania (Figure 10).

Not all strong reflections in the seismic sections are from fault zones. Fault zone identification often depends on whether the zones 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

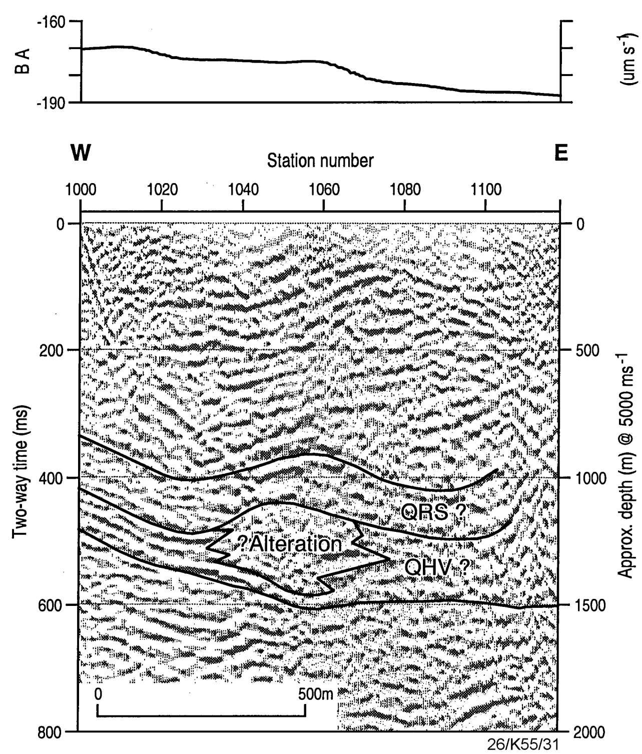

FIG. 10. Portion of the 1995 high-resolution seismic section recorded within the northern Mount Read VHMS district. The data show a bulge in the Que Hellyer volcanics (QHV) and weaker reflections in the bulge, suggesting alteration. High-amplitude reflectors above the bulge could represent dense rocks—perhaps carbonate, dolerite, or massive sulfides. QRS = Que River Shale; BA = Bouguer anomaly gravity values in micrometers per second squared (after Yeates et al., 1997).

itself or bound the extent of mineralization. In our experience, 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 kilometers of high-quality, deep seismic profiles now exist for a wide range of tectonic environments around the world. Most are in the public domain. In almost all cases, the data have not been examined extensively for pointers to areas of enhanced prospectivity.

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