Crust-Mantle Interaction and the Formation of Granitic Terranes in Eastern Gondwanaland

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Introduction

The dispute over the origin of granite in the Tasman Orogen and in particular the Lachlan Fold Belt (Fig. 1) has been considerable and encapusulates debate repeated in many other global granitic terranes (White and Chappell ,1988; Chappell and White, 1974, 1992; Collins, 1998). Are granites essentially an intracrustal phenomenon? Or, do they involve a mixture of crustal and mantle sources? A second issue in the Tasman Orogen questions the extent to which granites are directly related to subduction processes?

Since the end of the Proterozoic the eastern Pacific margin of Gondwanaland has formed a distinctive tectonic realm. Geological processes were dominated by the negative buoyancy and subduction of the Pacific lithosphere which being old and cold caused eastwards slab roll-back and retro-arc extension of the continental margin. Ridge -push stresses were often not transmitted to the continental margin. Throughout the Phanerozoic, the Gondwananan continental margin was regularly subjected to extensional or transtensional stresses, leading to asthenospheric upwelling and decompression and mantle melt production. These extensional complexes were up to > 1000 km "inboard" of concurrent subduction complexes and their associated magmatic arcs.

Regional Geological Setting

The Australian sector of this margin (Fig. 1) forms the granite-rich Tasman Orogen whose orogenic history spanned from the Cambrian to the Mesozoic (Coney et al., 1990). By contrast with the Andean margins of the eastern Pacific, this subduction margin owes a great deal of its geological history to rifting and repeated phases of "inboard" crustal extension, followed by rift closure.

The belt is continuous from northern Queensland across Antarctica via the Transantarctic Mountains to the southern African, Cape Fold Belt. Initial convergent deformation in this zone commenced in the Early to Middle Cambrian (Foden et al., 1999) and continued until the Triassic. Eastern Australia's Tasman Orogen with its associated felsic magmatic suites can be considered in three main tectonic divisions:

•The Cambro–Ordovician "Delamerian" Belt (DFB) lying directly to the east of the Precambrian craton and host to granitic rocks and felsic volcanics with ages in the range ~520 Ma to 480 Ma. This orogen underwent deformation from the early middle Cambrian (514Ma) through to the early Ordovician (~490Ma). This Cambrian activity is concurrent with subduction-related arc volcanism ~1000 km to the east in the Takaka Terrane in New Zealand (Fig. 1) (Munker & Cooper, 1995).

•The Lachlan Fold Belt (LFB) occurs to the east of Delamerian Orogen and to the south of the Permo-Triassic Sydney Basin. This terrane is characterised by widespread Late Cambrian to Early Silurian flysch and is intruded by dominantly Late Silurian – Devonian granites. Ordovician granites also occur in central western NSW and as recently as the Early Carboniferous in the North East. This terrane was compressed and extended in a series of localised fold and basin forming events ranging in age from Early Silurian to Early Carboniferous. An issue very relevent to the origin of granites and the subject of major continuing debate in the LFB, is the question of the nature of the basement beneath the widespread flysch blanket. Is it underlain by older Precambrian rocks, or simply floored by late Neoproterozoic to Cambrian oceanic crust?

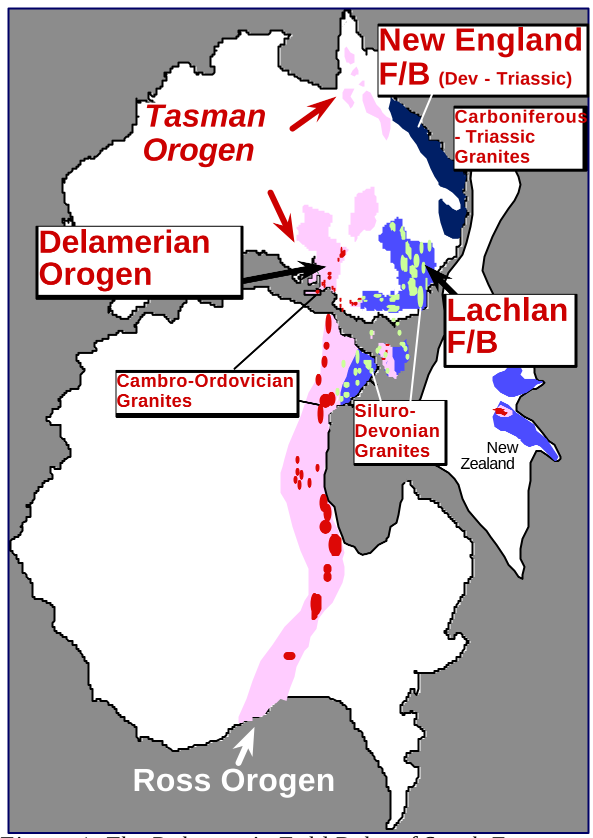

Figure 1. The Palaeozoic Fold Belts of South Eastern Gondwana

•The New England Fold Belt (NFB) occurs to the north of the Sydney Basin and has a Devonian to Late Triassic history. Like the Lachlan, the New England Fold Belt is characterised by periodic phases of convergent orogenesis punctuated by extensional intervals (Holcombe et al., 1997). Widspread orogenesis occurred in the Late

Devonian to Carboniferous ("Kanimblan Orogeny") and during the Mid Permian to Mid Triassic (Hunter-Bowen Orogeny). A major extensional phase of basin formation occurred in the Early Permian. Granitoid intrusion tends to have taken place as syn- to late- or post-tectonic activity, first during the Late Carboniferous to Early Permian and then in the Late Permian to Mid Triassic

In each of these three fold belts, evidence for the direct association of granite production with subduction is often (but not always) lacking. Felsic magmatism occurs during convergence and continues during the post-tectonic stages. Mafic magmatism occurs in the preconvergent extensional phase, and continues weakly during the convergent stage. In the Ross-Delamerian Orogenic Belt, the cessation of deformation is accompanied by abrupt uplift and by the onset of bimodal magmatism accompanying molassic sedimentation, suggesting a sudden change in crustal buoyancy. The convergent stage appears to localise initial deformation at the thermally weakened axes of prior rifts and following early recumbent fold-thrust dominated thickening, shortening proceeds by periodic phases of localised upright folding.

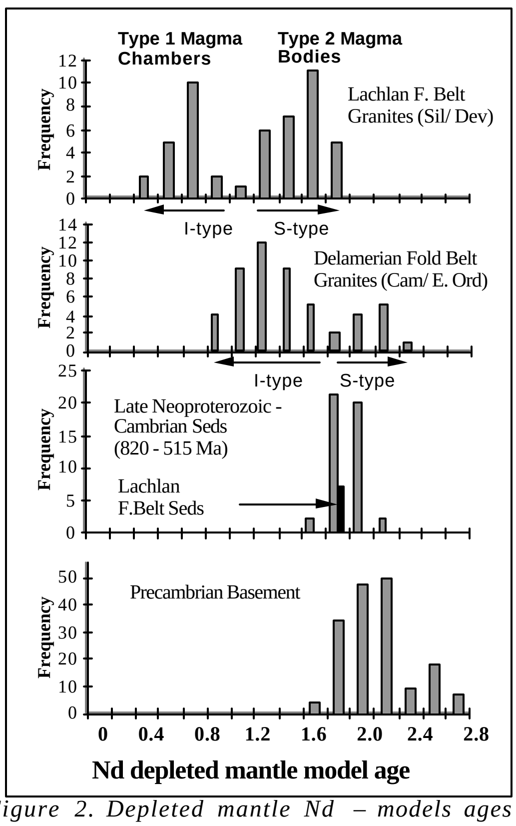

Figure 2. Depleted mantle Nd – models ages for Delamerian Fold Belt (Cambro-Ordovician) and Lachlan Fold Belt (Siluro-Devonian) Granites and for Late Precambrian to Early palaeozoic sediments and older basement.

Granite Sources

Chappell and White have established the Lachlan Fold Belt as one of the most comprehensively studied granite terranes in the world. Their data-set is mainly one of major- and trace-element analyses of whole-rocks. Their restite model (Chappell, 1997, 1996, 1984) regards granites as largely of intracrustal origin and views many granite suites (but not all) as isothermal mixtures of crystalline residues and near eutectic partial melts. This model regards granites as substantial samples of their source regions and thus as close geochemical reflections of those sources. In recognising two geochemically distinctive suites of granites (I-types and S-types) White and Chappell (1988) and Chappell and White (1974, 1992) concluded that two distinct sources existed. In their view S-types resulted from melting of the Ordovician/ Silurian flysch and I-types, although more problematic, were interpreted to be derived from melting a deep crustal suite of broadly intermediate igneous rocks of Precambrian age.

The alternative model emphasises the role of mafic magmas in both the advection of mantle heat to the crust and in mass transport across the Moho. In the Delamerian Fold Belt (Sandiford et al., 1993; Foden et al., 1999) this mixing –AFC model is clearly the best explanation of granite geochemistry (Fig. 3) and has also been strongly supported in the Lachlan Fold Belt by Collins, (1998) and Gray (1984). The model suggests that as mafic magmas cool and fractionate, they heat the intruded crust with which they hybridise to varying extent. Isotope-based arguments provide the strongest support for this AFC type model (Sandiford et al., 1993; Foden et al., 1999, Turner and Foden; 1996).

The application of Nd-, Sr- and O-isotope data and inherited zircon population age frequencies provide very firm evidence that both I- and S-type granites in both the Delamerian and Lachlan Fold Belts are continuum mixtures of contemporary mantle and crustal sources. The Nd model age data (Fig. 2) indicate that LFB and DFB granites are displaced towards values which are significantly younger than any of the known Precambrian crustal components. These data also indicate a strong bimodal distribution of model ages with the I-types having younger mean model ages than the S-types. Intriguingly, in the DFB and in some LBF granite suites, the crustal endmember of the mantle-crust source continuum appears to be the sedimentary fill of the directly pre-orogenic basin, with little or no older crust (Fig 3). In the Delamerian this crustal source is the Early Cambrian Kanmantoo Group which is easily distinguished from all Precambrian crustal sources by its very distinctive inherited zircon age frequency signature.

The Magmatic Sources and Magma Chambers.

Whilst the isotopic composition of granite suites from the LFB and the DFB fall between the crust and the mantle, there is a strong tendency for the I-types to cluster towards the mantle endmember and the S-types towards the crustal endmember (often demonstrably the fill of directly preceding basins). This dichotomy reflects two magma production situations:

1. "Mafic" magma chambers (Type 1, Fig 3) contaminated by and mingled with melts of the local meta sediments (I-types).

2. Crustal melts (Type 2, Fig. 3) formed in the heated *zones* around the upwelling mantle or its mafic intrusions.

Thermal models suggest that these zones can have volumes as great as those of the volume of the mafic magma bodies (S-types).

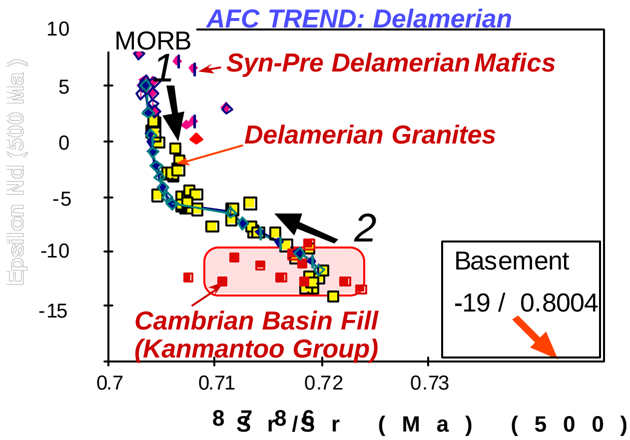

Figure 3. AFC Trend for Cambro-Ordovician mafic rocks from the Delamerian Fold Belt in South Australia. The AFC trend is described by the following parameters:

Type 1 magma chambers are dominated by fractionation and hybridisation of parent (I-type) mafic melts. Sr- and Nd- Kd values are low. Assimilation Rate/ Crstallisation Rate = 0.2

Type 2 magma generation zones dominated by Crustal melting and assimilation (S-types) High Sr-and Nd-Kd values

Thus on binary isotope mixing diagrams (Fig 3), notional evolutionary directions start at either endmember, I-types from the mantle, and S-types from the crust. S-type magma chambers are likely to originate above mafic or I-type granite intrusions, as migmatite complexes physically contaminated by veining and dyking from the underlying magmatic heat sources. General observations by Wiebe (1996) and those made specifically on the LFB plutons in the Bega and Moruya Batholiths by Collins et al (1999), indicate that I-type magma chambers (Type 1) are frequently the sites of repeated injection of mafic parental melt into cooling and fractionating melt bodies, yielding dynamic composite magma bodies.

Role and Character of Mafic Magmas

Listhospheric extension or transtension plays a repeated role in the tectonic evolution of the Tasman Orogen. As a consequence mafic magmatism at least partly due to decompressional melting of the asthenosphere is widespread. In South Australia the syn-Delamerian Woodside dykes are of E-MORB composition and post-date pre-tectonic MORB-like dykes. In South Australia, there are also Early Ordovician post-Delmerian mafic intrusions (Turner, 1996) whose isotopic and geochemical compositions indicate crustal contamination of mantle sources, apparently associated with the late stages of uplift and collapse of the Delamerian Orogen.

In the LFB in Victoria Devonian mafic dykes both pre-date, are synchronous with and post-date the Early- to Mid-Devonian granites (Soesoo and Nicholls, 1999). As in South Australian at least the pre-tectonic mafic dykes are of E-MORB composition. In the other areas of the LFB, in NSW, mafic dykes are also observed to bracket the mostly Early to Mid Devonian granites (eg. Carson and Rickard, 1998).

In the NFB Early Permian mafic magmatism is widespread between the Kanimblan and Hunter – Bowen orogenies, and often has a depleted MORB signature (Sivell and McCulloch, 1997). Some mafic activity also post-dates the Hunter-Bowen event in the Early Triassic.

At least in the Delamerian Orogen, there is good evidence that compressional orogenesis involved coupled strain of both the crust and the hot mantle beneath prior rift axes. This is the probable explanation for why the granites represent a binary source spectrum between mantle and pre-convergent rift basin –fill (Fig. 3). This coupling changes as the orogen cools and the restablishment of a planar Moho might be accompanied by crustal uplift and cooling and erosion and the delivery of crustally contaminated peridotite material back to the lithospheric mantle. This may then yield “enriched” post-tectonic basaltic melts (Fig 4).

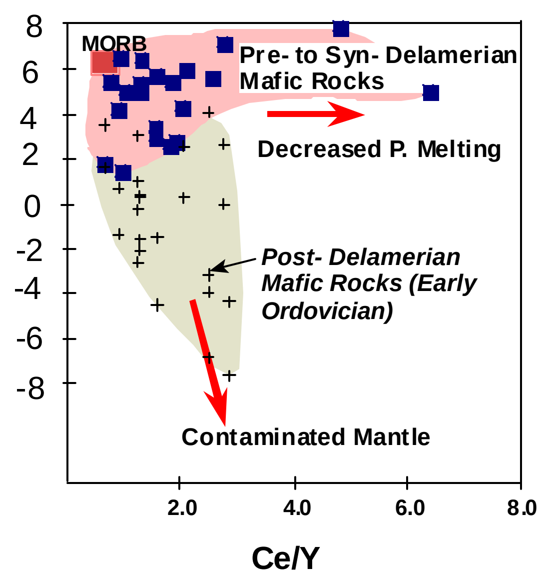

Figure 4. Mafic rocks from the Delamerian Fold Belt, South Australia. Illustrating the abrupt change towards lower epsilon Nd values for post-orogenic suites. These suites post-date rapid terminal uplift , erosion and metamorphic cooling of the orogen (Turner et al., 1996) The geochemistry of these mafic rocks is not consistent with crustal contamination of mafic melts , but requires melting of a mantle source which was contaminated by crust during the late stages of the orogenic cycle.

Conclusions: Granite Genesis in a Trailing Convergent Margin

The Tasman is a composite orogen whose character is more fashioned by lithospheric extension than compression. For numerous reasons it is difficult to associate the bulk of the magmatic history of much of the belt directly with wedge melting above subducting oceanic slabs.

Whereas subduction-controlled magmas inherit their geochemical characteristics from the wedge and subdcting slab before these melts arrive in the crust, many of the Tasman orogenic belts have magmatic histories whose compositions change in close concert with changing lithospheric / crustal strain histories. Initial crustal thinning is often associated with basin formation, turbiditic sedimentation and the production of alkaline and then E- to N-MORB style mafic magmas. This is followed by basin inversion with deformation of sedimentary fill, initially by thrust-nappe stacking. Individual compressional orogenic interludes are often short, lasting <~ 30 million years. At least in the Delamerian Orogen convergent deformation is terminated by extension with rapid exhumation, erosion and rapid metamorphic cooling and decompression. (Turner et al., 1992, 1996).

"Granitic" magmatism with compositions ranging from S- to I-type follows after the on-set of crustal thickening, though the majority of granite production tends to be late- to post-tectonic. Mantle-derived magmatic activity persists through the orogenic history as occasional mafic dyke complexes, but during compressional phases is mainly occult, identified by its isotopic signature as a component of syn-tectonic granites. Syn-tectonic mafic magmas tend to be of E-MORB and not of subduction character. Granitoid magmas inherit their orogenic style chemistry directly from the orogen's own crust and this tends to disappear from those post-tectonic granites which are often mainly mantle fractionates, having an A-type character. The sources of the granites are indisputable mixtures of concurrent mantle melts and crust.

References

Carson, L.J. & Rickard, M.J. 1998. Australian Journal of Earth Sciences, 45, 501-507.
Chappell, B.W. 1996. J. Pet., 37, 449-470.
Chappell, B.W. 1997.Transactions of the Royal Society of Edinburgh: Earth Sciences 87, 159-170.
Chappell, B.W. 1984. Philosophical Transactions of the Royal Society of London A310, 693-707
Chappell, B.W. and White, A.J.R., 1992.. Transactions of the Royal Society of Edinburgh: Earth Sciences 79, 71-86.
Chappell, B.W. and White, A.J.R., 1974. Pacific Geology 8, 173-174
Collins, W.J., Rodriguez, L.G., Wiebe, R.A., 1999, Fourth Hutton Symposium Abstracts, 20
Collins, W.J., 1998. Aust. Journal Earth Sci., 45, 483-500
Coney P.J., Edwards, A., Hine, R., Morrison, F. and Windrim, D., 1990. *J. Struct. Geol.* **12,** 519-543.
Foden , J., Sandiford, M., Dougherty-Page , J. & Williams, I., 1999. Australian J. Earth Sci. , 46,
Gray, C.M. 1984. Earth and Planet Sci Lett., 70, 47-60.
Munker , C. and Cooper, R.A., 1995. J. Geol., 103, 687-700
Holcombe, R.J., Stephens, C.J., Fielding, C.R., Gust., D., Little, T., Sliwa, R., McPhie,J. and Ewart, A., 1997, Geol Soc. Aust. Spec. Pub., 19, 66-79
Sandiford M., Foden J., Zhou S. & Turner S. 1992. *Transactions of the Royal Society of Edin*:**83**, 83-93.
Sivell, W. & McCulloch, M., 1997. Geol Soc. Aust. Spec. Pub., 19, 148-160
Soesoo,A. and Nicholls, I, 1999. Aust. Journal of Earth Sciences, 46, 725-734
Turner, S.P, Kelley, S., Vandenberg, A.H.M., Foden, J.,Sandiford, M and Flottman, T.1996. Geology, 24, 941-944.
Turner, S.P. 1996.*Mineralogy and Petrology, Vol.* ***56*** *pages 51-89*.
Turner, S. & Foden, J. 1996 *Mineralogy and Petrology, Vol.* ***56*** *pages 147-169*.
Turner,S.P., Sandiford, M. and Foden, J.D., 1992. Geology, 20, 931-934.
White, A.J.R. and Chappell, B.W. 1988. Transactions of the Roy Soc of Edinburgh: E S 79, 169-181, 1988
Weibe,R.A., 1996. Trans. Roy. Soc. Edinburgh, Earth Sciences. 87, 233-242.