Geometry of a Middle Proterozoic extensional décollement in northeastern Australia

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ABSTRACT


An 80 km-long belt of gneissic and mylonitic rocks is exposed in the core of a major anticlinorium in the Middle Proterozoic Mt. Isa Inlier of northeastern Australia. These rocks, in the Mary Kathleen Fold Belt, represent an early, originally horizontal, mid-crustal shear zone which is interpreted as an extensional décollement between a lower ductile sheet and an upper, more brittle plate. The décollement was subhorizontal over a distance of at least 80 km and its depth was perhaps as shallow as 7 km. Shearing was accompanied by the syn-tectonic intrusion of a bimodal complex of granitic and basic rocks over a period of 70-90 m.y.

Moderate, to extreme, ductile shearing was pervasive throughout the 1-1.5 km thickness of the lower plate that is now exposed. Massive dilation accompanied shearing and approximately 70% of the volume of the shear zone is occupied by igneous intrusive rocks (which have been variably deformed to gneissic granite, mylonite, and amphibolite). Strain softening driven by this high thermal input is responsible for the pervasive ductile response at such shallow depths. Peak metamorphic conditions at the décollement were approximately 625°C to 675°C at 2 kbar.

Intense ductile shearing in the upper plate is restricted to the lower few hundred metres. Above this zone, brittle processes dominate, although evidence is presented that the sheet as a whole has undergone a component of ductile shearing, probably heterogeneously distributed. Large, sheet-like granite and dolerite bodies were introduced into dilation sites associated with synthetic faults in this plate but, unlike their synchronous counterparts in the lower plate (about 1 km below), these are internally undeformed.

The Middle Proterozoic history of the area involves a cycle of extension and shortening with the shortening axis perpendicular to the earlier extension axis. We speculate that the driving mechanism for both extension and shortening is mantle convection, with switches in stress related to mantle upwelling.

Introduction

Australian Lower and Middle Proterozoic mobile belts have various orientations, are entirely intracratonic, and have a cyclic history of rifting and closure. This history is roughly synchronous from one belt to another, and generally involves two major cycles of rifting, thermal subsidence, and eventual closure accompanied by regional magmatism (Etheridge et al., 1984). The crustal extension part of each cycle has generally been inferred on sedimentological grounds and basin geometry. All of the belts show evidence for at least one compressional phase, commonly synchronous with regional metamorphism. The recognition and interpretation of apparently linked extensional and compressional tectonics provide important constraints on Proterozoic crustal evolution. This paper focuses on the observed structures and inferred processes in a mid-crustal extensional décollement within one of these belts, from which we present a schematic tectonic and thermal model that may have applications to other Proterozoic terrains.

The Mary Kathleen Fold Belt lies near the centre of the Middle Proterozoic Mt. Isa inlier in...
Fig. 1. Location map and highly simplified geological map of the Mary Kathleen Fold Belt. Most of the complex intrusive relationships and many faults have been omitted. Localities mentioned in the text are: B = Burstall Granite; LB = Little Beauty Syncline.
northwest Queensland (Fig. 1). The boundaries of the fold belt are only vaguely defined, it being simply an area of stronger deformation and higher metamorphic grade than is general for most of the Inlier. The fold belt has a dominant N–S structural grain defined by a regional upright folding event dated at about 1550 Ma (Page et al., 1984). This event is the culmination of the second major tectonothermal cycle in this area.

The core of the fold belt is a long (> 80 km), doubly plunging anticlinorium (Fig. 1) exposing, at the deepest structural level, intensely deformed gneissic granitoids and amphibolites intruding part of the older stratigraphy. Outside this core of gneissic rocks (known locally as the “Wonga Belt”) the flanking units are less deformed and are intruded by relatively undeformed granite, dolerite, and gabbro. The structure and tectonic history of this zone of anomalously high strain has been variously interpreted in the past. Early workers regarded the gneissic granites as being either a remnant of the deformed basement, or as syntectonic with the folding event, or as some unknown composite of both (e.g., Derrick et al., 1977). The “undeformed” granitoid bodies in the flanking units were commonly regarded as anorogenic (e.g., Etheridge et al., 1984). Bell (1983) first proposed high level pre-folding thrusts in the Mt. Isa inlier and Bell (pers. commun., 1985) has suggested that the Wonga Belt may be a vertical tear fault associated with this thrusting.

The structural model that we propose for the Mary Kathleen Fold Belt is that of an originally subhorizontal, roughly stratigraphy-parallel, shear zone with a N–S movement direction and an upper block to the north sense of shear (Holcombe et al., 1987; Pearson et al., 1987). This structure has been subsequently isoclinally folded (during E–W shortening) to produce essentially the present map pattern and the subvertical foliation (Fig. 2). The model is based on the recognition that a large component of the, now vertical, gneissic foliation in the Wonga Belt is inherited from an earlier deformation predating the regional

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**Fig. 2. Structural model of the evolution of the Mary Kathleen Fold Belt.**

(a) Early horizontal shear zone (D₁) showing the orientation of granite (crosses) and dolerite dykes and sills (herringbone dashes), and extension veins in the upper plate, and the extension lineation in the shear zone. The shear zone itself is a composite of many strongly sheared lithologies (70% of which are igneous intrusive). (b) Upright folding event (D₂) producing the general features of the present outcrop pattern.
upright folding event; recognition that the early foliation was originally broadly stratigraphy-parallel and produced by a shear-dominated deformation with a consistent sense of shear; and recognition that this early deformation is strongly localized on the Wonga Belt (that is, originally at the deeper structural levels), and decreases sharply away from the Belt (that is, into the higher structural levels).

We interpret this structure to be a mid-crustal extensional décollement based on the inferred geometry; the interpretation that the shear involved younger, more brittle, lower grade rocks overriding older, ductile, higher grade rocks; and the assessment that intrusion of the variably deformed granitoids and basic bodies was syntectonic with this early shear deformation and involved considerable dilation within the shear zone.

**Structural model**

The pertinent geological history is summarized in Fig. 3. The Kalkadoon Granite, intruded into the local basement rocks (Leichhardt Metamorphics), represents the tectono-magmatic event defining the end of the first tectonic cycle at about 1850 Ma (Page et al., 1984). The succeeding metavolcanic and metasedimentary units are themselves considered to be rift-related (Etheridge et al., 1984). The long period of syntectonic bimodal intrusive activity from about 1760 Ma to about 1670 Ma is the subject of this paper. The dominant structural event in the area is the regional folding at about 1550 Ma (referred to in this paper as D₂), and the preceding thrust event and the subsequent strike-slip event are possibly just phases of a protracted crustal shortening.

**Evidence of an early fabric**

The structural fabric (Fig. 4) within the gneissic rocks of the present Wonga Belt is characterized by a strong, consistently oriented foliation containing two lineations (Fig. 5). The foliation is defined by both a shape fabric and compositional banding and, in general, is parallel to the axial plane foliation of nearby D₂ folds in metasediments as well as being statistically parallel to the axial surface of macroscopic D₂ folds.

One of the lineations in this foliation, in both the gneissic rocks and the metasediments, is a weak to moderate mineral streaking lineation (generally defined by elongate biotite or amphibole grains). It is constantly oriented and is equated to the vertical extension lineation (L₂) of the folding event. This is confirmed by strain analysis in the gneissic granitoids (Fig. 6) using the Talbot (1970) method based on the deformation geometry of thin, deformed late aplite, quartz, and pegmatite veins (although the results must be viewed with some caution as some veins may have been deformed in the earlier deformation). A similar mineral streaking extension lineation in the same orientation is present in the metasediments outside the Wonga Belt, its nature being con-
WONGA BELT STRUCTURAL DATA

**Fig. 4.** Stereographic projections of $D_1$ and $D_2$ foliations and lineations in the southern and central parts of the Wonga Belt. The number of data are shown at the lower left of each stereogram.

Supported by strain analysis using mainly the Fry (1979) method. Stretched pebbles in rare conglomerates, and stretched scapolite porphyroblasts in some calc-silicate rocks (Fig. 7) also confirm the extension nature of this lineation.

The other lineation ($L_1$ in Fig. 4) in the gneissic rocks is variably oriented within the foliation. It is markedly doubly-plunging (through the horizon-tal) both at the scale of the exposed Wonga Belt and at an outcrop scale. It has both intersection and extension characteristics. That is, it is defined both by a compositional striping on the foliation as well as by elongate quartz and feldspar aggregates, and elongate xenoliths (Figs. 8 and 9). It is parallel to fold axes and an intersection lineation in adjacent metasediments and, much less commonly, to folds of the compositional layering in the granitoids. The extension characteristics of this lineation are considerably stronger than those of the vertical lineation.

Thus the gneissic fabric in general has the characteristics of a composite fabric produced by multiple deformation. In a few, rare, outcrops this fabric degenerates into two components—an early, strong gneissic foliation ($S_1$ in Fig. 4), folded around an axial plane structure parallel to the regional upright folds. The scale of such occurrences ranges from simple xenoliths containing randomly oriented gneissic foliation (Fig. 10), to mappable areas several hundred metres across
In all cases the older shape fabric is much stronger than the younger axial plane fabric. By comparing the shape fabric defining the earlier foliation in those outcrops where it can be independently defined (e.g. Fig. 10), with the normal, upright, Wonga Belt gneissic foliation in the same lithology (e.g. Fig. 5) it is apparent that the general foliation in the area is dominantly the earlier fabric \((S_1)\), rotated by folding into the vertical and then further modified by (relatively homogeneous) shortening during \(D_2\). Rarely are the two foliations superimposed as in Fig. 10. Flexural slip on discrete surfaces, such as mafic-rich folia parallel to \(S_1\) was probably an important process in the early stages of folding of the granitoids. This would produce the observed preservation of rotated \(D_1\) c-axis fabrics discussed below.

**Original orientation of the early fabric**

The variably oriented lineation in the gneissic foliation is a complex composite fabric. Its intersection characteristics are a remnant of the early fabric. In outcrops such as shown in Fig. 11, where the two foliations can be distinguished, this strong extension lineation is clearly separate from the upright folding fabric. Its intersection with the early gneissic foliation was parallel to the stratigraphic layering and the general macroscopic map pattern would suggest that stratigraphy was more or less horizontal. As discussed below, the structural boundary delimiting this zone of intense deformation was also subhorizontal.

**Nature of the early fabric**

Much of the layering in the granitoids is related to variable intensity of deformation, and locally the fabric is mylonitic. In one area (Fig. 11) where...
the two deformation fabrics can be separated, these mylonitic shear zones are clearly related to the early fabric and are folded by the later deformation. Progressive shear fabric development can commonly be traced into these local shear zones. In these zones the subhorizontal lineation becomes very prominent and shows the composite intersection/stretching characteristics common in mylonitic shear zones. Deformation intensity increases toward the upper structural margin of the Wonga Belt and early folds in metasediments in this zone either have fold hinges parallel to the stretching lineation or contain sheath folds with the sheaths parallel to the stretching lineation. Such structures are common in shear zone regimes. Narrow (centimetres-wide) shear zones, \( s-c \) fabrics, and asymmetric shear fabrics are relatively common throughout the granitoids. Thus the fabric was produced dominantly by shearing in the direction of the subhorizontal extension lineation (which also coincides with the intersection lineation during the subsequent folding).

A wide range of kinematic indicators have been used to determine the sense of shear throughout the belt (Pearson, 1989, Sliwa, 1986). These are not always easily interpreted because of the overprinting effects of the folding deformation. (In

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Fig. 7. Lineation \( L_2 \) on an \( S_2 \) cleavage surface in a cover sequence calc-silicate. The lineation is defined by deformed scapolite porphyroblasts and associated strain shadows. The pen is 14 cm long.

Fig. 8. Foliation surface in a strongly deformed gneissic granitoid phase in the Wonga Belt. The prominent compositional striping (parallel to the hammer handle) is the variably oriented lineation, \( L_1 \). Oblique to this is a much more subtle lineation, \( L_2 \), defined by, in this case, elongate biotite. The width of the hammer handle is 4 cm.
Fig. 9. Foliation surface in a coarsely blastoporphyryt granitoid phase in the Wonga Belt. The prominent extension lineation defined by the elongate xenoliths is the variably oriented lineation $L_1$. The length of the pen is 15 cm.

particular quartz $c$-axis fabrics are susceptible to variable resetting during the upright folding deformation depending on the scale of penetrative deformation. The sense of shear varies with position in macroscopic folds. In general it reverses across subhorizontal hinges in a systematic manner consistent with a sense of shear of upper plate to the north after “unfolding” the folds (Fig. 12). The main exceptions were found to be shear senses interpreted from quartz $c$-axis patterns and “Type

Fig. 10. Rotated xenoliths of coarse gneissic granite containing the early foliation in a younger phase granite. The pen (approximately 10 cm long) is parallel to the axial plane foliation of the upright folding event and the general aspect ratio of the early fabric is approximately preserved in the xenolith with the fabric at a high angle to this. This aspect ratio is only moderately modified in the xenolith with the fabric subparallel to the later foliation.
Fig. 11. (a) A map-scale example, and (b) fabric orientations, of the relationship shown in Fig. 10. In this outcrop the early D₁ fabric can be clearly separated from the later D₂ folding fabric in the hinge of an asymmetric D₂ fold. The early fabric contains variably oriented mylonitic shear bands cutting a strong shape fabric in the earliest phases. The later phases are increasingly more discordant to the early fabric.
2" mylonite oblique quartz fabrics (Lister and Snoke, 1984). In many instances these contradict mesoscopic shear sense criteria and perhaps indicate local shear reversals with time.

**Relative timing of the early deformation and intrusion**

There is considerable evidence that the granites and basic intrusives are syntectonic with this shear event over a period of 70–90 m.y. The most common outcrop relationship is one in which successive igneous phases showing the early deformation fabric intrude older phases containing a more intense version of the same early fabric. The outcrop shown in Fig. 13 is an example of such a relationship. The coarse granitoid phase shows clear intrusive relationships with a band of amphibolite and a parallel band of granitic mylonite. The mylonitic foliation contains a strong, shallowly plunging stretching lineation, the characteristic fabric element of the early pre-folding deformation. The cross-cutting granite is also moderately foliated and this foliation also contains a weak to moderate stretching lineation. The corresponding foliations and stretching lineations are parallel, and it is clear that both the earlier mylonite and the granite (and the amphibolite) have undergone equivalent deformation, although to vastly different degrees. (The granitic vein that cuts the intrusive contact is one of the youngest phases recognized in the belt and in an outcrop several kilometres away even this phase contains evidence of weak, pre-folding deformation.) Zircon ages of all granitoid phases that contain evidence of the early fabric span the range from 1759 ± 22 Ma to 1671 ± 8 Ma (Page, 1983; Page et al., 1984).

The small dolerite body shown in Fig. 14 occupies a small dilational zone produced by sinistral movement on a curved fault within one of the early shears. Not only does intrusion accompany the shear deformation but it is bimodal in composition. Xenoliths of dolerite/gabbro commonly occur in the granites and xenoliths of granite occur locally in basic rocks. Blake (1981) has described mixed magma textures between the Burstall Granite and Lunch Creek Gabbro (see Fig. 15) and we have observed similar features in the northern part of the Wonga Belt.

**Geometry of the early shear structure**

The eastern and western margins of the Wonga Belt (that is, the zone of intense gneissic foliation) are relatively well-defined. These margins define an upper structural boundary to the Wonga Belt which is exposed in the core of the major anticlinorium and this margin can be mapped around the closure. A similar boundary re-occurs in the next antiform to the east. Here the core of the antiform consists of foliated gneissic granite containing the complete fabric recognized within the
Fig. 13. Granite truncating amphibolite (dark layer) and already mylonitized granite, the contact being cut by a vein of younger granitic material. In fact, every rock type in this outcrop has the same fabric, but to different degrees. The hammer is approximately 40 cm long.

Wonga Belt and with the same orientations), passing structurally up into much less deformed rocks (Fig. 15). This is interpreted to be an extension of the same upper boundary of the Wonga Belt, although at a slightly higher stratigraphic position. This correlates with the western margin of the Wonga Belt being at a slightly lower stratigraphic level than the eastern. In the N–S direction (that

Fig. 14. Dolerite occupying dilational zone in a curved, weak, early shear (sinistral). The pen is approximately 14 cm long. We propose that dilation zones with similar geometry and origin exist at all scales and are the primary control on the emplacement of igneous material in a shear regime.
is, parallel to the early transport direction) this upper structural boundary of the Wonga Belt is approximately coincident with a prominent quartzite unit (Ballara Quartzite) for at least 80 km. Therefore, the upper structural boundary of the gneissic Wonga Belt is also inferred to have been approximately stratigraphy-parallel and sub-horizontal. The geometry suggests a slight westward dip of 1–2° relative to the stratigraphic dip. Whether this reflects an absolute structural surface dip or an initial sedimentological dip is uncertain. Williams et al. (1987) propose a system of sidewall ramps and flats to account for the geometry of this surface to the west.

Thus the Wonga Belt was a major subhorizontal shear zone separated by a décollement, or very low angle detachment surface, from an upper plate moving northwards (Fig. 2a).

In the upper plate (that is, the rocks flanking the Wonga Belt) ductile fabrics related to the early shear event are not common. Fabrics related to the upright folding event dominate. Locally, inclusion trails in syn-D₂ andalusite and garnet preserve relics of an early foliation. Refolded early folds are found locally but these have no axial plane foliation. Strong shear fabrics are restricted to a narrow zone at the base (< 200 m) where the subhorizontal linear stretching elements still persist, and in isolated zones higher in the stratigraphic pile. However, the refolded fold patterns that are found, do suggest a persistence of ductile strain for perhaps 2 km above the décollement.

Fig. 15. East-west cross-section (after Sliwa, 1986) of the Burstall Granite (B in Fig. 1) and the Lunch Creek Gabbro which together form a thick composite sill. The granite shown in the upper tectonic plate in Fig. 21b is based on this body. This section passes through the Mary Kathleen Mine shown in Fig. 1. The highly foliated zone marks the detachment surface and the top of the Wonga Belt.
Fig. 16. E-W vertical section through $D_1$ sheath folds cut by $D_2$ shears in a calc-silicate near the contact of the upper plate and the Wonga Belt. The sheaths have subhorizontal axes parallel to the lineation $L_1$. The length of the pen is 14 cm.

Fig. 17. $D_1$ sheath folds refolded by $D_2$ in a calc-silicate unit in the middle of the upper plate rocks. The compass is approximately 5 cm across.

Fig. 18. Ramsay Type 2 and 3 refolded fold patterns in a calc-silicate unit near the middle of the upper plate rocks. The pen is approximately 14 cm long and parallel to both $S_2$ and $L_2$. 
Fig. 19. Ramsay Type 1 refolded fold pattern in a calc-silicate unit near the middle of the upper plate rocks. The pen is approximately 14 cm long and approximately parallel to the $D_1$ hinge, which is here oriented E–W.

Fig. 20. Diagram showing (a) expected fold orientations within a shear zone; and (b) expected refolded fold geometries within a folded shear zone.
Within the basal zone (and in the lower plate) only Type 3 refolded fold patterns (Ramsay, 1967) are observed, reflecting the orientation of the early recumbent folds parallel to the stretching lineation. Above this zone complex patterns are found covering virtually the whole spectrum of interference patterns (Figs. 16-19). This is interpreted to reflect the variation in fold orientations to be expected within a shear zone (Fig. 20). In the areas of high shear strain (that is, in the basal zone and in other narrower shear zones higher in the plate, such as at the outcrop shown in Fig. 18) the folds formed during shearing are rotated toward the movement direction and are remarkably constant in orientation. Sheath folds are common in these zones (Figs. 16 and 17). We have not been able to map any systematic change in refolded fold pattern away from these zones of high strain and this is taken to reflect the heterogeneity of deformation in this plate.

Tectonic model

The tectonic model proposed for the early fabric in these rocks is a mid-crustal extensional décollement (Fig. 21a). An extensional shear rather than a thrust is proposed because of the time scale, the massive dilation implied by the intrusive rocks, and, particularly, the geometry of a lower grade, less deformed block overriding a higher grade, ductile block containing only the older stratigraphic units.

In detail (Fig. 21b), the lower plate in the model contains the present "Wonga Belt" rocks—numerous gneissic granitoid and basic phases syntectonically intruding metavolcanic,
schist, and quartzite units of the lower part of the stratigraphic sequence. These intrusive rocks, which occupy approximately 70% of the Wonga Belt, are envisaged as being "smeared out" dilational fillings in a broad shear zone. Figure 14 shows a small-scale example of dolerite filling such a dilational opening in one of these early shears. The maximum thickness of this zone observed within the Wonga Belt anticlinorium is probably only about 1.5 km and its original total thickness is unknown. There is some indication that the discordance of the intrusive bodies increases with the younger phases. The map outline of early phases commonly defines D_3 folds, whereas the later phases are locally, strongly discordant (e.g. Fig. 11). This perhaps reflects an increasing brittle component in the shear deformation.

The top ~ 400 m of the lower plate is the most homogeneously and intensely deformed part of the shear zone. It also contains the lowest proportion of intrusive material. Below this the intensity of deformation is more heterogeneous. Individual local shear zones are common and their orientation is variable. In the extensional environment envisaged, perhaps transtensional features associated with the more variably oriented shears are responsible for the increased dilation inferred from the increased volume of intrusive material.

Intense pervasive deformation in the upper plate decreases sharply away from the décollement. However, there is still a broadly distributed shear for several kilometres above the main shear zone, with more intense deformation in narrow zones and synthetic faults.

Pearson (1989) has delineated a series of (originally) high angle normal faults, around one of the marginal synforms (Little Beauty Syncline) immediately west of the Wonga Belt (Fig. 22a). These faults cut and rotate segments of a thick quartzite sequence near the base of the upper plate. The geometry and probable antithetic shear sense (Fig. 22b) is consistent with the stretching and thinning of rigid objects in a shear zone by the "bookshelf" or rotating "domino" mechanism (Mandl, 1987; see also Etchecopar, 1977; Simpson and Schmid, 1983) and is similar to the rotation sense of a string of boudins in such a zone (Ghosh and Ramberg, 1976). In this case it is suggested that the faults initiate as extensional fractures related to boudinage of the quartzite unit during ductile shear and thinning of the surrounding material. It is likely that the dilational constraints described by Mandl (1987) control the initial orientation of these fractures. Above these faulted and rotated segments the talc-silicate units have deformed more uniformly with the formation of the extension fractures described above.

An alternative possibility is that these faults are extensional synthetic normal faults in the upper plate. However the required sense of shear is reverse to that inferred elsewhere and an intervening transfer fault (e.g. Lister et al., 1986) is required between extending domains with opposed sense of shear.
Zones of anomalously oriented fold axes (related to the upright folding event) are relatively common in the mid to upper levels of the upper plate (e.g., Hill, 1986; Oliver, 1988; Pearson, 1989; Sliwa, 1986). We consider that such zones probably also represent rotated sections of bedding related to early high angle extensional normal faults.

The relatively undeformed granites and thick basic sills intruding the upper plate rocks are now known to be contemporaneous with gneissic equivalents in the lower plate. We know the three dimensional geometry of one of these granites (Burstall Granite) particularly well (Derrick, 1978, Sliwa, 1986). It is compositionally similar to one of the gneissic Wonga Belt phases. Its sill-like shape (Fig. 13) and relationship to an adjacent, peculiarly curved, early fault are responsible for the suggestion in the model that these bodies have intruded transtensional dilation zones in synthetic splay faults. The small dolerite body shown in Fig. 14 is consistent with the model envisaged. We suggest that not only are the “undeformed” granitoid bodies introduced into such brittle dilation zones but also the thick metadolerite bodies now found within the cores of the various synforms in the flanking rocks. We regard these as having formed by magmatic “leakage” from the bimodal material being introduced into the main décollement shear zone.

In some discussions of the tectonic evolution of the Mt. Isa area (e.g. Etheridge et al., 1984) the relatively undeformed granites, such as the Burstall Granite, are interpreted as representing a post-orogenic phase. This study suggests that the difference is a spatial one rather than temporal—the dilational zones, into which magma is introduced in the main shear zone, continue to become deformed themselves, whereas dilational sites, and the introduced material, in the upper plate are partitioned away from continuing deformation.

Speculation and discussion

The décollement is subhorizontal over a distance of at least 80 km. Depth constraints are somewhat problematical as most of the rocks involved are not amenable to geobarometry. We have modelled a range of possible depths for the décollement based on the thermal decay around the Burstall and Wonga Granites (the main mass of gneissic granites), and estimates of the geothermal gradient during extension. The available data suggests a maximum depth of 12 km on the décollement, and we favour a depth of between 7 and 10 km for this boundary. This is quite shallow if it is taken to represent a brittle–ductile transition but perhaps is reasonable in an area where the exceptionally high thermal gradients imposed by the introduced igneous material drive strain softening processes.

The large horizontal extent of this detachment suggests that some form of delamination model of crustal extension is operating (e.g. Lister et al., 1986) rather than a simple shallow-dipping crustal shear model (e.g. Wernicke, 1985).

It is difficult to evaluate the metamorphic evolution of rocks within the two plates during this extensional event, largely as a consequence of the later amphibolite-facies overprint associated with crustal shortening. Early sillimanite (overprinted by Dc crenulations) is observed within the upper part of the lower plate (and locally sillimanite–K-Feldspar), and sillimanite is also locally present near the base of the upper plate. This simply reflects the high thermal input of the magmatic material. No obvious migmatite is found in the lower plate, although a few strongly veined areas suggest incipient partial melting conditions. Thus the lower plate temperature conditions are set above the sillimanite-in and muscovite-out reactions, and below the minimum melt curve (Fig. 23). For near water-saturated conditions, the likely maximum conditions attained were between 625°C and 675°C at a pressure of about 2 kbar (see Kerrick, 1972).

Because of the largely horizontal nature of the décollement and the minor stratigraphic gap across it, adjacent points in each plate near the detachment surface will both have undergone similar P–T–t histories during extension (Fig. 23). Thinning of the upper plate during extension requires that all of the lower plate should have been depressurized with time during extension, with a concurrent increase in temperature due to melt input. Subsequently both thermal and mechanical
Fig. 23. Possible $P-Tt$ trajectory for points near the décollement during extension. $\text{AlSiO}_2$ triple junction from Holdaway (1971); muscovite-out curve from Chatterjee and Johannes (1974); minimum melt curve from Kerrick (1972). Peak metamorphic conditions in the upper plate (attained during $D_2$) are also shown (Oliver, N.H.S., 1988).

Crustal extension should produce rift- and sag-related deposits at the surface. Considering the original crustal depth of the area studied, and the subsequent crustal shortening, it is not surprising that such deposits are not seen in the very local stratigraphic record. However, a likely candidate for such deposits is the Mt. Isa Group found in the western part of the Mt. Isa inlier, and host to major stratiform silver-lead mineralization. This group, predominantly siltstone units overlying a basal quartzite, unconformably overlies a lower succession broadly equivalent to the sequence around the Wonga Belt. Zircons in a thin tuff marker in the Mount Isa Group sequence have been dated at 1670 ± 20 Ma by Page (1981). In this same paper Page also correlates the Mt. Isa Group with the McArthur Group to the northwest (also containing stratiform base metal deposits), for which he has obtained a zircon age of 1690 ± 29 Ma. Both ages are consistent with the later stages of the $D_1$ extension event proposed here.

Metasomatic activity is extreme around the décollement in the Mary Kathleen area and we feel that this shear zone has been a primary source of mineralizing fluids. In the immediate area reworking of this during the $D_2$ deformation has produced the Mary Kathleen uranium orebody. Perhaps the various base metal (Mt. Isa, Hilton, Dugald River, Lady Loretta, etc.) and gold deposits in the region also owe their existence to this feature.

As with most of the Australian Proterozoic mobile belts the history outlined is one of crustal extension followed by crustal shortening, but in this case apparently at 90° to the extension direction. At this stage we are not aware of any analogous situations in the other Australian Proterozoic belts. M. Sandiford (pers. commun., 1987) has observed similar phenomena in high grade Precambrian gneiss terrains in Antarctica and Sri Lanka, so this relationship may have implications for the evolution of Proterozoic Belts in general. Note that the stratigraphic sequence involved in this extensional deformation is itself a product of intracontinental rifting. (This earliest rifting is generally regarded as being an east–west extension (e.g. Derrick, 1982), which would require a 90° switch in the crustal extension orientation to produce the structure described here).

Houseman and Hegarty (1987) and Hegarty and Houseman (1988) see a similar relationship between extension and shortening axes in the Tertiary Gippsland Basin of southern Australia. They model the process as extension triggered by uplift over a mantle plume, followed by compression due to deactivation or decay of the plume with time. They document a similar 90° switch in the extension and compression axes which they explain by changes in the vertical component of stress during the process.

If the tectonic development of these Proterozoic mobile belts is ultimately controlled by the interaction of jostling Archaean (and Early Proterozoic) nuclei or continental segments as we believe (see also Etheridge et al., 1984), complexities in this interaction may conceivably give rise to the pattern of evolving strain histories suggested by our data. It is likely that the driving force for both extension and shortening is mantle convection. Mantle upwelling associated with adjacent convection cells may be analogous to the plumes in the Houseman and Hegarty model and cause the switching of stress axes.

Further regional studies and modelling are required to verify the magnitude of the change in kinematic axes and to generate a more concrete
tectonic model for the early evolution of the Mt.
Isa inlier. In a more parochial vein, the recogni-
tion of the enormous magmatic input into an
extensive, originally subhorizontal, mid-crustal
zone, has major implications for mineral explora-
tion strategies in the area.

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Note added in proof

Revision and re-dating of various Wonga
Granite phases using SHRIMP ion microprobe
now restricts the age range of extension and syn-
tectonic intrusion to 1760–1730 Ma (Pearson et
al., 1990).

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