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Mineral Systems and the Crust – Upper Mantle of Southeast Australia

Extended abstracts of papers presented at a symposium held in Canberra, 20-22 April, 1998

Edited by D.M.Finlayson & L.E.A.Jones

AUSTRALIAN GEODYNAMICS COOPERATIVE RESEARCH CENTRE

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FOREWORD

No two regions of Earth's crust have identical geological histories. This means that as geoscientists we cannot assume uniformity across broad regions, nor can we expect mimicry between the geological records of different regions. We must examine the rocks and develop specific concepts about how and when sequences and structures developed and what tectonic/thermal/hydrodynamic events occurred in the local geological history.

At the broader scales we can expect similarity between rock types, structures and events where similar geodynamic processes have driven and controlled the local geology. This is the basis for applying models such as plate tectonics, developed for active tectonic settings that are rich in empirical evidence, to ancient sequences where observations are limited. Geodynamic processes are also responsible for the formation and location of mineral deposits. In ore genesis studies similarity among deposits is correlated with similarity in geodynamic processes and this forms the basis for many exploration strategies adopted by industry.

How well these geodynamic processes are understood can readily influence perceptions of the geological history of an area as well as its mineral fertility. Geodynamic processes are intrinsically three-dimensional and their precise definition requires many streams of evidence, not least being a knowledge of present subsurface geology. Today seismic profiling methods can image sub-surface geology on a scale comparable with structural mapping and geochemical studies of ore deposits so the soundness of geodynamic concepts and interpretation can be tested. They can also be improved by the expanding use of precise geochronological tools to date geodynamic events. Truly, we are entering the age of 4-dimensional geological mapping.

The Australian Geodynamics Cooperative Research Centre (AGCRC) is concerned with developing an understanding of the geodynamic framework of the Australian continent. This geodynamic framework includes the structural, tectonic, thermal, hydrodynamic and geochemical events of Australia's geological history, together with their timing and how they are expressed in the crust and upper mantle at continental, province, terrane and deposit scales. The objective is to identify relationships between geodynamic factors and the formation of world-class deposits, and to use advanced technologies to predict the location of new deposits. In effect the AGCRC seeks to bridge the gap between earth science research and the exploration strategies adopted by industry. To this end the AGCRC has sponsored this Symposium on the ***Mineral Systems and the Crust-Upper Mantle of Southeast Australia.***

With a focus on mineral systems, structural architecture and tectonic history, this Symposium begins with a lithospheric-scale perspective of the crust and upper mantle of southeastern Australia. The focus then moves to the geological/mineral provinces of Broken Hill, Tasmania, Western Lachlan, Eastern Lachlan and New England. The presentations come from academic and government research groups and the emphasis shifts across a range of earth science disciplines. The AGCRC hopes that, by communication and discussion of key findings from the region, the geodynamical processes will be better understood and that this will be of lasting benefit to researchers and exploration companies interested in southeast Australia.

Dr. Graham Price
Director,
Australian Geodynamics Cooperative Research Centre

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Extended abstracts are listed alphabetically according to the surname of the first author. All reviewing of these extended abstracts has been done by the authors and colleagues of their choosing and thus any analyses or scientific opinions presented in this Record are the sole responsibility of the authors. The editors have made formatting, layout and spelling changes but have not conducted any independent peer review process.

Crustal Structure in the Western Lachlan Orogen, Based on a Seismic Transect to the North of the Grampians, Victoria

T. J. Barton[1], D. R. Gray[2], A J. Owen[1], R. J. Korsch[1], B. D. Drummond[1] and D. A. Foster[3]

[1] Australian Geodynamics Cooperative Research Centre, Australian Geological Survey Organisation, Canberra, ACT 2601
[2] Australian Geodynamics Cooperative Research Centre, VIEPS Dept. of Earth Sciences, Monash University, Melbourne, Vic. 3168
[3] Australian Geodynamics Cooperative Research Centre Department of Earth Sciences, Latrobe University, Bundoora, Vic. 3083

A crustal transect based on deep seismic reflection profiling in western Victoria provides insights into crustal evolution in the western Lachlan Orogen, and also into the structural relationship between the Lachlan Orogen and the Delamerian fold belt to the west. The transect was undertaken by the Australian Geodynamics Cooperative Research Centre as part of a multidisciplinary study of the geodynamic factors controlling gold mineralisation in the region (see also Gray et al., this volume).

The Transect

The transect location is shown in Figure 1. Three seismic lines combine to provide images of

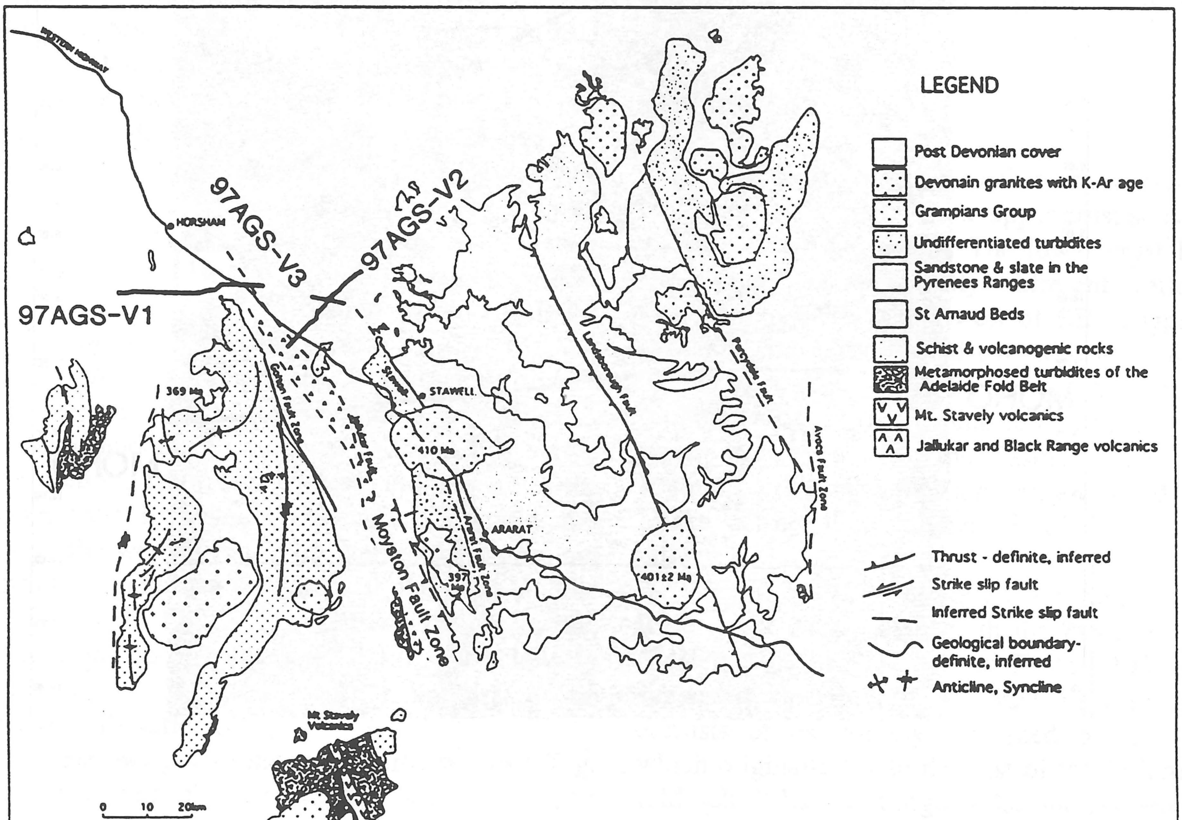

Fig. 1 - Lithology and structure of the western Lachlan Orogen, Victoria (modified from Wilson et al., 1992).

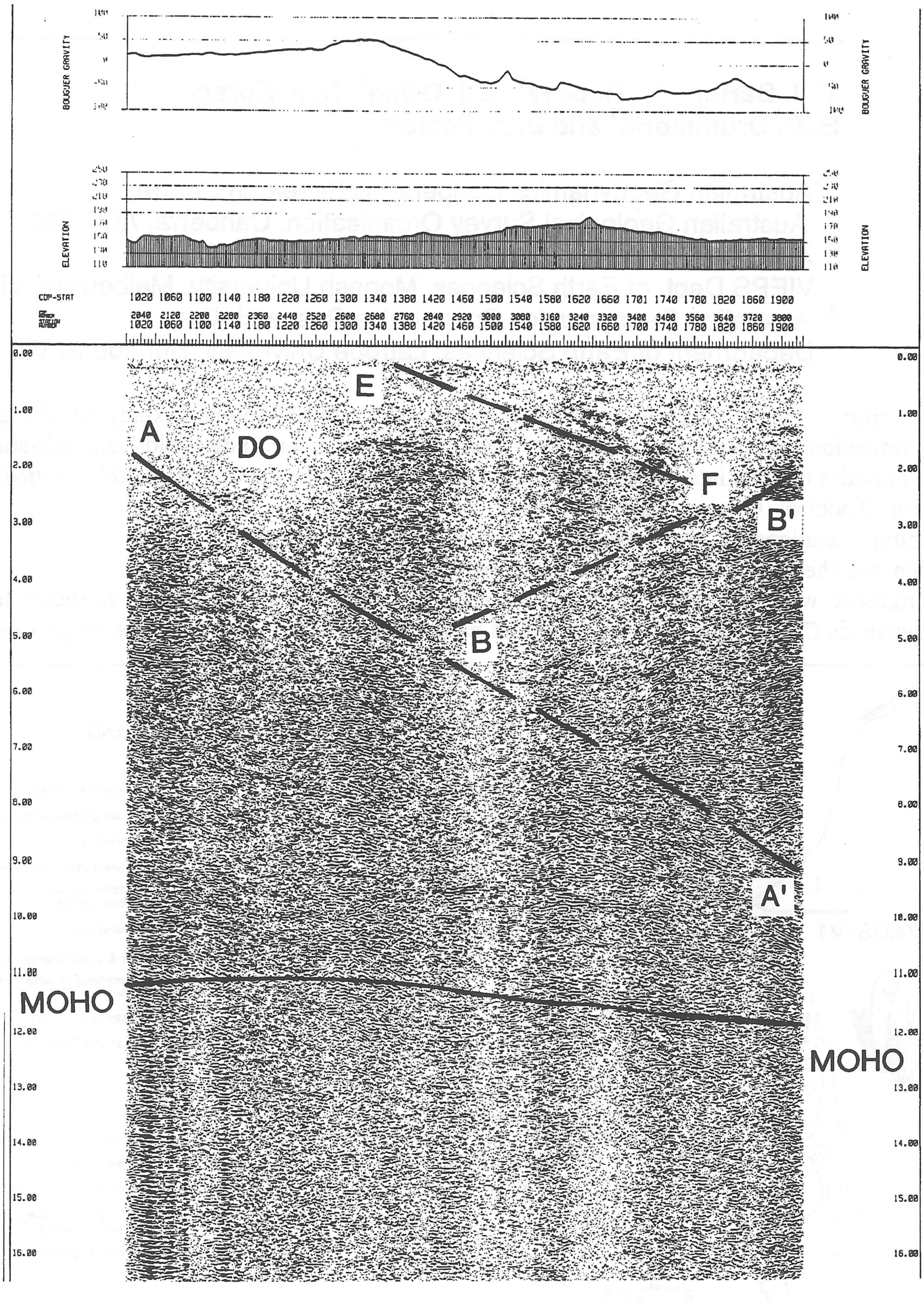

Fig. 2 - Line 97AGS V1 20 second TWT Preliminary Stack section. Display is at approximately 1:1 scale using an average crustal velocity of 6 km/s.

the sub-surface from west of the Grampians range (Grampians Group, Fig. 1) to east of the Stawell Ararat Fault Zone. Logistic difficulties required that the lines were positioned to the north and east of the Grampians range, in areas of poor outcrop. Structures mapped farther south were interpreted into the area of the seismic lines using magnetic images provided by the Geological Survey of Victoria. The lines were positioned to image at depth the projected northern extension of the Moyston Fault Zone, which has been interpreted by some workers (eg. Cayley & Taylor, 1996; Foster et al., 1996) as the boundary between older, pre-Delamerian orogeny rocks to the west and younger Early Palaeozoic rocks of the Lachlan Orogen to the east. However, other workers (Wilson et al., 1992) suggest that this boundary lies further to the east probably being located near the Avoca Fault Zone. The transect also crossed the Stawell-Ararat and Golton Fault Zones.

Crustal Architecture

The Moho is interpreted as the base of the reflective lower crust at 11-12 s twt, or about 33 35 km depth in both Figs. 2 and 3. This is consistent with crustal models based on earthquake travel times in the region (Gibson et al., 1981). That is, the transect suggests that the Moho is at the same depth beneath the Delamerian and Lachlan Fold Belts in this region if the Moysten Fault Zone is the boundary between these zones. Reflections below the Moho are steeply dipping. The data in Figs 2 & 3 are preliminary stack sections, and these steeply dipping Moho reflections are likely to belong within the lower crust when the data is migrated.

The region above the Moho can be divided into several blocks on the basis of reflection strength and dip. A boundary (AA') dips across the sections from west to east, and penetrates the lower crust. Projected to the surface, it would crop out to the west of Fig. 2. It intersects but does not appear to penetrate the Moho at about the middle of Fig. 3. In Fig. 2, it is defined mainly by the change in dip of reflections above and below. In the lower crust in Fig. 3, it appears to be intrinsically reflective.

Below AA' in the west of the transect (Fig. 2), reflections dip consistently east. The region above AA' can be subdivided into several sub-regions along a boundary (MFZ) which is interpreted to be the Moyston fault zone. To the west of MFZ, above AA', reflections are weaker than those deeper in the crust, and have a style and range of dips suggestive of folded rocks. Rocks of the Delamerian Fold Belt occupy this region below the surficial cover (Fig. 1).

East of the MFZ, the uppermost crust is very poorly reflective. These represent rocks of the Lachlan Orogen. Weakly reflective upper crust is found elsewhere in the Lachlan Orogen and has been attributed to the presence of granitic and strongly folded turbiditic rocks. The reflection labelled AFZ is an exception (Fig. 3). It projects to the surface along strike from the mapped position of the Ararat fault zone.

The lower crust below MFZ, and above AA' and the Moho has strong reflections with a range of dips (area labelled D in Fig. 3). Similar reflections in the Lachlan Orogen well to the east of the present study area have been interpreted as decollement surfaces (Gray et al, 1991), and as possible evidence for mafic sills. Along the current transect, the reflection character is reminiscent of thrusted, shortened and duplexed lower crust observed elsewhere (eg., Drummond et al., 1997).

Very weak sub-horizontal reflections at shallow depths in Fig. 2 (area labelled G) may be the decollement surface predicted to underlie the allochthonous Grampians Group (Cayley & Taylor, 1996).

Discussion

The Delamerian fold belt forms a triangular wedge of folded rocks in the upper crust above two surfaces (BB' and MFZ). The lower crust below the wedge has distinctly different reflection character to the east and west of BB', suggesting different crustal types and evolutionary histories. To the west, the lower crust has a dominantly east dipping fabric. This is similar to that found farther north on a transect of the Tasman Line, where Proterozoic basement has a dominant east dip (eg. Leven et al, this volume, Fomin et al., this volume).

East of BB', the reflection fabric of the lower crust is consistent with the model of Gray (Foster et al., 1996; Gray & Foster, 1997) who suggested that the lower crust in this region consists of extensively shortened oceanic crust which originally lay to the east of the Delamerian fold belt. It has been argued that the shortening is dominated by west over east thrusting. This cannot be confirmed by the transect data at this stage of the data processing (preliminary stacks in Figs 2 & 3). However, data from northeast Tasmania (see

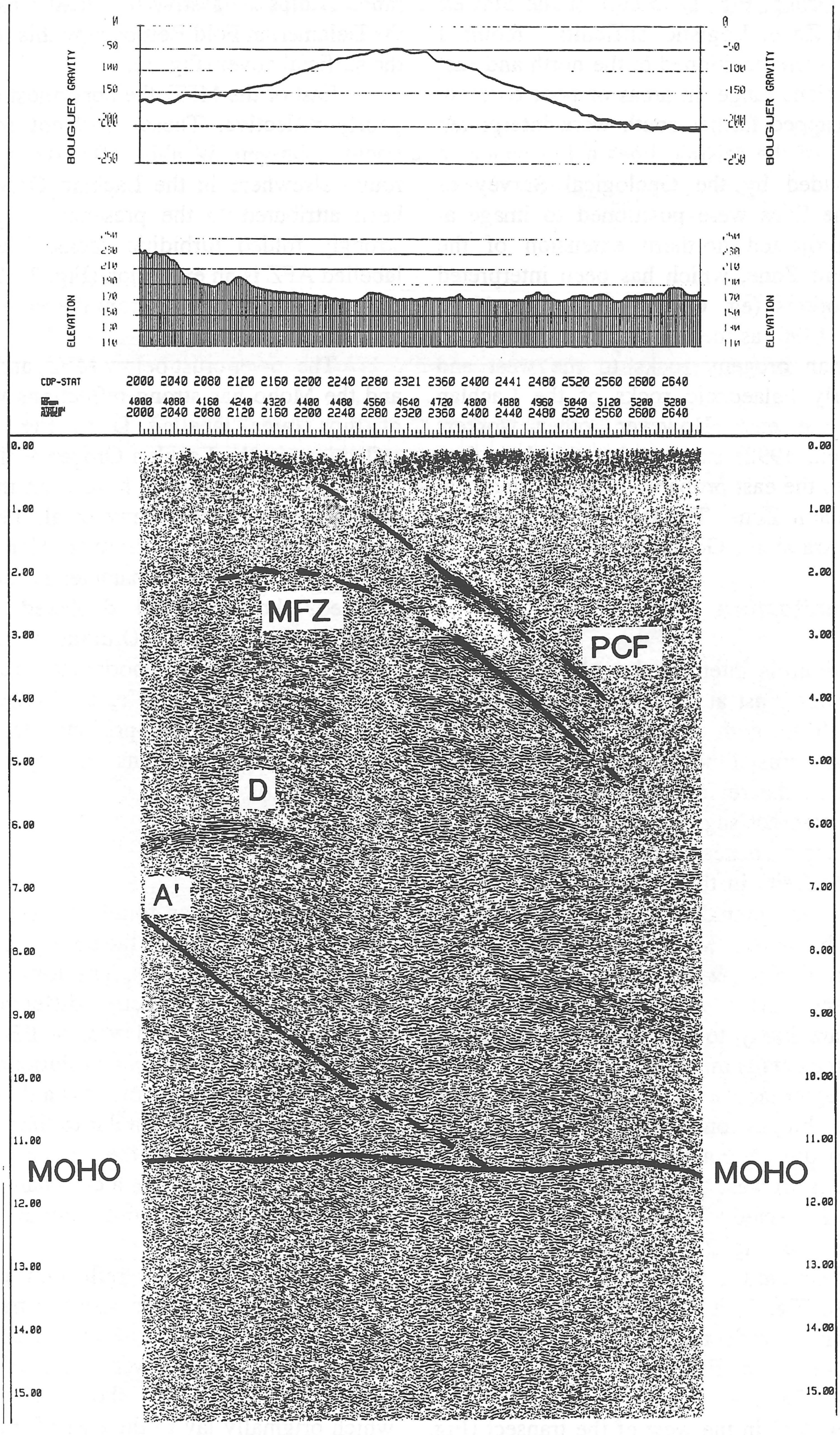

Fig. 3 - Line 97AGS V2 20 second TWT Preliminary Stack section. Display is at approximately 1:1 scale using an average crustal velocity of 6 km/s.

Collins et al., this volume), which are interpreted as Lachlan fold belt equivalents are consistent with this prediction.

A granite crossed by the transect in the western end of Fig. 3 must be only 1-2 km thick because weak reflections similar to those to the east of the granite can be seen below these depths. Moho depths of 33-35 km are consistent with surface elevations of 100-200m, as in this region, assuming an isostatically balanced crust. If the Moho is interpreted as the base of the crust (see Griffin & O'Reilly, 1987), the crust in this region is devoid of a thick dense lower crustal root that would have sourced I-type granites.

The above interpretation attributes essentially all features in the seismic sections to Pre-Devonian geology, with the possible exception of the decollement at the base of the Grampians Group and reactivation of some of the thrust faults. This region was exposed to extensive Recent volcanism of the Newer Volcanics, which crop out in the south of Fig. 1. The implication of the above interpretation is that the recent heat flux and volcanics have not altered the lower crust through underplating and the intrusion of sills in any significant way.

Gold mineralisation lies in the hanging wall block of the Ararat Fault Zone. The strong reflections from the Ararat Fault Zone may prove significant in mineralisation models for the region. Strong reflections from some fault zones have been observed elsewhere, and attributed to alteration zones associated with fluids moving along the faults (eg. Drummond et al., 1997). The reflections from the fault are particularly strong between 2 and 4 s twt (6-12 km depth), suggesting that the fault acted as a focussing mechanism for fluids at this depth before channelling them to higher crustal levels.

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Igneous Metallogeny of S.E. Australia

Phillip L. Blevin

GEMOC, Geology Department, Australian National University, Canberra ACT 0200

Many schemes exist for the metallogenic classification of igneous-related mineral deposits. These schemes have traditionally emphasised such factors as time ("metallogenic epochs"), tectonic setting ("metallotectonic provinces"), deposit type or style, and commodity associations (e.g. "Cu provinces" versus "Sn provinces"). Such schemes however are ultimately unsatisfactory from a genetic perspective because they do not take into account the role of magma source, composition and process in determining ore element ratios in related deposits. Because of these relationships, it is the grouping of ore-related granites by suites and supersuites that is preferred as the primary division for metallogenic classification purposes. This methodology, which is independent of genetic models relating granite compositions to source types, seeks to group together suites of similar character as a way of defining regions on the surface of the presently exposed crust where similar intrusive-deposit relationships may also exist. These regions were termed "Intrusive Metallogenic Provinces" by Blevin et al (1996).

An important consequence of this model is that magmatic suites that have fractionated over a large compositional range may be associated with a range of types and styles of mineralisation, as will intrusive metallogenic provinces defined on this basis. These provinces may be time transgressive, and may not correlate with tectonostratigraphic boundaries as defined by near-surface geology.

Some Intrusive Metallogenic Provinces in SE Australia

Lachlan Fold Belt

Mafic to felsic igneous rocks of Ordovician age are exposed in N-S trending belts in the central zone of the LFB. The mineralised complexes are not exclusively (or even dominantly) "shoshonitic" as previous thought. Related mineralisation comprises significant Cu-Au±Mo porphyry and minor skarn types. Alaskan-type ultramafic complexes are associated with Pt mineralisation.

The Silurian-Devonian and Carboniferous granites comprise 20% of the total exposed area of the LFB. Significant mineralisation associated with these granites is restricted to Sn in the western/central portion of the LFB in New South Wales, and Sn-W mineralisation in both eastern and western Tasmania. Numerous minor deposits of Sn, W, Mo, Au, W and Cu also occur elsewhere. Some gold deposits are clearly genetically related to Silurian magmatism, while most penecontemporaneous mesothermal vein-type Au deposits are ambiguous in their genetic relationships. Some specific supersuites (e.g. Boggy Plain) are associated with a range of deposits, while specific deposit types (e.g. Sn in the Wagga Tin Belt, Mo in the Bega Batholith), are associated with a number of granite suites of broadly similar character within discrete regions previously recognised as "granite basement terranes" by Chappell et al. (1988). Gold and base metal mineralisation is also associated with contemporaneous Silurian basins; however the (often presumed) syngenetic nature of many of these deposits remains in doubt (e.g. see Glen, 1995). The Carboniferous granites of the north east LFB are associated with Mo and Au mineralisation, consistent with their generally oxidised nature, and similar to their compositional equivalents (the Moonbi Supersuite) in the Southern New England Orogen (SNEO).

New England Orogen

Mid to Late Devonian magmatism in the NEO is widely distributed in the form of volcaniclastic sediments and related flows. The chemical composition of related intrusive rocks, such as the Mount Morgan Tonalite Complex, are oceanic in character and similar to the tonalitic intrusives of New Britain. Permian to Triassic I-type magmatism in the SNEO is related to Sn, W, Mo and minor Cu mineralisation. Mineralisation is mainly associated with the high-K Moonbi

Supersuite and other highly fractionated leucoadamellites. The central and northern portions of the NEO (CNEO and NNEO) were the sites of extensive plutonism in the Late Carboniferous to early Permian, and the early Triassic. These granites comprise typically low- to medium-K diorites, tonalites and granodiorites, with chemical and isotopic signatures indicative of continental margin and/or subduction affinity. While earlier magmatic-plutonic episodes in the CNEO and NNEO were probably subduction related, early Cretaceous magmatism was related to rifting and opening of the Tasman Sea (Ewart et al. 1992). All these magmatic stages are associated with numerous subeconomic porphyry style Cu-Mo-Au systems of the continental margin type.

The LFB and NEO compared.

The fold belts of south eastern Australia contain a range of granite compositions that may be grouped into three broad categories in terms of source: those produced directly from the mantle with or without contemporaneous subduction (e.g. Ordovician LFB magmatism); those derived dominantly from the fusion of older crust (e.g. Silurian-Devonian LFB magmatism); and those resulting from the reworking of juvenile crustal materials recently added to the crust, where fusion was associated temporally and spatially with active subduction or rifting process (e.g. magmatism in the NEO). There is a general correlation in the nature and style of mineral deposits and commodity associations with igneous rocks representing these categories, from Cu-Au porphyry styles with subduction-related and/or arc-like magmatism, through to lithophile dominated mineralisation associated with granites derived dominantly from older crustal materials. This is in part due to the degree of compositional evolution of the igneous source materials. Exceptions do occur however, for example, the presence of significant lithophile mineralisation (Sn, Mo, W) in the SNEO associated with granites derived from juvenile Palaeozoic source materials.

Contrasts in the magmatic and tectonic evolution of the NEO and LFB are profound. Notably, the NEO is much more easily accommodated into subduction and continental margin models than is the LFB. The igneous metallogeny of the LFB evolves with time, from Cu-Au through to lithophile dominated mineralisation during the Palaeozoic. In the NEO, lithophile (Sn, Mo, W) dominates in the SNEO while Cu-Mo-Au dominates in the CNEO and NNEO. There is a recurrence of these metallogenic patterns throughout time in both portions of the NEO.

Emplacement and Preservation Considerations

While the metallogenic scheme outlined above provides a useful conceptual framework for relating ore deposits back to igneous rocks and their sources, it cannot predict whether igneous suites may have generated mineralisation, and whether that mineralisation may have been preserved. A challenge for the future then is to give such schemes enhanced predictive capacity by assigning ore generative, and preservation potentials to granite suites and any related mineralisation. This will involve assessing the level of emplacement of the magma and the subsequent level of (tectonic) erosion that it has undergone.

The timing and efficiency of volatile saturation and extraction relative to the progress of crystallisation within granite plutons is very important (Candela & Holland, 1986). Most intrusive-related mineralisation is generated at shallow levels within the crust, particularly at epithermal to hypabyssal depths (1-5 km). Porphyry-type systems become less prominent below 4-6 km, with mineralisation styles comprising mainly skarns at greater depths (to 8-10 km). "Mesothermal" gold-quartz veins are problematical in their genetic relationships to contemporaneous magmatism, and typically form at depths of 4-15 km.

An unusual feature of the LFB is that the character of deposits through time does not correlate with their assumed preservation potentials. Ordovician volcanism in the LFB is shallow in nature, becoming subareal in the Late Ordovician. The associated porphyry style mineralisation is typical of subvolcanic porphyry style alteration and mineralisation elsewhere in the nature of its veining and infill, and relationship to shallow volcanism. Preservation of only mildly deformed Ordovician volcaniclastics requires that subsequent compression, uplift and erosion of the LFB, at least in central NSW, cannot have occurred evenly across the belt. The apparent time-space juxtaposition in the Silurian-Devonian of both volcanism and plutonism, and the apparent absence of subsequent crustal thickening and/or mountain building was accommodated into a "granite tectonics" model involving vertical crustal reworking driven by granite ascent in concert with basin formation (Blevin et al., 1997). However, problems remain with the dynamics of such models, and particularly evidence for diapirism.

Differential uplift of the order of only a few kilometres may be sufficient to alter the metallogenic character of a region. The S-type granites of the Wagga and Kosciusko Granite Basement Terranes are compositionally very similar at their mafic ends; however mineralisation is almost entirely restricted to small, high level stocks that are just being unroofed within the "Wagga Tin Belt". Preservation of these intrusives may be an artefact of differential uplift and exposure, with granites of the Kosciusko region perhaps representing more deeply eroded equivalents of those further inboard. In the Bega Batholith, low grade Mo mineralisation is associated with several granite suites. Determination of crystallisation depths in the weakly zoned Bemboka Pluton suggests that volatile exsolution occurred in these magmas at pressures too great to allow the efficient segregation of fluids and metals into large, high grade mineral deposits (Candela & Blevin 1995).

In the NNEO, emplacement levels of the magmas versus their current level of exposure may be important in understanding the nature of mineralisation within the region, particularly from a comparative metallogenic standpoint. For example, the Urannah Batholith is similar to the Sierra Nevada Batholith in terms of its gross compositional and petrographic character (Allen & Chappell, 1993). The two regions differ tectonically however, in that the Sierra Nevada have undergone significant uplift and erosion. Associated mineralisation in the Sierra Nevada is mostly skarn type (W, Mo, Cu) formed at intermediate crustal depths (Barton, 1996). Inboard of this region, similar age Cu mineralisation is dominantly porphyry style, and is associated with intrusive complexes exposed at considerably shallower erosional depths (0-4 km). Mineralisation in the NNEO includes a number of apparently metal-starved, porphyry-like Cu-Mo systems. Allen and Chappell (1993) have demonstrated from textural and Al-in-hornblende geobarometry data a lack of major uplift and erosion in the NNEO, in contrast to the Sierra Nevada.

Future Studies

In addition to developing better methodologies in assessing parameters such as volatile history and emplacement levels of magmas, and the preservation potential of related mineral deposits, more attention will need to be focussed on understanding the role of tectonics and crust/mantle processes in defining, or generating mineral provinces. This is being pursued petrologically by GEMOC through 4D lithospheric mapping utilising chemical and isotopic databases on granites, basalts and xenoliths. Such studies will help refine the petrological, temporal and spatial evolution of the crust/mantle system in south eastern Australia over time.

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The Eastern Boundary of the Melbourne Zone and the Northern Mount Howitt Province near Tatong, NE Victoria

Maxwell C Brown

151 Debenham St., Mawson, A.C.T. 2607

Tatong, about 160 km NNE of Melbourne, is close to the boundary between the Melbourne Zone of the Lachlan Orogen and the Tabberabbera Zone to the east. It is also close to the boundary between the northern part of the Melbourne Zone, characterised by E-W structural trends in early Palaeozoic rocks, and the central Melbourne Zone where N-S to NNW structural trends dominate.

Early Palaeozoic volcanic and sedimentary rocks of the Melbourne and Tabberabbera Zones are well-exposed near Tatong. They are overlain unconformably by Late Devonian to early Carboniferous acid volcanic and sedimentary rocks of the northern Mount Howitt Province. The Late Devonian Strathbogie Granite, south and west of Tatong, intrudes the Early Palaeozoic rocks and Late Devonian volcanics. Fig.1 shows outcrops of the main geological units, and also some previously-unpublished structural data. Mapped and inferred faults are shown by heavy lines, dotted where covered. Conventional dip and strike symbols are used for bedding in sedimentary rocks and bedded tuffs, and also for the planar preferred orientation of fiamme in ignimbrites and other planar flow structures in volcanic rocks.

The fault boundary between the Melbourne and Tabberabbera Zones is 2-3 km east of Tatong and trends NNW. It is covered by Cainozoic alluvium and Late Devonian rocks, but the fault zone can not be much more than 1 km wide. It separates folded Ordovician sandstones, shales, and cherts with NNW structural trends to the east, from Cambrian and Early Ordovician rocks with dominant E-W structural trends to the west. These latter rocks comprise Cambrian greenstones, including basalt and boninite lavas and tuffs, overlain conformably by Cambrian chert and cherty shale, in turn overlain conformably by a sandstone-siltstone-shale sequence with chert interbeds which is probably Early Ordovician. This sequence strikes E-W to NE-SW and dips north at 40 to 80 degrees. The E-W trend is overprinted locally by a minor NNW-plunging syncline. The section is repeated by a strike fault to produce two main outcrops of Cambrian rocks. The Cambrian and Early Ordovician rocks are uncleaved and, apart from albitisation of plagioclase in greenstones, are unmetamorphosed. Small scale cross bedding in sandstones and siltstones, and tiny inarticulate brachiopods in the cherty shales are perfectly preserved. Siluro-Devonian mudstones with E-W structural trends occur to the south west of the Cambrian outcrops, between Samaria and the Broken River.

The 15 km wide zone of intense deformation, the "Mount Wellington Fault Zone", which forms the eastern margin of the central Melbourne Zone, disappears around 30 km south of Tatong beneath the cover rocks of the northern Mount Howitt Province. This creates difficulties for previous interpretations of a substantial dextral shear component for the Mount Wellington Fault Zone in the Early Palaeozoic; and also for an interpretation that the structure of the Mount Howitt Province is the result of a later sinistral shear on the same fault zone.

The northern Melbourne zone appears to have acted as a "rigid block" following a north-south compression which produced the E-W trends, so that it resisted deformation during the E-W compression which produced the N-S folds and thrusts of the central Melbourne Zone. Sinistral shear due to differential strain between the northern and central parts of the Melbourne Zone may account for the prominent sigmoidal bends in fold axes in the north west of the central Melbourne Zone. E-W fracturing along the southern margin of the "rigid block" may have controlled the emplacement of the Strathbogie Granite, which has an E-W elongation.

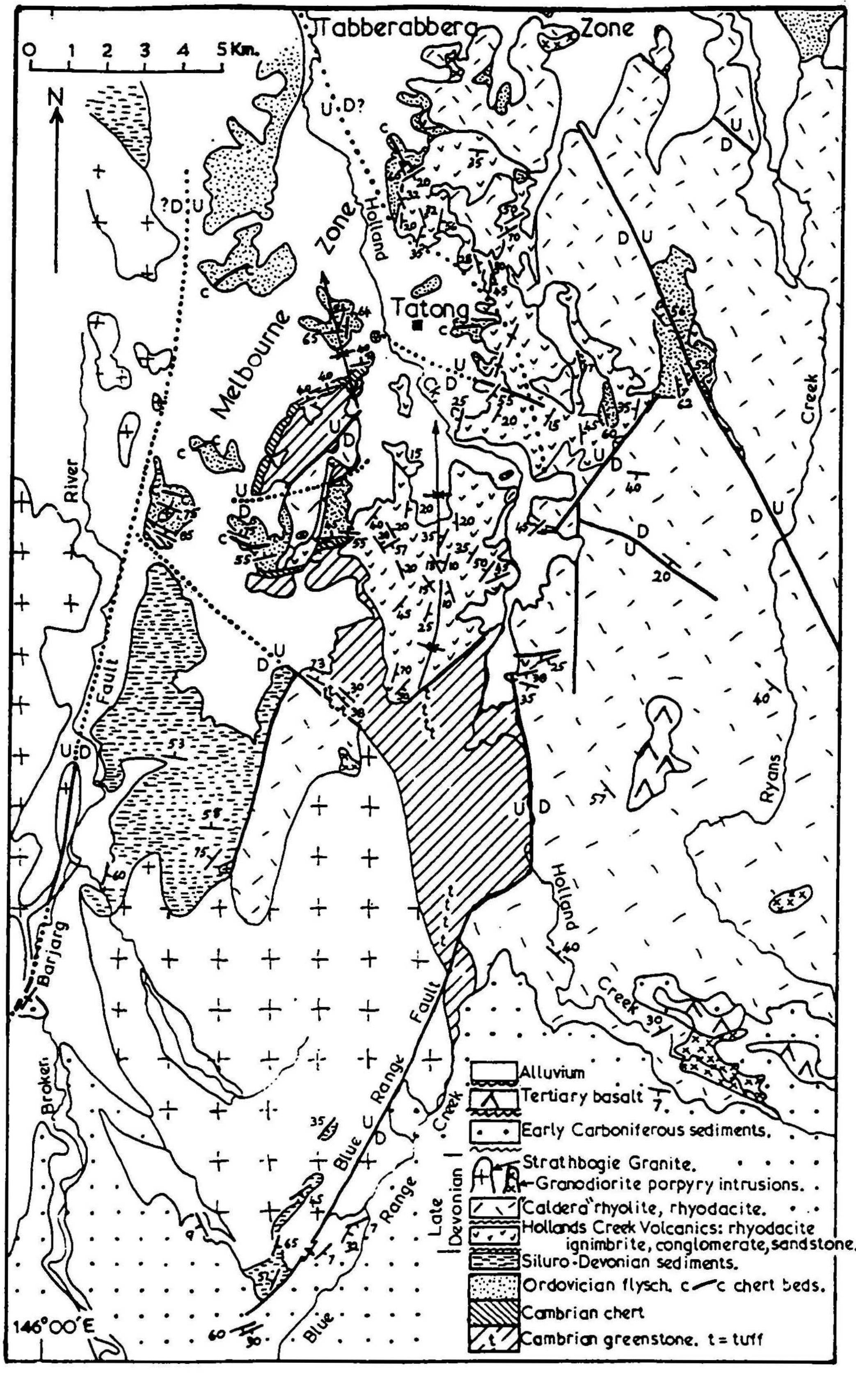

Fig.1 - Geology of the Tatong region, northeast Victoria.

The earliest acid volcanics and sediments of the northern Mount Howitt Province, the Hollands Creek Volcanics, are folded along N-S axes and are overlain unconformably by younger acid volcanics of the Tolmie Highlands Caldera Complex. The (?) Late Devonian to Early Carboniferous Mansfield Group sediments rest unconformably on these volcanics and the Strathbogie Granite. The final major displacements on the east and west boundary thrusts of the province occurred not earlier than Early Carboniferous. These relationships do not fit well with the concepts of a major mid-Devonian "Tabberabbera Orogeny" and a regional "Lambian Unconformity" truncating rocks deformed by the "orogeny". The oldest of the three "Lambian Unconformities" at the margins of the northern Mount Howitt Province could well be around 15 Ma older than the youngest.

The folding of the Hollands Creek Volcanics could be contemporaneous with folding of Late Devonian sediments and volcanics of the Jameison Syncline 50 km to the south - also folded along N-S axes. It could also be the same age as the folding along N-S axes of the early Devonian marine sediments of the Mitchell Syncline at Tabberabbera - the type locality of the "Tabberabbera Orogeny".

A WNW-ESE trending cleavage which occurs in much of the central Melbourne Zone can not be related to any documented folding or thrust faulting in the Melbourne Zone or the adjacent Tabberabbera Zone.

Overview of Tasmania's Tectonic Framework, Geological History and Mineralisation

A. V. Brown[1], D. B. Seymour[1], C. R. Calver[1], G. R. Green[1] & A. N. Yeates[2]

[1] Tasmanian Geological Survey, P O Box 56, Rosny Park, Tasmania., 7018
[2] Australian Geological Survey Organisation, GPO Box 378, Canberra ACT 2601.

Tasmania is divided into seven Proterozoic - early Palaeozoic stratotectonic fault-bounded elements with a younger, late Palaeozoic-early Mezozoic and Cainozoic cover (Fig. 1, Seymour & Calver 1995). They are: King Island; the Rocky Cape Element; the Dundas Element; the Sheffield Element; the Tyennan Element; the Adamsfield-Jubilee Element, the Northeast Tasmania Element, and the overlying Tasmania Basin and younger cover sequences.

The gross structure of Tasmania is evident from the Aeromagnetic Map of Tasmania (Fig. 2, Mackey et al., 1995). Each element has a geological history and internal structure differing in some respects from the others.

All elements are mineralised. Tasmania has a remarkable diversity and abundance of mineral deposits (Green, 1990; Collins & Williams, 1986), excellent mineral potential (Tasmanian Public Land Use Commission, 1996, maps S&E 5.3 and 5.4), and with its new mining Act and supportive infrastructure of towns, roads, ports and power, is an attractive place to invest in mineral exploration (Mining Journal, 1994).

This paper provides background information for an understanding of Tasmania's mineral systems. It gives an overview of the State's geological history and salient features of each element. The overview is based mainly on Seymour and Calver (1995), and the accompanying time-space diagram and 1:500,000-scale Stratotectonic Elements Map of Tasmania. These compilations were undertaken as part of the Tasmanian NGMA Project ("TASGO"). Tasmania's geology and tectonic history is also described in a time-stratigraphic format, by regions, in Burrett and Martin (1989), with some controversies being discussed in Cooke and Kitto (1995).

Overview of tectonic framework and geological history

Until the earliest Cambrian, most of what now constitutes Tasmania (with the apparent exception of the Northeast Tasmania Element) appears to have been a single entity.

Tasmania's oldest exposed rocks are Precambrian in age (Turner, 1989a) with poorly dated metamorphosed Mesoproterozoic and Early Neoproterozoic sequences being present in the western half of the State. Due, however, to the fact that Tasmania's crust appears to be 35km-thick (Drummond et al., in prep.), and the presence of inherited zircons in the oldest sequences (Black et al., 1997), older rocks may be also be present at depth.

Deformation with minor granitic emplacement, dated at between 777Ma and 750Ma, separate these oldest outcropping strata from widespread Neoproterozoic successions present in six elements. Neoproterozoic strata, which may possibly extend into the earliest Cambrian, have characteristic diamictite, dolomite, and basaltic units. Recent isotope chemostratigraphy of some carbonate beds has improved correlations (Calver, 1996) and some former continuity across several elements can now be confidently inferred.

In the latest Early Cambrian, there was substantial tectonism, metamorphism, terrane collision, and possibly emplacement of widespread serpentinitic successions as thrust sheets, over much of Tasmania (Berry & Crawford, 1988; Berry, 1995). Associated mafic/ultramafic complexes have minor accompanying orthomagmatic Os, Ir, Ni, Cu and Pt mineralisation (Brown, 1992) and stand out prominently as highs in aeromagnetic data (Fig. 2; Gunn et al., 1996). Succeeding sequences accumulated in short-lived troughs on the allochthons in the Dundas, Sheffield and Adamsfield-Jubilee Elements. Ultramafic rocks are also interpreted to be the floor of the Northeast Tasmania Element (Roach, 1994). Emplacement there may have occurred at the same time.

Rapid subsidence occurred during the Middle Cambrian in northwest and central Tasmania. This was followed by the initiation of felsic volcanism, and associated coarse clastic units, lavas, tuffs, associated volcanogenic mineralisation, including the Cu-Zn-Pb-Ag-Au-mineralised Mount Read Volcanics of the Dundas Element (Corbett, 1992; Large, 1992), granitic stocks and succeeding quartzose conglomerate successions. These successions all accumulated rapidly in the Dundas, Sheffield and Adamsfield-Jubilee Elements.

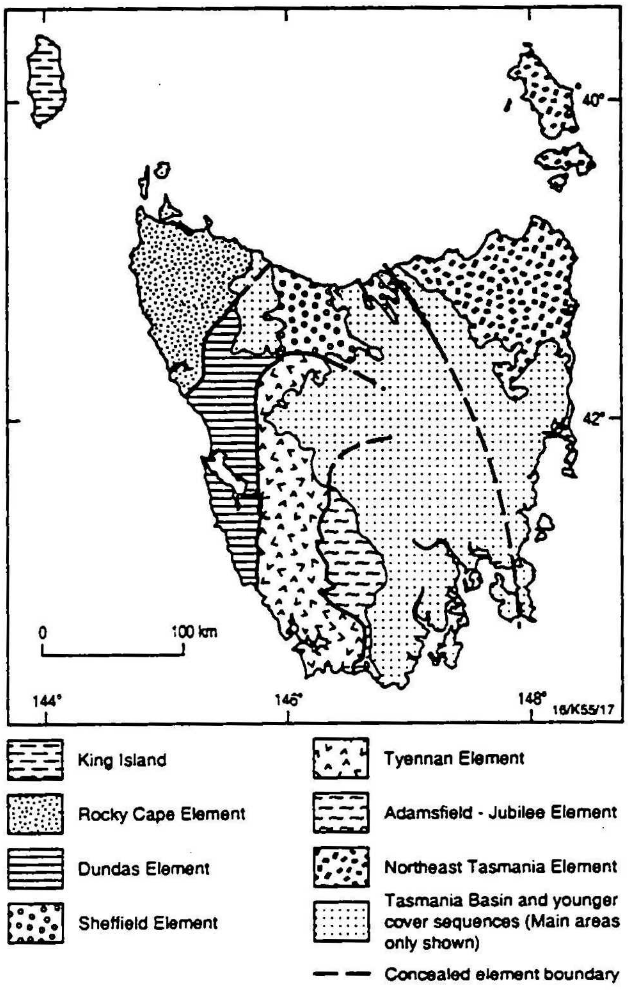

Fig. 1. Stratotectonic elements of Tasmania

In the latest Cambrian to Early Ordovician, major folding and reactivated faulting, correlated with the Delamerian Orogeny, occurred in western Tasmania. The Haulage Unconformity, near Queenstown, spans approximately 30My (Laurie, 1996) and is a well known expression of the orogeny, though its magnitude in time is variable, and its extent is not statewide. This unconformity also coincides with protracted heating detected by dating of alteration minerals in ore environments in west Tasmania (Perkins et al., 1995).

In contrast, during this time, deposition occurred in what is now eastern Tasmania. The earliest known strata, forming the Mathinna Group, are Ordovician, although Cambrian strata have been interpreted at depth (Leaman et al., 1973). While the Ordovician strata were accumulating in the Northeast Tasmania Element, platform sedimentation commenced in the Adamsfield-Jubilee Element, during the time that the Delamerian Orogeny was in progress in western Tasmania.

Following the Delamerian Orogeny, a central, shallow marine platform enlarged to cover much of northwestern and central Tasmania. Basal quartzose clastics were succeeded by limestone successions of the Gordon Group. There was a return to clastic deposition through Silurian and earliest Devonian times, and subsidence became more intermittent. In contrast, flysch deposits of the Mathinna Group accumulated uninterruptedly from Ordovician through to Early Devonian times in the Northeast Tasmania Element. Late in the Early Devonian, deposition ceased throughout Tasmania.

From the mid-Devonian, all of Tasmania (including the Northeast Tasmania Element) was once again a single entity. Major folding, cleavage development, heating to more than 300 degrees C (Burrett, 1992) metamorphism and associated thrusting occurred during multiple deformations. These are correlated with the Tabberabberan Orogeny (Williams, 1978). Its affects are observed statewide (Seymour & Calver, 1995).

In Late Devonian to Mississippi times, widespread granitic bodies intruded six elements (Williams et al., 1989). Many are the sources of, or hosts to, widespread tin mineralisation (Taylor, 1979). The mineralised granitic bodies have U-enrichment, and in the Northeast Tasmania Element, high U/Th ratios (Collins et al., 1981), and may be an upper crustal contribution to Tasmania's high heat flow (Green, 1989).

The sub-horizontal Pennsylvanian to Triassic Tasmania Basin, and its contained Jurassic dolerite intrusions, overlap element boundaries. So too do the Cretaceous-Cainozoic successions and Tertiary basalt flows with interflow sedimentary units.

Overview of element history

Event histories for each element, plotted against the AGSO Timescale (Young & Laurie, 1996) have been published by Seymour and Calver (1995).

King Island

Poorly dated, Mesoproterozoic, litho-feldspathic clastic units are the oldest rocks comprising this element. Cropping out in the western half of King Island, they were deformed and metamorphosed close to c.760-750Ma granitic emplacement. In latest Neoproterozoic time, these sequences were succeeded by fine clastic, diamictite, and dolomite units, and picritic and tholeiitic basaltic flows, which crop out in the eastern half of the island and which may have been formed in an intracratonic rift (Cox, 1989; Waldron & Brown, 1993).

The Tabberabberan Orogeny cannot be recognised with any certainty on King Island. It appears to be represented by a period of non-deposition. Tungsten-mineralised skarn is associated with the Grassy Granodiorite, which was emplaced during the Pennsylvanian (Kwak, 1978).

Boundaries of the King Island Element are offshore. Emplacement of ultramafic rocks and the Delamerian Orogeny, both notable early Palaeozoic events in the State's history, have not been detected on King Island.

Rocky Cape Element

A shelf facies of poorly dated Mesoproterozoic quartzose sandstone and fine clastic sequences, comprising the Rocky Cape Group, is the oldest rock succession in this element (Turner et al., 1992). Where unfaulted, the Group has a transitional contact into a northeast-trending high-strain metamorphic belt, the Arthur Lineament (Gee, 1967). The boundary is also a transitional contact with turbiditic wacke, mudstone and basalt of the Burnie and Oonah Formations to the east. Seismic data reveal the Arthur Lineament dips east in the southern part of the element (Drummond et al., 1996). Pillow basalts of the Bowry Formation within the Lineament, are hosts to substantial iron-ore deposits and some copper occurrences. Granitic stocks intruded the Lineament at 777Ma (Turner et al., in press).

The Rocky Cape Group is overlain by basal conglomerate beds succeeded by platformal, fine clastic, diamictite, and dolomite units with basalt flows of the Togari Group. These accumulated during late Neoproterozoic time in the Smithton Basin. The contact is a low-angle unconformity indicating a period of gentle warping prior to Togari Group deposition. The Ahberg Group, in the southern part of the Arthur Lineament, is thought to be equivalent to the Togari Group, and is important for its high-purity silica sand resources (Seymour & Calver, 1995).

The Rocky Cape Element is intruded by at least four geochemically distinct groups of dolerite dykes (Brown, 1989). The Togari and the Rocky Cape Groups were folded and metamorphosed in the latest Early Cambrian (Gee, 1967), the time of a major collisional event to the east. The Smithton Basin became a synclinorium and metamorphism occurred within the Arthur Lineament at this time.

Shelf conditions were re-established over the synclinorium later in the Cambrian when deposition of the Scopus Formation occurred (Seymour & Calver, 1995). Deformed vestiges of early to mid Palaeozoic post-orogenic sequences indicate the element was probably affected by the Delamerian Orogeny. Its affects though are difficult to distinguish from the mid-Devonian Tabberabberan Orogeny. Deformation was followed by intrusion of the tungsten-mineralised Pieman Granite and the tin-tungsten-mineralised Heemskirk Granite, in the Mississippian.

Dundas Element

The Oonah Formation, and equivalents in several inliers, form the oldest known successions. The Neoproterozoic Success Creek Group, consisting of basal diamictite, coarse and fine shelf clastic and minor carbonate and chert units, unconformably overlies the Oonah Formation (Brown 1986). The Success Creek Group is succeeded by an approximately 5km-thick succession of turbidite units with and numerous tholeiitic basalt lavas and sills, which constitute the late Neoproterozoic Crimson Creek Formation (Brown, 1986).

Neoproterozoic units are in tectonic contact with four suites of latest Early Cambrian mafic volcanics and associated rocks (Brown & Jenner, 1988) and three mafic-ultramafic rock associations (Brown, 1986). These Cambrian-aged associations are all considered to be allocthonous relics of a terrain which collided with, and were possibly thrust over, a passive continental margin from the east or north (Berry, 1995). Ultramafic rocks are strongly serpentinised and are hosts to some Os, Ir, Ru, Ni and Cr occurrences (Brown, 1992). Some serpentinitic bodies have shallow dips at depth (Drummond et al., 1996) and apparently form part of the floor for the succeeding Dundas Trough sequences, as some ultramafic detritus is present in overlying units.

In the Middle Cambrian, rapid subsidence allowed the formation of the short-lived, Dundas Trough, with felsic volcanism being initiated in the east of the Dundas Element. Coarse clastic beds of the Dundas and Tyndall Groups and their equivalents, with lavas, tuffs, and volcaniclastic sequences of the 250km-long belt of Mount Read Volcanics, all accumulated within a few million years (Black et al., 1997; Perkins et al., 1995).

The Mount Read Volcanics are mainly felsic and intermediate to acid in composition, with minor mafic lavas. They are also dominantly calc-alkaline (Corbett & Solomon, 1989; Corbett, 1992). The Henty Fault bisects them into two lithological and metallogenic segments (Green, 1990). Lavas of the Mount Read Volcanics are hosts to several high-grade Cu-Zn-Pb-Ag-Au volcanogenic deposits, with high precious metal contents by world standards (Large, 1992). The new Henty deposit is especially gold-rich (Halley & Roberts, 1997). Co-magmatic granitic stocks intrude the Mount Read Volcanics and may be the source of Cu-Au mineralisation south of the Henty Fault (Large et al., 1995).

By the latest Late Cambrian volcanism had ceased. Coarse quartzose clastic detritus, eroded from the Tyennan Element, was deposited in alluvial fans and shallow shelf and slope environments to form the approximately 1km-thick Owen Group and equivalents. These were deposited until onset of the Delamerian Orogeny in the latest Cambrian. Sedimentation resumed in Middle Ordovician times when the element had become a shallow marine platform. Limestone sequences of the Gordon Group were then deposited throughout the remainder of the Ordovician. They were succeeded by fine clastic successions of the Eldon Group until the earliest Devonian (Banks & Baillie, 1989). Stratabound Mississippi Valley-type Pb-Zn-Ag mineralisation occurs in Eldon Group limestone around Zeehan in west Tasmania (Taylor & Mathison, 1990).

This element experienced multiple deformations during the Tabberabberan Orogeny, in the Middle Devonian. Folding, thrusting and reactivation of faulting, heating and cleavage development overprinted the deformation of the Delamerian Orogeny (Berry, 1989; 1995; Green, 1990). Granitic emplacement followed. Notable associated tin mineralisation occurs in contact metamorphic skarns at Renison (Morland, 1990) and as Pb-Zn-(Ag-Sn) vein and stockwork deposits spatially associated with the Meredith, Heemskirk and Pine Hill Granite bodies. These granitic bodies are interpreted to be more extensive at depth (Leaman & Richardson, 1989). Tin-mineralised quartz porphyry dykes also formed at Mt Bischoff (Collins & Williams, 1986).

Sheffield Element

Inliers of pelitic, quartzitic and amphibolitic units, the protoliths of which are of suspected Mesoproterozoic age, comprise the Ulverstone and Forth Metamorphics, the oldest successions of the Sheffield Element. Contacts are thrust-faulted against younger successions (Elliott et al., 1993; Gray & Woodward, 1995). The younger Burnie Formation was intruded by the Cooee Dolerite (c.725Ma) while the sedimentary rocks were unconsolidated (Crook, 1979).

Metamorphism and deformation occurred during the late Early Cambrian. Slivers of (?) Early Cambrian Motton Spilite, Barrington Chert and ultramafic rocks were thrust onto the Sheffield Element during widespread, late Early Cambrian terrane collision. The sequences are all considered to be allochthonous (Seymour & Calver, 1995).

In the Middle Cambrian, two troughs formed: the Dial Range Trough, oriented north-south between the Forth Massif and Burnie Formation outcrops; and the east-west trending Fossey Mountains Trough, adjacent to the Tyennan Element. Rapid subsidence occurred and felsic volcanism was initiated.

Megabreccia units, and quartz and lithic wacke sequences of the Cateena and Radford Creek Groups, with associated felsic lavas, accumulated in the Dial Range Trough. The felsic Lobster Creek Porphyry mass was emplaced at this time (Seymour & Calver, 1995).

Equivalent successions in the Fossey Mountains Trough are not so well known, but include felsic, intermediate and mafic lavas. The Winterbrook lava and Minnow Keratophyre are local marker units, but they are slightly younger than the Mount Read Volcanics lavas in the Dundas Element (Black et al., 1997).

After a short break, the quartzose Roland Conglomerate, derived from the Tyennan Element, was deposited unconformably over the Sheffield Element, in the latest Cambrian. At this time the Beulah Granitic stock was also emplaced. This deposition and magmatism overlaps the onset of the Delamerian Orogeny in the Dundas Element. In the Sheffield Element, this orogeny is expressed as a period of non-deposition in the earliest Ordovician, by faulted rock relationships and west-trending folds in the Fossey Mountains Trough, the Beulah Granite emplacement (dated at 493.5Ma by Black et al., 1997), and by unconformable contacts with succeeding strata.

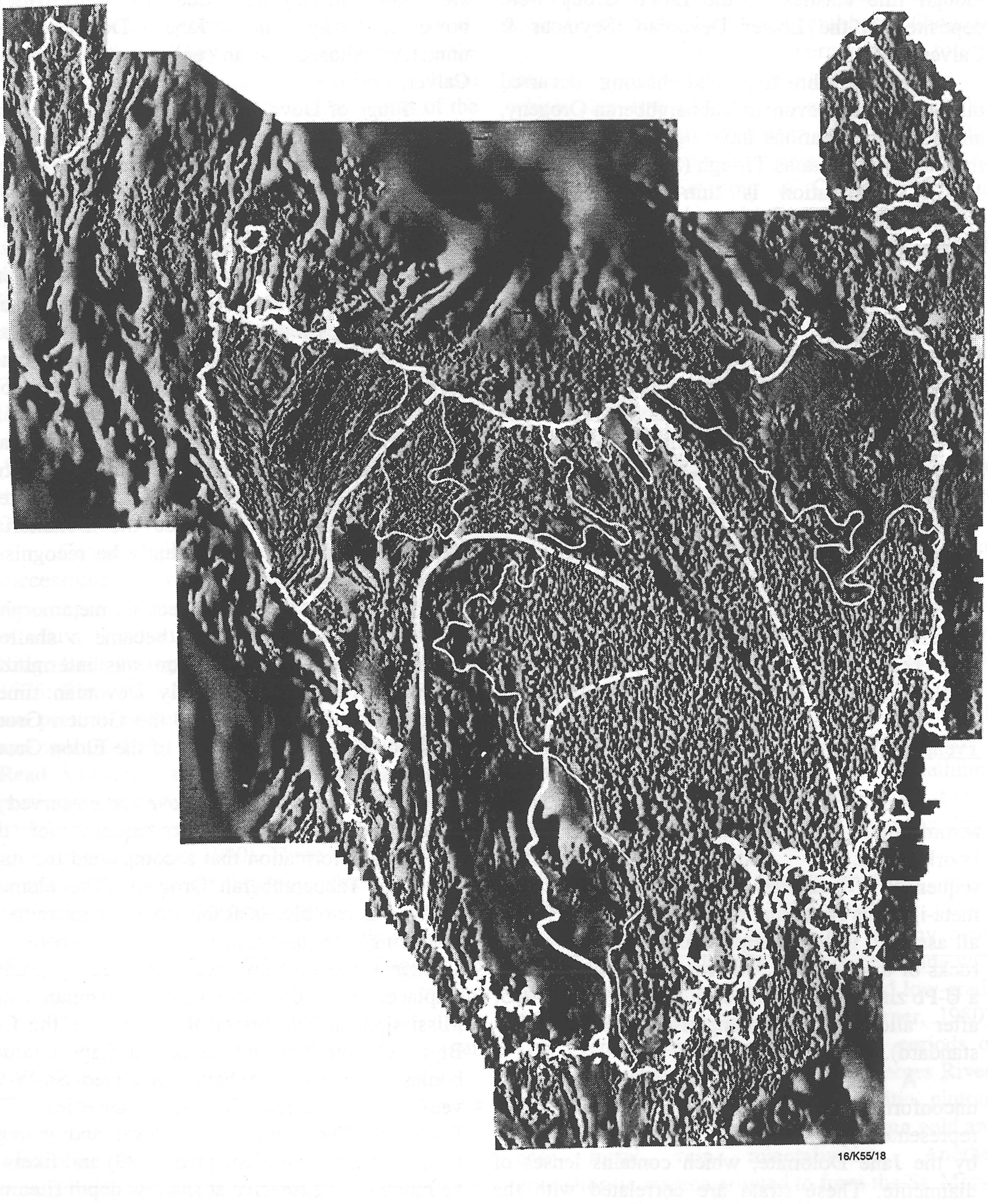

Fig. 2. Greyscale aeromagnetic image of Tasmania and surrounds (Mackey et al., 1995)

Deposition resumed locally in the Early Ordovician with clastic units (Caroline Creek and Moina Sandstones) accumulating. By mid-Ordovician times, platform conditions were re-established and Gordon Group limestone was deposited during the remainder of Ordovician time (Banks & Baillie, 1989). The Silurian is very largely represented by an hiatus in this element, though fine clastics of the Eldon Group were deposited in the Lower Devonian (Seymour & Calver, 1995).

Folding, thrusting and heating occurred during the mid-Devonian Tabberabberan Orogeny, and four deformations have been documented in the Fossey Mountains Trough (Seymour & Calver, 1995). Deformation is thin-skinned in style (Woodward et al., 1993). A minimum age for deformation is constrained by undisturbed karst deposits - the Eugenana beds - containing spores of late Givetian age (Balme, 1960) in Gordon Group limestone.

Deformation was followed by emplacement of the Housetop and Dolcoath granitic bodies in the Late Devonian with both having associated mineralisation (Collins & Williams, 1986). The Housetop Granite may be the source of tungsten skarn-mineralisation and minor Pb-Zn-Ag and Cu vein deposits at Kara Mine. The Dolcoath Granite also has tin-tungsten skarn and vein mineralisation. A significant gold-bearing quartz vein is present near Beaconsfield in the east of the element. Its genesis is uncertain but mobilisation of fluids may have been facilitated by orogeny and granitic emplacement (Green, 1990).

Tyennan Element

The Tyennan Element is conspicuous on aeromagnetic data as a regional low (Fig. 2). Poorly-dated, extensively-metamorphosed, sequences of quartzite, chloritic slate, with minor meta-igneous rocks and rare protoliths of eclogite, all assumed to be Mesoproterozoic, are the oldest rocks of the element. The resultant eclogite gives a U-Pb zircon age of c.510Ma (Turner et al., 1995, after allowing for comparison with a new standard).

A Neoproterozoic succession, apparently unconformably overlies the basal succession. It is represented by basal conglomerate units followed by the Jane Dolomite, which contains lenses of diamictite. These strata are correlated with the Success Creek Group in the Dundas Element (Seymour & Calver, 1995).

U-Pb zircon dating (Turner et al., 1995; Black et al., 1997) reveal that polyphase deformation metamorphism and thrusting occurred in the Cambrian, commencing during terrane collision and continuing whilst the Mount Read Volcanics were being erupted in the Dundas Element to the east. Previous dating of mica indicated older ages. The metamorphic complexes are now interlayered, due to deformation, however, why the Jane Dolomite is unmetamorphosed is an enigma (Seymour & Calver, 1995).

Plugs of Dove Granite were emplaced, and post-orogenic clastic sedimentary rocks of the Sticht Range Formation were deposited, during latest Early Cambrian times in the west of the element, whilst deformation was occurring elsewhere (Seymour & Calver, 1995).

This element lacks equivalent sequences to the Dundas, Dial Range and Fossey Mountains Trough successions. The Middle and Upper Cambrian appear to have been a non-depositional period in the Tyennan Element. Considerable uplift then occurred during polyphase deformation as the Tyennan Element provided a source for vast amounts of coarse quartzose clastic detritus deposited in neighbouring elements in the latest Cambrian. The uplift predates the Delamerian Orogeny which cannot confidently be recognised in the Tyennan Element.

Following the major tectono-metamorphic event, the Tyennan Element became a shallow marine platform. Sedimentation was intermittent between Ordovician and Early Devonian times. Limestone units equivalent to the Gordon Group are succeeded by clastic rocks of the Eldon Group (Banks & Baillie, 1989).

The strata described above are preserved in fault-bounded outliers, a consequence of the polyphase deformation that accompanied the mid-Devonian Tabberabberan Orogeny. The element behaved as two blocks at this time, the movements producing mega-kinking. As elsewhere in Tasmania, the orogeny was followed by granite emplacement in the Late Devonian and Mississippian. The principal masses are the Cox Bight, Granite Tor and Southwest Cape Granitic bodies. The first two have associated Sn-W-Cu vein mineralisation in their aureoles. The Southwest Cape Granite is coarser and younger than the others (McClenaghan, 1989) and likely to be much more extensive at shallow depth (Leaman & Richardson, 1989).

Adamsfield-Jubilee Element

The exposed portion of the Adamsfield-Jubilee Element is in central southwestern Tasmania (Fig. 1) but its extent is possibly greater beneath the cover of Tasmania Basin to the east (Leaman, 1990).

Poorly dated, fine clastic rocks, with quartzite and dolomite units of the Clark Group, are the oldest rocks and assumed to be Mesoproterozoic. They were gently warped in the Neoproterozoic prior to deposition of basal conglomerate, diamictite and dolomite units of the shallow marine Weld River Group, which were deposited in late Neoproterozoic time (Calver, 1989).

The strata were deformed into upright and overturned folds, cleaved and metamorphosed in the Early Cambrian, prior to the widespread late Early Cambrian collision event. As in other areas, ultramafic rocks were thrust into the region, along with allochthonous blocks of the Ragged Basin Complex, during the collision event. The Ragged Basin Complex consists of lithic sandstones, chert, red mudstone and minor mafic lavas and intrusives (Turner, 1989b). Serpentinised ultramafic rocks in the element have been mined for orthomagmatic Os and Ir (Brown 1992).

Coarse siliceous clastic and wacke successions, derived from the Tyennan Element, were deposited unconformably on older sequences as alluvial and submarine fans to form the Trial Ridge Beds during the Middle Cambrian (Corbett, 1975; Brown et al., 1989). Ultramafic rock clasts are present as detritus in this succession. Lavas and volcaniclastic rocks, equivalent to the Mount Read Volcanics are not known in the exposed portion of the Adamsfield-Jubilee Element, but have been interpreted beneath shallow cover strata to the east (Leaman, 1990). These strata were later warped with low-angle thrusting, which caused the Proterozoic and Cambrian strata to become interleaved, in a short space of time, before deposition of the Wurawina Supergroup equivalents which commenced in Late Cambrian time (Banks & Williams, 1986). This movement appears to predate the onset of the Delamerian Orogeny in western Tasmania.

Coarse clastics of the Denison Group were deposited unconformably on older rocks over an undulating surface. Conglomerates near Adamsfield contain palaeo-placer deposits of Os (Ford, 1981). Sedimentation was continuous into the Ordovician, with the formation of shale units, indicating that the Delamerian Orogeny did not affect this element. The shale units were an Early Ordovician prelude to eventual shallow marine platform sedimentation and Gordon Group limestone deposition which continued into the Late Ordovician.

Clastic sedimentation (Tiger Range Group, equivalent to the Eldon Group) resumed throughout Silurian to Early Devonian times, until close to the onset of the Tabberabberan Orogeny when the entire Wurawina Supergroup was folded into a synclinorium and cleaved. The deformation, which also tightened structures in older rocks, does not appear to have been as intense in this element when compared to other parts of Tasmania (Burrett, 1992; Seymour & Calver, 1995). In contrast to all other elements, the Adamsfield-Jubilee Element lacks granitic bodies in its exposed portion.

Northeastern Tasmania Element

Proterozoic rocks are unknown in the Northeast Tasmania Element, which includes Flinders Island (Fig. 1). Contacts with elements to the west are not exposed but considerable lithological and structural differences imply a major break.

Aeromagnetic and gravity data have been interpreted to suggest that the Mathinna Group lies on a basement which may include sheets of ultramafic rocks emplaced on deep, shallow-dipping thrusts (Roach, 1994; Gunn et al., 1996) perhaps during the widespread late Early Cambrian collisional event. This is consistent with a model of Keele et al. (1995). Sparsely fossiliferous flyschoid sediments of the Mathinna Group were deposited in the element from at least Early Ordovician through to Early Devonian times (Powell et al., 1993).

The first of two folding episodes, which deformed the Mathinna Beds, occurred in the latest Early Devonian, earlier than in any other part of Tasmania. Upright and inclined folds with axial plane cleavage were produced and low-grade regional metamorphism occurred (Turner, 1980). This event preceded the first of two periods of felsic magmatism during which the Georges River, Mount Pearson and other granodioritic plutons were emplaced. They have accompanying gold and base metal vein mineralisation. Another granodioritic magma erupted to form the St. Marys Porphyrite (Turner et al., 1986).

The second folding episode occurred during the Tabberabberan Orogeny, but compared to western Tasmania, it was not as intense in the Northeast Tasmania Element. The St. Marys Porphyrite was warped and some low-angle thrusting occurred (Seymour & Calver, 1995).

Gold-bearing quartz veins are widespread in the Mathinna Group, especially along a line of gold deposits that runs NNW through Mathinna and which lies between the Scottsdale and Blue Tier Batholiths (Keele, 1995). Source fluids of deep-seated metamorphic origin have been implied (Taheri & Bottrill, 1994).

Granitic emplacement followed in the late Middle and Upper Devonian (McClenaghan et al., 1982). Geobarometric data from hornblendes suggest that markedly different crustal levels are now exposed across the Northeast Tasmania Element (Varne & Fulton, 1995).

The composite Blue Tier Batholith contains early granodioritic bodies and younger biotite adamellite intruded by alkali granite (Groves et al., 1977; McClenaghan, 1985). The alkali granites are the sources of widespread tin-tungsten mineralisation in greisen and veins (Collins & Williams, 1986). The mineralised granitic rocks of the Blue Tier Batholith have U-enrichment and high U-Th ratios (Collins et al., 1981).

The composite Scottsdale Batholith is another large mass, with minor molybdenite-bearing pink alkali granite on its eastern side (McClenaghan et al., 1982). Geophysical data suggest all granitic rocks in the Northeast Tasmania Element may be part of a more extensive north-south trending mass in the subsurface of east Tasmania (Leaman & Richardson, 1992; Gunn et al., 1996).

Dolerite dykes intrude all major granitic bodies within this element and are thought to overlap in age with felsic dykes genetically related to granite emplacement (McClenaghan, 1985). Mega-kinking is present in the element. It postdates granitic emplacement, predates the formation of the Tasmania Basin and has been correlated with Mississippian mega-kinking in the Lachlan Fold Belt (Powell et al., 1985; Goscombe et al., 1994).

Cover sequences

Sub-horizontal Parmeener Supergroup strata were deposited in the Tasmania Basin from Pennsylvanian to Late Triassic times (Clarke & Forsyth, 1989). They unconformably overlie the older rocks and overlap element boundaries. Present basin limits are erosional.

A succession similar to other Gondwanan sequences commenced with glacigenic and glacio-marine deposits. Provincialism due to the cold climate makes biostratigraphic subdivision difficult, and a local scheme has been developed by Clarke and Farmer (1976). Conditions remained mostly marine and cold, until fluvial sands and coal measures were deposited in the Sakmarian. A widespread disconformity separates these strata from overlying paralic deposits, after which the terrestrial Late Permian to Triassic Upper Parmeener Supergroup was deposited. There was local volcanism in the Triassic. Coal measures are abundant in strata of latest Permian and earliest Late Triassic age (Bacon, 1991).

Large sheets of tholeiitic dolerite intruded the Tasmania Basin in the Middle Jurassic. Sills are typically up to 500m thick. At Lune River in southern Tasmania, magma erupted as basalt into a graben containing sedimentary rocks with plant fossils of probable Jurassic age (Hergt et al., 1989).

A vast extensional regime was initiated in eastern Australia during the Late Jurassic (Symonds et al., 1996). There is general agreement that the uppermost dolerites have been unroofed. Latest Jurassic and Early Cretaceous strata are present in the offshore Sorell (Hill et al., 1997) and Bass Basins (Williamson et al., 1987) but not onshore. However, a younger cover of Late Jurassic to Early Cretaceous strata, is now suspected of having extended over Tasmania. Apatite fission track data have been interpreted to reveal rapid cooling between 110 and 90Ma (mid-Cretaceous) implying prior burial of present-day surface rocks to at least 2.5km but possibly up to 4km, then uplift and erosion at the time of extension in the Tasman Sea (O'Sullivan & Kohn, 1997).

This burial may have brought parts of the Tasmanian Basin, in which a good source rock is known, into the oil window (Boreham, 1996). The now-vanished highland cover may have provided a source for deposits found in the offshore Sorell and Bass Basins. Both are prospective for petroleum, but under explored.

A second episode of rapid cooling at 60-50Ma (Palaeocene to early Eocene) has been detected along the east and west coasts (O'Sullivan & Kohn, 1997). Rifting between Antarctica and Australia (Veevers & Ettreim, 1988) would explain the west coast findings.

Northeast Tasmania is a site of present-day high heat flow (O'Sullivan & Kohn, 1997). Vestiges of Late Cretaceous and Cainozoic offshore basin sequences are also preserved in graben onshore (Baillie, 1989). Widespread basaltic flows, ranging from Palaeocene to Miocene age, occur throughout much of Tasmania (Sutherland & Wellman, 1986) similar to elsewhere in eastern Australia.

Surficial Quaternary sediments are also widespread and include glaciogenic, slope, coastal, aeolian, fluvial and cave deposits. Placer Sn and Au deposits occur in northeast Tasmania and some Os and Cr is concentrated in modern sediments of west Tasmania (Colhoun, 1989).

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The Metallogeny of the Broken Hill and Euriowie Blocks, New South Wales

Gary Burton

Geological Survey of New South Wales

This discussion is concerned with the characteristics and origins of mineralisation within the Willyama Supergroup in New South Wales, the bulk of which outcrops as two inliers - the Broken Hill and Euriowie Blocks.

The Willyama Supergroup comprises regionally metamorphosed sediments, volcanics and intrusives of early Proterozoic age. Interpretations of the geological history of the sequence vary. Probably the most popular model is that the rocks were deposited within an intracratonic rift environment around 1690 Ma with prograde metamorphism and deformation having occurred at about 1600 Ma. Prograde metamorphism has ranged from greenschist to granulite facies with significant partial melting. Retrograde shearing of the Willyama Supergroup followed prograde metamorphism in probably more than one event. The last major deformation event to affect the area was the Delamerian Orogeny, around 520 Ma, causing reactivation of shear zones in the Willyama Supergroup and folding of the overlying Adelaidean sequence.

There are many types of mineralisation within the Willyama Supergroup, ranging from stratiform, stratabound, vein-type and intrusive related. They encompass a wide variety of both metallic and non-metallic commodities.

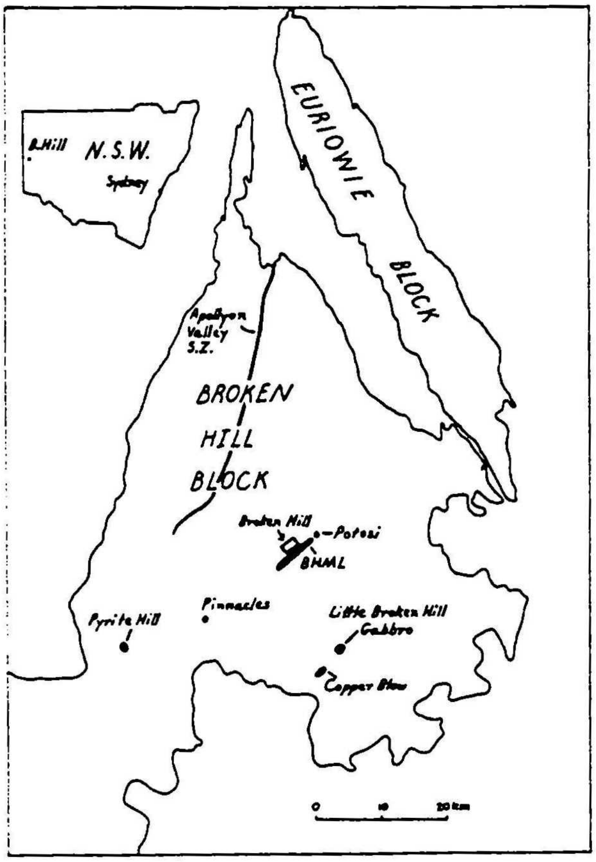

Fig. 1 - Broken Hill and Euriowie Blocks with locations of places referred to in the text.

Stratiform Mineralisation

Broken Hill Type

It must be emphasised that the Broken Hill Main Lode (BHML) is not the only deposit of this type within the Willyama Supergroup. There are several hundred small deposits of this type throughout the area but the BHML has several unique features (which will be discussed below).

The main primary ore minerals in Broken Hill type deposits are galena (commonly argentiferous) and sphalerite (commonly iron rich). Minor ore minerals include chalcopyrite, pyrrhotite, arsenopyrite and loellingite. Mineralisation occurs, commonly as shoots or pods, within "lode horizons" comprising various combinations of blue (or lodey) quartz-garnet (spessartine) rock, quartz-gahnite (zinc-spinel) rock, garnet-rich rock ("garnet sandstone") and green (plumbian) feldspar. The lode horizons are commonly up to several metres wide and tens or even hundreds of metres long. The immediate host rocks are generally pelitic/psammopelitic metasediments but the lodes occur within sequences comprising metasediment with quartzo-feldspathic gneiss (quartz + feldspar + biotite +/- garnet gneiss, including "Potosi" type gneiss), amphibolite, banded iron formation (comprising laminated quartz + magnetite + garnet + apatite) and calc-silicate rock. These sequences are diagnostic of the Broken Hill Group. The Pinnacles deposit is the only exception to this rule, occurring within a sequence interpreted as Thackaringa Group, stratigraphically below the Broken Hill Group.

Most Broken Hill type deposits within the Willyama Supergroup have produced no more than several thousand tonnes of ore. The larger deposits are the BHML with an estimated pre-mining tonnage of mineralised rock of 300 Mt, the Potosi with about 2 Mt, and the Pinnacles with about 1 Mt or less.

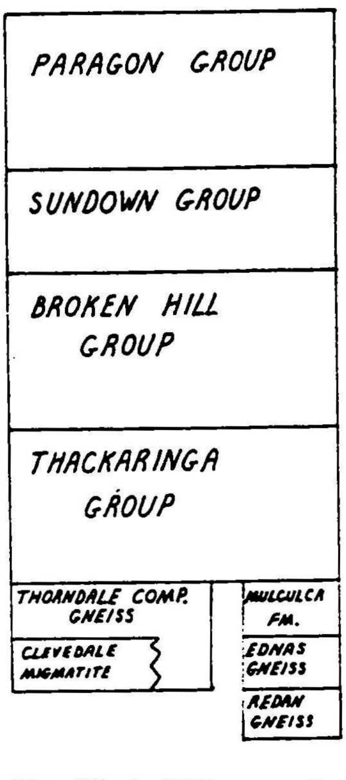

Fig. 2 - Simplified Willyama Supergroup stratigraphy.

The BHML is obviously the most outstanding deposit of this type in the Willyama Supergroup but it is different from the others not only in size but in its composition and structure. The deposit has a strike length of about 8 km and it is composed of at least six separate lenses, some of which have been subdivided, each with their own distinct chemistry and mineralogy. Minerals common in the BHML, but noticeably lacking from all other Broken Hill type occurrences, include Ca-bearing, Mn-bearing, F-bearing and P-bearing minerals such as rhodonite, bustamite, hedenbergite, wollastonite, calcite, fluorite and apatite. These minerals tend to form within the middle of the lenses in which they are found. The peripheries of the ore lenses tend to comprise the more usual combinations of quartz, garnet and gahnite.

Any model proposed to explain the origin of Broken Hill type mineralisation within the Willyama Supergroup must account for 1) the strong stratigraphic control and conformity with the host rocks; 2) the stratiform/tabular shapes of the lode horizons; 3) the systems of stacked lenses, each with their own chemistry, as in the BHML, Pinnacles and Potosi mines; 4) the fact that the textures of both sulphides and gangue indicate that they have undergone prograde metamorphism and that the BHML orebodies (and some other deposits) have been folded and sulphides have been remobilised during deformation and prograde metamorphism (e.g. droppers). The syngenetic exhalative model is favoured as it can account for these characteristics. In addition, the strong association of the mineralisation with a rock sequence containing what are probably metamorphosed volcanics, particularly the Potosi gneiss, gives a favourable comparison with more recent exhalative deposits. Sulphur and lead isotope studies of both the BHML and Pinnacles orebodies suggest deep crustal sources for both elements while REE patterns in garnets and gahnite at the Pinnacles mine have been interpreted as having a hydrothermal exhalative signature. Perhaps the BHML has resulted from the tapping of a deep crustal source by major faults which were active during rifting. The recent seismic cross-section reveals faults which extend down to the middle and lower crust and these may have been active since, or even before, deposition of the Willyama Supergroup. However, there is no evidence linking all of the ore lenses of the BHML with a pre-deformation shear zone.

Calc-Silicate Mineralisation

This type of mineralisation comprises galena (+Ag), sphalerite, chalcopyrite, pyrite and scheelite within calc-silicate rocks. The calc-silicates comprise quartz, grossular-andradite garnet, epidote and amphibole, with lesser calcite, wollastonite, idocrase and diopside. There are two types 1) Ettlewood: a well laminated type, occurring within metasediments, which may be a metamorphosed limestone; 2) Corruga: a mottled to laminated type, strongly associated with amphibolites and quartzo-feldspathic gneiss (Potosi), which may represent either syngenetic hydrothermal mineralisation or a kind of sea floor alteration of volcanics/volcaniclastics. Both types are confined to the Broken Hill Group, stratigraphically equivalent to Broken Hill type mineralisation. Some Corruga types have associated quartz-gahnite rock and/or quartz-magnetite rock, indicating compositional overlap with both Broken Hill type and iron formation type mineralisation. Lead isotope ratios of galena from Corruga types are virtually identical to isotope ratios of galena in Broken Hill types.

Iron Formation Type Deposits

There are two types of iron formation – 1) quartz-magnetite dominated, and 2) quartz-iron sulphide (pyrite, pyrrhotite) dominated. Commodities associated with both these types include copper and gold (in chalcopyrite), with Pb and Ag (in galena) and Zn (sphalerite), and small amounts of Co and Ni. Some have associated garnet (almandine), minor gahnite and tourmaline. The iron formations are generally several metres wide and several tens to hundreds of metres long with some being several kilometres long.

The immediate host rock to the iron formations is commonly metasediment or composite gneiss but the sequences in which they occur also include amphibolite, quartz-albite rock, quartzo-feldspathic gneisses and minor calc-silicate rocks. The host sequences have mainly been interpreted as being in the Thackaringa Group with some representing Thorndale Composite Gneiss and the Mulculca Formation, all stratigraphically below the Broken Hill Group. Indeed, Broken Hill type and iron formation type deposits are essentially mutually exclusive, though the Pinnacles deposit may provide a link, being associated with quartz-albite rock and quartz-magnetite rock.

The Copper Blow deposit is a unique form of iron formation deposit within the Broken Hill area and has been the most productive. It comprises several lenses, each several metres wide and several hundred metres long, of laminated quartz + magnetite + pyrite +/- pyrrhotite +/- chalcopyrite and gold. The system extends over four kilometres. Typical grades are several percent Cu and between 0.5 and 1.0 ppm Au. The immediate wallrocks are rich in biotite/chlorite and magnetite. It is very similar to the Selwyn Cu-Au deposit in the Mount Isa area and models explaining the origin of that deposit may be applicable to Copper Blow i.e. either syngenetic ironstone and Cu-Au mineralisation, or syngenetic ironstone but epigenetic mineralisation, or epigenetic ironstone and mineralisation.

Cobaltian Pyrite in Quartz-Albite Rock

This type comprises disseminated and massive pyrite pods within fine to coarse-grained quartz+albite rock. One occurrence, Pyrite Hill, has an estimated tonnage of up to 30 Mt with an average of about 0.1% Co. Quartz-albite rocks are generally interpreted as metamorphosed sediments or volcanics/volcaniclastics which were deposited within a saline lake / sabkha environment and enriched in sodium. The pyrite could be exhalative or was possibly precipitated by an organic process. This style of mineralisation is confined to the Thackaringa Group and may be related to iron formation types.

Stratabound Mineralisation

In this type the mineralisation is locally discordant to the host rocks but is confined to particular stratigraphic units. These bodies are interpreted as representing metamorphically remobilised stratiform mineralisation. Stratabound deposits include Pb, Zn, Ag, Cu, Au, W in quartz associated with amphibolites, and wolframite + scheelite-bearing pegmatites, both types being restricted to the Broken Hill Group. It is possible that the latter type may actually be intrusive and associated with tin-bearing pegmatites which occur adjacent to them. A third type comprises Au + Cu in pyritic quartz veins within migmatite which forms part of the Thackaringa Group.

Vein Type Mineralisation

Vein type mineralisation postdates high grade metamorphism in the Willyama Supergroup and occurs within or adjacent to retrograde schist zones. There are several different types and there have been several periods of vein formation. Veins are commonly around 1 m wide and several metres to tens of metres long though some systems of veins are hundreds of metres long.

Crustiform quartz + siderite veins with galena (+Ag), sphalerite and/or chalcopyrite (Thackaringa and Oakdale types) and crustiform pyritic quartz veins +/- Au are undeformed and are generally discordant to the steeply dipping retrograde foliation of the host rock, dipping at low to moderate angles. Their textures indicate that they are probably tension gash fills. It is considered that these veins formed during a dip-slip movement on the shear zones and this may have been synchronous with the Delamerian Orogeny.

Copper(+/-gold)-bearing quartz veins comprise quartz +/- minor calcite, with patchy to disseminated chalcopyrite and pyrite. They are massive, commonly sheared and deformed and in places contain relict vugs. They commonly dip vertically, being parallel to the retrograde foliation or discordant to it in plan view. These veins may have formed either early in the Delamerian Orogeny or during an earlier shearing event. It is possible, but highly speculative, that they were emplaced during dominant strike-slip movement on the shear zones.

The clustering of veins indicates that their host shear zones have tapped particular source areas, either within the Willyama Supergroup or deeper. The source of the metals and sulphur in the veins is not clear. One suggestion is that both were leached from the Willyama Supergroup, possibly from pre-existing mineralisation, by circulating cells of meteoric water or seawater. However, it is possible, that some metals were derived from deep crustal sources and interacted with shallow crustal fluids. For example, the Apollyon Valley Schist Zone contains numerous quartz-siderite veins with Ag, Pb, Zn mineralisation. The recent seismic cross-section indicates that this structure extends at least into the middle to lower crust, implying that it is possible that the mineralisation has a deep source. Lead isotope ratios from quartz-siderite veins do not rule out a deep crustal source for their Pb.

Intrusive-Related Mineralisation

Tin-Bearing Pegmatites

These pegmatites comprise quartz-green muscovite-albite and K-feldspar with patchy disseminations of cassiterite. Minor minerals present include tourmaline, apatite, fluorite, amblygonite and beryl. They are commonly one metre or so wide and several metres to hundreds of metres long, but mineralisation is very localised. They occur mainly within the Paragon Group and are both concordant and discordant to bedding. It has not been unequivocally demonstrated but there is some evidence to indicate that the pegmatites are genetically related to leucocratic granites which consistently occur stratigraphically below them. Structural fabrics indicate that the pegmatites and granites were emplaced either before or during prograde metamorphism and deformation.

PGE-Cu-Ni Associated with Ultramafic Intrusions

The ultramafic intrusions comprise dykes and sills of serpentinised harzburgite, being several hundred metres long in outcrop. Mineralisation occurs at their lower contacts and comprises pods, about one metre thick, of pyrite + pyrrhotite + chalcopyrite + pentlandite. The intrusions postdate high grade metamorphism but have been affected by retrograde shearing. They have not been dated, however, they have similar REE plots to the Little Broken Hill Gabbro which has been dated at 827 Ma. It is possible that the intrusions represent deeper equivalents to the rift-related Wilangee Basalt in the Adelaidean succession.

Other intrusive-related mineralisation includes various pegmatites with rutile, galena, chalcopyrite, radioactive minerals or beryl. One other type of intrusive deposit comprises granitoid with magnetite + pyrite and while it has similarities with textures present at Olympic Dam it contains no Au or base metal mineralisation.

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The Structural Framework and Tectonic Evolution of the Western Lachlan Fold Belt, Victoria

Ross A. Cayley & David H. Taylor

Geological Survey of Victoria.
Ross.Cayley@nre.vic.gov.au David.Taylor@nre.vic.gov.au

Recent GSV mapping of Western Victoria from Heathcote to west of the Grampians has resulted in a greatly improved understanding of the structural evolution of this region. The mapping has described in detail the geology of the Stawell and Bendigo Zones of the western Lachlan Fold Belt (LFB), resolved the nature of the boundary of the LFB to the older Adelaide Fold Belt (AFB) to the west, and significantly revised the structural setting of the Grampians Group which lies upon the AFB.

Our mapping has identified the Moyston Fault as the suture zone between the LFB to the east and the AFB to the west. The fault is the largest thrust recognized so far in the Victorian LFB and occurs just to the east of the Grampians as a major east-dipping structure. It separates areas with very different geological histories. The older rocks to the west are referred to as the Glenelg Zone (GZ) in western Victoria and have affinity with the South Australian AFB. To the east LFB rocks from at least mid-crustal levels have been emplaced upwards and westwards onto the GZ along the Moyston Fault (Cayley 1995; Cayley & Taylor 1996; Cayley & Taylor in prep.).

The Moyston Fault sharply delineates the western limit of the Victorian goldfields. Victoria's largest producing goldfield at Stawell is located a few km to the east, and the Moyston Fault at Moyston is itself mineralized, with a significant historical Au production. No significant gold mineralization occurs in the GZ to the west. The GZ is overlain by the Ordovician to Silurian Grampians Group, which outcrops as a spectacular series of rugged strike ranges. On structural, sedimentological and temporal grounds, the fold-and-thrust belt of the Grampians is regarded by us as a structural outlier of the LFB (Cayley & Taylor, 1997).

Geology of the western Lachlan Fold Belt (LFB)

The principal discriminating difference between the western LFB and the eastern AFB (GZ) is the age of regional deformation. The GZ was regionally deformed during the Delamerian deformation in the Middle to Late Cambrian (~518–500 Ma) and is intruded by post-tectonic granites of Late Cambrian age including the Bushy Creek Granite (495±5 Ma; U-Pb; Stuart-Smith and Black, in prep.). The western LFB is composed of Cambrian oceanic volcanics overlain by extensive Cambrian to Late Ordovician quartz-rich turbidites derived from the deformed highlands of the AFB (VandenBerg & Stewart, 1992). The age of the turbidites, the deformation of the Grampians Group and post-tectonic 400 Ma intrusions bracket the age of the deformation in the western LFB as Latest Ordovician to Silurian (~440–430 Ma)– significantly younger than the AFB. Recent $^{40}Ar/^{39}Ar$ dating of micas in the western LFB provide a range of apparent ages from 500 Ma to 410 Ma. The oldest ages probably reflect a detrital component (Bucher et al., 1996); the youngest reflect later reactivation (Foster, et al., 1996) with the bulk of dates at 440 Ma right across the region (see fig 9 Foster, et al., 1996) consistent with the timing inferred from the field evidence.

Most of the western LFB exposes only the upper (sedimentary) part of the stratigraphy which is tightly folded, cleaved and faulted. The wide expanse of this exposure and its consistent low, greenschist metamorphic grade suggests a flat enveloping surface so that the major faults must be listric, rooting into an underlying décollement (eg. Fergusson et al., 1986). Only in the immediate hangingwall of some of the major meridional thrust faults are parts of the lower volcanic stratigraphy brought towards the surface.

Near Ararat the nature of the LFB changes markedly across the west-dipping Coongee Fault. The region between the Coongee Fault and the parallel Moyston Fault 15 km further west is characterized by fundamental changes in structural, metamorphic, and geophysical character, and is here-in subdivided from the Stawell Zone as the Moornambool Subzone. The Moornambool Subzone represents the exposed midcrustal levels of the LFB being emplaced upwards and over the AFB to the west. Between the Coongee and Moyston faults successively lower stratigraphic levels of polydeformed volcanic and sedimentary rocks are exposed across numerous, large, closely spaced, sub-parallel west- and east-dipping thrust faults (Cayley & Taylor, in prep.). The metamorphic grade progressively increases from low greenschist facies adjacent to the Coongee Fault to amphibolite facies in the hangingwall of the Moyston Fault. The overall enveloping surface of this subzone is therefore no longer flat, instead dipping moderately to the east, reflecting the geometry of the underlying Moyston Fault. Metamorphic conditions in some of the lowest exposed levels have been calculated at 520–650° C and 3–5kb (Roder, 1977), and 600±20° C and 7.5±1 kbar (Radojkovic, 1989)—some of the highest metamorphic grades recorded in Victoria. The volcanics progressively alter to hornblende-garnet-quartz-plagioclase schist while the overlying turbidites become coarse quartz-muscovite-(garnet) schist. These units are structurally intercalated on all scales, and mylonite fabrics are ubiquitous, especially in the western parts of the subzone.

The Moyston Fault

The complex, high grade, polydeformed Moornambool Subzone is bounded abruptly on its western side by the Moyston Fault, which runs through Moyston, Londonderry, and just west of Mt Drummond (Cayley & Taylor, in prep.). Although most of the structural elements in the hangingwall dip moderately to steeply west, good exposures along the fault, old mine plans, and limited drilling show that it dips moderately east. Amphibolite grade schist in the hangingwall is thrust over weakly deformed, very low-grade sediments (Glenthompson Sandstone) and volcanics (Mount Dryden volcanic belt). These low grade rocks belong to the GZ, and form the footwall of the Moyston Fault. They are invariably overturned adjacent to the fault, consistent with a reverse/oblique displacement history.

The emplacement of LFB rocks from 15–20 km depth against near surface rocks of the AFB occurs within the 15 km width of the Moornambool Subzone, and thus indicates that the Moyston Fault dips east at approximately 45°—an orientation recently confirmed by deep seismic (Gray et al., 1997). Geophysical evidence supports the presence of the AFB beneath the Moornambool Subzone, forming the footwall of the Moyston Fault. The higher overall gravity and total magnetic intensity of the AFB extends east beneath the Moyston Fault as far as the Coongee Fault, interpreted by us to reflect the extent of AFB crust beneath the LFB. East of the Moornambool Subzone there is no evidence of pre-LFB crust at depth.

Tectonic evolution of the western LFB

The coincidence of the eastern margin of the Moornambool Subzone (which marks the abrupt change in overall dip of the regional LFB enveloping surface), the first geophysical indications of AFB crust at depth, and the geometry of the Moyston Fault is strong evidence for the westward emplacement of a wedge of deforming LFB rocks from mid-crustal levels onto a rigid, east-dipping crustal-scale ramp of AFB crust, acting as the backstop/indentor in a classical convergent setting (e.g. Norris et al., 1990).

The numerous west-dipping thrusts of the Moornambool Subzone are truncated by the Moyston Fault, and therefore must have developed outboard from the fault, most likely in the position of the Coongee Fault. Here successive antithetic faults (backthrusts) accommodated space problems created by the abrupt steepening of the LFB enveloping surface where west-moving LFB material encountered the AFB ramp at mid-crustal levels. East-dipping thrusts within the subzone have also been recognized, and these are interpreted as synthetic hangingwall step-off structures to the Moyston Fault. Deformation progressed outboard from this converging margin along the mid-crustal décollement (e.g. Norris et al., 1990), across the Stawell and Bendigo zones to form the east-verging parts of the fold and thrust belt already described by many authors (eg. Fergusson et al., 1986). As the leading thrust of the deforming Lachlan orogen, the Moyston Fault is likely to have remained continually active throughout the formation of the western LFB, accruing the largest displacement and longest-lived movement history of any exposed western LFB fault.

The fate of the lower LFB crust is at present unknown; no deeper LFB levels have been recognized at the surface. Although subduction has been proposed by some authors (e.g. Soesoo et al., 1997), definitive evidence is lacking, and we consider it to be unnecessary. The large degree of shortening of the upper western LFB allows for an alternative interpretation. During the development of the LFB simple oceanic crust of 5–7 km thickness (plus the 3+ km of overlying turbidites) may have undergone wholesale shortening of ~70% in a convergent setting, by internal duplexing of the lower crust and thin-skinned deformation of the upper crust, to achieve a final thickness of 35–40km – the crustal thickness now observed. In this scenario there need be no subduction–indeed all the oceanic crust is required to form the known lower crustal thickness. A dense, thickened, oceanic lower crust would be an inevitable consequence of this process and explains the limited post-orogenic uplift of the western LFB, provides a source for the numerous post-tectonic I-type intrusions and the gold-saturated metamorphic fluids which have formed the western Victorian goldfields.

The Grampians — a LFB outlier

Until 1995 the Grampians Group was interpreted as a thick, conformable, and relatively gently deformed fluvial to shallow marine sequence deposited in a passive basin setting. Detailed structural and lithological mapping (Cayley & Taylor, 1997) has recognized numerous bedding-parallel thrust faults that repeat large parts of the stratigraphy, effectively thickening the original sequence by around 100%. The thrusts are folded about large scale folds, and the whole complex is truncated at depth by a low angle décollement which gives the Grampians an allochthonous relationship to the older GZ bedrock beneath.

Assuming a simple and conformable sequence, the apparent stratigraphic thickness of the combined Grampians ranges appears close to 7000 m. However, when the effects of structural repetition have been removed, the true total stratigraphic thickness is approximately 3700 m. The restored stratigraphy consists of a lower quartzose-feldspathic to micaceous sandstone package (Red Man Bluff Subgroup; 1900 m thick), an intervening micaceous mudstone dominated package which represents an episode of restricted sedimentation (Silverband Formation; 750 m thick) and an upper, quartzose sandstone package (Mount Difficult Subgroup; 1050 m thick). Slate, sandstone and volcanic clasts in rare conglomerate are proximally sourced but their precise provenance is unknown.

The Grampians Group preserves evidence of fluvial, aeolian and shallow marine sedimentation, consistent with a low relief, marginal marine setting. It was probably accumulated in passive basins developed along the AFB margin, transitional to the central Victorian turbidite sequence accumulating in the oceanic setting to the east. A Late Ordovician to Early Silurian age for the Grampians Group is suggested by their regional geological setting and history (Cayley & Taylor, 1997). The Grampians Group appears to share the same deformation and intrusion history as the western LFB — a marked absence of internal sediment reworking and lateral facies changes argues against the development of the Grampians Group as a foreland basin to the accreting western LFB.

The Grampians Group is characterized by numerous bedding-parallel thrust faults that repeat parts of the stratigraphy. Although generally difficult to observe, thrust faults are obvious where they bifurcate or ramp through the sequence so that bedding is truncated and beds of different dip are juxtaposed. Where exposed, the faults are narrow zones of intense fracture networks and breccia ranging from one to several metres wide. Strain is generally very strongly partitioned into discrete zones, such as a ramifying network of cataclastic gouge and thin sub-parallel slickensided faults. The faults are often intruded by sill-like felsic dykes related to Early Devonian post-tectonic granites.

The systematic repetition of various units suggests three main detachment horizons exist within the Grampians Group: low in the Redman Bluff Subgroup, high in the Redman Bluff Subgroup, and most significantly, within the Silverband Formation. There are approximately 12 major thrust faults of significant extent splaying from these detachment horizons, but not all of these faults repeat stratigraphy. The fault ramps variously show footwall and hangingwall control, relationships suggesting a duplexed thrust stack geometry. The systematic repetition of adjacent stratigraphic units without the lowest stratigraphy ever being emplaced over the highest stratigraphy also supports a duplex rather than an imbricate thrust system. The absence of any in-faulted 'exotic' rocks into the Grampians Group suggests that the preserved parts of the thrust system did not involve the GZ beneath.

The internal repetition of stratigraphy rather than wholesale imbrication may have been controlled by the structural incompetence of the Silverband Formation lying between the two thick sandstone packages—in effect a roof thrust for the lower stratigraphy and a sole thrust for the upper stratigraphy. This suggests that the duplex system in the Grampians is a complex and multi-layered one. The thrust system has been folded about the Wartook Syncline and block rotated during later transport along a basal décollement, the Marathon Fault. Therefore, the present thrust orientations are not themselves diagnostic of the transport direction; the entire system may be interpreted as having an originally east-dipping and west-verging orientation.

Crustal shortening of the degree seen within the Grampians is not expressed in the GZ beneath or to the west, and is therefore inferred to be related to the LFB. The geometry of the east-dipping Moyston Fault shows that parts of the LFB were emplaced westwards onto the GZ during regional deformation at about 430 Ma. The Grampians Group sequence was probably shortened and thickened as it was pushed west across the GZ in a thin-skinned fashion as part of the emplaced LFB.

The Marathon Fault is the low angle décollement which separates the Grampians Group from the underlying bedrock. The fault truncates the structures of the earlier thrust belt; more than 3000 m of thrust-stacked and folded sequence may be missing from beneath the Wartook Syncline. The fault is very poorly exposed; however several key outcrops, especially in the Black Range region, together with recent company drilling and the gravity intensity measured over the Grampians support a thin-skinned allochthonous setting in contrast to the previous interpretation of a sedimentary basin 6–7 km deep. The Marathon Fault omits stratigraphy in contrast to the earlier thrust faults, and geometrical relationships suggest that it was initiated as a listric extensional structure, segmenting the thrust-and-fold belt. This fault may be one expression of extensional relaxation of the thickened and deformed LFB emplaced upon and against the AFB during strong convergence in the Silurian as recorded east of the Moyston Fault.

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Basement of the Lachlan Fold Belt: the Evidence From S-Type Granites

B. W. Chappell

ARC Key Centre for the Geochemistry and Metallogeny of the Continents (GEMOC), Department of Geology, Australian National University, Canberra, ACT 0200, Australia

S-type granites, derived wholly or largely from sedimentary source rocks, comprise more than half of the granites that are so extensively developed in the Lachlan Fold Belt (LFB) (White & Chappell, 1988). Apart from granites and their related volcanic rocks, the other principal component of the LFB consists of widespread Ordovician turbidites. Paradoxically, those sedimentary rocks have compositions that would not have been appropriate as source rocks of most of the S type granites.

The turbidites have very distinctive compositions. They are very mature and range from clay-rich shales to quartz-rich greywackes. When unmetamorphosed they consist dominantly of clay minerals and quartz; other minerals, notably feldspars, are present in small amounts. This is reflected in their chemical compositions which are distinctively low in the feldspar components Na, Ca and Sr (Wyborn & Chappell, 1983), shown by the average composition LOT in Table 1.

One areally restricted group of S-type granites, the Cooma Supersuite, shares the distinctive chemical features of LOT (average CSS in Table 1). These granites, which may occur in association with high-grade metamorphic rocks, apparently formed from sedimentary rocks with compositions close to the least feldspar-poor of the Ordovician turbidites. This also accords with the isotopic data for CSS and LOT, shown in Table 1.

The much more abundant batholithic S-type granites of White & Chappell (1988) occur in contact-aureole to subvolcanic environments and have extensive volcanic equivalents. The great abundance of these rocks in the Kosciuszko region and the area immediately to the east, implies that prior to 430 Ma, voluminous sedimentary source rocks of appropriate composition were present at depth in that part of the crust. This is in contrast to the area further east where such granites are not seen. Those observations led White et al. (1976) to propose an "I-S line" in the region of the Berridale Batholith, east of which S-type granites are not found. Those authors suggested that the I-S line corresponds to the eastern limit of crystalline basement, "possibly of Precambrian age". That line has subsequently been traced for a total distance of 600 km with only minor lateral discontinuities, from Bass Strait to the edge of the younger basin rocks north of Orange (Chappell et al., 1988), and it must mark a rather profound east-to-west discontinuity in the nature of the deeper crust.

The batholithic S-type granites range from very mafic to highly fractionated compositions. The more mafic rocks cannot be cumulates because of (i) the close correspondence in composition between some plutonic and volcanic rocks (Wyborn & Chappell, 1986); (ii) the fact that the Sr contents are transitional, without any hiatus, to those in granites of ternary minimum melt compositions; and (iii) because the variation in composition within individual suites is not consistent with their being cumulate rocks. The mafic rocks therefore were the parental magmas, which were either rather mafic melts (Gray, 1990; Collins, 1996), or mixtures of a more felsic melt and entrained restite (White & Chappell, 1988; Chappell, 1996). That the mafic magmas were restite-bearing magmas rather than melts, is evident, for example, from (i) the extensive zircon age inheritance (Williams, 1995); (ii) the fact that variation within the most mafic rocks of the Bullenbalong Suite has a component that is "sedimentary"; (iii) the gross isotopic heterogeneity within the one mafic S-type pluton which has been tested ($^{87}Sr/^{86}Sr$ = 0.71115 to 0.71541 at 430 Ma for the Jillamatong Granodiorite); and (iv) variation within the more mafic rocks in all suites, and more felsic rocks in some suites, is not consistent with melt compositions produced by fractional crystallisation. These observations elevate the compositions of the most mafic S-type granites to the status of source rocks that were mobilised by partial melting and which then moved bodily without any detectable fractionation of melt from restite. Such mafic granites form a strong image of their source rocks (Chappell, 1979). Since geobarometry on mineral assemblages in the Deddick Granodiorite (Maas et al., 1997) and volcanic rocks (Wyborn et al., 1981) gives pressures of equilibration of about 550 Mpa, it is inferred that those source rocks were located at depths of 15-20 km.

Inspection of the mafic Bullenbalong Suite composition MBS in Table 1 shows that the LOT composition is not an appropriate composition, at least on its own, to be the source material for the batholithic S-type granites. MBS contains substantially higher concentrations of Ca, Na and Sr, and is distinctly less radiogenic in Sr. This has long been recognised and has been accounted for in two contrasting ways. Wyborn (1977) suggested that the source of these S-type granites was a sediment, less mature and more feldspar-rich than the exposed Ordovician turbidites, which formed a basement to those younger rocks. The alternative view is that Ordovician sediments were mixed with mafic rocks (Gray, 1984), or that material of Cooma Granodiorite composition was mixed with mafic tonalite (Collins, 1996), to produce source rocks that were richer in Ca, Na and Sr, and isotopically less evolved than the Ordovician sediments.

Table 1 - Some average compositions from the Lachlan Fold Belt

	LOT	CSS	MBS	CPE
SiO_2	71.23	69.84	66.46	46.58
TiO_2	0.64	0.61	0.65	1.23
Al_2O_3	13.76	14.34	14.88	25.80
Fe_2O_3		0.77	0.77	1.64
FeO	4.74	3.56	4.21	7.03
MnO	0.05	0.07	0.07	0.14
MgO	1.90	1.94	2.52	4.53
CaO	0.31	1.09	2.68	2.90
Na_2O	1.02	1.52	1.94	1.82
K_2O	3.54	3.84	3.40	4.00
P_2O_5	0.13	0.15	0.16	0.17
Rb	168	182	175	191
Sr	64	127	147	135
$^{87}Sr/^{86}Sr$	0.717*	0.7176	0.7134	0.7128
ε_{Nd}	-11.1*	-11.2	-9.43	

LOT: Average of 38 analyses of Lachlan Ordovician turbidite
CSS: Average of 22 analyses of granites of the Cooma Supersuite
MBS: Average of four mafic granites from the Bullenbalong Suite
CPE: Average of 5 analyses of pelitic enclaves from the Cootralantra Granodiorite

Isotopic ratios calculated at 430 Ma

A less mature sedimentary source for the batholithic S-type granites is favoured by several lines of evidence. The variation within suites of those S-type granites cannot be the direct result of mixing of the Ordovician rocks with more mafic igneous rocks, because the S type granite suites become increasingly Al_2O_3-oversaturated with decreasing SiO_2 content (White & Chappell, 1988); this is now recognised by all authors. For the same reason, the simple "unmixing" of a felsic melt from a magma charged in some way with fragments or crystals of chemically and isotopically less evolved material, cannot have occurred. Any process of prior mixing should have produced source materials that were rather uniform in chemical but not isotopic composition, prior to separation of any crystals from melt. There are pelitic enclaves in the mafic S-type granites, which on the basis of the geobarometry of Maas et al. (1997) were derived from depths of 15-20 km. Such enclaves have compositions (CPE in Table 1) that are unlike any found among the Ordovician turbidites, and contain higher Ca, Na and Sr contents than those turbidites. Whether these enclaves represent accidentally incorporated material (Maas et al., 1997) or restite (Chappell et al., 1987) is not relevant to the present argument, and they clearly show that at least some more feldspar-rich sedimentary material was present in the mid-crust at 430 Ma. Other enclaves (microgranular or microgranitic) that occur in these granites have been cited as evidence for the presence of a mafic component in the source rocks, that may have contributed to melting, but it is highly probable that such enclaves are metamorphosed and partly melted fragments of marly sediments (D. Wyborn, pers. comm.). To increase Ca contents from 0.31% in LOT to 2.68% in MBS (Table 1) would require the addition of 25% basaltic material. It was pointed out by Wyborn (1977) that the addition of large amounts of basaltic material in that way would mean that the abundances of some other elements in the source rocks, such as K and Rb, would be too low to produce the observed compositions in the batholithic S-type granites. It is concluded that those granites were derived from the partial melting of sedimentary rocks that were less mature and more feldspar-rich than the exposed turbidites.

There is an extreme contrast between the iosotopic compositions of Sr and Nd for the Ordovician turbidites and all of the S-type granites at 430 Ma. The Nd values are extremely divergent from mantle values while in comparison the Sr compositions are not. ε_{Nd} values ~ -10 correspond to model ages of derivation from a depleted mantle ~1000 Ma older than the granites. Initial $^{87}Sr/^{86}Sr$ ratios and Rb and Sr contents of the batholithic S-type granites (MBS in Table 1) conform to a much younger model age. It is clear that the Sr isotopic compositions have been reset, while the Nd values probably have not. Resetting of the Sr isotopes would have occurred during sedimentation, from a high level down to a minimum level equal to sea-water values at that time. The MBS Sr isotopic compositions would have evolved from a Cambrian sea water Sr isotopic composition of 0.709 in 90 Ma, which is a maximum age of 520 Ma for deposition of the sedimentary rocks. The extent to which the isotopic composition in the sediments did not fully equilibrate with sea water, would correspond to a younger age of sedimentation. Hence the source rocks for the S type granites cannot be Precambrian or early Cambrian in age. They must, however, have been different in composition from the widely exposed Ordovician turbidites, and if they were Ordovician in age, they were distinct in composition from those exposed rocks. The residuum from partial melting of those rocks must now be an important component, at depth, of the crust of the LFB, in those areas where voluminous S-type granites are now exposed.

The question of source rocks for the I-type granites has not been addressed in this contribution. These generally had isotopic compositions when they formed which are not consistent with direct derivation from mantle materials. The proposal that those isotopic compositions reflect a component of Ordovician turbidite in the source rocks is not consistent with chemical data for the I-type granites (e.g. increasing Ca contents in I-type granites that are more isotopically evolved). It is highly likely that the source rocks of at least some of the I type granites, correspond with an older component than the S-type source rocks, in the basement of the LFB.

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An Evaluation of Petrogenetic Models for Lachlan Fold Belt Granitoids: Implications for Crustal Architecture and Tectonic Models

W. J. Collins

Department of Geology, University of Newcastle,
Newcastle, NSW 2308, Australia

The restite (one source-component) model (White and Chappell, 1977) suggests that granitoids are derived from contrasting source rocks, and that the typical linear chemical variation of Lachlan fold belt (LFB) granitoids is produced by restite separation. However, it cannot explain the general chemical and isotopic similarity of S- and I-type granitoids in the eastern LFB, the similarity of zircon inheritance patterns between the two granite types, nor their apparently simple Nd-Sr isotopic array. The restite model requires melting of Meso-Neo-proterozoic continental sedimentary rocks to produce the S-type granites, and 3-stage recycling or "remagmatism" of Proterozoic igneous rocks to produce the LFB I-type granites. In particular, a basement of extensive ~600 Ma Cordilleran-style granitoids is necessary. No independent geological evidence exists for any of these inferred Precambrian units, and the observed tectonostratigraphy of the LFB militates against it.

A two source-component mixing model, based on the Nd-Sr isotopic array, suggests that linear chemical variation of the granitoids reflects variable incorporation of deeply buried Ordovician sediment and basaltic magmas. However, isotopically defined mixes do not match the predicted chemical mixes, indicating either (1) that the number of source components exceeds two; (2) that other factors influence the chemical composition of the granitoids; or (3) that both situations apply. Furthermore, systematic and sympathetic isotopic and chemical variations are observed for both the felsic and mafic granites within suites across the Bega Batholith. For a simple two-component model to apply, both the crustal and mantle end members would have to change composition in the same way, which is unrealistic (Chappell, 1996).

A three source-component mixing model incorporates aspects of the other two models. It suggests that I-type magmas, derived in the lower crust by mixing of greenstone-derived partial melts and basaltic magmas, are variably contaminated in the deep crust by migmatised Ordovician metasedimentary rocks. If sufficiently contaminated, the I-type granites become peraluminous S-type granites, and a restitic component may be retained. For example, the S-type Bullenbalong Supersuite of the Kosciusko Batholith can be produced by a 30:70 mix of I-type Jindabyne suite tonalitic magma with Cooma diatexite, the latter being the only LFB "granite" to image its source rock (Collins, 1996). Linear chemical variation then results from differentiation. Accordingly, no Proterozoic continental basement, nor Proterozoic basement terranes, need exist beneath the LFB.

The 3-component mixing model also places several important constraints on eastern LFB tectonic evolution: (1) Widespread involvement of mantle-derived magmas was required during granite genesis; (2) Neoproterozoic-Cambrian greenstone and Ordovician sedimentary crust was considerably thickened before generation of the oldest S-type granites at ~430 Ma; (3) Greenstones dominated the lower crust after the crustal thickening, extending to depths between 20-30 km, whereas Ordovician metasediment dominated the higher crustal levels (0-20 km); (3) The midcrust may have been subjected to high heat-flux before generation of the I-type magmas in the lower crust, possibly associated with thermal recovery following end-Ordovician crustal thickening; (4) The remarkably homogeneous, high μ, Pb crustal reservoir of the LFB (Carr et al., 1996) is probably Ordovician sediment; (5) The I-S line is not a major tectonic boundary; rather, it reflects the eastern limit of Ordovician sedimentary rocks that

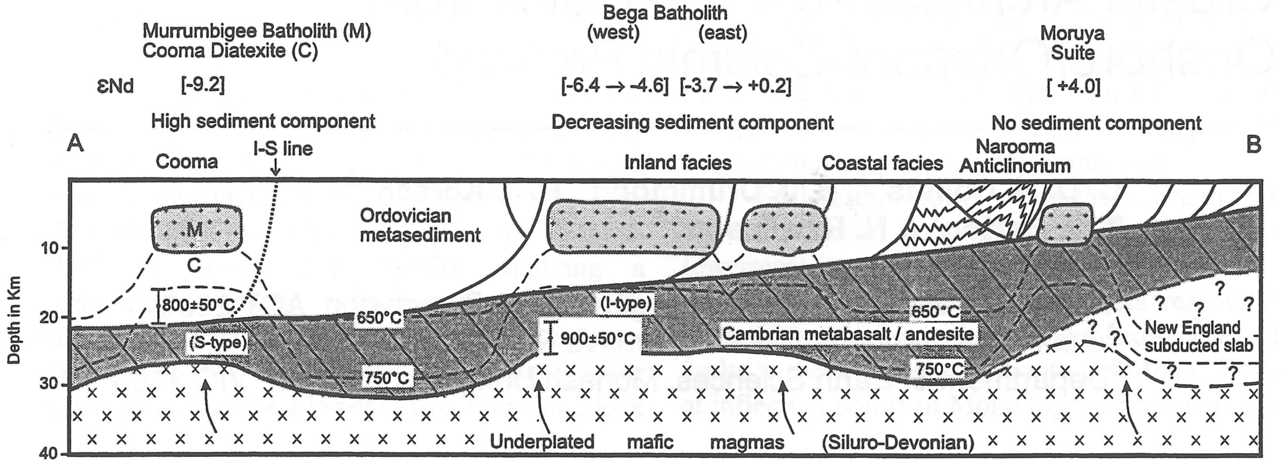

Fig. 1 - Inferred crustal architecture of the eastern LFB at ~400 Ma. Upper crustal structure from Miller and Gray (1996); P-T estimates for S- and I-type magma generation from Wyborn and Chappell (1986). Peak geothermal gradient from Wyborn (1992) and regional or "background" gradient derived from kyanite-bearing schists in LFB lower crustal analogues in Fiordland, New Zealand (Gibson, 1992). See text for discussion. An average of 5km erosion since the Devonian would expose the granitoids. Thrusting is required to uplift the migmatite complexes (cf. Glen, 1992) prior to exhumation.

were substantially melted; (6) Bega Batholith granitoids show a systematic eastward decrease in degree of contamination by Ordovician sediment, reflecting an eastward tapering Late Ordovician accretionary prism into which they intruded (Fig. 1); and (7) the inferred W-dipping décollement surface between Ordovician metasedimentary rocks and Cambrian greenstones could reflect a Late Ordovician fossil subduction zone; (8) Siluro-Devonian Bega Batholith granitoids are probably all subduction-related, which might apply to silicic magmatism throughout the entire eastern LFB.

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Crustal Architecture of Tasmania from Onshore/Offshore Seismic Profiling

C. D. N. Collins[1,2], B. J. Drummond[1], R. J. Korsch[1,2], T. J. Barton[1] & N. Rawlinson[2,3]

[1]Australian Geological Survey Organisation, Symonston, ACT 2609
[2] Australian Geodynamics Cooperative Research Centre
[3]Department of Earth Sciences, Monash University, Clayton, VIC 3168

In 1994, the Australian Geological Survey Organisation (AGSO) and the Tasmanian Geological Survey established the TASGO project as part of the National Geoscience Mapping Accord. The aim of the project was to understand the controls on Tasmania's geology and how its mineral and petroleum systems fit into this framework. One objective of TASGO was to map the three-dimensional structure of Tasmania down to the crust-mantle boundary using seismic and potential field methods. The seismic component of the TASGO project was completed in 1995, and consisted of a series of marine deep reflection profiles which encircle Tasmania, onshore deep reflection profiles, and the deployment of a network of seismic recording stations to provide refraction, wide-angle reflection and tomographic data (Figure 1).

Regional Crustal Structure

The large scale structure of the Tasmanian crust is interpreted from the refraction and tomographic data (Rawlinson, et al., this volume) and previous refraction data and earthquake analysis (Richardson, 1981, 1989). The crustal thickness varies from 30-32 km along the northwestern part of the north coast to 27 km along the eastern north coast. Along the east coast, from Binalong Bay to the Freycinet Peninsula the crustal thickness is 25 km, increasing southwards to 26 km near the Tasman Peninsula. Both seismic and gravity data (Leaman, 1989) indicate that the crustal thickness increases towards the centre of the island, perhaps by as much 5 km. The seismic refraction models show a two layer crust along both the eastern and northern coasts, with upper and lower crustal thicknesses consistent with a non-reflective upper crust and a reflective lower crust interpreted from seismic reflection data. The measured seismic velocities are consistent with an upper crust derived from lithified clastic and granite rocks and a lower crust that might contain significantly more mafic rock.

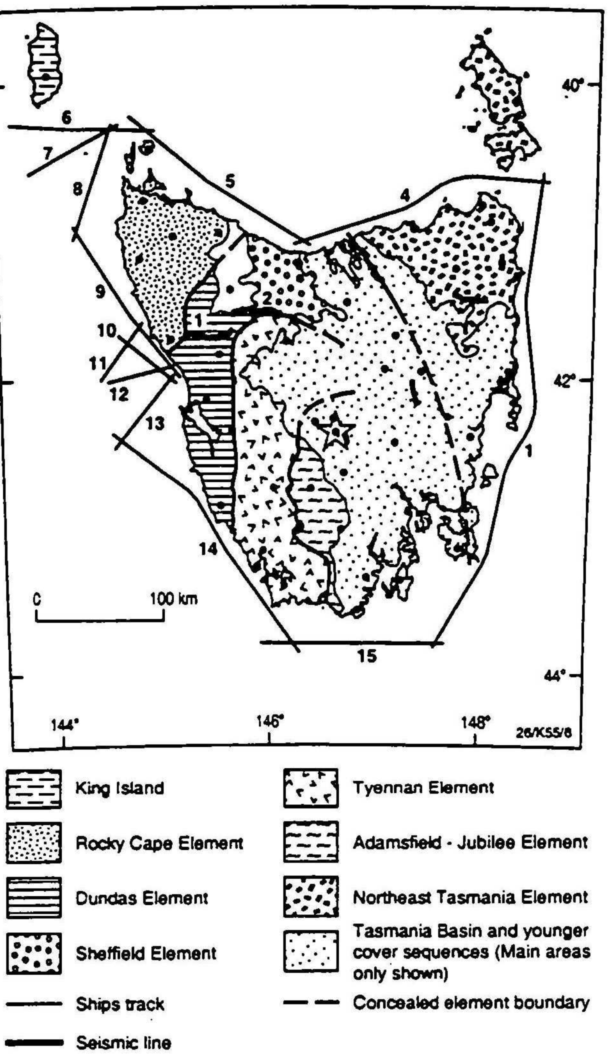

Fig. 1 - Location of seismic reflection profiles (numbered lines), refraction/tomography recording stations (black circles) and onshore shot-point (star). Onshore seismic traverses in the northwest which are referred to in this paper are labelled 1 and 2.

Crustal Architecture From Reflection Imaging

The seismic reflection profiles acquired offshore show the development of the present day structures from the Proterozoic Tyennan Block, which is considered to be the core of Tasmania. Along the southern reflection profile, the Tyennan Block is mostly non-reflective implying a monotonous lithology with few boundaries. Its eastern boundary dips gently eastward, and forms the basement to the younger sedimentary cover rocks of the Jubilee Element. The Tyennan Block continues farther east where it is imaged on a seismic profile subparallel to the eastern coastline. It is again non-reflective and can be traced in its pristine form as far north as the eastern Tasman Peninsula, but further north it appears to be broken into several crustal-scale, tilted fault blocks. Each fault block is bounded above and below by south dipping reflections which link into the Moho, mostly at significant inflections in Moho topography. The tops of the fault blocks now lie at mid-crustal levels, and are overlain by a non-reflective crust, typical of many parts of Palaeozoic basement in eastern Australia, and are interpreted in this part of Tasmania as the probable southernmost limit of the Mathinna beds.

Still further north, along the northern third of the eastern coastline of Tasmania, the lowermost crust has numerous strong reflections which can be interpreted as packets resembling apparent north-directed thrust duplexes. The sole faults to these duplexes link into the Moho, mostly at inflection points in Moho topography, as for the tilted fault blocks further south. The tops of the thrust duplexes lie below a set of weak, sub-horizontal reflections which forms the floor to a non-reflective upper crust correlated with the Mathinna beds. Reflections extending upward to the south, and weaker than those in the lower crust, are interpreted as back thrusts.

In the northwest of Tasmania, two onshore reflection profiles reveal the crustal architecture of

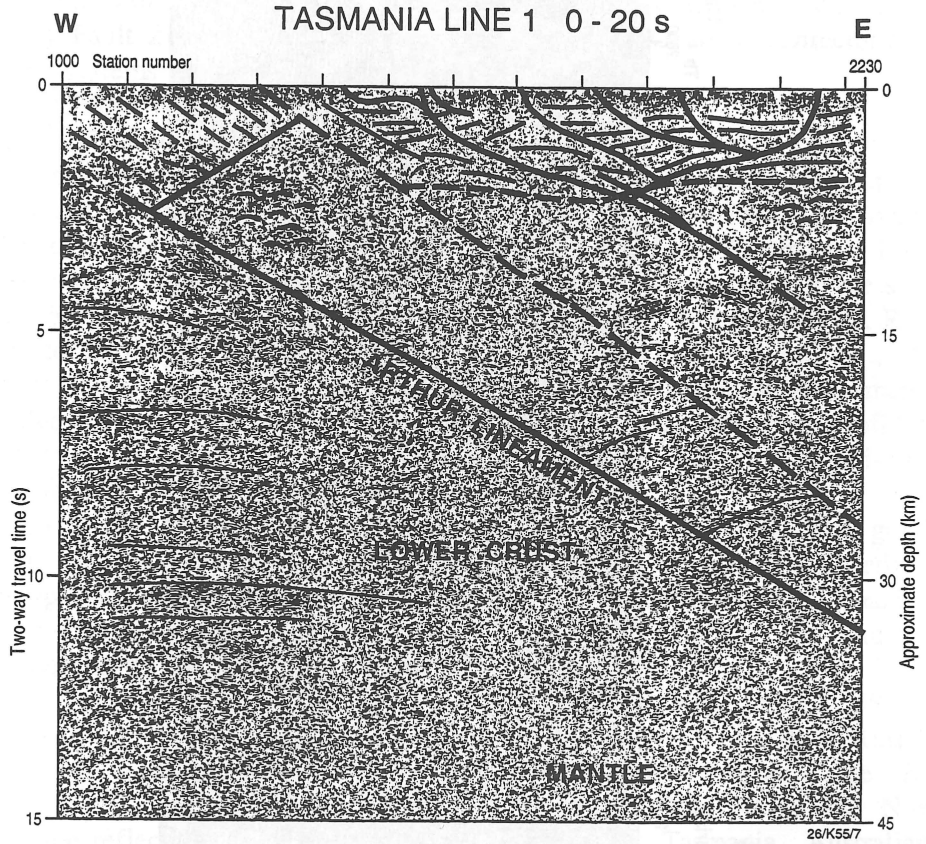

Fig. 1. - The axis on the right shows the approximate depth. (V/H = 1 for a seismic velocity of 6 km s^{-1}).

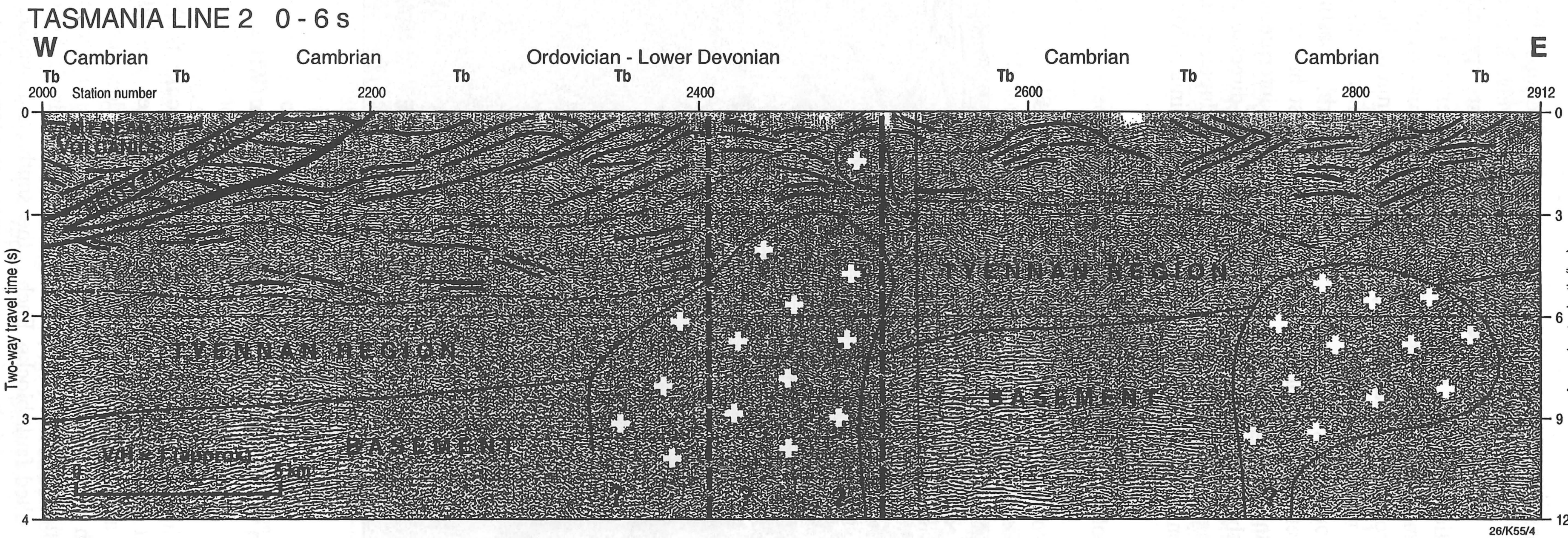

Fig. 3. - Seismic section of the upper crust along onshore line 2. The vertical dotted lines indicate major bend points in the seismic line. (V/H = 1).

the Paleozoic and Proterozoic elements (Drummond et al., 1996). The profiles commence just east of the Arthur Lineament, a major northeast-southwest oriented crustal feature, and continue eastwards across the Dundas Trough, the Mount Read Volcanics and the Henty Fault Zone and terminate near the northern Tyennan Block. Distinctive easterly-dipping reflections are attributed to the Arthur Lineament, and these underlie the Dundas Trough and probably the eastern Tyennan Block (Figure 2). A very reflective lower crust forms the basement of the Tyennan Block, which in turn is overlain by a reflective Lower Palaeozoic section. A major east-dipping fault system extends upwards from the Tyennan Block and is manifest at the surface as a number of splays and other linked fault systems such as the Henty Fault Zone and the Rosebery Fault. These fault systems are close to volcanic-hosted massive sulphides which suggests that the mineral deposits of northwest Tasmania are controlled by crustal-scale tectonics.

The cumulative thickness of the Cambrian section of the Dundas Trough and the Mount Read Volcanics varies from about 2 km in the east to 6 km in the west along the onshore seismic lines. The Ordovician to Lower Devonian section is about 3 km thick, though the magnitude of this may be partly due to shortening on a series of thrust ramps. Two zones of no reflections are crossed by the seismic lines. These coincide with low gravity anomalies, some of which are associated off-line with outcropping granites. They are therefore interpreted as buried granites (Figure 3). They each have similar width-to-depth ratios, and the easternmost body has a clearly imaged underside.

Summary

The geometry of the reflections from the seismic lines to the south and the east of Tasmania are interpreted to represent an inverted passive margin. In this model, the Tyennan Block formed a continent with ocean to the east or northeast. Crustal extension occurred through block faulting inboard and massive crustal attenuation farther seaward. The strongly reflective crust in the northern part of the profile along the eastern coast represents extended continental crust that accumulated passive margin sediments and perhaps volcanics and oceanic crust and was later inverted. Crustal shortening would appear to have been most extensive in the north, where the reflective lower crust is thickest and the Moho bowed down. The non-reflective upper crust through this region consists of highly folded Mathinna beds and granitic intrusions.

When combined with data from a transect along the northern coast (Barton et al., 1998), the apparent southern dips on thrust duplexes in the lower crust, and northern dips on inferred faults in the upper crust, translate to real dips more to the southwest and northeast, respectively. This implies a mass transfer direction of the upper plate from southwest to northeast in the lower crust, and an opposite sense on backthrusts in the upper crust.

Acknowledgements

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From Fission Tracks to Fault Blocks: An Approach to Visualising Tectonics in the Snowy Mountains

S. J. D. Cox[1], B. P. Kohn[2] and A. J. W. Gleadow[2]

Australian Geodynamics Cooperative Research Centre
[1] CSIRO Exploration and Mining, Nedlands, WA 6009
[2] Department of Earth Sciences, La Trobe University, Bundoora, VIC 3083

Apatite fission track (AFT) thermochronology is an unequalled tool for reconstructing the thermotectonic history of the upper ~2-5 kms of the continental crust. A key characteristic of the radiation damage of fission track systems which makes them amenable to thermochronological studies is the tendency for tracks to progressively anneal or repair themselves within a characteristic temperature interval. For apatite, this range typically occurs between ~120°-60°C over geological heating times of 106 yrs or more, and this interval is referred to as the AFT partial annealing zone. The annealing process results in an apparent age reduction and a progressive shortening of track lengths from their ends. As each individual track accumulates by a radioactive decay event at a different time it records a different part of the thermal history.

Flank uplifts at rifted continental margins frequently preserve uplifted peneplain surfaces of a previous period of stability which predate the tectonic reactivation. Such lengthy periods of tectonic quiescence lead to the establishment of a stable thermal regime in which a well defined AFT partial annealing gradient is developed. Subsequent uplift brings the rocks successively out of the annealing zone, such that those higher in elevation will display an older apparent AFT age. The AFT parameters (age and track length distribution) form a profile characterising paleodepth thermochronological markers within the rocks which can be used as an "invisible" stratigraphic tool and chronicle the passage of cooling through the fission track annealing zone.

If the erosion surface is disrupted by subsequent reactivation, block faulting and erosion, then samples may be retrieved straightforwardly from outcrops at a range of elevations, so that a characteristic profile can be established empirically. Segments of the profile maybe offset relative to each other across important structures, enabling the estimation of relative uplift between blocks and the amount of throw on bounding faults. This method is particularly powerful in crystalline terrains, where traditional stratigraphic and structural parameters are not available. This kind of temporal and uplift information is particularly suited to interpretation assisted by advanced visualisation techniques, which allow investigation in the appropriate spatial context.

The Snowy Mountains

The Snowy Mts of southeastern Australia, centred around Mt. Kosciusko (2228 m), mainly comprising Paleozoic granitoid rocks of the Lachlan fold belt form an elevated area which is geodynamically related to the opening of the Tasman Sea. A striking feature of the region is the contrast between the stepped fault block morphology of the uplifted Kosciusko massif and the old, gently dipping, erosion surface of the Monaro tableland to the east. The mountain blocks rise up to ~1 km above the tableland surface. Remnants of the erosion surface are also preserved at higher elevations in the Kosciusko uplift. In this morphotectonic setting, a combination of high relief, and suitable apatite-bearing lithologies provide near ideal thermochronological fission track markers which can be used to reconstruct the tectonic disruption of the palaeo erosion surface.

The area has received reasonable attention in geological mapping. In particular, maps published by Wyborn et al., (1990), and a regional compilation of linear features from air-photos by Browne (1969) allowing us to identify a large suite of potential faults. Of course, in crystalline terrains like this, conventional geological markers are relatively scarce, so this suite is likely to be far from complete.

We have assembled an apatite fission track (AFT) data set comprising 115 samples from the

Kosciusko region including nine vertical profiles which together cover over ~1700 m of elevation, from wide areal sampling and along tunnels

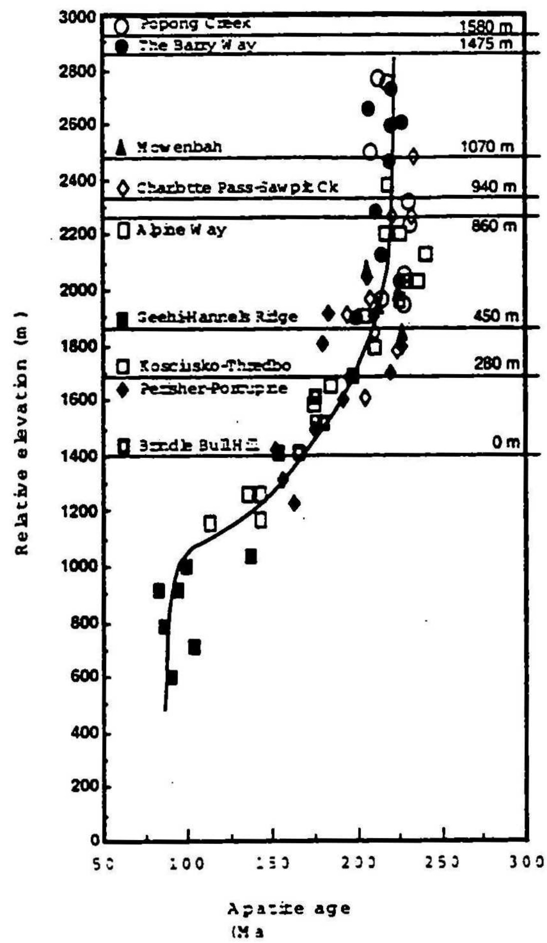


Figure 1: The variation of apparent apatite fission track age with elevation from nine vertical profiles in the Snowy Mountains. The raw data plot (a) shows disparate segments for each profile, but these can be translated vertically to demonstrate that they actually represent a single uniform reference profile (b) which has been disrupted by Tertiary faulting. The vertical offsets required are indicated relative to the Brindle Bull Hill profile which serves as a reference for comparison. For convenience, error bars on ages have not been shown but these are typically in the range of ±4-10% (at the 1s level).

excavated through the mountains during the course of the Snowy Mountains hydroelectric scheme.

The reference profile

Compiling the AFT results by plotting the elevation z_i at which the i'th sample was collected against its apparent AFT age t_i reveals a set of parallel sloping segments for apparent ages falling between ~100 Ma to ~220 Ma, and more-or-less constant ages with elevation for ages greater or less than the above range. We assume that the offset between the sloping segments corresponds to differential vertical movement between fault-blocks containing the different traverses. The segments may be corrected by adding a constant value Δz_j to the each of the elevation parameters for samples from the j'th profile, thus bringing the suite of measurements into approximate coincidence and establishing a reference profile Z(t), for which Z(100 Ma) is set to be zero (see Fig. 1).

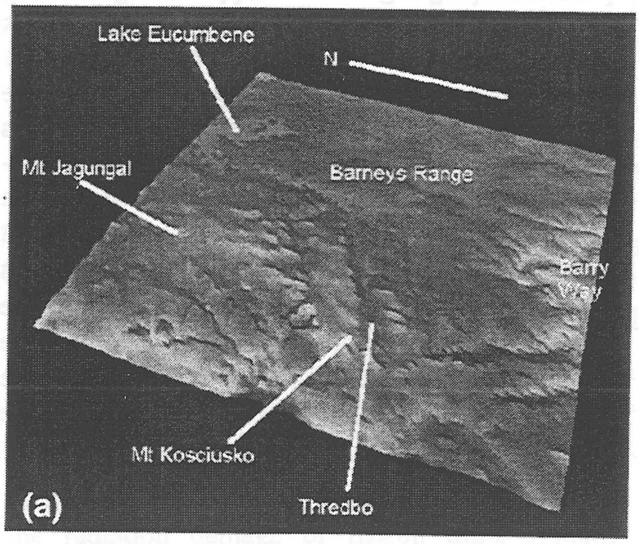
Conversion to z

A tectonically useful parameter is then derived from the parameters measured for individual samples by the following procedure. If the apparent AFT age is $t_i \pm \delta t_i$ (the estimated error in the age), then an elevation can be taken from the master profile corresponding to that depth, $Z(t_i)$, with a range $Z(t_i-\delta t_i)$, $Z(t_i+\delta t_i)$. However, the current elevation is a known value z_i, so we can determine the displacement for each sample point from the reference profile to be $\eta_i = z_i - Z(t_i)$ with limits of $z_i - Z(t_i-\delta t_i)$, $z_i - Z(t_i+\delta t_i)$.

Note that the absolute value of this displacement is not meaningful as it is determined relative to an arbitrary datum, but the differences between the various η_i's correspond to a consistent estimate of relative vertical displacements from a uniform master profile. If this profile is assumed to have been located at a constant absolute depth (elevation) prior to tectonic movements occurring sometime after 100 Ma, then these displacements give us a measure of relative vertical movement of the sample points.

The surface of relative vertical displacements

The dataset η_i, therefore, may be taken to constitute samples at a set of locations (x_i, y_i) within a surface H_i giving the relative displacements of the entire study area. It is easiest to understand the predicted vertical movements whole area by visualisation of this complete surface. This also allows us to compare the movements determined using the AFT method with the topography. The degree of correspondence between these indicates the degree



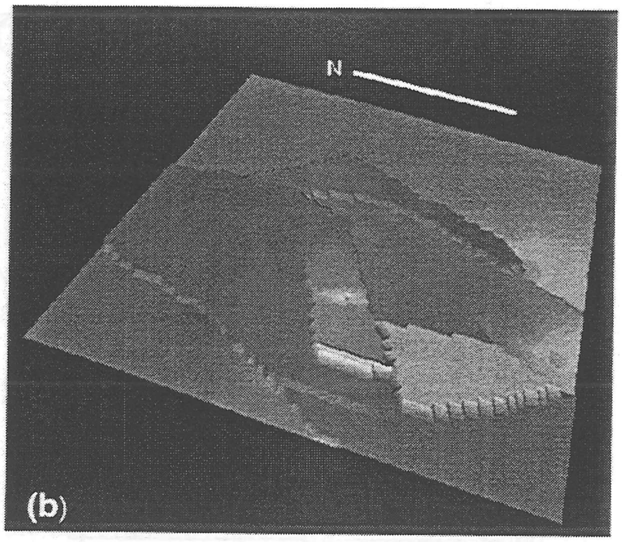


Fig. 2 - Perspective views of (a) present topography and (b) uplift predicted from apatite fission track parameters. Vertical exaggeration is 2.5x.

to which the present day topography has been determined by relative vertical movements since the time at which the thermal profile was uniform across the area (see Fig. 2).

We may approximate this surface based on the constraints η_i. Two methods were used to approximate the surface:

1. A smooth and continuous surface ${}_cH_i$ was calculated using a regularised spline with tension (RST) method (Mitasova and Mitas, 1993; Mitasova et al., 1995) over the whole area. Two adjustable parameters are available in this method, corresponding to the stiffness or thickness of the plate or membrane, and to the stiffness of the links to the control points, ie the weighting given to each control point. Here we set the weighting for each control point to be inversely proportional to the error δt_i, so that the continuous surface passes within the limits corresponding to $2\delta t_i$ at each point. We found that this method produced an irregular surface with many steep gradients.

2. The study area was divided into 13 discrete blocks, delimited by faults selected from the suite mentioned above. Some extrapolation of individual faults was necessary in order to make the network fully connected. The selection of blocks was designed to minimise the total number of blocks consistent with the fault population, while grouping sample points with similar ηi into the same block. This procedure corresponds to the basic assumptions that the faults are vertical, with dip-slip displacements, that deformation within blocks is minimal, and that the AFT profile should be approximately uniform within each block. The RST method was used again to estimate the surface, with the same control parameters, but this time run separately for the set of points within each block. The resulting patches were then joined together to produce a complete surface ${}_dH_i$. This estimate of the surface has a set of discontinuities located at the block margins, but with mainly flat patches within each block (see Fig. 2).

Results

The results of the modelling shows that the general topography is predicted quite well. High elevations near Mt Kosciusko and the elongate Barneys Range are particularly well resolved. However, there are a number of areas where the relative elevations do not appear to be directly related to uplift that can be measured by the AFT parameters. In the south of the area down the Snowy River the apparent ages are generally ~200-230 Ma which is at the extreme end of the profile (the upper right side in Fig. 1b) and thus do not allow the elevations to be very well resolved. In the block to the south of the Crackenback Fault a topographic high is not seen in the AFT predictions, and to the north, high elevations around Mt Jagungal are not resolved, partly as we have much less data.

Acknowledgements

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Tectonic Setting of Mineralisation, Mt Read Volcanics, Western Tasmania

A. J. Crawford

CODES; SRC for Ore Deposit Research, University of Tasmania

The Mount Read Volcanics (herein MRV) comprise an economically important belt of lavas, associated pyroclastics, and subordinate granitic rocks of Mid- to Late Cambrian age in western Tasmania. Five major volcanic-hosted massive sulfide deposits, and a large number of smaller deposits are known within the MRV, with an accumulated reserve of more than two hundred million metric tons of relatively Au-rich Cu-Zn-Pb ore. The recently developed Henty gold deposit provides the first example of an additional style of mineralisation within the MRV. Detailed geological, and petrological-geochemical studies of the MRV have been presented by Corbett (1992) and Crawford et al. (1992), and details of the mineralisation are reported in Large et al. (1987). On the basis of these data, the MRV were assigned a post-collisional setting by Crawford & Berry (1992), and an origin as part of a Middle Cambrian island arc (often referred to as the Mt Read Volcanic arc) was refuted. This report updates the pre-1992 understanding of the MRV, and includes some unpublished Nd-Sr isotopic data collected by AJC and DJ Whitford (CSIRO, N Ryde).

Geological background

The MRV belt is ~200km long and 20km wide, and lies mainly along the western and northern margin of a Precambrian Tyennan Region basement block. Importantly, however, MRV lavas are also present around the northern end of the Tyennan Region, and occur in at least one drillhole in the Hobart region. The main west coast belt of MRV is divided into two major segments by the important Henty Fault System, a northeast-trending fault that bifurcates southward, and contains the intriguing Henty Fault Wedge sequence between its northern and southern arms. In western Tasmania, the MRV interfinger westwards with Cambrian volcano-sedimentary and sedimentary sequences of the Dundas Group. Middle Cambrian (514 Ma) mafic-ultramafic complexes (MUC) occur west of the MRV in this trough, and include high-Mg, low-Ti lavas and associated cumulates of boninitic affinities, detritus from which occurs in basal Dundas Group sedimentary rocks. The MRV sequence culminates in a unit of siliciclastic conglomerate and sandstone, the Owen Conglomerate and correlates, of Precambrian derivation and late Cambrian to early Ordovician age..

Lithological - lithostratigraphic associations

At least five lithological - lithostratigraphic associations constitute the MRV (Corbett 1992), and considerable stratigraphic complexity and lateral facies changes complicate nomenclature: The key points are the following.

1: Earliest magmatism in the MRV is dominated by felsic volcanic, volcaniclastic and shallow intrusive rocks of the Eastern Sequence. Some Eastern Sequence felsic bodies intrude the adjacent Precambrian basement, indicating that these volcanics were erupted through and onto the Precambrian basement along the eastern side of the MRV belt. Initial ε_{Nd} values for these felsic lavas indicate that they are largely crustal melts.

2: The Central Volcanic Complex (CVC), a volumetrically dominant part of the MRV, is a belt of predominantly felsic lava-rich volcanics occurring both on the southern and northern sides of the Henty Fault System. In the upper part of the southern CVC, significant andesites occur immediately beneath the Tyndall Group. Basalts are unknown within the CVC sequences, and initial ε_{Nd} values for the andesites are mainly between -1 to +1, indicating a significantly decreased crustal component compared to the earlier felsic lavas.

3: Towards the top of the MRV, a complex unit termed the Western Volcano-sedimentary Sequences by Corbett (1992) includes an extensive succession of interbedded tuffaceous sediments, with some lavas and intrusives, which interfingers with the main lava-rich MRV volcanic belt (particularly the CVC) along its western and northern margin. The important feature of these sequences is the appearance of basalts, particularly in the north of the MRV (Hellyer Basalts), but also in equivalent stratigraphic positions south of the Henty Fault System (Lynch Creek Basalts). An important observation is that Western Volcano-sedimentary Sequence sandstones immediately below basalts both north (Animal Creek Greywacke) and south (Miners Ridge Sandstone between the Que Footwall Andesites and the Hellyer Basalts) of the Henty Fault System are dominated by pelitic metamorphic-derived quartz and muscovite, but contain large red boninitic-derived chromites from the eroding ophiolitic mafic-ultramafic complexes. Late in this episode of basaltic magmatism a sharp change is recorded in the compositions of erupted basalts, from shoshonitic to tholeiitic compositions (e.g. Sock Creek basalts), and then to the Henty Dyke Swarm - Hellyer Dolerite tholeiitic intrusives. Foundering of the basalt-dominated volcanic succession in Late Cambrian led to cessation of basaltic magmatism, accumulation of black shales, and then to the final gasp of the MRV, the extensive felsic pyroclastics and occasional lavas of the Tyndall Group.

4: The Tyndall Group (and correlated Southwell Subgroup) comprises mainly volcaniclastic rocks, but also includes felsic lavas and ignimbrites in several areas (White & McPhie 1996). These rocks overlie the CVC and Eastern Sequence south of the Henty Fault, and contain eroded blocks of Darwin Granite at Mt. Darwin, and late Middle Cambrian fossils at Queenstown. The Tyndall Group is usually overlain by the Owen Conglomerate. Initial ε_{Nd} values (-7 to -9) for Tyndall Group felsic lavas indicate that they too are largely crustal melts.

Key points

In interpreting the tectonic significance of the MRV, the following key aspects of these sequences need to be considered:

(a) Early MRV magmatism is entirely crustal-derived felsic volcanics and shallow intrusive rocks. Limited crustal extension in early MRV times, and pooling of mantle-derived magmas in the lower crust, led to production and eruption of dominantly felsic magmas.

(b) Increasing volumes with time of andesitic and basaltic lavas were erupted both north and south of the Henty Fault System (Que Footwall Andesites, Hellyer Basalts, Sock Creek Basalts, Lynch Creek Basalts, Curtin Davis Volcanics). Within the best understood sequence, around the Que and Hellyer mines, this pillow basalt-andesite pile shows a pronounced temporal increase in the volumes of basalt erupted. The Hellyer Basalts reach at least 400m thick in places, and include common very mafic (8-15% MgO) phenocryst-rich pillow basalts that vary from medium-K to shoshonitic. This reflects increasing crustal extension with time, so that shallow lithosphere-derived basaltic magmas underwent decreasing pooling, cooling and fractionation, and led to eruption of the remarkably primitive upper Hellyer Basalts.

(c) The rapid transition from shallow lithosphere-derived shoshonitic basalts (Hellyer and Lynch Creek Basalts) to tholeiitic basalts with convecting asthenospheric mantle ε_{Nd} values indicates that late in MRV history, crustal extension was so advanced that the asthenosphere rising beneath the developing rift eventually itself decompressed and partially melted, to yield the tholeiites of the Henty Dyke Swarm and Henty Fault Wedge sequence. Sudden cessation of crustal extension after intrusion of the Henty Dyke Swarm led to pooling of hot mafic magmas in the lower crust, and generation and eruption of the crustally-derived felsic magmas of the Tyndall Group.

A post-collisional origin for at least the upper part of the MRV can hardly be denied. The presence of distinctive high-Cr boninitic chromites as detrital grains in sandstones dominated by pelitic metamorphic-derived quartz and muscovite, indicates that the boninitic ophiolites had been emplaced and were being eroded before strongest extension and basaltic magmatism late in the MRV history. As isotopic signatures of andesites above and below these sandstones are essentially identical, I rule out the possibility that most of the MRV (e.g. the CVC) were produced in a continental margin arc via contemporaneous subduction, with only the last basalts as post-collisional magmas.

Preferred model

A preferred model for MRV magmatism is that:

1: East-directed subduction beneath an intra-oceanic arc ceased upon arrival at the trench of highly attenuated continental crust representing the late Neoproterozoic eastern rifted margin of the

Australian craton. Arc-continent collision probably close to 510 Ma emplaced boninitic forearc crust onto the thinned continental crust, to form the allochthonous ophiolites of western Tasmania.

2: Subsequent gravitational collapse, perhaps aided by regional plate kinematics, led to collapse of the new crustal collage assembled in this collision, and triggered crustal extension. This led in turn to eventual emergence of underthrust crystalline, continental passive margin crust (to form the Precambrian Tyennan Region core of Tasmania), and formation of grabens around the exhumed and rising crystalline crust.

3: Post-collisional magmatism was focussed into extensional basins marginal to the exhumed crust. Early felsic magmas were largely of crustal derivation, but increasing extension led to increasingly mafic magmatism, with late andesites and basalts including abundant high-K and shoshonitic compositions derived from shallow lithospheric mantle. Rifting of crust towards the end of MRV magmatism produced asthenosphere-derived tholeiitic magmas, including the Henty Dyke Swarm and pillow basalts and mafic intrusives of the Henty Fault Wedge.

4: In the Late Cambrian, a sudden change in regional plate kinematics terminated crustal extension, aborted generation of new oceanic crust, and led to pooling of basaltic magmas in the lower crust, and subsequent Tyndall Group felsic magmatism, at least some of which was subaerial.

Major VHMS-type ore deposits , and the Mt Lyell deposit, are all located within the upper part of the MRV, close to the time of transition from andesitic to basaltic magmatism, although Rosebery itself is hosted by a felsic pyroclastic succession at this same stratigraphic level. This apparent clustering of major volcanic-hosted ore deposits into a narrow time interval may reflect the significant role played by strong crustal extension and attendant lithosphere-derived basaltic magmatism in generating appropriate ore-forming fluids. Such ore-forming fluids are not typically produced during strong crustal extension and tholeiitic magmatism associated with seafloor spreading for example, reflecting the important role of magma type in controlling the availability of the required S and chalcophile metal budget for ore-forming fluids. An extensional post-collisional setting, particularly if submarine conditions prevail, can provide these necessary ingredients

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The PREDICT Management Information System and its Application to Southeast Australia

R. Dabrowski[1,2], R. J. Korsch[1,2] & T. S. Loutit[1,3]

[1] Australian Geodynamics Cooperative Research Centre
[2] Australian Geological Survey Organisation, GPO Box 378, Canberra ACT 2601
[3] SRK (Australasia) Pty. Ltd., PO Box 250, Deakin West ACT 2600

The PREDICT management information system (MIS) provides key information about the nature, timing and distribution of tectonic events, at varying scales, which have had a bearing on the formation and evolution of terranes/tectonic assemblages and sedimentary basins which host petroleum and mineral resource systems.

System design

PREDICT is based on two key concepts:

- The current understanding of the hierarchy of geological processes and the tectonostratigraphic units that are produced (Figure 1).
- The petroleum system concept (Magoon and Dow, 1994), which is now starting to be applied to minerals systems.

The objectives of the system are to:

- Provide access to the critical information for decisions
- Provide a quantitative estimate of the quality and adequacy of the work
- Document the reasoning behind the interpretation
- Document the source of the information

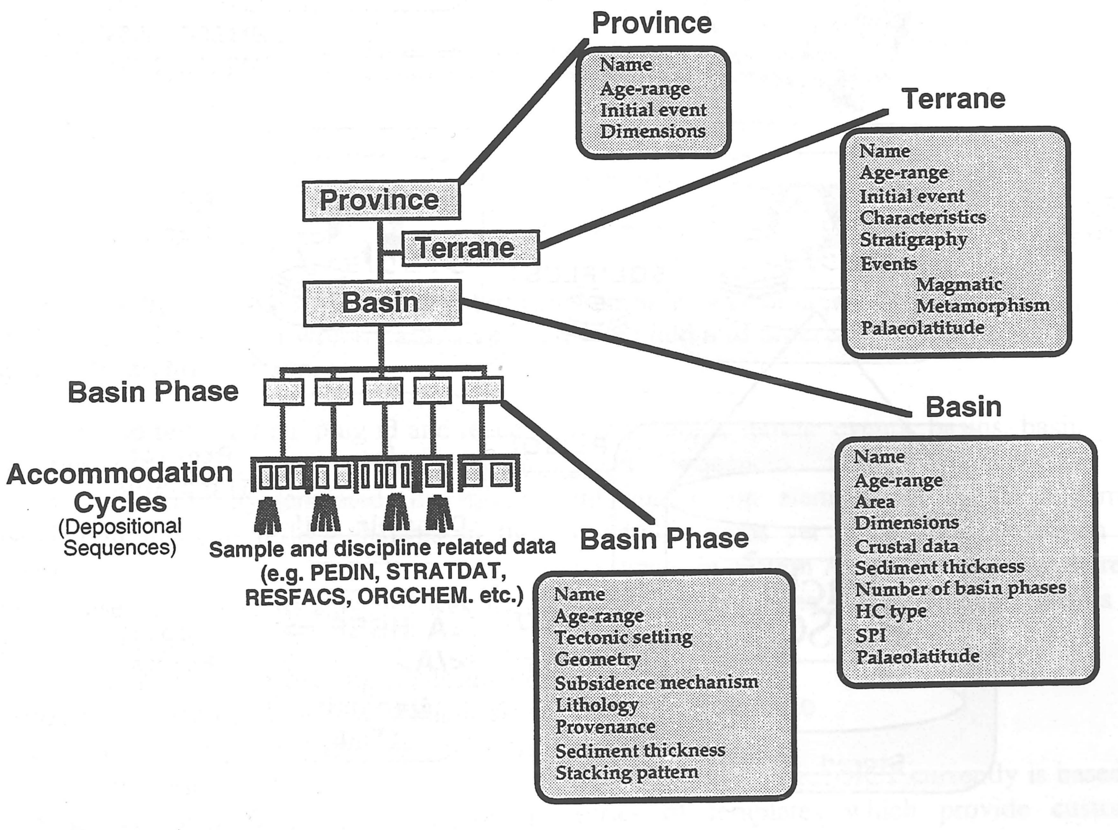

Fig. 1 - Hierarchy of tectonostratigraphic units that provide the basis for the relational database structure in the PREDICT management information system (MIS).

- Document the nature, timing and character of petroleum systems
- Document the impact of geologic events and processes on resources

PREDICT attempts to quantify and synthesise this information in a series of relational database tables which can be interrogated in a structured and meaningful fashion. The outputs from these queries can be represented in a series of pre-defined graphical templates which provide powerful visual tools in assessing resource systems. All aspects of PREDICT can now be accessed via a single world wide web interface, both input and output forms and output templates.

The key features and benefits of this web

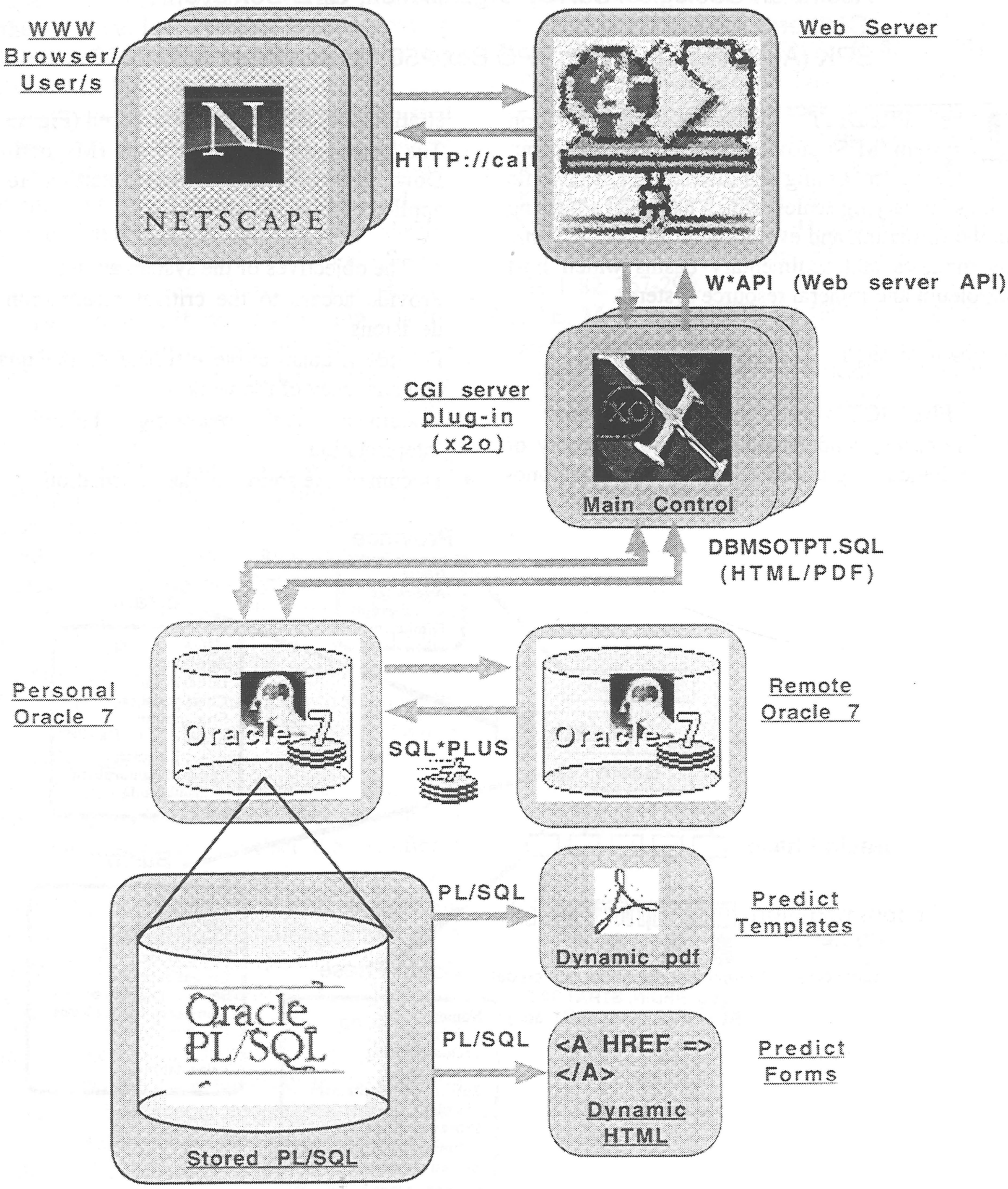

Fig. 2 - Software configuration for PREDICT behind the world wide web-based access interface.

based architecture (Figure 2) are:

- Dynamically generated HTML forms, direct from the database, with no static pages. This means data on pages are a true reflection of the current state of the database, as are any hyperlinks which may be generated.
- Fast response due to tight integration of database and web server.
- Dynamically generated graphics, also direct from the database in a web compatible format known as PDF (Portable Document Format). All that is required is a PDF plug in and reader application on the client's side. These graphics can have dynamically-generated hyperlinks embedded in them to reflect changes in the database.
- Easier to use because of its standard web user interface paradigm.
- Overall, a simpler system because rendering of information is done by off-the-shelf client side applications. Only descriptions of the information are sent to a client.
- Greater access to PREDICT; the web is the best possible audience.
- Platform independent from the client's perspective.
- Quicker prototyping because more effort can be spent on content generation.

Application to the New England Orogen

As a test data set, the terranes/tectonic assemblages of the New England Orogen (Figure 3) have been synthesised (Korsch et al, 1998) and entered into PREDICT, along with the adjacent and overlying sedimentary basins of Permian to Eocene age, some of which are prospective for oil, gas and oil shale. At this stage, most of the effort has been to synthesise information on the terranes, terrane units, terrane events, basins, basin phases, basin sequences and basin events, with information on elements of the petroleum and mineral systems yet to be done. Work on other provinces in eastern Australia, and elsewhere, and some of Australia's sedimentary basins will commence shortly.

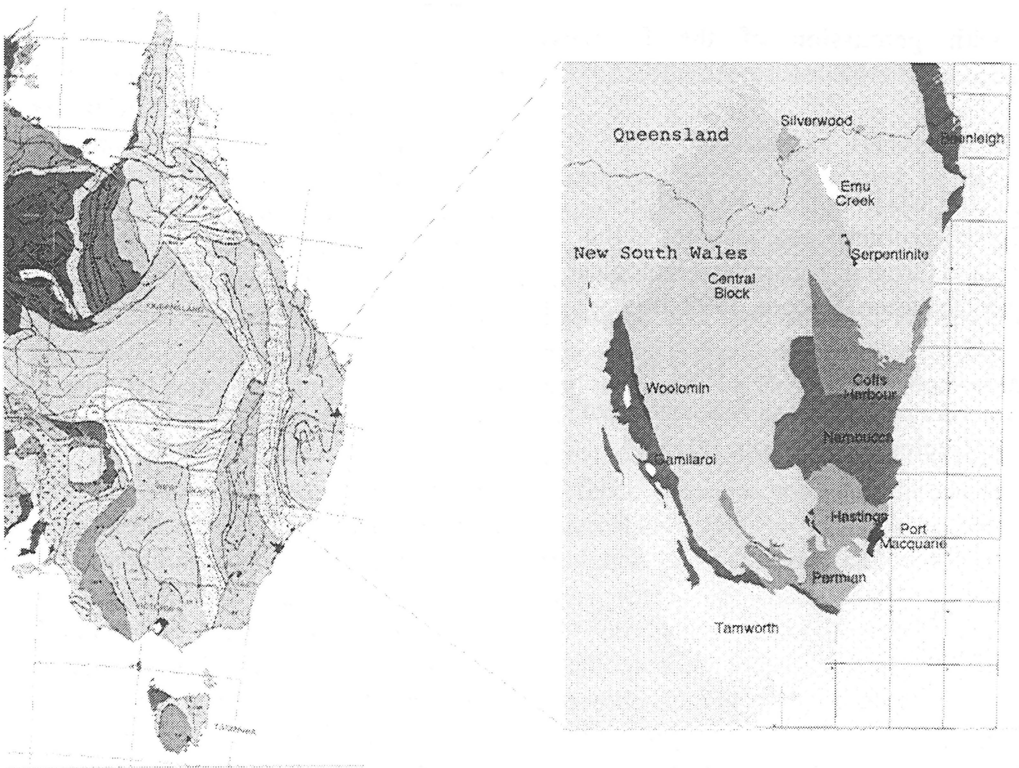

Fig. 3 - Tectonostratigraphic map showing terranes/tectonic assemblages of the southern part of the New England Orogen for which data have been compiled and entered into the PREDICT geological information system.

Future directions

The output from PREDICT currently is based on a series of templates which provide customised views of the interaction of geological processes and their influence on the development of sedimentary basins and their petroleum systems.

The development of the graphic templates allows the digital construction of time-space plots to compare tectonostratigraphic histories for several terranes. Under construction are computer-generated cladograms to allow inspection of the relationship of tectonic processes at plate boundaries with the development of sedimentary basins in intraplate settings. This suggests that there is a causal link between the rotation of the Hastings Block away from the Tamworth Belt and the initiation of the Sydney-Bowen basin system.

Acknowledgements

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Revision of the Type Sections for the Thackaringa Group, Lower Willyama Supergroup Stratigraphy, Broken Hill.

Tony Donaghy[1], Mike Hall[1] and George Gibson[2]

[1] Australian Geodynamics Cooperative Research Centre, VIEPS, Department of Earth Sciences, Monash University, Clayton, VIC 3168
[2] Australian Geological Survey Organisation, Canberra, ACT 2601

The Thackaringa region, located 35 km southwest of Broken Hill, is important for the understanding of the Broken Hill Block. It contains the type localities for the Thackaringa Group, the basal unit of the intracontinental basin-fill Palaeoproterozoic Willyama Supergroup, host sequence of the giant Broken Hill Pb-Zn-Ag ore body (Willis et al. 1983; Stevens et al. 1988). Here we question earlier conclusions regarding the nature of the inferred protoliths and the structural geometry erected on the basis of the assumed stratigraphy. Potential exists for gross simplification of the Willyama Supergroup stratigraphy by removal of units with similar lithological associations that are structurally, rather than stratigraphically repeated within the sequence. Lithologies are reoriented and attenuated on all scales by D2 and D3 mylonite formation, isoclinal folding and transposition, and the superposition of regional scale F4 folds. These observations, combined with mapping of S2 and S3 fabrics and the removal of clearly intrusive "stratigraphic" markers, raise questions about the need for stratigraphic repetition of lithologically similar units attributed to the Lady Brassey and Himalaya Formations and the Cues and Parnell Formations. There is a strong possibility that this repetition is instead structurally controlled and due to the presence of previously unrecognised isoclinal folds. Furthermore, since such repetition occurs at the type localities for the units ascribed to the Thackaringa Group, a complete reassessment of the Thackaringa Group stratigraphy is needed. This has important ramifications for mineral exploration as the Broken Hill style of mineralisation is believed to occupy a discrete stratigraphic position (Willis et al. 1983).

Introduction and background

The Thackaringa region is underlain by lithologies currently assigned to the central and lower portion of the Willyama Supergroup stratigraphy. Stratigraphic units represented include the Thackaringa Group (including all type localities and type sections except for the Rasp Ridge and Alma Gneisses); the Broken Hill Group; and the Sundown Group. The outcrop in the region is dominated by the Thackaringa Group, previously interpreted as a 1-3 km thick sequence of felsic volcanics/volcanosedimentary facies with intercalated feldspar-rich sediments and mafic tholeiitic lavas (summarised in Table 1). Previous work within the Thackaringa region concentrated on producing highly-detailed 1:25,000 scale lithological maps (e.g. Willis 1985). Notwithstanding the absence of reliable sedimentary structures and younging criteria, the intense nature of strain and the degree of partial melting in the region, a stratigraphy was erected using key marker horizons, particularly mafic and quartzofeldspathic gneisses.

Previous structural interpretations of the Thackaringa region (eg Funnell, 1983; Willis, 1984a) were derived mainly from form-line mapping of the assumed stratigraphy. In this approach it was necessary to reconcile perceived repetitions in the assumed stratigraphy with a structural history involving regional-scale, east-northeast-trending F2 folds, subsequent overprinting by minor mesoscopic-scale north-trending F3 and easterly trending F4 folds, all with upright to steep-inclined axial surfaces (Funnell 1983; Willis 1981, 1984a, b, 1985). Fold interference patterns compatible with such an interpretation may indeed be present in the Thackaringa area but they cannot possibly account for many of the new structural observations made in this study, and an alternative view of the regional structure is presented below.

Central to any new structural and stratigraphic interpretation of the Broken Hill region are the enigmatic quartz-albite rocks of the Thackaringa Group. Being so distinctly different from the surrounding psammopelitic lithologies, they have often been used as important marker horizons. Their origin is uncertain and they have been variously described as (a) Na-metasomatised metasediments locally occupying a number of (stratigraphic) horizons (Vernon 1961); (b) partially Na-metasomatised meta-evaporitic horizons, ~1700-1710 Ma A-type metavolcanics and sub-volcanic intrusions, occupying discrete positions in the Willyama Supergroup stratigraphy (Ian Plimer and Paul Ashley pers. comm. 1997); or as (c) well bedded, possibly reworked, sodic felsic analcitised air fall tuffs, deposited in an alkaline lacustrine environment, occupying two discrete positions in the Willyama Supergroup stratigraphy - the Lady Brassey and Himalaya Formations (Willis et al. 1983; Stevens et al. 1988). The Thackaringa region contains the only locality where quartz-albite lithologies are in direct contact with quartzofeldspathic gneisses attributed to the Alma Gneiss. This was used to demonstrate stratigraphic equivalence between one of the quartz-albite localities (the Lady Brassey Formation) and the Alma Gneiss and pin the lowermost portion of the Thackaringa Group stratigraphy (Willis 1984b, Willis et al. 1983; Stevens et al. 1988). The perceived presence of two evaporitic horizons punctuating a predominantly clastic sedimentary sequence of pelites and psammites was used to postulate a cyclic nature of basin formation and water depth during deposition of the Willyama Supergroup (Willis et al. 1983; Stevens et al. 1988).

New observations

The identification of five regional scale deformational events, two of which were associated with widespread shearing and mylonite development, necessitates an alternative explanation for the present distribution of lithologies within the Thackaringa region. Particularly important in this reinterpretation are the D2 and D3 mylonite zones which, together with coaxial folding during the F2, F3 and F4 events, have brought about large-scale transposition, gross attenuation and reorientation of lithological layering. Previously neither the mylonites nor the regional isoclinal D3 folds had been recognised. Moreover, folds previously mapped as F2 either (a) locally do not exist, but are the intersection of D2 and D3 mylonite zones; (b) are F3 folds of D2 mylonite zones; or (c) are D4 folds superimposed on F2 and F3 structures. This provides adequate potential for structural repetition of lithological associations previously separated as different stratigraphic units.

S1 is best preserved within large quartzofeldspathic masses, particularly kilometre scale bodies of quartz-albite rock of the Thackaringa Group, bounded by S2 and S3 mylonites. S1 within the quartz-albites is defined by a biotite foliation axial planar to rare small upright isoclinal folds (F1) and layer parallel along the F1 limbs. Many internal fabrics within the quartz-albite rocks, previously thought to be well developed sedimentary bedding, are better interpreted as syn-S1 and -S2 transposition of layering accompanied by insitu partial melting.

Table 1. Stratigraphic column for the Thackaringa Group with previous interpretations of protoliths. After Willis *et al.* 1983)

Thackaringa Group Stratigraphic Unit	Metamorphic Lithology	Previous Interpretation of Protoliths
Himalaya Formation	Thin-layered albite-quartz rocks; minor basic gneiss;	Thin-bedded, possibly reworked, sodic felsic analcitised air fall tuffs; minor tholeiitic volcanics;
Rasp Ridge Gneiss	Quartz-feldspar-biotite gneiss; minor basic gneiss.	Rhyolitic to dacitic volcanics; minor tholeiitic volcanics; possible subvolcanic intrusives.
Cues Formation	Psammite to psammopelite & composite gneiss; with interbedded basic gneiss; quartz-feldspar-biotite-garnet gneiss, leucogneiss.	Thin-bedded feldspathic sands, silts; with interbedded tholeiitic, rhyodacitic volcanics; rhyolitic air fall tuffs.
Alders Tank Formation	Albitic quartzo-feldspathic composite gneiss.	Bedded feldspathic sediments/volcaniclastics.
Lady Brassey Formation	Layered leucocratic albite-quartz rocks; massive basic gneiss.	Thin-bedded sodic rhyolitic or altered air fall tuffs and volcaniclastics; interbedded tholeiitic volcanics.
Alma Gneiss	K-feldspar megacrystic quartz-feldspar-biotite gneiss; minor basic gneiss.	Rhyolitic-dacitic porphyritic volcanics; and interbedded tholeiitic volcanics.

The first mylonite fabric (S2) is of high metamorphic grade - containing garnet porphyroblasts, melt segregations and a prominent L2 sillimanite mineral lineation within pelitic lithologies. S2 is best preserved within large quartzofeldspathic and mafic gneiss packages boudinaged by the S3 fabric. Within the S2 fabric are numerous quartzofeldspathic melt segregations and rootless isoclinal folds (F1) boudinaged parallel to the sillimanite lineation. S2 and L2 fabric formation is regionally extensive and best developed in pelitic lithologies. Kinematic indicators on rare F2 folds indicate a vergence to the north-west.

The D3 mylonites occur mainly on the limbs of regional-scale F3 isoclinal folds developed in the earlier formed S2 fabric; a composite S2/S3 fabric has resulted. S3 overprints S2 and formed at lower metamorphic grades, bringing about replacement of sillimanite and K-feldspar (in melt segregations) by sericite and muscovite, and garnet by biotite. The axes of the F3 folds plunge parallel to the L2 lineation. The principal extension direction within the S3 fabric is perpendicular to the L2 lineation and leads to extreme attenuation and transposition of competent lithologies along the F3 fold limbs. Kinematic indicators consistently indicate a vergence to the south-east.

S2 and S3 are overprinted by upright mesoscopic asymmetric folds (F4) with variably developed crenulation cleavage as the axial plane fabric (S4). F4 largely forms broad, kilometre scale, monoclinal warps of the S2/S3 fabric. However, tight D4 folds with short 10-20 m wavelengths also occur locally. This is particularly the case within zones of strain partition on the contact between metasediments and large quartzofeldspathic masses.

There is no direct evidence for splitting the quartz-albite lithologies into two distinct stratigraphic horizons. SHRIMP U/Pb zircon studies of quartz-albite samples from the Lady Brassey and Himalaya Formations reveal near-identical sedimentary detrital patterns terminating with a significant population at ~1700-1710 Ma, suggesting a strong correlation with similar rocks in the Olary region west of Broken Hill. Whether they are direct stratigraphic equivalents or the Olary region forms part of the sedimentary provenance for the Thackaringa Group is uncertain. Mapping of the quartz-albite lithologies, as well as S2 and S3 fabrics, reveals that they form a single horizon repeated by regional D2 mylonites, F3 isoclines and local F4 folds. Detailed mapping shows that the Alma Gneiss and many mafic gneisses are clearly intrusive into the surrounding quartz-albite lithologies and not part of the original depositional sequence. Their presence, or lack thereof, should not be used to define a stratigraphic difference. The validity of using other post-depositional features to differentiate between Willyama Supergroup units, such as degree of partial melting and minor Na-Fe metasomatism, is also questioned.

New stratigraphic models

Two scenarios are postulated to explain the observed field and structural relations: (1) the Thackaringa Group comprises two units (Cues Formation and overlying Himalaya Formation) and is at most half its previous interpreted thickness; or (2) the Thackaringa Group comprises a single unit (Himalaya Formation) and the other constituent lithologies are structural repetitions of units from higher within the Willyama Supergroup stratigraphic section.

The former model is the most probable. However, the exact nature of the Cues Formation is controversial and currently under examination. It is largely defined by the presence of Na-Fe metasomatism; mafic-, quartzofeldspathic- and leuco-gneisses; and chemical lithologies (calc-silicates, quartz-gahnites, quartz-magnetites, etc.) of an ambiguous nature. Also, due to mis-interpretation of the quartz-albites as two separate units, not all lithologies previously mapped as Cues Formation belong to this unit, but should be attributed to the Parnell Formation within the Broken Hill Group.

The latter model requires that all quartz-albite outcrops contain anticlinal closures, otherwise basement would be exposed. However, given that (a) the nature of basement in the Broken Hill region is unknown; (b) recognising basement in a severely migmatised and mylonitised granulite-facies terrane would be extremely difficult; (c) the regional effects of D1 are speculative; and (d) quartz-albite lithologies contain abundant F1 and F2 closures, the scenario cannot be discounted.

Implications

The Thackaringa region is important for the understanding of the Broken Hill Block. It contains the type localities for the Thackaringa Group, the basal unit of the intracontinental basin-fill Palaeoproterozoic Willyama Supergroup, host sequence of the giant Broken Hill Pb-Zn-Ag ore body. As demonstrated above, potential exists for gross simplification of the Willyama Supergroup stratigraphy within the Thackaringa region by removal of units with similar lithological associations that are structurally, rather than stratigraphically repeated within the sequence. Consequently some revision of the structure, stratigraphy and palaeoenvironment is necessary. This in turn has implications for mineral exploration in Broken Hill as the Broken Hill Pb-Zn-Ag style of mineralisation is believed to occupy a discrete stratigraphic location.

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Crustal Architecture and Processes in Southeast Australia from Seismic Studies

Barry J. Drummond & Clive D. N. Collins

Australian Geodynamics Cooperative Research Centre
Australian Geological Survey Organisation
GPO Box 378
Canberra ACT 2601

High surface topography is usually compensated isostatically by a combination of crustal roots floating in the mantle (Airy isostatic equilibrium), and low density rocks in the crust (Pratt isostatic equilibrium). Wellman (1976) found that in eastern Australia isostatic compensation is mainly at the base of the crust, and only partly in the upper mantle. This would imply a predictable relationship between elevation, crustal density and crustal thickness. In this paper, the relationship is discussed for each of the geological provinces in southeast Australia as a first order study of the evolution of the crust. The provinces discussed in this paper are shown in Fig. 1

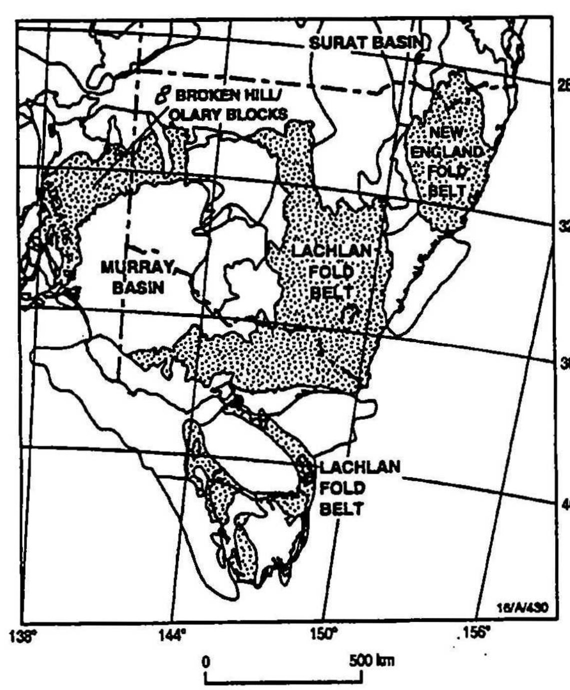

Fig. 1. Area of southeast Australia discussed in this paper

Southeast Australia contains both the highest topography and the thickest crust mapped to date in Australia. The thickest crust, at 50-55km, was measured along a profile from Dartmouth in north west Victoria to Marulan New South Wales, where the elevation in places reached nearly 2,000m, and averaged over 850m. Very high elevations (by Australian standards) are also found in the New England Fold Belt, but the crust there does not seem to be abnormally thick. A plot of surface elevation versus crustal thickness for the main geological elements of southeast Australia, for which crustal thickness measurements have been made, is shown in Fig. 2. In Fig. 2, average elevations along the profile were used. Crustal thicknesses were derived mostly from Collins (1991). The value for Broken Hill is from Leven et al. (this volume). In the sections below, the measurements for each province are compared to values for an average Earth.

Average Earth models

Christensen & Mooney (1995) derived estimates of average seismic velocity at 5 km depth intervals through the crust, based on 560 seismic refraction profiles from around the world.

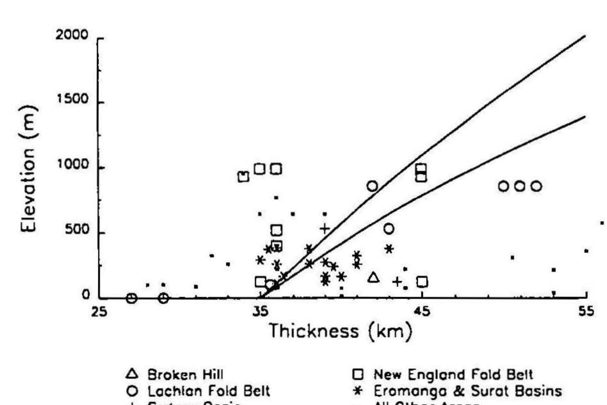

Figure 2. Surface elevation versus crustal thickness. Symbols used are defined in the legend. The continuous curves are for average crust floating in average mantle (upper curve), and for average crust floating in mantle typical of southeast Australia (bottom curve).

Their values, with standard deviations shown as "error bars", are plotted in Fig. 3. The smooth curve plotted through the values is a second order polynomial fitted to the values in a least squares of residuals sense. It predicts a velocity at the surface, ignoring sediments, of 5.75 kms^{-1}. The velocity increases to 7.14 kms^{-1} at 50 km depth. Most crustal models have intracrustal discontinuities but they have been smoothed out in the global average. Christensen & Mooney (1995) estimated average upper mantle Pn velocity to be 8.09 kms^{-1}.

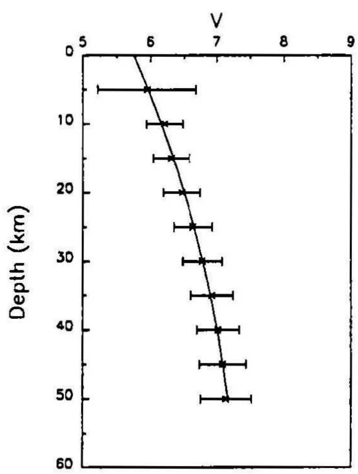

Figure 3: Average velocity values in the crust (from Christensen & Mooney, 1995)

Figure 4 shows two crustal density-depth models derived using the global average curve in Fig. 3 and the velocity-density relation of Dooley (1991). The curve labelled (a) has depth to the top of the Moho transition zone of 30 km. The curve labelled (b) has it at 50 km depth. The Moho transition zone is 5 km thick in both models. The models have densities of 2.67 tm^{-3} at the surface, 3.05 tm^{-3} at 50 km depth and 3.35 tm^{-3} in the mantle.

Surface elevation was predicted for a number of models with different crustal thicknesses (Fig. 5). The assumptions made were:

1) Model (a) in Fig. 4 has no surface elevation. In Fig. 2 crust is thicker than 35 km, and thinner crust generally has very little surface elevation.

2) Thicker crust floats higher because the base of the crust displaces more dense mantle. The surface elevation due to perfect, point wise Airy isostatic equilibrium is shown in Fig. 5 by the curve labelled 100%. The other curves show the cases where only 75% and 50% of the crustal load is supported by buoyancy, and the rest by other means, eg., the strength of the crust or lower than average crustal densities.

The model predicts elevations up to 2,000m for crust where the depth to the bottom of the Moho transition zone is at 55 km depth. Elevations of this order are found in southeast Australia where the crust is 55 km thick, but regionally elevations are generally less.

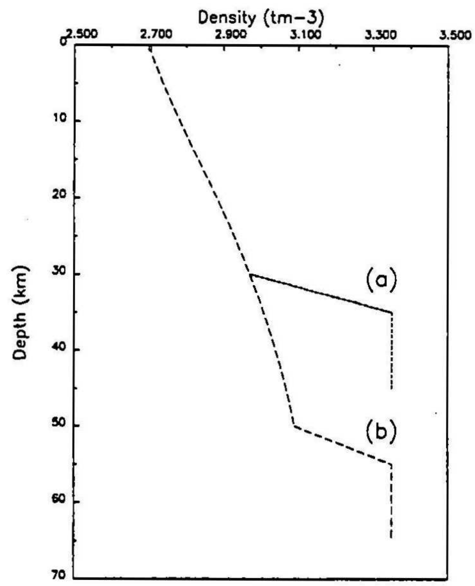

Figure 4. Models of standard crust (a) depth to Moho transition zone 30 km, and (b) 50 km. Moho transition zone 5 km thick in each case.

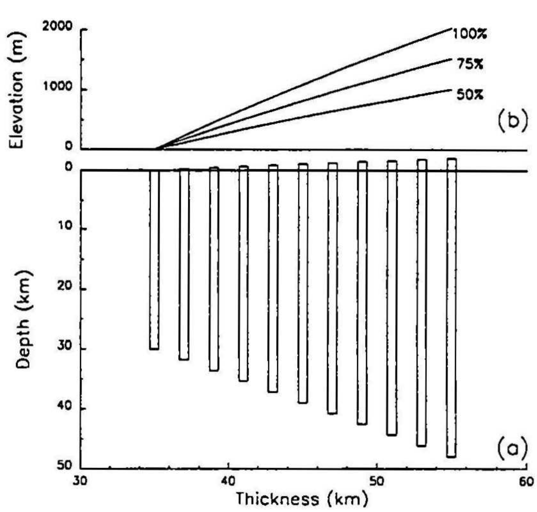

Figure 5. (a) columns of crust of different thickness floating in the mantle. The column on the left (35km) is assumed to have no elevation. (b) surface elevation supported 100%, 75% and 50% by buoyancy forces.

Lower than predicted surface elevations could also result if the crustal root displaces mantle of a lower density than that in the average model. Figure 6 shows histograms of uppermost mantle (Pn) seismic velocities. Figure 6(a) shows measure-ments from southeast Australia; Fig. 6(b) shows data from other Australian provinces. The dashed vertical line at 8.09 kms^{-1} is the global average Pn velocity from Christensen & Mooney (1995). Values in Fig 6(b) from provinces not in southeast Australia cluster around the global average. However, those in southeast Australia (Fig. 6(a)) are significantly lower, around 7.8 kms^{-1}. The lower measurements come predominantly from the Lachlan and New England Fold Belts. These histograms reflect the numbers of measurements, and not necessarily the areal distribution of Pn velocities.

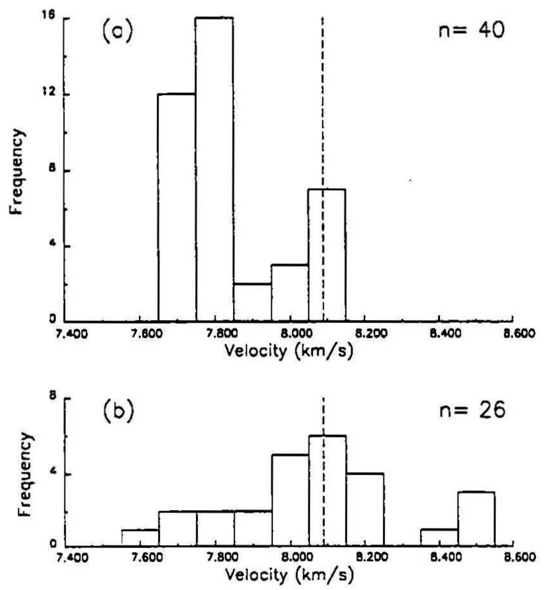

Figure 6. Histograms of upper most mantle (Pn) velocities. (a) values from SE Australia. (b) all other areas in Australia. The dashed line shows world average value from Christensen & Mooney (1995).

A Pn velocity of 7.8 kms^{-1} corresponds to a density of 3.25 tm^{-3} using Dooley's (1991) velocity-density relation. This is 0.1tm^{-3} less than the global average value. In Figure 2, the lower of the two continuous curves represents the estimated surface elevation of standard crust floating in upper mantle with a seismic velocity similar to that observed under the eastern Lachlan Fold Belt. The lower value of upper mantle velocity results in less buoyancy for the crust, so the crust has a commensurate lower surface elevation; the effect is of the order of 600 m for the thickest crust, and less for thinner crust. It may be a factor in why regional elevations in southeast Australia are less than predicted from global average models, but compensation by some other means is also likely, as shown in the elevation curves in Fig. 5(b).

Velocity models in each province

Broken Hill Block

The velocity depth model for the Broken Hill Block is shown in Fig.7. World average values, at 5 km depth intervals are also shown.

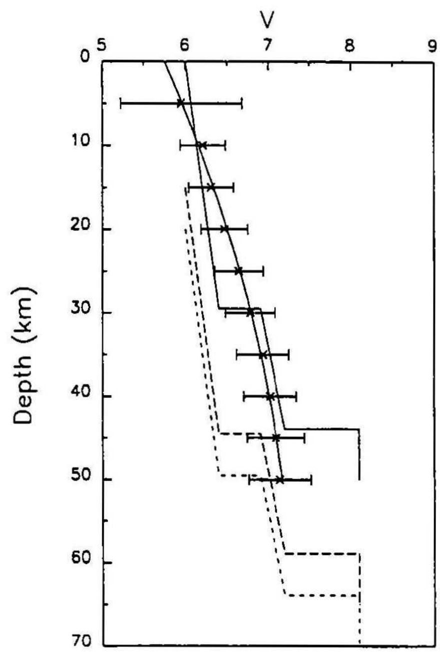

Figure 7. Velocity depth model for the Broken Hill Block (solid curve). Dashed and dotted curves show the model displaced downwards by 15 km and 20 km, respectively.

In Fig. 2, the model for Broken Hill (triangle) lies below the theoretical curve; that is, the crust in Broken Hill must be slightly denser than average crust. The solid curve in Fig. 7 shows the velocity-depth curve in its present position. It has higher than world average velocities near the surface, lower than world average velocities between 10 and 30 km depth, and higher velocities in the lower crust.

The Broken Hill Block has undergone significant uplift; metamorphic grades at the surface reach 0.5 - 0.6 Gpa (5 - 6 kBars) (Phillips & Wall, 1981). That is, about 15-18 km have been removed by erosion, and the crust must once have been 55-60 km thick.

Uplift and erosion can be estimated from the surface elevation model in Fig. 5. This is done by removing the elevated portion of the crustal column (eroding it). This unloads the crust, allowing it to rebound. The height of rebound is less than the height of the topography removed. Gradually the crust will reach a new equilibrium, with no surface elevation and a very much thinner crust, but with a higher average crustal density. Estimates of rebound are shown in Fig. 8; they may be underestimates because of the numerical approach used in the calculations.

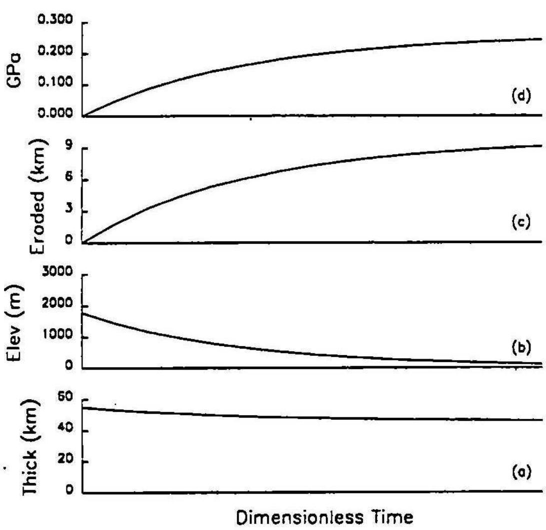

Figure 8. (a) Crustal thickness as a function of time, as surface topography is removed. (b) Surface elevation in metres. (c) Amount of erosion in kilometres. (d) Metamorphic pressures at the surface in Gpa.

Global average crust originally 55 km thick (curve (b) in Fig. 4) will eventually rebound to produce crust approximately 46 km thick. The pressures at the surface would be about 0.25Gpa, or approximately half those observed in Broken Hill. In Fig. 7, the present day velocity depth model has been replotted displaced downwards by 15 and 20 km (dashed and dotted curves, respectively), or about the amount of observed uplift. These curves show what the velocity depth model would have been before the crust was eroded. The velocities in the displaced models fall well below world average values throughout most of the crust. This means that the crust in the Broken Hill Block must have been very much more buoyant than global average crust. If the original crust was 55 - 60 km thick, it would have rebounded and eroded considerably more than that predicted in Fig. 8 for global average crust.

Lachlan Fold Belt

The velocity depth models for the Lachlan Fold Belt plot below and to the right of the theoretical curves in Fig. 3. This means that the average velocity (density) in the crust in the Lachlan Fold Belt is presently higher than global average. Velocity depth models for the Lachlan Fold Belt, with sediments excluded, are shown plotted with global average values in Fig. 9.

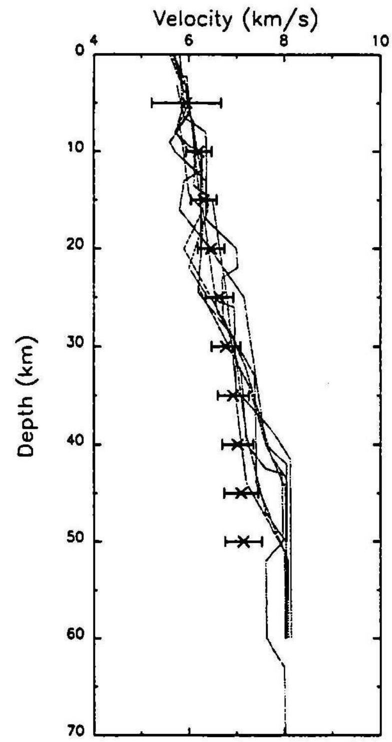

Figure 9. Velocity depth curves for the eastern Lachlan Fold Belt, with global average values superimposed.

Velocities in the upper crust show considerable variation either side of global average values. However, the velocities in the lower crust between 30 and 50 km depth are consistently higher than global average. This means the buoyancy of the lower crust is less than predicted from global average models and the Lachlan Fold Belt will have lower elevations than predicted.

The high velocity and therefore dense lower crustal root in the Lachlan Fold Belt is the proposed source of I-type granitoids. It contrasts with that of the lower crust in the Broken Hill Block, which has S-type granitoids (Wyborn et al., 1992) and much lower seismic velocities in the lower crust.

New England Fold Belt

The models for the New England Fold Belt plot either side of the global average curves in Fig. 2, suggesting the crust there has close to average densities (and velocities). This is shown in Fig. 10. Velocities in the upper and lower crust are close to or just below global average values; low values are offset by high velocity lenses in the middle crust on some profiles.

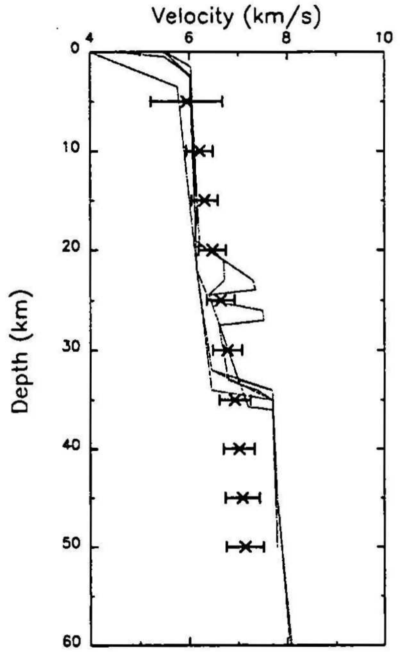

Figure 10. Velocity depth models for the New England Fold Belt, with global average velocities.

<u>Sydney Basin</u>

Models for the Sydney Basin plot below the curve for global average crustal models in Fig. 2. This means that the crust is probably denser (higher velocities) than global average crust of that thickness. This is shown in Fig. 11. Velocities are close to global average in the upper crust and above it in the middle crust. The region has a thick Moho transition zone, resulting in lower crustal velocities considerably above global average.

<u>Eromanga & Surat Basins</u>

The Eromanga and Surat Basins have low surface elevations. Their models plot either side, and perhaps biased slightly to the right of the curves for global average models in Fig. 2. The crust there must be close to global average. This is shown in Fig. 12, where, neglecting sediments, velocities plot close to global average values throughout the crust.

Tectonic processes

The previous discussion ignores the tectonic processes which generated the crust. Drummond & Collins (1986) considered a number of mechanisms for generating thick crust with high velocity lower crustal roots, and especially mechanisms for forming it from thin crust in which the lower crustal velocities are less. They

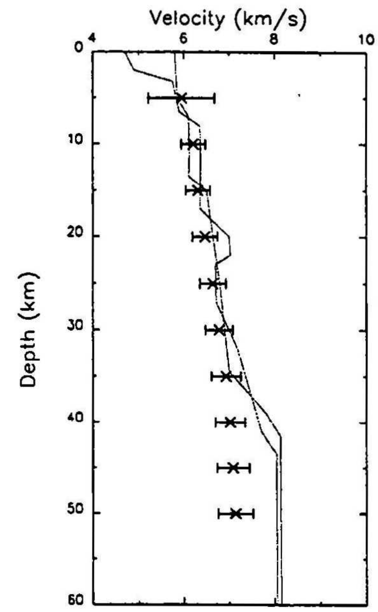

Figure 11. Velocity depth models for the Sydney Basin, with global average velocities.

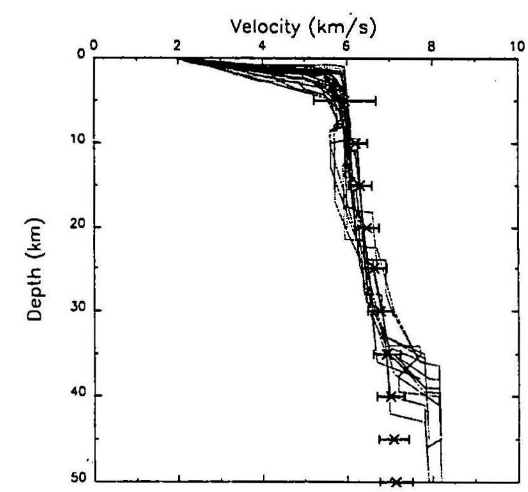

Figure 12. Velocity depth models for the Eromanga and Surat Basins, with global average velocities.

favoured a mechanism including underplating by mafic magmas for the Lachlan Fold Belt, where a mafic lower crust is required by geochemical models for the generation of I-type granites in the eastern Lachlan Fold Belt. This is consistent with the velocities in the lower part of the thickest crust in the Lachlan Fold Belt being higher than global average.

Mafic rocks are not required by the seismic models for the Broken Hill Block; rather tectonically thickened, previously thin crust is more appropriate.

Seismic sections of Broken Hill show strong linear east-dipping reflections, many of which correlate with shear zones(Fig. 13). However, shortening on steeply dipping faults sufficient to thicken thin crust to 60 km prior to uplift and erosion, is difficult to achieve on steeply dipping faults. Sub-horizontal decollement surfaces have been interpreted between stations 2,000 and 2,400. These decollement surfaces, if previously present throughout the crust, must have been overprinted by younger, steeply dipping shear zones.

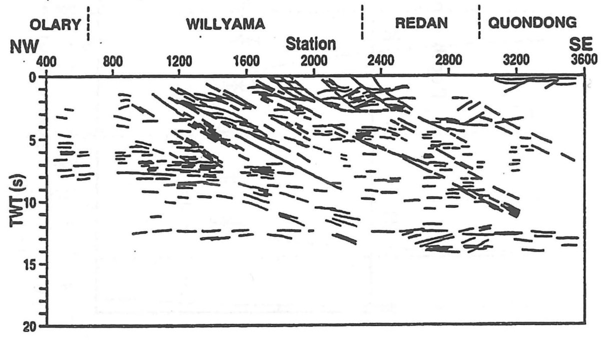

Figure 13. Line drawn interpretation of a seismic cross section of Broken Hill (Fomin et al., this volume).

Decollements have been interpreted in the crust below the Cobar Basin east of the Broken Hill Block (Drummond et al., 1992). There, modelling of upper plate movement across a ramp in the mid-crustal decollement reproduces the overall geometry of the Cobar Basin and the areal distribution of faults along the basin margins and within the basin. The decollement has a distinctive reflection character (DD' in Fig. 14) that can be found in other reflectors (eg., the Moho MM'), suggesting the presence of a number of stacked decollement surfaces which were probably active at different times.

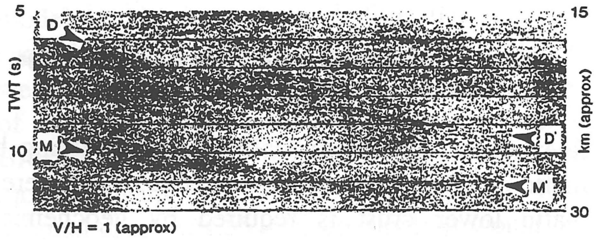

Figure 14. Part of a seismic image of a mid-crustal decollement under the Cobar basin.

The implication is that thin crust can deform by thin skinned tectonics along sub-horizontal decollement surfaces, but once it has reached a critical thickness, it can deform only by thick skinned processes acting on shear zones and faults which penetrate almost the whole of the crust. Once that happens, more vertical, buoyancy driven tectonics inferred earlier in the paper are likely dominate.

Acknowledgments

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Tectonic Setting of Silurian-Devonian Deformation Patterns, Eastern Lachlan Fold Belt, Southeastern Australia

Christopher L. Fergusson

School of Geosciences, University of Wollongong, NSW 2522, Australia

The tectonic setting of the Lachlan Fold Belt in southeastern Australia for the Silurian to Devonian interval has been related to a number of possibilities. Powell (1984), on the basis of palaeogeography and structure, suggested that the Silurian-Devonian tectonic setting was a dextral transtensional margin somewhat akin to an inverted image of the Pacific coast of North America. Chappell (1994) does not nominate a tectonic setting for this time but notes that the I-type granites of the Lachlan Fold Belt were not related to subduction. Coney (1992, p. 9) found the precise tectonic setting puzzling but noted that a "seemingly necessary major convergent plate boundary between the proto-Pacific plates and the Lachlan must have existed somewhere to the east of present Lachlan exposures". This view was particularly influenced by the extent of convergent deformation although he noted that the magmatism was probably unrelated to a "flapping" Benioff zone.

Collins (1994) related the Silurian-Devonian tectonic setting of the Lachlan Fold Belt to a subduction zone at the eastern margin of the belt. He suggested that the unusual width of magmatism could be attributed to lithospheric delamination processes. Earlier, Collins and Vernon (1992) had used multiple subducting slabs to explain the magmatic pattern of the Lachlan as noted in some older reports. More recently Gray (1997; Gray et al. 1997) has also argued for multiple subducting slabs in the Lachlan in an attempt to account for the complex deformation patterns. He has suggested that three accretionary subduction complexes and associated magmatic arcs dominate the Lachlan Fold Belt.

Fergusson and Coney (1992) related the tectonic setting of the Silurian-Devonian Lachlan Fold Belt to a convergent margin, with remnants of the subduction zone preserved in the neighbouring New England Fold Belt. Thus the Lachlan was thought to contain intra-arc to backarc settings. They emphasised that the deformation within the Lachlan Fold Belt was an example of intraplate deformation rather than occurring at a plate boundary or in a collisional setting.

In this report, the tectonic setting for the Silurian-Devonian history of the Lachlan Fold Belt is related to a convergent margin. The former subduction zone is inferred to have existed in the New England Fold Belt as argued by others. An analogous modern setting is considered for the Lachlan Fold Belt followed by an analysis of the subduction zone and the deformation patterns in the Lachlan Fold Belt.

Analogous modern setting

One of the most puzzling features of the Lachlan Fold Belt is the exceptional width of the zone of intense deformation, which is over 700 km in an east-west extent across the Victorian sector of the fold belt. This fact alone has even led some to question the role of plate tectonics in the evolution of the belt. Most convergent margins are considerably narrower than the Lachlan Fold Belt that in any case does not contain the full spectrum of forearc elements. The Central Andes is an example of a convergent margin where the system is up to 800 km across from the coast inland. A foreland fold-thrust belt is exposed at the eastern part of the Central Andes in Bolivia and is characterised by east-vergent thin-skinned thrust systems (Roeder 1988). In the Altiplano and eastern Cordillera of the Central Andes, west-vergent thrusts are well developed and synthetic to the Andean subduction zone (Lamb et al. 1997). The widespread Cainozoic deformation has been accompanied by significant tectonic erosion in the forearc as is well documented off the coast of Peru (von Huene and Lallemand 1990).

Although the extent of deformation in the Central Andes is reminiscent of that in the Lachlan Fold Belt there are still many significant differences between these two convergent margin systems. The Central Andes has developed from crust of normal continental thickness and Precambrian crystalline basement probably underlies much of the belt. Cainozoic tectonics in the Central Andes has resulted in a present-day crustal thickness up to double normal continental crust. In contrast the Silurian crust of southeastern Australia developed from a type of Cambrian oceanic crust (infant arc crust of normal oceanic thickness) and crustal thicknesses probably never far exceeded normal continental crust. The widely developed shallow marine environments that occurred in the Silurian-Devonian interval in the Lachlan Fold Belt show this. In contrast to the Central Andes, no antithetic Silurian-Carboniferous foreland fold-thrust belt occurs along the craton-ward margin of the Lachlan Fold Belt.

Subduction zone

As noted above it has been suggested that remnants of the subduction zone associated with the Lachlan Fold Belt in the Silurian-Devonian interval may be preserved in the New England Fold Belt. Evidence for subduction in the Early Palaeozoic of the southern New England Fold Belt is indicated by the presence of Cambrian supra-subduction zone ophiolites, Ordovician blueschists and a Cambrian-Ordovician subduction-related volcanic succession. In-situ Silurian - Early Devonian rocks appear to be largely absent from the southern New England Fold Belt, but a well developed mid- to Late Devonian subduction-related volcanic and marine succession is present (Tamworth Group).

The lack of a Silurian - Early Devonian record could reflect several possibilities: (1) cessation of tectonic activity; (2) removal of this record by terrane displacements; (3) the record is hidden at depth; and (4) removal of the record by tectonic erosion at that time or at a later time. Unless widespread terrane displacements have occurred it seems plausible that a continuous active subduction zone has existed in the New England Fold Belt throughout the Palaeozoic era. The existence of Ordovician blueschists in the western part of the accretionary subduction complex is taken as evidence that the subduction zone has been in more-or-less its present tectonic location.

By the Early Carboniferous major growth of the subduction complex was occurring. No Silurian to mid-Devonian subduction complex is recognised, although Silurian rocks are incorporated in the Late Devonian - Carboniferous subduction complex. The lack of a subduction complex of Silurian to mid-Devonian age, and even the lack of volcanic rocks and their derivatives of this age, could reflect tectonic erosion occurring along the subduction zone. In this respect tectonic erosion was probably synchronous with major deformation and crustal development in the Lachlan Fold Belt as has been the case for the Cainozoic development of the Central Andes.

Deformation Patterns

The eastern Lachlan Fold Belt is affected by intense deformation with many spaced discontinuous faults and abundant folds. The pattern of shortening is variable with the oldest rock units usually showing the most intense folding. Ordovician quartz turbidite successions are always tightly folded with mainly upright structures although areas with gently dipping axial planes occur. Multiple deformation is documented in many areas although typically only one major episode of intense folding is developed in most regions. Shortening values of 50-60% have been calculated on the basis of folding in the Ordovician rocks. Silurian to mid-Devonian successions are also affected by abundant, mainly upright folds although in most areas shortening estimates are less than for underlying Ordovician rocks (see Fergusson and Coney 1992). Fold vergence is variable but in many areas of the eastern Lachlan Fold Belt vergence is towards the east.

Across the Lachlan Fold Belt cleavage development is variable with metamorphism usually of biotite grade or lower with some areas of regional low-pressure metamorphism associated with plutonic rocks. Metamorphic rocks have been exhumed from a depth of no more than 10-12 km (Collins and Vernon 1994). The widespread development of intensely folded strata and the lack of any demonstrated undeformed basement are consistent with a thick-skinned style of deformation; presumably all of the original crust of the Lachlan was involved in the deformation.

The nature of the faults in the Lachlan Fold Belt is diverse. Thrust faults have been mapped but mostly are characterised by steep dips and usually relatively modest net slips (< 5 km). In some areas major low-angle thrusts must be present as occurs in the Yalmy region of eastern Victoria (see Glen 1992). Here the low-angle thrusts are linked into a décollement that most likely separates underlying Early Ordovician Pinnak Sandstone at depth from an overlying structural lithic unit containing Late Ordovician Warbisco Shale and Early Silurian Yalmy Group. Presumably all thrusts in the Lachlan Fold Belt formed at relatively low-angle dips (< 40°) and were subsequently steepened during contractional deformation. Many strike-slip faults also occur. Faults were developed as parts of networks and individual faults characteristically are discontinuous. Many steepened thrusts have probably been reactivated as strike-slip faults. The significance of extensional faults in the Lachlan Fold Belt is unresolved.

Structural trends are remarkably variable in the eastern part of the Lachlan Fold Belt. Much of this variation has been attributed to multiple deformation. In many regions structural trends are northerly. The presence of early east-west trending structures has been identified in parts of the belt and these have been related to an overall major dextral transpression (e.g. Powell 1984). These structures are particularly well developed in the southern Tabberabbera zone of eastern Victoria. It appears that the structural grain of the southern Tabberabbera zone swings from an easterly trend to a more east-northeast trend in the Yalmy region and then to a more north-northeast trend across the border into southeastern New South Wales. The structural trends are defined by the strikes of bedding, cleavage and faults. The full significance of these curved structural trends are not yet fully understood but presumably are related to some overall control from the tectonic geometry and are not a reflection of oroclinal bending.

Collins and Vernon (1992), Fergusson and Coney (1992), Glen (1992) and more recently Gray (1997) and Gray et al. (1997) have reviewed the deformation patterns with respect to timing in the Lachlan Fold Belt. The pattern of timing of deformation is complex and far from fully determined. In the former Hill End Trough and adjoining platforms in the northeastern Lachlan Fold Belt the regional deformation is of latest Devonian to Early Carboniferous age. Elsewhere Silurian to mid-Devonian deformation is far more prevalent although in some areas (e.g. Yass region) the timing of regional deformation is uncertain. Much intense deformation must have occurred during the Silurian to accomplish crustal thickening required for widespread shallow-marine deposition in the Late Silurian and major intrusion of granitic rocks at the same time.

Concluding discussion

The tectonic development of the Lachlan Fold Belt in the Silurian to mid-Devonian reflects a convergent margin setting with widespread contractional deformation. At the same time much of the Lachlan Fold Belt was characterised by basinal deposition with deep- to shallow-marine and subaerial settings with accompanying silicic to mafic volcanism. Most deep-water sedimentation was restricted to the volcanic Hill End Trough and the non-volcanic Melbourne Trough apart from areas of deep-water sedimentation in the Cobar Basin and elsewhere.

In contrast, the Cainozoic history of the Altiplano in the Central Andes was dominated by fluvial sedimentation accompanied by silicic (ignimbrites) and mafic volcanism (Lamb and Hoke 1997). The settings in both the Silurian-Devonian Lachlan Fold Belt and the Cainozoic Central Andes are considered similar in that they both represent sedimentation during crustal thickening rather than crustal extension. Many authors have inferred that significant extension occurred during the Silurian - Early Devonian history of the Lachlan Fold Belt despite its well documented orogenic history. At the broadest scale deformation and sedimentation have been synchronous in both the Lachlan Fold Belt ("Lachlan Orogeny", see Gray et al. 1997) and the Central Andes (see Lamb and Hoke 1997). In detail within regions, such as eastern Victoria and elsewhere, distinct phases of deformation are recognisable and attributable to the traditional orogenic scheme (e.g. Benambran, Bindian, Tabberabberan and Kanimblan).

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(Note that only recent references to Lachlan Fold Belt and Central Andes are included.)

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Wide-angle Seismic Profiling and Crustal Architecture along the Molong-Wyangala Structural Zone, Eastern Lachlan Orogen - Preliminary Interpretation

D. M. Finlayson, J. H. Leven, A. Owen, T. Barton and D. W. Johnstone

Australian Geodynamics Cooperative Research Centre,
Australian Geological Survey Organisation, GPO Box 378,
Canberra A.C.T. 2601

The tectonic history and structural development of the Lachlan Orogen has been described at length by numerous authors but there are still conflicting opinions on quite fundamental questions regarding the subsurface geology. Most authors agree with outcrop descriptions summarised by VandenBerg and Stewart (1992) indicating that Ordovician rocks form the bedrock throughout most of the Lachlan Orogen. Ordovician turbidites deposited in a deep-water environment are seen in outcrop over a large area and Ordovician mafic volcanics are evident in the northeast. These volcanics are the target of much mineral exploration activity and, in particular, those in the Bathurst-Orange region of New South Wales are associated with some world-class copper and gold orebodies. Hence there is considerable economic interest in determining a better understanding of the tectonic history and sub-surface geology of that region.

This paper contains the preliminary results from a wide-angle seismic investigation of intra-crustal velocities (compositions) from the Eastern Belt of the Lachlan Orogen that includes the Bathurst-Orange region (Fig. 1). A 350 km seismic profile was located along the north-south trending Molong - Wyangala High described by Scheibner(1996) that includes outcrop of the Molong Belt of Ordovician volcanics. In particular, the seismic work investigated the Lachlan Transverse Zone (LTZ), a west-northwest trending structural zone through the Bathurst-Orange region regarded by Glen and Wyborn (1997) as an important feature of early tectonic development with possible contrasting intra-crustal structures and compositions across the zone to the north and south.

Geological background

Although there is agreement that the Lachlan Orogen of eastern Gondwanaland developed into continental crust during the early Palaeozoic, there is still debate about how it evolved and what forms the substrate to the exposed rocks. Glen (1997) describes the Lachlan Orogen as forming at a convergent continental margin from mid-Cambrian to Early Silurian times, before being subjected to back-arc extension, felsic volcanism, and granite emplacement until the Late Devonian. Using recent geochemical data, Glen (1997) favours an intra-oceanic island arc setting for the Ordovician volcanics of the Lachlan Orogen resting on a Cambrian oceanic crust and related to west dipping subduction of the palaeo-Pacific plate beneath eastern Gondwanaland.

VandenBerg & Stewart (1992) indicate that four belts of Ordovician volcanics are recognised but the belts are thought to have been originally connected; they favour hot-spot volcanism as the mechanism for the volcanics. Wyborn (1992), using geochemical arguments, prefers a model involving delayed heating, melting and thinning of a sub-continental lithosphere. Gray et al. (1997) envisage southwest-Pacific-type subduction processes acting on an oceanic crust adjacent to the Gondwana continental margin.

In the Eastern Belt of the Lachlan Orogen, Glen (1992) describes the major structures in terms of "thin skinned" tectonics, with surface contractional faults flattening into upper crustal detachments at about 4 km depth but also with some deeper level thrusts to about 10-14 km. Below these depths however, Glen (1992) speculated (to accommodate evidence from

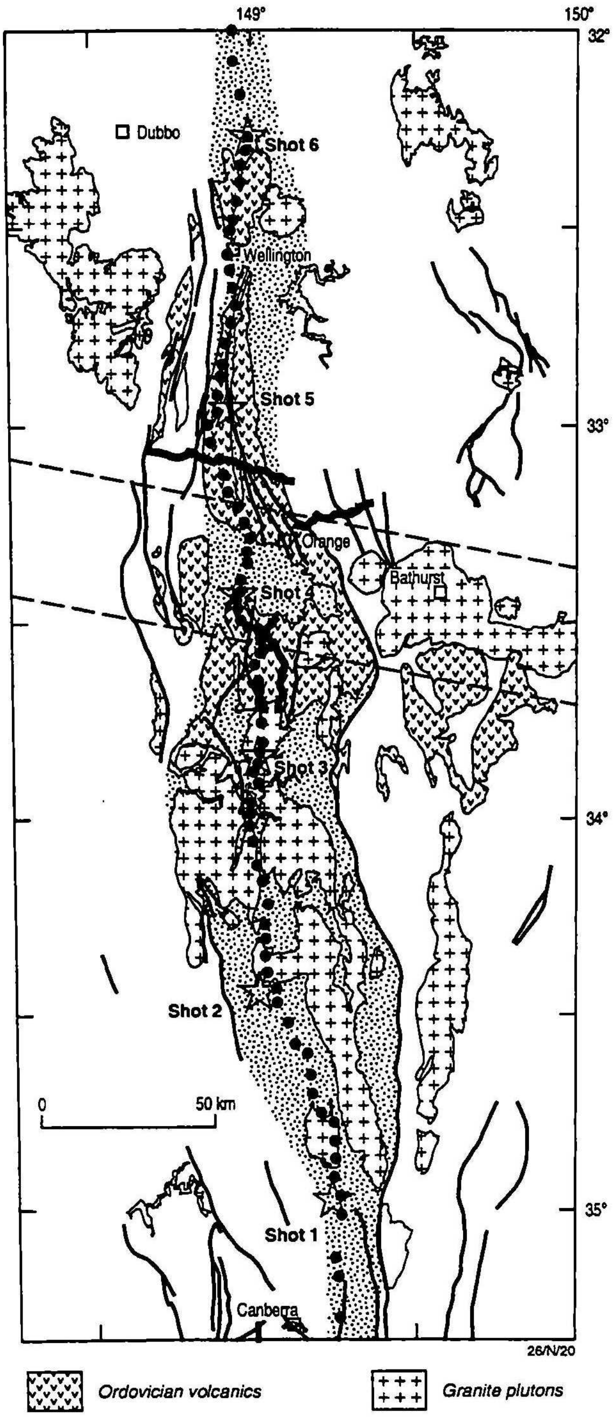

Fig. 1 - Simplified geology of the Molong-Wyangala Structural Zone and location of 1997 wide-angle seismic profile. Also shown are the locations of three 1997 seismic reflection profiles (heavy black lines).

granite source rock geochemistry) that the middle and lower crust of the Eastern Lachlan Belt comprises an underthrust Precambrian slab about 30 km thick.

In the Orange-Bathurst region there are three belts of Ordovician volcanics and Glen (1997) interprets these three present-day belts as being relics of a single large belt that has been subjected to extensional thinning, thrusting and strike-slip faulting. Glen & Wyborn (1997) have drawn attention to west-northwest oriented structures across the region that form what they call the Lachlan Transverse Zone (LTZ). This zone is regarded as being a crustal-scale tear / fault / accommodation zone controlling deformation in the region and it is inferred to be the locus of large mineralised intrusive/volcanic complexes along its length, known to host some world-class porphyry copper and gold orebodies.

Previous crustal models

A number of wide-angle seismic surveys have been conducted previously across the Lachlan Orogen during the 1960s and 1970s and, in the target region for this current investigation, we can obtain velocity data from interpretations by Finlayson et al. (1979), Finlayson & McCracken (1981) and Finlayson et al. (1980). These interpretations provide simple velocity models of a 43 km thick crust in the Canberra and Wyangala Dam regions. However, in the current target region these surveys provided only reconnaissance information on intra-crustal features because of wide recorder spacings and shot sites remote from the region.

1997 wide-angle seismic survey

In July, 1997 a wide-angle seismic investigation was conducted to determine intra-crustal velocity features of the Molong-Wyandra Structural Zone (Scheibner, 1996). Seismic recorder station spacing was set at 2.5-5.0 km along a 350 km north-south line that crossed the Lachlan Transverse Zone (Fig. 1). The recording instruments comprised ninety Seismic Group Recorders (SGRs) on loan from the IRIS organisation in USA (Incorporation Research Institutions in Seismology) and serviced by the US Geological Survey at Menlo Park, California. Seismic signals were recorded digitally (12 bit gain ranging, 6 db steps, 16 steps, 0-90 db) onto a digital audio tape (DAT) drive in each instrument pre-programmed to turn on for 80 s at specific time windows using a master clock set to the Global Positioning Satellite (GPS) timing system. Shots were fired within these time windows. The seismic signals were from single vertical component 2 Hz Mark Products geophones dug into the surface soils. Field tapes were returned to Menlo Park at the end of the survey where data was retrieved and converted to SEG-Y standard format.

Shots were fired at six locations (Fig. 1). Two 3000 kg shots were located near the northern and southern ends of the recording line and were recorded over distances of about 300 km, thus enabling the identification of upper mantle seismic refracted phases as first arrivals as well as intra-crustal phases. The other four shots were about 1000 kg each and designed to examine intra-crustal structures and compositions along the traverse straddling the Lachlan Transverse Zone.

Data and preliminary interpretation

All seismic data were compiled into seismic record sections; an example from the northernmost shot (Shot 6) is shown in Fig. 2 where data have been filtered in the bandpass 5-20 Hz and displayed with a travel-time reduction velocity of 6.5 km/s (i.e. phases with apparent velocities of 6.5 km/s appear as being parallel to the horizontal distance axis). This record section illustrates some of the principal seismic phases recorded, namely the refracted phases through the upper and middle crust (Pgl, Pg2), a refracted phase through the lower crust (Plc), reflected phases from mid-crustal and Moho boundaries (PcP, PmP), and the refracted phase through the upper mantle (Pn). The P-wave travel-times for the various phases for all seismic sections have been digitised using FOCUS® software and imported into simple one-dimensional velocity modelling software R1D (Leutgert, 1992) to obtain a first-pass impression of velocities throughout the crust for the various parts of the profile. Following the lead of Mooney et al. (1998) who considered world-wide data, we descibe velocities in terms of near-surface rocks, upper crust, middle crust, lower crust, and uppermost mantle.

Preliminary interpretation of the travel-time data enables the following general observations to be made about P-wave velocities along the Molong-Wyangala Structural Zone (Fig. 1):

- At near-surface depths (0-2 km) under the shot sites, velocities are in the range 5.63-5.75 km/s except for the Cadia site (Shot 4) which had a near-surface velocity of 5.29 km/s.
- There are significant velocity increases in two depth ranges under the shot sites along the traverse, at 8-15 km depth and at 18-22 km depth.
- The Moho depth is at about 44 km along the traverse with an underlying upper mantle P-wave velocity of about 8.02 km/s.
- Upper crustal P-wave velocities are in the range 5.92-6.28 km/s (mean 6.09 km/s) in the depth range 2-15 km.
- Middle crustal velocities are in the range 6.28-6.58 km/s (mean 6.44 km/s) in the depth range 15-22 km.
- The lower crustal velocities are in the range 6.5-7.27 km/s (mean 7.04 km/s) at depths greater than 22 km.

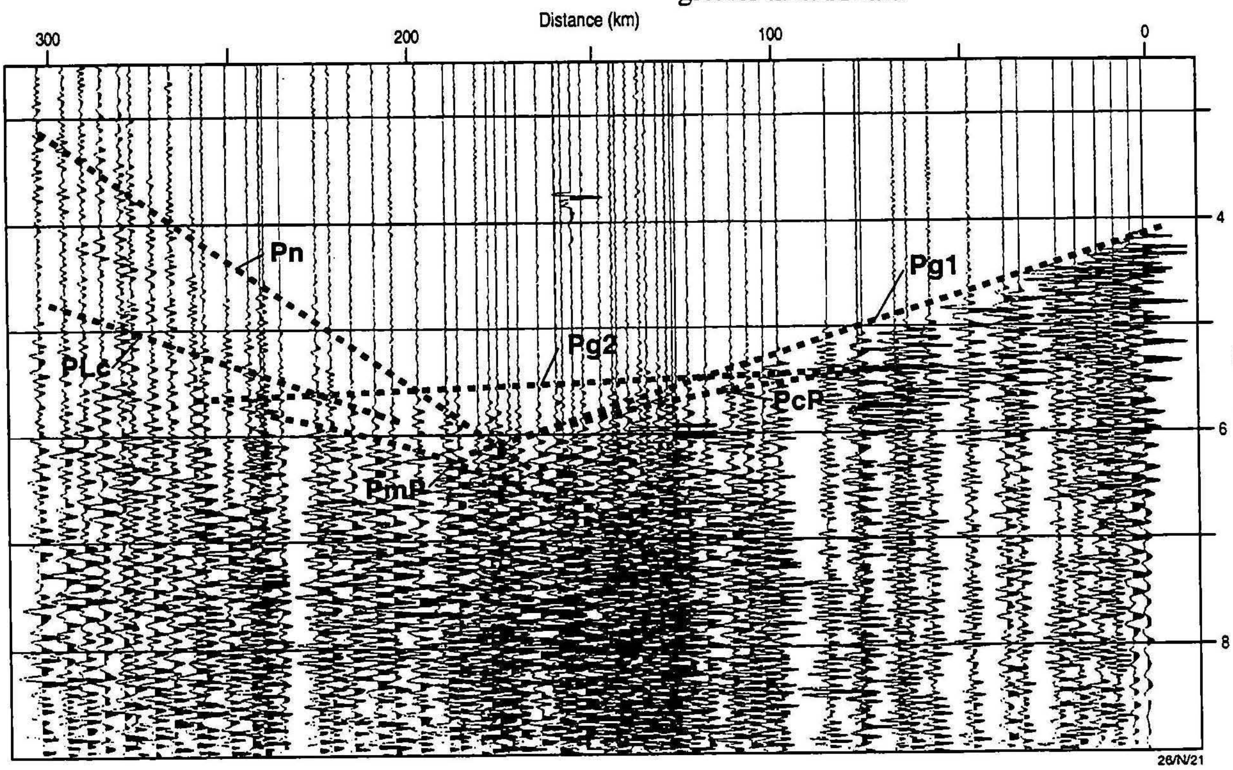

Fig. 2 - Wide-angle seismic record section from Shot 6 at the northern end of the 1997 profile and some of the P-wave seismic phases identified and interpreted (see text for display details).

- Velocities of 6.5 km/s and greater are not evident at depths of less than ~17 km.
- Velocities of 6.8 km/s and greater are not evident at depth less than 24 km.
- Data from the Shots 1, 3, 5 and 6 require low velocity zones in the upper and middle parts of the crust to satisfy travel-time observations.

Some geological insights

It is premature to make any strong geological inferences into crustal features based on the seismic interpretation so far but some aspects of the results merit comment.

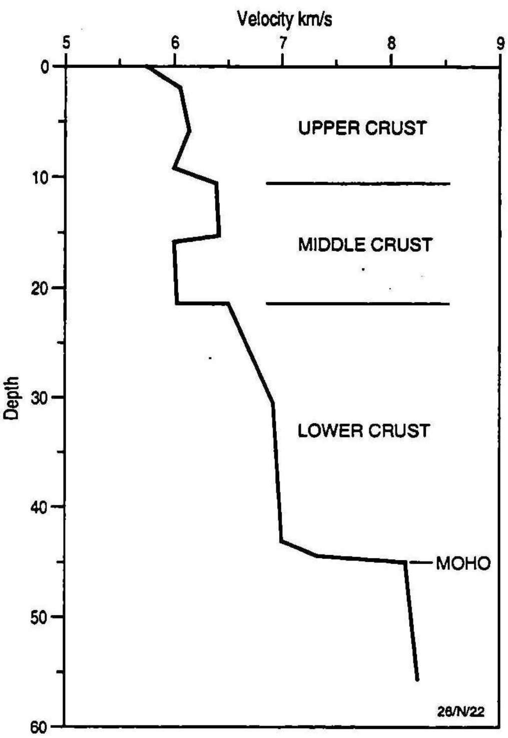

Fig. 3 - One-dimensional P-wave velocity-depth profile derived from data recorded from Shot 6 at the northern end of the 1997 wide-angle seismic profile.

- The velocity gradients within the crust at 8-15 km and 18-22 km depths probably indicate significant compositional changes as highlighted by Christensen & Mooney (1995) in their consideration of global datasets.
- The observed velocities may be representative of a wide variety of rock types and geological interpretation will have be done in conjunction with structural interpretations.
- It is not possible to make comments about whether or not the middle to lower crust is Precambrian based on velocities alone. Global data indicate a wide variation in velocity structure for shield and platform areas (Christensen & Mooney, 1995).
- The high velocity gradient zones and low velocity zones in the upper crust must be considered as sites of compositional change and possible detachment surfaces in any structural modelling.
- The upper and middle crustal velocities of the Molong-Wyangala Structural Zone are significantly higher than those for comparable depths under the Proterozoic areas near Broken Hill investigated in a companion 1997 survey (Leven et al., 1998).
- There is no clear evidence yet for high velocity (>6.8 km/s) mafic rock at middle crustal levels (about 20 km depth) as has been interpreted for some parts of the crust under the Precambrian Mount Isa Block (Goncharov et al., 1998).
- Christensen & Mooney (1995) give us some idea of rock types to expect in the crust at 20 km depth in average heat flow regimes. P-wave velocities below and above 6.5 km/s seem to separate upper from lower crustal rocks.
    - ♦ Upper/middle crustal rocks (velocities <6.5 km/s at 20 km depth) include andesite, metagraywacke, quartzite, basalt, granite gneiss, slate, tonalitic gneiss and felsic granulite.
    - ♦ Lower crustal rocks (velocities >6.5 km/s at 20 km depth) include diabase, mafic granulite, and amphibolite.
    - ♦ Velocities >6.8 km/s at 20 km depth would be typical of anorthosite, gabbro, hornblendite, mafic garnet granulite and eclogite.

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The Seismic Transect through the Broken Hill Region

Tanya Fomin, George M. Gibson, Andrew Owen, Barry Drummond, Kevin Wake-Dyster and David Maidment

Australian Geodynamics Cooperative Research Centre and Australian Geological Survey Organisation, GPO Box 378, Canberra, ACT 2601

A deep seismic reflection survey was carried out in the Broken Hill region by AGSO in 1996. The main transect, comprising a total length of about 130 km incorporates two parts. One is a 45 km-long segment oriented E-W which crossed major geological structures such as the Mundi Mundi Fault, and the Mt Franks and Apollyon Valley Shear zones. An 85 km segment which was oriented NW to SE crossed Stephens Creek shear zone, Broken Hill synform and the Mulculca and Redan Faults.

The results of this survey enabled a fundamental review of the existing geological model of the region. Fault zones are well distinguished in the seismic record section and one of the most unexpected results was that the majority dip south-east in contrast to an earlier view that north-west dips prevail in the region. Good examples are the Mundi Mundi Fault and Mt Frank Shear zone which incorporate a major fault and a zone of splay faults which spread displacement over a large area around the main fault. Some of the faults penetrate the whole crust while others extend down to the middle crust at least.

Three blocks - western, central and eastern - are recognised due to their distinctive seismic features. Weak reflectivity with flat, short reflectors is typical of the western block. The central block is a very broad shear zone containing many high-amplitude continuous reflections. It is recognised as an imbricate zone formed as a result of thrusting and folding with both strike-slip and reverse-slip movements. Seismic features of the eastern block which borders the Broken Hill Synform in the west, are similar to those of the western block. An apparent rift geometry with rotated fault blocks and asymmetrical sedimentary basins is recognised in the eastern block. Some SE-dipping faults (Mulculca and Redan faults) are detected in the seismic data although they are discontinuous and not quite as obvious. There are also several minor NW dipping faults which seem to have affected the sediments, i.e. these structures are syn- or post-depositional.

Several zones of sub-horizontal reflectors have been imaged in the seismic data. One possible interpretation of these seismic reflectors is that there are sub-horizontal detachments present at several different levels (at ~10 and ~18-24 km depth). Alternatively, the zones of sub-horizontal reflectors simply represent those areas where the major shear zones flatten out at depth into major regional detachment. As well it can be a result of an over-interpretation of a very complex reflection pattern in the region. For example the ~18-24 km depth level became recognisable only after special processing which emphasised seismic signal with a certain direction of propagation. As a result of this processing we obtained a scheme of the main features of the structure but some artefacts were created as well so this part of the interpretation remains open for discussion. However, the possibility that the faults flatten out in this region at a shallower depth than elsewhere cannot be completely ruled out due to the high temperature regime of the Broken Hill region.

The character of the Moho in the western block differs from that in the central block. In the western block a band of reflectors is about 3 km thick and this reflective zone is quite simple and contains flat and discontinuous elements that is consistent with the reflection pattern of the block in general. In the central block the similar reflective zone at the Moho is approximately twice as thick and its internal seismic structure is more complicated. On average the thickness of the crust is ~ 40 km.

Structural and Tectonic Evolution of the Broken Hill Region Revisited: Implications for Mineral Exploration in the Willyama Supergroup

George Gibson, Barry Drummond, Tanya Fomin, Andrew Owen, David Maidment, & Kevin Wake-Dyster

Australian Geological Survey, PO Box 378, Canberra, ACT 2601

The traditional view of regional structure in the Paleoproterozoic Willyama Supergroup at Broken Hill is one of large-scale, mainly southeast-verging nappes (D1) refolded in a coaxial manner about more upright, tight to isoclinal D2 and D3 folds with north- to northeast-trending axes (Marjoribanks et al., 1980; Laing, 1996). In this interpretation, deformation led to the widespread overturning of bedding on the lower limbs of the D1 nappes although there was little or no disruption of the regional stratigraphy by high-temperature shear zones and mylonites. Until recently, mapped shear zones in the Willyama Supergroup were thought to be almost exclusively of retrograde (post-metamorphic) origin, effecting little or no significant displacement of the regional stratigraphy. Lateral continuity of stratigraphic units was therefore widely assumed, and repetitions of the regional stratigraphy put down to the presence of folds rather than shear zones (eg Willis et al., 1983).

Structural mapping and deep seismic reflection profiling recently undertaken by AGSO as part of the Broken Hill Exploration Initiative (BHEI) have reinforced the importance of shear zones in the structural and tectonic evolution of the Broken Hill region. Many of these shear zones originated during high-grade metamorphism accompanying the Mesoproterozoic Olarian orogeny but others (e.g. Redan Fault) lie parallel to the geophysically-defined late Proterozoic continental margin of Australia and thus more likely owe their origin to continental rifting and the events accompanying the break-up of Rodinia. Alternatively, a few of the inferred Rodinian structures may simply be older Mesoproterozoic shear zones that were reactivated during late Neoproterozoic continental rifting. The difficulty is that many shear zones were reactivated during the early Palaeozoic Delamerian orogeny (500-520 Ma), and possibly again during the late Palaeozoic Alice Springs orogeny, so that much of their earlier structural history has been obscured. Only where relicts of the earlier-formed Precambrian shear fabrics are preserved is it possible to derive a more complete geological record for these shear zones.

This paper presents some of that record and attempts to show that there can be no complete understanding of the regional geology or its mineralisation without an accompanying appraisal of the shear zones. Some shear zones are mineralised and at the very least acted as conduits for fluid flow; others post-date mineralisation and simply brought about a redistribution of the already-formed lode rocks. Exploration strategies which ignore the importance of shear zones in the Broken Hill region must inevitably be less successful.

Mesoproterozoic high-grade shear zones and mylonites

The Willyama Supergroup underlies much of the Broken Hill-Olary region and consists mainly of multiply-deformed (D1-D6) Paleoproterozoic sediments and minor volcanic rocks metamorphosed up to the granulite facies (Willis et al., 1983). Amphibolites and felsic gneisses within this sequence yield ages between 1590 and 1690 Ma (Page and Laing, 1992; Gibson et al., unpubl. data), and a few (?1690 Ma) granite orthogneisses were emplaced directly into high-grade shear zones thereby giving a well constrained age for some of these structures. Mylonitic fabrics are commonplace in many of these shear zones and several contain a conspicuous sillimanite lineation consistent with mylonitisation during, or immediately following, peak metamorphism. Peak metamorphism occurred during the D2 deformation and was followed by a further episode of intense deformation (D3) and associated shear zone (mylonite) development during which time many of the older D2 shear zones were folded and/or rotated into parallelism with the regional D3 schistosity. The best example of a folded D2 shear zone is in the Broken Hill synform where a mylonite zone containing sillimanite and magnetite has been folded about a steeply-plunging D3 fold axis.

Late Neoproterozoic shear zones

Late Neoproterozoic continental extension (D4) associated with the break-up of Rodinia brought about the reactivation of many older structures as well as the formation of new shear zones with northeast and northwest trends (Gibson et al., 1998). Northeast-trending shear zones are oriented parallel to the late Neoproterozoic continental margin and accommodated a significant degree of sinistral, mainly strike-slip displacement. These shear zones were subsequently reactivated as northwest-directed, and in some cases as southeast-directed, thrust faults with only minor amounts of horizontal displacement (mainly dextral) (cf. White et al., 1995). Consequently, save for a few relict S-C fabrics, shear bands and rotated boudins, these structures preserve very little of their early displacement history. Reactivation was most likely a response to the early Palaeozoic Delamerian orogeny (D5) although further movement may also have occurred on some structures during the late Palaeozoic Alice Springs orogeny (D6).

The northwest-trending D4 shear zones originated as normal faults; they parallel the Gondwana margin and controlled both the distribution and orientation of the ultramafic Broken Hill dyke swarm, the bulk of which occurs within the Stirling Hill shear corridor. These dykes truncate, and cut across, the regional D3 schistosity and are considered age equivalents of the Little Broken Hill Gabbro recently dated at 827 ± 9 Ma (Wingate et al., 1997). A comparable age is therefore inferred for normal displacement on the Stirling Hill shear zone and the D4 shear zones in general. Unlike a younger suite of westnorthwest-trending metadolerite dykes in the Broken Hill region, these ultramafic dykes contain conspicuous Cu mineralisation.

The northwest shear zones exerted a significant control on sedimentation patterns in late Neoproterozoic sedimentary basins (Adelaide Supergroup) which unconformably overlie the Willyama Supergroup. These pericratonic basins trend northwest, subparallel to the margin of Gondwana, and occasionally exhibit a marked asymmetry consistent with deposition of the Adelaide Supergroup in a series of fault-angle depressions or half-grabens (Preiss, 1987). Sedimentation itself probably commenced around 830 Ma in common with other parts of the Adelaide Supergroup (Preiss, 1987). Basaltic flows developed at the base of the Adelaidean sequence in the Broken Hill region may have been derived from the same magmatic source as the 827 Ma Little Broken Hill Gabbro.

Following the onset of deformation associated with the Delamerian orogeny, the Neoproterozoic sediments were folded and locally thrust over the underlying Willyama basement rocks. At the same time low-angle D4 normal faults were reoriented into their present steep attitudes. Further thrusting of Adelaidean rocks on to Willyama basement occurred during the Alice Springs orogeny.

Late faults (?D5 or younger)

Overprinting the D4 retrograde shear zones is a conjugate set of near-vertical strike-slip shears with east-west and north-south-trending components (cf. Katz, 1978). Displacement on the east-west shears is consistently dextral whereas the north-south structures consistently give sinistral offsets. These shear zones disrupt the younger suite of metadolerite dykes and thus cannot be any older than either the Adelaide Supergroup or the 827 Ma Stirling Hill dyke swarm, members of which are occasionally cut by the younger metadolerites. Best known of these shear zones are the British and De Bavay faults and the Stephens Creek shear zone, all of which disrupt the line of lode. The Stephens Creek shear zone, one of the most obvious east-west-trending structures in the Broken Hill region, was previously interpreted (Marjoribanks et al., 1980; White et al., 1995) as an important boundary between different structural domains. However, in the analysis presented here it is reinterpreted to be of secondary importance to the earlier northeast-trending structures, merely causing a change in orientation of the latter from northeast to east-west. Kinematic indicators (shear bands, rotated quartz veins and asymmetric boudins) within the shear zone indicate dextral, dominantly strike-slip movement whereas offsets in the regional stratigraphy require an earlier and even greater amount of sinistral displacement (Gibson et al., 1998).

Structural synthesis

The BHEI seismic data reveal several shear zones extending to middle and lower crustal depths. Their age remains uncertain although the foregoing structural analysis indicates both late Proterozoic and Delamerian shear zones are probably represented, in addition to older reactivated structures. A particularly prominent set of shears has disrupted the lithostratigraphic package in the Barrier Range where a 20-25 km-wide southeast-dipping imbricate zone is developed. This imbricate zone has the character of a fold and thrust belt and incorporates structures on which there has been multiple movement with both strike-slip and reverse-slip components recognised in the field. It is also a structure of regional significance separating an unexposed western block dominated by subhorizontal reflectors from an eastern block in which an apparent rift geometry (rotated fault blocks, asymmetric sedimentary basins) of problematic age is preserved. The western margin of this central zone is the Mundi Mundi Fault, a crustal penetrating structure which might also serve as the boundary between the Olary and Broken Hill blocks. In contrast, shear zones in the eastern block penetrate to only mid-crustal levels and flatten out at depth into regional décollements at about 10 or 18 km.

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Fission Track Modelling and the Thermotectonic Evolution of Southeastern Australia

A. J. W. Gleadow[1,2], B. P. Kohn[1,2], P.B. O'Sullivan[1,2], R.W. Brown[2] and K. Gallagher[3]

[1]Australian Geodynamics Cooperative Research Centre
[2]Department of Earth Sciences, La Trobe University, Bundoora, Vic 3083
[3]Department of Geology, Imperial College, London SW7 2BP England

Over the past decade it has been recognised that thermochronology can provide quantitative constraints on long-term patterns of denudation at the Earth's surface and test alternative models for the tectonic evolution of the crust. One of the most important of these methods is based on the apatite fission track dating system, which is a particularly sensitive low-temperature thermochronometer for studies of the thermal environment of the upper crust. Until recently, however, the results of such studies, mostly on a local to regional scale, have been difficult for non-specialists to interpret and the implications have been difficult to visualise over large areas. A major objective within the AGCRC has been to develop new methodologies for interpreting and visualising the results of Apatite Fission Track Thermochronology (AFTT) and to apply these, for the first time on a continental scale, to the whole of Australia. The Fission Track Thermotectonic Imaging project (#2005LO) aims to develop this approach to produce images of the Australian continent which are both accessible, and in a form that can be combined with other continental data sets.

The apatite fission track system is particularly important for this purpose in that the accumulating radiation damage, on which this dating method depends, is only stable over geological time at low temperatures, below about 120°C. Such temperatures are characteristic of the upper 3-4 kilometres of the continental crust, so that rock cooling histories reconstructed from the fission track measurements can quantify cooling through this upper crustal zone. Cooling through this upper crustal zone is mostly controlled by proximity to the land surface so that a first-order interpretation can be made in terms of the amount of denudation that has occurred through time.

Analysis of samples representing a range of depths within the crust, reveals distinctive profiles of fission track parameters with depth, controlled by the cooling history experienced in that area. The pattern of cooling may be due to denudation at the surface and/or by changes in the thermal regime, which may in turn be a reflection of underlying tectonic processes. For each individual sample, numerical forward-modelling procedures are used to reconstruct the "best fit" thermal history, which, in most cases will trace the sample's movement towards the landsurface as overlying material is gradually removed by denudation.

Applying these modelling techniques to large regional arrays of fission track data means that the thermal history information can now be accessed and visualised in a variety of novel formats. The most direct fission track images that are generated are those that simply reveal the palaoetemperature of present-day surface rocks at various times in the past. These images can be viewed sequentially to show how palaeotemperature has varied with time. From such regional palaeotemperature information a second group of images can be generated which describe the amount of surface denudation based on estimates of the thermal gradients. In turn these estimates of the amount of removed section can be combined with digital topographic data and isostatically adjusted to show how the palaeotopography has evolved. These images provide a striking new perspective on crustal processes and landscape evolution over time scales of hundreds of millions of years.

The fission track images are not only valuable for visualising an otherwise rather intractable data set but also allow a whole new range of quantitative measurements to be made on the virtual landscapes constructed. For example, a direct consequence of the denudation models is to predict sediment volumes and to trace the evolution of drainage basins, at least on a broad scale. This opens up a new range of mass-balance calculations on the amounts of eroded material and sediment accumulation in appropriate depocentres. The patterns of sediment movement down the reconstructed drainage lines can also give new insight into the migration of economic mineral deposits, such as diamond placers.

The fission track images we have constructed across southeastern Australia show an overall decrease in the maximum apatite fission track age from around 350-400 Ma in the west to 250-300 Ma in the east. In part this represents a general background of final cooling and the onset of tectonic quiescence following the wave of orogenic activity which migrated across eastern Australia in the Palaeozoic. Superimposed on this trend is a major episode of cooling during the Late Permian and Early Triassic which forms a background to much of the fission track pattern in the region of the eastern highlands. In Tasmania a much younger background is seen where most of the apatite ages are Cretaceous or younger and virtually none are older than the widespread episode of dolerite emplacement in the Jurassic.

Some of the most obvious features of the overall regional pattern relate to younger events, especially the new cycle of denudation initiated by continental breakup during the Mesozoic on both the eastern and southern margins. The overall trend of decreasing fission track age towards the coast is indicative of increasing levels of denudation in this direction, and possibly cooling following exposure to elevated geothermal gradients associated with rifting. This pattern of decreasing age, which has long been known around this and other rifted continental margins, appears to be abruptly truncated in western Victoria, possibly indicating Mesozoic reactivation of an old terrane boundary between the Delamerian and Lachlan Fold Belts. Other factors in the regional pattern include the thermal evolution and subsequent exhumation of sedimentary basin fills, such as in the Sydney and Clarence-Moreton Basins, and localised effects of Tertiary magmatic activity. The pattern of block uplift of the Snowy Mountains has also exposed a cross-section through the upper crustal fission track age profile. To the south, Tasmania shows the effects of younger cooling episodes and generally deeper erosional levels than observed on the mainland, possibly due to its position surrounded by rift systems which were evolving during the Late Cretaceous and Tertiary.

The development of quantitative thermal modelling and regional imaging techniques for large data sets now means that fission track analysis can be used to investigate patterns and timing of denudation, and post-orogenic tectonic activity over broad areas of the crust. In addition to the already widespread application of apatite fission track data in petroleum exploration and sedimentary basin analysis, these new approaches are expected to find application in exploration programs for commodities where the relative position of deposits to a palaeolandsurface is an important factor. Fission track imaging can also reveal discontinuities associated with major lineament features, possibly indicating the presence of long-lived fundamental faults. The Fission Track Thermotectonic Imaging Project within the AGCRC is now developing this new source of information for various other regions in Australia to provide coverage for the whole of the continent.

The Eastern Belt of the Lachlan Orogen

R. A. Glen

Geological Survey of New South Wales, Department of Mineral Resources, Box 536 St Leonards, NSW 2065,
Australian Geodynamics Co-operative Research Centre

The Lachlan Orogen is a major component of the Neoproterozoic to Mesozoic Tasmanides that developed by interaction between the Australian craton and the proto Pacific plate. The western boundary of the Lachlan Orogen lies against the Delamerian Orogen that was deformed in the Cambro-Ordovician Delamerian orogeny (c. 500 Ma). Most of the interface between these two orogenic belts is obscured by the Cainozoic sediments, but it appears to coincide with the east-dipping Moyston Fault in western Victorian and part of the Olepoloko Fault in far western NSW. The eastern boundary of the Lachlan Orogen extends below Permian-Triassic cover of the Sydney and Gunnedah basins. In the latter, it extends under the western part (Tamworth fold-thrust belt) of the New England Orogen.

It is now well established that the Lachlan Orogen is divided into several major structural belts, each with its own tectonic history and structural vergence. When one considers the poorly known western half of New South Wales, it is apparent that there are (at least) four structural belts on the mainland—western, southwestern, central and eastern. If one adds the eastern part of Tasmania (Mathinna beds), then there are five belts. In concentrating here on the Eastern Belt, it should be noted that previous suggestions that (part) of the Southwestern Belt may be allochthonous (having formed along strike and south of the Eastern Belt) are still viable.

Three aspects of the tectonic history of the Eastern Belt will be discussed: tectonic history, crustal architecture, and substrate.

Tectonic history

Table 1 summarises the tectonic history of the Eastern Belt. Key points flowing from Table 1 are:

i) Little direct evidence for a Cambrian greenstone basement (as in the Southwestern Belt) apart from the Narooma Terrane that consists of accreted seamount and oceanic rocks (but see later).

ii) A convergent margin setting in the Ordovician (extending from earliest Ordovician to earliest Silurian), consisting of a back arc basin filled by craton-derived Early Ordovician turbidites and Late Ordovician black shales±turbidites, an intra-oceanic island arc with attached volcaniclastic apron, and forearc (or structurally emplaced) craton-derived Early Ordovician turbidites overlain by Late Ordovician black shales.

iii) The Benambran Orogeny equates with an arc-back arc collision that led to widespread deformation (folds, thrusts, some oblique, and cleavage) which extended across the orogen. Thickening of Ordovician turbidites down to granite melt depths led to formation of Cooma-type granitoids.

iv) This collision was followed by an oceanwards jump of the subduction zone, so that from mid-Silurian to mid-Devonian, the Eastern Belt lay in an extensional back arc environment. Extension-related subsidence led to formation of clastic and volcanic/clastic basins and shelves and disruption of the Ordovician arc. Extension also led to emplacement of major granitoids.

v) There is increasing realisation that a series of significant deformations occurred from the ?late Early to the Middle Devonian. In the Orange-Bathurst region, many Middle Devonian structures have been largely overprinted by, or lie parallel to, Carboniferous structures.

Crustal architecture — thrusts

The interpretation of the structural style of the Lachlan Orogen before 1983 was that faults maintained their surface dips down to unspecified depths. This yo-yo tectonic paradigm implied that crustal blocks moved up and down on (sub)vertical faults, that there was insignificant horizontal

Table 1 - Tectonic history of the eastern Lachlan Orogen

	LITHOTECTONIC UNIT	TECTONIC SIGNIFICANCE/SETTING
GRANITES	I type granites (Bathurst type).	? melting Ord volcanics (or their source) especially along LTZ.
KANIMBLAN DEFM	widespread defm. Folds, thrusts, local cleavage. Reactivation of earlier faults.	? collision with New England Orogen.
MID-LATE DEV.	qtz ss, cgl, shale.	gen. fluviatile deposits—orogen-wide blanket?
"TABBER". DEFM	regional uplift, major but variable defm, thrusts and folds. Variable fabric.	Age spread from late Early to Middle Dev?. Cause? Some due to transpression along previous transtensional faults.
MIDDLE DEV.	felsic volcanics.	A type volcs in continental rifts (ie intraplate).
EARLY DEVONIAN	1. Shallow water shelves, clastics, ls and felsic volcanics. Syn and post-rift packages. 2. Deep water basins, rich/poor in volcanic rocks. Syn and post rift packages. 3. Granites emplaced.	1. back arc extension eg in pull-aparts or transtensional basins. 2. extensional, transtensional and ramp basins in back-arc setting. 3. I, S and rare A type granites. I-type Boggy Plain Supersuite from melting Ord. volcanics at depth or Ord. volcanic source material.
LATE SILURIAN	1. Shallow water shelves, clastics, ls and felsic volcanics. Syn and post-rift packages. 2. Deep water basins, rich/poor in volcanic rocks. Syn and post-rift packages. 3. Granites emplaced. 4. Splitting of Ordovician arc.	1. back arc extension. 2. extensional, transtensional and ramp basins. 3. I, S and rare A type granites. Syndefm (along thrusts or s-slip faults) and elongate or post defm and equant/round.
BENAMBRAN DEFM	regional defm--folds, thrusts, cleavage and met. Some granite fm.	Arc collision with back arc basin. Cooma g/diorite from melting of thrust-thickened Ordovician turbidites at 12 km.
ORDOVICIAN (TO EARLIEST SILURIAN)	1. Early Ord. qtz-rich turbidites pass up into starved Late Ord. black shale. 2. mafic volcanics/clastics with mid-Ord. limestones. Local Late Ord. high-K lavas.	1. craton-derived fans in back arc and locally forearc settings. Source blocked from forearc in mid-Ord. 2. intraoceanic island arc on ?Cambrian seafloor with mid-Ord. hiatus due to seamount subduction. High-K lavas in Late Ord. along intraplate tears.
DELAMERIAN DEFM (only in Delam. Orogen)	in Delamerian Orogen, regional folds, thrusts, cleavage. Granite-fm.	in Delamerian Orogen, arc collision with thinned passive margin (incl. Kanmantoo Trough). Source for Early Ord. turbidites.
CAMBRIAN	Mafic volcanics, cherts, shales.	Oceanic terrane (Narooma Terrane) with accreted seamount.

shortening across steep faults, and that the entire crust deformed in the same way. Implicit was the lack of any connection between faults and folds and the assignation of any low-angle structures to soft-sediment slumping.

In the Eastern Belt, the shift to the thrust or thin-skinned paradigm took place in 1985. It was the outcome of geological and palaeontological mapping in East Gippsland and the NSW Monaro by the Victorian and NSW Geological Surveys that showed that what was thought to be one lithotectonic unit of interbedded Late Ordovician turbidites and black shales actually consisted of three separate lithotectonic units—Early Ordovician turbidites, Late Ordovician black shales and Early Silurian turbidites—structurally interleaved by thrusts. We know now that thrust tectonics affects all rocks from Cambrian up to Late Devonian in the Eastern Belt. In the absence of substantial vertical topographic relief, three dimensional geological data, or even basic information on thicknesses of stratigraphic units, construction of cross sections is necessarily subjective, with many admissible interpretations possible.

In the thin-skinned paradigm, contractional faulting is an integral part of deformation in the Lachlan Orogen. Because these contractional faults are curved (listric), they are called thrusts. The textbook distinction between thrusts and reverse faults at a dip of 45° was based on Rocky Mountain type thrusts and does not apply in the Lachlan where thrusts formed at different times, and where there is evidence in some areas that the steepness of some thrusts reflects passive rotation or reactivation during subsequent deformation. Lachlan thrusts obey the main thrust "rule" in that they cut up-section in the direction of transport—except where rocks were already folded or faulted or where thrusts are influenced by inversion tectonics. However, there is no overall vergence direction across the Lachlan Orogen, even although there is within its subordinate structural belts, and late-stage out-of-sequence thrusting is present. In some cases changes in thrust geometry account for formation of ductile folds such as ramp anticlines. Hangingwall anticlines and footwall synclines are common in some regions. Importantly, many thrusts in the Eastern Belt of the Lachlan have undergone oblique shortening—

i.e. thrusting coupled with a component of strike-slip movement.

A key feature of the thin-skinned paradigm is that faults sole into one or more subhorizontal master faults in upper crust called detachments or décollements. These are slip horizons that divide the crust into different mechanical packets, each deforming with a different style (e.g. fold-dominated as opposed to fault-dominated) while preserving approximate overall uniform shortening.

The Late Ordovician Warbisco Shale is one such key detachment horizon. It separates folds and break thrusts below (in Early Ordovician turbidites) from shear thrusts, or from a combination of shear and break thrusts, above. Break thrusts formed after folding, when folds became so tight that they "locked up", and further compression could only be achieved by brittle faulting rather than ductile folding. Shear thrusts, in contrast, have ramp-flat geometries and formed early in the deformation history, before any significant folding had taken place.

Other detachment horizons include the base of the Ordovician pile in central Victoria and perhaps in the Eastern Belt, and a ~12 km deep metamorphic layer that is exposed locally in the hangingwall of major deep-biting thrusts such as the Murrumbidgee Thrust. The presence of these weak layers that permit strain partitioning implies a multi-layered crust. Do all thrusts die out into through-going detachments or are there soft linkages at depth? Do detachments continue for ever or only for short distances? Because there is no basement-involved or thick-skinned thrusting (whatever basement is) we do not really know how shortening in the lower crust is taken up to balance thrust/fold shortening in the upper crust.

Two other key points follow from the new paradigm—the recognition of more tectonic shortening than previously recognised, and the ability, by constructing crustal-scale cross sections, to compare tectonic models derived by study of the structural architecture of the upper crust with tectonic models derived from geochemical/geophysical inferences of the middle and lower crust.

The empirical observation that most (?all) major metal deposits in Silurian and Devonian rocks and some in Ordovician rocks are associated with high-strain thrust zones supports the concept that linked fault systems represent connected pathways that enable the movement of metal-bearing fluids within the upper crust and for the migration of fluids from the middle and lower crusts into the upper crust.

Crustal architecture — cross structures

Subtle yet important cross structures occur in the Eastern Belt of the Lachlan Orogen. Most are WNW trending, the best known being the Lachlan Transverse Zone (LTZ), a crustal-scale structure that was active from (at least) the Late Ordovician to the Tertiary. These cross structures are an additional component to the structural architecture of the crust that is not predicted from thin-skinned tectonics. Yet they influence the way in which the upper crust deforms in response to orogen-wide oblique compression. These cross structures also interact with meridional or NNW structures in defining discontinuity boundaries to "homogeneous" blocks of crust. The scale of these blocks controls major aspects of crustal evolution, ranging from partitioning regional extensional and shortening strains, to how melts at depths are generated or reach the surface. The blocks also tell us where to explore for ore deposits.

Basement types

Critical to an understanding of the dynamics of the Lachlan Orogen is the controversial topic of the nature of its substrate. This paper suggest that oceanic basement (of presumed Cambrian age) underlies the Ordovician arc and its forearc. The back arc (perhaps extending west to the western edge of the Central Belt) may be underlain by a combination of ocean floor material together with thinned Precambrian continental crust. Farther west the western belt is inferred to be underlain by discrete blocks of Precambrian continental crust.

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Crustal Structure of Eastern Lachlan Orogen Based on Preliminary Interpretation of 4 sec TWT Seismic Reflection Data

R. A. Glen[1,2], R. J Korsch[1,3] and D. W. Johnstone[1,3]

[1] Australian Geodynamics Cooperative Research Centre
[2] Geological Survey of New South Wales, Department of Mineral Resources, PO box 536 St Leonards NSW 2065
[3] Australian Geological Survey Organisation, PO Box 378, Canberra ACT 2601

As part of its contribution to the geological understanding of the mineral-rich eastern part of the Lachlan Orogen, the AGCRC recently acquired approximately 103 km of deep seismic reflection data in the Orange district of New South Wales. Three lines were acquired using conventional explosive charges, two east-west lines (lines 97AGSEL2 and 97AGSEL3) across the regional meridional grain of the orogen, and one north-south line (line 97AGSEL1) that crosses the Lachlan Transverse Zone, a major crustal tear oblique to the regional grain.

Lines 97AGSEL2 and 97AGSEL3 provide a staggered transect across the major tectonic elements in this part of the orogen. From west to east, these are the Silurian to Early Devonian Cowra Trough, the Ordovician Molong volcanic belt (a rifted piece of Ordovician volcanic arc), the overlying Mumbil Shelf (mid Silurian to mid-Devonian) and the deepwater (mid Silurian to mid-Devonian) Hill End Trough to the east.

This paper presents a preliminary interpretation of lines 97AGSEL2 and 97AGSEL3 that is constrained by the recently mapped geology in this region (Raymond et al. 1997). Future processing, however, and migration of the seismic data may result in changes to the shapes and dips of these faults. Correlation with surface faults will be field-checked as part of the AGCRC project.

Key features of the interpretation

1. The seismic data confirm the presence of east-dipping faults cutting the Ordovician volcanics of the Molong volcanic belt, but show little evidence for west-dipping faults. Based on the previous geological work, we interpret these east-dipping faults as contractional structures, some with younger-on-older (out-of-sequence) relations.

2. Although, at present, it cannot be tracked shallower than about 1 sec TWT, the lowest and most westerly of these east-dipping faults appears to steepen and coincide with the east-dipping Molong Fault (wrongly called Columbine Mountain Fault in cross section by Glen et al., in Raymond et al., 1997). This fault juxtaposes Ordovician volcanics on the east above Late Devonian rocks on the west and has thus undergone Carboniferous contraction.

3. Folded Silurian and Early to mid-Devonian rocks of the Cowra Trough lie west of (?and below) the Late Devonian strata. The Cowra Trough is underlain at reasonably shallow depths (>1.2 sec TWT) by inferred Ordovician volcanics. These volcanics are cut by west-dipping faults (also inferred to thrusts), that are truncated by the east-dipping Molong Fault (see Point 2. above).

4. East of the Molong volcanic belt, rocks of the mid-Silurian Mumbil Shelf are cut by east-dipping faults parallel to the set mentioned in Point 1. above. Interpretation of relations in the western part of line 97AGSEL2 suggests that these faults have undergone east-block-down extension during formation of the Mumbil Shelf, followed by reactivation as east-over-west thrusts during regional inversion.

5. The Godolphin Fault marks the eastern boundary of this east-dipping system of faults. It still displays net major extension, with Ordovican volcanics in the hangingwall of the fault lying at

depths >1.8 sec TWT, below rocks of the Hill End Trough and ?Mumbil Shelf.

6. West-dipping structures are present in inferred Ordovician volcanics in the eastern part of line 97AGSEL2. West-dipping structures interpreted from surface mapping in the overlying parts of the Hill End Trough do not show up in the seismic section.

7. The seismic data lends considerable weight to previous suggestions that Ordovician volcanics underlie the Hill End and Cowra troughs flanking the Molong volcanic belt. In this model, the Molong belt is a largely unextended but shortened structural relic of a much more extensive Ordovician volcanic unit that extended from the arc (Junee-Narromine volcanic belt passing through Forbes and Parkes) eastwards as a largely volcaniclastic apron that includes the outcropping Rockley-Gulgong volcanic belt along the western edge of the Sydney Basin (Glen et al. 1997).

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The Western Lachlan Fold Belt: Example of a Propagating "Oceanic" Thrust-System in a Late Ordovician-Early Devonian Accretionary Wedge

David R. Gray[1] & David A. Foster[2]

Australian Geodynamics Cooperative Research Centre

1 - Department of Earth Sciences, Monash University, Melbourne VIC 3168 dgray@earth.monash.edu.au

2 - Department of Earth Sciences, La Trobe University, Melbourne VIC 3083

The Lachlan Fold Belt of eastern Australia is a turbidite-dominated orogenic system. The western subprovince of the Lachlan Fold Belt, which makes up western and central Victoria, consists of Cambrian-Ordovician and Silurian-Devonian interbedded quartz-rich sandstones and black shales, underlain by Cambrian oceanic crust. Structurally, the western subprovince consists primarily of a sequence of upright chevron folds and steep faults zones that generally show

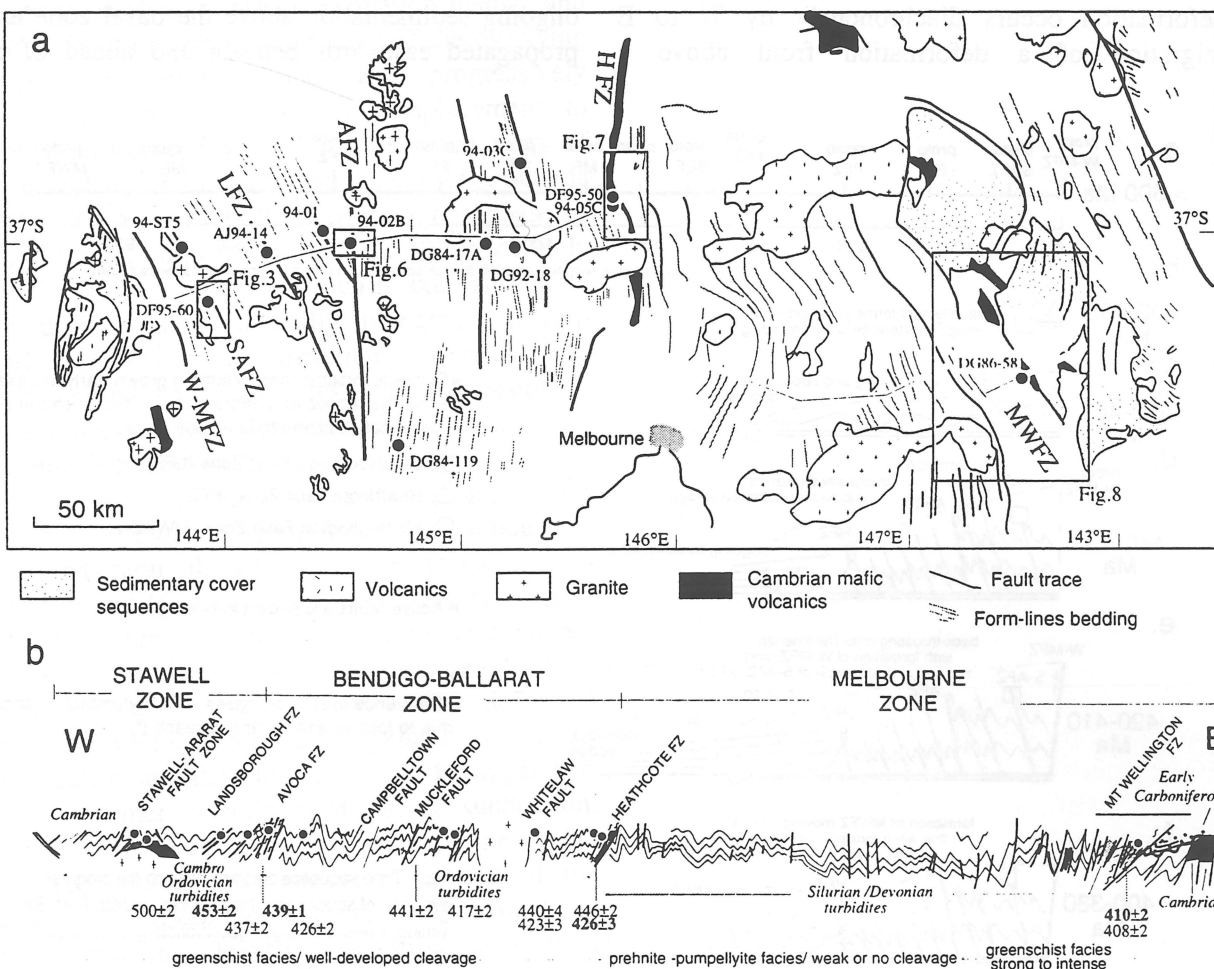

Fig. 1 - Map of central Victoria showing structural zones and major fault zones. Structural profile (b) shows structural style and $^{40}Ar/^{39}Ar$ data from white mica in slates and auriferous quartz veins.

vergence away from the Australian craton. It consists of three structural zones (Stawell, Bendigo-Ballarat, and Melbourne Zones) which are bounded by a series of major strike-parallel, west-dipping, reverse faults (Moyston, Avoca, Heathcote and Mount Wellington Fault Zones) (Fig. 1). These fault zones expose Cambrian metavolcanic rocks (tholeiitic submarine basalts, boninites, andesites, minor rhyolite, and rare ultramafics), cherts, and volcaniclastics in their immediate hanging walls. They are 2 km wide zones of strongly deformed rocks with intense development of obliquely-trending crenulation cleavages associated with generally, but variably steeply plunging meso- and micro-folds.. The western boundary fault to the subprovince, the Moyston Fault dips east and is attributed to back-thrusting that is synchronous with the later stages of thrusting, or younger than the development of the east-vergent system.

$^{40}Ar/^{39}Ar$ data from white mica in slates and auriferous quartz veins from the western subprovince of the Lachlan Fold Belt indicate that deformation occurs diachronously by W to E migration of a deformation front above a décollement, with progression of imbrication and unroofing from this décollement at approx 8 mm/yr. Polydeformed and strongly cleaved slates and phyllites from the Stawell-Ararat (and Œ. Moyston), Avoca, Heathcote and Mount Wellington Fault Zones give dates of ~500, ~455, ~440, and 410-395 Ma , but younger dates are revealed in the same fault zones of ~440 Ma, 426-420 and ~380 Ma respectively. This suggests that reactivation occurred along the bounding faults in the west during periods of unroofing in the east. Also, some ages within the Heathcote and Mount Wellington Fault Zones are older than some dated faults in their respective hanging walls. These mica fabrics grow along the basal detachment outboard of the locked and previously thrusted parts of the wedge, but eventually get carried to higher structural levels as the zone-bounding faults form splays off the basal zone (see Fig. 2). Mica ages in the Mount Wellington Fault Zone are older than the ages of the youngest sedimentary sequence (Eifelian, late Early Devonian: 384-378 Ma) of the former Melbourne Trough, requiring ongoing sedimentation above the basal zone as it propagated eastwards beneath and ahead of the

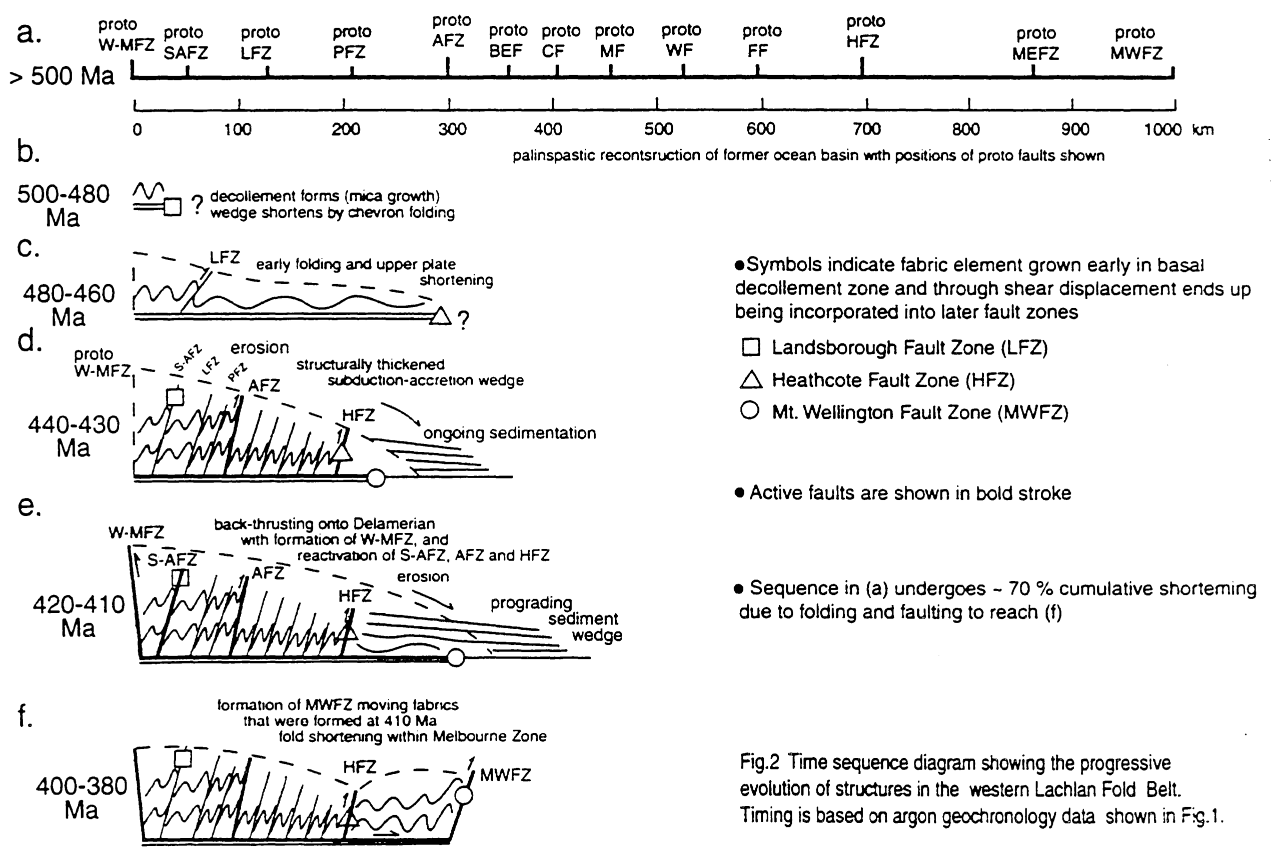

Fig. 2 - Time sequence diagram showing the progressive evolution of structures in the western Lachlan Fold Belt. Time based on argon geochronology data shown in Fig. 1.

structurally thickening turbidite wedge. This geometry and relative chronology arises because deformation is occurring in an accretionary wedge rather than a traditional thrust-belt overlying continental basement.

Model

Oceanic thrust-systems develop as leading-imbricate fans associated with tiered detachment-systems, by footwall collapse and duplexing of oceanic crust in the subduction zone, and imbrication in the overlying turbidite wedge. Deformation within the structurally thickening wedge occurs by chevron-folding, cleavage development, and imbricate thrusting. About 60 % shortening takes place via chevron-folding with late cleavage development. Imbrication is along high strain zones (~ 500 m width with effects to 2 km), characterised by polydeformation, stronger phyllitic fabrics, with intense development of crenulation cleavage transitional into transposition layering. The fault zone fabrics record a progressive shear-related deformation history and evolve initially during shortening of the overlying sedimentary wedge, and are progressively modified during rotation and emplacement to higher structural levels along the steep parts of inferred listric faults. The deformed wedge outside the fault zones generally undergoes one phase of deformation, shown by a weak to moderately developed slaty cleavage which is axial surface to the upright, subhorizontally plunging chevron-folds. Recycling of metamorphic mica into younger sediments indicates that contraction is simultaneous with sedimentation outboard in the oceanic sediment-wedge.

Deformation in such southwest Pacific-style oceanic settings involving low angle subduction and structural thickening of thick (> 5 km) turbidite wedges does not leave evidence of a classic suture typical of continent-continent collisions. Ophiolites may occur as remnants along major faults preserved within the deformed turbidite wedges, and are products of thrust-imbrication and detachment within the upper part of the former oceanic crust during subduction. Liberation of Au occurs from the turbidite wedge and the duplexed oceanic crust as part of the structural thickening process, accompanied by metamorphism, cleavage formation, and fluid flow.

The Mineral Systems of Tasmania

Geoffrey R. Green

Mineral Resources Tasmania

Two metallogenic events account for over 90% of the metallic mineral production of Tasmania:

- hydrothermal activity and associated submarine hot springs debouchment during the formation of the Mount Read Volcanics during the late Middle Cambrian, and
- magmatic and ancillary groundwater hydrothermal activity related to Late Devonian and Early Carboniferous granitoid plutonism.

Other significant events include:

- ?Mesoproterozoic hydrothermal activity responsible for the formation of poorly studied magnetite and magnesite deposits of uncertain origin,
- Early Cambrian forearc orthopyroxenite-harzburgite-dunite dominated ultramafic complexes associated with Os-Ir-Ru (iridosmine) alloys,
- Ordovician syndiagenetic replacement and vein filling Zn-Pb-Ag mineralisation in dolomite,
- mesothermal gold deposition accompanying Middle Devonian deformation,
- gold formation associated with Cretaceous syenite formation, and
- formation of eluvial, alluvial and residual deposits of a wide range of metals during Cainozoic erosion and weathering.

These multiple events, combined with the small scale complexity of Tasmanian geology and consequent overprinting relationships, have contributed to an unparalleled and confusing variety of mineralisation types within an Australian context. They also may be responsible for an unusually diverse array of world class deposits within a small area and suggest further opportunities for major discoveries.

Cambrian mineralisation associated with the Mount Read Volcanics

This is the most important metallogenic event in terms of Tasmania's mineral production and was responsible for the formation of three world class deposits, the classic Zn-Pb-Au-Cu-Ag volcanic-hosted massive sulphide (VHMS) deposits of Rosebery and Hellyer, as well as the smaller Hercules and Que River orebodies and the Cu-Au Mount Lyell field. These deposits have been reviewed in depth recently (Solomon and Groves 1994; Large 1992) and details will not be repeated here.

The high grade gold deposit at Henty (Halley and Roberts 1997; Taheri and Green, unpublished, 1991) is also related to the Mount Read Volcanics (MRV) and is believed to have formed as part of a submarine hydrothermal system, although the spectacular gold grade (27 g/t) may be partly a result of redistribution of gold within the mineralised system by dissolution from rocks undergoing ductile deformation and reprecipitation within multiply brecciated massive quartz alteration.

The major deposits are grouped within districts sharing a broadly common geological history and have similar sulphur and lead isotopic signatures. The nature of the underlying rocks in particular has a major influence on the morphology of the VHMS ores. For example, the Rosebery orebody lies at the top of a thick pumiceous breccia unit, consists of a number of thin lenses of massive sulphide and has broad diffuse footwall alteration zone (or coalescing zones) and a widespread alteration halo. In contrast, when the effects of post ore faulting are removed, the Hellyer deposit is a sharply defined cigar shaped body underlain by a well defined, fracture controlled, alteration pipe which is hosted by andesite lava. Structural control may however be subtle and difficult to detect through the effects of superimposed Devonian deformation in volcanic sequences with few stratigraphic markers.

There are a number of barren pyritic alteration zones within the MRV interpreted as the product of hydrothermal systems which did not reach sufficiently high temperatures (ca. 230°C) to generate a VHMS deposit on or near the seafloor (Boco, Chester, Basin Lake). There are also minor base metal deposits developed on the margins of intrusive rocks (Mount Cattley). These alteration styles can usually be distinguished from those associated with VHMS mineralisation on the basis of sulphur and oxygen isotope systematics.

A further significant mineralisation type is clastic VHMS mineralisation hosted in debris flow deposits. These may be up to several metres long (e.g. Bastyan Dam, north of Rosebery; Wart Hill near Elliott Bay) and in most cases a possible parent VHMS deposit has not been identified. In some cases (Wart Hill) it is apparent that the clasts have been derived from what would be the top Zn-

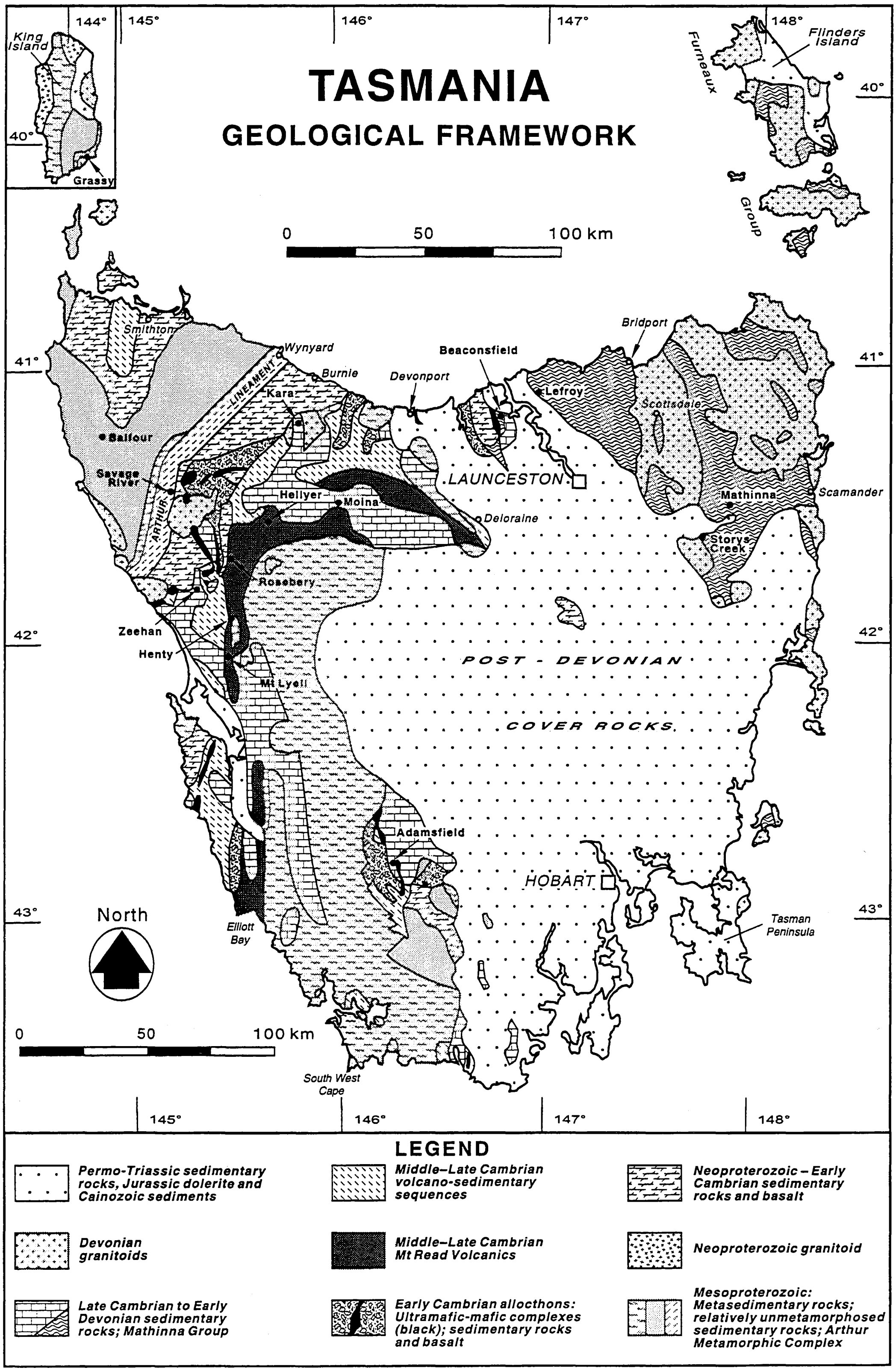

Fig. 1 - Geological framework of Tasmania.

rich sections of a zoned VHMS deposit.

Devonian granitoid hosted mineralisation

There is a significant distinction between the bewildering variety of styles of Late Devonian mineralisation in western Tasmania (the Taswegian Terrane of Chappell, White and Hine, 1988) and the limited range in the eastern Tasmanian Bassian terrane, a contrast ascribable to the more complex geology and presence of carbonate and, to a lesser extent, ultramafic rocks, in the former region (Green, 1990) and a higher degree of granite unroofing in the Bassian Terrane (Solomon and Groves, 1994).

Western Tasmania is the site of the world class carbonate-replacement or distal skarn tin deposits of Renison Bell and Mount Bischoff and the proximal exogranitic scheelite skarns of King Island. As pointed out by Solomon and Groves (1994) the former are associated with highly fractionated ilmenite series granites, whereas the latter are related to magnetite series, I-type granitoids. In contrast in eastern Tasmania, the most important Sn-W deposits are veins adjacent to granite cupolas (Aberfoyle, Storeys Creek) and there are also sizeable endogranitic Sn greisen deposits (Anchor, Royal George). These styles are also present in western Tasmania, but they are relatively insignificant.

Proximal stanniferous skarns are also common in western Tasmania (Moina, St Dizier, Mount Lindsay, Tenth Legion), but their low grade and the fact that in these deposits much of the tin is in metallurgically unfavourable silicates and magnetite renders them unattractive exploration targets, particularly at current world tin prices. However, cassiterite is present in retrogressed skarn at Mount Lindsay (Kwak, 1987) and zones of retrogression of garnet-pyroxene skarn to amphibole and chlorite bearing rocks also present interesting exploration opportunities (e.g. Zn-Au mineralisation within the large magnetite skarn at Moina). Despite their complex and fascinating metal and mineralogical associations, the only proximal skarn currently mined in Tasmania is the Kara scheelite deposit for its magnetite content (used as an industrial mineral). It is also worth noting that the Moina Sn-W bearing skarn, containing 26 Mt of 18% CaF_2, is one of Australia's major fluorite resources.

Historically important Pb-Ag vein deposits, notably those of the Zeehan field, flank plutons associated with the Devonian tin systems, but do not form significant haloes around the scheelite skarns related to magnetite series granitoids. The largest individual deposit of the hundreds known, Magnet, west of Mount Bischoff, contained 0.63 Mt of ore grading 7.3% Zn, 7.3% Pb and 427 g/t Ag. A distal skarn deposit near the old Sylvester Mine, west of Zeehan, discovered in 1989 by RGC Exploration Pty Ltd, contains an inferred 6.1 million tonnes of mineralisation with a grade of 3.3% Pb, 5.5% Zn and 40 g/t Ag (i.e. more contained zinc and lead than in the largest vein deposit discovered during 130 years of prospecting and mining) suggests that systematic exploration for distal base metal skarns is warranted.

There is also current exploration by Allegiance Mining N.L. for a new type of nickel sulphide deposit which occurs within Cambrian ultramafic rocks adjacent to Devonian granite west of Zeehan. These deposits have been inferred to be related to hydrothermal dissolution of nickel from the ultramafic rocks by granite-related fluids and reprecipitation in sulphide skarns.

Mesoproterozoic mineralisation of the Arthur Lineament

The Arthur Lineament is a NNE-trending belt of strongly deformed rocks of high pressure amphibolite facies largely retrogressed to greenschist facies which passes gradationally into relatively undeformed Mesoproterozoic to ?Early Neoproterozoic platform and turbidite successions to the west and east respectively, both of which have been thrust over the rocks of the Lineament. Rock types within the Arthur Lineament include psammitic and pelitic metasediments, dolomites and tholeiitic metavolcanics and intrusives. K-Ar metamorphic ages of 495 to 510 Ma and lithologic similarity with Neoproterozoic (ca. 700 to 600 Ma) sequences overlying the clastic units flanking the Lineament have led to suggested correlations with the Bowry Formation and other sequences within it. This suggestion has been questioned with a U-Pb zircon age of 777 Ma obtained by L.P. Black from a granitoid near the western faulted margin of the Bowry Formation. A more significant doubt for the validity of the theory is provided by the fact that unique (for Tasmania) styles of mineralisation occur within the Bowry Formation, the eastern of three fault separated horizons of tholeiites and associated clastic and carbonate rocks within the Lineament.

The most important of these styles is stratiform cupriferous magnetite-pyrite deposits, the largest of which at Savage River is currently being mined, which occur sporadically along some 50 km of strike. Additionally, major magnesite deposits occur at roughly the same stratigraphic horizon. The magnetite and magnesite deposits are currently interpreted as hydrothermal or diagenetic replacements of dolomite and submarine exhalative precipitates respectively. However, the deposits are poorly studied and the scanty evidence is equivocal. The magnetite deposits might also be skarns. Irrespective of their origin, the nature of the deformation in the area and a number of occurrences of alluvial and hard rock gold within and adjacent to the Arthur Lineament have led to current active exploration for Homestake-style gold deposits.

Platinoid mineralisation associated with Early Cambrian ultramafic suites

Brown (1986) recognised three intrusive assemblages within what are now believed to be allochthonous ultramafic and mafic forearc rocks emplaced during an Early Cambrian collisional event (Berry and Crawford, 1988). One of these assemblages, the layered dunite-harzburgite association of Brown (op. cit.), appears to be the source of historically important Os-Ir-Ru production from alluvial deposits.

Ordovician carbonate-hosted base metal deposits

Exploration since the late 1970s has established that part of what had been previously interpreted as the outer halo of classical zoned Devonian magmatic hydrothermal mineral fields was, in fact, mineralisation of Ordovician age closely related in time to host dolomitised limestone sequences. Lead isotope analyses by Gulson and Porritt (1987) have supported this and subsequent work, most recently extensive exploration by Rio Tinto Exploration Pty Ltd, has confirmed similarities with Irish-style syndiagnetic mineralisation. A variety of associations is present, including galena-rich discordant ore, mined at the old Oceana Mine, stratiform sphalerite and distal very S-poor Zn-rich mineralisation in which part of the zinc is contained within zincian ankerite and smectite and, despite the low silver tenor of the mineralisation, silver is present as Ag-rich electrum.

Devonian syn-deformational mineralisation

Gold deposits are historically significant in north-eastern Tasmania, with the Tasmania Mine at Beaconsfield, a high grade (24 g/t) million ounce producer, with similar resources at slightly lower grade, predominant. Mesothermal gold deposits are widespread in north-eastern Tasmania and are concentrated in provinces and linear zones, the most obvious of which is the Mangana-Mathinna-Lyndhurst belt, an 80 km-long NNW trending lineament, which contains the second largest deposit, the New Golden Gate Mine. Gold mineralisation throughout the region, including at Beaconsfield, is related to the second phase of Tabberabberan deformation in this region, middle Middle Devonian west vergent folding and thrust faulting (A.R. Reed, pers. comm.).

Cretaceous gold

Syenite intrusives at Cygnet in south-eastern Tasmania dated at around 100 Ma, and possibly heralding the first stages of Australia-Antarctica continental separation, are the locus of a small goldfield. Mineralisation occurs both within the intrusives and Permian country rocks and may have formed from high temperature, saline magmatic fluids (J. Taheri and R.S. Bottrill, in prep.).

Cainozoic deposits

Alluvial tin, gold and osmiridium placer deposits are of considerable historic importance, although there is little recent production from these sources. Pleistocene dune systems on eastern King Island host rutile-zircon deposits from which production is expected to resume shortly.

Given the youthful topography of much of Tasmania, deep weathering and residual deposits are much less a feature of the geology than in mainland Australia, although there are pockets of Tertiary weathering preserved, and also exhumed from beneath, basalt. Significant Co-bearing nickeliferous laterite occurs west of Beaconsfield and there is also potential for similar deposits above ultramafic rocks in western Tasmania.

Acknowledgments

In addition to the references cited herein, invaluables source of information in compiling this review have been the Time-Space Diagram for Tasmania (Seymour and Calver, 1995) compiled as part of the National Geoscience Geological Mapping Accord TASGO Project and the mineral resource potential studies of Tasmania carried out by scientists from the Bureau of Resource Sciences and Mineral Resources Tasmania in 1996 (Tasmanian-Commonwealth Regional Forest Agreement, Social and Economic Report Vols. III and VI, Background Report Part D. Tasmanian Public Land Use Commission, Hobart. November 1996).

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The Structural History of Northern Tasmania and the Bass Strait Connection

Mike Hall

Australian Geodynamics Cooperative Research Centre,
Department of Earth Sciences, Monash University, Clayton, VIC

The Otway and Bass Basins, lying between Victoria and Tasmania, conceal the answer to one of the great enigmas in the geology of southeastern Australia - i.e. the continuity of the geology between northern Tasmania and southern Victoria. Within Tasmania itself other enigmas are posed by the nature of the relationship between strongly deformed Proterozoic rocks with high grade metamorphic mineral assemblages and those with low grade assemblages, and between these metamorphic rocks and Proterozoic sediments that are relatively gently deformed and preserve their sedimentary features in almost pristine condition. Also, questions are often asked about the possible continuation of the Tasmanian West Coast mineral belt into Victoria and the Victorian goldfields into Tasmania.

In northern Tasmania a major difficulty in understanding the tectonic history lies in being able to differentiate between the effects of two severe Devonian ("Tabberabberan") deformations, a major late Cambrian-Silurian basin forming event, a late early Cambrian (Delamerian) deformation, a Neoproterozoic basin forming event and a probable Mesoproterozoic deformation. Also, a major contrast exists between northeast Tasmania, where Ordovician-Devonian sediments with a pronounced northwest structural trend are heavily intruded by granites, and north central and northwest Tasmania where the dominant regional structural trend is northeast and involves rocks ranging in age from Mesoproterozoic to Devonian.

Work undertaken in compiling a regional transect along the north coast of Tasmania, together with interpretation of AGSO deep seismic lines shot just offshore and newly acquired aeromagnetic data, has helped to shed light on these problems.

Northern Tasmania

In northeast Tasmania Ordovician-Devonian turbidites have been deformed in two major events (Powell and Baillie, 1992), the first resulting in east-facing recumbent to overturned folds with strong cleavage development, and the second refolding locally gently dipping cleavage and the limbs of earlier folds. Based on the relationship with granites emplaced between 398 Ma and 364 Ma, the first event was probably early Devonian while the second was middle Devonian (A. Reed, pers comm). Roach (1995) has modelled an east-dipping sheet of ultramafics beneath the central part of this region. Large northwest trending normal faults, which extend onshore from the late Cretaceous-Tertiary Bass Basin, now dissect the region.

West of the Tamar graben, a subsidiary arm of the Bass Basin, a similar sequence of Devonian deformation can be discerned (Elliott et al., 1993). The deformed Paleozoic rocks are dominantly platform sediments of shallower water origin than those to the east, but similar to those occurring in central and western Tasmania (Gee and Legge, 1979). Exposed thrust slices dip east at the surface, but evidence from the deep seismic and within the Badger Head Block (Komyshan, 1977) indicates a complex structural history involving both east and west-directed tectonic transport.

On the central north coast the Forth Metamorphics, dominantly quartzose rocks with mineral assemblages containing garnet and kyanite, represent an apparently exotic high grade block in a region of generally low grade metamorphics derived from Proterozoic sediments. The metamorphics formed under peak conditions of 700±50° C and 13±2kb (Lewis, 1991) at about 510 Ma (Ar/Ar age from hornblende; Turner et al., 1994), during the Delamerian deformation, and occur in a stack of recumbent folds that has subsequently been refolded (Burns, 1964). The metamorphics are overlain by late Cambrian-Ordovician sediments and were clearly exposed a relatively short time (c. 20 Ma) after their formation.

The high grade rocks are flanked to the west by low grade metamorphics which pass further west into Proterozoic turbiditic sediments deformed into upright to slightly overturned folds, generally verging eastwards. Examination of the contact between the sediments and low grade metamorphics suggests that strain in the sediments increases markedly towards the metamorphics, with only a slight increase in metamorphic grade. Although this zone includes thrust and reverse

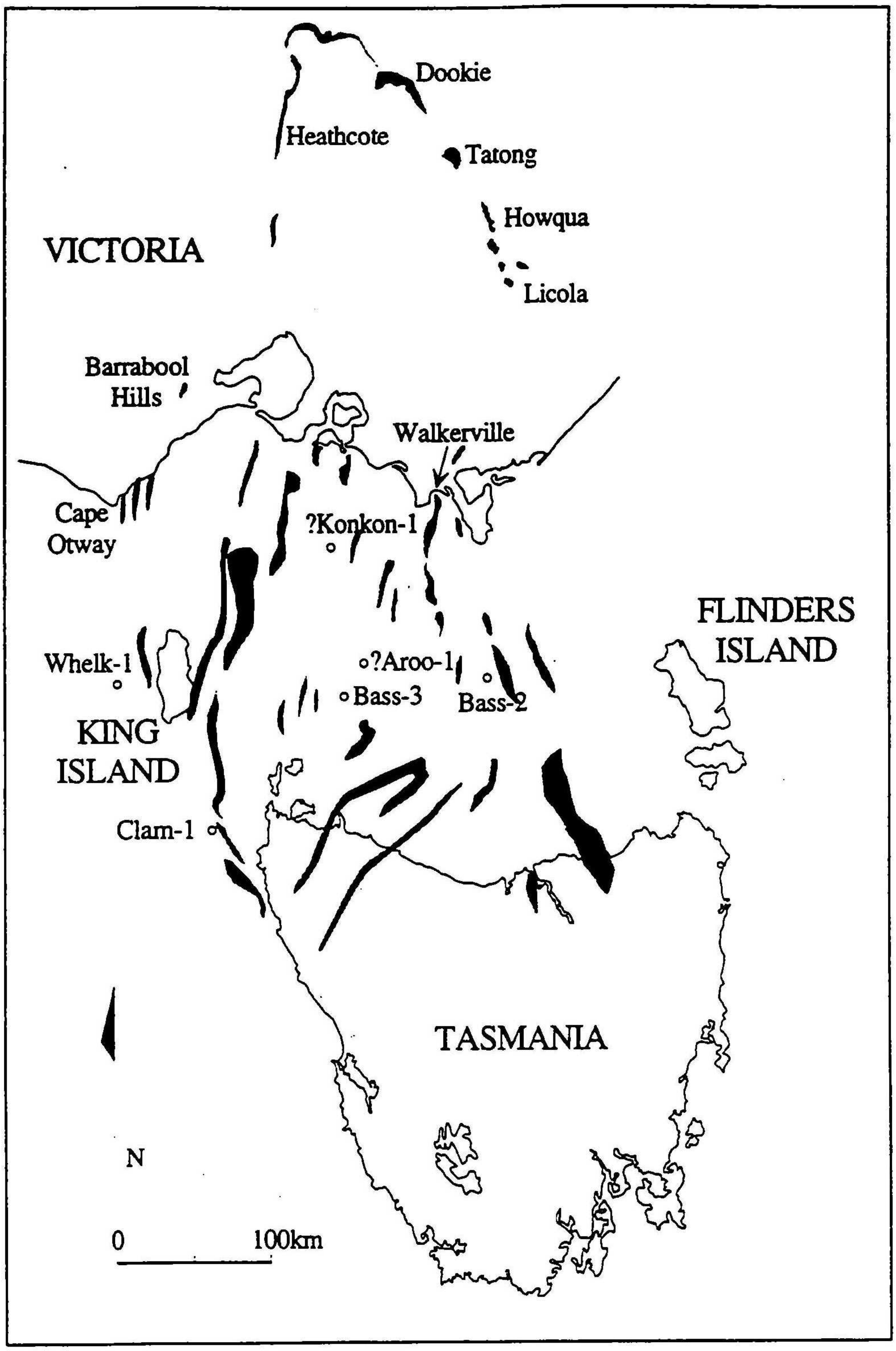

Fig. 1 - Map of the Bass Strait region showing the main magnetic anomalies related to Proterozoic and Lower Palaeozoic rocks, petroleum wells terminating in pre-Permian basement, and named greenstone localities in southern and central Victoria.

fault bounded strips of Cambrian rocks, probably resulting from Devonian deformation, the rapid change in grade to the high grade metamorphics represents a major structural problem. Hall and Barton (1997) proposed that the high grade rocks were part of a metamorphic core complex exhumed during late Cambrian extension.

Immediately to the west is a structurally complex zone of probable Neoproterozoic-Lower Cambrian sediments and mafic volcanics and Ordovician sediments resting unconformably on the older Proterozoic rocks. This is followed to the west by a 30 km wide zone of Proterozoic rocks, dominated by turbidites, which abut along their western margin against the medium to high grade Keith Metamorphics in the steeply dipping zone of the so-called Arthur Lineament (Gee, 1967). The lineament appears to be a high strain zone formed during ductile faulting, probably during the Delamerian deformation. Detailed aeromagnetic data and geological mapping indicate that the zone has subsequently been displaced by younger faults (eg. Calver et al., 1995).

The strain transition is more marked and better exposed west of the lineament zone, in the Rocky Cape block, where folds in Mesoproterozoic shallow water sediments become markedly tighter towards the Keith metamorphics. West of the Mesoproterozoic sediments are the unconformably overlying Neoproterozoic-Upper Cambrian sediments and mafic volcanics of the Smithton Basin (Brown, 1989). The entire succession, including the Mesoproterozoic, is folded into north to northeast trending structures and cut by reverse faults and thrusts as well as a sub-vertical cleavage. However, as different Mesoproterozoic rocks underlie the Neoproterozoic at different localities, it appears that the older rocks have at least been gently folded prior to the deposition of the Neoproterozic sediments.

The effects of the Delamerian deformation in northern Tasmania are not completely clear, although the age and nature of metamorphism is fairly well established. Apart from the occurrences of high grade minerals in the Keith and Forth Metamorphics, most other mineral assemblages are lower greenschist and lower. Wherever Lower Cambrian rocks are found east of the Arthur Lineament there is some evidence that they were deformed prior to the middle Palaeozoic, and it is difficult to establish whether structures formed during the early Cambrian were reactivated and tightened during middle Palaeozoic deformation.

However, near Penguin in north central Tasmania, Upper Cambrian-Ordovician sediments appear to transgress a structural contact between deformed Neoproterozoic-Lower Cambrian and older Proterozoic rocks, but are themselves strongly folded, and it difficult to be certain about how much of the deformation predates the Devonian. A number of phases of deformation have been described by Gee (I967) from the Proterozoic turbidites of the Burnie region west of Penguin, but are most likely to result from the effects of events ranging in age from Proterozoic to middle Palaeozoic.

Deformation in north central and northwest Tasmania during the middle Palaeozoic appears to have occurred in two major events. The first event was east-directed and is responsible for the north to northeast trending faults and folds, although these may be superimposed on older structures and possibly have reactivated and reoriented some of them. The second event was southwest-directed and resulted in northwest striking folds, reverse faults and thrusts, and refolded the slightly older structures (eg. Brown, 1994).

Regional Correlations

On a regional scale aeromagnetic data from the Bass Strait region outline a number of anomalies that can be traced from the north coast of Tasmania northwards towards southern Victoria (Fig. 1) and indicate a possible continuity of Tasmania geology beneath the Bass Basin. Rocks with definite Tasmanian affinities have been encountered beneath Cretaceous sediments in Bass-2 (tuffaceous mudstone and mafic volcanics with a K/Ar age of 589.1±2.6 Ma), Bass-3 (interbedded quartzite and siltstone with a minimum K/Ar age of 418 Ma) and Clam-1 (Mesoproterozoic Cowrie Siltstone with a K/Ar age of 630±21 Ma). Undated basalt at the base of Whelk-1 is likely to be Neoproterozoic-Lower Cambrian, while thick basalt in the lower part of Aroo-1 and at the base of Konkon-1 could be Lower Cretaceous or Neoproterozoic-Lower Cambrian.

These well results indicate that rocks of the western Tasmanian terrane extend at least half way across Bass Strait and to the west of King Island. The Neoproterozoic-Lower Cambrian basalts of the Smithton Basin appear to be the cause of the main magnetic anomalies in northwest Tasmania and similar anomalies extend to the Victorian coastline. The basalts have rift affinities (Crawford and Berry, 1992) and were erupted onto continental crust. If the basalts are indeed the cause of the anomalies northeast of King Island, it is reasonable to assume that Tasmanian continental crust extends at least as far as the south coast of Victoria. If this interpretation is accepted the question then becomes how far northwards does "Tasmanian" continental crust extend beneath the Melbourne Trough?

The western boundary of the northeastern Tasmania terrane may continue northwest across Bass Strait towards the Walkerville area, and then northeast and northwest again, coinciding with outcrops of mafic and ultramafic rocks between Licola and Dookie. In the west a relatively shallow basement block, containing linear magnetic anomalies modelled as mafic rocks, occurs near Cape Otway in southwest Victoria (Lammens, 1997). Mafic rocks also occur in the Barrabool Hills west of Geelong (Morand, 1995) and in folded thrust slices in the Heathcote area north of Melbourne (Crawford, 1988).

Lines joining these Victorian occurrences of mafics and ultramafics outline a roughly wedge shaped zone in central Victoria, which is tentatively interpreted as outlining the northern extent of "Tasmanian" Proterozoic-early Palaeozoic continental crust. This block may have been trapped between closing oceans to the east and west during the middle Palaeozoic, thus reflecting the effects of east-directed deformation followed by west-directed deformation.

Conclusions

Following the Delamerian Orogeny in northern and western Tasmania, and the subsequent development of the middle Cambrian Mt. Read Volcanics, a major extensional event occurred. Rising metamorphic core complexes shed debris into fault controlled troughs which were eventually overstepped by a major marine transgression in the early Ordovician. In basin analysis terminology, the surface on which the marine sediments rest is a classic "break up unconformity" and believed to indicate the beginning of thermal subsidence, and possibly sea floor spreading, following a period of active rift development. At this time northeast Tasmania may have been the site of either highly attenuated continental crust or newly formed oceanic crust on which a turbidite dominated succession was deposited.

A similar situation may have occurred off northwest Tasmania, although evidence for the location of the edge of continental crust is much more tenuous and largely concealed beneath Cretaceous-Tertiary basins related to a younger episode of extension and sea floor spreading.

If this interpretation is correct, Tasmania and much of the area now beneath the Bass Basin and central Victoria may have remained as an isolated fragment of continental crust, with new oceans forming on either side. During the early Devonian this continental fragment was involved in a collision along its western margin. During the middle Devonian a collision occurred along its eastern margin, deforming the slightly older structures. The deformation resulting from these two events, especially in the marginal areas, is preserved as a collage of folds, thrusts, reverse faults and strike slip faults. Also related to these events, but just post-dating them, especially in northeast Tasmania, is a period of extensive granite intrusion.

If the tectonic picture outlined above is accurate, it is highly unlikely that the geology of the central Victorian goldfields extends into Tasmania. It is also unlikely that the Mt. Read volcanic belt of western Tasmania extends onto the mainland, despite the occurrence of similarly aged Cambrian volcanics in western Victoria.

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The Broken Hill Ore Body: A High Temperature, High Pressure Scenario

B. E. Hobbs, J. L. Walshe, A. Ord, Y. Zhang, and G. R. Carr

Australian Geodynamics Cooperative Research Centre
Department of Exploration and Minerals, CSIRO, Perth, WA

The Broken Hill Pb-Zn Ore Body occurs within a multiply deformed Proterozoic amphibolite to granulite facies terrain of considerable complexity. It is not the intention of this study to advocate a specific origin for the ore body but rather, to postulate one particular mode of formation, out of the many that have been considered in the literature, and to explore the consequences of such a proposition. Our contention is that if an internally consistent model can be developed which encompasses a specific mode of formation and if the total ore forming system can be explained by this model, with a minimum number of ad hoc propositions, then perhaps the model has some credence and the exploration implications of the model are worthy of further examination.

We emphasise that we are not in the business of advocating one scenario at the expense of others.

Aim of this study

The specific aim of this study is to explore the consequences of assuming that the Broken Hill Pb-Zn Ore Body formed synchronously with amphibolite to granulite facies metamorphism.

We admit from the outset that other scenarios are feasible; our goal is to explore whether an internally self consistent model can be developed utilising existing knowledge to explain the genesis of the ore body as part of a syn-metamorphic scenario. In part, this conceptual modelling is stimulated by recent empirical argument (e.g. Walters 1996) that Broken Hill type deposits are intrinsically different to other Proterozoic Pb-Zn deposits.

Geological constraints for a syn-metamorphic scenario

The literature on the geology of Broken Hill is contentious to the extent that there is no consensus at the time of writing regarding whether a clearly recognisable stratigraphic sequence exists, whether some quartz/feldspar rocks have an extrusive or intrusive genesis or whether the structural/metamorphic geometry/history has been adequately delineated. Our intention here is to adopt a rather broad perspective and present a series of geological constraints for a syn-metamorphic model that are reasonably well accepted by a wide range of present-day workers in the region.

Regional crustal architecture

Figure 1 presents the results of a recent reflection seismic traverse conducted in a general NW-SE orientation across the Willyama Complex (Gibson et al, 1998) with an interpreted nappe complex added.

The traces of several regionally important faults are highlighted. The important aspects of this traverse are:

- to the NW of the Mundi-Mundi Fault and to the SE of the Redan Fault, the crustal structure is heterogeneous but characterised by the lack of through going fault systems; the upper crust and lower crust appear distinctively delineated by their own seismic characteristics;
- between the Mundi-Mundi and Redan Faults there are a number of faults some of which extend to close to the Moho;
- the Globe Vauxhall Fault is distinct from the other faults in the crustal system in that it is listric, extends at mid-crustal depths to near the Redan Fault and forms the detachment fault for a number of other prominent faults such as the Stephens Creek Shear Zone;
- the present day crustal thickness is 38 km.

Based on the metamorphic assemblage, the granulite facies rocks have been loaded to attain pressures of at least 400 MPa and work by the Monash University group indicates peak pressures of approximately 500 Mpa at temperatures in the range 650-750°C. The grade of metamorphism decreases from SE to NW across the terrain. We propose that, on the basis of these observations, a thrust nappe pile 15 km thick should be included in Figure 1 as shown and the Redan Fault has been used as the basal thrust in this nappe pile.

Recent interpretations of refraction seismic data indicate that, contrary to other Proterozoic terrains, the Broken Hill region lacks a significant layer of mafic material in the lower crust; most if not all, of the crust is comprised of quartz-feldspathic material.

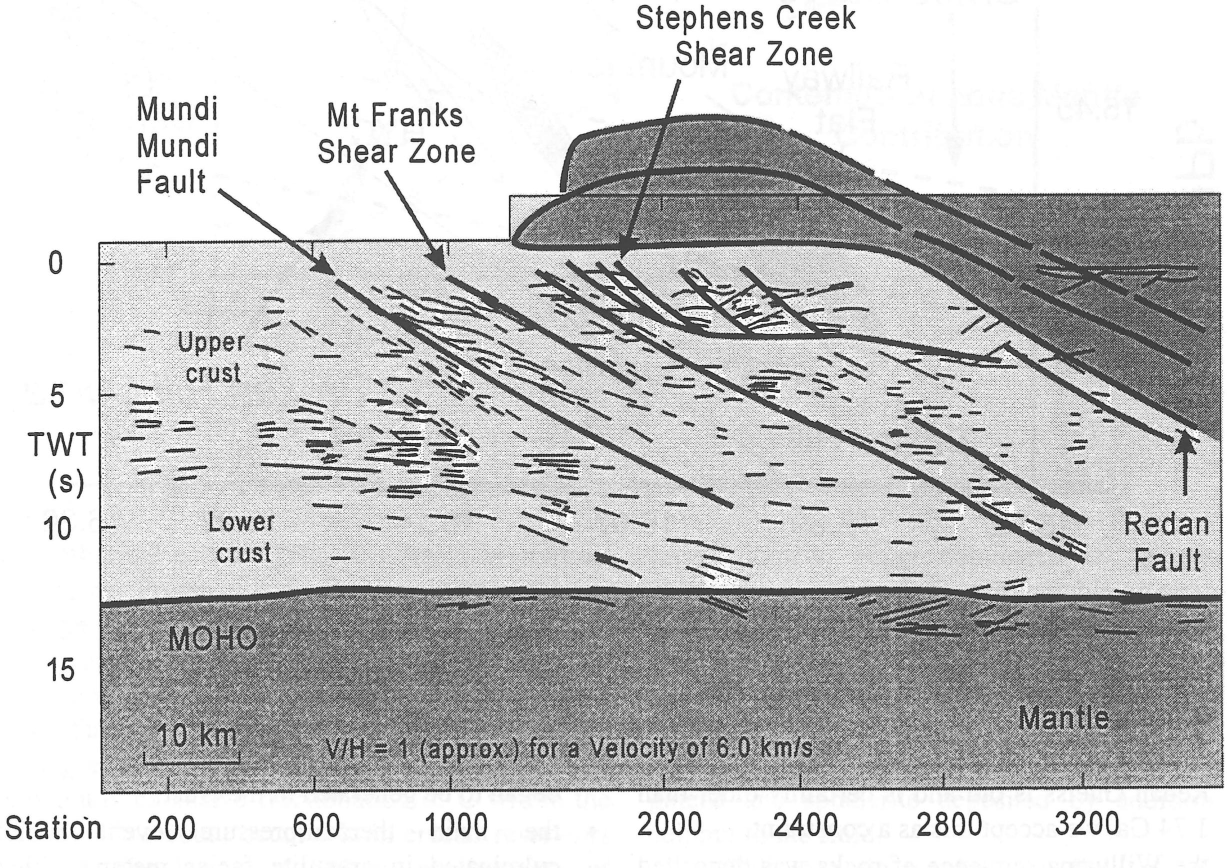

Fig. 1 - Interpreted seismic section across Broken Hill.

Stratigraphy and structure of the Willyama Complex

The published literature shows conclusively that the Willyama complex has suffered many periods of deformation, many of which have been under conditions of granulite or amphibolite facies metamorphism. The fold interference structures indicate shortening in a NW-SE direction but other shortening histories in an E-W direction or even in a NE-SW direction are not precluded.

These deformations have resulted in interference fold structures that now are exposed on the scale of individual outcrops and, at the map scale, with length scales up to 5 km across. The seismic sections indicate that complex folding structures were not formed at a scale much smaller than this; in fact, at the crustal scale, the deformation is dominated by fault geometries rather than fold geometries, and there is even a strong suggestion in the seismic data that initial sedimentological environments (such as grabens, sag phases and the like) are preserved on the crustal scale even though, on the outcrop scale, such preservation is beyond the comprehension of many workers.

Geochronology

The geochronological data on the Willyama Complex continues to accumulate. We present here what we consider to be a "minimum - consensus" view of the present geochronological data set. By this we mean that even the most extreme workers would be willing to accept our "minimalist" point of view.

The important points here are:

- the Redan Gneiss contains a zircon population that records ages back to 2.7 Ga; some workers claim this indicates an Archaean age for the Redan Gneiss. Others propose a Proterozoic age. A consensus would seem to be that the Redan Gneiss is old and is certainly older than 1.74 Ga; we accept this as a constraint.
- the Willyama sequence of rocks was deposited in the time period 1.74 to 1.71 Ga; some workers would prefer this range extended to 1.69 Ga, the argument resting on whether the Hores Gneiss is intrusive or extrusive.
- high temperatures in the crust, as evidenced by amphibolite to granulite facies metamorphism and/or by the emplacement/deposition of restite S-type layer parallel intrusives/extrusives occurred in the time interval 1.69 Ga to 1.59 Ga with the peak of pressure and temperature at 1.59 Ga;
- the lead model age for the Broken Hill Ore Body is 1.67 Ga; others claim ages less than 1.67 Ga (as young as 1.553 Ga) but the essential point to grasp is that all arguments based on lead-ages point to an age less than 1.69 Ga, the latest age for deposition of the Willyama sequence;
- other events occur within the Willyama sequence, in particular, intrusion of melts at 1.28 Ga at Mt Robe; this is 310 million years after the peak granulite facies heating event.

The important constraints to arise from the above data are;

- the model age for the Broken Hill Ore Body is at least 20 million years after high temperatures began to be generated in the crust;
- the main thermal/pressure event which culminated in granulite facies metamorphism lasted at least 100 million years.

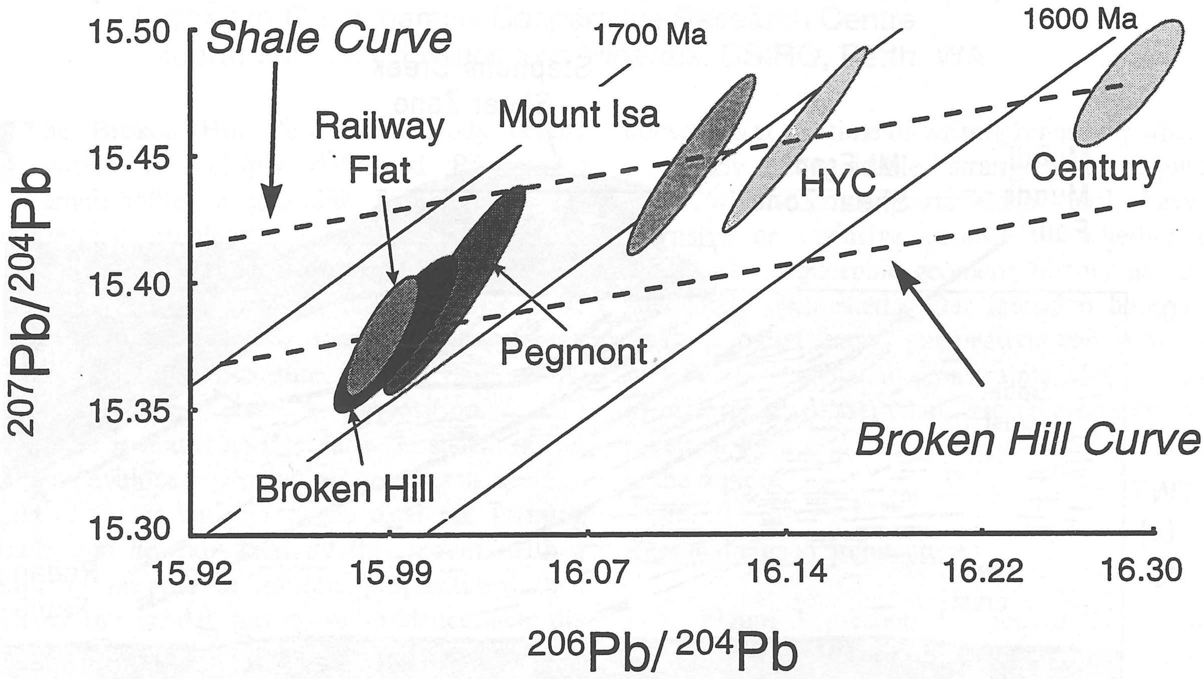

Fig. 2 - Comparison of Pb isotopes of Broken Hill type deposits with shale-hosted Pb-Zn deposits of northern Australia.

<u>Isotopic Data</u>

The Pb isotope data shown in Figure 2 indicates a distinctly different source for the Pb in Broken Hill type deposits as compared to the shale hosted Mt Isa type deposits. The Proterozoic sediment-hosted deposits of northern Australia all have crustal Pb isotope signatures which lie on a single, crustal growth curve indicative of derivation of metals from the intracratonic rift sedimentary pile. Broken Hill, and other Broken Hill type deposits (Pegmont, Mount Isa Eastern Fold Belt; Railway Flat, Georgetown Province) lie on a lower m growth curve suggesting a fundamental difference in the metallogenic process. The data are consistent with the input of a mantle component either earlier in the history of the protolith or contemporaneous with

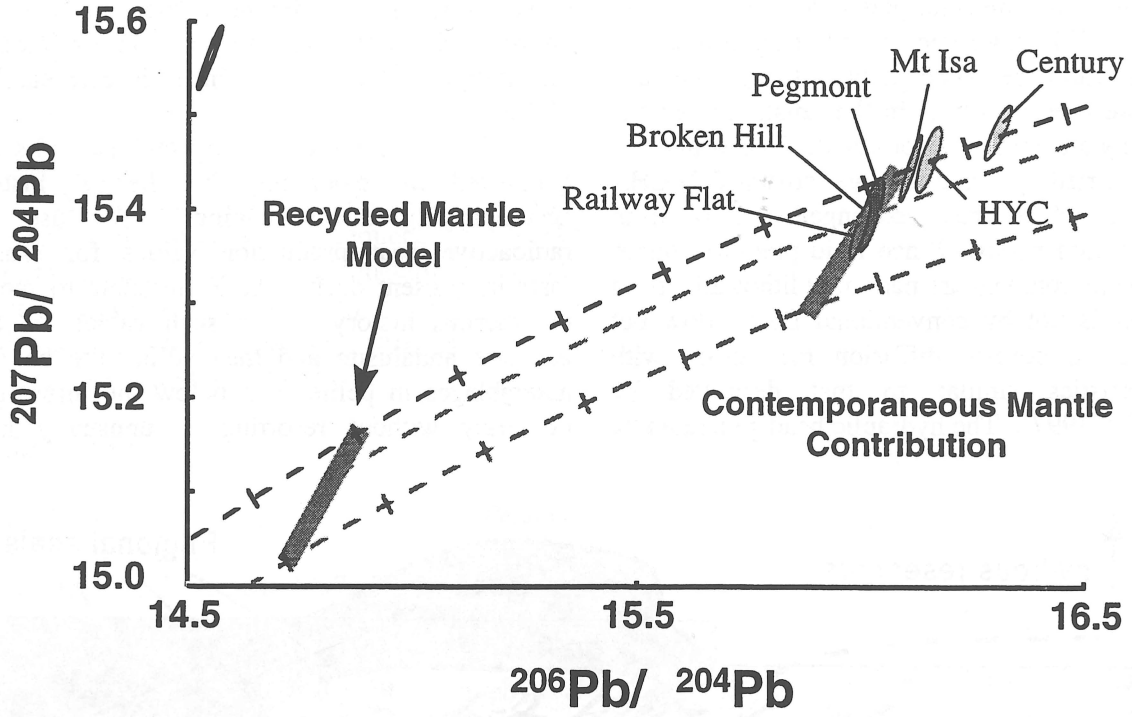

Fig. 3 - Possible Pb-isotope evolutionary paths for Broken Hill type deposits.

hydrothermal activity (Fig. 3). Again in contrast with other Proterozoic Pb-Zn deposits the sulphur isotope data for the Broken Hill orebodies are close to zero and suggestive of a mantle source for the sulphur. The carbon isotope data on calcite from the main lode are around -20 to -23 per mil (Dong et al., 1987; John Smith, unpublished data) and imply extensive fractionation of C within the system. This could occur within crustal reservoirs through dissolution of carbon, precipitation of carbonate or loss of CO_2.

Metamorphic Fluids

The syn-metamorphic model for the genesis of the Broken Hill lodes raises important geochemical questions. Lead and zinc are highly soluble in high temperature H_2O-NaCl-rich fluids. It is difficult to envisage sphalerite and galena being saturated at peak metamorphic conditions given the normal constraints on the availability of Pb and Zn in earth materials. Although these sulphides become less soluble with increasing pressure this effect does not appear sufficient to saturate the sulphides at high temperatures and pressures for reasonable concentrations of Pb and Zn in aqueous fluids (Bastrakov, 1997).

The syn-metamorphic model requires a radically different geochemical paradigm. Consider the lower to mid-crust, the granulite facies domain, being dominated by anhydrous fluids: fluids rich in CO_2 with variable amounts of CH_4 H_2, N_2 and H_2S. Such fluids have potential to stabilise metals in complexes not normally considered important, such as cyanides, amides and carbonyl complexes. Potentially Pb and Zn could be transported as amide complexes and galena and sphalerite deposited by addition of sulphur to the fluid.

This scenario requires two fluid reservoirs in the system, one rich is base metals, the other rich in H_2S. Both reservoirs must be depleted in salt and water effectively eliminating basinal and magmatic brines as important contributors in the system.

The isotopic data are consistent with a mid-lower crustal reservoir of CO_2-CH_4-N_2-rich fluids that were the main source of the metals as envisaged in Figure 4 and a lower-crust - mantle reservoir that was the main source of the sulphur and possibly a component of the Pb and Zn.

The conceptual model

We explore here, based on the observations set out above, a quantitative syn-metamorphic model for the Broken Hill Ore Body whereby mineralization occurs within a sedimentary basin loaded by Himalayan Style nappe structures resulting in a crustal thickness at the time of peak granulite facies metamorphism of approximately 60 km. Metamorphic fluids responsible for mineralization are non-aqueous although aqueous fluids are present higher in the crust. Sulphur is carried by a deep crustal or mantle fluid whilst Pb, Zn are carried by a mid to lower crustal CO_2-CH_4-N_2 fluid which has scavenged metals from feldspars and micas. Since fluid pressures under such an environment are near or at lithostatic, fluid transport is not by conventional Darcy flow but rather by a porosity-diffusion mechanism with characteristics similar to that described by Connolly (1997). The hydraulic head generated by the thrust loading drives fluid flow. A similar system has recently been analysed by Hanson (1997). In order to keep the two fluids separated during transport through the crust we propose that major thrust structures act as "aquicludes"; these thrusts focus fluids of contrasting chemistry into the zone of ore deposition and maintain a non-aqueous nature of the lower to mid-crustal reservoirs.

Note that because of the metamorphic conditions under which permeability is essentially zero but porosity is locally high, the term "aquiclude" here does not imply relatively low permeability. The mechanisms of excluding fluid transport are quite different to those involved in conventional Darcy flow and are more related to the strength rather than the intrinsic permeability of the material.

The positions of the crustal reservoirs are delineated by modelling the thermal history accompanying thrust loading. We use the radioactive heat production values for crustal material present during the Proterozoic to model the thermal history. With such values we can generate andalusite and then sillimanite bearing assemblages in pelites just below the thrust pile boundary without resorting to unusually high thermal fluxes through the Moho as was proposed by Loosveld and Etheridge (1990). The modelling clearly outlines regions of melting in the crust and regions of granulite facies metamorphism from which to derive anhydrous fluids. The time for the crust to reach a steady state thermal regime is 100 million years. These calculations assume slow erosion rates. A local model for fluid mixing is proposed whereby the two chemically contrasted fluids are "attracted" to and finally mix in localized deformation zones where deformation induced dilatancy (and hence increased permeability) acts as the focussing mechanism.

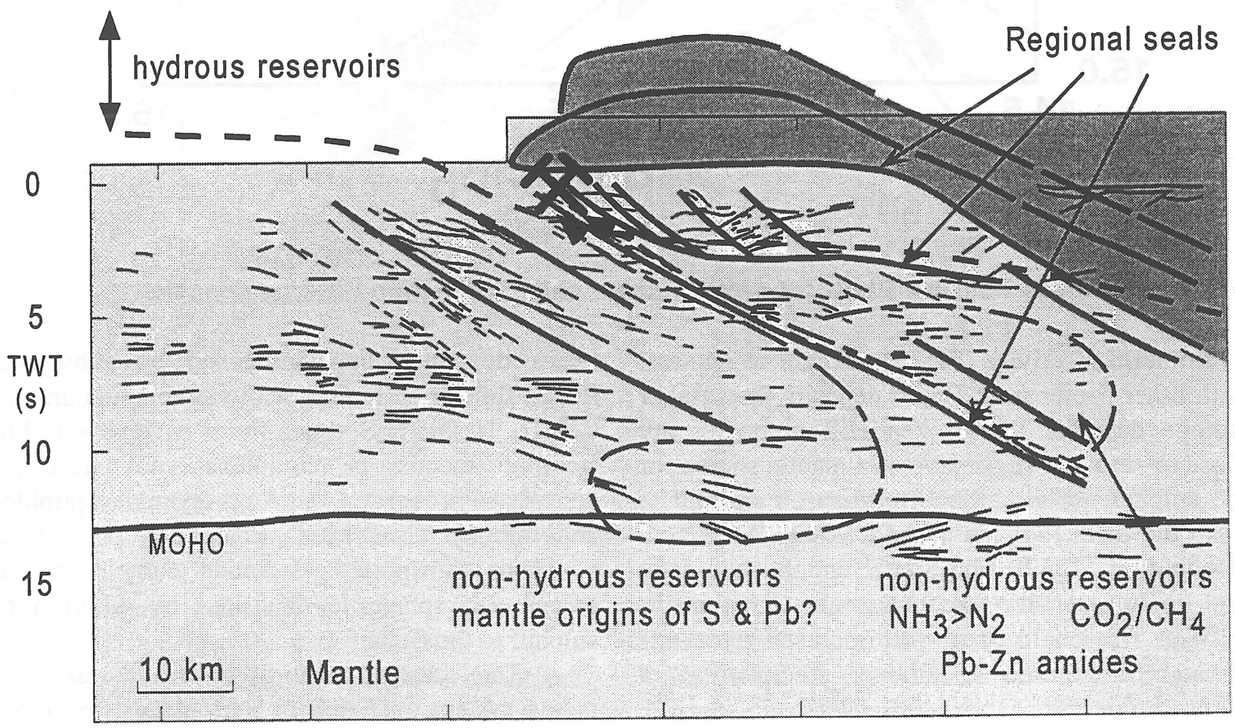

Fig. 4 - Postulated localities of non-hydrous fluid reservoirs in the syn-metamorphic model of the Broken Hill deposit.

Under this scenario, the "line of lode" appears as the mixing front between the two contrasted fluids.

Mapping and understanding the geometry of the "mixing front" or "fronts" emerge as the primary exploration indicators for future discoveries of mineralization.

This model raises a number of issues with respect to the stratigraphic sequence at Broken Hill, the timing of deformation, metamorphism and melt intrusion, the precise siting of mineralization and the oxidation/reduction characteristics of rocks in the Willyama sequence.

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The Seismic Structure of the Lithosphere and Mantle beneath Eastern Australia

Brian L. N. Kennett

Research School of Earth Sciences, ANU, Canberra ACT 0200

The earthquakes lying in the major earthquake belt to the north and east of the continent provide useful probes of the seismological structure beneath the Australian region. Suitable events are quite frequent in the zone of seismicity which extends from Indonesia, through New Guinea to Fiji and then down through Tonga and New Zealand. Although the number of permanent stations with high-fidelity recording is small, a systematic program of deployment of portable broad-band seismographs (the Skippy project) has provided over 60 different recording sites across the continent which have typically been occupied for 5 months.

Using broad-band seismometers with 24 bit digital recording we are able to capture the many different of types of waves which travel from the source to the sensors, each of which acquire during their passage information about the seismic velocities along their path from source to receiver. The techniques used to extract information from the seismograms on three-dimensional structure are similar in principle to medical tomography. The characteristics of waves which have travelled in many different directions through the region beneath Australia are combined to build up images of the three-dimensional seismic structure. We have exploited both the high frequency body waves and the large amplitude surface waves which occur late in the seismograms; the various phases carry different classes of information about the structure so that we are able to construct a more comprehensive image.

The favourable distribution of paths has enabled us to build up a high resolution model for the three-dimensional shear wavespeed structure in central and eastern Australia. We have been able to achieve a resolution of about 200 km in the horizontal direction below 60 km depth, and as a result can examine the relation of the structures in the mantle to the geology exposed at the surface.

The most prominent feature in the seismic wavespeed is a strong contrast in the structure between central Australia and the eastern seaboard. To the west of about 140°E the seismic velocities down to 200 km or more are high whilst to the east they are significantly lower. Along much of the eastern seaboard there is a pronounced zone of reduced velocities centered at 140 km depth. The pattern of lowered velocities fits in well with the presence of recent volcanism and regions of high heat flow, and so it is likely that the cause of the reduction of the seismic wave speeds is hotter material.

The strong contrast in seismic structure in the mantle does not have a simple relationship to the edge of the ancient Precambrian rocks as seen at the surface (the conventional Tasman line) even though there is a general association with lower seismic velocities at depth beneath the younger rocks of eastern Australia. Also, there is a distinct zone of moderate seismic velocities extending to about 150 km depth to the east of the major zone of high velocities. Such clear indications of substructure appear to be related to the way in which the different parts of the continent were assembled.

The studies of the mantle stucture have been complemented by work on the structure of the crust derived from the analysis of distant earthquakes. The structure near the receiver imposes a pattern of conversions and reverberations which can be analysed to extract crustal velocities and thicknesses which are in good accord with refraction results where available. The coverage is much more comprehensive than from refraction work and by using a common style of analysis at all stations we can look at systematic patterns in crustal structure. For example, in eastern Australia there is a general correlation of a broad transition from crustal to mantle velocities with regions where there are sigificant zones of reduced seismic velocity at depth.

The information on three-dimensional seismic structure provides new insights into the nature of our continent; the challenge remains to integrate these new classes of information into our geodynamic models.

Tectonic and Mineralisation Insights from the Australian Polepath: Phanerozoic Examples with Emphasis on the Late Palaeozoic Path for New England

Chris Klootwijk

Australian Geodynamics Cooperative Research Centre
Australian Geological Survey Organisation, Canberra, ACT 2601

A direct relationship between plate reorganisation, in which intraplate deformations can be linked to interplate events, and tectonic and mineralisation events is increasingly recognised (Loutit et al. 1994; Kesler 1996). Plate geodynamics prior to seafloor spreading — prior to Bathonian-Callovian for the Australian plate — can only be traced by using the plate's apparent polar wander path (APWP). Various overseas studies have highlighted links between APWP kinks, reflecting changes in plate motion, and tectonic and mineralisation events. For instance, May et al. (1989) linked the J2 cusp on the North American APWP to the start of the Nevadan Orogeny, Klootwijk et al. (1985) linked cusps on the Indian Cenozoic APWP to distinct tectonic phases in the India-Asia convergence, and Lewchuk & Symons (1995), by dating North American MVT mineralising events through comparison of the palaeomagnetic overprints associated with the mineralisation with the North American Palaeozoic APWP, were able to link some of those mineralisations to APWP kinks and orogenic events. In Australia such palaeomagnetic studies have so far concentrated on the Proterozoic.

Kinks on the Palaeoproterozoic APWP of the McArthur Basin have been linked to regional compressional events and mineralising events (Loutit et al. 1994; Idnurm et al. 1994). Idnurm and coworkers identified six inflections on the APWP between ~1700 and ~1500 Ma; two inflections can be related to major deformational events, three to major magmatic events and five to mineralising events. They also linked three of the kinks/mineralisations to basin-wide regional magnetic overprints imposed by hydrothermal fluid movements. This recognition allows, inversely, unravelling the evolution of fluid movement pathways and plumbing systems from the regional and temporal evolution of magnetic overprints.

The potential of the Australian Phanerozoic APWP for tectonic and mineralisation studies has not been explored systematically. Attention until now has focussed on definition of the polepath, which remains controversial in part. The Palaeozoic trajectory is under dispute with two different interpretations proposed for the Middle-Late Palaeozoic. The Mesozoic trajectory is poorly defined with little work done in the past two decades, and the precise shape of the better-established Cenozoic trajectory has been questioned. Despite such uncertainties, study of the Phanerozoic APWP is nevertheless providing new insights into geodynamic evolution, basin development and mineralisation (Klootwijk 1996).

Mesozoic and Cenozoic path

The Mesozoic path has not advanced much beyond that defined by Embleton (1981). It is based only on a few averaged poles, but its general outline is supported by the Indian path (Klootwijk 1996). The path (Fig.1) shows two major loops, one of Late Triassic-Early Jurassic age (apex ~185+ Ma, or 210-200 Ma according to the Indian path) and the other of Late Jurassic-Early Cretaceous age (apex ~140 Ma). The loops reflect major reversals in Australia's latitudinal movement, from northward during the Triassic to southward during the Jurassic and back again northward during the Cretaceous and Cenozoic. These reversals of plate motion can be correlated with the starts of major phases of extension and basin development: Early Jurassic development of the Clarence-Moreton, Maryborough, Surat and Eromanga Basins (Williams & Korsch 1996) and rifting in New Guinea (Symonds et al. 1996) and possibly Late Triassic development of the Ipswich and Tarong Basins (Holcombe et al. 1997), followed by Late Jurassic and Early Cretaceous rifting along the Queensland coast and between Australia and Antarctica (Symonds et al. 1996). Major periods of contraction such as the Late Permian to Middle Triassic Hunter-Bowen Orogeny (Korsch et al. 1997; Holcombe et al. 1997) are less evidently reflected on the path as a broad cusp and extensive APWP movement.

The Cretaceous and Cenozoic path defined by Idnurm (1994) is mainly characterised by cusps of middle Cretaceous and approximately K-T boundary age. These cusps may be related respectively to initiation of extension in the Tasman Sea and in the Australia-Antarctica region — an event manifested by widespread acquisition of Late Cretaceous magnetic overprints — and by northward propagation of seafloor spreading from the Tasman Sea into the Capricorn Basin and Coral Sea

Palaeozoic path, (neo-)Craton

The Early Palaeozoic part of the path is the least contentious and has not advanced much in its definition beyond the early 1980s apart from a suggested Kanimblan origin (Klootwijk 1996) for widespread overprints previously interpreted as Delamarian. The amount of Middle and Late Palaeozoic data has increased and two different interpretations have emerged for the Middle-Late Palaeozoic part of the APWP (see discussion in Klootwijk 1996): the established SLP-path proposed by Schmidt, Li, Powell and coworkers and the alternative KG-path proposed by Klootwijk and Giddings. The two paths agree for the Middle Palaeozoic on a tropical to low-southerly position for Australia but show different orientations for Australia, with profound implications for the Late Palaeozoic Gondwana-Laurentia convergence and formation of Pangaea.

The KG-path is extensive but without the sharp hairpins characteristic of the Mesozoic APWP. The path shows a broad loop in the Cambro-Ordovician, probably related to the Delamarian Orogeny and to Early Ordovician initiation of the Canning Basin, and a broad Late Devonian (to possibly Early Carboniferous) cusp defining a substantial northward movement of Australia which may be related to the initial phases of the Alice Springs Orogeny. Some of the Palaeozoic mineralisation phases in the Tasman Orogen dated by $^{40}Ar/^{39}Ar$ methods (Perkins et al. 1994,1995) may be related to magnetic overprint phases, e.g. for the Early Carboniferous and possibly the middle Silurian to Middle Devonian, but such overprint phases are not greatly reflected in the shape of the path.

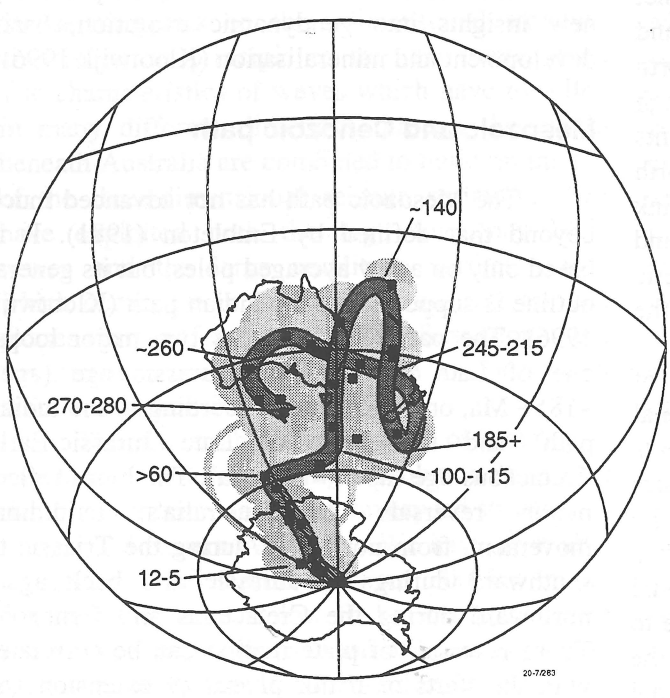

Fig. 1 - Australian latest Palaeozoic-Cenozoic APWP, approximate dates for loops and cusps after Klootwijk (1996).

Late Palaeozoic path, New England

Definition of the Late Palaeozoic APWP for New England has progressed considerably. Palaeomagnetic studies by AGSO, and lately AGCRC, have been carried out on mainly Carboniferous successions in four areas of the Tamworth Belt: the Gravesend-Rocky Creek and Werrie Synclines and the Rouchel and Gresford blocks. The studies have focussed on volcanics because these are best able to retain primary magnetisations despite widespread remagnetisation by a reverse polarity "Kiaman" overprint, and also because SHRIMP U-Pb zircon dates (e.g. Roberts et al. 1995) are becoming increasingly available. The Carboniferous APWP for New England is extensive with a pronounced middle Carboniferous eastward loop (apex ~335-330 Ma), followed by a pronounced latest Carboniferous-earliest Permian westward

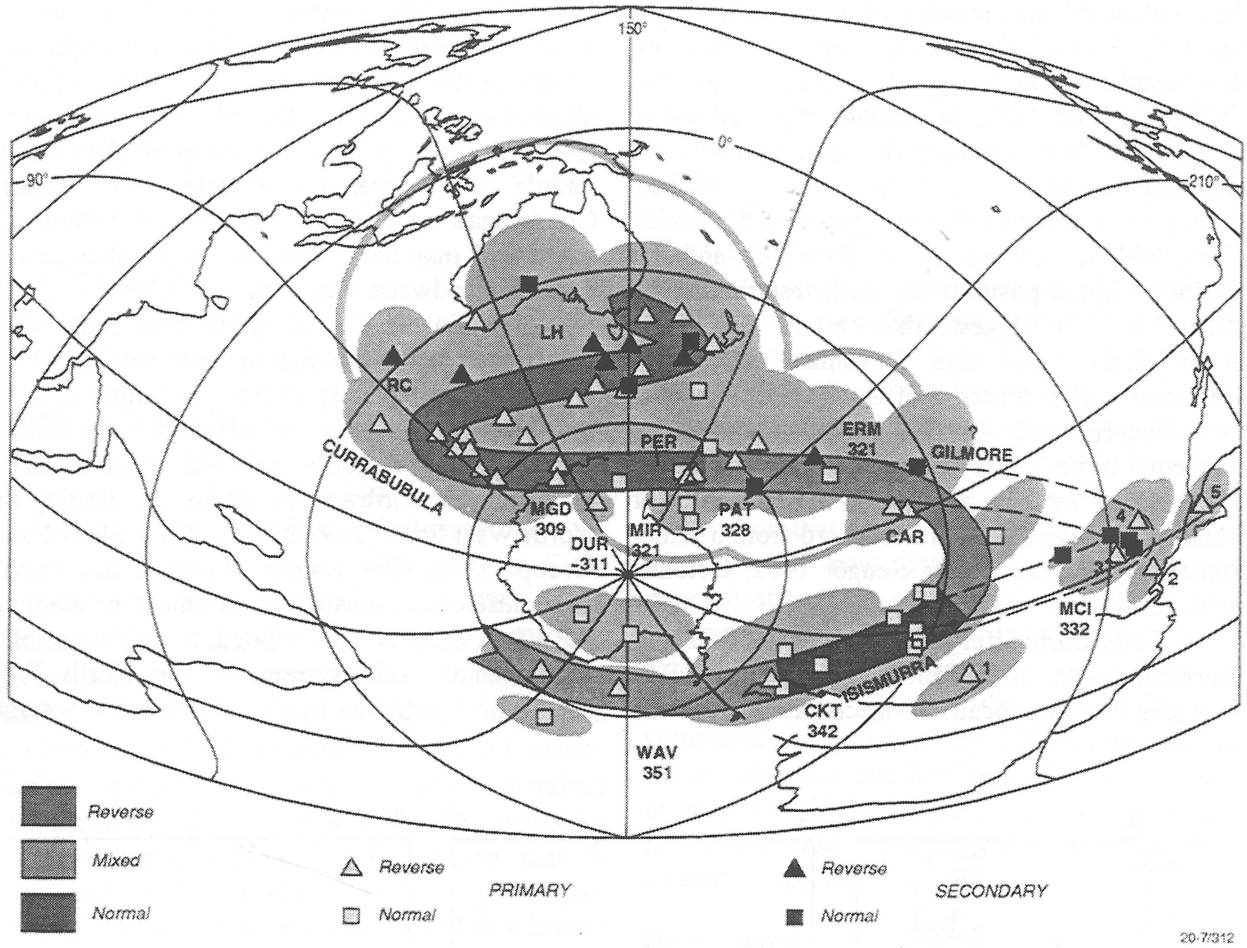

Fig. 2 - Carboniferous APWP for New England based on integration of APWP trajectories for four tectonic blocks from the Tamworth Belt. The preferred polepath excludes several pole positions from the Isismurra Fm of the Gresford block, possibly affected by local rotation and incomplete component separation. See Klootwijk (1996, Fig.13) for acronym legend.

loop (Fig.2). The path shows general agreement with the earliest Carboniferous and Late Carboniferous parts of the KG-path for (neo-) cratonic Australia, as is to be expected following latest Devonian accretion of the Gamilaroi Terrane. The middle Carboniferous eastward loop of the New England path is, however, more extensive than the eastward swing of the KG-path. This is interpreted as refinement of a common APWP rather than differential movement; the New England APWP is thus taken to reflect Greater Australia's movement during the Late Palaeozoic.

The Late Palaeozoic APWP implies extensive palaeolatitudinal movement, shown separately for the older, middle and younger segments of the APWP (Fig.3). The middle segment (Fig.3B) documents the late Visean-Namurian large-scale southward movement to South polar latitudes that is expected from bio- and litho-stratigraphic evidence for cooler conditions in eastern Australia. The preceding Early Carboniferous movement to moderate northern latitudes (Fig.3A) is unexpected and controversial because it imposes very high movement rates on the subsequent southward movement. This northward movement has been based mainly on results from the Isismurra Formation of the Rouchel and Gresford blocks, but is now supported by results from current studies in the Rocky Creek Syncline. Low to moderate northern palaeolatitudes from volcanics in the lower part of the Caroda Formation add some detail to the previously undefined initial part of the southbound palaeolatitude curve (Fig.3B).

The Early Carboniferous northward excursion has significant implications for Gondwana's convergence with Laurasia and in particular for the tectonic evolution of Greater Australia in relation to the Central Asian Fold Belt. Integration of palaeolatitude data from the New England APWP and the KG-path show that this northward movement had already started in the Late Devonian. A northward movement of comparable magnitude and timing can be concluded from Tarim block data, if preference is given to the "southern" polarity option for its Late Devonian results. There is also well-established geological evidence for convergence of the Tarim block with the Central Asian Fold Belt and for Tarim's original position off northwestern Greater Australia. This suggests that eastern Gondwana acted during the Late Devonian and Early Carboniferous as a carrier of Gondwana fragments now incorporated into southern Laurasia, a concept quite at variance with prevailing geodynamic models purporting that a series of continental slivers drifted northward from a rather stationary Gondwana (e.g. Sengör 1987; Golonka et al. 1994).

Early Carboniferous convergence of Greater Australia with the Central Asian Fold Belt provides a provocative mechanism for the Kanimblan-Alice Springs Orogeny: it can be viewed as the result of far-field stresses originating from a nearby region, rather than as the result of northwest Gondwana-southern Laurentia interaction suggested by Veevers et al. (1994). The middle Carboniferous reversal of eastern Gondwana's movement from northward to southward may have been the trigger that parked several Gondwana fragments, such as the Tarim block, within the Central Asian Fold Belt, while others such as the Cathaysian fragments may have separated subsequently at tropical latitudes. Such movement reversal may be reflected in the middle Carboniferous to Early Permian passive-margin extension off northwest Australia, developing the North West Shelf (AGSO North West Shelf Study Group 1994). The younger limb of the middle Carboniferous eastward loop on the New England APWP (Fig.2) is thus related to initiation of a fundamental basin system on the North West Shelf, the Westralian Basin. Likewise the younger

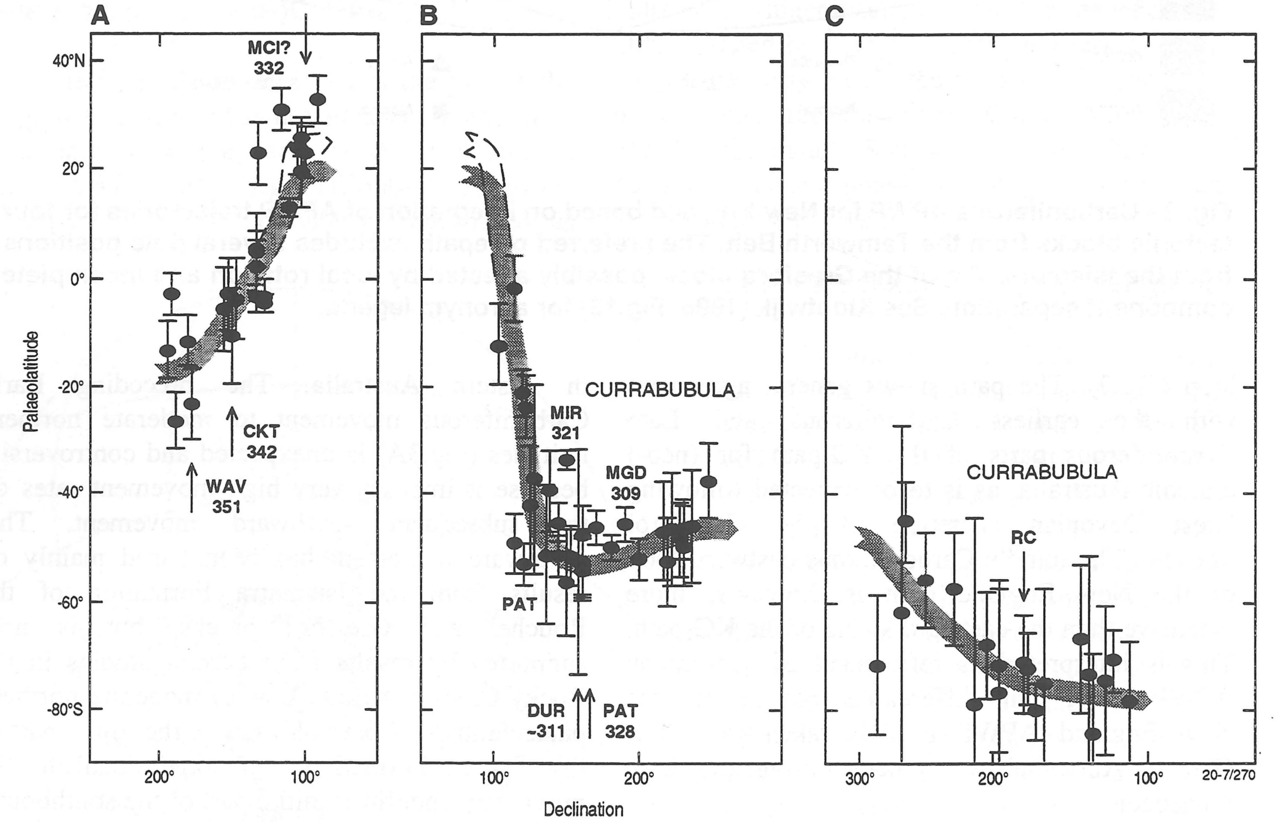

Fig. 3 - Palaeolatitudinal evolution of New England/Australia (Armidale reference point) based on pole positions detailed in figure 2. Palaeolatitudes are shown against declinations as a proxy for relative age control, for the three successive APWP swings, A: Early Carboniferous - Waverley Fm to Martins Creek Ignimbrite Mb, "eastward" limb, B: middle-Late Carboniferous - Martins Creek Ignimbrite Mb to Currabubula Fm, "westward" limb, C: latest Carboniferous - Currabubula Fm to Lark Hill Fm, "eastward" limb. See caption to Figure 2 for the preferred polepath/palaeolatitude pattern and acronym legend.

limb of the Late Carboniferous-Early Permian westward loop can be related to initial development of a fundamental basin system in eastern Australia, latest Carboniferous-Early Permian initiation of the Sydney-Gunnedah-Bowen Basin (Korsch & Totterdell 1995; Fielding et al. 1997; Holcombe et al. 1997).

Discussion

Australia's Phanerozoic APWP is characterised by five major loops. There is a one-to-one correspondence between the timing of the loops and the initiations of major basin systems, that is, Late Cambrian-Early Ordovician — Canning Basin; middle Carboniferous — Westralian Basin; Late Carboniferous-Early Permian — Sydney-Gunnedah-Bowen Basin; Late Triassic-Early Jurassic — Ipswich-Tarong-Clarence-Moreton-Maryborough-Surat-Eromanga Basins and rifting along the Australian plate's northern margin in New Guinea; and Late Jurassic-Early Cretaceous — rifting along Australia's northeastern and southern margins. The excellent correspondence suggests a relationship that is consistent and sensible. APWP loops reflect reversals of interplate movements and this causes intraplate extension and basin development.

The Phanerozoic APWP also shows several cusps which can be related to contractional or extensional events, that is, Late Devonian-Early Carboniferous — initiation of Kanimblan Orogeny and Alice Springs Orogeny; Early-Middle Triassic — Hunter-Bowen Orogeny; Early-Late Cretaceous — onset of extension in the Tasman Sea and along Australia's southern margin; latest Cretaceous earliest Tertiary — northward propagation of extension from the Tasman Sea into the Capricorn Basin and Coral Sea. Again the relationship is simple. APWP cusps reflect directional changes, rather than substantial reversals in interplate movements, and this causes intraplate deformation and extension.

The changing stress regimes indicated by the loops and cusps on the Australian APWP create or re-activate basement fracture systems and permeable domains with focusing of fluid flows and lead ultimately to hydrothermal mineralisation and hydrocarbon movements. These fluid movements can cause secondary magnetisations and their pole positions are to be expected to lie on the younger limb or apex of the APWP loops and cusps. The emerging Phanerozoic overprint story seems, however, more complex than the Palaeoproterozoic picture with its well-defined and confined overprint poles which are related to specific APWP features. Some Phanerozoic overprint poles are confined in time, ie the ~90-95 Ma overprint following the Early-Late Cretaceous cusp; others are drawn-out, for example, the Early Carboniferous polepath trajectory for the (neo-)Craton following the Late Devonian (-Early Carboniferous) cusp, and the Late Carboniferous trajectory for New England following the middle Carboniferous loop. The drawn-out overprint patterns have the advantage that they reflect fast and large-scale plate movements and thus facilitate considerable resolution in identification and dating of mineralisation phases. It is, however, a sobering observation that so far only one, possibly two, of the overprint pole patterns can be related to mineralisation phases, that is, the Early Carboniferous and possibly the Middle Silurian-Middle Devonian mineralisation events in the Tasman Orogen. There is thus a need for more systematic definition of the Phanerozoic APWP, for the Mesozoic and the Early-Middle Palaeozoic in particular, if the APWP's potential for insights in tectonic and mineralisation phases is to be gainfully exploited.

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Phanerozoic Thermotectonic History of the Southwestern Tasman Line-Willyama Inliers Region

B. P. Kohn[1], P. B. O'Sullivan[1], M. M. Mitchell[1], A. J. W. Gleadow[1] and S. M. Hill[2]

[1]Australian Geodynamics Cooperative Research Centre, VIEPS, Dept. of Earth Sciences, La Trobe University, Bundoora, VIC 3083
[2]Cooperative Research Centre for Landscape Evolution and Mineral Exploration, The University of Canberra, Belconnen, ACT 2616

Analysis of apatite fission track (AFT) data from outcrop and deep drillhole samples has been used to document the variation of fission track parameters within the upper crust of the southwestern Tasman Line (in the Darling River area) and the Willyama Inliers (Broken Hill and Olary Blocks). Numerical forward modelling of measured AFT parameters and their matching with time-temperature paths allow constraints to be placed on the magnitude of denudation and timing of relative fault displacement. Periods of major Phanerozoic cooling, hitherto unknown before AFT studies in the region, are identified, and these can be related to tectonic events reported from elsewhere in Australia, and intraplate stresses resulting from tectonism around the plate margins.

Southwestern Tasman Line

The Tasman Line is a fundamental suture in Eastern Australia defining the boundary between the Proterozoic Craton to the west and the younger Tasman fold belt system to the east. To the east and northeast of the Broken Hill Block the Tasman Line is partly defined by geophysical anomalies and the straight course of the east-northeasterly-trending Darling River flowing along a feature known as the Darling River Lineament (DRL) which extends northeastwards to the offshore continental margin of Queensland. The DRL is believed to have originated as a Neoproterozoic deep-crustal feature along which right-lateral strike-slip motion occurred, possibly during the breakup of the Rodinia Supercontinent at ~700-725 Ma.

Results of AFT data collected from 21 outcrops (Proterozoic and Lower Palaeozoic) and 18 deep drillhole samples (Lower Palaeozoic) along the DRL northeast of Broken Hill suggest that there is a major crustal discontinuity which follows the river. This north to south transition seems to occur gradually across a ~20-30 km wide band, about the same width as the proposed lineament.

Interpretation of the data suggests that the Proterozoic and Lower Palaeozoic rocks presently exposed north of the DRL experienced a major cooling episode during the middle Palaeozoic between ~350-400 Ma, after which they experienced palaeotemperatures of ~70-90°C (Fig. 1). At that time, the same Lower Palaeozoic rocks, now outcropping south of the DRL, were still exposed to higher palaeotemperatures >110°C. Therefore, rocks to the north of the DRL moved upwards ~2-3 km relative to the same rocks south of the DRL, possibly in response to the Alice Springs or Lachlan Orogeny.

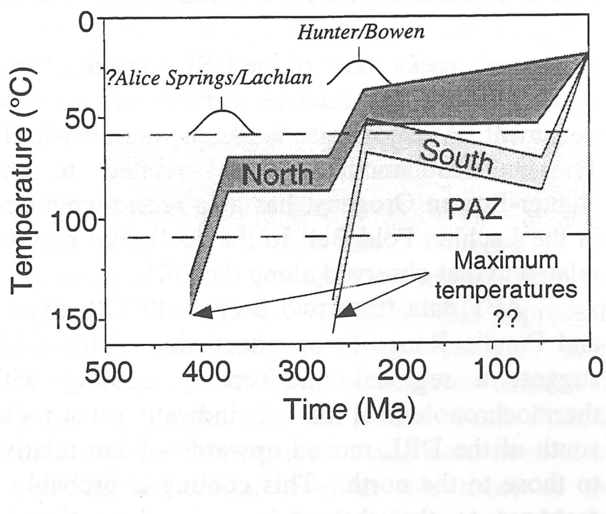

Fig. 1 - Proposed time-temperature histories for rocks located on either side of the southwestern Darling River Lineament based on AFT data from outcrop and deep well samples.

A second major cooling event occurred during the Late Permian-Early Triassic resulting in rocks on either side of the DRL being rapidly cooled at ~240-260 Ma (Fig. 1). However, it is evident from the AFT data that rocks south of the DRL cooled significantly more (from palaeotemperatures >110°C to between ~60-80°C) than those to the north (from palaeotemperatures of ~70-90°C to between ~50-70°C). Based on these results, we suggest that during the Late Palaeozoic, rocks south of the DRL were displaced upwards ~1-1.5 km relative to rocks north of the lineament. A major episode of Late Permian-Early Triassic denudation, possibly related to the Hunter-Bowen Orogeny, has also been recognised in the Lachlan Fold Belt to the south and may be related to that observed along the DRL.

AFT data from two deep wells (Blantyre-1 and Pondie Range-1) on either side of the DRL suggest a regional mid-Tertiary cooling with thermochronological markers indicating that rocks south of the DRL moved upwards ~1 km relative to those to the north. This cooling is probably a response to the change in regional continental plate stresses which occurred at this time. It is concluded that the southwestern portion of the DRL has been a sensitive recorder of at least three major episodes of Phanerozoic reactivation.

Willyama Inliers

The Willyama Inliers comprise a series of shallowly buried to outcropping 'blocks' of Early Proterozoic Willyama Supergroup and syn- to post-tectonic granites which were metamorphosed during the mid-Proterozoic and reactivated during the Olarian and Delamerian Orogenies. AFT data have been collected from 15 outcrop and 25 deep drillhole samples (from two wells at the Broken Hill North Mine - DD3186 and DD3288, and the Bancannia South -1 well) - see Fig. 2 for localities. Outcrop samples over much of the Willyama Inliers display a similar Phanerozoic thermal history to that previously shown for the adjacent Curnamona Craton and Adelaide Fold Belt suggesting events of regional extent. Modelling of the AFT results indicates a significant amount of regional cooling of >90°C since the Late Palaeozoic. Results from the Broken Hill borehole samples suggest that the cooling was via removal of overburden and that the palaeogeothermal gradient was not significantly elevated above the present-day regional estimates of ~20°C/km. Therefore, the suggested mechanism of cooling is the removal of >4 km of section via denudation. Most cooling occurred in two stages (see Fig. 3).

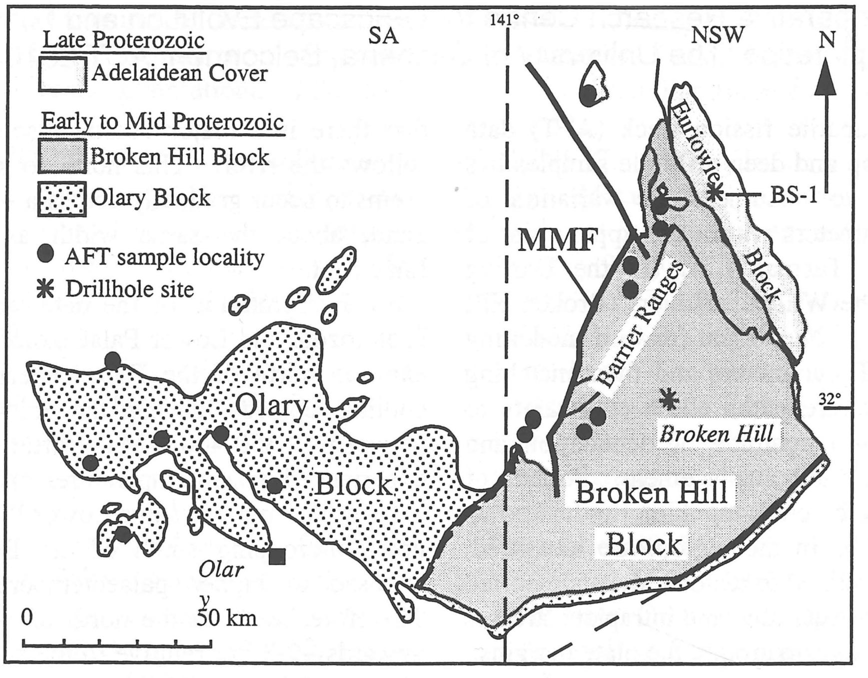

Fig. 2 - Geological sketch map of the Willyama Inliers showing sample locations of outcrops and drillholes. BS-1 = Bancannia South -1 drillhole; MMF = Mundi Mundi Fault.

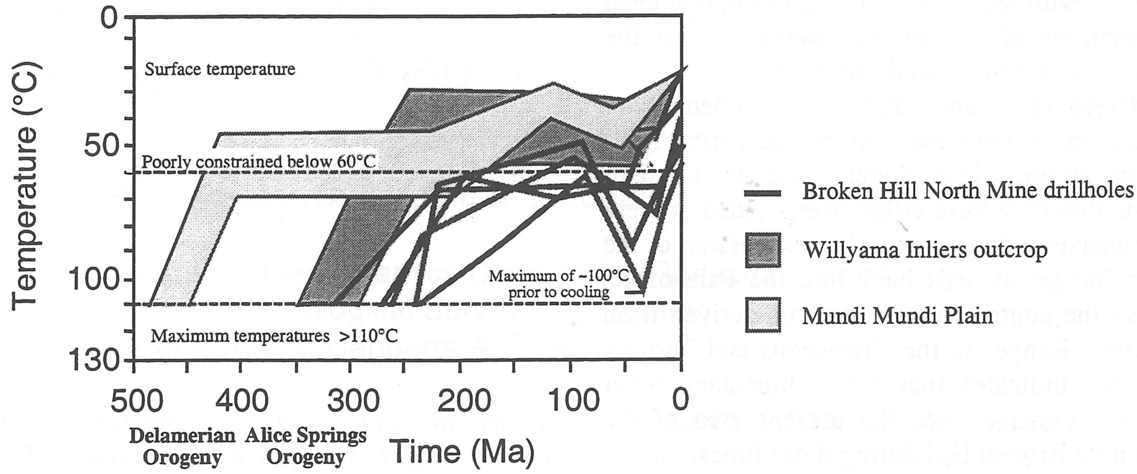

Fig. 3 - Modelled time-temperature cooling envelopes and paths for the Willyama Inlier samples derived from AFT data.

The first stage involved regional cooling during the Late Carboniferous to Permian in response to removal of ≥3 km of overlying material. This event was possibly associated with the Alice Springs Orogeny (~300-400 Ma) of central Australia or other orogenic events in the Tasman Orogen (such as the long-lived Lachlan Orogeny). A second, younger episode of cooling is also suggested throughout the region. The maximum timing of the second cooling episode is the mid-Cretaceous, but modelling suggests latest Cretaceous to Tertiary cooling. This cooling was of smaller magnitude than the Late Palaeozoic cooling and as such, is difficult to resolve in detail from the outcrop data. The detailed investigation of the two boreholes from the Broken Hill Block provides a more accurate constraint on the timing and magnitude of this cooling, and indicates that the area experienced ~25-35°C cooling, probably between ~60-20 Ma, with a paleogeothermal gradient of ~20°C/km (similar to that of the present day). This cooling phase is possibly associated with denudation in response to intraplate stresses related to the reconfiguration of the Australian Plate and its margins during this time.

An exception to the regional cooling history described above is found in rocks located on the Mundi Mundi Plains to the west of the Broken Hill Block. The Mundi Mundi Escarpment is predominantly a NE-SW trending feature that divides the Mundi Mundi Plain from the Barrier Ranges to the east (Fig. 2), and approximates the trend of the Mundi Mundi Fault. The Mundi Mundi Fault appears to be of major regional landscape significance, marking the western, upthrown edge of a major tilted block. It is an ancient structural feature, possibly dating back to the Proterozoic which has continued to be active up to recent times.

AFT results clearly suggest very different temperature-time paths for rocks on either side of the Mundi Mundi Fault. Samples from west of the fault record initial cooling from palaeotemperatures >~100-110°C during the Early Palaeozoic (Cambrian-Ordovician), suggesting an association with the Delamerian Orogeny (see Fig. 3), whereas samples immediately east of the fault show a significant Late Paleozoic (Carboniferous) cooling possibly related to the Alice Springs Orogeny. Further cooling of rocks on both sides of the fault is also suggested during the Tertiary but the timing is less well constrained because it occurred from relatively shallow crustal levels. To the east a greater amount of denudation has occurred than to the west, such that at the time of onset of Late Palaeozic related cooling, rocks presently exposed to the west were ≥40-50°C cooler than those to the east. In terms of the present day geothermal gradient known from the Broken Hill region (~20°C/km) this represents removal of at least 2-2.5 km of section. It is emphasised that because the chlorine content of apatite in samples from the Mundi Mundi Plain is relatively high the samples could have been at an even deeper crustal level at this time, so the calculated amount of denudation should be regarded as a minimum. The present data set does not allow a specific timing to be placed on movement along this fault; however it must have occurred post Late Palaeozoic. The disparate time-temperature histories across the fault are consistent with geological and geomorphological interpretations of greater denudation east of the fault, and long term tectonic activity.

Cretaceous and Tertiary sediments are abundant and widespread west of the fault. Their apparent absence immediately east of the fault suggests that they have either been eroded or were not extensive in these parts. The expression of the Barrier Ranges at least back into the Palaeozoic, and also the contribution of detritus derived from the Barrier Ranges in the Cretaceous and Tertiary sediments, indicates that the sedimentary cover was not extensive over the present area of the ranges near Broken Hill during those times.

Conclusions

Time-temperature modelling of AFT data from outcrops and deep drillholes straddling the southwestern portion of the Tasman Line, and in the Willyama Inliers has identified distinct episodes of Phanerozoic cooling which can can be tentatively linked to tectonism elsewhere. The results reveal that the magnitude of cooling across major Neoproterozoic structures such as the southwestern Tasman Line and Mundi Mundi Fault differed significantly indicating a long history of Phanerozoic reactivation.

Acknowledgments

This study was carried out as part of AGCRC Project 2005LO and also partly as a joint project with the CRC LEME. Access to core material from drillholes was made available by Pasminco Exploration for Broken Hill North Mine, and for others by the NSW Department of Mineral Resources.

Crustal Geometry and Tectonics of the New England Orogen

R. J. Korsch, D. G. Lund & L. Rogers

Australian Geodynamics Cooperative Research Centre
Australian Geological Survey Organisation,
GPO Box 378, Canberra ACT 2601

The easternmost tectonic unit in eastern Australia, the New England Orogen, consists of arc and arc related rocks produced during Devonian Early Cretaceous plate convergence at the interface of eastern Gondwana and Panthalassa. Several sedimentary basins developed inboard of this margin during this time span. The Australian Geodynamics Cooperative Research Centre (AGCRC) project Tectonic Framework of Eastern Australia aims to provide new geological syntheses and to develop an understanding of the 4D geometry of the New England Orogen and its component tectonic assemblages, along with the adjacent Bowen, Gunnedah and Surat sedimentary basins. To do this we have undertaken a terrane analysis and are defining the nature and timing of interplate and intraplate tectonic events in eastern Australia. These events, in the New England Orogen and further afield at the plate margins, have influenced the evolution of the adjacent basins.

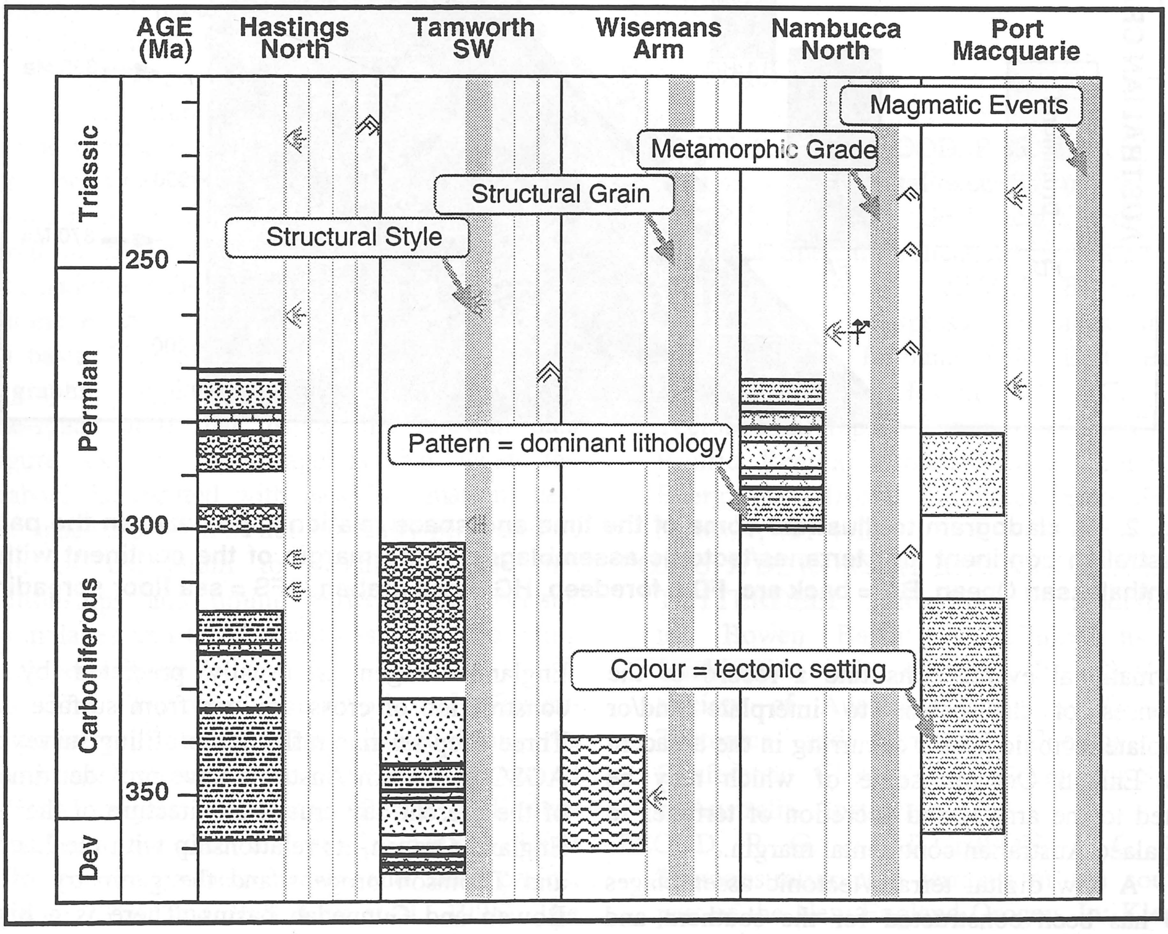

Figure 1. Computer generated time-space plot for some of the tectonostratigraphic assemblages in the southern New England Orogen.

The Early Permian - Middle Triassic Bowen and Gunnedah basins and the Early Jurassic - Early Cretaceous Surat Basin developed in a backarc tectonic setting behind the active convergent plate margin, but suffered a series of intraplate deformational events which included the initiation of the basin system by an extensional event in the Early Permian, several contractional events (Early Permian; mid-Permian; latest Permian; Early Triassic; Middle Late Triassic; ? latest Jurassic - earliest Cretaceous; early Late Cretaceous), and finally another, minor, extensional event in the Eocene. These deformational events constitute a record of the responses of the basins to interplate and/or intraplate tectonic events occurring in the adjacent New Enland Orogen, some of which may be related to the arrival and accretion of terranes to the palaeo Australian continental margin.

A new digital terrane/tectonic assemblages map has been constructed for the southern and northern New England Orogen, based on an interpretation of the surface geology in combination with aeromagnetic and gravity images. This builds on previous terrane interpretations by several workers including Cawood & Leitch (1985), Scheibner (1985, 1996), Leitch & Scheibner (1987), Flood & Aitchison (1988) and Ashley & Flood (1997). In the area between the southern and northern New England Orogen, where the tectonic assemblages are hidden by younger sedimentary rocks of the Surat and Clarence Moreton basins, the assemblages have been correlated beneath this cover using the images created from aeromagnetic and gravity data, including newly acquired high resolution aeromagnetic data where it is available.

The 3-dimensional geometry of the New England Orogen is usually predicted by the construction of cross sections from surface data. Three deep seismic reflection profiling surveys by AGSO in eastern Australia have provided images of the present day crustal architecture of the New England Orogen, its relationship with the Lachlan and Thomson orogens and the geometry of the Bowen and Gunnedah basins. There is a highly variable crustal architecture along the suture between the New England and the Lachlan-Thomson orogens. In the north, the Bowen Basin seismic lines are dominated by east-dipping

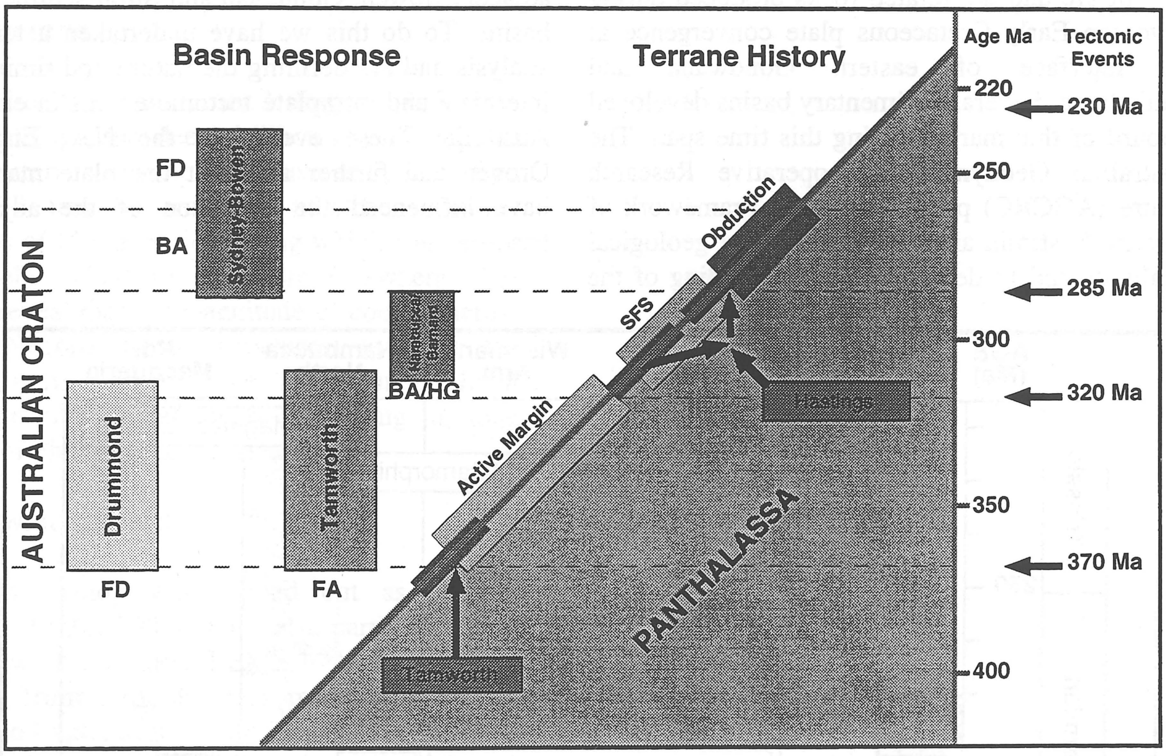

Fig. 2. - A cladogram to illustrate some of the time and space relationships between the palaeo-Australian continent and terranes/tectonic assemblages at the margin of the continent with the Panthalassan Ocean. BA = back arc, FD = foredeep, HG = half graben, SFS = sea floor spreading.

structures, with the New England Orogen thrust westwards over the Thomson Orogen. The lines in southernmost Queensland are dominated by gently west-dipping structures in the lower crust, but with east-dipping thrusts in the upper crust. The accretionary wedge part of the New England Orogen has been thrust beneath the easternmost Lachlan Orogen, but with the forearc basin component (Tamworth Belt) of the New England Orogen being obducted (backthrust) on top of the Lachlan Orogen. The line in the southern New England Orogen contains both east- and west-dipping structures and shows similar relationships between the orogens as in the lines in southernmost Queensland. Thus, the New England Orogen is a doubly vergent orogen that developed this geometry in the Late Palaeozoic to Triassic. The deep seismic data in eastern Australia show present day crustal architectures that are the responses of the crust to interplate and intraplate deformational events superimposed on a crustal architecture that was established by a subduction-related convergent plate margin in the Late Palaeozoic. The data provide insights into the 3D geometry of some of the terranes/tectonic assemblages in the New England Orogen.

A synthesis of the stratigraphic units and their timing within the tectonic assemblages, along with a summary of sequence stratigraphic data from the adjacent sedimentary basins, is being entered into the PREDICT information system and stored in an Oracle database. Also included is information on the nature and timing of the main tectonic events within each tectonic assemblage and basin. This allows, through the development of graphic templates, the digital construction of time-space plots that display the relevant data (Figure 1). One advantage is that when the database is updated with new information, new time space plots will be automatically generated. A form of cladogram to visually display the relationships and timing between the tectonic assemblages and the inboard basins is also being developed (Figure 2).

The Tectonic Framework of Eastern Australia project utilised data collected during the Australian National Geoscience Mapping Accord (NGMA) project Sedimentary Basins of Eastern Australia to construct a three dimensional digital model for the northern Bowen and Surat basins, between 23°30' and 26°S (Cox et al., 1995). The model is being extended southwards to include the Gunnedah Basin in New South Wales, and will eventually cover an area of nearly 1000 km x 300 km to a depth of over 10 km. The model is based on a structural and sequence stratigraphic interpretation of a regional grid of seismic reflection data in the Bowen, Gunnedah and Surat basins. This seismic mapping has provided the geometry and timing of the deformational events (Korsch & Totterdell, 1995, 1996) as well as the geometry of about 20 sequence boundaries (Totterdell et al., 1995).

Thus this project is undertaking a terrane analysis of eastern Australia that will attempt to provide essential information for basin analyses and detailed mineral province studies, hopefully leading to an enhanced ability to predict the distribution of mineral and petroleum systems in understudied areas of eastern Australia.

Acknoweldgements

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A Seismic Model of the Crust Through the Broken Hill Block and Tasman Line

J.H. Leven, D.M. Finlayson, A. Owen, & D. Johnstone

Australian Geodynamic Cooperative Research Centre (AGCRC)
Australian Geological Survey Organisation (AGSO)
GPO Box 378, Canberra ACT 2601

The Broken Hill Block lies just inboard of the late Neoproterozoic continental rift margin and hosts one of the world's major mineral deposits. In 1997, the Australian Geodynamics Cooperative Research Centre undertook a wide angle refraction survey across the Broken Hill Block and Tasman Line (Darling Lineament) to:

- investigate the crustal structure beneath the Broken Hill Block and Tasman Line,
- determine if a mid-crustal mafic body had sourced the prominent amphibolite dykes within the Broken Hill Block, and
- compare the structure of the Broken Hill Block with the Mt Isa Block.

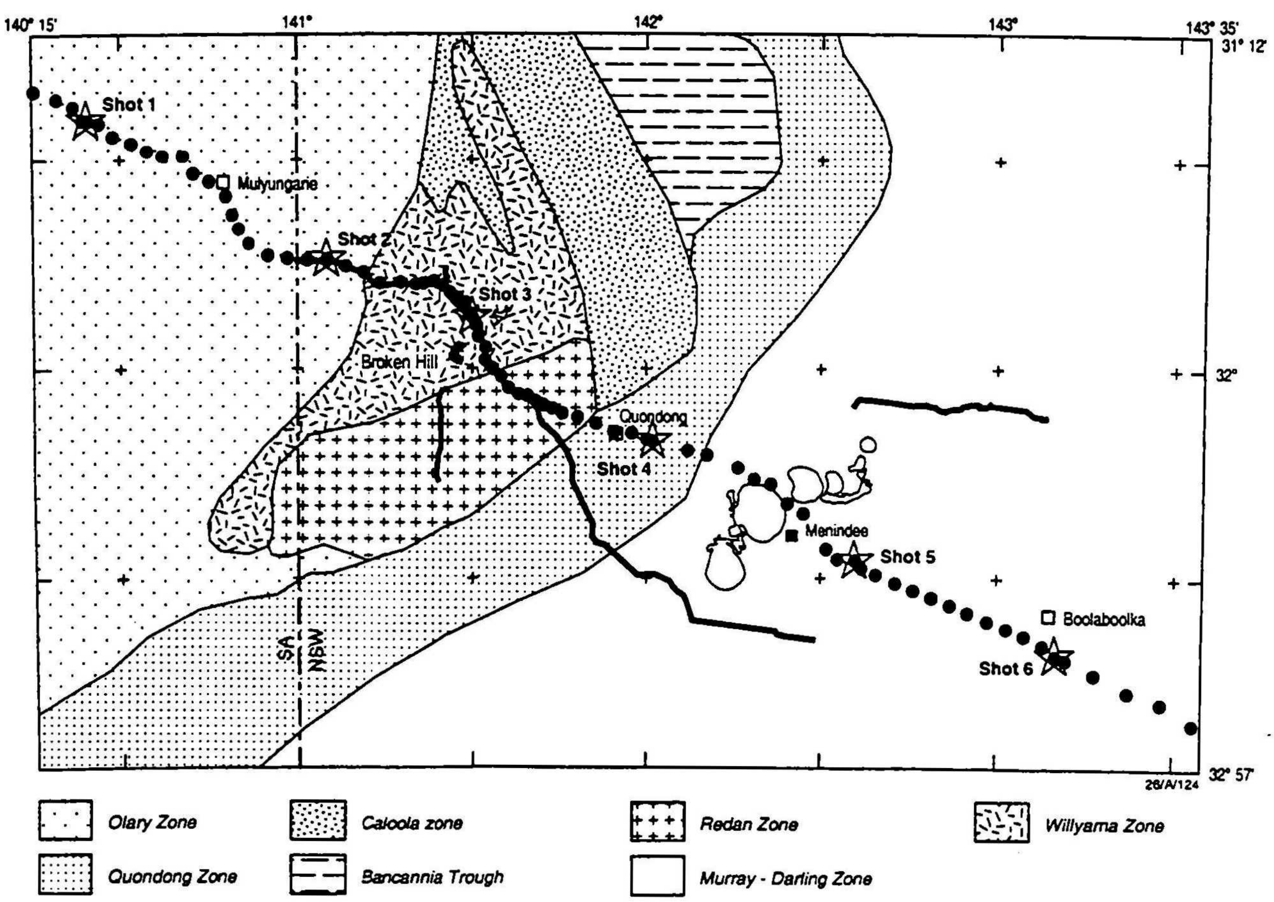

Fig. 1 - Location map showing the position of the SGR recorders (dots) and the six shot sites (stars) for the refraction profile. The seismic reflection lines are indicated as solid lines.

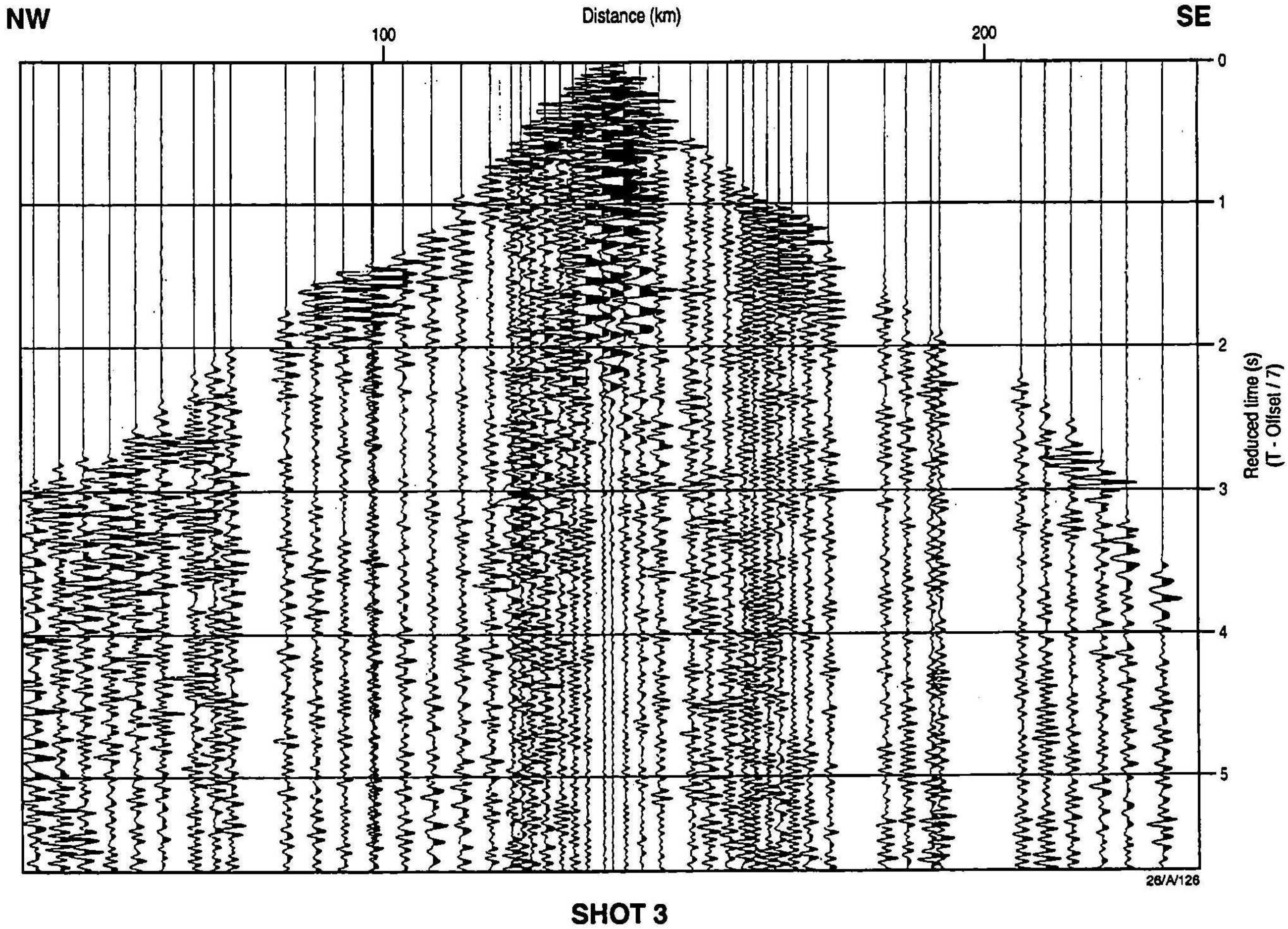

Fig. 2 - An example of the Pg1 arrivals from shot 3 detonated north of Broken Hill recorded across the Broken Hill Block. These Pg1 arrivals show little delay time, indicating the presence of basement rocks with a P-velocity near 5.9 km s^{-1} near the surface.

Method

Eighty six Seismic Group Recorders (SGRs) were deployed along a NW-SE oriented profile extending over 350 km through the Broken Hill Block (Figure 1). The station spacing varied from 2.5 km over the Broken Hill Block to 10 km near both ends of the profile.

The seismic signals were detected by 2 Hz geophones buried beside the SGR recorders. The geophone output was recorded digitally on a tape drive in each instrument during pre-programmed time windows, and shots were fired within these time windows.

Six shots were detonated during this program. Two 3000 kg shots (1 and 6) were positioned at the NW and SE ends of the profile to provide wide-angle data to offsets in excess of 300 km, and four intermediate 1000 kg shots (2 to 5) positioned along the profile to provide additional control on the mid-crustal seismic structure.

Geology

Along the profile, the geology has been divided into five zones on the basis of the magnetic and gravity and geological data (Figure 1). At the northwestern end of the profile, the Olary zone is characterised in the TMI image by a variable signature and the Proterozoic geology is largely obscured by a veneer of Cretaceous to Cenozoic sediments. East of the Mundi Mundi Fault, the Willyama zone is characterised by a relatively subdued magnetic signature, apart from a series of dykes with a prominent magnetic expression. The total thickness of the Willyama Supergroup has been estimated at approximately 7-11 km (Stevens et al., 1988). The Redan Zone is characterised by a highly magnetic signature. Glen et al. (1977) proposed that the Redan zone forms an older basement to the Willyama Supergroup rocks; however, Willis et al. (1983) correlated the Redan zone to the base of the Willyama

Supergroup. North of the profile, the Willyama Supergroup is unconformably overlain by sediments of the late Neoproterozoic Adelaidean succession. The Quandong zone is a belt of predominantly Cambrian rocks which abuts the eastern edge of the Redan zone and the Bancannia Trough (farther north), and is characterised by a strong negative anomaly in the TMI image. The Murray-Darling Zone at the SE end of the profile is magnetically quiet and characterised by large negative Bouguer gravity anomalies associated with a series of Cambrian to Devonian troughs.

Structural models for the Broken Hill region range from those of Laing et al., (1978), Marjoribanks et al., (1980) who interpreted the structure in terms of a series of refolded nappes, to White et al (1995) who reinterpreted the Broken Hill block as a series of SE verging thrust packages. Recently Gibson et al., (1998, this volume) have interpreted reflection seismic data in terms of strike slip and reverse slip movement on southeast dipping structures, with evidence for the preservation of an earlier extensional geometry of unknown age.

Previous crustal models

Branson et al. (1976) interpreted reflection test data from the Broken Hill region and proposed a two layer crustal model, with an upper layer (5.92 km s^{-1}) with a thickness of 14.5 km overlying a 12 km thick lower crustal layer (6.97 km s^{-1}).

Reflection seismic data

Recent AGSO reflection seismic data (Gibson et al., 1998) show prominent southeast dipping events, interpreted as shear zones, that in some cases extend through the entire crust. Within the eastern portion of the Broken Hill Inlier, the upper crustal shear zones have a listric character and appear to sole into a major décollements at around 10 and 18 km depth.

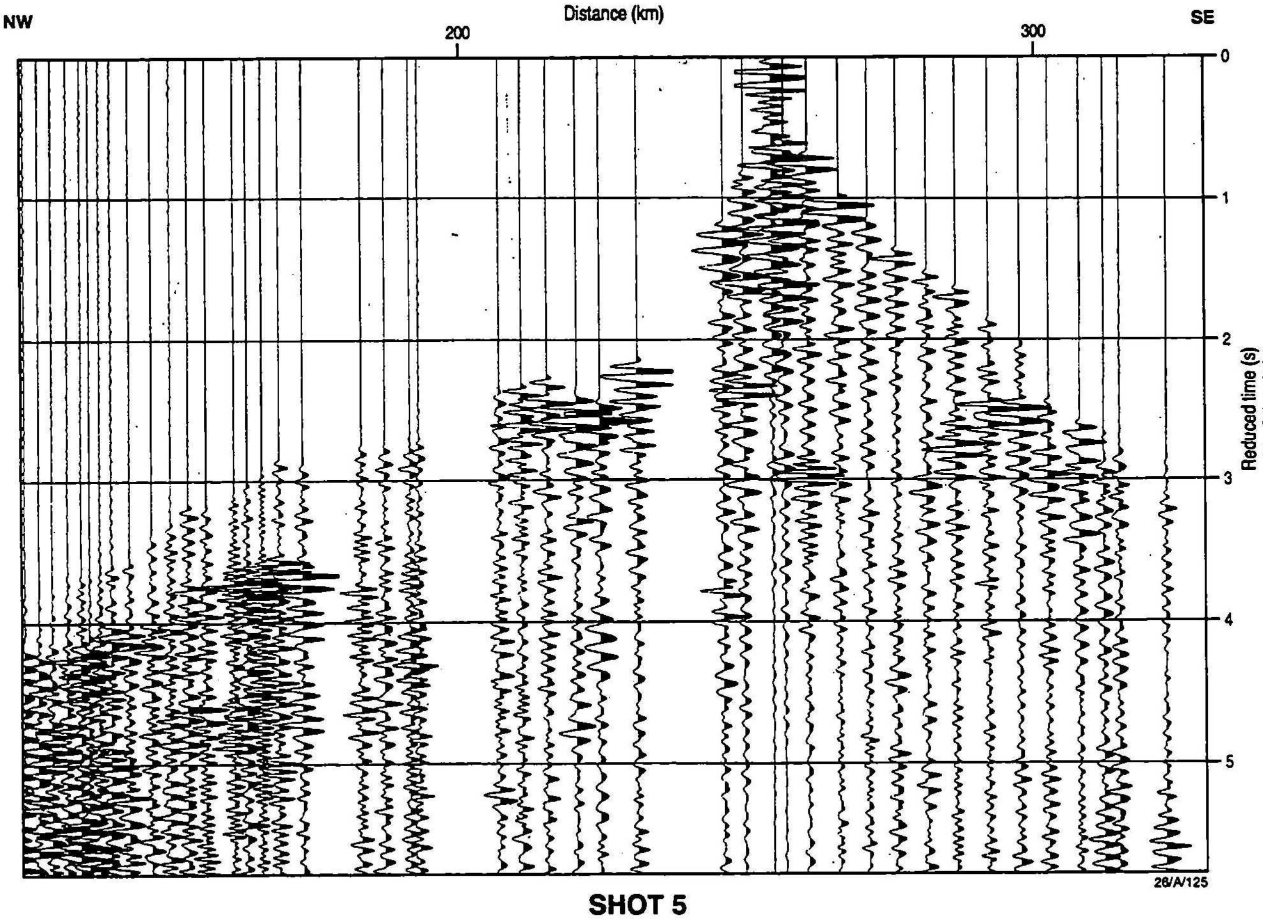

Fig. 3 - An example of the Pg1 arrivals from shot 5 detonated east of Menindee. These Pg1 arrivals show a significant delay time, indicating the presence of near-surface low-velocity rocks. The striking asymmetry of the Pg1 arrivals indicates rapidly changing geometry of this low-velocity zone which corresponds to the Menindee Trough.

Wide angle seismic phases

The seismic arrivals have been classified into five major phases: Pgl(upper crustal refracted phase), Pg2 (lower crustal refracted phase), PcP (reflected phase from the mid-crustal boundary), PmP (reflected phase from the Moho), and Pn (Moho headwave phase).

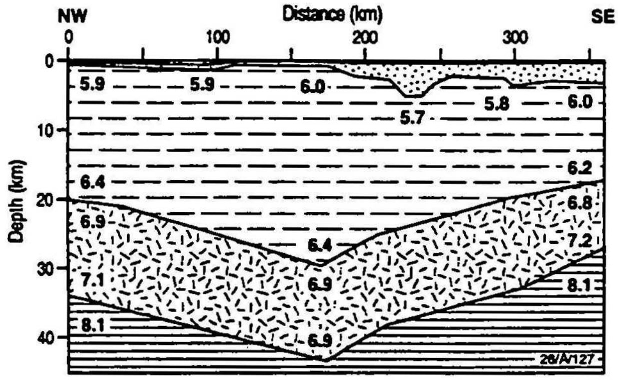

Fig. 4 - The crustal P-velocity model along the profile. The annotated numbers are the velocities (P-wavespeeds) in km s^{-1}.

The Pgl phase represents seismic energy which has turned in the upper crustal layer, and is generally prominent to offsets of 170 km. Figure 2 shows the Pgl phase for shot 3 detonated just north of Broken Hill. For shots 1, 2, and 3, this phase has a relatively symmetric travel time curve about the shot, and indicates a P-velocity gradually increasing from 5.9 km s^{-1}, with no evidence for significant structure in the upper crust. Figure 3 shows the Pgl phase for shot 5 detonated east of Menindee. In contrast to shot 3, the Pgl phase from this shot has a delay time of 600 ms indicating a low velocity near-surface layer. The prominent asymmetry and delays indicate a large variation in the thickness of this near-surface layer and/or upper crustal velocity (P-wavespeed) on either side of this shot.

Pg2 is interpreted as a lower crustal refracted phase. This phase is rarely seen as a first arrival, but is evident as second arrivals in the offset range 170 to 200 km, and is interpreted in conjunction with the higher amplitude PcP cusp resulting from energy reflected from the mid-crustal boundary around the critical angle. PcP is generally observed in the offset range 110 to 150 km.

Pn arrivals are generally low amplitude, and are evident on some shots at offsets beyond the crossover distance around 165 km. Pn arrivals are not detected from shots 1 and 2, but are clearly seen over a small offset range to the SE from shot 3. Pn arrivals to the NW have been recorded from shots 5 and 6. The PmP cusp results from energy reflected around the critical angle from the Moho

Interpretation

Records from shots 1, 2, and 3 showed clear Pgl arrivals which are interpreted to indicate an upper crustal P-velocity increasing from 5.9 km s^{-1} to around 6.4 km s^{-1} over the NW end of the profile. The significant delays in the Pgl arrivals at the SE end of the profile recorded from shots 4, 5, and 6 are interpreted to result from low-velocity remnant troughs of Darling Basin sediments, and low P-velocity zones extending into the upper crust (Fig. 4).

Although rarely recorded as a first arrival, Pg2 is important because it constrains the velocity in the lower crustal layer, and this, interpreted in conjunction with the high amplitude PcP cusp, gives constraints on the depth of this mid-crustal boundary. These data indicate a thickening of the upper crust beneath the Broken Hill Block (Fig. 4).

Pn arrivals were generally low amplitude. In the case of shots 1 and 2 they are below the noise level and have not been observed. Clear Pn arrivals were recorded over limited range to SE from shot 3, with the crossover distance at 165 km. No Pn was recorded from Shot 4 due to the offset range, but Pn arrivals were recorded over an extended range to the NW from shots 5 and 6. These arrivals indicate a sub-Moho P-velocity of 8.1 km s^{-1}. The PmP arrivals constrain the geometry of the Moho, and indicate the lower crustal layer has a relatively constant thickness.

Results

- Two layer crust:
- upper layer 5.9 km s^{-1} to 6.4 km s^{-1} with variable thickness ranging from 20 to 30 km.
- lower layer 6.8 km s^{-1} to 7.2 km s^{-1} of relatively constant thickness of around 14 km.
- Moho depth ranges from 35 km on either side to 43 km beneath the Broken Hill Block. Sub-Moho P-velocity of 8.1 km s^{-1}.
- No evidence for a mid-crustal body with high P-velocity beneath the Broken Hill Block which might have sourced the mafic dykes.

- Thickening of the upper crustal layer beneath the Broken Hill Block by 50%, with the lower crustal layer maintaining a thickness of ca. 14 km.
- Low seismic velocities in the upper crust associated with the Menindee and Blantyre Troughs, in the region of the Darling Lineament.
- Relatively low crustal P-velocities compared with those of eastern Australia. No evidence of an underplated lower crustal layer with P velocities around 7.7 km s^{-1}.

Discussion

The preferred seismic model resulting from this work over the Broken Hill Block differs significantly from the model for the Mt Isa Block, where Drummond et al. (1998) have interpreted major dipping high-velocity (mafic?) bodies in the middle crust. No such high velocity bodies are required to explain Pg1 arrival times for rays which travelled beneath the Broken Hill Block.

Reflection seismic profiles acquired across the Broken Hill Block as part of the Broken Hill Exploration Initiative show a series of pervasive southeast dipping events that are interpreted as shear zones Gibson et al. (1998). The thickening of the upper crustal layer has not affected the thickness of the lower crustal layer and suggests a décollement surface exists between the upper and lower crust.

The low P-velocity upper crustal zone in the vicinity of Menindee is interpreted to be the seismic expression of the Tasman Line, indicating the suture zone between the rift margin of the Proterozoic continental crust to the west and the Palaeozoic Lachlan Fold Belt to the east.

Acknowledgements

The authors gratefully acknowledge the contribution of the IRIS Organisation and Walter Mooney, Tom Burdette, and Simon Klemperer for the loan of the SGR recording equipment. We thank Brian Laird for his considerable effort in managing the logistics, training AGSO staff in the use of the SGRs and transcribing the data. We thank the AGSO drilling and explosives crew for their work within a tight schedule in adverse weather conditions. This work is published with the permission of the Executive Director, AGSO.

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The Nature of the Tasman Line Southeast of the Broken Hill Block

J. H. Leven, T. Fomin, A. Owen, D. W. Johnstone, B. J. Drummond, K. D. Wake-Dyster, & D. M. Finlayson

Australian Geodynamics Cooperative Research Centre
Australian Geological Survey Organisation, GPO Box 378,
Canberra ACT 2601

The Tasman Line is defined as the boundary between outcrops of Precambrian crustal elements to the west and Palaeozoic crustal elements to the east. It separates the older Mt Isa and Broken Hill Blocks from the younger Lachlan and Thomson Fold Belts. In the region southeast of Broken Hill, it is marked by NE-SW trending gravity and magnetic anomalies, and a topographic feature bounded by the course of the Darling River.

In 1997 the acquisition of reflection seismic data by the Australian Geodynamics Cooperative Research Centre (AGCRC) and the NSW Department of Mineral Resources was completed across the Tasman Line to the east of the Broken Hill Block which supplemented the 1996 seismic acquisition of the NSW Government Broken Hill Exploration Initiative across the Broken Hill Block and the Tasman Line by the AGCRC. Additionally, the AGCRC acquired a regional-scale wide-angle profile trending NW-SE through the Broken Hill Block and the Tasman Line (Leven et al. 1998).

Interpretation of the wide-angle seismic data shows the thickening of the upper crust beneath the Broken Hill Block, a lower crust with a relatively constant thickness along the profile, and a region of low velocity in the upper crust beneath the Menindee and Blantyre Troughs of the Darling Basin.

The most prominent features on the reflection seismic data across the Broken Hill Block are the southeast dipping events. These have been interpreted as shear zones; some events can be directly correlated with particular surface-mapped features, such as the Mundi Mundi Fault. Fomin et al. (1998) have interpreted this reflection seismic data to indicate several different levels of sub-horizontal detachments within the crust at ~10 and ~18-24 km depth. The Moho is not well defined beneath the Broken Hill Block on these reflection data.

East of the Broken Hill Block the reflection seismic data show a series of troughs containing Darling Basin sediments beneath a relatively undeformed blanket of Murray Basin sediments. The Mendinee Trough has a deformed western edge, in which the upper succession has been homoclinally upturned and the lower succession has been truncated, producing a structure analogous to that seen on the northern margin of the Officer Basin (Leven & Lindsay, 1995). This structural analogy and the position of the inflection point of the gravity data suggest the presence of a triangle zone of low-density material to the west of the Menindee Trough in front of a southwest directed thrust sheet, corresponding to the Broken Hill Block. However, unlike the Officer Basin profile, these seismic data do not clearly image the detachment surface at the base of this thrust sheet.

The Blantyre Trough has a similarly structured western edge, and a series of west dipping (~17°) reflection events appears to image the associated thrust.

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Ore-bearing Fluids at the Fosterville Gold Mine, Victoria and Implications for Mineralisation in the Western Lachlan Orogen.

Terrence P. Mernagh,

Australian Geological Survey Organisation, GPO Box 378, Canberra, ACT 2601

The Fosterville goldfield is located in Victoria, 22 km ENE of Bendigo and produced 1,480 kg of gold between 1884 and 1910, at an average grade of around 3.2 g/t. Perseverance Corporation Ltd. has been open cut mining ore in the oxide zone at Fosterville since 1992 and has produced over 5,000 kg of gold at an average grade of 1.4 g/t. The measured, inferred and indicated resource for the oxide zone is 5.9 mt at 1.1 g/t gold while that of the sulphide ore zone is 8.3 mt at 2.8 g/t gold.

Mineralisation at Fosterville differs from the other major deposits in central Victoria. The latter reef gold deposits have laminated to massive quartz veins related to faults, saddle reefs, extension veins, and en-échelon gashes. The gold at Fosterville is associated with disseminated arsenopyrite and pyrite and hosted by fault breccia (Roberts, 1995). The results of the present study indicate that mineralisation at Fosterville occurred at temperatures varying from 270°C to 160°C and at higher structural levels (3.5 to 5.5 km) than those estimated for the major reef gold deposits (Cox et al., 1995). The lower confining pressures in the surrounding host rocks allowed greater fluid flow within the sediments and led to the more disseminated style of mineralisation at Fosterville.

Structure and lithology

The Fosterville goldfield is situated on the eastern limb of the north-south trending Strathfieldsaye Synclinorium within a turbidite sequence of marine greywackes, sandstones, mudstones and shales of Ordovician age. The sequence is characterised by close to tight (interlimb angle 30° - 40°) upright folding with shallow plunge reversals.. The most significant structural feature is the NNW-trending Fosterville Fault (Fig. 1), a high angle reverse fault consisting of a complex series of shear zones and fault breccias up to 35 m wide. Numerous crosscourses and offsets along the 10 kilometre-long fault zone and evidence for backthrusting suggest repeated reactivation of the fault system (McConachy and Swensson, 1990; Wang and White, 1993). Other areas of mineralisation appear to be controlled by an adjacent strike fault known as the O'Dwyers Line (Fig. 1) which is sub-parallel to and approximately 1.5 km east of the Fosterville Fault. These contain mineralised quartz porphyry dykes and are closely related to the NNW-trending faults (Wang and White, 1993). These dykes have been pervasively altered to illite and kaolin and are crosscut by later generations of quartz veins. Based on preliminary U-Pb dating of zircons from these dykes, Arne et al. (1998) inferred the age of hydrothermal alteration and mineralisation at Fosterville to be Early to Middle Devonian.

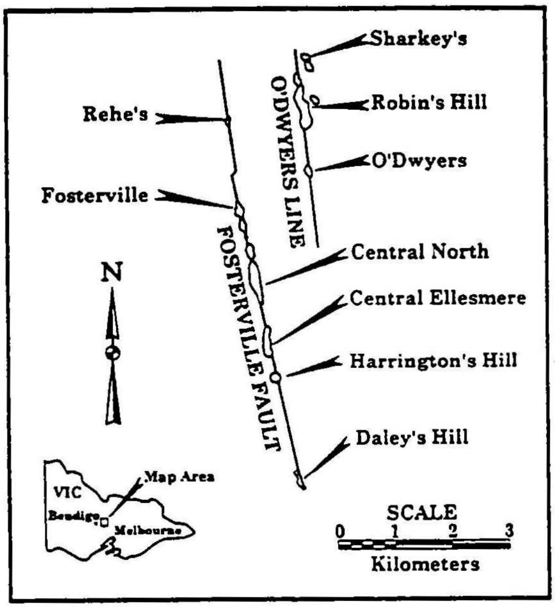

Fig. 1 - Simplified map of the Fosterville gold field.

Alteration and mineralisation

In the oxidised zone, gold mineralisation is hosted by lithic fault breccias and fine quartz vein stockworks in silicified and ferruginised sediments. Gold particles (typically < 1 mm in diameter) are contained within disseminated arsenopyrite and pyrite. The sulphide ore zone sits below the oxidised zone and a complex array of anastomosing quartz/carbonate veinlets and stockworks occur in drill core from this zone, particularly below shears and faults. Vein textures vary from laminated (crack-seal types) to massive extensional veins often with vuggy zones towards the centre of the veins. Evidence for wallrock alteration in drill core is limited to inconspicuous discolouration, silicification, minor sericitisation and abundant fine-grained disseminated arsenopyrite and pyrite (Bierlein et al., 1998).

PIMA studies

Previous infrared studies using the PIMA spectrometer (Merry and Pontual, 1996) have demonstrated a good correlation between the distribution of gold and illite at O'Dwyers. A preliminary traverse between more recent mine workings has confirmed this result (Fig. 2). No kaolinite was identified in the drill spoil samples used in the present study and this indicates that kaolinite is restricted to the more weathered samples. The more detailed study of Merry and Pontual (1996) also further divided the illites into so-called "normal" illites and more Mg-Fe-substituted illites. They found that the higher grades are associated with illites of "normal" composition.

Fluid inclusion studies

The following three types of fluid inclusions occur within the quartz/carbonate veins:

- Type Ia are two-phase, liquid-rich inclusions with less than 10 vol. % vapour and no detectable CO_2. Type Ib inclusions are also liquid-rich but contain CO_2 in the vapour phase.
- Type II are vapour-rich (>30 vol. % vapor), CO_2-bearing inclusions and are the most abundant. Many Type II inclusions have only a thin meniscus of water or appear to consist of only CO_2.
- Type III are three-phase inclusions containing liquid and vapor CO_2 and these are also very common.

Many inclusions showed evidence of necking but such inclusions were avoided during further studies.

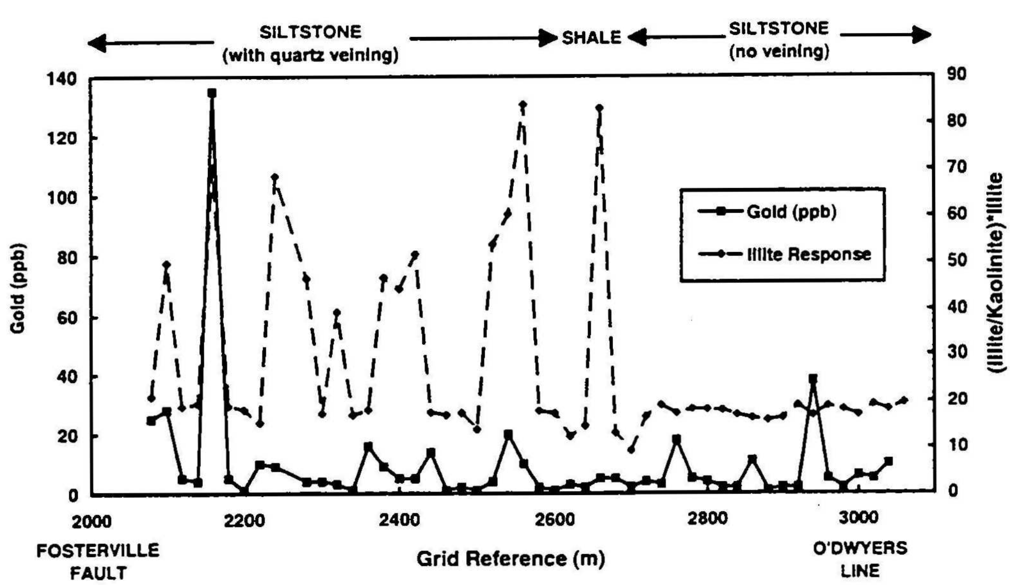

Fig. 2 - A plot of the illite response of PIMA spectra verses gold concentration (ppb) from selected drill spoil sample across a mine traverse.

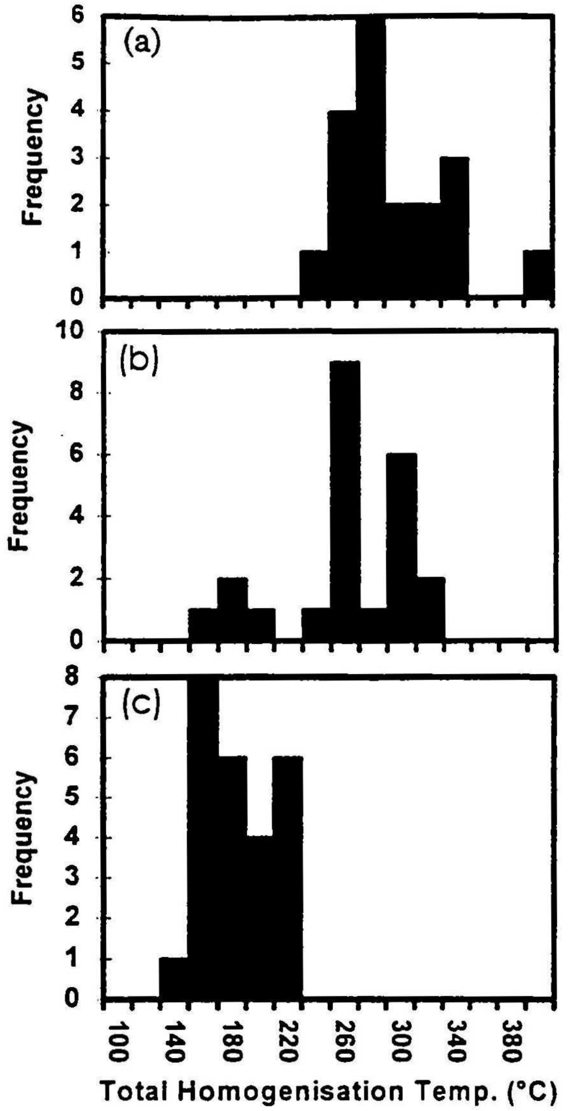

Fig. 3 - Histograms showing the total homogenisation temperatures for (a) CO_2-bearing inclusions homogenising to the vapour or by critical behaviour, (b) CO_2-bearing inclusions

Raman microprobe analysis of the vapor phase of Types II and III inclusions confirms the presence of CO_2, but also indicates that N_2 and CH_4 occur in some inclusions. The N_2 content of the vapor phase varies from 0 to 18 mol.% and is believed to reflect interaction of the fluids with organic material within the turbidite sequence. CH_4 varies from 0 to 25 mol. % with the highest concentrations occurring proximal to black shales. These results are in accord with microthermometric analyses which showed CO_2 final melting temperatures varied between -58.8 and -56.6°C with the overwhelming majority being close to -56.6°C.

Clathrate melting in CO_2-bearing inclusions occurred around 8.5°C giving salinities ranging from 0.5 to 5.8 equiv. wt.% NaCl with a distinct mode at 3.5 wt.% NaCl. Most CO_2-rich inclusions decrepitated before total homogenisation but the remaining inclusions exhibited a bimodal temperature distribution (Fig. 3). The majority homogenise between 234 and 384°C with a mode at 270°C and similar temperatures are observed for homogenisation into both the liquid and vapour phases with some inclusions exhibiting near critical behaviour. However, a small number of Type II inclusions homogenise between 146 and 198°C. Liquid-rich inclusions coexisting with Type II inclusions also homogenise between 133 and 218°C with a mode at 162°C (Fig. 3c). Their salinities are typically close to 6 equiv. wt.% NaCl. Other primary, aqueous inclusions in growth zones in bladed carbonate crystals homogenise between 212 and 338°C with a mode at 247°C. These inclusions have much lower salinities (typically less than 1 wt.% NaCl).

Type Ib fluids containing up to 25 mol.% CO_2 represent the least reacted, deeply sourced fluids that have migrated through the fault zone at Fosterville. These fluids were initially at near critical conditions and were trapped at about 270°C and at pressures from 130 to 200 Mpa. The presence of coexisting aqueous and CO_2-bearing inclusions which homogenise around 162°C suggest that this fluid undergoes phase separation and cooling. Other inclusions in bladed carbonate indicate the ingress of a lower salinity, meteoric? fluid which underwent phase separation at around 247°C.

Gold deposition is interpreted to be due to desulphidation reactions caused by phase separation and subsequent fluid mixing. Mineralisation within the host rocks occurred as the fluids flowed from the overpressured faults and veins into the host rocks and reacted with more reduced fluids or carbonaceous material to precipitate gold and associated sulphide minerals (Fig. 4). This disseminated style of mineralisation, the brittle fracture nature of the depositional sites, and the lower confining pressures (130 - 200 Mpa) suggest that the Fosterville deposit occurs at a higher structural level than the other major reef gold deposits of the Bendigo - Ballarat zone (Cox et al., 1995).

Acknowledgments

I would like to thank Trevor Jackson for his assistance while I was at Fosterville and Perseverance Exploration Pty. Ltd. for permission to publish this work. This paper is published with the permission of the Executive Director, AGSO.

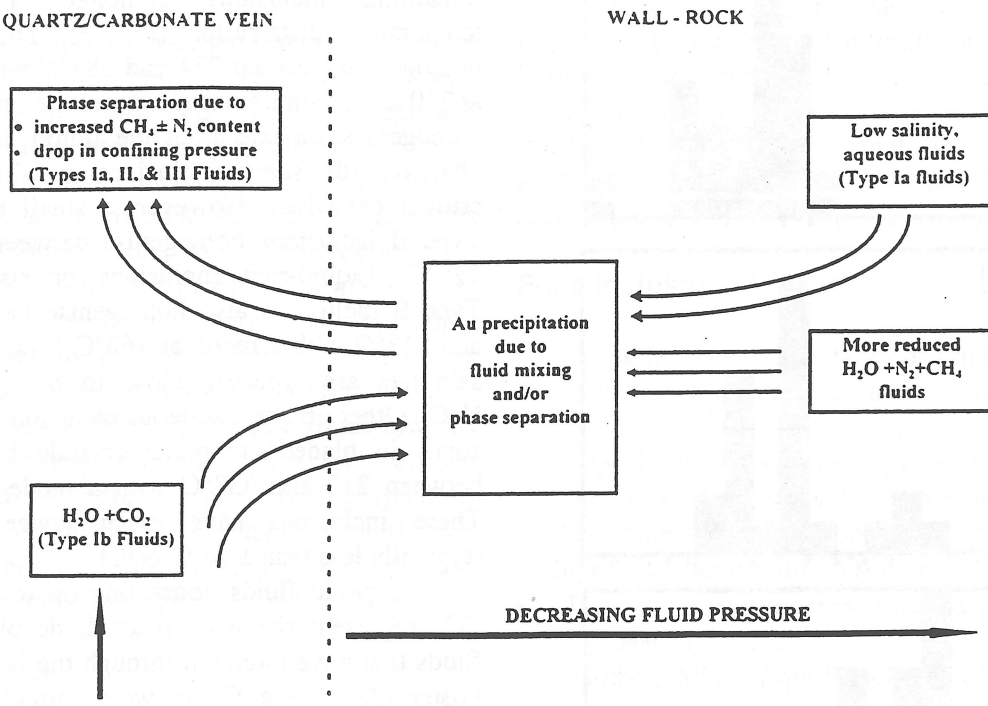

Fig. 4 - Schematic illustration of fluid flow paths and reactions leading to gold precipitation at Fosterville.

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Recent Developments in the Modelling of the Emplacement of Granites in the Crust and their Gravity Signatures

Louis Moresi, Fabio Boschetti and Hans Mühlhaus

Australian Geodynamics Cooperative Research Centre,
CSIRO Exploration & Mining, PO Box 437, Nedlands, WA 6009

Here we wish to demonstrate the powerful tools of forward modelling and interpretation of surface observables in terms of multiscale edges. The intention is to show how the representation of the gravity field as multiscale edges gives a strong insight into subsurface crustal structures. Rather than simply introducing arbitrary density anomalies and finding the maps of the edges in the resulting gravity field, we use self-consistent numerical models of fluid diapirs intruding a crust which has a brittle-viscous rheology. In this way we can show how realistic geological structures appear in the wavelet representation of the gravity field.

Idealized models of granite intrusions

A brief survey of the literature reveals little agreement on the manner in which granites penetrate to the shallow parts of the crust, and how the crust can make way for the emplacement of this material. Possible mechanisms include the small-scale mechanical erosion of the walls and roof of a magma chamber, the melting of root rocks with crystallization at the floor, the ascent of highly viscous diapirs of partially molten rock through a viscous crust, doming of the Earth's surface, taking advantage of local extension within a tectonically active region or reactivation of preexisting structures not directly related to the intrusion, inflation of an existing weak region by narrow feeders, and so on. [A useful summary is given by Paterson et al. 1991]. Supporting and contrary field evidence is available for all such mechanisms; however, some agreement can be found. For example, diapirs appear to be more important at greater depths where temperature and pressure conditions favour ductile flow of the crust around the intruding magma; at shallower depths, brittle structures appear to dominate (Pitcher, 1979).

For the sake of developing a simple mathematical model of the granite emplacement process, we must concentrate on just a few important physical processes. Here we consider a hot (1000°C), inherently buoyant blob of low viscosity material at a depth of ~25 km in the crust which represents material which has been melted by some underlying heat source. The blob rises through a crust which is layered in density and viscosity, and which has simplified brittle properties represented through a pressure dependent yield stress with mild strain softening. The initial condition is illustrated in Figure 1a. The regional geotherm is set to be 17°C/km. We solve the appropriate equations of motion self-consistently to obtain velocities and pressures, and the energy equation gives the temperature at each point in the simulation. Compositional variations and history dependent rheology are handled by using an active particle-in-cell version of the CITCOM code which has recently been developed.

<u>Case 1: Yield stress in the crust unimportant</u>

The initial blob of material rises rapidly in the warm, lower-viscosity, higher density layers at the base of the model forming into a rounded shape. As the blob approaches the first density and viscosity boundary, it slows, flattens and traps some of the surrounding material between itself and the upper layer. Some of this material is lost through very small scale instabilities which develop in this trapped layer and divide the large blob into a series of smaller blobs. Convection within the small blobs transports heat to the upper layer rendering it less viscous until the blobs can begin to penetrate (Fig. 1b). They continue into the next layer, carrying a halo from the lower layer. Some blobs cool sufficiently that they start to become too viscous to make further headway and become stalled. The remainder of the blobs

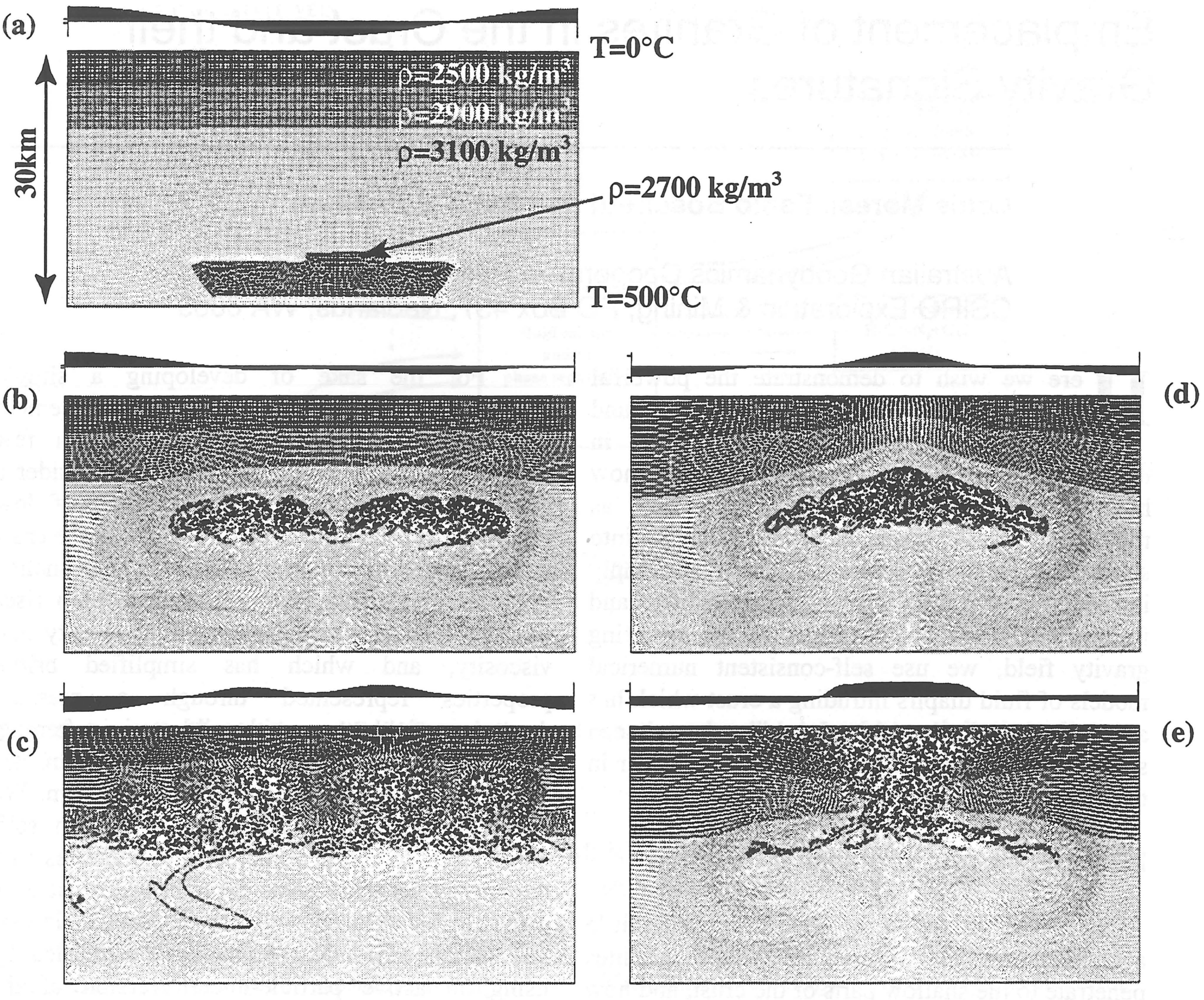

Fig. 1 - Ascent of viscous diapir in a low predominantly viscous, layered crust. Initial condition in (a) evolves differently depending on whether the crust has a high yield stress (b,c) or very low yield stress (d,e). The gravity anomalies for each case are shown.

continue to the neutral buoyancy level. Whenever a blob encounters an unfavorable density or viscosity layering it is delayed and tends to become stirred in with the lower fluid layer and surrounded by a halo of this lower layer which gradually drains as the blob ascends (Fig. 1c).

Case 2: Uppermost crust may yield

Here we assume the crust has been weakened by numerous unspecified earlier faulting events rather than being explicitly fractured solely by the rising blob, and we include this through a reduced yield stress. Under these conditions, the behaviour of the blobs may be quite different as they near the surface. At depth the behaviour is modified slightly because the ambient crust supports stresses in a slightly different manner. However, the broad behaviour of the rising blob is similar — it rises as a viscous diapir in the lowermost crust, it can be stalled, destabilized and entrain lower-layer materials when it encounters a density interface, and continue as a series of blobs. In this case, as the blob nears the brittle uppermost layers and is beginning to break up, the upper layers begin to fail which allows much more rapid horizontal deformation near the surface (Fig. 1d). This deformation is localized in the region of the rising blob (and, in our models, near the vertical boundaries) and allows the blob to rise more rapidly as the adjacent crust moves out and down as a coherent unit. The result of the way in which this failure occurs is that the blob may rise above its neutral buoyancy level. The shape of the blob in the upper layer is now controlled by angular brittle structures rather than the rounded mushroom shape characteristic of a viscous diapir (Fig. 1e).

Interpretation of gravity signatures

The fundamental equations of potential field theory have an interesting interpretation when regarded as a particular case of a multiscale wavelet transform. Drawing upon recent results in

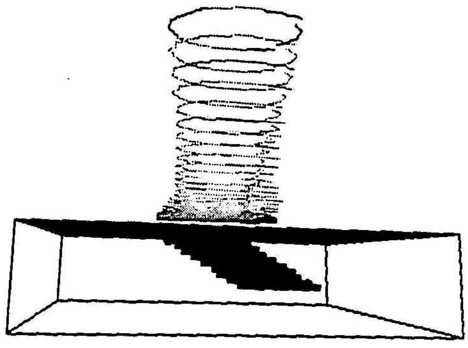

Fig. 2. Visualisation of the multiscale edges due to a dipping cylinder. Notice the effect of the dip on the bending of the edges at different height.

the wavelet processing of images (e.g. Mallat and Zhong, 1992) and of potential fields (e.g. Hornby, Boschetti, and Horowitz, 1997), we present a new method of analyzing gravity fields, based upon a generalization of the concept of edges. Singularities in the mass density distribution of the sources are assumed to correspond one-to-one with apparent edges in the gravity field at different levels of upward continuation. Apparent edges in the field are defined to be local extrema of the horizontal gradient, which correspond nicely with the first stages of some traditional hand-drawn interpretation techniques. Upward continuation is used as the change of scale operation in defining the appropriate wavelet. The collection of apparent edges at all scales is termed a skeletonization of the field. Some properties of the skeletonization are (a) the variation of amplitude with position contains recoverable information about the type and location of the source density singularity, and (b) the field can, in most cases, be reconstructed from the skeletonization.

Behaviour of multiscale edges for simple geological shapes.

In order to give a simple example of skeletonization in Figure 1 we present a 3-D visualisation of the multiscale edges corresponding to the gravity field due to a dipping cylinder of anomalous density. Mallat and Zhong (1992) show that the set of multiscale edges can be used to reconstruct the gravity image. This new representation allows an immediate understanding of some aspects of the shape of the causative body. The most obvious feature is the variation of the location of the edges at different levels as a function of the dip of the cylinder. Figure 2 shows a vertical section of the evolution of edges at different scales for faults of varying dip. The edges give a clear visual indicator of the direction of dip and also of the dip angle. In particular, vertically dipping density variations have vertical edges. These simple observations show the usefulness of this technique even for a first pass visual inspection.

Multiscale edges for well-characterized complex systems

The numerical simulations of diapirs shown in Figure 1 are fully characterized in the sense that the density field everywhere is known. However, this density field is the result of an intricate stirring history of several viscous fluids under the action of their own relative buoyancies. It is very simple to determine the gravity field associated

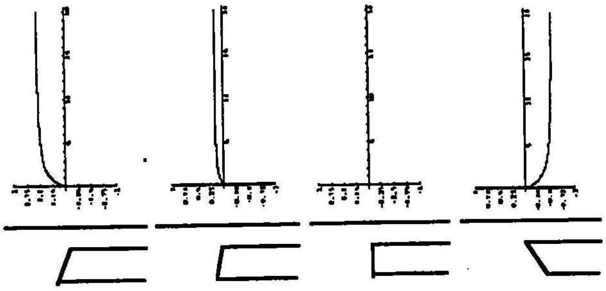

Fig. 3 - From the evolution of edges at different scales it is easy to determine the direction of dip and, to a lesser extent, the inclination of a fault.

with the density anomalies at depth. The standard techniques described above can then be applied to obtain multiscale edges from the gravity field (Fig. 4). Interpreting Figure 4, it is difficult to ignore the actual structures which lie beneath the surface but it is clear that the representation of the gravity field in terms of multiscale edges helps in understanding the basic structure of the sources even from a purely visual perspective. In Figure 4a, for example, the major edges give the approximate position of the main body and tell us that at large scales the source can be approximated by a single anomalous body. At finer scales however, secondary edges show that we are actually dealing with two similar, closely spaced bodies. Similar observations can be drawn from Figure 4b, for more, smaller bodies. Of particular interest are Figure 4c and 4d. In Figure 4c the edges at large scales indicate the presence of the major anomalous body while at finer scales the pattern of intrusions is well represented. The location of the edges on the surface mark quite accurately two cells in the convection pattern. Similar observations are valid for Figure 4d, with the edges being more marked because of the anomalous body almost reaching the surface. By comparing the multiscale edges in Figure 4c and 4d the different behaviours due to the different vertical positions of the anomalous body is evident. More insight may be obtained by mathematical inversion (see below).

Inversion and sensitivity to noise.

The evolution of edges at different scales contains also information about the kinds of source singularities underlying a data set. This property can be used in an inverse procedure to recover the shape and location of anomalous bodies from gravity fields. For example, we can invert the synthetic profiles shown in Figure 2 for the depth and dip of the causative faults. The results are reported in Table 1 for an inversion after 20% of random noise was added to the synthetic data.

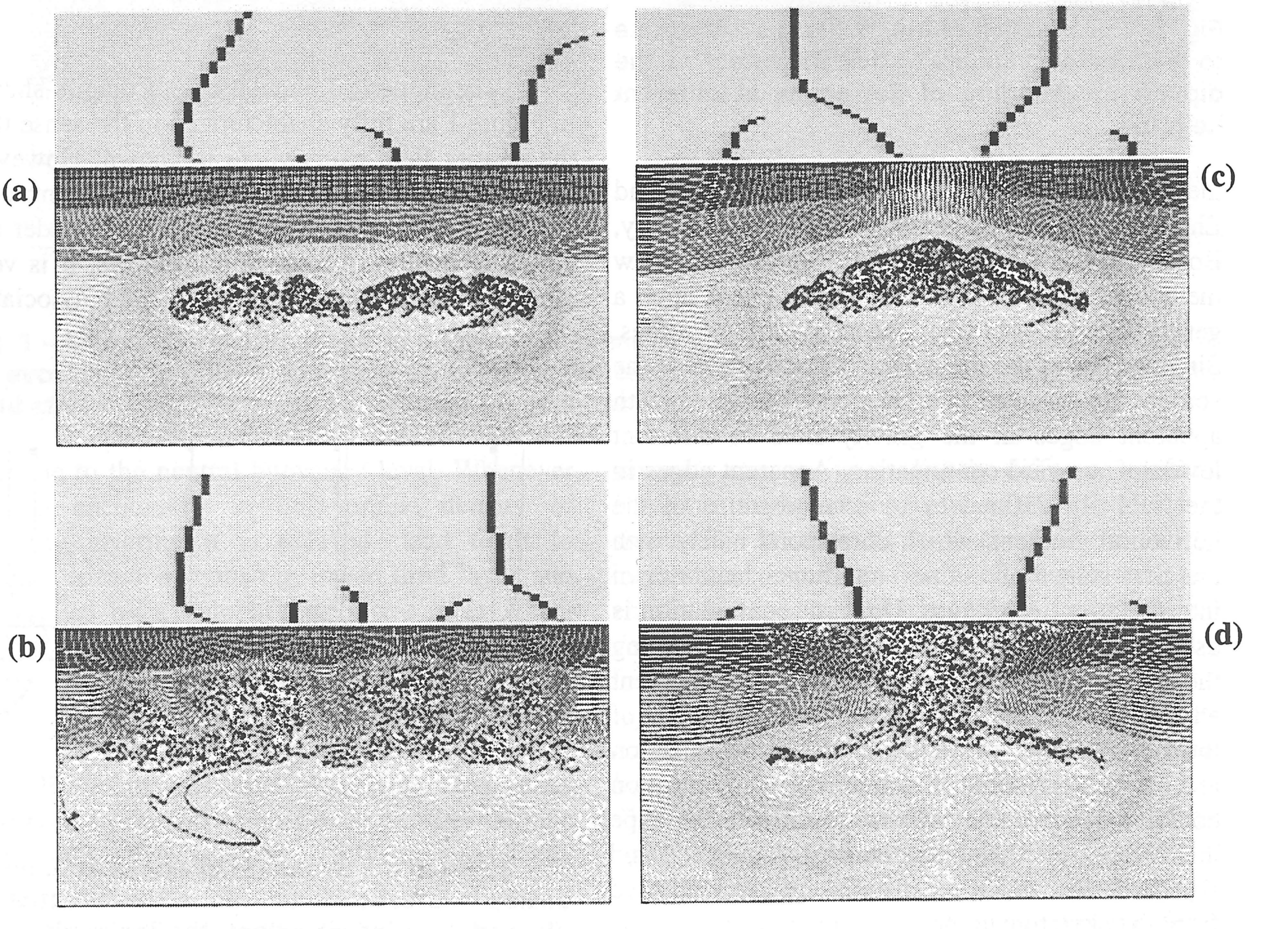

Fig. 4 - Wavelet analysis of gravity signatures of the diapir structures shown in Fig. 1.

Table 1: Inversion of synthetic profiles, after adding 20% of random noise to the data. The density contrast, dip, depth to top and bottom for a fault is given in the first row. The result of inversion with a Genetic Algorithm is given in the second row. The third row gives the local optimisation of the GA solution. The fault is recovered with good accuracy.

	Density	Dip	Depth to Top	Depth to Bottom
Synthetic	0.2	90	-1.0	-4.0
GA Solution	0.23	90	-1.0	-3.6
Loc. Optim.	0.23	88.6	-0.66	-3.12

This style of inversion appears to be very powerful, but is somewhat limited by the requirements of dealing with regular shaped bodies. This also contradicts the main advantage of the technique, i.e., the ability to automatically determine the parameterisation of the inversion (ie. the multiscale edges) depending on the complexity of the data set under analysis.

In order to circumvent this problem a new style of inversion is currently being developed. An example is given in Figure 5. Figure 5a shows the vertical section of a 2-D synthetic model used to generate a gravity profile. Figure 5b shows the result on the inversion. Despite the high level of noise at the bottom of the image (due to the exponential enhancement of high frequency in the downward continuation process) the top of the causative sources are well defined by the inversion. This technique is in its very first stages. More results and further insight will be available by the time of the conference.

Summary

We have demonstrated the modelling capability of our new finite-element particle in cell code for the modelling of viscous behaviour deep in the crust, and the inclusion of a very simple representation of brittle behaviour near to the surface. We have combined this forward modelling approach with state-of-the-art wavelet methods for interpreting the gravity field and inverting for structure.

While the complexity of real geology may not be yet in the reach of the algorithms we have presented (for example, we cannot model turbulent low viscosity intrusions, and elastic effects have yet to be implemented; in addition the presence of multiple bodies overlying each other would mask their multiscale edges), we can obtain a better basic understanding of the general geological behaviours we observe in the field, and employ more efficient methods for interpreting remotely

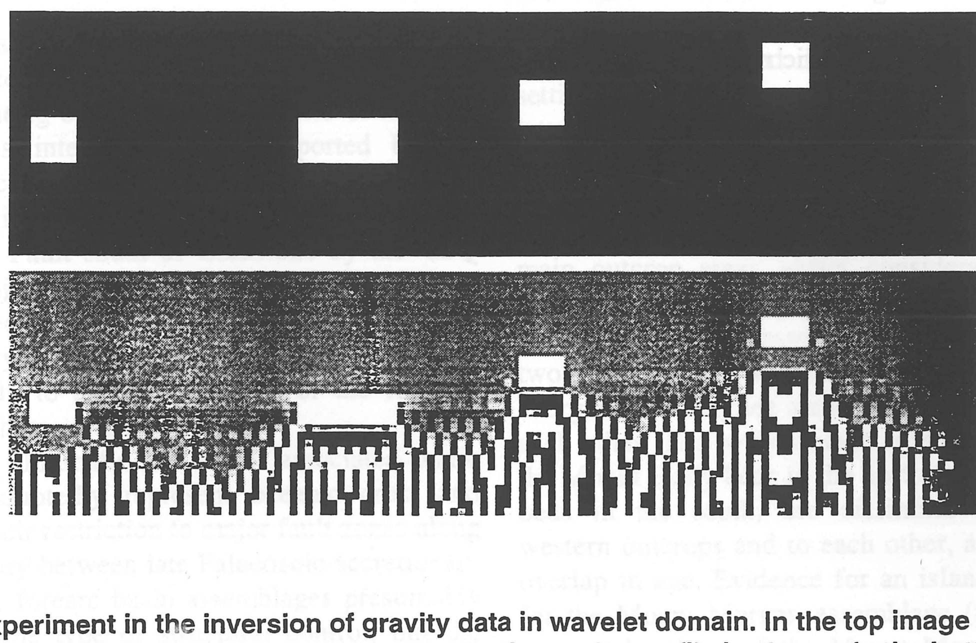

Fig. 5 - Experiment in the inversion of gravity data in wavelet domain. In the top image a vertical section of a 2-D model used to generate a synthetic gravity profile is shown. In the bottom we can see the result of the inversion. The top of the bodies is well recovered.

sensed potential field data.

The application to granite intrusions is appropriate since these are near-surface bodies whose structure may be partially a result of viscous processes and partially a result of brittle ones. In the case of viscous emplacement, we expect the diapirs will be unable to rise beyond their neutral buoyancy level and hence be less likely to be exposed. This means that a combination of potential field inversion and forward modelling is the best way for us to learn about these bodies.

Movies of the numerical simulations and background information are available at the following web page:

http://www.ned.dem.csiro.au/research/solidMech/Geodynamics/AGCRC-plutons

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Tectonic Evolution and Metallogeny of the Northern New England Orogen

C. G. Murray

Geological Survey of Queensland, Brisbane

The New England Orogen (NEO) has often been described as the easternmost and youngest part of the Tasman Orogenic Zone or System. However, its history is now known to cover the full range of Phanerozoic time.

Throughout its evolution, the NEO was located along or close to the edge of the Australian continent, which was at times a convergent margin. As a result:

- the NEO has been a tectonically active and complex region, with the possibility of exotic terranes, large scale strike slip faulting etc;
- it incorporates elements of both oceanic and continental crust and mantle, and transitional stages between these;
- spasmodic intrusive and extrusive magmatic activity occurred throughout its history; and
- the mineral systems which characterise the NEO were mainly related to magmatism.

Early Palaeozoic ultramafics

Ultramafic rocks along the Yarrol Fault are presumed to be of early Palaeozoic age, based on isotopic dating of ophiolite complexes of the Peel Fault. This interpretation is supported by the recent discovery of a very localised outcrop of mid-Ordovician strata just west of and adjacent to the Yarrol Fault south of Gladstone by the GSQ Yarrol Project (Murray et al. 1997). To date, the early Palaeozoic record in the northern NEO is too fragmentary and poorly known to contribute significantly to an understanding of the tectonic setting of these rocks.

The ultramafic and minor associated mafic rocks undoubtedly represent oceanic crust and mantle. Their restriction to major fault zones along the boundary between late Palaeozoic accretionary wedge and forearc basin assemblages presumably reflects some type of structural control, but the nature of this is as yet unclear. The most significant mineralisation styles associated with the ultramafic rocks are related to Cenozoic weathering and groundwater movement. Lateritic profiles developed on extensive outcrops of ultramafics between Marlborough and Canoona are the world's largest source of gem grade chrysoprase, and are currently being re-evaluated for their nickel and cobalt content. The Kunwarara and Yaamba magnesite deposits are world class orebodies formed by magnesium-rich groundwater in abandoned stream channels. The only primary deposits are podiform chromite bodies which are too small and low grade to be of economic significance.

Middle Palaeozoic volcanic arc assemblage(s)

Rocks of latest Silurian to Middle Devonian age occur as isolated fault blocks and inliers in the region between Marlborough and Warwick. There is ongoing debate whether these represent a convergent continental margin assemblage, in which case they are essentially autochthonous, or whether they formed in an oceanic island arc setting, and therefore must be exotic terranes. The latter interpretation is supported by work of the GSQ Yarrol Project in the Rockhampton region (Yarrol Project Team 1997). Here, latest Silurian to Middle Devonian strata, which occur in four main outcrop areas, differ considerably in rock type and stratigraphic sequence. The data indicate that three separate assemblages are present. The two most inboard (western) outcrops, in the Mount Morgan and Craigilee areas, can be correlated with each other. The two outboard (eastern) sequences, the Mount Holly beds in the north and the Calliope beds in the south, are dissimilar to both the western outcrops and to each other, although they overlap in age. Evidence for an island arc setting for the Mount Morgan assemblage (for example, the geochemistry of the Mount Morgan Tonalite and the fact that the entire stratigraphic sequence is submarine) suggests that all the middle Palaeozoic rocks may be exotic. The Mount Holly beds and Calliope beds are certainly the best candidates for exotic terranes, because of their outboard position. However, an exotic origin for the Calliope beds is complicated by the fact that a conglomerate within the unit contains clasts of both Devonian and Ordovician limestone (Murray et al. 1997). Wherever the Calliope beds were deposited, there were Ordovician rocks in the source area.

In terms of metallogenesis, the middle Palaeozoic rocks are significant because they contain the world class Mount Morgan gold-copper deposit, which produced more than 250 tonnes of gold. Like its host rocks, the origin of this orebody is controversial. The most favoured theory is that it is an atypical VHMS style deposit, but some workers consider that the Mount Morgan Tonalite played a key role in ore formation. A combined model of a Middle Devonian VHMS deposit modified by Late Devonian tonalite intrusion has considerable appeal in view of the unusual size and grade of the Mount Morgan orebody. In terms of prospectivity, the two inboard terranes at Mount Morgan and Craigilee have potential to host VHMS deposits of Mount Morgan type, but if emplacement of the Mount Morgan Tonalite was a key factor, the area of prospective rocks is much reduced.

Late Palaeozoic convergent continental margin

The NEO was the site of a convergent continental margin from Late Devonian to mid- or Late Carboniferous time, with readily recognised parallel belts of accretionary wedge (outboard) and forearc basin assemblages. Although the associated western arc is not well preserved, its presence is clearly indicated by the dominance of westerly sourced volcaniclastic sediments in the forearc basin sequence, and by local Early Carboniferous volcanics. Until recently, it was assumed that large granitic batholiths along the western edge of the northern NEO represented the final magmatism related to the westward dipping subduction zone. However, zircon dating of the main phases of the Urannah Complex west of Mackay indicates that this batholith was emplaced a considerable time after the interpreted cessation of subduction (Allen et al. in press).

The relative absence of mineralisation in Late Devonian to mid-Carboniferous rocks of the northern NEO (Murray 1986) is presumably related to the poor preservation of the volcanic arc.

Latest Palaeozoic extension

Holcombe et al. (1997a) proposed that the Late Carboniferous to Early Permian history of the northern NEO saw a transition from a convergent to an extensional regime characterised by the formation of rapidly subsiding rift basins, as well as the Bowen Basin to the west. One problem is that subsidence rates calculated for this time interval from measured sections in the northern NEO are much less than typical values associated with significant amounts of crustal extension (Yarrol Project Team 1997). Nevertheless, other aspects of Early Permian sedimentation and volcanism are consistent with this extensional basin model.

Early Permian styles of mineralisation are also supportive of the extensional model. Base and precious metal deposits at Mount Chalmers and Develin Creek have been described as VHMS deposits, and Mount Chalmers is regarded as a classic example of a Kuroko style VHMS. The sediment hosted silver-lead deposit at Silver Spur SW of Warwick appears to have formed in a similar environment. The important epithermal gold mineralisation at Cracow probably formed in the Early Permian (Dong & Zhou 1996), close to the age of the host volcanics. The deposit at Mount Mackenzie west of Marlborough may be another example of epithermal mineralisation of this age, although alteration has given younger dates.

Hunter-Bowen Orogeny

The Hunter-Bowen Orogeny was characterised by WNW-directed thrusting, at least locally thin-skinned in style. It was originally defined as a Late Permian event, but recent authors have suggested that it continued to mid-Triassic time. If so, it must have been punctuated by extensional episodes, at least one of which was substantial enough to form the Esk Trough, containing a thick fill of continental volcanics and sediments.

The role of the Hunter-Bowen Orogeny in providing structural controls for ore formation in the northern NEO has probably been underestimated. The gold veins of the major Gympie goldfield may be the prime example of structurally controlled deposits related to this compressional event (Holcombe et al. 1997b); other possible examples of this style of gold mineralisation occur at Rannes (Holcombe et al. 1997b) and in the Raglan area west of Gladstone (Yarrol Project Team 1997).

Triassic plutonism and volcanism

The northern NEO from Rockhampton south was the site of widespread magmatism throughout the Triassic. Gust et al. (1993) proposed that the magmatic regime changed from subduction related in the Early and Middle Triassic to extensional in the Late Triassic, when widespread bi-modal volcanics were erupted. Early and Middle Triassic plutons are mainly hornblende-bearing I-type granitoids, with granodiorite being the dominant composition; they range in size from small stocks to large composite batholiths. Triassic volcanic rocks are entirely continental, and range from basalt to rhyolite. The plutonic rocks include several layered gabbros.

The latest Permian and Triassic magmatism was the major metallogenic event in the NEO, and is associated with numerous ore deposits encompassing a wide variety of styles of mineralisation and contained metals (Murray 1986). However, there are significant differences between the northern and southern NEO. Blevin & Chappell (1996) pointed out that the northern NEO is a Cu-Mo-Au province (characterised by porphyry style deposits), whereas the southern NEO is a Sn-Mo-W-polymetallic province. This difference may be related to crustal and upper mantle structure, because granitoids of the southern NEO are restricted to the area east of the Peel Fault, largely within rocks of the late Palaeozoic accretionary wedge assemblage, and those of the northern NEO occur mainly west of the Yarrol Fault in strata of the coeval forearc basin sequence. Despite the importance of the Triassic metallogenic event, there is no comprehensive database of petrology, geochemistry and age of the plutonic rocks, and in some cases only preliminary field mapping data are available. Detailed studies of mineralising systems and compositional controls on ore formation are virtually nonexistent.

Cretaceous

The northern NEO was a relatively stable region for much of post-Triassic time, with the exception of the Early Cretaceous. Scattered granitic plutons were emplaced in the Bowen area, and subaerial volcanics were erupted along and offshore from the present coastline. Ewart et al. (1992) concluded that this plutonic-volcanic province, although calc-alkaline in composition, was related to crustal extension. Further south, a slightly older sequence of calc-alkaline volcanics was formed in the Maryborough Basin.

Mineralisation associated with the Early Cretaceous plutonic rocks includes sub-economic porphyry copper deposits, and gold-bearing quartz veins at intrusive margins.

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Are Lithospheres Forever? Some Applications of 4-D Lithosphere Mapping

S. Y. O'Reilly[1], W. L.Griffin[1,2], N.J.Pearson[1], O. Gaul[1], & Y. Poudjom Djomani[1]

1 - GEMOC National Key Centre, School of Earth Sciences, Macquarie University, Sydney, NSW 2109
2 - CSIRO Exploration and Mining, PO Box 136, North Ryde, NSW 2113

The subcontinental lithospheric mantle (SCLM) carries a geochemical, thermal and chronological record of large-scale tectonic events that have shaped the Earth's crust. The SCLM is part of the continental plate, and moves with the plates over the less rigid asthenosphere. It has long been accepted that "old" (cratonic) lithosphere is relatively deep, depleted and cold; more recently it has been recognised that "young" lithosphere is relatively thin, fertile and hot.

Development of the 4-D Lithosphere Mapping methodology (O'Reilly and Griffin, 1993; 1996) has provided tools for constructing realistic geological sections of the SCLM. 4-D Lithosphere Mapping is a xenolith-based methodology drawing together many strands of geochemical, geophysical, tectonic and age information. Together these allow a synthesis of the nature of the lithosphere to depths that can be accessed directly by xenoliths and mineral debris of deep-seated rock types and extended laterally by geophysical data. This information can be used to construct sections of the lithospheric stratigraphy and physical state, which can constrain the interpretation of geophysical models. Geophysical data can then be used to map the lateral extent of individual mantle domains. Lithosphere Mapping is an integrated approach to understanding the composition, stratigraphy and thermal state of the lithosphere, the nature and significance of its important boundaries (e.g. the crust-mantle boundary and the lithosphere-asthenosphere boundary) and its evolution.

The basis of Lithosphere Mapping is the direct evidence for the petrology of the lower crust and upper mantle provided by xenoliths and xenocrysts of deep-seated rock types entrained in basaltic, kimberlitic and lamproitic magmas. These samples are generally transported to the surface in 10-30 hours, too fast for alteration or significant re-equilibration to occur. They yield the compositions and locations of specific rock types in the underlying crust-mantle section, and large specimens can be used to determine the petrophysical characteristics (density, acoustic velocity, magnetic properties, electrical and thermal conductivity, heat production) of the rocks at given depths.

The key technique of Lithospheric Mapping is the construction of empirical (paleo)geotherms at specific localities by use of xenoliths and xenocrysts. This information is then used to place individual samples (for which temperature (T) can be calculated) in their original vertical sequence, and thus give the distribution with depth of rock types and mantle processes such as metasomatism. The thermal state of a lithospheric column also influences geophysical characteristics: T determines density and thus affects seismic velocities and gravity; magnetic responses are confined to rocks above the Curie isotherm. Mantle-derived material sampled by volcanic episodes of different ages allows interpretation of the evolution of the lithosphere in four dimensions (i.e. time as well as space).

Some Global Applications

4-D lithosphere mapping shows that the depth of the lithosphere-asthenosphere boundary (LAB) can range from about 250 to 150 km in cratonic areas, while it is seldom >150 km in circumcratonic areas. Distinctive rock-type profiles (mantle stratigraphy) can be mapped, followed laterally, and correlated with surface geology. In Siberia within-craton domains with distinctive mantle stratigraphy coincide with crustal terranes mapped at the surface (Griffin et al. 1998b). Markedly different SCLM sections sampled by Ordovician kimberlites in the Sino-

Korean craton suggest that the major TanLu fault penetrates the lithospheric mantle and separates two Archean terranes (Griffin et al. 1998e). These studies provide evidence that individual Archean terranes or microcontinents developed their own distinctive SCLM, which survived accretion of the terranes into cratons and plate-tectonic translation during subsequent aeons. However, later tectonothermal events, such as rifting or large-scale magmatism, are associated with major changes in SCLM thickness and stratigraphy, and especially in composition. Why is this so?

Secular Variation in Lithosphere Composition

Boyd (1989, 1997) recognised a fundamental distinction between Archean cratonic mantle, represented by xenoliths in African and Siberian kimberlites, and Phanerozoic circumcratonic mantle, represented by xenoliths in intraplate basalts and by orogenic lherzolite massifs. Archean xenoliths are not only more depleted on average, but have higher Si/Mg (higher opx/olivine), and subcalcic harzburgites are well-represented in Archean xenolith and xenocryst suites, but essentially absent in younger ones. Analysis of >13,000 garnet xenocrysts from volcanic rocks worldwide shows a clear correlation of garnet composition with the tectonothermal age of the crust penetrated by the volcanic rocks (Griffin et al. 1998a, d). The xenolith and garnet data, taken together, indicate that the Archean/Proterozoic boundary represents a major change in the nature of lithosphere-forming processes. The garnet data further indicate that newly-formed SCLM has become progressively less depleted from Archean, through Proterozoic to Phanerozoic time.

In xenoliths, the Cr_2O_3 content of garnet correlates well with the Al_2O_3 content of the host rock (Griffin et al. 1998c). Xenolith suites also show good correlations between the content of Al_2O_3 and those of other major and minor elements; these correlations make it feasible to calculate the composition of a mantle section, given the median Cr_2O_3 content of garnet xenocrysts from that section (Griffin et al. 1998c). The mean composition of SCLM beneath terrains of Archean, Proterozoic and Phanerozoic

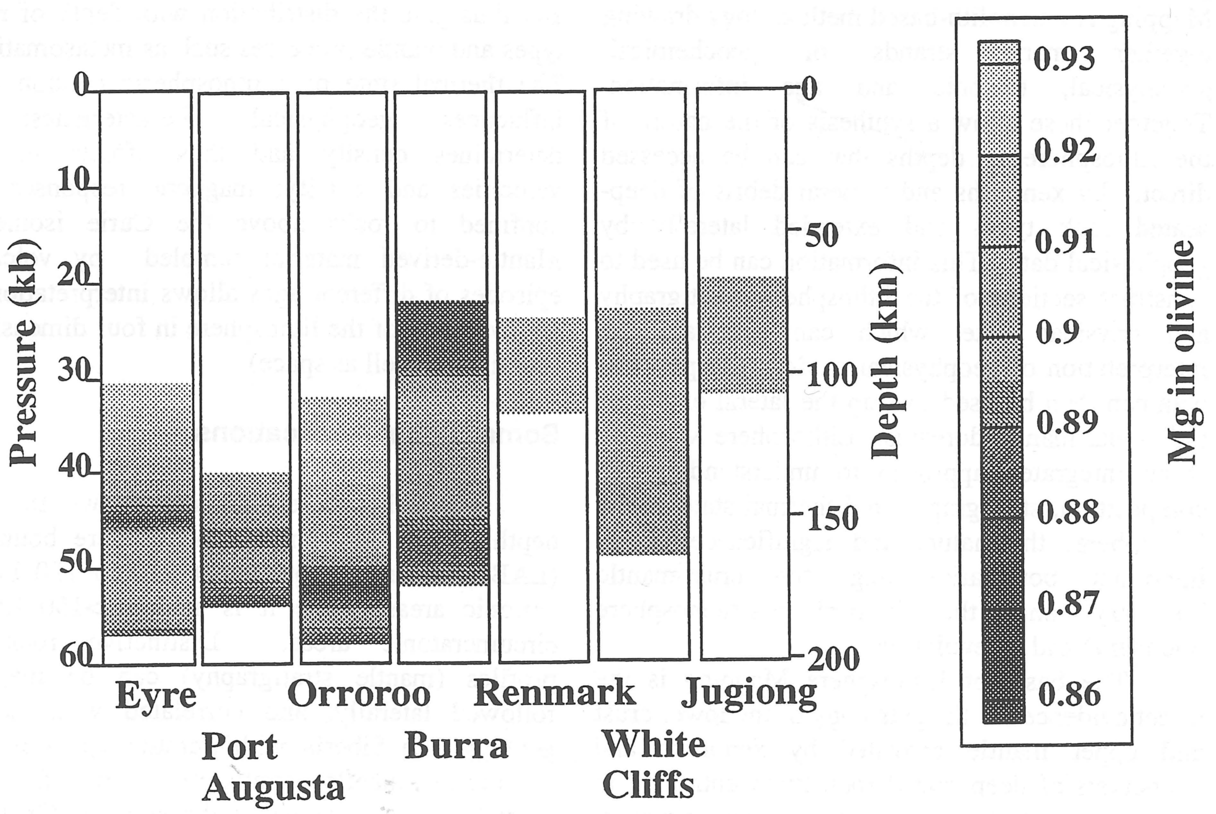

Fig. 1 - Lithospheric transect across southeastern Australia (see text for detailed description).

tectonothermal age, calculated in this way, show a clear secular evolution in all measures of depletion, such as Al, Ca, mg#, and Fe/Al. Pristine Proterozoic SCLM is moderately depleted, and intermediate in composition between Archean and Phanerozoic SCLM. Cenozoic SCLM, exemplified by Zabargad peridotites and by garnet peridotite xenoliths from young extensional areas of China, Siberia and Australia, is only mildly depleted relative to Primitive Mantle. SCLM beneath some Phanerozoic terrains, especially in Europe, is more depleted and may represent reworked Proterozoic SCLM.

Significance of SCLM evolution to geophysical interpretation

Average mineral compositions for each age group have been used to calculate average modes, densities and seismic velocities . Archean SCLM is 2.5% less dense than the asthenosphere (approximated by PM); for the less-depleted Phanerozoic mantle the difference is <1%. Thermal expansion coefficients are identical within error for all compositions, so that these differences persist to high temperatures. At 25°C, the V_p and V_s of Archean SCLM are higher than that of Phanerozoic SCLM by ca 0.5% and 1.2%, respectively; the compositional differences thus account for ca 25% of the range observed by seismic tomography. Typical geotherms for cratonic and Phanerozoic areas were used to calculate the difference in V_p and V_s at 100 km depth; the Archean values are higher by 4-5%, corresponding to the ranges commonly seen by seismic tomography.

Lithosphere evolution and destruction

These physical property data are important constraints on the delamination and recycling of the SCLM. Thermal expansion coefficients and bulk modulus of minerals have been used to calculate the temperature-dependent density variation with depth for typical Archean, Proterozoic and Phanerozoic mantles. The results show that the entire section of Archean lithospheric mantle is significantly buoyant relative to the underlying asthenosphere. For Proterozoic and Phanerozoic mantles, a minimum thickness of ca 60km must be reached before each section becomes buoyant: these are the minimum conditions for lithosphere delamination.. This effect explains the thickness and apparent longevity of existing Archean lithosphere, but suggests that no deep continental root could be constructed from Phanerozoic lithosphere.

Tectonic or magmatic events that lead to the replacement of old SCLM by younger material cause changes in the density and geotherm of the lithospheric column, with major effects at the surface. In the Kaapvaal Craton (Brown et al., 1998) thermal and chemical erosion produced in a thinner, hotter and chemically recharged (metasomatised) lithosphere, and led to significant uplift of the craton. In the eastern Sino-Korean craton, the removal of ≥100 km of Archean lithosphere during the late Mesozoic was accompanied by uplift, basin formation and widespread magmatism. In this case, lithosphere replacement involved rifting, with contemporaneous upwelling of fertile asthenospheric material (Griffin et al., 1998e; Yuan 1996).

Consequences

Correlations between mantle type and crustal age indicate that continental crust and its underlying mantle are formed together and remain coupled for geologically long times. Destruction of Archean SCLM is difficult, but where it occurs, by thermal and chemical erosion and/or rifting, thinning and displacement, it has major thermal and tectonic consequences. These processes are important in area selection using geophysical techniques. For example, in diamond exploration, Archean areas penetrated by old kimberlites and subsequently affected by lithosphere erosion will not show the geophysical signature of old, cold lithosphere even though the old, potentially diamond-bearing kimberlites or alluvial diamond concentrations derived from them may still be present at the surface, as in the Sino-Korean craton.

Some applications of 4-D lithosphere mapping to Australia

Geothermal state of lithospheric domains

Empirical paleogeotherms constructed from geothermobarometry of deep-seated xenoliths and garnet ± chromite concentrates from basalts, lamproites and kimberlites around Australia reveal regions of different paleogeothermal signatures (O'Reilly et al., 1997). Differences between the tectonically young eastern areas and the cratonic western part of the Australian continent correspond to those shown on a large scale by long-wavelength magnetic data, which integrate the total magnetic signature from the lithospheric column where temperatures are below the Curie Point. Surface heat-flow measurements may not reflect deeper geothermal gradients and model-dependent extrapolations to lower crust and mantle depths must be used cautiously. In eastern Australia, where xenolith data are available (coinciding with the basaltic provinces), there is a remarkably consistent geotherm, which is independent of the age of the basaltic volcanism. This inflected (advective) geotherm is higher than conventional ocean basin geotherms and reflects thermal perturbation associated with volcanic episodes. It records the thermal state at the time of the particular volcanic activity, and decays towards a conductive geotherm with a relaxation time of 40–50 m.y. Data from the eastern craton margin (in South Australia and western New South Wales) indicate significant changes in the thermal state through time, while Archaean and Proterozoic areas in Western Australia reflect typically low geotherms. Knowledge of a robust geotherm for a specific lithospheric column can be used to construct a realistic distribution of rock types with depth. This lithospheric column provides constraints for the geologically meaningful interpretation of geophysical data and for placing geochemical and mantle process information in a spatial context.

Lithosphere transect across southeastern Australia

A lithosphere transect from Jugiong in Phanerozoic eastern NSW across the Tasman Line to the Eyre Peninsular in Proterozoic South Australia was carried out using xenoliths and garnet concentrates. The paleogeotherm is consistent with a model conductive geotherm with a surface heat flow of greater than 50 mW/m^2 at Jugiong, decreasing westward to 40 mW/m^2 in South Australia.

"Chemical sections" were constructed using minor and trace element characteristics of garnet for each vertical section making up the transect, revealing:

- maximum Cr_2O_3 content of garnet increases from 3% in Phanerozoic areas to >10% in the Proterozoic sections
- mean TiO_2 content does not vary systematically across the transect but increases with depth in all sections, reflecting increasing influence of melt-related metasomatism with depth
- mean Y/Ga ratios are extremely high in the Jugiong section and decrease rapidly to the west, indicating an increase in the degree of depletion through partial melting in this direction.

Although garnet reflects important chemical variations in the lithosphere, it is olivine that is the most abundant mantle mineral. The Fe/Mg ratio of olivine is important in controlling the physical properties of lithospheric regions (density, Vp, Vs) and indicating the melting history (depletion events through basalt extraction) in the lithosphere. We have developed a technique involving inversion of O'Neill and Wood's (1979) garnet-olivine Fe-Mg exchange geothermometer to calculate the Fe/Mg of olivine coexisting with each garnet grain. The algorithm for his inversion was calibrated using garnets from xenoliths where the composition of olivine was known. Xenoliths from both Archaean (Kaapvaal Craton) and Phanerozoic (eastern China) mantle were used in this test to ensure applicability to a variety of tectonic areas. The tests indicate that the inversion can reproduce olivine Fo contents with an error of ±0.5.

The results of applying this inversion to the southern Australian transect show high Mg# olivine (Fo 92-93) in the shallow portions of the Proterozoic westerly sections (Fig. 1) with olivine of Fo 90-91 in the Phanerozoic east. There also is an overall trend to lower Mg content values with increasing depth in each section.

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Cretaceous and Tertiary Thermotectonic Evolution of Tasmania

Paul B. O'Sullivan, Barry P. Kohn and Andrea J. O'Sullivan

Australian Geodynamics Cooperative Research Centre
VIEPS, Department of Earth Sciences, La Trobe University,
Bundoora, VIC 3083

Previous studies of southeastern mainland Australia have suggested that denudation along the margins occurred in association with rifting and separation of Australia from Antarctica (~120-90 Ma) and the Lord Howe Rise (~90-60 Ma). In New South Wales and Victoria apatite fission track studies suggest that rifting resulted in <1.5-2 km of denudation along the coast while ŏ4 km of denudation occurred within some parts of the eastern highlands located inland from the coast.

To further constrain a model for the extensional tectonics of southeastern Australia, ~250 apatite fission track analyses from a wide range of rocks throughout Tasmania have been generated (Fig. 1).

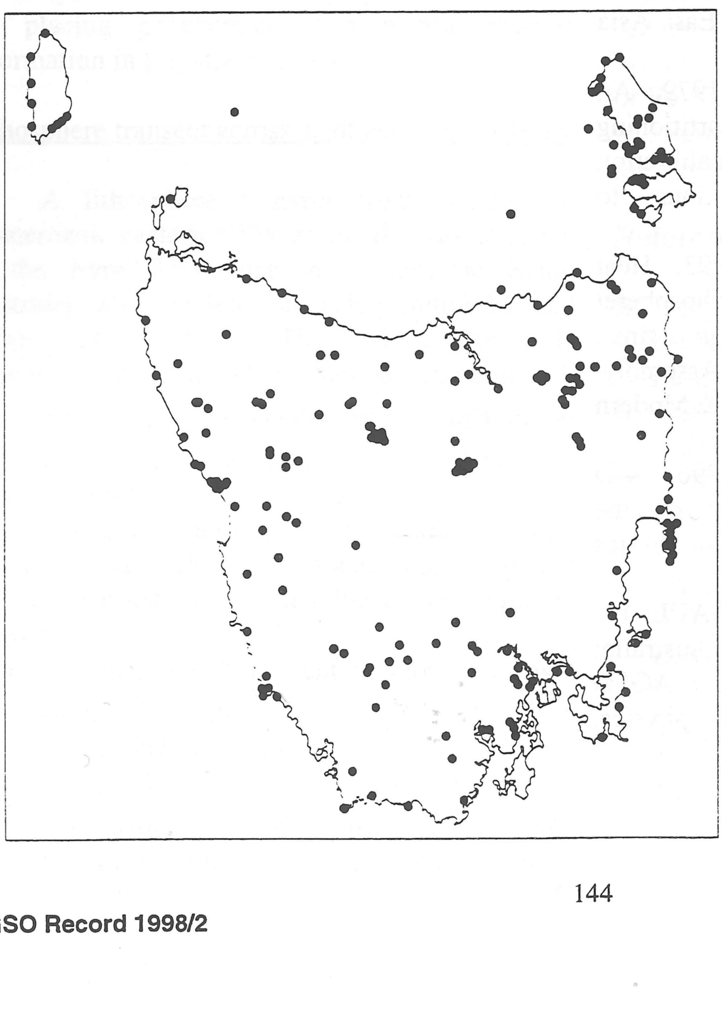

Fig. 1 - Location map showing samples collected and processed from Tasmania under the auspices of the Australian Geodynamics CRC and the Tasmania NGMA Project ("TASGO"). Wells with more than one sample at depth are represented by the uppermost sample.

Tasmania is an ideal site to study the complexities associated with the continental extension tectonics of southeastern Australia as it has rifted margins on all sides. These include the Early Cretaceous failed rift to the north between Antarctica and the mainland, which at that time also included Tasmania, the middle Cretaceous to Paleocene rift between Antarctica and Australia along the west coast, and the middle Cretaceous to Paleocene rift between New Zealand and Australia along the east coast. Furthermore, the distance between Tasmania and its adjacent rifts is minimal due to a very narrow continental shelf; hence any rift-related effects should also be evident onshore.

The fission track results show that: 1) all apatite fission track ages are younger than their sample depositional, intrusive, or metamorphic ages, and most are <120 Ma; 2) in many cases, the sampled rocks cooled rapidly from temperatures >~110°C to temperatures <~70°C at the time suggested by the apatite fission track age; 3) Tasmanian rocks experienced at least two regional cooling episodes; during the middle Cretaceous and the Paleocene to Eocene (Fig. 2); and 4) the rocks have continued to cool to present-day temperatures. The two cooling episodes were probably directly related to continental extension along both the eastern and western margins. There is also evidence for a third, more-localised episode of rapid cooling during the Late Tertiary, possibly in response to Miocene tectonism in the Bass Basin region.

The first episode of rapid cooling, recorded throughout much of the eastern Tasmania highlands, occurred during the middle Cretaceous between ~90-110 Ma. This cooling was most likely in response to km-scale denudation following the onset of continental extension in the Tasman Sea at ~96 Ma, possibly as a result of underplating inward of the rift, as has been proposed for much of the southeastern highlands of Australia. Furthermore, in many localities throughout eastern Tasmania, Permo-Triassic sediments presently exposed beneath (and intruded by) Jurassic dolerites, yield apatite ages which indicate rapid cooling from elevated palaeotemperatures ≥95°C during the middle Cretaceous. Since cooling from elevated palaeotemperatures occurred long after the emplacement of the Jurassic rocks, either: 1) following shallow-level intrusion, the dolerites were deeply buried by a Upper Jurassic to middle Cretaceous sedimentary succession (>~2.5-4 km) which may have covered most of Tasmania prior to middle Cretaceous rifting, or 2) the dolerites were intruded at much deeper levels (>2.5 km) than previously proposed and the entire km-scale section of overburden has subsequently been removed since the middle Cretaceous. Based on field evidence, including localities where the Jurassic 'dolerites' were extruded as basalts, and thick accumulations of Upper Cretaceous to middle Tertiary deposits located offshore western Tasmania, we prefer the first option.

The second episode of rapid cooling occurred during the middle Paleocene to Early Eocene between ~50-60 Ma. Evidence for this event is restricted to the eastern and western coastal areas, and throughout Flinders Island. During the Early Cenozoic, rifting between Antarctica and Australia along the western coast of Tasmania resulted in higher heat flow. The apatite fission track data probably record the subsequent relaxation of geotherms as rifting progressed beyond the region, possibly in combination with some denudation. However, it is not clear at this time what is responsible for the cooling ages along the eastern coast of Tasmania and this will be addressed in future studies.

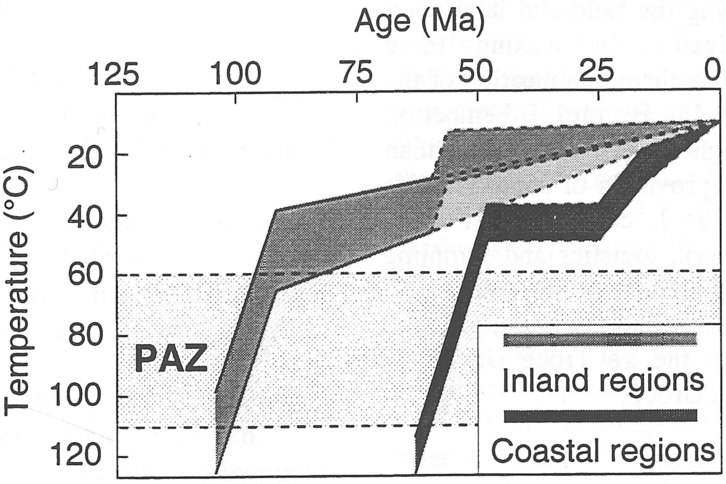

Fig. 2 - Schematic proposed time-temperature histories for the different regions of Tasmania inferred from apatite fission track data from Tasmania (modified after O'Sullivan and Kohn, 1997). Solid lines along cooling paths represent times when thermal history is constrained by the data; dashed lines represent times when thermal history is less constrained. PAZ refers to the apatite partial annealing zone, the temperature zone (~60°-110°C) in which fission tracks in apatite undergo accelerated annealing for heating times >10^6 years.

A third episode of localised cooling is recorded by many samples from the Flinders Island region as well as a few from northwest Tasmania. These samples characteristically contain a high proportion of very young single-grain ages <~15 Ma suggesting that the rocks have recently experienced ~30-40°C cooling. Since the evidence for this event seems to be limited to the far north of the state, we propose that either: 1) northern Tasmania experienced isolated fault reactivation related to Miocene tectonics previously recognized along the southern margin of the Australian continent, or 2) the reduced ages are due to hot fluid migration associated with the zone of elevated heat flow presently located beneath northwestern Tasmania.

Acknowledgments

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Tectonic Framework of Eastern Australia from ~1,100 Ma to ~320 Ma

C. McA. Powell

Tectonics Special Research Centre, Department of Geology and Geophysics, University of Western Australia, Nedlands, WA 6907

The tectonic development of eastern Australia between ~1,100 and 320 Ma can be considered in nine broad stages:

- ~1,100 – 830 Ma: Subaerial erosion and ephemeral deposition within Rodinia.
- ~830 – 750 Ma: Pre-breakup extension and deposition within Rodinia.
- ~750 – 600 Ma: Passive continental margin facing the Palaeo-Pacific Ocean.
- ~600 – 510 Ma: Intracontinental dextral shear leading to breakup along the continental margin.
- ~520 – 490 Ma: Continent-ocean convergence leading to the Ross–Delamerian orogen.
- ~490 – 430 Ma: Passive margin and marginal sea behind an oceanic arc facing the Pacific Ocean.
- ~430 – 380 Ma: Oblique dextral transpression, transtension and subduction.
- ~380 – 340 Ma: Andean-type convergence along the Palaeo-Pacific Ocean.
- ~340 – 320 Ma: Orogenesis as part of the global Variscan events.

Australia as part of Rodinia (1,100 – ~750 Ma)

Final assembly of Rodinia took place during the late Mesoproterozoic along the Grenvillian-aged (1300 to 1100 Ma) orogenic belts which can be traced through India and Antarctica into the Albany, Fraser and Musgrave belts in Australia. By 1.1 Ga mafic dykes were intruded across the Musgrave fold belt in central Australia. The eastern margin of Australia in Rodinia lay along or to the east of the Tasman Line. In Rodinia, Laurentia lay to the east of Australia, possibly with South China (Li *et al.* 1995, 1996) or another small continental block in between.

Palaeomagnetic data indicate that the Rodinia configuration is permissible at 1,100 Ma and ~750 Ma, but that Laurentia may have begun to separate from Australia–Antarctica around this time (Wingate & Giddings in review). In the Adelaidean Geosyncline, the time of the breakup can be inferred to coincide with the end of the Sturtian glaciation, after which a broad marine transgression represents the drift sag-phase (Powell *et al.* 1994). Before Rodinian breakup, the interior of Australia was covered by a shallow epicontinental sea. Rifting and volcanic activity in northwesterly- and northerly-trending basins along what was to become the eastern margin of Neoproterozoic Australia occurred from ~830 Ma until breakup. The NW-trending Gairdner dyke swam was emplaced during this early extension.

During breakup the extension direction was oriented NE–SW, implying that the rectilinear margin of old Precambrian rocks along the Tasman Line comprises a series of NE–trending transform and NW-trending rift margins. The preservation of a wide rift margin in South Australia, which formed the base on which younger Adelaidean sediments were deposited, indicates that the South Australian segment of the Rodinian margin had lower-plate geometry, whereas the north Queensland segment could have been an upper-plate margin.

Breakup of Rodinia to form the Palaeo-Pacific Ocean

Australia was in low northern latitudes at 750 Ma, and remained in low latitudes for the rest of the Neoproterozoic and the early Palaeozoic (Powell *et al.* 1993a). Laurentia was in low southern to equatorial latitudes around 720 Ma, and moved to high southern latitudes by 600 Ma when the palaeo-South pole lay near northeastern Laurentia. Stratigraphically, the rift-drift transition in Australia is at the end of the Sturtian glacial interval. The age of the proposed correlative glacial unit in Laurentia, the Rapitan Group (Young 1992), can be no older than 755 ± 18 Ma (G.M. Ross in Klein & Beukes 1993). An older limit to the age of the breakup is 802 ± 10 Ma, given by the U-Pb age on zircons from the Rook Tuff, which is stratigraphically well below the Sturtian glacial interval. The age of breakup of Laurentia from Australia is thus younger than 800 Ma, and more likely around 750 Ma

New palaeomagnetic data from South China (Zhang & Piper 1997), combined with unpublished data (Li in Li *et al.* 1996, p. 600), show that South China could have lain near the eastern margin of Australia in Laurentia, possibly more northeasterly than previously thought. The Neoproterozoic stratigraphy of South China is comparable with that of southeastern Australia and western Laurentia up to, and including, the first glacial unit (Liantuo = Sturtian = Rapitan), but differs thereafter in that there is no equivalent of the younger Marinoan (= Ice Brook) glacial unit in the succeeding carbonate succession. We infer that South China broke away from the Australia during the ~750 Rodinia breakup.

Palaeomagnetic evidence does not support the suggestion of Veevers *et al.* (1997) that Laurentia did not break away from Australia until 560 Ma. Nonetheless, a smaller continental fragment from eastern Australia could have broken away near the end of the Precambrian, though this was not Laurentia.

A second continental breakup between ~590 Ma to 550 Ma

After deposition of the Sturtian glacial rocks, many parts of Australia were covered by platform carbonates and shales. Starting around the time of the Marinoan glacial episode and continuing to the end of the Precambrian, dextral transpression occurred along the Paterson–Petermann tectonic zone, dividing the former Centralian Superbasin into two parts and forming foreland basins either side of the ESE-trending orogen. Renewed continental breakup could have developed along or close to the earlier Rodinian breakup, as indicated by ~590 Ma rift-related alkaline volcanics in western NSW (Crawford *et al.* 1997) and similar-aged tholeiitic basalts in Tasmania. The width of the continental ribbon is not known, but, by analogy with the succession of continental breakups inferred to have occurred off the northwestern margin of Australia since the beginning of the Phanerozoic, it could have been not very wide.

The ~600 to 540 Ma dextral transpression reactivated old sutures beneath the Centralian superbasin as part of a wider set of "Pan-African" tectonic events associated with the assembly of Gondwanaland in the latest Precambrian or Early Cambrian by the closure of two major ocean basins. The eastern ocean, the Mozambique Ocean, lay between East Gondwanaland and the Congo–Kaapvaal craton, and closed along a late Neoproterozoic zone running through Madagascar, Sri Lanka and into East Antarctica east of Queen Maud Land. The western line of oceans, the Brazilide–Pharusian Oceans, runs between the Amazonia–West African craton and Congo–San Francisco–Kaapvaal craton. These oceans may not have been fully closed until the Early Cambrian, but if they had closed in the latest Neoproterozoic there is a possibility that an end-Precambrian supercontinent, Pannotia (Powell 1995) could have existed for a few million years around the Precambrian boundary.

Cambrian convergence between the Palaeo-Pacific Ocean and Australia

The passive margin facing the Pacific Ocean persisted into the Early Cambrian in southeastern Australia, albeit with a hiatus around the Precambrian boundary. However, deformation and magmatism began to affect parts of the East Antarctic margin in the earliest Cambrian (Goodge *et al.* 1993), and convergence, possibly within the Palaeo-Pacific Ocean, led to the subsequent emplacement in the Middle Cambrian of an ophiolitic sheet in Tasmania (Crawford and Berry 1992) and oceanic island-arc rocks in the Bowers Terrane in Victoria Land (Findlay 1991).

The position of Tasmania, which is anomalous in comparison with the rest of the Tasman Orogen in that it has an exposed core of Precambrian metamorphic rocks, is uncertain in the late Neoproterozoic. It lies outboard of a zone of turbidites that can be correlated from western Victoria to the Wilson Terrane in Northern Victoria Land (Flöttmann *et al.* 1993), and thus could have been a ribbon of continental crust stranded between Laurentia and Australia–Antarctica during the breakup of Rodinia or during the second continental breakup (Powell and Baillie, in review). The postulated collision between Tasmania and an oceanic island arc (Crawford & Berry 1992) could have occurred well east of Australia, with Tasmania later closing back onto Australia during the Late Cambrian. Notwithstanding this possible Neoproterozoic separation of Tasmania from Australia, palaeomagnetic data show that northwestern Tasmania was in its present place relative to Australia by the end of the Cambrian (Li *et al.* 1997). Convergence between Australia and the Palaeo-Pacific Ocean led to formation of the Ross-Delamerian mountain belt by the end of the Cambrian, thus marking the end of the first 200 to 250 million-year-long cycle of ocean opening and closing along the Pacific margin of Australia–Antarctica.

Palaeozoic island arcs, marginal seas and subduction zones

At the beginning of the Ordovician, widespread quartzose turbidites derived from Gondwanaland were deposited throughout the Lachlan Fold Belt, and possibly extended into the New England Fold Belt. Mafic volcanic rocks form the substrate to the turbidites, and are inferred to represent oceanic crust. By the Late Ordovician, shoshonitic mafic volcanoes with fringing carbonate platforms developed in the eastern Lachlan Fold Belt, and are interpreted to have been part of an oceanic island arc separated from the Gondwanan continental margin to the west by an oceanic marginal sea.

In the Early Silurian, significant regional differences developed in Lachlan Fold Belt, which up to that stage had a common history throughout. Silicic magmatism with deep-water transtensional basins flanked by carbonate platforms developed east of the Wagga Metamorphic Belt, whereas to the west passive-margin turbiditic sedimentation continued (Powell *et al.* 1993b, in review). By the end of the Silurian, deformation and granitic intrusion had begun to affect the western Lachlan Fold Belt, and this deformation migrated eastward during the Devonian . The present juxtaposition of the eastern and western parts of the Lachlan Fold Belt was achieved by dextral transcurrent movement along the Wagga Metamorphic Belt, possibly with several hundred kilometres offset, during the Late Silurian and Early Devonian.

In the Middle Devonian, the Lachlan Fold Belt was deformed by the widespread Tabberabberan event centred in southeastern Australia. The succeeding palaeogeography was an Andean-type margin along the eastern edge of the Lachlan Fold Belt with the New England Fold Belt lying in the forearc position. This configuration persisted into the Early Carboniferous with intracontinental deformation that commenced in the Late Devonian in Central Australia culminated in north–south lithospheric shortening of more than 100 km in Central Australia in the mid-Carboniferous. This event, known locally as the Kanimblan–Alice Springs deformation, was part of the Variscan orogenic events related to the coalescence of Gondwanaland and Laurussia. After the mid-Carboniferous, the Lachlan Fold Belt was stable, and the active margin of Australia stepped east into the New England Fold Belt.

These nine tectonic stages over 800 million years show that for 350 million years Australia was part of Rodinia, and for the next 430 million years the Tasman–Ross Orogen formed in a zone of interaction between the Palaeo-Pacific ocean and the Australian continent. Much of the preserved Lachlan Fold Belt formed in a back-arc position. Convergence between the Palaeo-Pacific Ocean and Gondwanaland occurred during the Cambrian and later during the Middle Devonian to mid-Carboniferous, and dextral transcurrent movement parallel to the continental margin was important during the Early Silurian to Early Devonian.

There are few candidates for exotic terranes in the Tasman Fold Belt, except possibly along the eastern parts of the New England Fold Belt, or the Tasmanian continental ribbon during the late Neoproterozoic. The entire Lachlan Fold Belt is underlain by a mafic volcanic–quartzose turbidite succession derived from Gondwanaland, so that any younger terrane boundaries recognised in this fold belt are the result of disruption of one large super-terrane. This Late Cambrian/Ordovician mafic volcanic–quartzose turbidite apron could have extended into the New England Fold Belt, implying that this belt was also part of the marginal sea and volcanic arcs formerly adjacent to Gondwanaland.

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Metallogenic Evolution in Victoria, Southeast Lachlan Fold Belt

W. R. H. Ramsay

Deakin University, Rusden Campus, Clayton, VIC 3168

Metallogeny in the Victorian segment of the Lachlan Fold Belt (LFB) within the larger Tasman Orogen, shows evolutionary mineralising styles with crustal thickening, orogeny, and stabilisation. Cambrian seafloor development commences with ophiolitic podiform chromites and exhalative volcanogenic Cu-Fe-Mn ± Au occurrences. Adjacent calc-alkali volcanic sequences in ensimatic islands or within crustal rift-related locations, host exhalative Fe-Cu mineralisation and epithermal gold occurrences.

By Ordovician-Silurian time, seaboard accretionary quartz turbidite sedimentary sequences were being deformed and regionally metamorphosed. Extensive vein-gold mineralisation began to be injected into the sedimentary prism and ranged in mineralising style from deeper shear-hosted mesothermal deposits to shallower epithermal affiliated, higher sulphide Sb-As-Au occurrences dominated by meteoric water derived fluids.

Crustal thickening resulted in bimodal and silicic volcanism in the Silurian (Cowombat Rift) and the Devonian (Buchan Rift and Boulder Flat Syncline) with the development of volcanogenic Cu-Zn-Fe deposits which in turn gave way to Mississippi Valley type Pb-Zn-Ba deposits in the Devonian shelf carbonate sequences.

Intracratonic basin development in the Late Devonian-Carboniferous associated with acid cauldron volcanism gave rise to fluvio-lacustrine red-bed sediments of possible molasse affinity. Minor sedimentary Cu-V-U mineralisation has been recorded in these sediments around Mansfield though the small areal size of the depositional basin makes the chance of economic deposits unlikely.

Granite injection continued intermittently following on from the Cambrian-Early Ordovician Delamerian event in the west of the state. Within the LFB itself, the earliest recorded plutonism in Victoria is represented by S-type Early Silurian muscovite-bearing granites which are typically foliated and followed by Early Devonian hornblende-bearing I – type granites. Sn, W, and Mo all make their appearance and these elements are repeated in Devonian plutonics which culminated in the central Victorian Cauldron Volcanic Province of Late Devonian to Carboniferous age.

Central and Eastern Victoria are part of the Lachlan Fold Belt which is contained within the larger Tasman Orogen. This fold belt, noted as being anomalous and enigmatic (Powell, 1988; Ramsay and VandenBerg, 1990; Coney, 1992), is located east of the Tasman Line which locates the rifted margin of the late Mesoproterozoic Rodinia supercontinent (Powell, 1996; Preiss, 1996). Rift margins associated with this break up trend NW and orthogonal linear magnetic features are thought to represent transform faults. Palaeomagnetic data indicate initial Rodinia break-up as commencing from around 725 Ma with the eastern continental block (Laurentia?) separating around a rotation pole 126°E, 7°S (Powell, 1996). Geological development in Victoria extends from post-Rodinia break-up through to the present day with the most significant event being the development of the LFB adjacent to and seaboard to proto Australia.

Victoria has been subdivided into a number of structural zones (VandenBerg, 1978; Gray, 1988) with, in some cases, zone boundaries thought to represent large scale listric faults which extend down into décollement zones located within possible duplexed Cambrian? ocean floor greenstones (Fergusson et al., 1986 ; Gray, 1988; Morand, 1996). Metallogenically, Victoria has been also subdivided into a number of gold mineralising provinces (Ramsay and Willman, 1988) and these closely follow many of the structural zones with the major exception being the recognition by Ramsay and Willman of the Stavely and Pyrenees provinces with the former separated from the Stawell province to the east by the Moyston Fault. More recently, the Glenelg province has been subdivided by Moore (1996, 1997) into four lithogeophysical subzones which from west to east are the Ozenkadnook, Miga, Upson, and Dimboola subzones.

Subsequent to Rodinia break-up, late Proterozoic sedimentation derived from late Grenville-aged crust continued in the Ozenkadnook Subzone and these sediments were regionally metamorphosed around 589 ± 14 Ma (Maher et al., 1997) making this event the oldest recorded east of the Tasman Line on mainland Australia. Rifting continued with the development (Buckland et al., 1985) continued through 500 Ma (Stuart-Smith and Black, 1994) and the regionally deformed area is cut by the undeformed Bushy Creek Tonalite (495 ± 5 Ma; Stuart-Smith and Black, 1994). Crawford et al. (1996) compare the calc-alkaline volcanics of the Mount Stavely Volcanic Complex (Buckland, 1987) with the Mt Reid Volcanics in west Tasmania on the basis of medium to high-K compositions, an age of volcanism around 500 Ma, association with

Table 1 - Cambrian metallogenic environments, Victoria.

Tectonic Setting	Deposit	Host Rocks	Other
Ophiolite cumulate	Dolodrook chromite	Peridotites, serpentinites, minor metabasite	
Ocean floor exhalative volcanogenic deposits	Mt Ararat copper body	Quartz-actinolite, quartz-biotite, and graphitic schists, serpentinite	1.1mt @ 2.7% Cu, 9 g/t Ag, 0.6 g/t Au, 0.5-1% Zn
	Mt Major Fe-Mn-Ba	Bedded siliceous shales	
	Colbinabbin sulphidic interflow sediments	•Tholeiitic flows, pillow lavas, carbonaceous shales, cherts	
	Tatong Fe-sulphides	Tholeiitic flows	
Calc-alkaline epithermal and exhalative sulphide deposits	Black Range Cu-Au deposit	Argillic and propylitic altered andesites	5.0 m @ 12.1% Cu, 11.0 m @ 1.2 g/t Au
	Mount Stavely Victor 2 Cu deposit	Medium to high-K calc-alkaline volcanics	
	Barkly River Cu-Au deposits	Andesitic breccias, rhyolites, epiclastic sediments	Epimorphous quartz after carbonate veins suggest that Hill 800 is epithermal

to the north of the 600–580 Ma rift-related mafic Mt Arrowsmith Volcanics. These are in turn possibly linked to the Crimson Creek Formation and other basaltic correlatives in Western Tasmania by the prominent NNW trending broad magnetic zone within the Dimboola subzone of Victoria (Crawford et al., 1996). This rifting gave way to oceanic spreading in Victoria in the period 580-520 Ma (Crawford et al., 1996) coupled with the development of an intraoceanic island arc comprising high-MgO, low-Ti volcanics comparable to offshore Papua New Guinea today (Buckland et al., 1985)

The onset of the Delamerian orogenic event resulted in compression, collisional tectonism and the proposed obduction westward of both the intraoceanic volcanic islands and associated oceanic crust. This terminal obduction event is placed at around 515-510 Ma (Crawford and Berry, 1992; Crawford et al., 1996). Continental margin medium to high-K calc-alkaline volcanism boninitic rocks, and the occurrence of crustal melts of rhyo-dacitic composition.

The various tectonic settings, developed during the late Proterozoic - early Palaeozoic initiation of the proto LFB in Victoria, are reflected in the styles of mineralising environments and these include cumulate orthomagmatic processes within ophiolitic assemblages, volcanogenic seafloor exhalative processes, and continental margin calc-alkaline epithermal-exhalative sulphide deposits (Table 1).

Conformably overlying this 'oceanic' sequence of the LFB is a sheet of quartzose turbidites of Siluro-Ordovician age and this extends over much of Victoria (Cas and VandenBerg, 1988). Deformation of this sedimentary prism commenced in the west in the Stawell metallogenic province in late Ordovician time and apparently migrated eastward with time to the Early Devonian in the Barkly River Belt (Bucher et al., 1996; Foster et al., 1996; 1998) and the development of the Woods Point Dyke Swarm at around 372 Ma. Accompanying this time-transgressing deformation was the development of an extensive mesothermal gold-mineralising system. Subsequent Devonian felsic plutonism resulted in small scale modification and associated gold mineralising systems (Foster et al., 1996)

Total recorded gold production is in the order of 2,460,000 kg Au of which some 60% is sourced from alluvial deposits. Mineralising styles include turbidite-hosted, dyke-hosted, and Cambrian greenstone-affiliated deposits. Granite-hosted occurrences have so far been shown to be of minor significance. Within Central Victoria sediment-hosted deposits show a continuum in depositional styles and assumed depositional depth from shear-hosted deposits at Stawell to brittle-ductile site deposits of Ballarat-Bendigo, to higher level epithermal style Sb-As-Au deposits of central Victoria. Examples of the latter include Fosterville, Costerfield, and Warrandyte. The concentration of some eleven mining centres in Victoria which each produced over 30 t Au, when compared to the sparse occurrences of similar production elsewhere in the Tasman Orogen, suggests the occurrences of processes and/or the presence of gold-enriched subcrustal rocks peculiar to Victoria.

Crustal extension in the Silurian in eastern Victoria, resulted in the Cowombat Rift (Allen, 1987; VandenBerg, 1978) that filled with thick sequences of marine volcaniclastics, sediments, minor carbonates, and bimodal volcanics. Marine exhalative mineralisation resulted in stratiform sulphide occurrences with the Wilga and Currawong deposits occurring a few kms apart near Benambra. Both are hosted by chloritised and silicic volcanics, basalt, and andesite with initial announced reserves of 3.93 Mt @ 3.0 % Cu, 6.2 % Zn, 23 g/t Ag at Wilga and 9.5 Mt @ 1.65 % Cu, 0.86 % Pb, 4.33 % Zn, 38 g/t Ag, and 1.3 g/t Au at Currawong (Macquarie Oil, 1987).

Following the Late Silurian Bindian deformational event a further phase of crustal relaxation occurred in eastern Victoria with the development of the Buchan Rift and the Boulder Flat Syncline, with the former overstamping the earlier Cowombat Rift. The Buchan Rift comprises several kilometers thickness of dominantly subaerial silicic volcanics (Snowy River Volcanics) overlain by >1 km shallow marine shelf carbonates of the Buchan Group. The equivalent Errinundra Group in the Boulder Flat Syncline is similar but thinner with less pyroclastics and only minor rhyolite. Mineralisation in both rift systems shows a transition from exhalative style volcanogenic mineralisation (Fe-Cu-Zn ± Pb) to Mississippi Valley type Pb-Zn-Ba in the overlying carbonate sediments.

Intracratonic fluvio-lacustrine red-bed sedimentation following on from Late Devonian acid cauldron igneous activity resulted in minor Cu-V-U mineralisation in the Mansfield area of central-eastern Victoria.

Within the Victorian segment of the LFB, granite injection continued at various times following on from the Delamerian event. The earliest recorded incoming of sialic-related W – Mo – Sn mineralisation is associated with the Late Silurian granites associated in the Wagga - Omeo metamorphic belt in north-eastern Victoria (Wagga Basement Terrane of White and Chappell, 1988). Here S – type granites with abundant muscovite have often resulted from high degrees of deep crustal fractionation and are regarded as being derived from a sedimentary source (White and Chappell, 1988). Examples include Thologolong (Mo), Burrowye (W), and Koetong (W/Sn). Renewed introduction of minor amounts of Mo, W has occurred with the Early Devonian granites of White and Chappell's Stawell Terrane (Mafeking Mo, Au; Mt Moliagul Mo; and Henrys Hill W). By Late Devonian widespread silicic volcanism and cauldron collapse had developed in central Victoria. Geochemically these rocks include both S – and I – types, are highly reduced, and are high in barium (White and Chappell, 1988). Sn, W, and Mo are all represented with this phase of silicic activity.

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Crustal Architecture from Seismic Refraction Data along the North and East Coasts of Tasmania

N.Rawlinson[1,2], C.D.N. Collins[1,3], T.O. Semenova[1,3] & G.A. Houseman[2]

1 - Australian Geodynamics Cooperative Research Centre
2 - Department of Earth Sciences, Monash University, Clayton VIC 3168
3 - Australian Geological Survey Organisation, Canberra ACT 2601

In 1995, as part of the TASGO project, a three-dimensional refraction and wide-angle reflection dataset was recorded throughout Tasmania. The principal aim of this survey was to create a dataset that could be used to construct a high resolution tomographic image of the Tasmanian crust. Currently, we are developing methods and software that will allow us to achieve this goal. In the interim, we can apply less sophisticated techniques to the data to extract

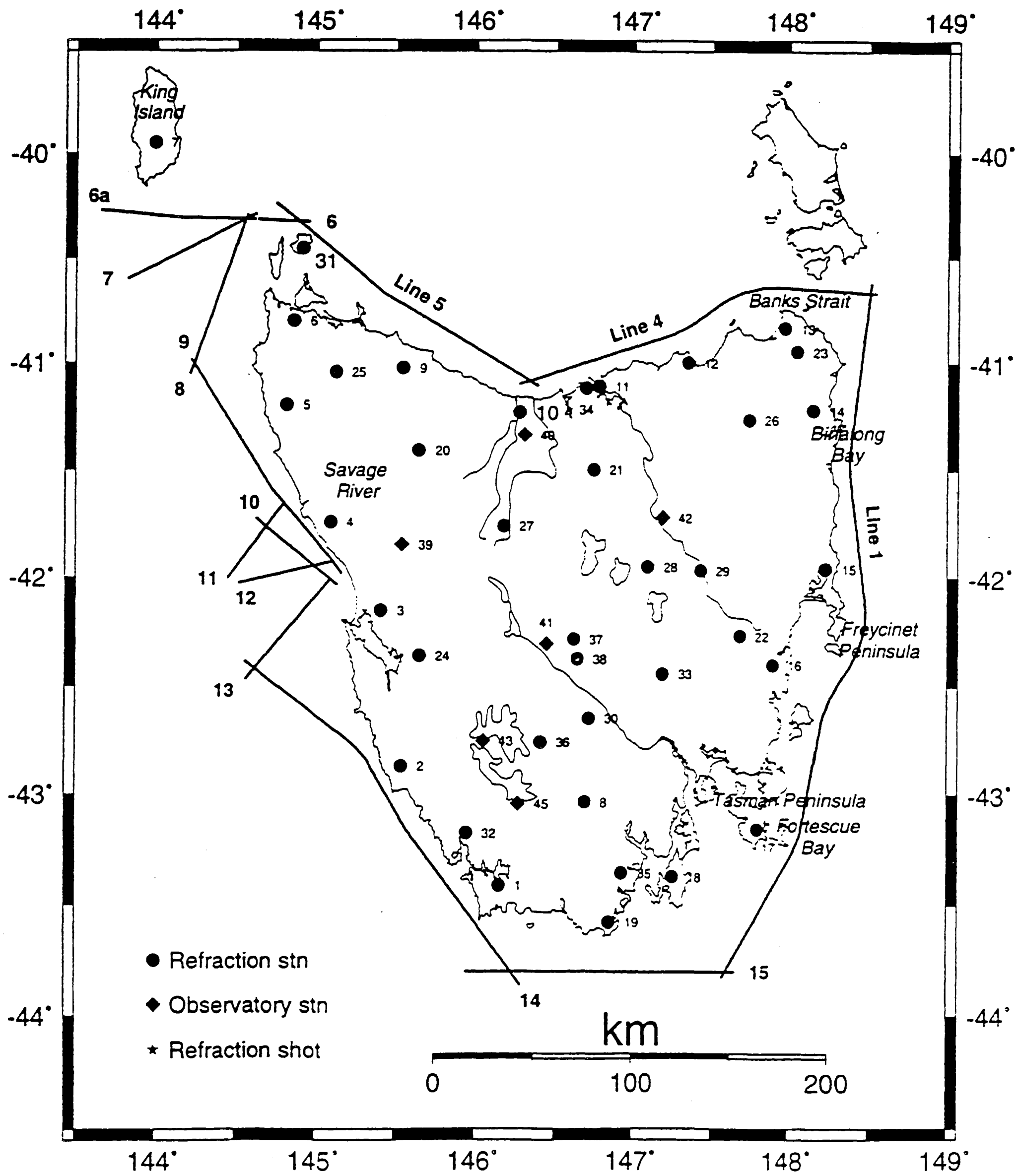

Fig. 1 - Map of Tasmania showing the offshore seismic lines and the onshore recording sites. Also shown is the onshore refraction shot location.

information about Tasmania's crustal architecture. Below, we briefly describe the results of previous geophysical work in Tasmania and several aspects of the TASGO seismic survey, before presenting some preliminary results along the north and east coasts based on simple refraction interpretation and 2-D forward modelling.

Previous geophysical work

The analysis of deep crustal structure necessarily requires the application of geophysical techniques. In Tasmania, estimates of crustal structure have been derived mainly from seismic and gravity data. Richardson (1981) recorded a reversed seismic traverse along northern Tasmania between Savage River in the west and Binalong Bay in the east, and found that the crustal thickness varied from 23.4 km near Savage River to 27.4 km in the vicinity of the Tamar fracture system before thinning out to 22.3 km near Binalong Bay. The same study found that the Tasmanian crust has an average P1 velocity of about 6 km/s and an average Pn velocity (the velocity of the Mantle beneath the Moho) of about 8 km/s. A more recent seismic traverse between Savage River and Fortescue Bay on the south-east coast indicated a crustal thickness of approximately 32 km beneath central Tasmania (Richardson 1989). The gravity field in Tasmania (Leaman 1989) is well resolved, with station spacing on shore ranging from about 1 to 7 km. Bouguer anomaly values range from about –50 to 100 mGal and are consistent with a maximum crustal thickness of 27.5 km under central Tasmania, with regions closer to the ocean basins being as much as 5 km thinner. The interpretations of these previous surveys imply that Tasmania is composed of relatively thin continental crust.

New seismic survey

The seismic component of the TASGO project was completed in 1995, when AGSO's research vessel Rig Seismic performed a circumnavigation of Tasmania during which approximately 36,000 shots were fired from the air guns it deployed. A network of 38 portable analogue recorders and 6 digital observatory stations recorded the seismic energy produced by the air guns. Marine deep reflection profiles, which are not considered in this study, were also recorded as part of the survey. The source-receiver configuration is shown in Fig 1. Solid lines indicate the path of Rig Seismic during the operation of its air guns. Shots from Lines 1, 4 and 5 recorded at a selection of stations on or near the north and east coasts form the dataset on which the results presented in this paper are based.

Simple refraction interpretations

Our preliminary refraction interpretations assume that the first arrivals are head waves which travel along horizontal planar interfaces separating constant velocity layers. Reflections are not considered so low velocity layers cannot feature in the 1-D models that are produced. The description of seismic crustal structure below is based on a larger number of refraction interpretations than was considered in a similar description by Rawlinson et al. (1997).

Down the east coast, from just north of Binalong Bay to the Freycinet Peninsula, reversed profiles show that the crustal thickness is relatively uniform at 25 km with an average P1 velocity of about 6 km/s and a Pn velocity of 7.8 km/s. Continuing south to the Tasman Peninsula, the crust thickens slightly to 26 km and the Pn velocity increases to 8.0 km/s. Two crustal layers separated by an interface at approximately 10 km depth are discernable from the east coast data; the upper crustal layer has a velocity of approximately 5.8 km/s while the lower crustal layer has a velocity of about 6.2 km/s. From the northwestern most point of the Tasmanian mainland to the central north coast, the crustal thickness appears to be relatively uniform at 30-32 km with an average P1 velocity of 6.0 km/s and a Pn velocity of about 7.9 km/s. Two distinct crustal layers can be identified beneath the north-west coast, and are similar in character to the east coast crustal layers. In addition, a 1-3 km thick layer with a P-wave velocity of about 4.5 km/s overrides the two main crustal layers and represents the clastic carbonate sequence known as the Rocky Cape Group (Williams 1989). Further east, across the Tamar Fracture System, the crustal thickness decreases to 27 km and remains at this value as far as Banks Strait.

2-D forward modelling

Only a limited amount of 2-D forward modelling can be accomplished with the TASGO refraction data because few shot lines exist that have more than one receiver lying approximately in-plane. In Fig 2, we illustrate a simple 2-D forward model of the region between stations 31 and 10 that has been constrained by both refraction and reflection arrivals from Line 5 (model traveltimes are indicated by solid or dashed lines; observed traveltimes are indicated by crosses or circles). Interfaces are described by uniform cubic B-splines in parametric form. The advantage of parametric form is that both the x and z coordinates are functions of the same independent variable, so the interface is able to fold back on itself if necessary. Velocities within layers are allowed to vary linearly with depth so that ray paths consist of circular arc segments.

The most prominent lateral feature of the model is the upward deflection of the Moho (the bottom interface) and the interface directly above it between x = 40-110 km. This antiform in the lower crustal layer is in the vicinity of the Arthur

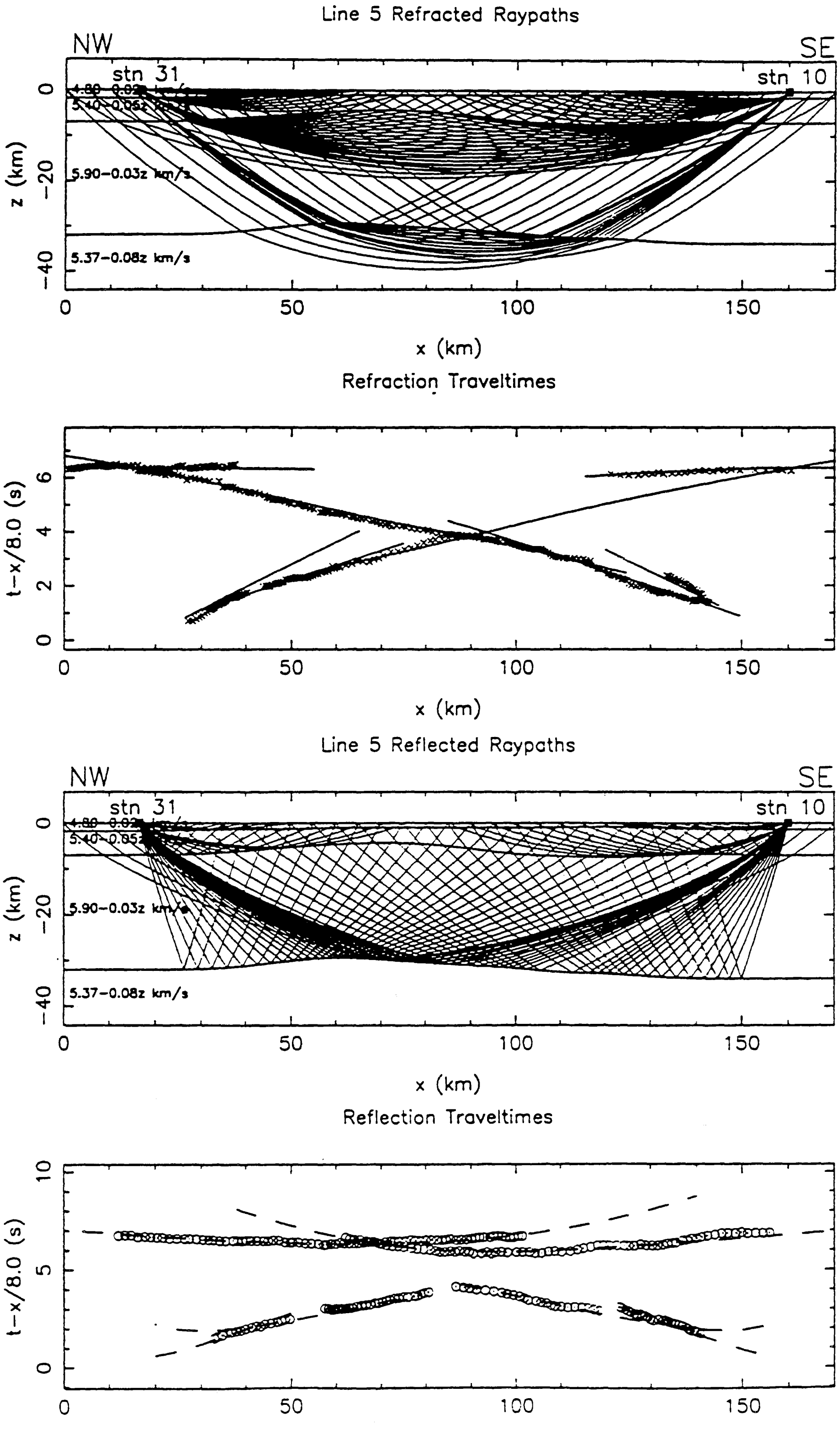

Fig. 2 -Seismic P-wave raypath diagrams and travel-times for refracted and reflected phases for Line 5 along the northwest Tasmanian coast between seismic stations 31 and 10 (see Fig. 1 for locations).

Lineament, a linear belt of regionally metamorphosed and highly deformed rocks (Turner, 1989). Our model is supported by free-air gravity data, in which the Arthur Lineament is expressed as a gravity high.

Conclusions

Preliminary results along the north and east coasts of Tasmania suggest a relatively thin continental crust, with the thickest regions occurring along the western north coast and the thinnest regions occurring down the east coast. Although we cannot directly compare our results with those of Richardson (1989) and Leaman (1989), they do seem to be in broad agreement, with the possible exception of the western north coast where we find the crust to be approximately 30 km thick; Richardson estimates the crust to be only 23.4 km thick some 100 km south near Savage River. The mean P1 crustal velocity of 6.0 km/s and Pn velocity of 8.0 km/s found by Richardson (1981) for Tasmania are consistent with our results. Our 2-D forward model along Line 5 represents the Arthur Lineament as an upward deflection in the lower crustal layer.

Future work

The current first-order analysis of the TASGO refraction data will continue as more data from other regions of Tasmania are processed. While 2-D modelling will also continue, our long term goal is to invert the data for 3-D crustal structure and velocity, so as to produce a high resolution tomographic image of the whole island. Such an image will be invaluable in helping to describe Tasmania's deep geology, and will enhance our current understanding of the tectonic evolution of the region.

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Geological Evolution of the Central Eastern Margin of Australia: Fission Track Thermochronology

Asaf Raza[1], Kevin Hill[1], Russell Korsch[2], Roderick Brown[3]

[1] AGCRC, Department of Earth Sciences, La Trobe University, Melbourne.
[2] Australian Geological Survey Organisation, Canberra.
[3] Department of Earth Sciences, La Trobe University, Melbourne.

Palaeozoic to Early Mesozoic rocks of the New England Orogen dominate the geology of the central eastern margin of Australia. Study of the orogen suggests that convergent tectonics played a significant role in the geological development of the eastern Australia during the Palaeozoic to Triassic. However, the tectonic configuration for the Jurassic-Early Cretaceous period prior to Tasman rifting is enigmatic generally due to the lack of clear geological evidence.

It is widely held that prior to Tasman rifting, a convergent boundary and associated volcanic arc existed along the Australia's eastern margin. However, the only part of the volcanic arc preserved is along the north-eastern coast of Queensland. It is also commonly believed that this arc, active during 132-95 Ma, was a major source of voluminous volcanogenic detritus to the then subsiding Mesozoic basins such as the Surat, Eromanga and possibly the Clarence-Moreton, Gippsland and Otway Basins. Petrological and geochemical evidence from these volcanics suggest that volcanism was related to continental extension leading to the opening of the Tasman Sea. The youngest age measured for these volcanics is 95 Ma.

What happened geologically during the last 100 Ma is also poorly known as little or no strata of this age are preserved onshore along the eastern Australian margin. The youngest sediments in the neighbouring Mesozoic basins are no older than 99 Ma yet magnetic anomaly data from the Tasman sea indicate that during the last 100 Ma rifting occurred which attenuated the Lord Howe Rise and New Zealand from Australia. Apatite fission track (AFT) analysis has the potential to determine the timing and magnitude of geological cooling events over this period of minimal record and therefore has been applied to rocks of southern New England Orogen (SNEO). 31 outcrop samples were analysed along the four east-west directed transects that run from the present shoreline to the inland neighbouring Gunnedah-Bowen and overlying Surat Basins.

All measured AFT ages from the SNEO are younger than the stratigraphic age of the host magmatic or sedimentary rocks signifying cooling from elevated palaeotemperatures. Ages are 60-83 Ma close to the continental margin and tend to get older, up to 214 Ma, away from it. Mean track lengths for young samples are long with narrow and unimodal distributions typical of a rapidly cooled sample from maximum palaeotemperatures of ≥110°C. Further inland ages are mixed with either bimodal or unimodal but negatively skewed track length distributions suggesting that these samples once resided within the partial annealing zone before cooling to surface temperatures. The regional thermal history can be summarised by portraying the relationship between AFT ages and mean track lengths (Fig. 1). The resulting 'U' shape plot indicates all samples have experienced a common style of cooling history and young ages with long mean track lengths record the latest discrete cooling events.

Three phases of cooling have been recognised from AFT data from the SNEO. These are: 1) during the Hunter Bowen Orogeny at ~252 Ma; 2) during the mid-Cretaceous at ~100-80 Ma and; 3) during the Late Cretaceous-Early Palaeogene at ~60 Ma. The mid-Cretaceous cooling is significant as other regional AFT studies elsewhere along the eastern margin record this event suggesting it is an important period in the geological history of the region. The Late Cretaceous-Early Palaeogene event is restricted to the coast and has affected a ~50 km zone of along the modern coast line.

The regional cooling at 100-80 Ma was caused by widespread denudation across the study area. The estimated amount of denudation is greatest close to the margin where up to 3 km of section has been eroded in some places. However,

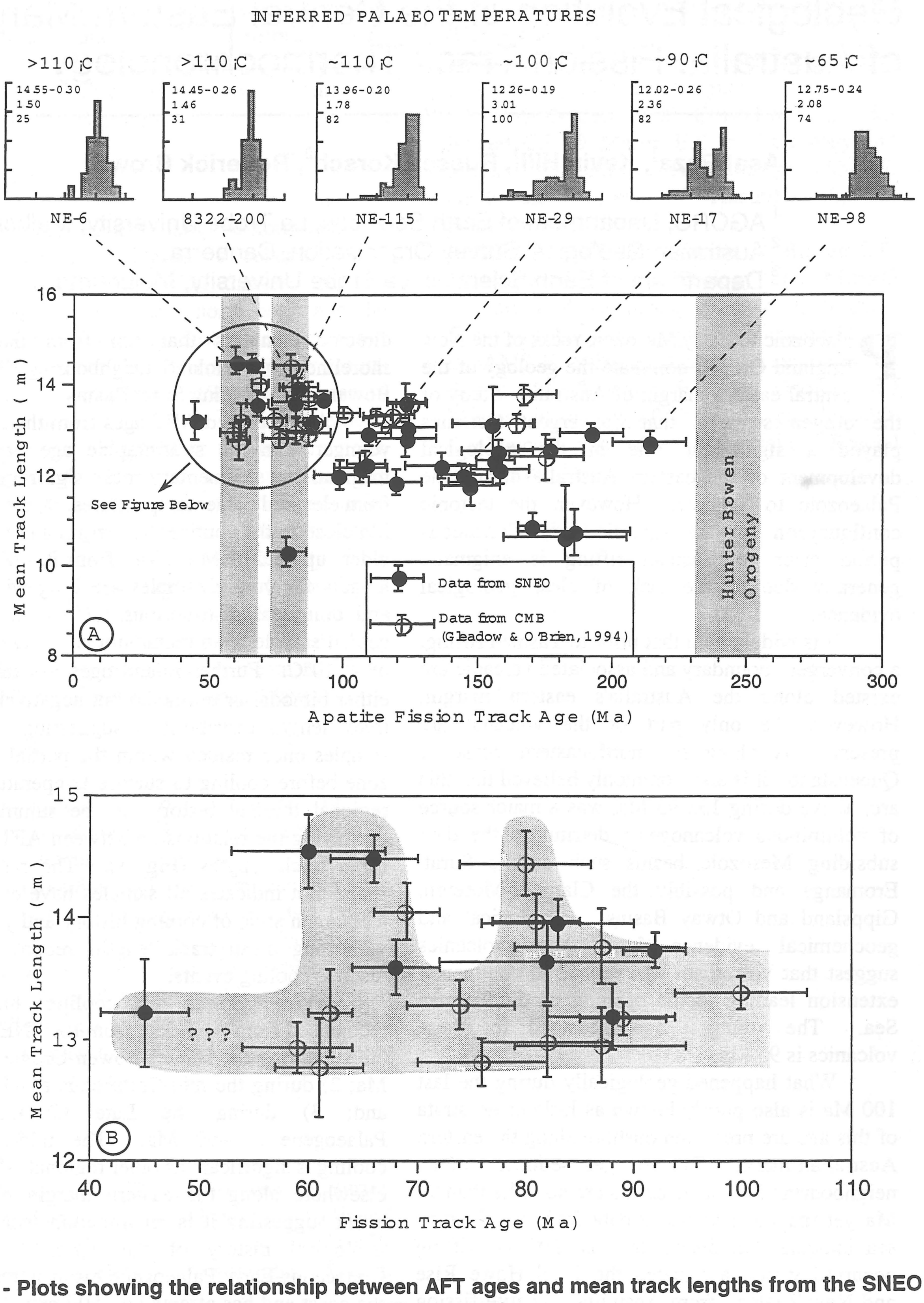

Fig. 1: - Plots showing the relationship between AFT ages and mean track lengths from the SNEO and Clarence Moreton Basin (Gleadow and O'Brien,1994)

the amount of denudation is variable and progressively decreases inland where it ranges from <1-1.5 km.

The cooling during the mid-Cretaceous can be linked with a number of changes affecting the Australian plate at that time. Among them: 1) realignment of the spreading ridge system in the southeast Indian Ocean with the start of an increased spreading rate and hence rapid northward movement of the Indian Plate (Powell et al., 1988); 2) final separation of Australia from Antarctica with the onset of spreading in the

Southern Ocean (Veevers & Eittreim,1988); and 3) rifting of New Zealand from western Antarctica (Kamp, 1986).

The Mesozoic Surat, Eromanga, Gippsland, and Otway Basins along the eastern and southeastern margin record this event in the form of major erosional unconformity. Concurrent with it is the sudden cessation of volcanic activity in Queensland (youngest K-Ar age of 95 Ma). The mid-Cretaceous is also the time of formation of core complexes and extensional basins in New Zealand associated with major uplift and erosion. Also at this time nature of magmatism changed from subduction to extension-related in Marie Byrd Land (Weaver et al., 1994).

The Late Cretaceous-Early Palaeogene cooling along the eastern margin is coeval with the second phase of plate readjustment at (60-65 Ma). The onset of seafloor accretion in the Coral Sea and Cato Trough took place at ~62 Ma. There is a sharp bend in the apparent polar wander path of the Australian continent at ~60 Ma (Idnurm, 1985). A little earlier, ca. 70 Ma but significant in terms of the tectonic evolution of eastern Australia, basaltic volcanism began along the eastern margin of Australia.

Taken together, these data lead to the conclusion that the temporal and spatial changes in the tectonic configuration of the Australian plate during the mid-Cretaceous and Late Cretaceous-Early Paleocene were genetically linked to the deformation and regional denudation. The broad coincidence in timing between the plate rearrangements and the time of cooling from peak palaeotemperatures revealed by the AFT results along the Australian central eastern margin provides a tectonic cause for the denudation during the mid-Cretaceous and Late Cretaceous-Early Paleocene.

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Mafic Magmatism in the Evolution of the Southern Lachlan Fold Belt

Alvar Soesoo & Ian Nicholls

Department of Earth Sciences, Monash University, Clayton, VIC 3168

The Palaeozoic Lachlan Fold Belt (LFB) is a part of the Tasman Orogenic Belt that formed along the eastern margin of Gondwana. The surface geology of the fold belt is dominated by Ordovician oceanic sediments intruded by a large number of granitoids and fewer mafic intrusives. There has been controversy related to the tectonic setting, orogenic processes, and the nature of the lower crust of the LFB. Recent models (Gray 1997; Soesoo et al. 1997) explain the crustal structure and magmatic features involving three subduction zones during the evolution of the belt.

Mafic rocks are represented either by gabbroic/dioritic intrusives and/or basaltic dykes or basaltic lavas in addition to abundant enclaves within the granitoids. These occurrences indicate that mafic magmas were mechanically and geochemically involved in granite petrogenesis and probably provided a heat source to facilitate crustal melting. It will be shown that some I-type granites may be formed by fractional crystallisation of mafic mantle-related melts with or without minor crustal contribution.

Mafic rocks - southern Lachlan Fold Belt

Mafic rocks were studied along a 200 km approximately east-west traverse from eastern to central Victoria including the Tambo River, Tabberabbera, Snowy Bluff and Mt Buller areas. The central part of the Tambo River area exposes a number of Early Devonian tonalitic to granitic intrusions (e.g., Tambo Crossing, Ensay, Doctors Flat, Swifts Creek), and a variety of dykes ranging in composition from tholeiitic and alkaline basalts to high-Mg andesites and rhyolites. The Tabberabbera area contains the Angusvale dioritic intrusion and a swarm of Middle to Late Devonian dykes ranging in composition from basaltic to rhyolitic. The Late Devonian/Early Carboniferous Snowy Bluff volcanic complex represents bimodal magmatic activity including basalts/andesites and rhyolites. The Middle Devonian Mt Buller igneous complex includes gabbro-diorite-granite composite intrusions. Within granitoid intrusions, the mafic rocks occur as enclaves and/or mafic dykes. Dykes usually vary in width from tens of centimetres to tens of metres. Two major preferred strike directions can be distinguished: (a) northwesterly trending dykes, parallel to the major fold axes; and (b) westerly and southwesterly trending dykes, which are less common. In some cases two or three generations of basaltic to andesitic dykes are present within a single felsic complex: (a) those which intrude country rock and predate the emplacement of plutons; (b) those more or less contemporary with pluton emplacement; and (c) those postdating pluton emplacement.

Most mafic rocks show trace-element abundance patterns with significant negative Nb anomalies, similar to those of subduction-related rocks of active continental and island arc-type margins. However, several dykes demonstrate MORB-like trace-element signatures. The Snowy Bluff basalts, in contrast, have relatively high Nb contents. These basalts show the flattest trace-element patterns.

The most significant geochemical differences between mafic rocks from the studied

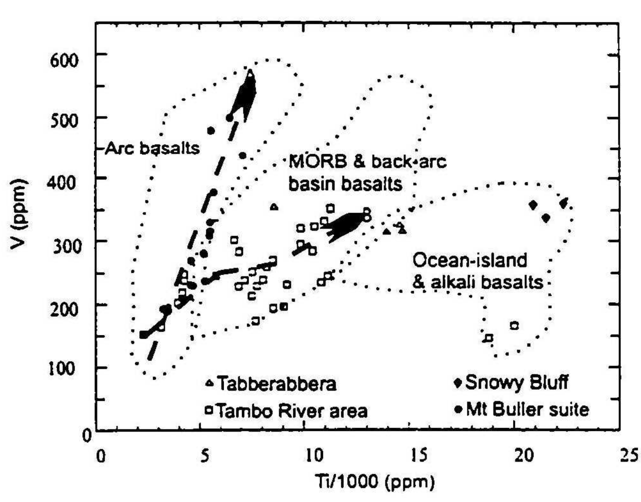

Fig. 1 - Mt Buller, Tabberabbera, Tambo and Snowy Bluff mafic rocks in a V-Ti discriminant plot.

complexes are evident when plotting them on a V-Ti diagram (Fig. 1). Mt Buller rocks and some Tambo dykes plot in an arc-tholeiite field while the rest of Tambo rocks occupy the MORB and back-arc basin basaltic fields. Tabberabbera rocks lie between the fields of alkali and MORB/back-arc basin rocks with one exception plotting in the MORB/back-arc basin rock field. This sample also shows other geochemical similarities to MORB. The Snowy Bluff basalts demonstrate chemical characteristics which are typical of ocean-island and alkali basalts. Two Tambo dykes plot also in this field and show geochemical similarities with the Jurassic Freestone dykes (Soesoo et al. 1999; in print). This may indicate that some of the Tambo River dykes may be Jurassic in age.

Fractional crystallisation of mantle-derived melts as a mechanism for some I-type granite petrogenesis: the Mt Buller example.

Recent models of magma generation proposed for LFB granitic complexes, involving contributions from mantle derived magmas, are supported by Sr, Nd and Pb isotopic and trace element studies. Fractional crystallisation of a mantle magma to produce an I-type granitic end-member will be exemplified by the Mt Buller igneous complex, southern LFB.

The Mt Buller igneous suite encompasses a large variety of rock types, from gabbros through diorites to granites. Mafic rocks and enclaves have primitive, mantle-like initial $^{87}Sr/^{86}Sr$ values (0.7037 - 0.7045), and ε_{Nd} values (+5.6 - +4.1). The granites do not show distinctively more radiogenic initial $^{87}Sr/^{86}Sr$ values, suggesting they are derived from the same parent as the gabbros. Most of the Mt Buller rocks do not show positive correlation between silica and initial $^{87}Sr/^{86}Sr$, neither between silica and $^{143}Nd/^{144}Nd$ values, indicating that neither crustal contamination nor mixing between mantle- and crustal derived melts has been important and that these rock types are likely to have formed by fractional crystallisation from a common mantle-derived parent. An alternative possibility is that the assimilant is geochemically similar to the primary magma composition. Some Cambrian Howqua greenstones (Crawford & Cameron 1985) are geochemically indistinguishable from mantle-derived magmas. Despite the fact that the Mt Buller rocks show primitive, mantle-like isotopic signatures, we do not have unequivocal evidence about the very

Table 1 - Parental magma and modelled and natural rock compositions at different stages of low pressure fractional crystallisation of the Mt Buller igneous suite. HQ, MB and ST stand for Howqua, Mirimbah, and Mt Stirling intrusions, respectively.

Sample	Parent	Average	*Modelled diorite*	Average HQ	Average MB	Average ST	*Modelled granite*	Average HQ	Average MB	Average ST
Rock		Gabbro		Diorite	Diorite	Diorite		Granite	Granite	Granite
SiO_2	48.27	49.75	*53.94*	56.52	58.56	58.89	*66.09*	67.45	70.79	70.05
TiO_2	1.14	1.20	*0.71*	0.76	0.77	0.95	*0.10*	0.40	0.40	0.44
Al_2O_3	15.57	18.04	*21.61*	17.44	16.74	16.12	*21.10*	15.06	14.28	14.90
Fe_2O_3	11.42	11.38	*6.67*	7.38	6.40	6.28	*2.44*	3.77	2.33	2.60
MgO	10.38	6.11	*3.82*	3.91	3.89	3.34	*1.10*	1.81	1.03	1.24
CaO	10.38	10.00	*8.78*	7.37	6.41	5.52	*2.50*	3.60	2.07	2.81
Na_2O	2.22	2.56	*3.35*	3.69	3.78	4.47	*4.85*	3.55	4.10	4.15
K_2O	0.52	0.80	*0.92*	1.17	1.59	1.91	*1.50*	3.03	3.32	2.63
P_2O_5	0.10	0.15	*0.20*	0.17	0.24	0.29	*0.32*	0.05	0.12	0.11
Cr	100	60	*25*	63	44	26	*1*	62	12	24
Ba	400	340	*390*	586	615	519	*720*	675	737	499
Sc	19	30	*24*	19	17	16	*12*	14	7	5
V	200	300	*125*	202	191	137	*39*	122	46	51
Co	69	60	*34*	52	56	45	*8*	45	93	47
Ni	100	100	*32*	39	46	25	*1*	8	14	14
Zr	250	200	*60*	107	125	183	*120*	151	136	120
Y	22	15		18	19	22		22	15	8
Sr	800	750	*940*	659	623	570	*1200*	402	281	489
Rb	25	19	*30*	42	57	59	*80*	82	105	90

early history of the most primitive magmas itself. It cannot be ruled out that the composition of the primary magma was modified by assimilation near or at the upper mantle - lower crust interface. Thermodynamic modelling confirms a comagmatic origin of the suite and suggests at least two stages of fractionation, at intermediate pressure, probably in the lower crust, and low pressure. We argue that fractionation of mantle-derived melts is primarily responsible for geochemical and petrological variation within the Mt Buller suite and that this mechanism may play a more important role in the evolution of Lachlan Fold Belt I-type granitic suites than previously recognised. A possible parental magma and fractionation members are presented in Table 1.

Implications for crustal evolution

Commonly, I-type granite suites have only minor mafic components (dykes and/or enclaves) exposed, and thus the identification of genuine parental magmas and relationships between granites and mafic rocks is hindered. The occurrence of cogenetic mafic plutons within the LFB granitic suites is probably much more common than one can see at an exposed upper crustal level. In this respect, the Mt Buller igneous suite provides a unique opportunity to study fractionation processes and the contribution of mafic magmatism to crustal evolution.

Other somewhat similar geological observations have been made on the Moruya suite in the southeastern LFB (Keay et al. 1997; Collins 1996). This suite contains a gabbroic component and shows similar primitive isotopic compositions. The isotopically most primitive compositions in both intrusions are obtained from dykes and they show similar geochemical characteristics.

The evolution of the Mt Buller magmatic system may be related to a double subduction system in the western part of the LFB (Soesoo et al. 1997; Fig. 2). After closure of an oceanic basin in the Middle Devonian, the sinking of an "inverted U" shaped slab started to detach from the overlying crust. This detachment would have necessitated inflow of mantle which led to decompressional melting of the asthenospheric mantle. These melts supplied lower to middle crustal magma chambers. Some pieces of the sinking slab may have stayed attached to the overlying crust and may have undergone restricted partial melting. Partial melting of oceanic crust alone cannot account for the geochemistry of the Mt Buller parental magma as it would have required almost complete melting of basaltic material to produce the high-magnesian parental magma. However, a possible minor contribution of partial melting of oceanic basaltic crust is difficult to constrain due to its similarities with mantle-

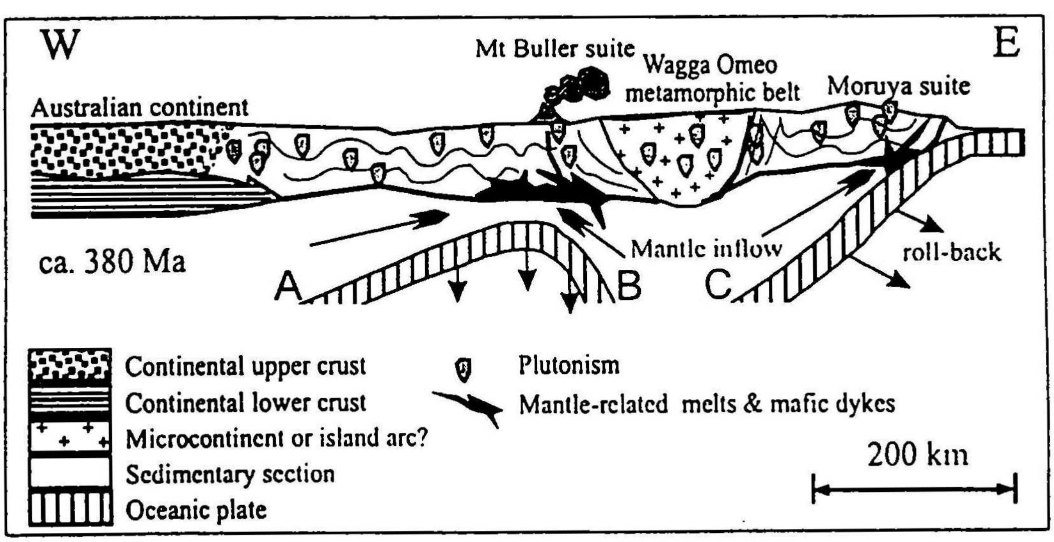

Fig. 2 - Schematic tectonic east-west profile through the southern Lachlan Fold Belt, at latitude of central Victoria. Two subduction systems, A-B and C, are shown. The Mt Buller suite has probably formed during the cessation stage of subduction in the Middle Devonian when the lower crust became exposed to mantle inflow due to sinking oceanic lithosphere.

derived magmas in trace element and isotopic composition. Geochemical and petrological similarities between the Mt Buller and Moruya suites can be explained by similarities in crust-mantle dynamics. The Moruya igneous suite is situated above a westward dipping Palaeozoic subduction zone (C in Fig. 2). Instead of diverging flanks of the double divergent subduction system A-B, the Moruya suite may have formed during an efficient slab roll-back, which also created upper mantle inflow and subsequent decompressional melting.

Any tectonic system that causes inflow of hot mantle, as for instance slab roll-back or sinking of a double divergent subduction system, exposes the overlying lower crust to the hot mantle and leads to partial melting of the inflowing mantle material. The combination of a number of factors, such as thermal regime, tectonic forces, type and thickness of the crust, etc., determines the fractionation history of mantle-related magmas as well as the type of intrusions that are produced, which range from dykes to major granitoid suites. At Mt Buller, and probably also at Moruya, fractionation reached granitic compositions, but all intermediate stages, ranging from gabbros to granodiorites, are also represented. Other similar I-type granite suites in the LFB may also have been derived by fractionation from mafic parental magmas. In most cases, mafic enclaves are the only remaining representatives of the early and intermediate stages of fractionation.

Conclusions

1. The mafic rocks associated with southern LFB felsic complexes include tholeiitic to mildly alkaline minor plutons, lavas, dykes and enclaves.

2. Many mafic rocks show mantle-like isotopic and trace element geochemistry.

3. Some I-type granites may represent fractionated derivatives of basaltic mantle-derived melts.

4. Devonian magma generation for some granitic and majority of basaltic complexes probably took place within the upper mantle in the subduction-related environment.

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Intermediate P Metamorphism in Cambrian Oceanic Sequences, Western Lachlan Fold Belt and Implications for Tectonics

Catherine V. Spaggiari[1], David R. Gray[1] & David A. Foster[2]

Australian Geodynamics Cooperative Research Centre
1 - Department of Earth Sciences, Monash University, Melbourne VIC 3168, Australia, ST-cath@earth.monash.edu.au
2 - Department of Earth Sciences, La Trobe University, Melbourne VIC 3083, Australia

Occurrences of intermediate pressure assemblages within chaotic block-in-matrix melange from the fault-bounded Cambrian? oceanic successions within the turbidite-dominated western Lachlan Fold Belt have important implications for the tectonic evolution of these rocks. Rock associations and inferred P conditions match those of the classical 'B' or 'Cordilleran' type blueschists (after Maruyama et al., 1996) as part of a subduction-related accretionary setting where protoliths include bedded chert, MORB and ocean island basalts, reef limestones and greywackes. The Cambrian? successions in central Victoria are the oldest known rocks, and occur as three generally elongate belts of largely meta-igneous "greenstones". They consist predominantly of mafic to ultramafic metavolcanic rocks, where the MORB metabasalts are often pillowed and are found associated with deep marine sediments (mostly bedded cherts). These may represent the top of an oceanic stratigraphy as part of a Cambrian? through Devonian small, ocean basin. Current work focuses on the central part of the Heathcote belt and the Howqua River area of the Mt. Wellington belt.

In the past it has been thought that the Cambrian? meta-igneous rocks have undergone low P, burial metamorphism up to greenschist facies conditions. However, in the Heathcote belt, intermediate pressure assemblages occur sporadically, close to the Heathcote fault, over a distance of about seven kilometres. The best exposure is found at Red Hill where pods of coherent, "blue-coloured" rocks occur surrounded by strongly foliated and fragmented meta-igenous rocks with minor chert, which are in fault contact with strongly deformed turbidites to the west. The coherent rocks consist of the assemblage Ca-Na amphibole, albite, stilpnomelane, Mg-Cr spinel, chlorite and epidote. Electron microprobe analyses have shown the amphibole phase to be winchite, which is transitional between glaucophane and actinolite (classification scheme of Leake et al., 1997). Optically, the amphibole is blue-green to lavender blue. Geobarometry using this assemblage indicates pressures up to 6-7 kb which translates to a depth of around 18 km. This is in agreement with depth estimates for a major detachment fault at Heathcote as shown by seismic data (Gray et al., 1991). Intermediate pressures (up to 4 kb) are also indicated by b_0 cell parameter and illite crystallinity data of phengitic micas in the turbidites (Offler et al., 1998). As the turbidites would occur at a structurally higher level these data support the 6-7 kb of the underlying meta-igneous rocks.

Recent fieldwork in the Howqua River area of the Mt Wellington belt has shown that similar rocks crop out at Tobacco Flat. The mineralogy is not as well preserved as that at Heathcote; i.e. there is retrogression to chlorite, at least on the exterior of the blocks where the samples were taken. The outcrop is flanked by strongly deformed and veined, green sandstones and hence appears to be an isolated block. Mapping has shown an extensive melange zone from Frys to Wares, a map distance of about 4-5 km. The blocks exist either within black mud-matrix or serpentinite matrix melange, not unlike those of the Fransciscan complex of California, which have been inferred to form in a deformed, subduction-related accretionary complex.

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Tectonics, Structure and Metallogenesis - Their Interaction in the Southern New England Fold Belt

W. J. Stroud, R. G. Barnes, R. E. Brown, J. W. Brownlow and H. F. Henley

Geological Survey of N.S.W., Department of Mineral Resources, ABS House, Faulkner St, Armidale, NSW 2350

The interplay of crustal and mantle magmatism with other complex geological processes in the southern New England Fold Belt (SNEFB) has resulted in a diverse metallogeny. Crustal processes dominated the formation of the NEFB and significantly influenced the metallogeny. Interactions with upper mantle processes have also left a significant metallogenic fingerprint in the area.

The SNEFB is remarkable for the variety of mineral deposit types and the concentration of specific metals. The fold belt is characterised by major concentrations of Sn, Mo, W, Au and Sb (Gilligan & Barnes 1990). The hard rock Sn deposits associated with particular granite plutons, and their associated alluvial wash, have produced more than 200,000 t of cassiterite. Tertiary volcanics overlie the central part of the SNEFB. The basal section of these volcanics has produced extensive placer deposits of high quality sapphire. Production to date is in excess of 500 million carats.

Over 5000 mineral occurrences have been documented during the Department of Mineral Resources metallogenic mapping program (Gilligan & Brownlow 1987, Gilligan et al. 1992, Brown et al. 1992, Brown & Stroud 1997 and Henley et al. in prep). Only now, using GIS, have the more subtle associations between structure, geological setting and resultant metallogeny become apparent. Mineral exploration has defined significant orebodies (eg Timbarra Au mine-Simmons et al. 1996) and some has highlighted areas previously under-explored or overlooked (eg Mt Terrible epithermal Au). Much of the SNEFB though, remains under explored.

Regional setting

The NEFB (Leitch 1974) is the easternmost preserved part of the Tasman Fold Belt System (Scheibner 1987; Day et al. 1978). The fold belt comprises numerous fault-bounded tectono-stratigraphic units or terranes (eg Scheibner & Basden 1996). These aggregated during the Palaeozoic, were intruded by granitoid plutons and overlain by cover rocks. The current consensus is that during the Devonian and Carboniferous the SNEFB developed at a convergent plate margin. An accretionary complex developed to the east of a forearc basin and volcanic arc. In this paper we assume this model is essentially correct. The mineral deposits of the SNEFB are described within their interpreted geological - tectonic settings.

Ophiolites

Serpentinite and other associated mafic and ultramafic rocks occur at significant terrane boundaries in the SNEFB. Most occurrences are interpreted to represent the dismembered remnants of Cambrian to Silurian ophiolitic sequences finally emplaced in the Late Carboniferous (Benson 1913; Aitchison et al. 1994; Aitchison and Ireland 1995). These ophiolitic rocks have been extensively dismembered and have been involved in repeated emplacement to higher levels. The northern occurrences, along the Peel Fault, are interpreted to have formed in an open oceanic basin, possibly a backarc basin (Yang and Seccombe 1997). The southern occurrences associated with fault splays along the Manning Fault system and the Gordonbrook Serpentinite Belt represent former upper plate and basement of an island arc or forearc (Aitchison and Ireland 1995, Qureshi et al. 1993).

Podiform chromite deposits are scattered throughout the serpentinite. Nickel, cobalt and scandium are present at elevated levels and secondary processes have in places produced ore-grade Ni, Co and Sc-rich laterite (e.g. near Pt Macquarie). Significant magnesite and asbestos,

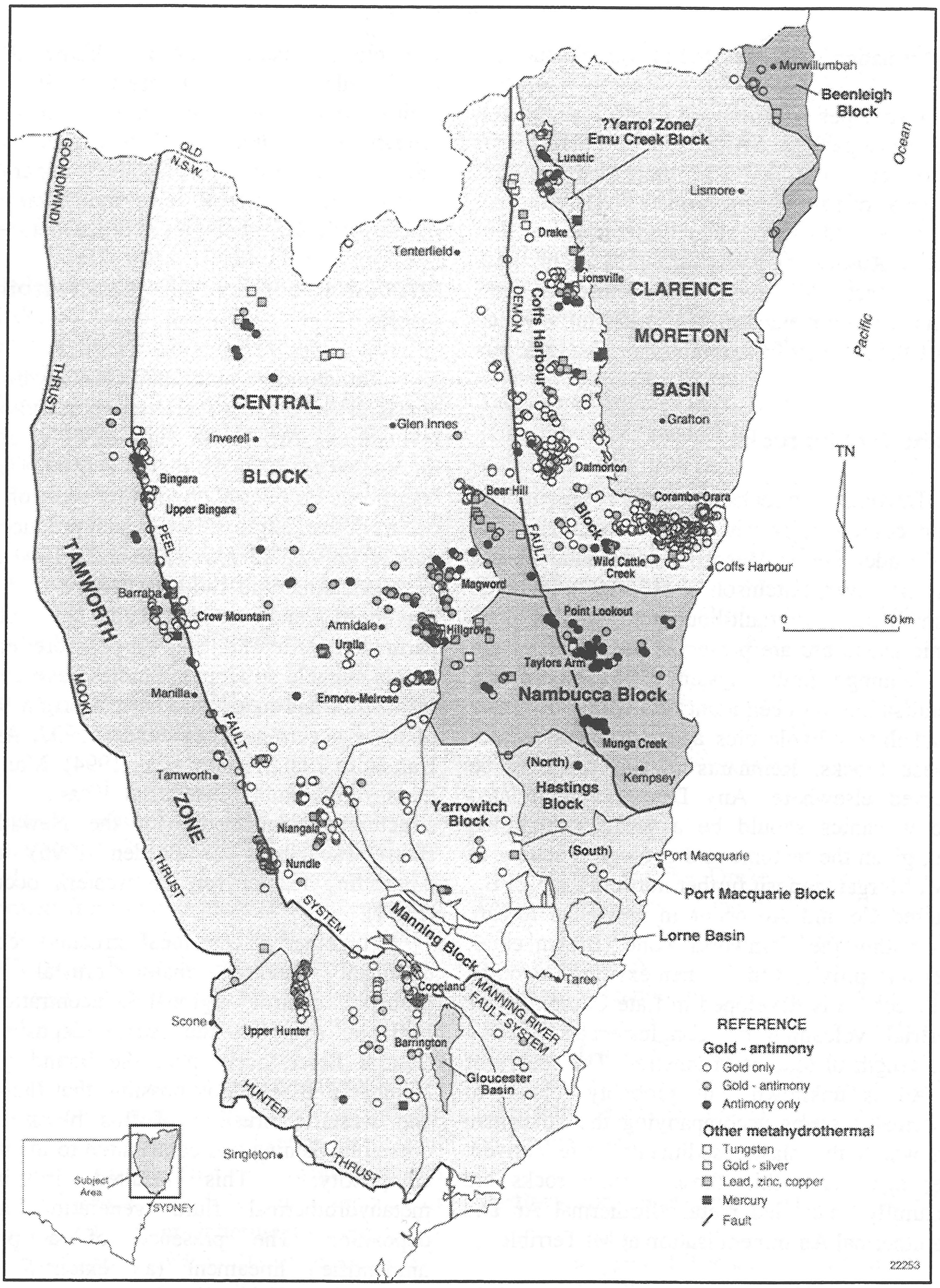

Fig. 1 - Geological subdivisions and metahydrothermal mineral deposits in the southern New England Fold Belt

nephrite and olivine occur. Reports of scattered platinoid occurrences need further evaluation.

Oceanic crustal rocks

Deformed and metamorphosed oceanic sediments and volcanics constitute much of the eastern part of the SNEFB. They make up many of the structural blocks east and north-east of the Peel-Manning Fault system. Small stratiform and stratabound occurrences of Cu, Mn and lesser Au are widespread. The Cu deposits (Cypress and Besshi type) occur in massive sulphide lenses in greenstone-rich intervals in metasediments. Like the Mn occurrences, the Cu occurrences are widespread suggesting that conditions leading to their formation may be found throughout the region.

Two types of chert are present within the crustal rock package (Aitchison & Flood 1990) and reflect proximity (or otherwise) to the continental margin during formation. Elevated Au is associated with some chert horizons. Small but abundant Au-bearing veins are present in these cherts. Most of these Au-occurrences are accompanied by metabasalt and mafic tuffs, which may be the source of the remobilised Au (Keevers 1987).

Arc and forearc rocks

Devonian arc rocks are virtually absent. The current consensus is that the arc rocks are now buried under Permo-Mesozoic sedimentary basin cover. However, Aitchison et al. (1997) conclude that small areas of a fault-bounded Devonian intra-oceanic island arc are preserved along part of the Peel-Manning fault system. No significant mineralisation has been identified within the felsic calc-alkaline subvolcanics and extrusives present in these blocks. Remnants of this arc may be preserved elsewhere. Any Devonian arc-related felsic volcanics should be a prime exploration target, given the tectonic and geological setting of the Mt Morgan deposit further north in the NEFB. Scattered Cu and Au occur in Devonian forearc rocks within the Tamworth Zone (Brown et al. 1992) very proximal to the then existing Devonian arc. Placer Au is developed in Late Carboniferous terrestrial volcaniclastic conglomerates over a strike length of tens of kilometres. The source of this Au is unknown, but probably related to epithermal systems accompanying the volcanism from which the clastic sediments were derived. Other deposits within these forearc rocks are structurally controlled metahydrothermal Au and the epithermal Au mineralisation at Mt Terrible.

Permian rift basins

Formation of Early Permian basins throughout the NEFB is well documented (Leitch 1988, Silwa et al. 1993). The largest of these is the Nambucca-Dyamberin blocks (NDB) in the central SNEFB. Most of the areas of basin sediments occur as isolated Early Permian fault blocks within accretionary complex rocks (Leitch 1988). Submarine felsic to intermediate volcanic rocks occur within part of the NDB, are rift related and host volcanogenic sulfides (Moody et al. 1993). The volcanics and associated epithermal Au at Mt Terrible also formed in a very Early Permian rift setting overprinting a forearc. This mineralisation appears to be related to a major Permian volcanic cauldron structure, with the mineralisation occurring as epithermal veins and disseminations within particular lithologies in this structure.

Structural control of metahydrothermal fluids

Structurally controlled metahydrothermal quartz ± Au ± Sb mineralisation (slate-belt Au, low sulfide Au quartz vein type) is abundant throughout much of the region (Fig 1). The most significant concentration of this type of deposit occurs at the Hillgrove field which produced more than 25 t of Au, 46 000 t of Sb and 2 100 t of W.

Metamorphic fluids generated in the crust scavenged and concentrated ore elements, particularly Au and Sb. These were emplaced within suitable structures. Studies have confirmed the crustal and metahydrothermal origin for some of these occurrences (eg Ashley 1997, Ashley & Hartshorn 1988, Ashley et al. 1994). Many of the metahydrothermal deposits are strongly structurally controlled with the New England suture (Scheibner & Basden 1996) a major controlling feature for the western occurrences (Fig 1).

In other places, local structural control is dominant although major crustal fractures probably control regional concentrations. For example, many of the Au-Sb deposits in the Central Block occur near the boundary of the Nambucca Block. It is possible that the northern and western thrusting of this block produced crustal thickening and contributed to the structural complexity. This resulted in increased metahydrothermal fluid generation and ore deposition. The presence of a previously unidentified lineament (an extension of the Bendemeer lineament) at the northern boundary of the Nambucca block, and its west-southwest continuation, possibly further focussed and enhanced the fluid tapping and ore deposition systems.

Late Carboniferous to Triassic magmatism

The SNEFB magmatism resulted in the intrusion of extensive S- and I-type granitoid plutons and extrusion of Late Permian volcanics.

S-type granites

Deformed, syntectonic Late Carboniferous S-type granitoid plutons (the Hillgrove Plutonic suite of Shaw & Flood 1981) are present in the central part of the SNEFB. Some of these granitoids help define part of a ENE trending belt which may in part mark a major crustal lineament (the Bendemeer lineament). Although numerous mineral deposits have a close spatial relationship with some of the Hillgrove Granitoids, they are metahydrothermal in origin.

Post tectonic S-type granitoids (the Bundarra Plutonic Suite of Shaw & Flood 1981) form a meridional belt in the central west of the region. In contrast to the highly mineralised S-type granites of the Lachlan Fold Belt, little mineralisation is associated with this granite suite. While significant F and B are in places present, only minor Sn mineralisation is present and its relationship to this suite is contentious.

Late Permian to Early Triassic late or post kinematic (I-type) granites

I-type granites make up the remainder of the New England Batholith and have been subdivided into suites (Shaw & Flood 1981) and supersuites (Chappell 1994). Most of these granitoids have been formed from partial melting of juvenile and volcaniclastic-rich crustal sediments. An exception is the Clarence River Supersuite (Bryant et al. 1997) which appears to be derived from isotopically primitive lower crustal or mantle material.

Some of these I-type granitoids have generated major mineralising systems in the SNEFB. However, the mineralisation associated with them is a product of magmatic and hydrothermal process, and is not a product of anomalous metal contents inherited by the magmas (Blevin & Chappell 1996). Blevin et al. (1996) have demonstrated a correlation between the evolution of metallogeny with evolution of magma chemistry for any particular plutonic suite. This ranges from Cu-Au associated with relatively unevolved magmas, through to Sn and Mo-rich mineralisation associated with highly evolved magmas that have undergone fractional crystallisation.

In the SNEFB abundant mineralisation is particularly associated with fractionated I-type granitoid plutons. Thousands of low tonnage deposits are concentrated within and around the margins of the Gilgai and Mole Granites. Mineral zoning is present. The magmatic-hydrothermal systems associated with these plutons were large and operated over a long period of time (eg Kleeman et al. 1997, Brown & Stroud 1997).

An unusual type of Au occurrence ("Timbarra-style") is associated with a fractionated granite at Timbarra. Low grade Au mineralisation is scattered through altered granite (Simmons et al. 1996). The presence of economic Au in this new class of deposit indicates that other similar deposits may be present in other fractionated granites in the SNEFB.

Precious metal mineralisation may be associated with the Clarence River Supersuite (CRSS) in the south of the Fold Belt (eg Copeland Au field - Gibson & Seccombe 1997) and is peripheral to and within the Dumbudgery Greek and Towgon Grange Granodiorites (Henley et al. in prep). There is a suspicion that much of the Drake mineralisation may also be related to CRSS plutons (eg Houston 1993). Some of the Drake Volcanics may be co-magmatic with the CRSS. Many precious metal veins may be related to nearby or buried CRSS plutons.

Permian volcanics

Except for the Drake Volcanics, the Late Permian volcanics of the SNEFB (Barnes et al. 1991) are devoid of any known co-genetic mineralisation. Numerous workers have concluded that these volcanics are co-magmatic with many of the plutonic suites in New England. The general absence of mineralisation is remarkable but may be attributable to extrusion of the volcanics before magmatic processes concentrated ore minerals within the magma.

Tertiary volcanics covering the SNEFB

Two types of Tertiary volcanism have been identified in the region - that associated with shield volcanoes (eg Tweed, Nandewar), and that associated with fissure eruptions and the generation of extensive areas of flood basalt (Wellman & McDougall 1974). These volcanics are part of the Cainozoic anorogenic volcanism that extends discontinuously for about 3000 km along the eastern Australian coastal region. This Tertiary volcanism shows prominent southward migratory components which appear to originate from the 65 Ma Coral Sea spreading rift (Sutherland 1985). In the New England region outcrop of the flood basalts defines a semicircular pattern. Early Tertiary concentric fracturing over a diameter of about 350 km, or a long lived torus-shaped mantle plume may have been the controlling influence in this volcanism.

The Tertiary volcanics in the New England region are host to primary sapphire deposits and may be host to primary diamond deposits. North and east of Inverell and west of Glen Innes, high to bonanza grade placer deposits of sapphire have been and still are being exploited (eg Pecover 1993). Over 500 million carats of sapphire have been produced from this field.

Extensive placer diamond deposits were worked late last century west of Inverell (Brown & Stroud 1997). Only scattered and non commercial occurrences of diamond have been reported from other areas in the New England region. An innovative subduction-related explanation for the formation of these and other Tasman Fold Belt diamond occurrences has been offered by Barron et al. (1996). No unequivocal source rock for these diamonds has been found, though dolerite dykes are implicated (Brown & Stroud 1997). The presence of diamonds to the west and south west of Inverell and sapphire to the north and northeast is either fortuitous or the result of related geological processes.

Acknowledgements

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Depth to Magnetic Basement in Southeast Australia

C. Tarlowski and B. J. Drummond

Australian Geodynamics Cooperative Research Centre
Australian Geological Survey Organisation, GPO Box 378,
Canberra ACT 2601

Sedimentary basins are important barometers of regional tectonics. Korsch et al., (1996) showed that the intracratonic basins of eastern Australia recorded the effects of tectonic processes in the continent margin to the east. Their study looked at the detailed evolution of structure within the sedimentary fill. However, estimates of more basic parameters such as the thickness of sediment fill are also important. The thickness of fill is a key indicator of whether deeper parts of the basin would have been buried to sufficient depth to reach the hydrocarbon maturation window. Variations in the thickness of fill also provide the overall geometry of a basin and this in turn is an important pointer to the tectonic processes which formed the basin. Thickness is an important parameter in regional studies based on gravity modelling, because the gravity anomaly map of Australia shows significant anomalies associated with some basins which must be accounted for in any study of the underlying basement

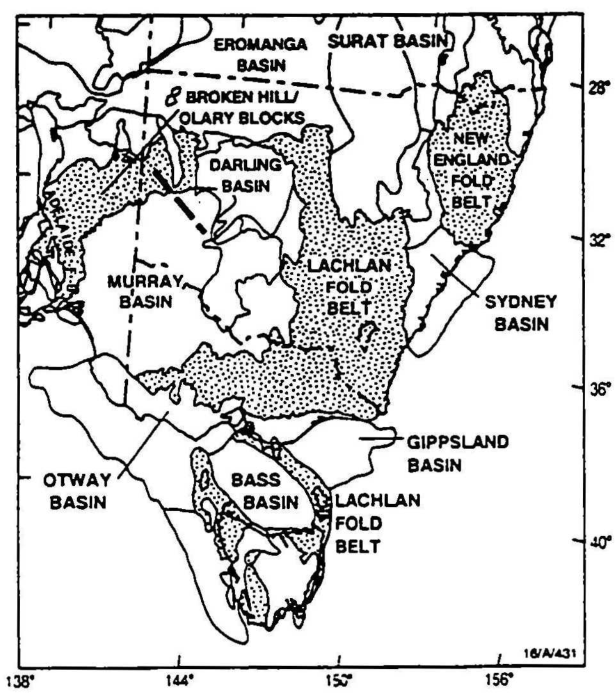

Fig. 1 - Geometry and location of the sedimentary basins in southeastern Australia. The broken line indicates the approximate location of the seismic refraction profile.

Relatively undeformed sedimentary basins cover nearly half of the outcrop area of south east Australia; the rest consists of fold belts which in turn contain older, folded basins and form the basement to the younger basins. The younger sedimentary basins can be broadly categorised into those which are deep and relatively narrow and have a clear tectonic origin; eg., Darling Basin and its sub-basins, Otway, Bass and Gippsland Basins, and those which tend to be much broader and whose tectonic origins are not so clear. They are more like sag basins; eg., Eromanga Basin, Surat Basin and Murray Basin (see Fig. 1).

Basin thickness and geometry are usually determined by seismic methods. Considerable amounts of seismic data exist for the Eromanga Basin, especially in south west Queensland and north east South Australia, and in the Gippsland and parts of the Bass and Otway Basins where petroleum exploration has been extensive. However, large areas of south east Australia have little or no seismic data.

This paper presents the first results from an inversion of the regional magnetic anomaly map of Australia. The process produces estimates of the depth to the magnetic sources under the surface that create the magnetic anomalies. As discussed below, when used to map thickness of basin fill, it provides first order estimates of basin geometry that appear consistent with results from seismic surveys.

Method

The depth estimates to the magnetic sources were obtained using Naudy technique (Naudy, 1971). The method assumes two-dimensional geology and does not make any provision for overlapping anomalies. Although the technique can utilise a dipping dyke model, thin sheet model, plate model or an edge model, depths to the upper surface of the causative bodies were estimated using a vertical dyke model.

The area studies in this analysis was from 131.5°E to 153.3°E and from 23.5°S to 43.94°S. The data were derived from the grid of the AGSO and has a 15s of arc grid cell size. The part of the grid used in analysis was divided into standard 1:1Million map sheet blocks. Magnetic traverses were extracted from the grids of each of these blocks. The spacing between traverses was 120 s of arc (approx 3200 m). The direction of the traverse was E-W or N-S within each block

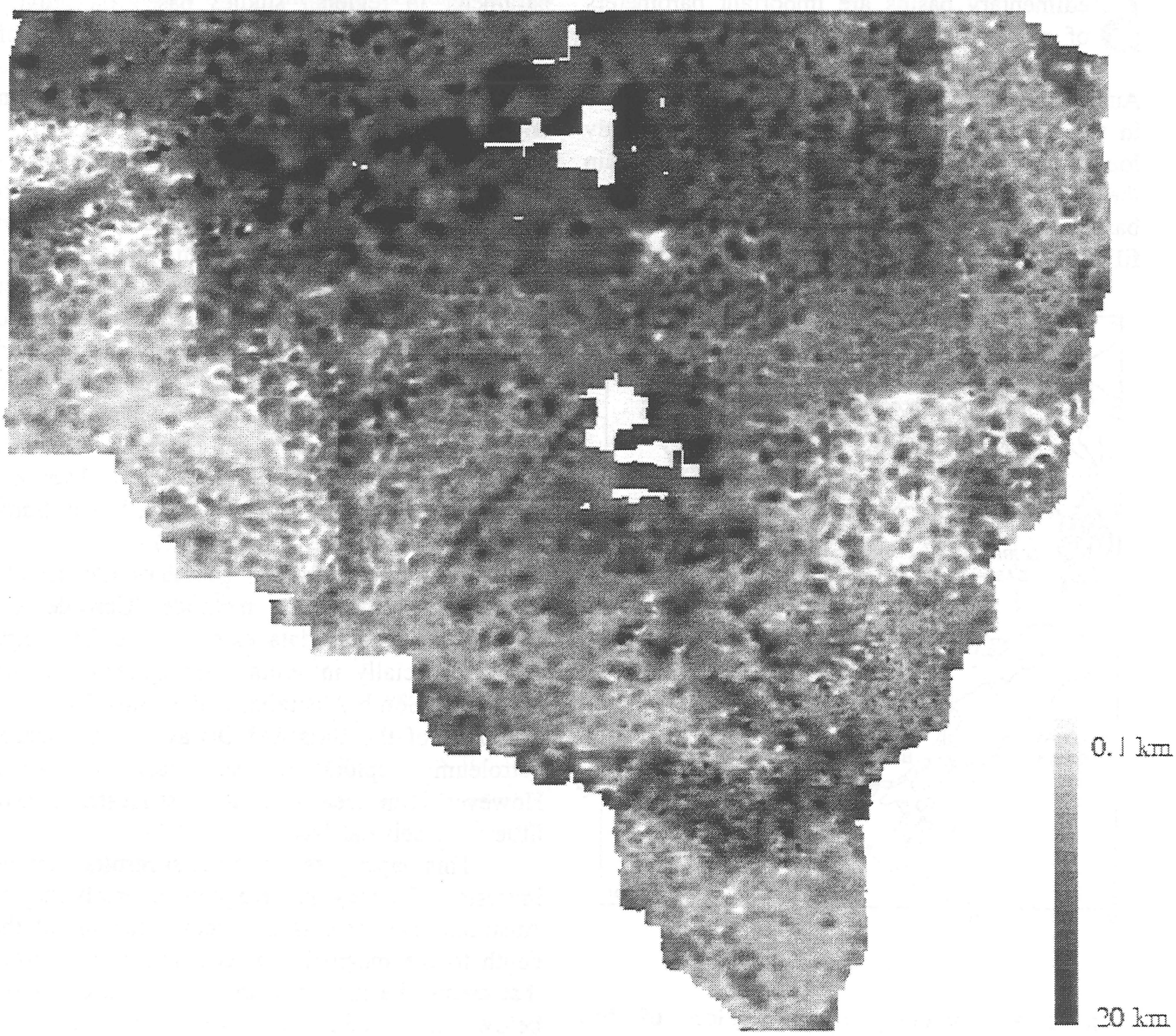

Fig. 2 - Grey scale image of depth estimates in geodetic coordinates. The study area extends from 131.5°E to 153.3°E and from 23.5°S to 43.9°S.

Magnetic Anomaly Map of Australia that was corrected for spurious warps using long aeromagnetic traverses (Tarlowski et al., 1996).

The grid used here supersedes the Second Edition of Magnetic Anomaly Map of Australia depending on the dominant general orientation of the known geological structures.

The estimates of the depths to the dyke-like bodies were then gridded at 3200 m grid cell size and separate blocks were put together for the whole of south east Australia. The resulting image is shown in Fig. 2.

Discussion

In Fig. 2, dark areas have a greater depth to magnetic basement, and in light areas the magnetic basement is shallow. Fig. 2 therefore shows clearly relative depths to magnetic sources under the surface. In basins where the sedimentary rocks are largely non-magnetic, it shows the thickness of basin fill.

The basement areas in Figure 1 are all light grey, indicating shallow magnetic sources. The western margin of the Adelaide Fold Belt shows as a clear boundary with the extremely light, and therefore shallow basement of the Gawler Craton. Some small areas of basement, particularly in the south central Lachlan Fold Belt, have deeper sources; further work is needed to see if they correlate with Palaeozoic sedimentary rocks, or with non-magnetic granitic rocks.

In the north of the map (top middle and left), the deeper basement correlates with the Eromanga Basin and the underlying Cooper Basin, and farther west with the eastern Officer Basin. This result is pleasing because many of the magnetic data sets from this area are considered to be sub-standard because they have been digitised from old analog records. Also in the north of Fig. 2, but farther to the east, and west of the New England Block, basement under the Surat Basin appears to shallow to the south and east until it is evident in outcrop rocks.

The Sydney Basin has deeper magnetic basement in the south east, near the coastline, but magnetic basement farther north under the Gunnedah Basin is very shallow, probably reflecting the presence at the surface and within the basin fill of volcanic rocks. A string of grey anomalies appears to outline the boundary between the eastern Gunnedah Basin and western New England Block, suggesting weakly magnetic rocks at the surface along the boundary.

The Darling Basin has a very pronounced dark grey to black zone (east of a gap in the data in the centre of the figure). This correlates very well with areas of major sediment accumulations. A linear dark grey feature extending south east from there correlates with the Menindee Trough of the Darling Basin and the Tasman Line (Leven et al., 1998). Fig. 3 is a cross section (see Fig. 1 for its position) which shows the shallow basement of the Broken Hill Block in the west, and the deep trough of the Darling Basin in the east. The section implies over 10,000 m of sedimentary rocks above magnetic basement. This is consistent with estimates of basin fill from Level et al. (1998). The mottled dark grey zones east of this anomaly, and south east of the no-data area near the major Darling Basin section discussed above, correlate with sub-basins of the Darling Basin, or probable correlatives, under the cover of the Murray Basin.

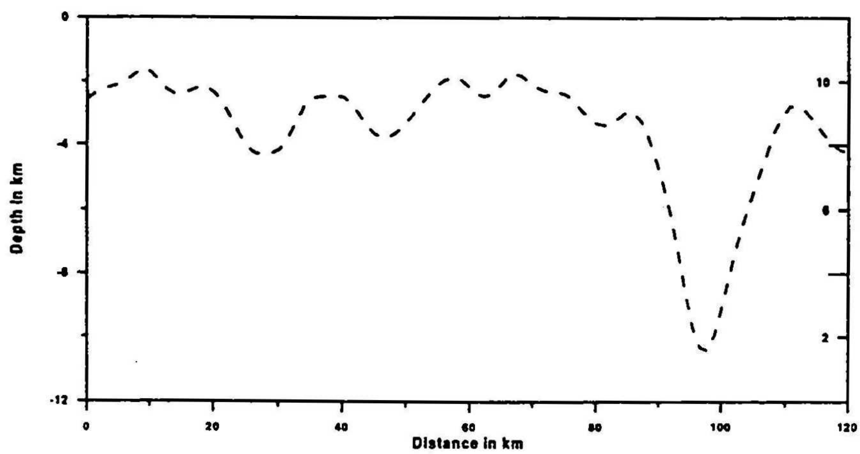

Fig. 3 - The depth estimates along the seismic refraction profile. The profile starts at 140.25°E, 31.3°S and ends at 143.17°E, 32.68°S.

Farther south, the Gippsland, Bass and offshore Otway Basins all show considerable depths to magnetic basement. The seismic coverage in these areas will eventually be used to calibrate the image.

The Tasmania Basin in central Tasmania has magnetic basement at or near the surface, correlating with the extensive younger dolerites at the surface and within the basin section.

Summary

The Naudy approach has produced depths to magnetic basement in south east Australia which correlate well spatially with known depocentres. The relative depths between depocentres generally agree with the known depth estimates from other studies, and the results from the Darling Basin appear to correlate well with those from seismic studies. The next step will be to make a closer correlation between estimates from the basement areas and mapped areas of folded sedimentary rocks, volcanic rocks, and granites.

Acknowledgements

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Subsurface Shape of Granites in the Northern Lachlan Fold Belt and Implications for the Tectonic Setting

Robert Trzebski, Paul Lennox and Derecke Palmer

Department of Applied Geology, UNSW, Kensington NSW 2052

The subsurface shape of granites helps to constrain the spatial and geometric relationship between intrusive bodies and deformation. Vigneresse (1995) distinguished three deformation styles, a/ compression, b/ extension, c/ shear faulting which control the morphogenesis of plutons and emplacement mode with respect to the related deformation. In the northern Lachlan Fold Belt structural data on granites and country-rocks is sparse due to the relatively poor exposure conditions. Petrological features and deformation structures of granites at outcrop level only rarely reflect the 3D geometry of plutons at depth. Granites are detectable on gravity maps as negative anomalies due to their lower density compared with the surrounding denser country rock. High-resolution gravity data and modelling of granites reveal the subsurface shape of plutons and along with structural field evidence enable us to interpret the tectonic setting

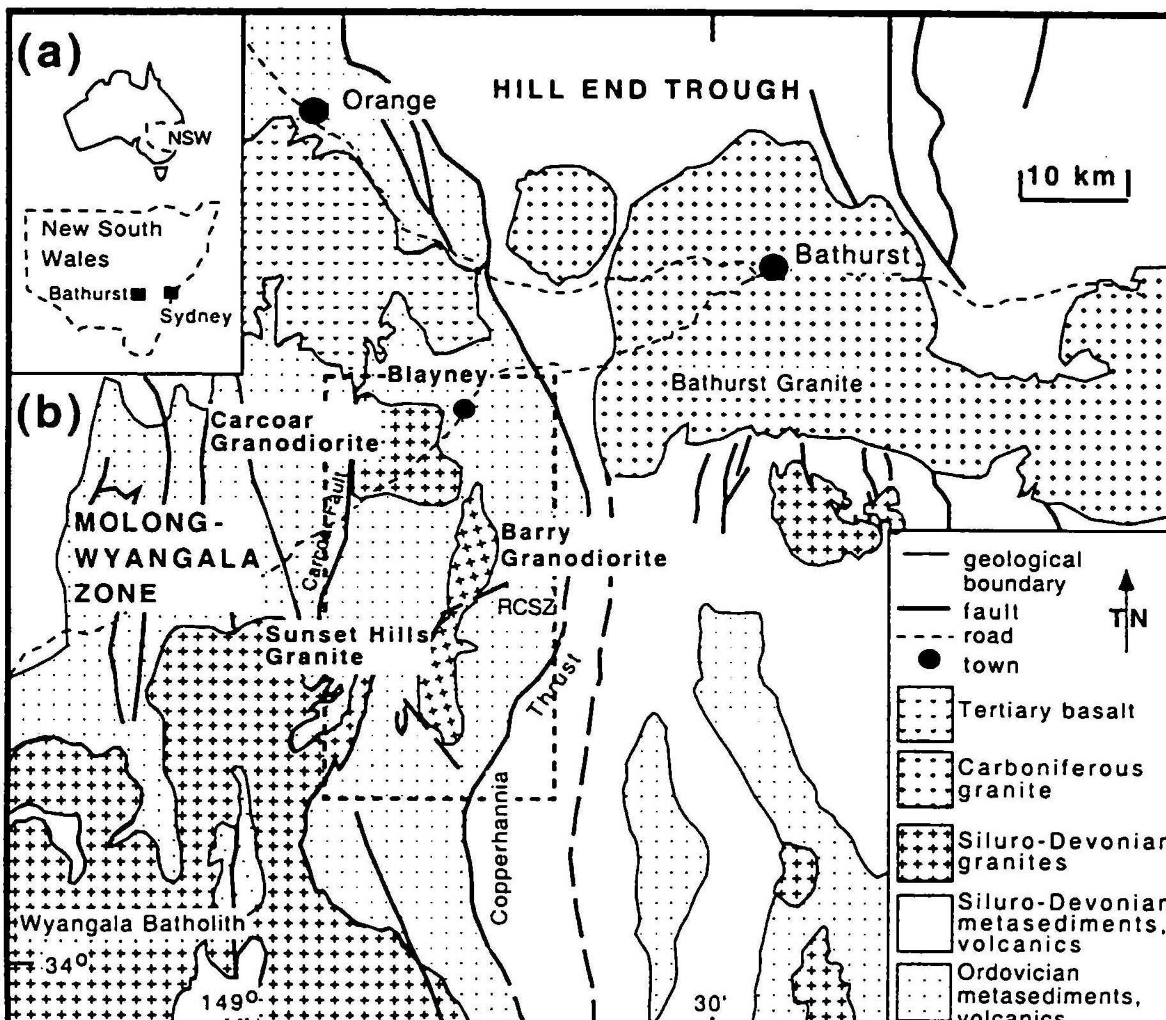

Fig. 1 - Simplified regional geology of the study area.

during magma emplacement. In this study, we show an example of three granites with contrasting emplacement modes, intrusion geometry and deformation style. Using high-resolution gravity and detailed structural data we demonstrate that the nearly coeval magma emplacement occurred during both transtensional and shear deformation.

This study focused on three granitoids in the Molong-Wyangala Zone (Fig. 1). The weakly deformed I-type granodiorites of Carcoar and Barry, and the moderately deformed S-type granite of Sunset Hills in the northern Lachlan Fold Belt intruded Ordovician, mainly volcanic and meta-sedimentary rocks during extension following the Benambran phase of the Lachlan Orogeny. The Carcoar Granodiorite in the north shows a rather large tabular body bounded by the Carcoar Fault in the west and the Ammerdown Fault in the east. The narrow, north-south elongated Barry and Sunset Hills granitoids both parallel the Ammerdown Fault or its extension to the west and the Copperhannia Thrust to the east. However, evidence is lacking to constrain the spatial relationship between the plutons and faults and the timing of their kinematics.

Detailed gravity surveys provided data to produce highly resolving (0.5-1 km) Bouguer gravity maps which were used for the modelling of the Carcoar, Barry and Sunset Hills granitoids. The Bouguer gravity map of the Carcoar Granodiorite is characterised by two, roughly north-south striking, negative anomalies with strong gradients and maximum magnitudes of 25 mGal which extend along the granite margins in the west and the east, respectively. In the central part a broad, meridionally striking gravity high

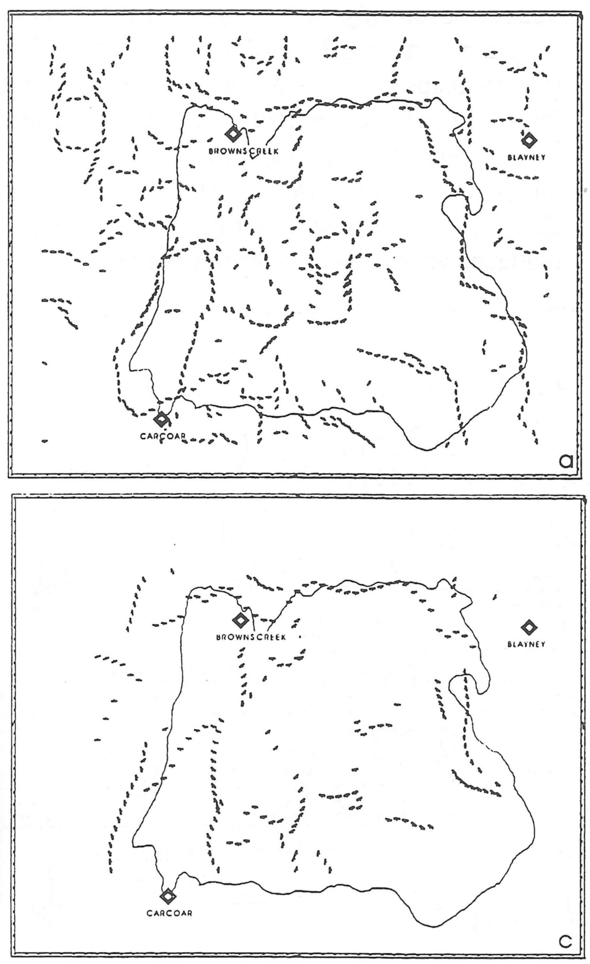

Fig. 2 - Linsser indications (tick marks) of the Carcoar Granodiorite (outlined) at levels a/ 0.5 km, b/ 1 km, c/ 1.5 km and d/ 2 km.

(<15 mGal) divides the Carcoar Granodiorite gravity anomaly into western and eastern segments. The 2.5D density models across the Carcoar Granodiorite show maximum basal depths of 5 km along the margins and 2-3 km in the central part. The strong gradients along the granite flanks in the west and east indicate fault-related density contrasts between the granodiorite and the volcanic host-rocks ($2.67/2.85 \times 10^3$ kg.m^{-3}) which dip steeply (60-70°) towards east on the western side or west on the eastern side. Both marginal anomalies merge in the southern part of the pluton and form a broad basin with an average depth of 5 km. In contrast to the northern margin which is bounded by moderate east-west striking gradients indicating a gently south-dipping contact between the granodiorite and the Blayney volcanics, the southern margin shows a relatively smooth gradient. We therefore assume that the Carcoar Granodiorite extends further to south underneath the adjacent Coombing Formation.

In order to map faults by gravity detailing we used the Linsser filtering (Linsser 1967, Trzebski et al. 1997) which generates a/ a tomography of the Bouguer gravity field at selective depth levels and b/ a gradient analysis using variable densities. The gravity tomography shows horizontal slices of the Carcoar Granodiorite in depth levels between 0.5 and 4 km and is largely consistent with the 2.5D density models. The gradient analysis which discloses density contrasts caused by geological bodies, e.g. magmatic intrusions, salt diapirs, and/or tectonic faults, shows three dominant lineament systems: a/ north-south, b/ east-west and c/ southwest-northeast structures (Fig. 2 a-d). The north-south lineaments are consistent with the Carcoar Fault, Mount Davis Fault and Ammerdown Fault which are members of the meridional fault system which occurs widely in the Molong-Wyangala Zone. The subsidiary east-west lineaments may be related to the extensional pull-apart formation in the Silurian which probably accompanied the passive emplacement of the Carcoar Granodiorite. The southwest-northeast lineaments, e.g. south of the Browns Creek Mine (Fig. 2 a, b), are similar in orientation to the Reedy Creek Shear Zone identified by Lennox et al. (in press) between the Barry and Sunset Hills granites. This shear zone may have aided granite emplacement and deformation during the Kanimblan phase of the Lachlan Orogeny.

The Barry and Sunset Hills granites both show north-south striking, negative anomalies with maximum magnitudes of 17 mGal for the Barry Granodiorite and 13 mGal for the Sunset Hills Granite. The Barry Granodiorite anomaly is bounded by steep gradients along the eastern pluton margin, whereas the Sunset Hills Granite shows a rather symmetrical anomaly with smooth gradients on either side. The 2.5D modelling of the Barry Granodiorite yielded a wedge-like body with steep (~60°), west-dipping flanks along the east-margin and moderate (~35°), east-dipping flanks along the west-magin. The maximum basal depths range between 3-4 km and occur along the east-margin of the pluton. In contrast, the Sunset Hills Granite is a symmetrical body with equally dipping flanks (~40°) and maximum depth of 3 km in the centre of the pluton. The geometry of the gravity anomaly and the subsurface shape of the Barry Granodiorite suggest a link to the Ammerdown Fault extending along the east-margin of the pluton.

The gravity models and structural data suggest that the Carcoar Granodiorite intruded transtensional faults which were formed due to pull-apart movements related to the oblique opening of the adjacent Early Silurian Hill End Trough. In contrast, the Barry Granodiorite and the Sunset Hills Granite show some evidence for emplacement via oblique shear zones between the precursors of the Ammerdown Fault and Copperhannia Thrust.

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Geodynamic Modelling: Deformation and Fluid Flow in 3-Dimensional Basins

P. Upton, A. Ord, & B. E. Hobbs

CSIRO Exploration and Mining
Australian Geodynamics Cooperative Research Centre

Basins throughout the globe are often the site of mineral deposition, with deposition and concentration of the minerals occurring both during and after formation of the basin. We show some initial coupled mechanical/fluid flow models of a three dimensional basin. The models develop anticlinal structures under compression and suggest that the location of the anticlinal axis is controlled by the presence of the half-graben and its fill of weaker rocks. Fluid flow occurs within the basin and is a function of the hydraulic properties of the basin-fill and other rock units. Modelling of deformation and fluid flow in three dimensions provides a powerful tool to other project areas of the AGCRC, offering the capability to test conceptual models and scenarios of deformation, fluid flow and mineral deposition.

Introduction

Crustal lows on the Earth's surface are filled by the processes of erosion with materials deposited by wind, rivers and ocean currents. The shape, size and final geometry of the resulting sedimentary basins are determined by geodynamic processes both during and after the formation of the basin. Basins and basin-fill are important to Earth scientists as an information source and also because they contain most of the fossil fuel, ground water resources and many of the mineral resources of this planet. Focussing on mineral resources, we find that many of the world's largest ore deposits are situated in basins or in the remains of highly deformed basins. Examples include the Wittwatersrand gold deposits, Mississippi Valley Type deposits, and the intracontinental basin-fill of the Palaeoproterozoic Willyama Supergroup hosting the giant Broken Hill Pb-Zn-Ag ore body. Such mineral deposits have been concentrated into a specific part of the basin through the processes of deformation, fluid flow, chemical reaction and thermal transport. This paper addresses two of these coupled processes, deformation and fluid flow and discusses the potential application of these models and modelling techniques for mineral systems of southeastern Australia.

Many of these systems have been modelled in two dimensions (e.g. Upton & Ord 1996, Ge & Garven 1994) but increasingly it is being recognised that three dimensional models are required to represent these systems realistically. Most deforming systems have some degree of obliquity and this can be significant for the deformation and fluid flow patterns that develop (Koons 1994). This paper illustrates coupled deformation/fluid flow models of basins in three dimensions and discusses the implications of these models and modelling techniques for mineral systems of eastern Australia.

3D geodynamic modelling

Within the deforming crust, deformation and fluid flow are inextricably linked, as are fluid flow and the deposition of minerals. Thus understanding the coupling between fluid flow and deformation is critical to our understanding of mineralisation. We have been modelling coupled deformation and fluid flow in two dimensions for a number of years (Ord 1991, Upton & Ord 1996, Ord & Oliver 1996). In particular, these models have shown that, regionally, permeability contrasts and the amount of strain are significant in determining the fluid flow regime that develops. Low permeability contrasts and low strains lead to pervasive regional flow. Higher permeability contrasts and increasing strain result in focussing of fluid flow, particularly for highly dilatant materials.

We are now beginning to advance these techniques into three dimensions. As well as being able to consider the issues of permeability contrasts, material properties and localisation of strain, as we can do with our two dimensional

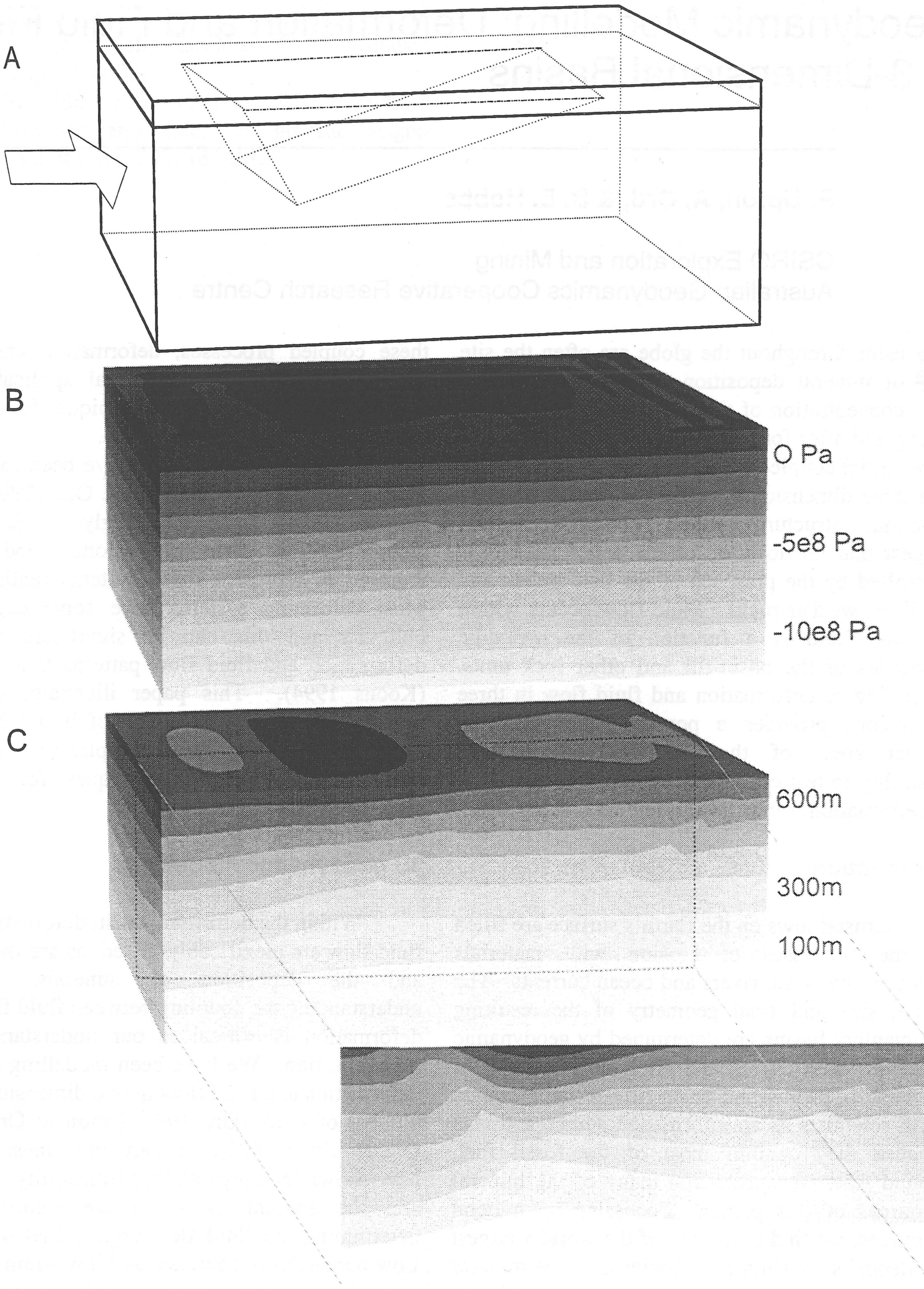

Fig. 1 - Mechanical model. A: The outline of the model with a half-graben of basin-fill within stronger basement rocks. These are overlain by 4 km of cover. The top surface of the half-graben is 60 km by 60 km and it reaches a maximum depth of 15 km. The model has been pushed from one side to approximately 4% shortening. B: Contours of vertical stress after 4% shortening. C: Contours of vertical displacement after 4%. A maximum has formed above the deepest part of the half-graben and, as seen more clearly in the section through the centre of the half-graben, an anticlinal structure is being formed with its location controlled?? by the half-graben.

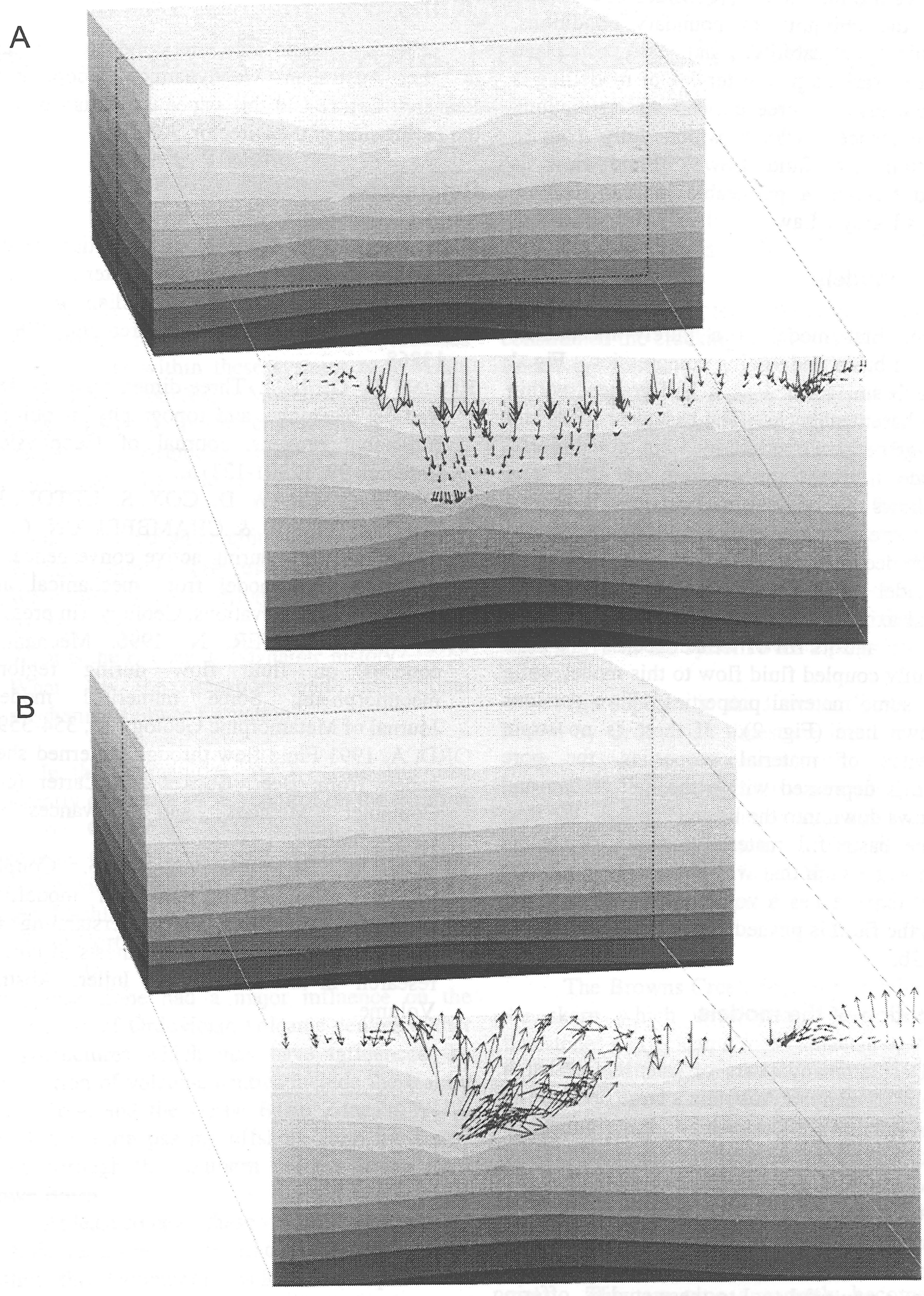

Fig. 2 - A coupled mechanical/fluid flow model with the same geometry and boundary conditions as the model shown in Fig. 1. A: Pore pressure contours and, in the section through the centre of the half-graben, Darcy fluid flow vectors. Pore pressure is depressed within the half-graben and fluid flows downward. The main driving force for fluid flow appears to be topographic effects. B: Pore pressure contours and fluid flow vectors for a model in which the basin fill has a strain dependent dilation angle. Volume decreases in the basin and fluid is pushed up and out of the basin.

models, we are now able to consider new factors such as the obliquity of boundary conditions, anisotropic permeability, and out of plane variation of various parameters. Our modelling is carried out using a three dimensional continuum, finite difference package which fully couples deformation and fluid flow. Fluid flow is modelled through a permeable, porous medium and obeys Darcy's Law.

Example models

Our first model is a purely mechanical model of a basin undergoing compression. Fig. 1 shows a basin, formed as a half-graben, within stronger basement rocks. The basement rocks and the half-graben are overlain by 4 km of sediments. The model has been pushed from one side. The figure shows that an anticlinal structure is formed with the greatest amount of uplift concentrated above the deepest part of the half-graben (Fig. 1c). This model suggests that the location of the anticlinal axis is controlled by the presence of the half-graben and its fill of weaker rocks. We have added fully coupled fluid flow to this model while varying some material properties. Two versions are shown here (Fig. 2). If there is no strain dependence of material properties, the pore pressure is depressed within the half-graben and fluid flows down into the basin (Fig. 2a). We then gave the basin fill material a strain dependent dilation angle such that with increasing strain, the material experiences a volume decrease. As this occurs, the fluid is pushed out of the basin as seen in Fig. 2b.

Application of the models

Despite many years of intensive research, the origin of many of Australia's large ore deposits remains unknown. The AGCRC has a number of projects aimed at unravelling the evolution of these deposits, including Broken Hill, the gold deposits of central and western Victoria and the metallogeny of the Lachlan Fold Belt. Modelling of deformation and fluid flow in three dimensions provides a powerful tool to these studies, offering the capability to test conceptual models and scenarios of deformation, fluid flow and mineral deposition. Such modelling has already been carried out for the Mount Isa Tectonic Synthesis in two dimensions (Upton & Ord 1996) and the time is ripe for the extension of this type of modelling into three dimensions.

Acknowledgments

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Lachlan Fold Belt Metallogeny: Systems, Architecture, Reservoirs, Processes, Dynamics

John L. Walshe

Australian Geodynamics Cooperative Research Centre
Division of Exploration and Mining, CSIRO, Nedlands, WA

Increasingly metallogenic studies are looking to understand mineral systems and the processes that operate within these systems to generate high quality resources. Modelling of mineral systems aims to place constraints on these processes. A beginning point is to ask five questions about the system:

- What is the size and architecture of the system?
- What is nature of fluid reservoirs in system?
- What mechanisms drive the fluids in the system?
- What is the P-T and geodynamic history?
- What are the transport and depositional mechanisms of ore formation?

In the Tasmanides, WNW cross-structures apparently exerted a strong control on the location of the Cambrian VMS system in western Tasmania, the slate-belt gold system in Victoria, the Ordovician-Silurian Cu-Au system in the eastern Lachlan of NSW and the Carboniferous Au system in North Queensland.

In the eastern Lachlan, the Lachlan Transverse Zone had a major influence on the distribution of Ordovician volcanic centres. Other cross-structures which may have influenced the distribution of volcanic centres include the Hunter River Zone and the Lorne Basin Zone, a WNW oriented feature passing offshore from the Lorne Basin through the southern margin of the Lord Howe Basin.

At least some of these volcanic centres acted as fluid reservoirs. The Endeavour 26N deposit within the Goonumbla volcanic complex was deposited from oxidized magmatic fluids focussed from the magmatic chamber beneath the complex (Heithersay and Walshe, 1995). What was the focussing mechanism and what was the trigger? One clue may be the Endeavour Linear, a north-trending feature defined from the magnetic image of the complex and the distribution of the E22, E26N, E28 and E48 deposits. Right-lateral shear on the WNW cross-structures may have constrained the cracking of this reservoir along the Endeavour Linear.

Reservoirs of reduced fluids were present during the Late Ordovician and Early Silurian within and/or subjacent to the Lachlan Transverse Zone. The Au skarns in the Junction Reefs area (Sheahan Grants, Cornishmens and Frenchmans; Gray et al., 1995) and the Cu-Au skarn at Browns Creek formed from reduced fluids. The age constraints on the deposits (Perkins et al., 1995) indicate that reduced fluids, whatever their origin, were active in the system over a period of at least 20 Ma.

The deposits in the Junction Reefs area are hosted by Ordovician limestone interbedded with chert. Gold is associated with a pyrrhotite-arsenopyrite-carbonate-chlorite assemblage that, in part, developed as a retrograde assemblage on prograde skarn assemblages. The deposits are distributed around the Late Ordovician Junction Reefs stock and are typical of reduced Au-skarn deposits associated with oxidized magmatic systems.

The Browns Creek deposit is a Silurian Cu-Au skarn which developed within Ordovician limestones and volcanic rocks adjacent to the Long Hill Granodiorite, a small intrusion on the northwest corner of Carcoar Granite. The dominant skarn asssemblages are wollastonite-garnet skarn and garnet-pyroxene-epidote skarn. The sulphides, mostly bornite and chalcopyrite, and gold were deposited at a retrogressive stage. Some gold occurs with a pyrrhotite-arsenopyrite assemblage within altered Ordovician volcanic rocks. This ore type apparently becomes more common at depth. The silicate assemblages within the wollastonite skarn and the sulphide assemblages within the volcanic rocks clearly indicate reduced conditions.

The origins of the reduced fluids and their relationship to the oxidized magmatic fluids within the eastern Lachlan and elsewhere are problematical. Kjolle et al. (1994) suggested Au and Cu were leached from the Ordovician volcanic rocks to form the deposit at Browns Creek. However, the redox conditions suggest some additional complexity. Isotopic studies on the Sheahan Grants deposit give no hint of the ore fluid having equilibrated with the Ordovician sedimentary sequences. The S, C and Pb isotope signatures indicate magmatic fluids or magmatic source rocks (Gray et al, 1995; Carr et. al, 1995). It may be that these reduced fluids are the products of sub-solidus reaction with deep-crustal source rocks and that the Lachlan Transverse Zone tapped these deep-crustal reservoirs.

Both the Long Hill Granodiorite and Carcoar Granite are non-magnetic, ilmenite and hornblende-bearing granites. The Long Hill Granite has an ε_{Nd} signature of 0 - 1 which is at the positive end of the range for I-type granites and significantly different from the values for the S-type granites. An explanation of these reduced I-type granites in the Lachlan Transverse Zone is that the I-type magmas were modified by interaction with reduced fluids from these deep crustal reservoirs either in their source regions or along the ascent paths.

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Lithospheric Structure and Stress in SE Australia

Y. Zhang[1], E. Scheibner[2], P. Morgan[3], B. E. Hobbs[1], A. Ord[1] and S. J. D. Cox[1]

1 - AGCRC, CSIRO Exploration & Mining, Nedlands WA 6009
2 - AGCRC, CSIRO Exploration & Mining, North Ryde NSW 2113
3 - Information Sciences Faculty, University of Canberra, ACT 2601

The Australian continental lithosphere has been evolving as a separate major continent since the breakup of Gondwanaland in Jurassic-Cretaceous time (Veevers, 1984, 1990), which was accompanied by a series of mantle convection-related processes such as rifting, divergent plate motions and sea floor spreading. These processes led to the formation of passive margins surrounding the Australian continent, with the eastern Australian upper-plate passive margin setting developing behind the active plate margin of the Southwest Pacific (Lister & Ethridge 1989).

Absolute plate motion is oriented approximately N-S in SE Australia over the period Miocene-present. Hence one might expect high horizontal stresses oriented N-S. However, regional stress data (e.g. Denham et al., 1979; Enever et al., 1990; Zoback, 1992) indicate that the contemporary stress field in SE Australia is characterised by high horizontal compressive stresses (~50-100 MPa) oriented predominantly in an E-W direction (only locally in N-S direction). This stress regime seems to have been present in SE Australia at least back to the Miocene (30 million years) as demonstrated by displacements on N-S striking reverse faults. This means that the stress pattern of SE Australia cannot be explained simply by considering plate motion-related boundary forces. In this study we aim to explore what is behind the stress regime of SE Australia and how this is related to the regional geology and tectonics.

A Model for the regional lithospheric structure

Scheibner et al. (1991a) incorporated the idea of the upper-plate passive margin in the construction of the Broken Hill-Sydney-Tasman Sea Global Geoscience Transect, and further suggested a denser mantle wedge beneath the edge of extended eastern continental lithosphere (see also Scheibner 1992, Zhang et al. 1996, 1998). Based on the structural framework outlined in this transect, we have attempted to refine lithospheric structure for SE Australia by modelling gravity and geoid. In this approach, gravity and geoid anomalies are calculated for E-W profiles across the passive margin, and are compared with observed gravity and geoid anomalies. A close match between the calculated and observed values is achieved by adjusting the geometries and densities of the layers in the studied profiles. This approach enables us to define a lithospheric structural model for SE Australia, compatible with gravity and geoid observations, geological arguments and density distributions constrained by petrological observations. The model is characterised particularly by upper-plate passive margin geometries, a lithosphere with a variable thickness (about 75-120 km), a thinned continental lithosphere near the continental/oceanic boundary (COB), a dense mantle wedge with particular geometrical configuration beneath the thinned continental margin, and various density contrasts between neighbouring layers (e.g., between the oceanic and continental lithosphere).

Modelling stress on vertical 2D transects

Two dimensional finite difference models have been constructed to simulate the mechanical behaviour of the geometry and density structures of the E-W 2D transects constrained by gravity and geoid modelling. These models also involve the use of a set of mechanical parameters and the assumption of initial stress status and boundary conditions.

The displacement results demonstrate that material creep movements are dominantly towards the continent, with highest uplift located at the Great Dividing Range (GDR) and subsidence located in the oceanic lithosphere. This kinematic movement pattern is dominantly driven by gravity relaxation associated with the geometry-density configuration of SE Australia.

The stress results indicate that high horizontal compression, expressed as negative (σ_{xx} - σ_{yy}) values, could occur in the bulk of the modelled 2D section purely due to regional geometry-density structures. High vertical compression (deviatoric extension in the horizontal direction) is only observed in the shallower locations below topographic elevations (e.g., the GDR) and at the coast.

The projection of this stress pattern into the 3D space of SE Australia means that the regional maximum compression should be roughly horizontally E-W oriented, essentially in line with the bulk of the measured stress orientations in the region (Denham et al. 1979; Enever et al. 1990); this is based on the consideration that the variation in lithospheric geometry is negligible in the N-S direction in comparison to the E-W direction and the geometry is essentially prismatic perpendicular to our 2D transect. The mechanism behind this is probably that the dense oceanic lithosphere and mantle wedge induce gravity relaxation body forces pushing the continent (expressed as the continent-ward material creep movement). Any EW horizontal compressive remnant stress or any compressive plate boundary force from the east boundary could further enhance this EW compression dominated stress regime.

Plate stress model incorporating boundary forces

Another way to study the stress regime of SE Australia is to model the whole Australian plate on the horizontal plane. We have constructed a new mechanical model of the Australian plate using plate boundary forces as constraints. The model also incorporates the latest ideas and data about the tectonics of the Australian plate such as the existence of the thrusting convergent boundary between the Australian and Indian plates. The plate is simulated as two major parts, that is, the oceanic and continental parts. The geometries for the plate boundaries are mainly determined according to the world plate tectonic framework of Scheibner et al. (1991b), but modified according to new data. The plate boundary forces used in the model include: ridge push along active ridge boundaries; slab pull along active subducting boundaries; and compressive forces along collision boundaries (PNG), the convergent boundary between the Australian and Indian plates and the strike-slip convergent boundary (New Zealand). Plate basal tractions are not considered here.

Predicted stress orientations in the plate are locally consistent with observations, such as oblique maximum compressive stresses to the PNG collision zones and the New Zealand strike slip fault boundary. The maximum compressive stresses in the major part of the continent are dominantly oriented from N-S to NE, reflecting the extensive ridge push from southern ridge boundaries, the compressive force at the PNG collision zones and the slab pull along most of the eastern boundary.

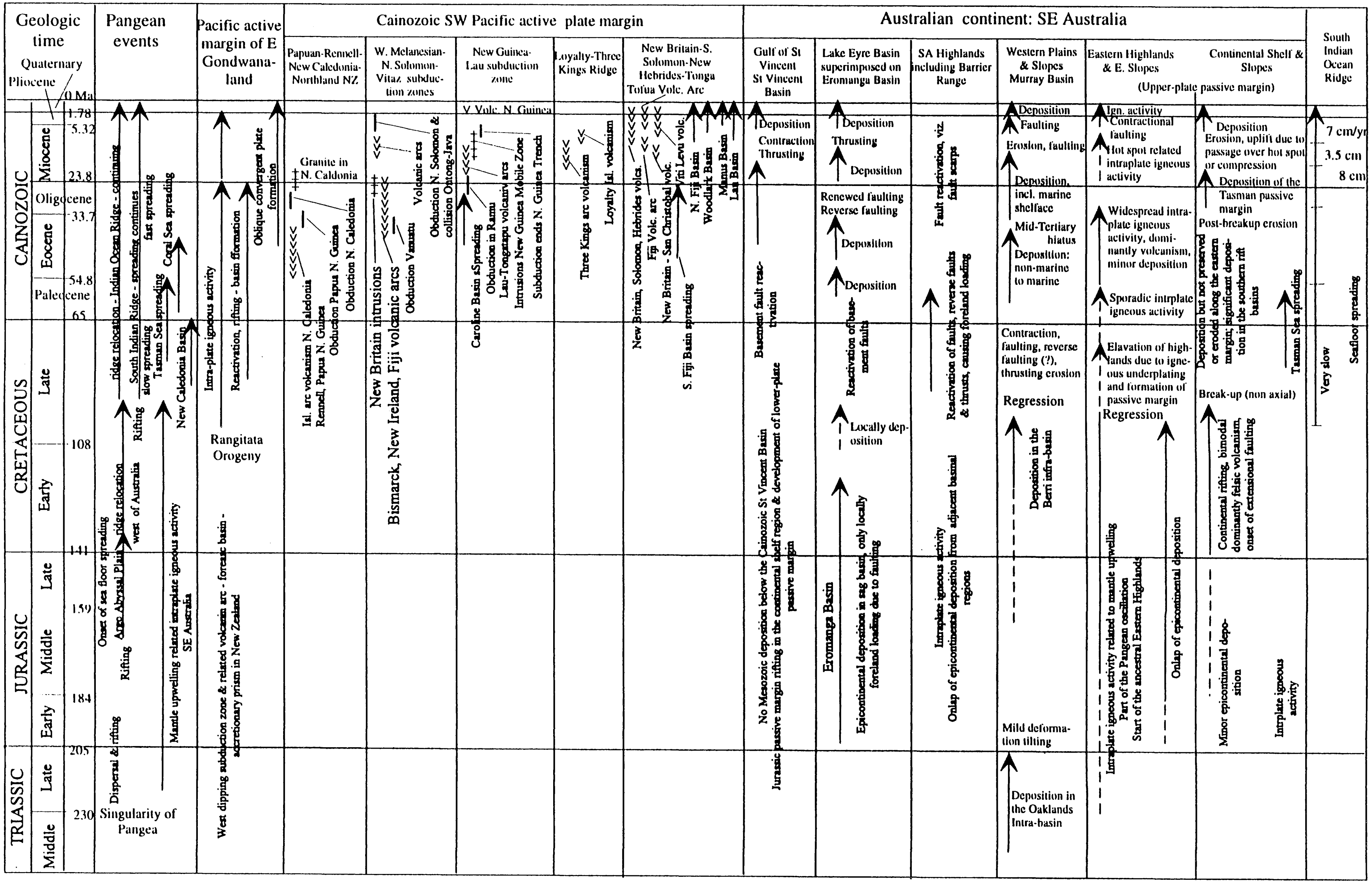
However, a problem area is SE Australia where the predicted stresses from this model do not agree with the observed stresses; the same problem is found in previous studies (e.g. Cloetingh & Wortel 1986, Coblentz et al. 1995). In other words, one of the conundrums of the Australian Plate, viz. the dominantly east to west oriented stresses in eastern Australia, cannot be predicted by the computation. Further modelling demonstrates that the east-west oriented maximum compressive stresses can only be reconstructed in part of the Australian continent (e.g. SE Australia) if slab pull forces along the eastern boundaries are replaced by compressive forces. This may be considered to simulate the gravitational body forces associated with the passive margin geometries/densities or the remnant in-plate forces or unknown plate boundary forces (also see Zhang et al. 1996, 1998).

Continent stress models constrained by GPS velocities

An alternative constraint on the Australia plate model is to use plate motion velocities at plate boundaries. GPS technology offers one such possibility, which has been recently used to monitor the motion of Australian plate (e.g. Morgan et al. 1996). Because the measured GPS velocities contain the information of not only plate translation/rotation but also relative internal movements, they offer a very promising means to determine intra-plate deformation and stress distribution. The idea is that if the true material movements along plate (continent) boundaries are known, we can use such movements (velocities) as boundary constraints in a mechanical model to simulate the internal deformation field and therefore determine the stress field. This represents a new approach to plate scale mechanical modelling for the Australian plate.

The existing GPS velocity data (Morgan et al. 1996) is mostly located on land for the

Table 1. Post - orogenic development of SE Australia



Australian continent with only a few data points located near the margin of the Australian plate (PNG, New Zealand). Based on the scope of the present data set, we have constructed a mechanical model of the Australian continent confined by the coast line, using the GPS velocity data near the seaboard to define (interpolate) velocities along model boundaries.

In contrast to all the models involving plate boundary forces, the stress results of this model interestingly reproduce the E-W to NE high compressive regional stress pattern for eastern Australia. The orientation of major horizontal compression seems to vary further inland so that NE compression dominates. The normalised GPS velocities of Australia (after elimination of the rigid translation portion of the velocities) show that the east seaboard is moving towards the west, that is, there seems to be a contraction between east and west Australia. This material movement pattern is also consistent with the continent-ward material movement predicted by our 2D models of vertical transects. This probably explains why east-west compression occurs in east Australia.

Differences between the GPS velocity resultant stress and the observed stress have been observed in some other parts of the continent. This could be due to insufficient coverage of GPS data along the margin of the continent. We now have new GPS data being processed for west Australia and Queensland. This will allow us to build more rigorous mechanical models of the continent and produce an Australian stress map.

Temporal post-orogenic development of SE Australia

After the last orogenic collisional accretion on the mainland (mid-Triassic, Gympie Terrane) and at the Pacific active margin of Gondwanaland (Early Cretaceous Rangitata Orogeny, the New Zealand-New Caledonia region), the geologic development of SE Australia seems to be an integral part of the Pangean oscillation, which involved Jurassic-Cretaceous rifting, Late Cretaceous breakup and formation of a passive margin (Table 1). These events were preceded by mantle upwelling as evidenced by Late Triassic-Jurassic intraplate igneous activity mainly south of the Darling River Lineament, which caused the rise of ancestral Eastern Highlands due to igneous underplating. The region of the Great Australian Basin subsided, either due to basin sag as a compensation for uplift in the southeast, or due to mantle downwelling. The Late Cretaceous regression in this basin and generally in Australia is anomalous compared to other continents which experienced widespread eustatic transgressions. This general elevation of Australia is not yet convincingly explained and might have had multiple causes like: 1) termination of B-subduction in the New Zealand region leading to collision and causing contraction further west; 2) igneous underplating causing isostatic rise; 3) general change in mantle convection; etc.

By Early Cretaceous times a volcanic rift was present from Queensland down to a triple point east of Gippsland Basin. These thermal events caused weakening of the lithosphere and formation of deep, west dipping detachments or a more complex interplay of décollements and detachments which led to thinning of the lower crust and elevation of upper mantle. Further lithospheric extension eventually led to upper-plate passive margin formation along eastern Australia and non-axial breakup at about 84 Ma ago. Seafloor spreading in the Tasman Sea terminated around 54 Ma ago. The oceanic crust in the Tasman Sea subsided significantly after about 30 million years owing to thermal decay. Similarly the upper-mantle wedge under the edge of the upper-plate passive margin, also became thermally mature (denser). This means that probably already at about 54 Ma (Eocene), perhaps even earlier (end of Paleocene), the mantle wedge and the oceanic lithosphere started to exert continent-ward gravity relaxation-induced compressive stress (Zhang et al. 1998).

Theoretically the intensity of compression should have increased in proportion to progressively thermally maturing lithosphere. This can explain: 1) the Paleocene-Eocene non-deposition or erosion ('post-breakup erosion') along the continental shelf and slope next to the Tasman Sea; 2) subsidence due to flexure (e.g. Murray Basin); 3) reactivation of old basement faults causing foreland loading and basin subsidence (e.g. Murray Basin. Lake Eyre Basin); 4) rise of the South Australian Highlands, etc. During the Eocene the collisional accretion of volcanic arcs and obduction of ophiolitic nappes in New Caledonia and Papua-New Guinea might have contributed additional compressional forces. The subsequent Oligocene to Holocene development of the SW Pacific active margin had a rapid pace and the poor resolution of events affecting the mainland make it difficult to attempt a correlation at this stage. However, the Miocene collision of the Ontong-Java Plateau, obduction of ophioltic nappes in the Solomon region and contractional reactivation of basement faults on the mainland might be related.

In addition to the continuous gravitational relaxation-induced compression, episodes of plate margin-induced compression and extension have affected the region. Further forces were caused by fast and slow spreading along the South Indian Ocean Ridge; during fast spreading (Oligocene-Miocene) deposition occurred along the passive margin and epicontinental basins. During slow spreading (Late Miocene) contractional deformations are widespread and erosion occurred at the passive margin and within the basins.

At present the plate convergence along Tonga-Kermadec trench involves major roll-back of the Pacific Plate which causes lithospheric extension and rotation of the frontal volcanic arc away from the main Australia Plate (based on GPS data). Extension is also present in the Woodlark and Manus Basins and the east dipping Solomon and New Hebrides trenches, as the north dipping New Britain trench exerted slab pull. Oblique transpression/transtension characterises the Papua-New Guinea region where the Australian and Pacific Plates converge. Partitioning of plate convergence makes it difficult the calculate the stresses involved as the GPS data indicate that the solutions appear to represent the least mechanical work, least resistance. More numerous GPS data might be the answer to these problems.

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