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# Observations on the tectonic evolution of the southern Adelaide Fold Belt

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ABSTRACT

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The Mount Lofty Ranges, Fleurieu Peninsula and Kangaroo Island regions of South Australia expose a section across the west and northwestern margin of the southern Adelaide Fold Belt that was deformed and metamorphosed during the Cambro-Ordovician Delamerian Orogeny. In the external parts of the belt, thrust complexes involving basement and a late Proterozoic platformal succession show a characteristic asymmetry reflecting west to northwest vergence towards the Australian craton. In the more internal zones, convergent deformation involving large-scale upright folding and high-$T$, low-$P$ metamorphism of mainly Cambrian sediments, which were in part turbiditic, occurred between c. 516 and c. 490 Ma. In this part of the belt the distribution of heat and, possibly, strain reflects intimately the advective movement of magmas within the orogenic belt. Convergent deformation in the southern Adelaide Fold Belt was immediately preceded by rapid subsidence initiated during the deposition of the upper parts of the Normanville Group and which continued during deposition of the Kanmantoo Group. Mafic alkaline volcanism attendant with Normanville Group deposition is indicative of lithospheric thinning at c. 526 Ma.

## Introduction

The Adelaide and Lachlan Fold belts record the spatial and temporal evolution of the southeastern margin of the Australian continent through the late Proterozoic and the Palaeozoic. In the southern Adelaide Fold Belt, comprising the Mount Lofty Ranges–Fleurieu Peninsula–Kangaroo Island regions of South Australia, the terminal stages of sedimentation as well as the deformation, metamorphism and felsic magmatism during the Delamerian Orogeny are restricted to the Cambrian and earliest Ordovician: that is, at the same time as the formation of the Cambrian magmatic "arcs" and the initial accumulation of vast "mud piles" in the southern part of the Lachlan Fold Belt now only several hundred kilometres to the east (e.g., Coney et al., 1990). Consequently, constraints on the evolution of the southern Adelaide Fold Belt may provide additional insights into the nature and timing of processes attendant with initiation of the Lachlan Fold Belt. In this paper, we briefly review some recent developments in our understanding of the tectonic evolution of the southern Adelaide Fold Belt, concentrating particularly on the timing and significance of events during the Cambrian and Early Ordovician.

The exposed portion of the Southern Adelaide Fold Belt in the Mount Lofty Ranges, the Fleurieu Peninsula and on Kangaroo Island provides a section through the western and northwestern margin of an orogenic belt that extends eastwards beneath the Tertiary Murray basin and southeastwards probably as far as the Glenelg River Com-

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plex in Western Victoria, and almost certainly was formerly continuous with the Early Palaeozoic Ross Orogen in northern Victoria Land, Antarctica. To the northwest the fold belt is bounded by a foreland of early–middle Proterozoic metamorphic basement forming part of the Australian craton (Fig. 1). The southern Adelaide Fold Belt exhibits a characteristic stratigraphic, structural and metamorphic asymmetry allowing the (somewhat arbitrary) subdivision of the belt into an *external* zone, bordering the foreland along the western and northwestern margins of the belt, and a more *internal* strongly metamorphosed zone of higher-grade metasediments and gneisses in the eastern and southeastern parts of the belt. In the central parts of the belt, in the

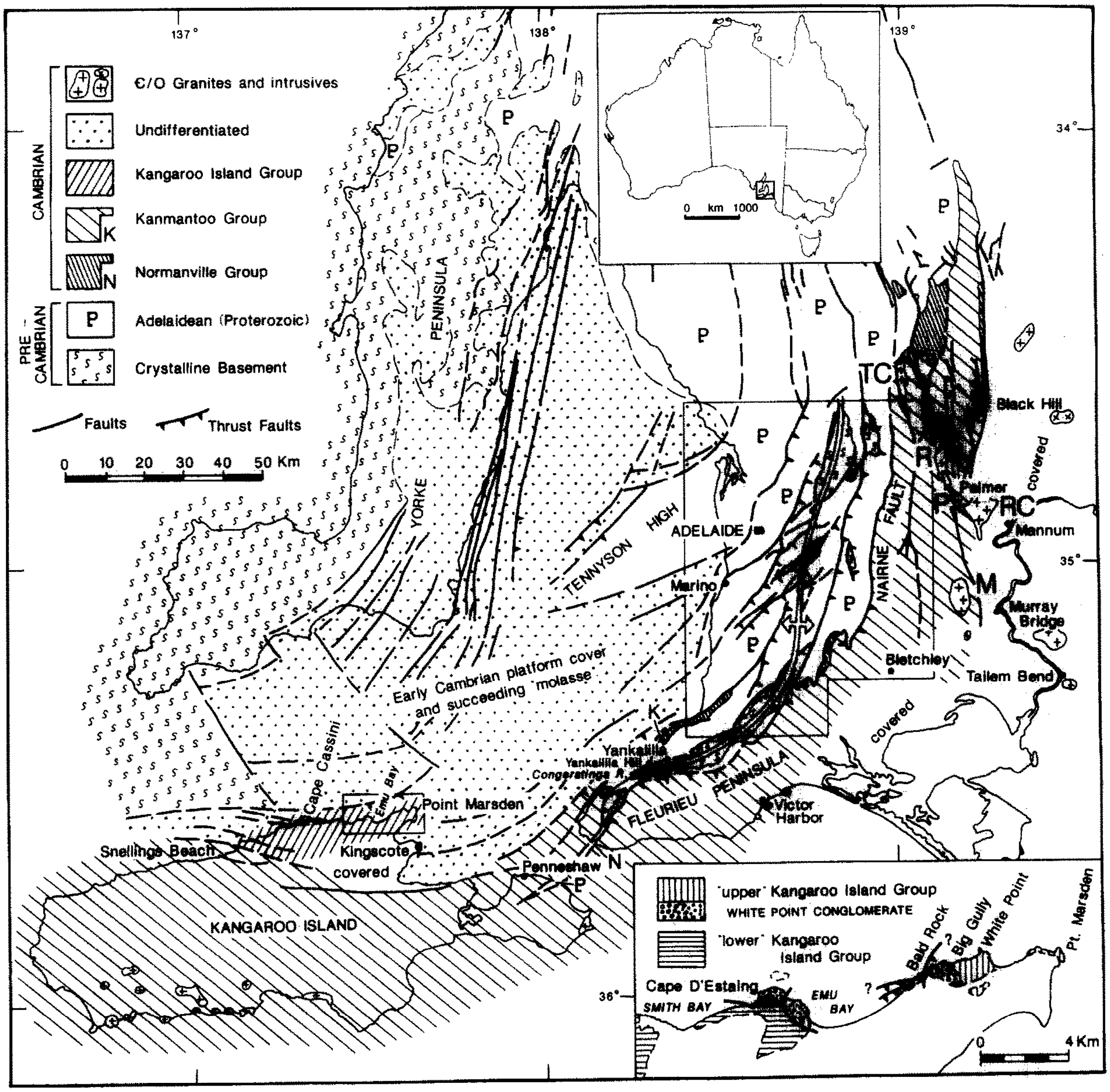


Fig. 1. Tectonic map of the southern Adelaide Fold Belt. The inset on the lower right shows details of outcrops of "Upper" Kangaroo Island Group on the north Coast of Kangaroo Island. The region outlined in the centre right of the diagram (including Adelaide and Bletchley) is shown in greater detail in Fig. 3. The granites in the vicinity of Palmer are labelled as follows: *M* = Monarto Granite; *P* = Palmer Granite; *R* = Rathjen Gneiss; *RC* = Reedy Creek Granodiorite; *TC* = Tanunda Creek Gneiss.

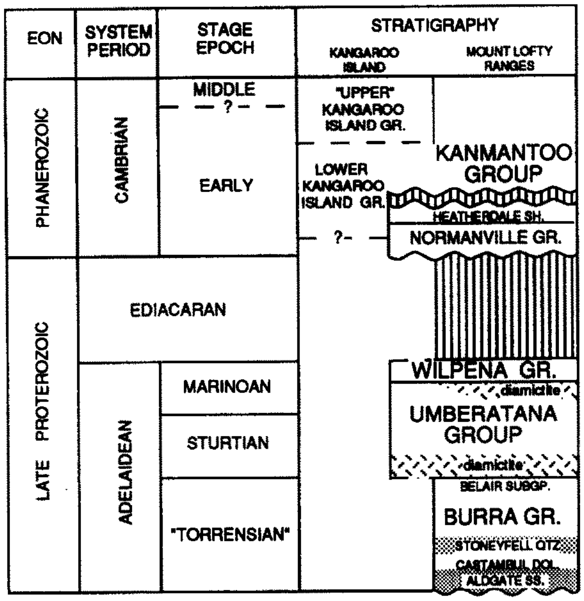


Fig. 2. Summary of key stratigraphic elements of the southern Adelaide Fold Belt.

Mount Lofty Ranges, the boundary between these zones corresponds to an abrupt change in metamorphic grade along the Williamstown–Meadows Fault (Fig. 3), whereas in the southern part of the belt on the Fleurieu Peninsula and Kangaroo Island the boundary is not precisely defined.

## Stratigraphic relationships

The southern Adelaide Fold Belt comprises three broad stratigraphic elements (see Figs. 1 and 2), namely, an early–middle Proterozoic basement complex, a late Proterozoic–Early Cambrian platformal succession comprising the Burra, Umberatana, Wilpena and Normanville Groups, and an Early to ?Middle Cambrian sequence, in part turbiditic, comprising the Kanmantoo and Kangaroo Island Groups (a summary of the important stratigraphic relationships in the southern Adelaide Fold Belt is shown in Fig. 2).

The platformal successions record the evolution of successive rift and sag phase subsidence over c. 275 Ma (Preiss, 1987; Jenkins, 1990), with significant mafic volcanism associated with both the initial stages (the Wooltana Volcanic suite of the Callanna Group in the Flinders Ranges) and the final stages (the Truro Volcanic suite of the Normanville Group) of the platformal successions. The youngest sediments in the sequence may be represented by the "Upper" Kangaroo Island Group (Figs. 1 and 2) which Jenkins (1990) controversially suggested may represent a molassic phase of sedimentation. The events leading to the terminal stages of deposition during the Cambrian, which herald the Delamerian Orogeny, are especially significant and are discussed below.

## Structural architecture of the Southern Adelaide Fold Belt

The structure of the *external* parts of the belt in the Mount Lofty Ranges and Fleurieu Peninsula has been summarized by Jenkins (1990). This region is dominated by an anastomosing set of SW–NE-trending thrust faults which dip c. 15–35°SE and isolate (and lie at the base of) a series of lens-shaped inliers of crystalline basement rocks (Figs. 1 and 3; Steinhardt, 1991). Cover rocks in contact with the basement inliers show distinctly differing styles of deformation. Cover in hanging walls of major thrusts lie unconformably *above* basement in the Central Ranges. It is commonly little deformed and is subhorizontal or forms relatively minor, upright kink folds, with weak development of fabric. Such a para-autochthonous cover commonly includes the basal Aldgate Sandstone and the Castambul Formation, of dolomite and minor quartzite. In contrast, cover structurally in footwalls beneath basement thrusts locally shows intense deformation. For example, in the Yankalilla area basal conglomerates of the Burra Group are commonly highly stretched and are associated with strong lineated fabrics, especially at overthrust contacts such as near the mouth of Little Gorge (James and Anderson, 1989, p. 58).

In the central Mount Lofty Ranges, middle to upper parts of the Burra Group are commonly strongly deformed into either recumbent or isoclinal folds and show a prominent low-angle cleavage inclined towards the southeast (Fig. 4). Tight folds shown by thin quartzite beds are commonly boudinaged or rootless; it is possible (but not yet demonstrated) that considerable

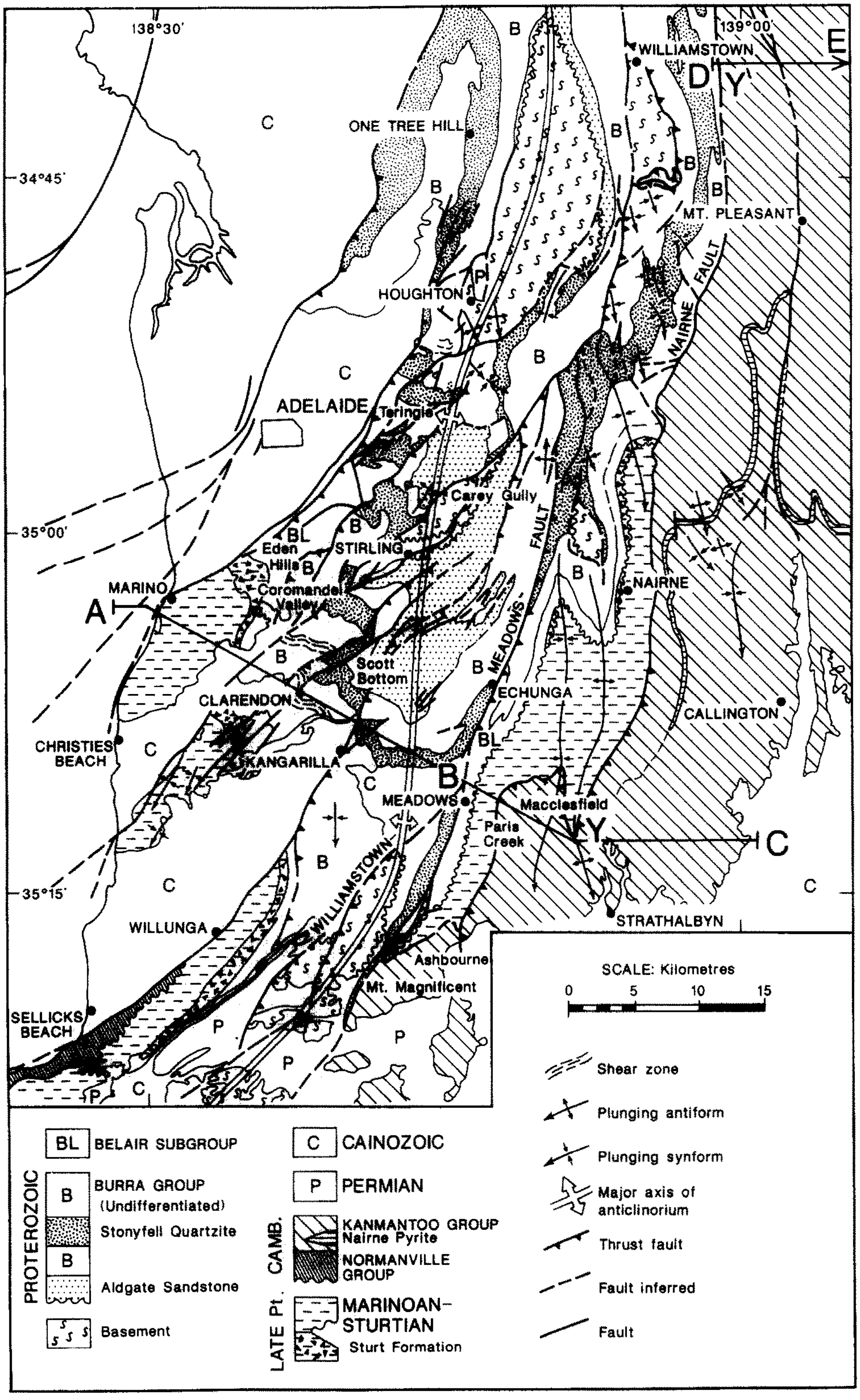


Fig. 3. Geology of the Mount Lofty Ranges showing the detailed pattern of faulting in the external parts of the belt. In this region the boundary between the lower-grade external and higher-grade internal parts of the fold belt occurs along the fault system trending from Williamstown in the north to Meadows in the south.

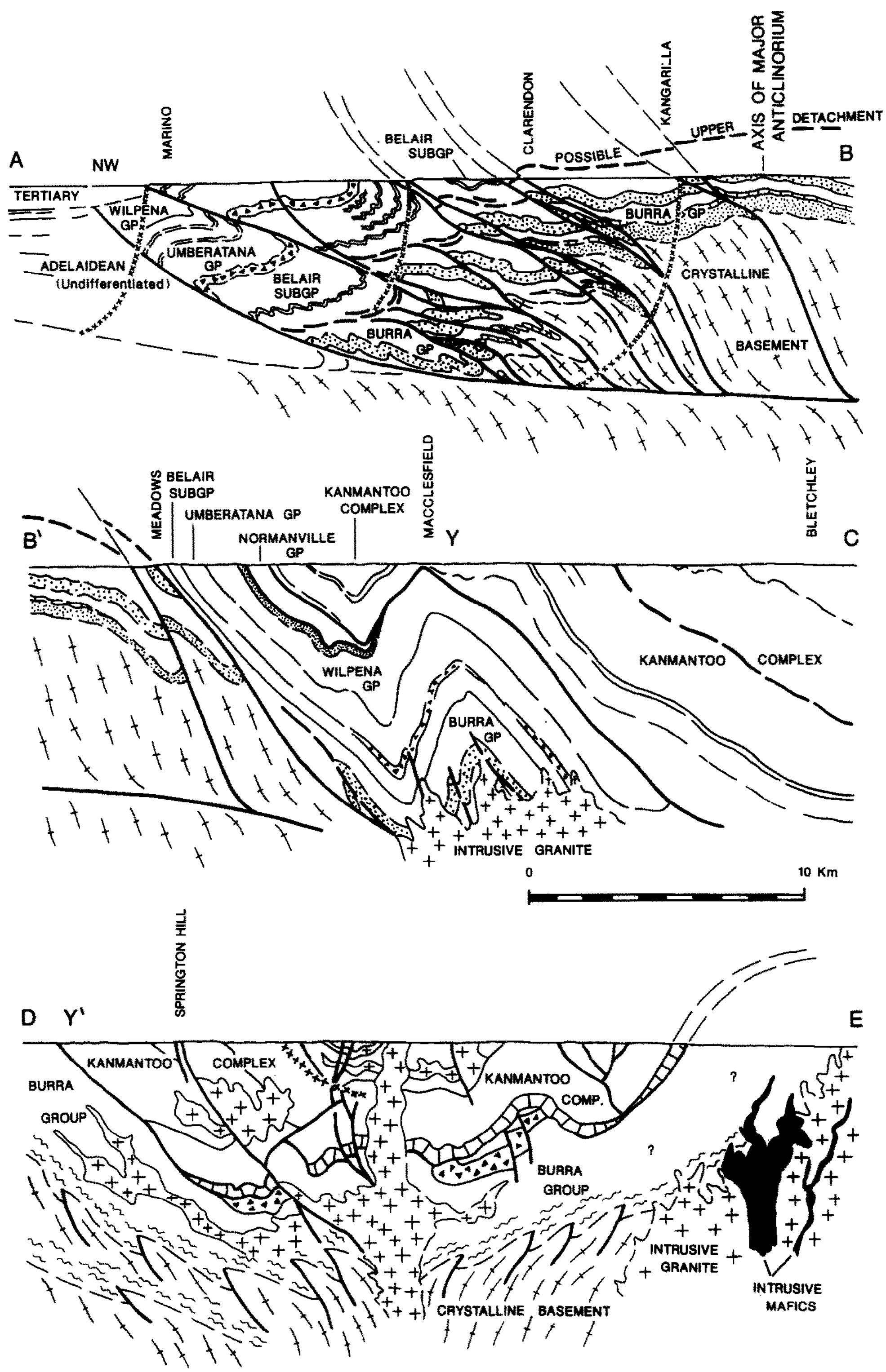


Fig. 4. Interpretive geological cross sections of the Mount Lofty Ranges between Marino and Bletchley (*A,C*), and along a line east of Williamstown through Springton Hill to Black Hill (*D,E*). The approximate equivalent line of strike between the Macclesfield (*B',C*) and Springton (*D,E*) sections is through *Y-Y'* (see Fig. 3). Tertiary fault systems are marked by lines of "x".

thrusting has occurred in the phyllitic rocks that separate the lower para-autochthon from overlying more intact parts of the stratigraphy such as the Stonyfell Quartzite. In this central part of the belt, the uppermost Burra Group (Belair Subgroup) and the overlying Umberatana Group and older Wilpena Group (Marinoan) tend to be much more weakly deformed and are characterized by broadly open, inclined folds verging westward or northwestward (Jenkins, 1990, fig. 7). It has been considered that the Umberatana Group is disconformable above the Burra Group (Coats, 1967; Preiss, 1987, pp. 125, 143–144). However, on the Fleurieu Peninsula, this middle section of the late Proterozoic sequence (Fig. 1) is intensely deformed (James, 1989; Jenkins, 1990) disproving the idea that, at least on the regional scale, it was somehow immune from deformation. Instead we suggest that the two structural regimes may be separated by an upper detachment (Fig. 4).

In the internal parts of the belt, in the eastern Mount Lofty Ranges and much of the Fleurieu Peninsula and Kangaroo Island, sequences metamorphosed to biotite grade and higher are folded about upright to gently inclined, symmetric structures (Offler and Fleming, 1968; Mancktelow, 1990). As summarized by Fleming and White (1984) and Sandiford et al. (1992), map-scale fold interference patterns have not been demonstrated. However, complex foliation patterns associated with the development of these folds, particularly in the higher-grade parts of the belt, suggest a number of phases of deformation which has lead to various interpretations of the structural history of this region (Offler and Fleming, 1968; Mancktelow, 1990; Sandiford et al., 1992). We regard the main upright folds as second generation features, which at least in the regions of highest-grade metamorphism overprint a prominently developed layer-parallel foliation (see also Fleming and White, 1984).

## Metamorphism

In the external parts of the fold belt, metamorphism is characteristically chlorite- or, at most, biotite grade, with mineral growth in foliations related to the imbricate thrust structures. In the central Mount Lofty Ranges, an abrupt increase in metamorphic grade occurs across the N–S-trending Williamstown–Meadows Fault within the late Proterozoic platformal succession, while in the southern parts of the belt the metamorphic distinction between the external and more internal parts of the belt is less obvious. East of the Williamstown–Meadows Fault, metamorphism is characteristically biotite grade or higher with sillimanite and migmatite grades attained in the vicinity of deformed granitic intrusive bodies (Offler and Fleming, 1968; Mancktelow, 1990; Dymoke and Sandiford, 1992). While these higher-grade regions of the fold belt are largely restricted to outcrops of the Kanmantoo Group, they also include elements of the late Proterozoic–Early Cambrian platformal succession. Most importantly, at Williamstown, along the western limit of the metamorphic sequences, imbricate thrust slices of crystalline basement and its platformal cover including the Aldgate Sandstone have been metamorphosed to sillimanite grade (Mills, 1973). Isograds apparently cut tectonic contacts, implying that this regional high-$T$, low-$P$ ("Buchan-style") metamorphism is superimposed on the presently observed thrust-related juxtaposition of the stratigraphic elements.

In the eastern Mount Lofty Ranges, migmatite, prismatic sillimanite, fibrolite, andalusite and staurolite, and biotite zones (defined by first appearances) are arranged about a zone of plutons including the Tanunda Creek Gneiss, the Rathjen Gneiss, the Palmer Granite, the Reedy Creek Granodiorite and the Monarto Granite (Fig. 1) (Offler and Fleming, 1968; Mancktelow, 1990). Separate andalusite and staurolite isograds have been mapped northeast of Springton (Offler and Fleming, 1968), staurolite generally appearing down-grade of andalusite (see also Sandiford et al., 1990). However, near the eastern margin of the exposed terrain, the andalusite and staurolite isograds apparently cross each other, such that staurolite appears first, up-grade of andalusite (Offler and Fleming, 1968). In the sequence of assemblages preserved in the field, the first appearance of andalusite and staurolite coincides with the disappearance of primary chlorite (Offler and Fleming, 1968) while the first appearance

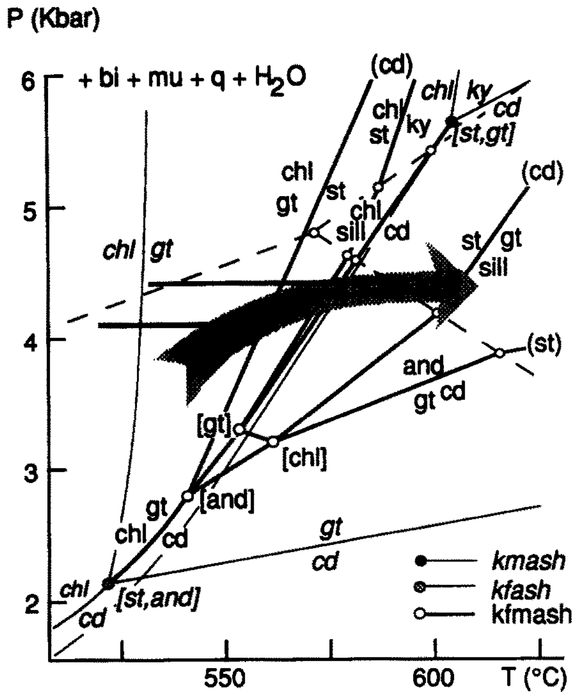


Fig. 5. $P$–$T$ grid for the system $K_2O$-FeO-MgO-$Al_2O_3$-$SiO_2$-$H_2O$ (KFMASH) appropriate to the assemblages in eastern Mount Lofty Ranges pelites (after Dymoke and Sandiford, 1992). The array of maximum $P$–$T$ points (or metamorphic field array) for the region extending from Palmer (at highest grade) down grade to the north is shown in the stipple while the inferred heating paths of individual rocks is shown by the solid arrows. The $Al_2SiO_5$ phase diagram is shown in dahed lines. Mineral abbreviations are as follows: *and* = andalusite; *bt* = biotite; *cd* = cordierite; *gt* = garnet; *ky* = kyanite; *mu* = muscovite; *q* = quartz; *sill* = sillimanite; *st* = staurolite.

of prismatic sillimanite as mapped by Mancktelow (1990) occurs before the disappearance of andalusite and staurolite. Fibrolite is commonly present in andalusite-bearing assemblages. These observations suggest the array of metamorphic pressures and temperatures define a metamorphic field gradient that is approximately isobaric or shows a slight increase in pressure from about ~500°C (or lower) to about 650°C at pressures of about 4–4.5 kbar (Dymoke and Sandiford, 1992; Fig. 5). The maximum lateral gradients in the peak metamorphic temperatures are estimated to be of the order of 10°C $km^{-1}$ in the vicinity of the andalusite and sillimanite isograds (Dymoke and Sandiford, 1992), while the presence of kyanite in early layer parallel segregations, subsequently overprinted by andalusite and sillimanite implies essentially isobaric heating to peak temperatures (Sandiford et al., 1990, 1992).

In the internal parts of the belt, the metamorphic peak is closely associated with large upright folds that dominate the outcrop pattern. However, in detail the timing of metamorphism in the highest-grade regions shows some subtle variations (Sandiford et al., 1992). In the migmatite zones much of the migmatisation occurs before the upright $F_2$ folding (Fleming and White, 1984; Sandiford et al., 1992) with products contained in an early layer-parallel fabric. At lower grades, staurolite and andalusite porphyroblasts typically overgrow developing $S_2$ crenulations, although locally may apparently predate foliation development (Offler and Fleming, 1968). This typical sequence of mineral growth suggests that the lower-grade exposures attained peak temperatures later than higher-grade regions. One plausible interpretation is that this delay in attainment of maximum temperature metamorphism reflects the significant lateral heat transfer outward from the zone of plutonism, with the inference being that these magmas are representative of the main metamorphic heat source. However, the thermal history is complicated by the fact that zone of plutonism seems to have been active for at least ~26 Ma from about ~516 Ma to ~490 Ma spanning the complete strain history of this part of the belt (see discussion below). Moreover, on the basis of their inferred dimensions, these bodies provide insufficient heat for the observed metamorphism and it is necessary to appeal to additional, but related, magmatic input at structural levels not in the present erosion surface to explain the observed metamorphism (Sandiford et al., 1992).

In view of the absence of evidence for significant post-metamorphic extension and evidence for present-day crustal thickness of ~35 km (Greenhalgh et al., 1989), the metamorphic pressures imply crustal thicknesses of the order of 50 km during the metamorphic culmination.

## Discussion

In as much as the southern Adelaide Fold Belt has formed in a zone of west to northwest convergence against the Australian craton, an understanding of the nature and timing of events must provide constraints on the kinematics of the lithosphere further to the east in the region in which the southern Lachlan Fold Belt may have been developing. Major episodes of regional geodynamic significance during the Cambrian to early Ordovican in the southern Adelaide Fold Belt relate to the significance and timing of (1) the deposition of the Normanville and Kanmantoo Groups, and (2) the convergent deformation. In the following discussion we address these two points.

During the late Proterozoic, the Adelaide Fold Belt seems in general to have been an extensional regime which engendered repeated cycles of subsidence and deposition of thick intervals (c. 5–7 km) of sediments (Jenkins, 1990). A late subsidence during the Early Cambrian deposition of the Normanville Group is recorded by the transition of the shelfal carbonates of the Fork Tree Limestone into the dark, laminated and commonly phosphatic pelites of the Heatherdale Shale. The latter is overlain at an erosion surface by medium to massive bedded turbidites of the Carrickalinga Head Formation, apparently forming the basal unit of the Kanmantoo Group and testifying to remarkable change in the dynamics and the basin and surrounding hinterlands. Described fossil assemblages provide a somewhat equivocal biostratigraphic control for the timing of this subsidence at about the Atdabanian–Botomian transition or marginally later (Cooper et al., 1992). Shelfal carbonates of broadly overlapping age on Yorke Peninsula and in the Flinders Ranges (Bengtson et al., 1990) include a striking, red-stained disconformity or surface of condensation that may record regional uplift signalling either a thermal bulge or a flexural high linked to the subsidence associated with the deposition of the Heatherdale Shale in the area of the Mount Lofty Ranges. A tuff bed in Heatherdale Shale at Sellicks Hill has given an ion-probe, U-Pb zircon age of c. $526 \pm 4$ Ma (Cooper et al., 1992). More extensive alkali basalts interbedded with the Heatherdale Shale on the eastern side of the Mount Lofty Ranges (Forbes et al., 1972; Gatehouse et al., 1990) seem to signify a regime of lithospheric extension (Turner and Foden, 1990).

Following closely on the deposition of the Normanville Group with attendant mafic alkaline volcanism, the Kanmantoo Group has traditionally been associated with ongoing lithospheric attenuation (e.g., von der Borch, 1980; Parker, 1986; Jenkins, 1990), with the provenance located to the northwest on cratonic Australia. The Nd-isotopic signatures of Kanmantoo Group sediments (Turner, work in prep.; Sandiford et al., 1992) lend some support to this hypothesis, as do the characteristic southeasterly current directions determined from climbing ripples (Daily and Milnes, 1973; Gatehouse et al., 1990) and the presence of locally abundant, pre-metamorphic dolerite dykes which may reflect essentially syn-depositional mafic magmatism (Fleming and White, 1984). However, there is little compelling evidence for the dramatic and sustained emergence of topography within this part of the craton required to trigger the massive input of the Kanmantoo turbidites (some estimates, e.g., Daily and Milnes, 1973, put the Kanmantoo Group as thick as 12 km). Rather, much of the region separating the craton and the basin at this time, e.g., the area of Yorke Peninsula, seems to have been covered by shallow carbonate banks. The alternative possibility, that the provenance of the Kanmantoo Group sediments lay to the east and southeast and reflects the first emergence of the encroaching orogen, has been recently suggested by Mancktelow (1990) and Coney et al. (1990), but has not yet received serious critical evaluation. Simultaneously, Jenkins (1990) proposed a southerly or southeasterly derivation for some of the older, coarser clastic phases in the "Upper" Kangaroo Island Group, which therefore may represent true syn-orogenic "molassic" sediments.

Within the internal parts of the fold belt deformation is bracketed by the intrusive ages of the granitic rocks, with granite emplacement spanning a period of about 30 Ma (Milnes et al., 1977; Sandiford et al., 1992; Foden et al., in press) with two distinct chemical, spatial and temporal, associations developed (Foden et al., 1990; Turner and Foden, 1990): (1) an older suite of dominantly I-type granites (encompassing a spectrum through to S-type) characterised by (variably developed) tectonic fabrics, with zircon ion-microprobe ages in the range 516–490 Ma (Foden, et al., in press) and found within presently exposed Kanmantoo Group sediments; and (2) a younger suite of undeformed A-type granites associated with further mafic magmas, with intrusion ages of 490–480 Ma, and now found as isolated monadnocks within Tertiary sediments of the Murray Basin east of the main exposures of the Adelaide Fold Belt (Turner et al., 1992). As summarized by Sandiford et al. (1992), the oldest of the deformed intrusives at c. 516 Ma (Foden, et al., in press) contains evidence for both of the main deformation fabrics, and thus provides an oldest age limit to the deformation. Deformation was certainly initiated prior to the intrusion of the Victor Harbour and Palmer granites at about 505 Ma (Milnes et al., 1977; Foden, et al., in press), which contain only evidence of the second generation structures (Sandiford et al., 1992). Essentially undeformed mafic and felsic rocks east of Palmer at c. 490 Ma (Milnes et al., 1977; Turner et al., 1992; Sandiford et al., 1992; Foden, et al., in press) provide an upper age limit to deformation in fold belt.

The relationship between the deformation in the external zone, with its characteristic asymmetry reflecting vergence onto the Australian craton, and in the internal zone, where the structures are typically more symmetric particularly in the high-grade regions around Palmer, remains problematical. The geometry of both sets of structures reflects, in part, the buttressing effect of the margin of the Australian craton during westwards to northwestwards convergence (Clarke and Powell, 1989), and thus the structures may be essentially coeval. However, the apparent metamorphism of thrusted contacts at Williamstown (Mills, 1974) suggests that the characteristic deformation style preserved in the external parts of the belt occurred before the regional low-$P$, high-$T$ metamorphism associated with deformation in the internal parts of the belt. As discussed earlier, the main deformation in the internal parts of the belt, manifest as broad upright folds (Fig. 4), is clearly contemporaneous with high-$T$, low-$P$ metamorphism suggesting that the arrival of the granites provided sufficient thermal weakening to trigger deformation within this part of the developing orogen (Fleming and White, 1984; Sandiford et al., 1991, 1992). Thus it is conceivable that the arrival of these granites lead to a fundamental change in the deformation regime from "thin-skinned" as evident in the external parts of the belt to a more distributed style of deformation as observed in the higher-grade internal parts of the belt. If indeed this was the case, then the isotopic character of the granites, which implies involvement of significant mantle melts (Turner et al., 1992; Sandiford et al., 1992), suggests that the tectonic evolution of the southern Adelaide Fold Belt was strongly influenced by events affecting the lower part of the mantle lithosphere or upper convective mantle at this time, and which conceivably relate to processes occurring further east in the region in which the incipient Lachlan Fold Belt was developing.

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