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STRATIGRAPHIC AND STRUCTURAL CONSTRAINTS ON THE PROTEROZOIC TECTONIC HISTORY OF THE OLARY BLOCK, SOUTH AUSTRALIA

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ABSTRACT

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The lower Proterozoic of the Olary Block is divided into five rock suites defining a conformable stratigraphic sequence correlated with the Willyama Supergroup of the Broken Hill Block, which has a probable depositional age no greater than 1800 Ma. The sequence was deformed and metamorphosed during the 'Olarian' Orogeny at ~1580 Ma. Definition of the stratigraphy permits regional structural analysis and the resolution of two folding events: an initial recumbent fold terrain redeformed by upright folds with a near vertical axial surface. The 'Olarian' Orogeny comprises a single regional compression axis, with both folding events indicating a SE direction of transport. The described tectonic fabrics are consistent with simple shear deformation generating the early recumbent terrain.

INTRODUCTION

The concept of plate tectonics leads to a better understanding of the processes of mountain building in terms of unifying many aspects of earth sciences into a coherent framework. However, only detailed field observations and regional geological synthesis make it possible to constrain and to begin to understand the tectonic processes which determine how rocks present in the Earth's crust are arranged. Such geological information is particularly pertinent to Proterozoic orogenic belts (and any Precambrian deformation) for comparison with better known Cenozoic tectonic regimes. The interpretation of kinematic indicators provides constraints on global scale tectonic processes (e.g., Escher and Watterson, 1974; Escher et al., 1975; Park, 1981) that may have varied during the early history of the

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Earth in response to changing rheological properties of the lithosphere (Windley, 1983).

In this article we consider constraints imposed on the tectonic evolution of an early Proterozoic terrain by kinematic indicators present within the metamorphic sequence. The case history is taken from the Willyama Complex (Mawson, 1912; Vernon, 1969) which straddles the New South Wales and South Australian borders and has been informally divided into two blocks (Fig. 1) separated by the state border (Thompson, 1976). To the east, the Broken Hill Block (BHB) has been the focus of considerable work with incentive provided by the stratiform Pb—Zn—Ag orebodies at Broken Hill. Detailed systematic mapping by the Geological Survey of New South Wales generated a broad stratigraphic sequence (Stevens et al., 1980) with subsequent work deriving a formal stratigraphy with detailed subdivisions (Willis et al., 1983). Structural studies (Hobbs, 1966; Rutland and Etheridge, 1975; Marjoribanks et al., 1980) have recognised a succession of deformation events but have failed to accurately constrain strain patterns associated with the early recumbent to reclined fold structures. Contrasting the extensive data available for the BHB is modest mapping of the Willyama Complex within the Olary Block (OB) by the South Australian Department of Mines and Energy (Pitt, 1977; Forbes and Pitt, 1980) and structural work of a fragmentary nature with limited regional context (Talbot, 1967; Berry et al., 1978; Grady et al., 1984). Detailed

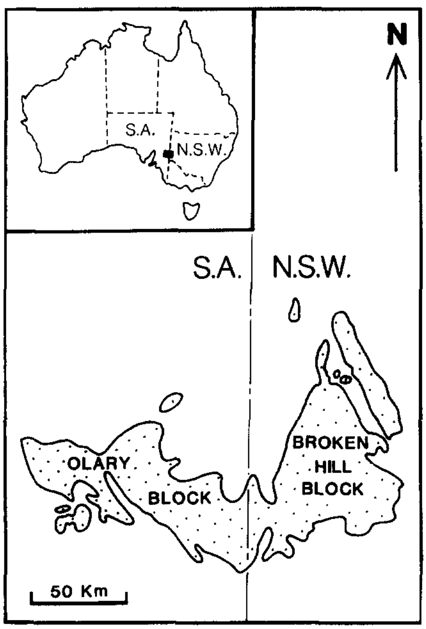

Fig. 1. Extent of outcrop of the Willyama Complex (after Thompson, 1976; Stevens et al., 1980).

mapping by mineral exploration companies (Esso Exploration and Production Aust. — Cotton, 1980; Archibald, 1983; and Carpentaria Exploration Company — proprietary information) has demonstrated the presence of local stratigraphies in scattered localities throughout the OB and much of this information is used in the definition of a regional stratigraphy.

The aims of this study are to describe the regional geology of the OB thereby constraining the tectonic development of the gneissic terrain. A coherent strain pattern is described for the high-grade fabrics including the development of an early recumbent terrain. Within any recumbent terrain, the observation of the relationship between stratigraphic younging and fold geometry allows the delineation of areas possessing normal or inverted sequence (e.g., Shackleton, 1958; Wilson, 1961; Arthaud, 1970). The knowledge of a regional stratigraphy permits this exercise on a regional scale and hence an evaluation of the magnitude of recumbent folding. Since a regional stratigraphic sequence has not been previously reported for the OB, a framework stratigraphy is presented and then tectonic events imposed upon this sequence described. The defined stratigraphy, sequence of deformation and associated strain patterns for the OB allows comparison with that reported for the BHB.

LOWER PROTEROZOIC STRATIGRAPHY OF THE OLARY BLOCK

Previous work

Mawson (1912) first separated the Willyama Complex from the 'unmetamorphosed' sediments of the Adelaide geosyncline (Mawson and Sprigg, 1950; Sprigg, 1952). The lower Proterozoic Willyama Complex (Vernon, 1969) within the OB crops out as a series of semi-isolated blocks, in fault contact with the upper Proterozoic Adelaidean succession to the west or southwest and with onlapping Adelaidean to the north or northeast (Forbes and Pitt, 1980). Campana and King (1958) divided the Willyama Complex within the OB into four broad metasedimentary units (Table I) of inferred Archaean age 'granitised' during the Proterozoic to produce large granitic terrains within the metasediments. Talbot (1967) investigated a portion of granitic terrain and adjacent metasediments (within the central Weekeroo Inlier, Figs. 2 and 3) and inverted the stratigraphy of Campana and King (1958) to place the granitic terrains at the base of the stratigraphy. Talbot mapped an area predominantly composed of the lower part of the stratigraphy proposed herein with the upper part remaining undivided and lumped into his Mica Schist and Bedded Mica Schist units. Parker (1972), working west of Wiperaminga Hill (Fig. 4) and Flint and Flint (1975), in small areas near Billeroo Hill and Mt Howden (Figs. 3 and 4) divided the sequence into units directly correlatable with the stratigraphy proposed herein. Forbes and Pitt (1980), from a considerable amount of regional mapping, chose to delineate metamorphic rather than

TABLE I

Correlations between proposed stratigraphy and previous work in the Olary Block

Campana 1958	Talbot 1967	Parker 1972	Flint and Flint 1975	Wiltshire 1975	Glen et al 1977	Flint et al 1978	Grady et al 1984		Forbes and Pitt 1980		Proprosed Stratigraphy
Weekeroo Schist	Mica Schist	Mica Schists	Arenaceous mu schist Quartzite Coarse mu-chi schist	Bedded Schist Layered Schist	Bedded mica schist Quartzitic Schist Chi schist	Chi Schist Carbonaceous Schist	Meta greywacke and Schists	5	PwS2 PwS4	Pelite Suite	5-4 5-2 5-1 5-3
Weekeroo Schist Ethiudna CS Group	Mica Schist	Ethiudna Type CS	Sulphide bearing marble	Calcareous rocks	Calc-silicate	Marble	Siderite pyrolusite unit		e	Bimba	4-2 4-3 4-1
Weekeroo Schist Ethiudna CS Group	Mica Schist		Laminated siltstone minor ep Mu schist Brecciated ep-quartzite ep-act-plag hornfels	Epidote Schist Mica Schist		Layered C-S		6	e	Ca-silicate Suite	3-3 3-5 3-6 3-4 3-7 2-2 3-1 3-2
Weekeroo Schist Outalpa Quartzites Migmatite and Granite Gneisses	Mica Schist Bedded Mica Schist Leucogneiss	Layered Gneiss and Schist Quartzite	Andalusite schist Quartzite mu schist qtz-granofels	Layered albite rock Layered Gneiss Granitic Gneiss	B.I.F Gneiss and Quartzite		Andalusite Schist Mica Schist Bedded Schist	4 7 8 9 3	Pwg4 Pwb f Pwf Pwq Pwg3 f Pwc Pwl	Quartzofeldspathic Suite	2-9 2-7 2-6 2-8 2-3 2-4 2-5 2-3 2-0 2-1
Migmatite and Granite Gneisses	Migmatitic Schist Leucogneiss	Anatexites			Granodiorite Gneiss Migmatitic Schist Leucogneiss			2 1	Pwo Pwz	Composite Gneiss Suite	1-0 1-3 1-2 1-1 ? Microcline Granitoids

stratigraphic units but generated no clear distinction between the two. Their stratigraphy (interpreted from the metamorphic units) is too broad and they frequently failed to realise large-scale fold repetitions of stratigraphic units. Suggested correlations between these stratigraphies and that described by Grady et al. (1984) for the NE portion of the Weekeroo Inliers are shown in Table I.

Within the BHB Rb—Sr whole-rock isotopic analyses of gneisses and mineral analyses of pegmatites are interpreted as dating the metamorphism at 1600±40 Ma, with a depositional age for the sequence no greater than 1820±100 Ma (Richards and Pidgeon, 1963; Pidgeon, 1967). Dating is less comprehensive within the OB but derived ages are consistent with the age ranges for the BHB. Rb—Sr ages of 1580±32 Ma by Compston et al. (1966) from a muscovite within gneisses near Binberrie Hill (Fig. 4) and 1466±185 Ma (whole rock) by Flint and Webb (1979) for granitic gneisses at Perryhummuck and Doughboy Well (10 km SE and 6 km W, respectively, of Bimbowrie HS, Fig. 3) constrain the metamorphic age for the OB. Later unfoliated granitoids give a similar Rb—Sr whole-rock age of 1503±233 Ma (Flint and Webb, 1979). In addition, Webb and Lowder (1971) measured K—Ar ages from micas within pegmatites and granites in the Alconie Hill (Fig. 4) to Bimbowrie HS area showing variable resetting associated with the Palaeozoic 'Delamerian' Orogeny and giving apparent ages ranging from ~ 459 to ~ 1328 Ma. Ludwig and Cooper (1984) sug-

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Abbreviations from Forbes and Pitt (1980): PwS2 — Pelitic qtz—mu schist; PwS4—Mu—qtz schist and quartzite; e—calc-silicate, calc-albitic rocks; Pwg4 — layered qtz—plag gneiss; Pwb — coarse grained semi-pelitic biotite gneiss; f — iron formation and facies variants; Pwf — plag gneiss, massive to thickly layered, disseminated mte; Pwq — massive to layered plag—mte quartzite; Pwg3 — layered qtz—plag—bi gneiss, migmatoid in places; Pwc — undifferentiated complex gneiss terrain; Pwl — layered quartzite and qtz—plag leucogneiss; Pwo — migmatitic gneiss; Pwz — granitic migmatite.

Abbreviations for the Olary Block stratigraphy: 5-4 Plag—mica quartzites; 5-3 discontinuous qtz—mte; 5-2 mica schists (± sill, and), interbedded silts; 5-1 carbonaceous mica schists, and/chi/sill rich near base. 4-3 Amphibolite; 4-2 siltstone and mica-ser (±gr) schists, frequently gossanous; 4-1 laminated feldsparite/calc-silicate/carbonate. 3-7 Amphibolite; 3-6 laminated qtz—mte—barite; 3-5 brecciated equivalent to 3-3, stringer cpy—py; 3-4 mica—qtz—sill—plag schist; 3-3 layered plag—ep—mte—act—qtz (±gr, mica) gneiss; 3-2 quartzo-feldspathic gneiss; 3-1 plag—ep—act di—mte gneiss. 2-9 Layered qtz—mte—barite horizon; 2-8 andalusite—staurolite—mica schist; 2-7 laminated plag—py—mte rock; 2-6 mica—qtz—feld (±sill) schist; 2-5 interlayered mica schist and qtz—feldspathic gneiss; 2-4 qtz—mte—barite horizon; 2-3 qtz—mte (±py, po) horizon; 2-2 quartzofeldspathic gneiss; 2-1 massive quartzite (±martite, mte) with qtz—feld gneiss; 2-0 quartzofeldspathic gneiss with composite gneiss. 1-3 Perryhummuck 'adamallite'; 1-2 qtz—mte (±gr, amph, py) horizon; 1-1 composite gneiss with interlayered schist (± qtzite); 1-0 composite gneiss. act — actinolite; amph — amphibole; and — andalusite; bi — biotite; chi — chiastolite; chl — chlorite; ctd — chloritoid; cpy — chalcopyrite; di — diopside; ep — epidote; f — fibrolite; feld — feldspar; gr — garnet; mu — muscovite; mte — magnetite; plag — plagioclase; po — pyrrhotite; py — pyrite; qtz — quartz; ser — sericite; sill — sillimanite; st — staurolite.

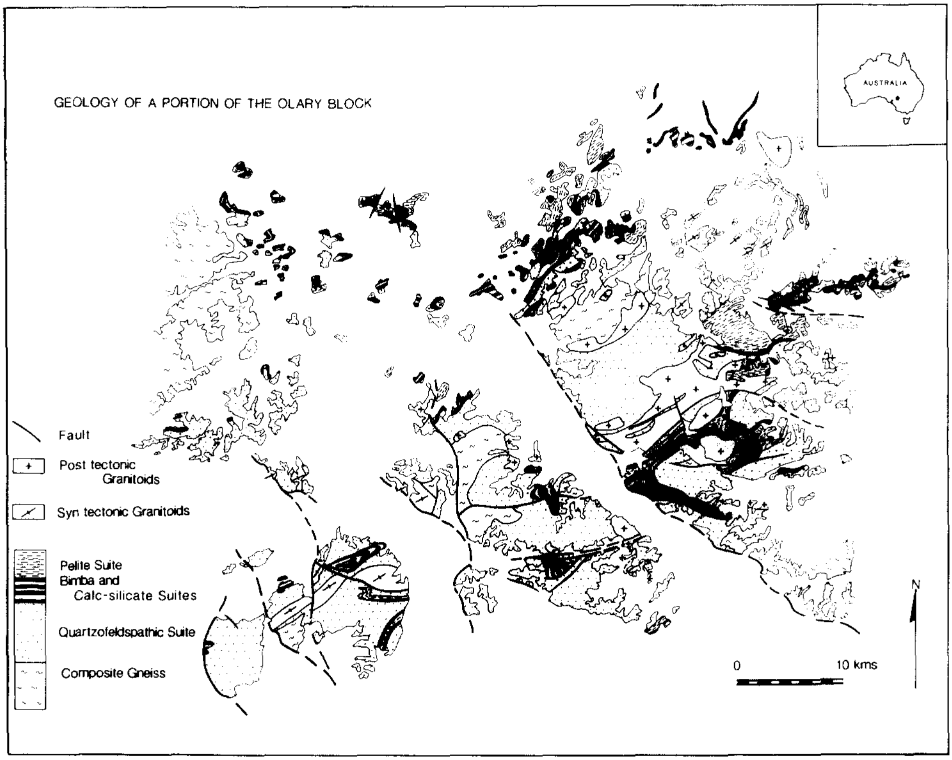


Fig. 2. Geology of the Olary Block. The location of the five stratigraphic units is based upon a reinterpretation of Forbes and Pitt (in press).

gested a tightly constrained U—Pb—Th zircon age of 1579±02 Ma for the syntectonic brannerite-bearing sodic granitoids in the Crockers Well (Fig. 4) area (cf. Ashley, 1984a).

Regional succession

Five rock suites are proposed for the OB changing in general composition from quartzo-feldspathic to calcic to pelitic but unlike the BHB there is no significant single change to pelitic sedimentation (cf. Willis et al., 1983). The stratigraphic sequence in the BHB has been interpreted as a progressively developing rift system (Willis et al., 1983).

In defining the regional structure of the OB the middle and upper parts of the proposed stratigraphy (Table I) are the most useful since these parts contain the marker horizons allowing recognition of fold duplication. The lower parts of the stratigraphy contain crudely layered quartzo-feldspathic gneisses within which characteristic horizons are infrequent. Hence most work has been completed in the middle and upper parts of the stratigraphy and it is these sections that are proposed with most confidence

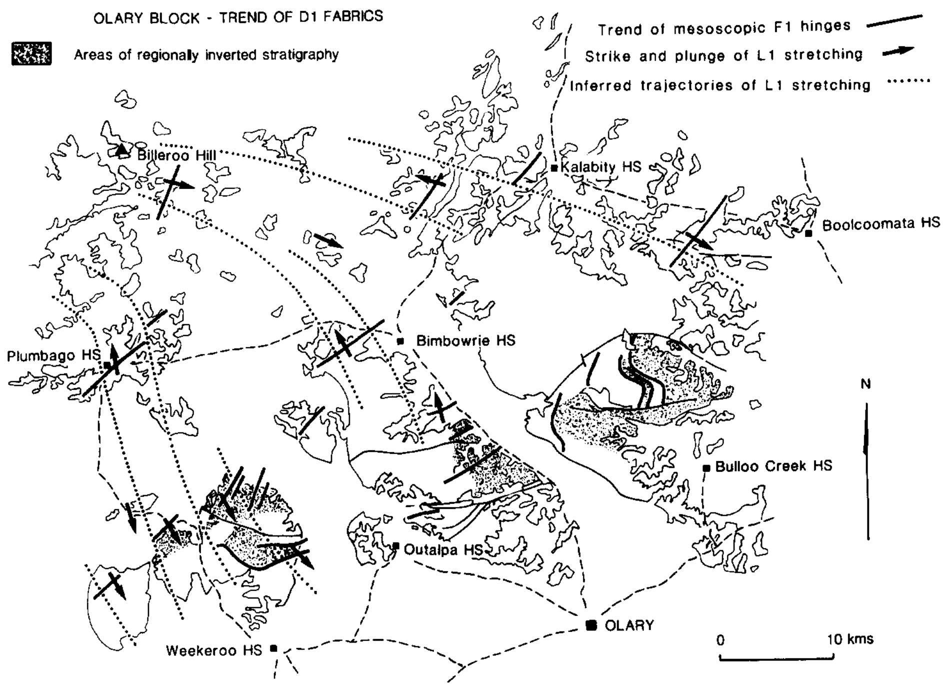


Fig. 3. Trend of D1 fabrics and areas of regionally inverted stratigraphy within the Olary Block.

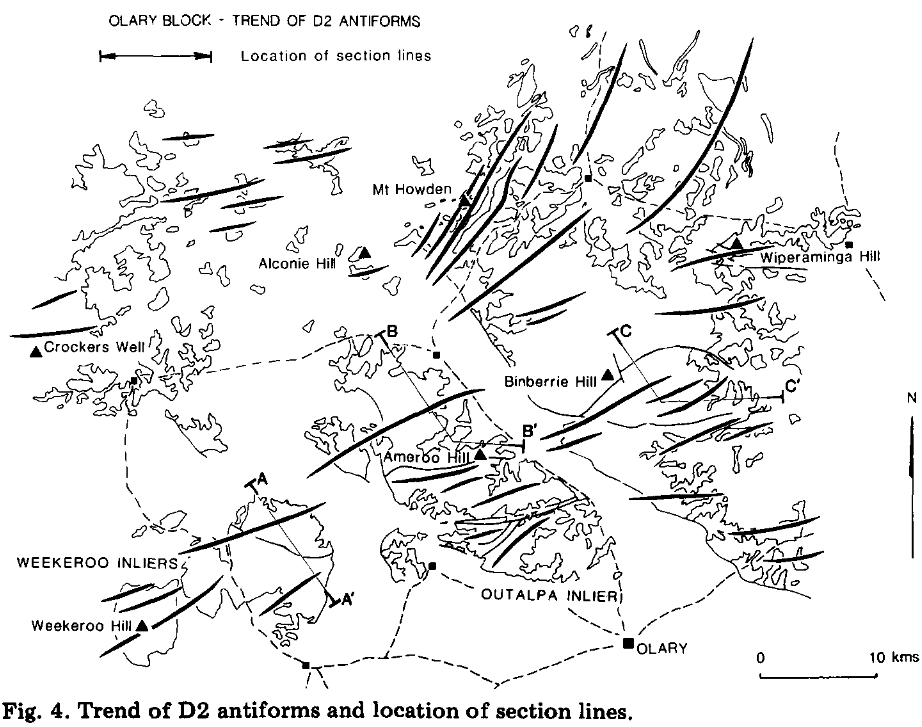


Fig. 4. Trend of D2 antiforms and location of section lines.

Fig. 5. Post-tectonic granitoid intruding metasediments, 6 km south of Bimbowrie (located in Fig. 3).

and relevance. A regional interpretation of the distribution of the stratigraphy (Fig. 2) is based upon a reinterpretation of regional mapping by Forbes and Pitt (in press).

Forbes and Pitt (1980 and in press) distinguish two phases of granitoid emplacement into the metasediments. Foliated granitoids are interpreted as syn-tectonic and include tonalitic and albite rich (granodiorite, adamellite) compositions. These display concordant and intrusive contacts with the metasediments. Later unfoliated granitoids are post-tectonic,, range from granitic to granodioritic in composition and usually preserve intrusive contacts (Fig. 5).

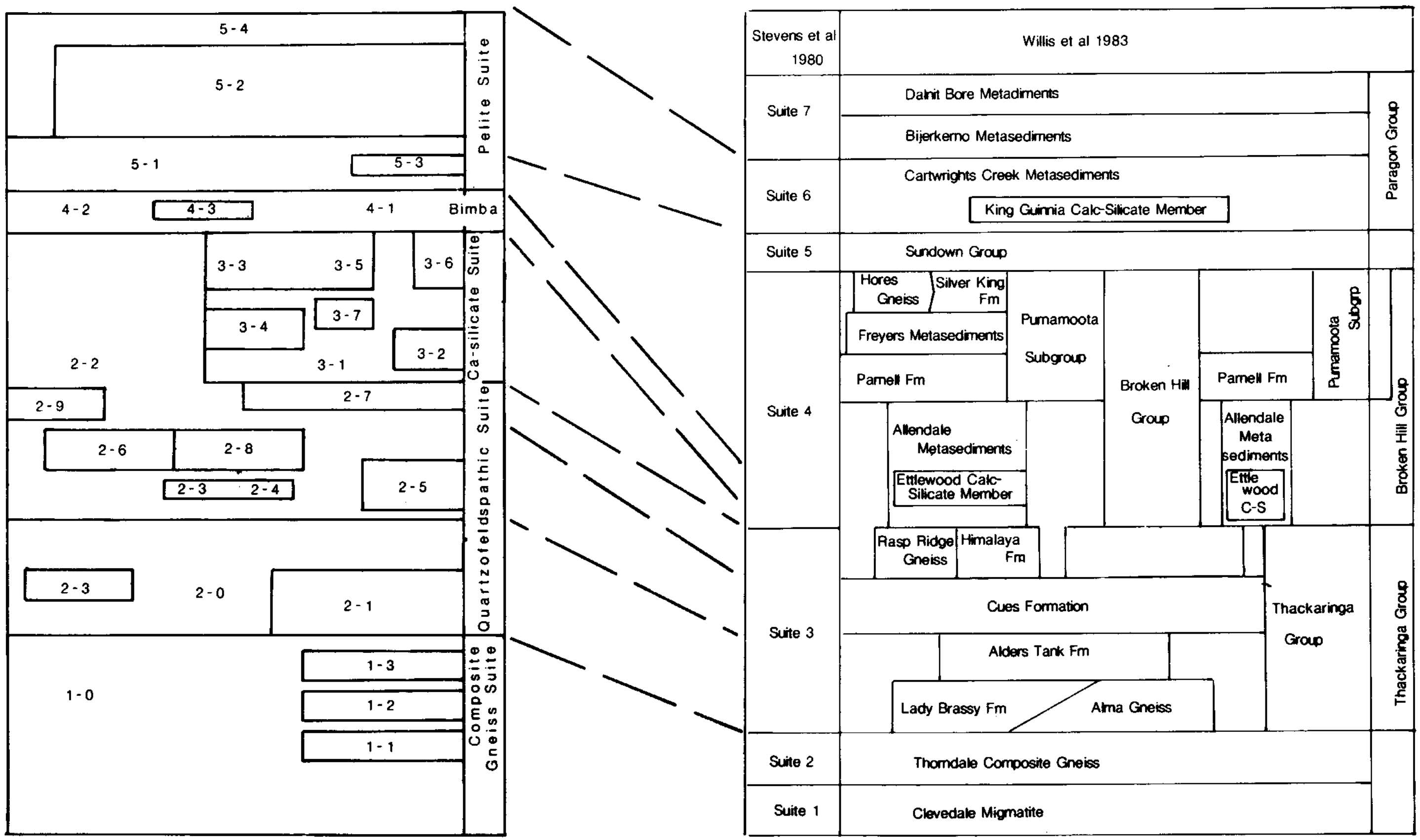
Correlations between the proposed stratigraphy and previous work within the OB are shown in Table I and with the Willyama Supergroup (Willis et al., 1983) indicated in Table II. The strong correlation of stratigraphies between the two blocks suggests that the OB succession has a similar thickness to the Willyama Supergroup of the BHB (~ 6000 m, Willis et al., 1983). The five rock suites proposed for the OB are described below:

Composite Gneiss Suite

Basal to the OB stratigraphy are coarse-grained quartz—feldspar—biotite (± sillimanite, garnet) gneisses with a coarse migmatitic texture and abundant sodic plagioclase—quartz laminae. Occasional stratiform quartz—magnetite (± sulphide, amphibole, garnet, apatite), mafic gneiss, sillimanite—garnet

TABLE II

Correlation between the stratigraphy proposed for the Olary Block and the Willyama Supergroup, Broken Hill Block



schist and quartzite (± pyrite, martite) horizons are present but comprise a small part of the suite. The suite commonly includes coarse, massive to porphyritic to gneissic microcline granitoids (Spry, 1977) which Liverton (1967) describes as similarly deformed to enclosing migmatites. Emplacement of the microcline granitoids is therefore pre- to syn-tectonic but Ashley (1984a) distinguishes them from the sodic granitoids which are derived by anatectic melting of sodic-rich metasediments.

The Quartzo-feldspathic Suite

The characteristic rock type for this suite is a crudely layered quartz—plagioclase—biotite (± K-feldspar) gneiss, commonly with disseminated magnetite and/or pyrite. Lithological layering varies from a few millimetres to tens of metres and several major but discontinuous quartz—magnetite (± pyrite, barite) horizons are contained within the suite. Interlayering of Composite Gneiss is common in the lower part of the suite. Locally (in the Weekeroo Inliers, Fig. 4) a thick basal martite quartzite unit occurs. Major pelitic units containing coarse andalusite schists with well-bedded metasilts and magnetite-bearing gneisses crop out in the Weekeroo Inliers and N of Ameroo Hill (Fig. 4). Present within the Kalabity area (Fig. 3) are quartz—muscovite schists containing minor quartzite and epidote metasiltstone. Sedimentary structures are common in suitable rock types (graded bedding, ripple cross-laminations as shown in Fig. 6, and ball and pillow structures). The top of the suite contains a finely laminated plagioclase—

Fig. 6. Ripple crests within a quartzite, 5 km west of Bimbowrie (located in Fig. 3).

pyrite—magnetite unit at Waukaloo Dam (8 km N of Kalabity HS, Fig. 3), a quartz—magnetite—barite horizon at Old Boolcoomata (6 km SW of Binberrie Hill, Fig. 3) and a garnet—grunerite—quartz horizon associated with garnetiferous amphibolites within the Weekeroo Inliers.

The Calc-silicate Suite

Massive, banded or finely laminated calc-silicate beds, commonly interlayered with metasiltstones and lesser felsic gneiss characterise this suite which is inconsistently developed over the OB. Rock types are typically finer grained and more finely laminated than the Quartzo-feldspathic Suite. The thickest and most continuous exposure occurs on the northernmost segment of the block where a laminated plagioclase—actinolite—epidote—magnetite (± clinopyroxene, garnet, pyrite) bed (the Upper Albite of Willis et al., 1983 and Ashley, 1984b) persists from Billeroo to Wiperaminga Hills (Figs. 3 and 4). Magnetite and plagioclase-rich horizons are interlayered within the suite and north of Kalabity HS (Fig. 3) a quartz—magnetite—barite horizon occurs adjacent to albite—quartz—garnet—piemontite—tremolite rock (Ashley, 1984b). Quartzo-feldspathic gneisses are a common part of the suite, usually plagioclase rich but often also bearing K-feldspar. Poorly exposed mica schists appear to be a probable lateral equivalent to the calc-silicates north of Kalabity. The prevalence of magnetite throughout the suite distinguishes it from the overlying Bimba.

The Bimba Suite

A thin but laterally persistent unit, the Bimba Suite is usually a finely laminated host to predominantly pyritic sulphides. Laminated carbonates interbedded with calc-silicates are diagnostic but pyrite—quartz—feldspar—sericite schists, pyritic feldsparites and rare gneisses occur. Compositionally layered, most of the calc-silicates consist of combinations of calcite, siderite, quartz, plagioclase (albite to andesine), amphibole (tremolite, actinolite, hornblende, cummingtonite), epidote (zoisite, clinozoisite), garnet, scapolite, vesuvianite and sphene (Spry, 1977), and occasionally wollastonite (P.M. Ashley, personal communication, 1986). Compositional layering is interpreted as reflecting primary sedimentary layering. The suite has extensive stratiform Fe sulphide dominated gossans derived from abundant pyrite/pyrrhotite mineralisation. Cu—Co mineralisation at Mt Howden (Fig. 4) and Cu—Zn within the Old Boolcoomata (6 km SW of Binberrie Hill, Fig. 4) area occur as accessory to the carbonate hosted Fe sulphides. In the Weekeroo Inliers (Fig. 3), fine-grained quartz—plagioclase—biotite—garnet gneiss and a ribbon carbonate occur within plagioclase mica schists.

The Pelite Suite

The entry of the Pelite Suite into the stratigraphy is commonly marked by carbonaceous mica schists immediately overlying the Bimba Suite. Often containing pyrrhotite, they also include two horizons containing coarse chiastolite in the Kalabity area (Mawson, 1911; Flint and Flint, 1975; Flint et al., 1978). Further south, andalusite occurs in place of chiastolite but both are regionally pseudomorphosed by fibrolite and lesser prismatic sillimanite. The carbonaceous schists juxtaposed with the Bimba represent one of the few reliable, albeit sporadic, marker horizons throughout the OB. Stratiform tourmaline horizons commonly mark the lower part of the suite. At Meningie Well in the Old Boolcoomata area (immediately S of Binberrie Hill, Fig. 4), a quartz—magnetite horizon is located near the top of the basal carbonaceous schists which usually pass up into quartz—plagioclase—biotite—muscovite schists with interbedded quartzofeldspathic metasilts and thin quartzite horizons. The uppermost exposure of the stratigraphy is interpreted as occurring in the NE portion of the Weekeroo Inliers (Fig. 3). Fine-grained plagioclase—mica quartzites with thin discontinuous calc-silicate horizons and disseminated calc-silicate spheroids occur in the core of a dome imposed upon inverted stratigraphy.

STRUCTURE OF THE OLARY BLOCK

Introduction and analysis method

The OB has suffered five deformational episodes (D1—5) (Berry et al., 1978). The Proterozoic 'Olarian' Orogeny (Glen et al., 1977) comprises events D1—3 affecting solely the lower Proterozoic gneisses and events D4—5 took place during the Cambrian 'Delamerian' Orogeny deforming the upper Proterozoic Adelaidean sequence. Minor crenulation of the 'Olarian' deformation fabrics near contacts of the two sequences and broad warping of the basement are the D4—5 effects within the gneisses.

Within the lower Proterozoic metasediments the stratigraphic unit repetition is principally controlled by NE to E trending, upright, open to tight D2 folds, refolding an earlier D1 recumbent terrain. Moderate to strong crenulation of a pre-existing and previously shallow dipping or flat lying fabric is present in most localities. Development of the later near-vertical D2 schistosity obliterates much of the earlier fabric in pelitic rocks. Effects of D3 are mostly gentle warps of pre-existing fabrics and dissection by retrograde shear zones (RSZ) but have only minor consequence upon stratigraphic unit geometry. F3 folds suggest compression from the same direction as the RSZ, hence both are part of the one event.

Owing to abundant sedimentary features, the Willyama Complex is particularly suitable for rapid analysis of outcropping sequence to elucidate early fold structures. Fold 'asymmetry' is generated by the alternation of long and short limbs (S, Z and M fold shapes of Ramsay, 1962) when observed in a section that cuts the hinge lines and is viewed down the plunge of the hinge line (Hansen, 1971). By recording on a map the sense of 'asymmetry' (the shape) of minor folds developed on a major structure, the field geologist is able to locate the position of the large fold. Of concern

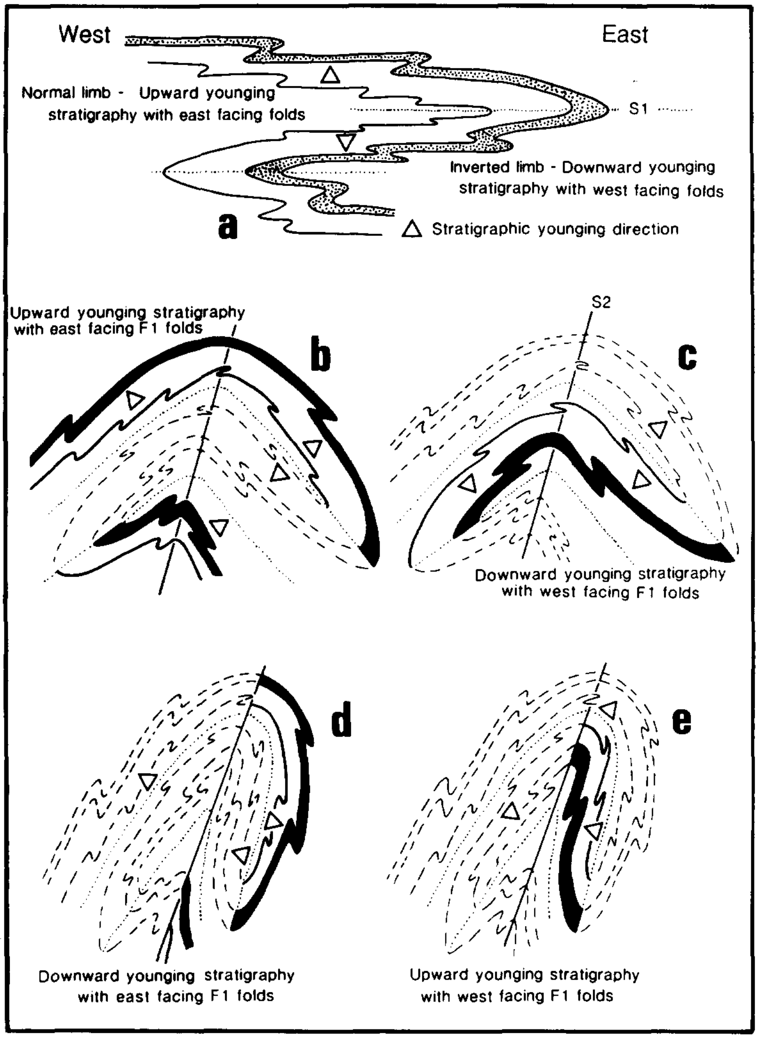


Fig. 7. Relationship between stratigraphic younging and F1 facing in a refolded recumbent terrain.

in this article is a recumbent fold terrain in which the normal and inverted limbs of a regional (or first order) fold possess upward and downward younging stratigraphy, respectively. The sense of asymmetry (or apparent facing direction) of parasitic (second order) folds on a singular limb of the regional fold will be constant thereby generating a pattern of parasitic apparent facing and stratigraphic younging. This is illustrated in Fig. 7a. By contrasting the fold apparent facing with stratigraphic younging, the amplitude and eventually the regional transport for generation of the recumbent terrain can be demonstrated (Hansen, 1971). The upright to reclined folding of this recumbent fold creates four possible relationships of F1 facing relative to stratigraphic geometry. Simple open refolding of the recumbent terrain (Fig. 7b, c) results in little change to geometry but does change the outcrop pattern of stratigraphic units. The consistent pattern of F1 apparent facing to stratigraphic younging may be reversed by tight reclined refolding: in Fig. 7d stratigraphy in the normal F1 limb is inverted by the D2 folding and in Fig. 7e stratigraphy twice inverted becomes upward younging. Note, however, that the sense of F1 fold facing is maintained for rotation about the D2 axial plane. The apparent F1 facing only changes across a regional F1 axial trace. Once the pattern of F1 facing and stratigraphic younging is established, the rapid and easy observation of either with respect to local D2 geometry is sufficient for analysis of D1 morphology. The use of these fabrics demonstrates microtectonics as a powerful tool in macroanalysis of polyphase deformation areas.

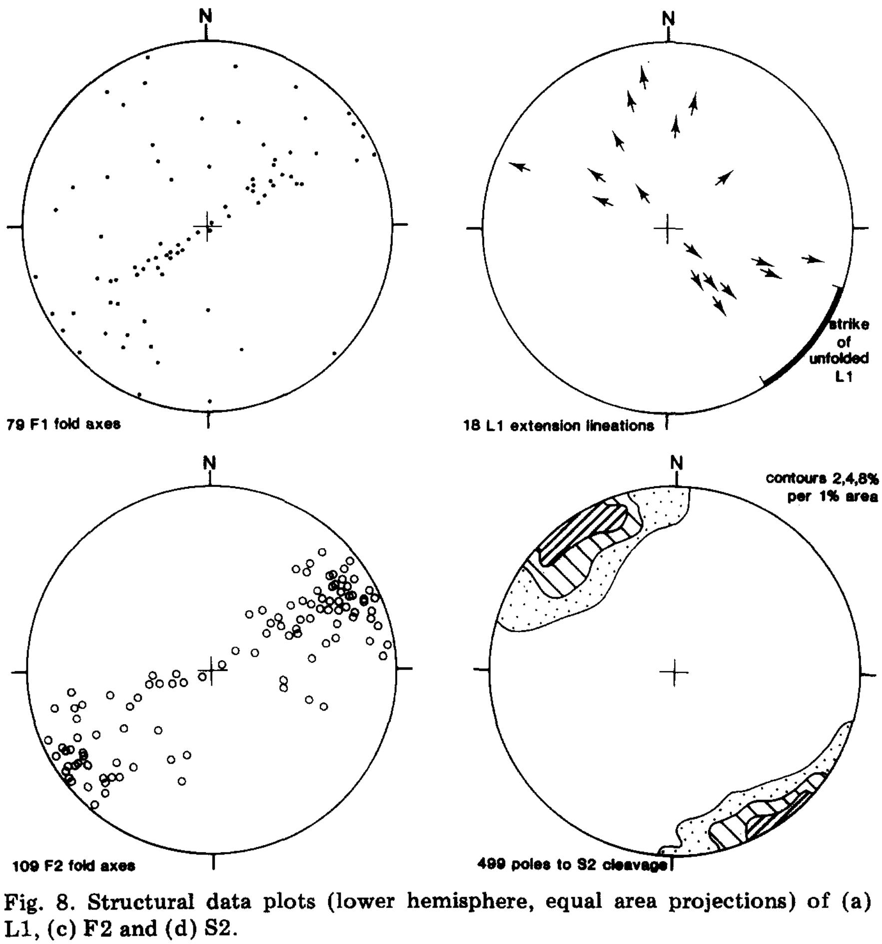


Fig. 8. Structural data plots (lower hemisphere, equal area projections) of (a) F1, (b) L1, (c) F2 and (d) S2.

The 'Olarian' Orogeny

D1 event

The earliest recognised event is characterised by mesoscopic to macroscopic, tight to isoclinal recumbent F1 folds with an axial surface, S1, defined by the preferred dimensional orientation of micaceous minerals. On a mesoscopic scale the F1 fold axes trend mostly NE to E (Figs. 3 and 9) and in places possess an elongation and mineral lineation, L1, (Fig. 10) orientated at a high angle to the axes. The F1 folds usually rotate bedding into an orientation sub-parallel to S1 so that intersection lineations are rare. The weak but discrete L1 lineation is irregularly developed across the OB but consistent trends have been found and are indicated in Figs. 3 and 8. The lineation, which is not distorted in individual mesoscopic F1 hinges, appears genetically related to the S1 fabric. From its consistency of orientation, discordance with F1 hinges and mineral streaking characteristics, L1 is taken as indicating a movement direction. The observation of curved F1 hinges on a local scale in calc-silicate rocks accords with rotation of the hinges towards parallelism with the flow direction (L1) during progressive shear (Bell, 1978; Cobbold and Quinquis, 1980; Berthé and Brun, 1980) and the genetic relationship of L1 and S1. Also supporting this interpretation

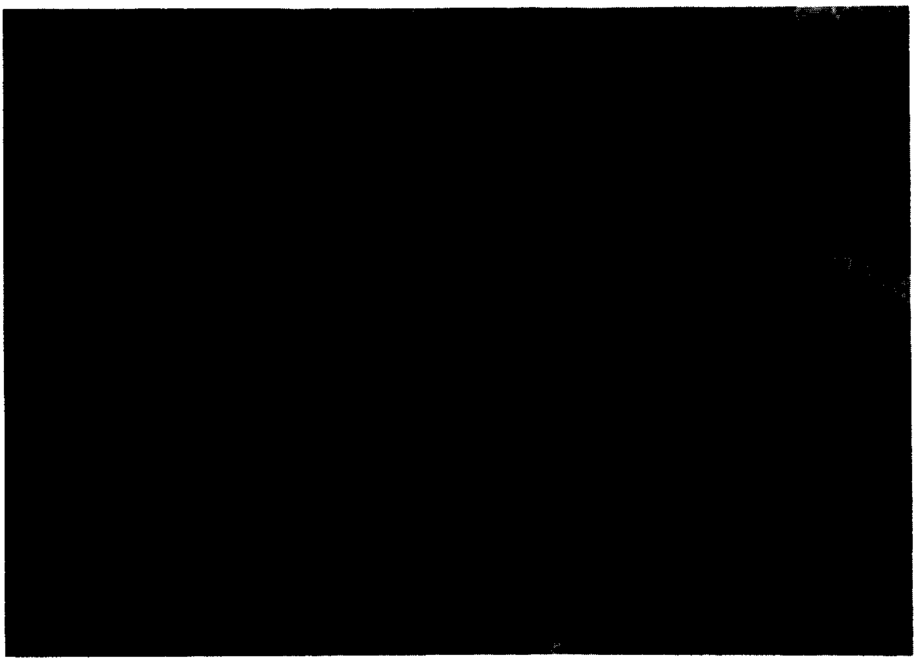


Fig. 9. Recumbent folds within the NE portion of the Weekeroo Inliers (located in Fig. 3), hammer arrowed for scale.

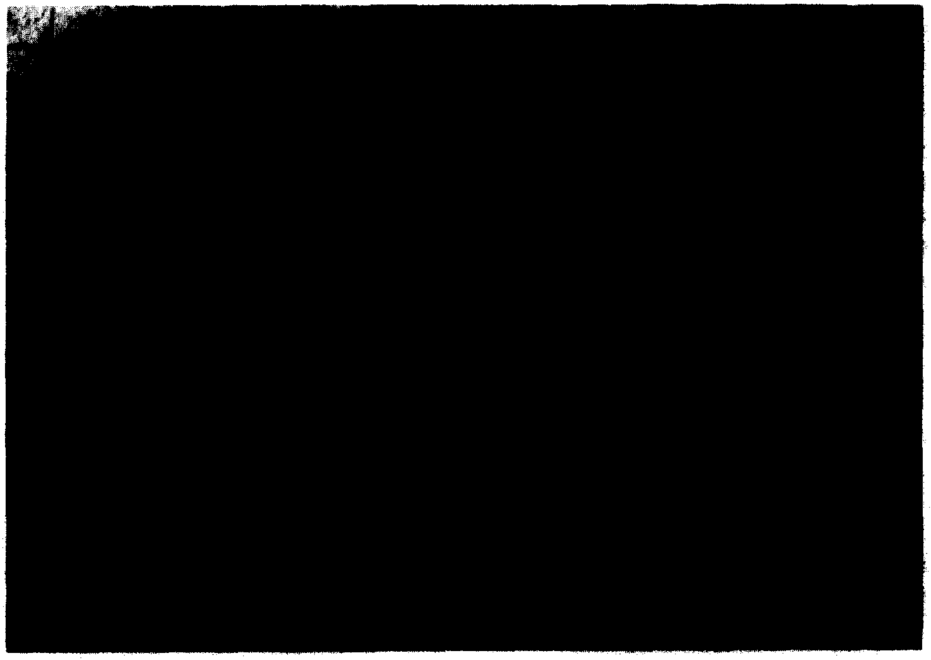


Fig. 10. L1 elongation and mineral lineation within S1. Plumbago HS (located in Fig. 3).

Fig. 11. C—S1 planes indicating southward (dextral in photograph) shear in quartzo-feldspar gneisses, Plumbago HS (located in Fig. 3).

is the observation of C—S planes (Berthé et al., 1979) persistent for several kilometres within quartzo-feldspathic gneisses (Fig. 11) in the vicinity of Plumbago HS (Fig. 3). Both the C and S1 planes contain identically trending lineations which parallel L1 observed elsewhere and both C—S1 planes are similarly deformed by later structures. The trend of S1 where the C—S1 planes are observed is consistent with S1 trends elsewhere, however, the reorientation of S1 by the D2 event makes it difficult to confidently identify any C—S1 relationship in other areas.

Recognition of F1 folds throughout most of the OB is restricted to intrafolial isoclinal folds where the S1 surface has been rotated by later deformations. Within the NE portion of the Weekeroo Inliers, however, not only can a change between major areas of (pre-D2) overturned and

Fig. 12. Parasitic F2 fold. Bimbowrie HS (located in Fig. 3).

upright stratigraphy be demonstrated (Fig. 3) but D1 folds of a several tens of metres scale may be observed (Fig. 9). The documented relationship of westward-facing F1 folds with downward-facing stratigraphy in the NE portion of the Weekeroo Inliers demonstrates a SE direction of transport for the F1 deformation. This is verified by eastward to southeastward facing F1 folds within other parts of the OB with upward-younging stratigraphy and supported by the C—S1 relationship.

The consistent trends of F1 and L1, the coherent pattern of these D1 fabrics with stratigraphic younging and the compatibility of the C—S1 planes show that the recumbent terrain has suffered a southeastward directed shear on a regional scale.

D2 event

The D2 deformation is characterised by mesoscopic to macroscopic, upright to reclined, open to tight F2 folds with a steeply NW dipping S2 axial surface. Cylindrical on a sub-regional scale, major D2 folds commonly have wavelengths of tens of kilometres and amplitudes of some kilometres. Parasitic F2 folds are commonly tight with interlimb angles of 50—60° (Fig. 12) but the regional F2 folds are mostly open with larger interlimb angles (Fig. 13). The S2 axial plane is commonly defined by moderate to strong crenulation of the S1 fabric producing a widespread intersection

Fig. 13. Macroscopic F2 synform folding downward younging stratigraphy. NE portion of the Weekeroo Inliers (located in Fig. 3).

and crenulation lineation, L2. A weak elongation fabric, often defined by micaceous aggregates haloing andalusite grains parallels the L2 and in Fig. 14 the complete alignment of andalusite grains during D2 can be observed. Approximately 40% shortening is inferred for D2 from detailed sections measured and then 'unfolded', in the NE portion of the Weekeroo Inliers (Fig. 4). Fry analyses (Fry, 1979), completed in the same area on a deformed siliceous breccia with no D1 penetrative fabric, suggest strain during D2 as apparent constriction (X:Y:Z ratios are ~ 1.7:1:0.9 giving a shape factor K=6.4, Flinn, 1962, and an intensity r=1.8, Watterson, 1968). Measurements on ellipsoidal andalusite nodules within pelitic schists in the Old Boolcoomata area indicate a flattening type strain (X:Y:Z ratio of ~ 1.6:1:0.45 giving a K=0.5 and an r=4.6). The difference in K and R values reflects differing bulk rock composition — the siliceous breccia suffering lower strain (hence lower r value) than the strongly foliated pelite. Mesoscopic F2 folds possess a vertically fanning S2 (Fig. 8) but regional F2 folds have a steep NW dipping axial surface.

The sub-parallelism of the F1 and F2 axial traces (Figs. 3 and 4) causes interference patterns on a mesoscopic scale to be rare. However, in the Weekeroo Inliers and at Old Boolcoomata, the F1 axes are oblique to F2 and

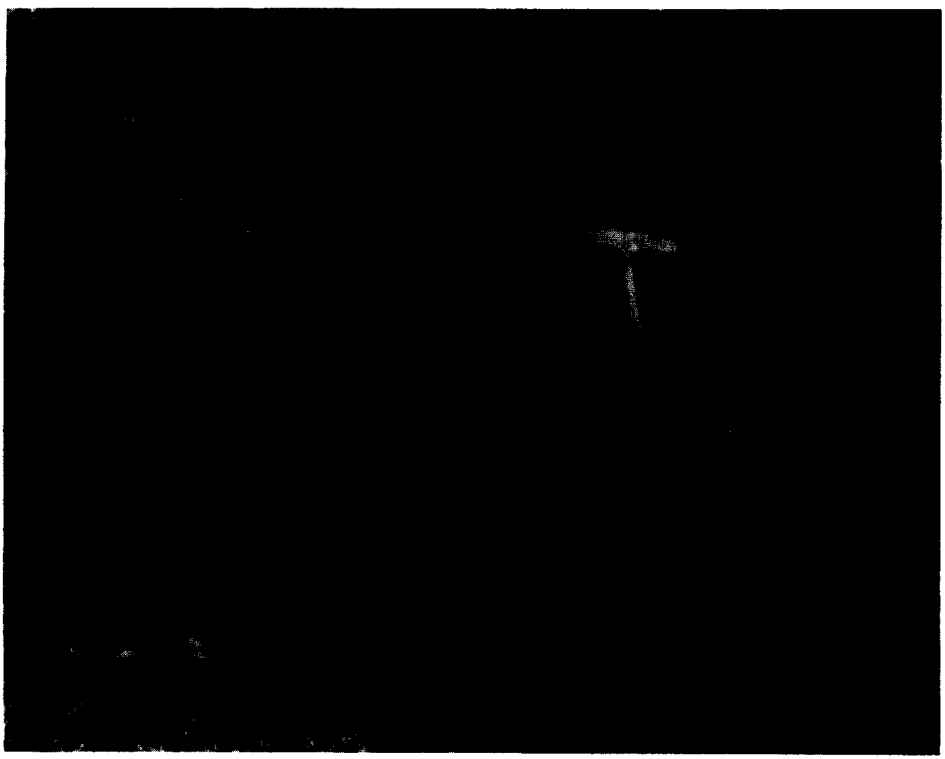


Fig. 14. Andalusite porphyroblasts aligned with L2. Wiperaminga Hill (located in Fig. 4).

Fig. 15. Type 2 interference pattern. Old Boolcoomata area (S of Binberrie Hill, Fig. 4).

Type 2 interference (Ramsay, 1962) may be observed (Fig. 15). This general sub-parallelism of F1 and F2 fold axes also explains the distinct L1 trajectories, with F2 preserving the primary orientation of L1 and affecting mainly the plunge. This similarity in trend of the major F1 and F2 axes (Figs. 3 and 4) is consistent with the generation of D2 along the same compression axis as for the D1 and the asymmetry of the NW dipping S2 associated with regional F2 axes, consistent with continued movement toward the south-east (Hansen, 1971). In conclusion, it seems simplest to consider the D1 and D2 events as having developed progressively during the same continuum of orogenic event, which suggests that the time span between them could be small.

Regional interpretation of D1 and D2 interference

Given the separation of structural fabrics outlined above and the model for regional analysis outlined in the introduction to this section, it is possible

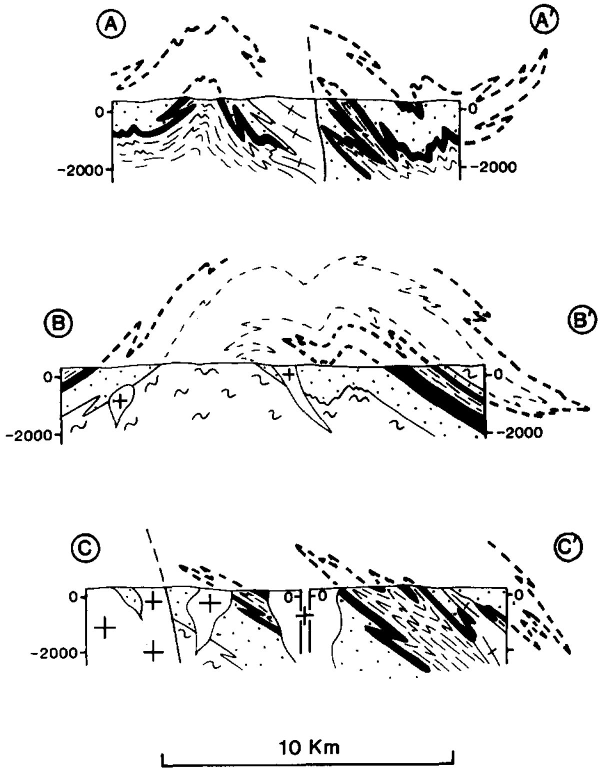


Fig. 16. Interpretative cross sections. A—A' Weekeroo Inliers; B—B' Outalpa Inliers; C—C' Old Boolcoomata Area. Location shown in Fig. 4.

to define areas of pre-D2 upright and pre-D2 inverted stratigraphy. This then allows macro-analysis of the OB and interpretation of the form of the early recumbent terrain. Areas of regionally inverted stratigraphy are found in the Weekeroo and Outalpa Inliers and at Old Boolcoomata (Figs. 2 and 3). The inverted areas are on a scale of several kilometres indicating macroscopic folds of a similar scale. Inferred sections through these critical areas demonstrating unit geometry and F1 fold scale are shown in Fig. 16. Various relationships of D1—D2 interference shown in Fig. 7 can be observed in different parts of the OB — Fig. 7b in the Kalabity area; Fig. 7c and locally 7d in the NE portion of the Weekeroo Inliers; Fig 7d and 7e in the SE portion of the Weekeroo Inliers (compare Figs. 7 and 16).

The proposed deformation sequence and structure accords with detailed work in restricted areas by other workers. Parker (1972) described the deformation west of Wiperaminga Hill (Fig. 4) and interpreted the outcrop pattern as due to a first phase of isoclinal folding followed by a second phase of intense buckling. Wiperaminga Hill comprises a F2 syncline, such as shown in Fig. 7b. Flint and Flint (1975) ascribed the NE trending folding

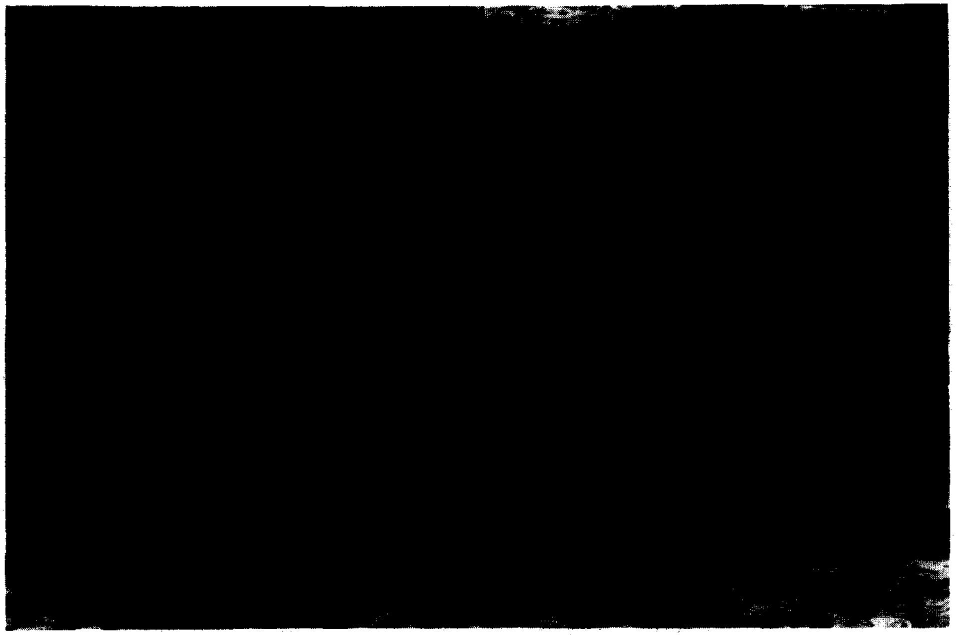


Fig. 17. F3 folds. Mt. Howden (located in Fig. 4).

at Mt Howden to a second deformation event, correlating westward to Billeroo Hill (Fig. 3) where similarly oriented upright folds are again the pervasive folding. Within the Outalpa Inlier, Berry et al. (1978) suggested that the pervasive NE trending event (indicated in Fig. 4 and herein described as D2) was a third deformation phase, with rare low angle discontinuities between an interpreted S2 and earlier isoclinal hinges being the principal argument for two previous deformations (D. Flint, personal communication, 1984). The F2 fold axes of Berry et al. (1978) are very restricted in development and poorly constrained in orientation. From these observations Grady et al. (1984) correlate the pervasive upright folding in the Weekeroo Inliers (herein described as D2) as a third deformation phase. Archibald (1983) mapping an area near Old Boolcoomata recognised three deformation phases. Again, however, the second phase is very localised, parallels D1 fabrics in orientation and has only minor effect upon stratigraphic geometry. After the work of Harris et al. (1982) and Coward and Potts (1983) on the relationship between strain patterns and deformation fabrics, it is suggested that the inferred two early phases of Berry et al. (1978) and Archibald (1983) are local perturbations and occurred in response to continued movement from the one deformation episode (no strain patterns are reported for the work in Outalpa and Old Boolcoomata). The major deformation in the OB are thus ascribed to the two episodes described herein.

D3 event — RSZ

Throughout the OB, east-striking retrograde shear zones dissect the sequence, overprinting D1 and D2 folds. Any pre-existing fabrics are rotated into parallelism within the narrow (<50 m) and generally steeply south-dipping, strongly foliated zones. Recrystallization of mineral fabrics to lower amphibolite—greenschist metamorphic facies occurs, with extensive hydration of previous assemblages. Within the Kalabity area (Fig. 4), interference between the NE trending F2 folds and later, E striking F3 folds (Fig. 17), possessing a near-vertical axial surface, produces dome and basin outcrop pattern. This folding is not pervasive throughout the OB and effects of D3 are mostly restricted to the discrete shear zones which preserve greenschist facies mineral assemblages. The RSZ cross-cut the unfoliated (post-tectonic) granitoids (Fig. 18). Steeply plunging elongation and mineral lineations present within the E striking RSZ preserve evidence for a reverse sense of movement (S over N) whilst zones oblique to the approximately N—S compression axis preserve a considerable transcurrent component of movement.

Fig. 18. Retrograde shear zone dissecting a post-tectonic granitoid. 6 km south of Bimbowrie (located in Fig. 3).

D4, D5 events — the 'Delamerian' Orogeny

Analyses of the effects of the Cambrian 'Delamerian' Orogeny within the OB are presented by Forbes and Pitt (1980 and in press) for the upper Proterozoic Adelaidean sequence, and in Berry et al. (1978) and Grady et al. (1984) for the Willyama Complex. Fabrics produced by the 'Delamerian' Orogeny within the Willyama Complex rocks include regional warping of the basement blocks (demonstrated in rotation of F1 and F2 axes about a NW trending structure, Fig. 8) and crenulation of the 'Olarian' Orogeny fabrics proximal (<1 km) to the unconformities. However, these fabrics are of little consequence in the basement terrain, in which the dominant response to the orogeny is represented by mylonite zones (e.g., the MacDonald Hill Fault). These shear zones may be distinguished from the pre-Adelaidean RSZ by the presence of sheared pebbles sourced from the Adelaidean sequence in the younger shear zones, and the more hydrous nature of mineral assemblages in the older zones.

METAMORPHISM

Petrological investigation (Clarke et al., in press) of pelitic rocks characterises S1 as comprising prograde assemblages involving a combination of staurolite, biotite, muscovite, quartz, andalusite and garnet. S2 contains mineral assemblages characterised by some chloritoid, chlorite, garnet, sillimanite, muscovite and quartz. Prograde S1 assemblages may be discerned in most places although overprinting associated with D2 creates S2 as the dominant mineral assemblage and obvious fabric in the field. The thermal peak of metamorphism is marked by sillimanite overprinting andalusite late in D1 and continuing post D1 accompanying the intrusion of the syn-tectonic granitoids.

Of concern in this article is an estimate of peak metamorphic conditions accompanying deformation. The pervasive nature of the S2 makes the overprinting assemblages the most reliable for these estimates. Sampling of pelites throughout the OB reveals a geographical partitioning of staurolite within the S2 assemblages. Staurolite is present within S1 and S2 in the southern portion of the OB but in the north the S2 assemblage chloritoid, fibrolite is interpreted as the retrograde products of S1 staurolite (Clarke et al., in press). The geographical partitioning is inferred as reflecting higher grade conditions during S2 in the southern portion of the OB, which is consistent with the SE increase in metamorphic grade documented for the BHB (Phillips and Wall, 1981; Hobbs et al., 1984). The breakdown of staurolite to chloritoid plus fibrolite suggests regional peak temperatures higher than 520°C (Bickle and Archibald, 1984). Both prismatic sillimanite and kyanite may be observed overprinting S1 andalusite in the southern portion of the OB. The presence of the three aluminosilicate polymorphs suggests peak metamorphic conditions in the upper part of the andalusite field giving pressures of 4—5 kbar (Richardson et al., 1969; Holdaway, 1971). The presence of S2 kyanite and inferred *P—T—t* path for the OB (Clarke et al., in press) suggests D2 is associated with isobaric processes. Higher temperature conditions during the D2 overprinting are experienced by rocks in proximity to the syn-tectonic granitoids (Berry et al., 1978; Grady et al., 1984).

DISCUSSION

The observation of (unfolded) SE to south-facing F1 folds associated with upward younging stratigraphy and NW to north-facing F1 folds associated with downward younging stratigraphy indicates a southeasterly direction of transport for the F1 fold generation. The presence of a near-vertical to steeply NW dipping S2 is consistent with the D2 as resulting from continued shear in the same sense and direction as for D1. This single, continued compressional episode comprises the 'Olarian' Orogeny.

The metamorphic assemblages in the OB suggest the currently exposed rocks were buried to a depth of 15—20 km. Estimates of present-day crustal thickness in the Australian Proterozoic metamorphic belts are of the vicinity of 30—35 km (Cleary, 1973; Mathur and Shaw, 1982) and thus the inferred eroded crust for the OB would give an orogenic crustal thickness of about 50 km. This thickening was accompanied by a thermal anomaly which allowed granitoid formation. The overprinting during D2 being accompanied by isobaric processes suggests the orogenic crust maintained a constant thickness of ~ 50 km during deformation and did not record any uplift. This in turn supports the contention that D1 and D2 in the OB were temporally close (England and Richardson, 1977; England and Thompson, 1984) and is consistent with the 'Olarian' Orogeny comprising a single continued compression event.

The extent of isotopic homogenisation is poorly constrained throughout the OB but peak metamorphic conditions late in D1 are followed by the intrusion of syn-tectonic granitoids dated at 1579±2 (Ludwig and Cooper, 1984) as a minimum. This is consistent with similar metamorphic ages in the BHB where NE striking F2 folds deform an earlier recumbent (Marjoribanks et al., 1980) to reclined/recumbent (Hobbs et al., 1984) terrain. No regional analysis of F1 fold orientation is given but in Fig. 6 of Hobbs et al. (1984) several regional S1 traces run from near Silverton NE to Yanco-Glen. A scale of tens of kilometres is suggested by Hobbs et al. (1984) for the F1 closures. The relationship between F1 facing and stratigraphic younging in the BHB has not been described but NW verging F1 folds are inferred. However, the presence at Stirlingvale Homestead of a regional F1 anticline (inferred from stratigraphic facing), with closure facing southeast to south (Fig. 19); and at Twenty Mile near Thackaringa Homestead, an F1 syncline closing to the west (Fig. 19) demonstrate F1 generation by transport in an east to southeasterly direction on a regional scale. A preliminary survey by the authors throughout the BHB confirms this transport

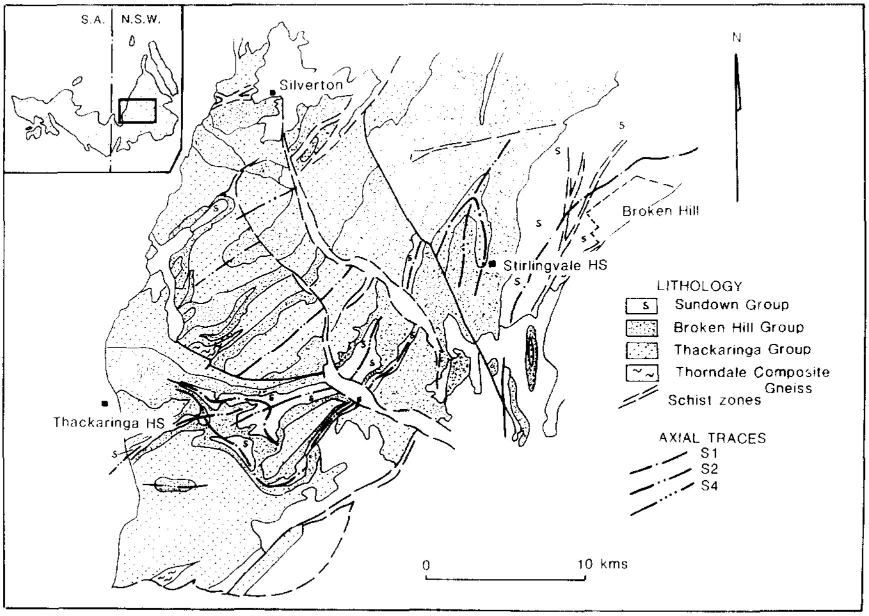


Fig. 19. Geological map of a portion of the Broken Hill Block (after Hobbs et al., 1984). Note location of F1 closure discussed in text at Stirlingvale HS and 6 km east of Thackaringa HS.

direction. This is inconsistent with the interpretation implied (Fig. 7, Hobbs et al., 1984) of upward younging stratigraphy with regionally NW verging F1 folds. The nature of D2 folding in the BHB has been well documented by the above authors and is identical to that described herein for the OB. Thus, stratigraphy and major deformation events in the OB and BHB may be correlated.

Hobbs et al. (1984) do not suggest any mechanism for the generation of the recumbent terrain. Marjoribanks et al. (1980) suggested that the F1 generation for the BHB was associated with a root zone of intense deformation, centred on the migmatites and granite gneisses of the Darling Range, south of Broken Hill. A principal vertical extension is implied for this root zone, with nappes flanking off either side under gravitational collapse. This model contrasts the observed sub-horizontal strain indicators associated with the D1 event in the OB (and by inference in the BHB) and necessitates the opposite direction of transport to that described herein. The migmatite terrain of the Darling Range has been shown by Willis et al. (1983) to be a conformable sedimentary (and not a tectonic) unit and no S1 fabric analysis is described in Marjoribanks et al. (1980) to support nappes fanning away from the Darling Range.

CONCLUSION

The lower Proterozoic gneisses and schists comprising the OB have been divided into five rock suites correlatable with the Willyama Supergroup (Willis et al., 1983) of the BHB. The five rock suites comprise a conformable Proterozoic sequence with no recognised component of pre-Willyama Archaean basement (cf. Glen et al., 1977). The resolution of the stratigraphy has allowed regional structural analysis with outcrop geometry explained by a refolded recumbent terrain. The recumbent terrain can be demonstrated as possessing inverted limbs on a scale of several kilometres. A transport direction is represented by an L1 mineral and elongation lineation which follows consistent trajectories at a high angle to the fold axes on a regional scale. This southeastward transport direction can be demonstrated in both the Olary and Broken Hill Blocks and the two blocks comprise the one orogenic domain. Dissection of the gneissic pile by RSZ postdates the 'Olarian' Orogeny but predates deposition of the upper Proterozoic Adelaidean sediments.

The tectonic boundary responsible for generating the 'Olarian' Orogeny probably strikes NE, paralleling the major F1 and F2 axes and with the L1 mineral lineation transverse to the margin of the mobile belt (Cloos, 1952; Kvale, 1953; Bryant and Reed, 1969; Escher and Watterson, 1974). The L1 and S1 fabrics described herein are more consistent with a model of simple shear deformation generating the recumbent terrain (see Escher and Watterson, 1974; Escher et al., 1975; Coward and Potts, 1983; Mattauer, 1975). Recumbent folds, present in the OB on the scale of tens of kilometres may present a plausible mechanism for crustal thickening during deformation.

It has been suggested that the Archaean—Proterozoic boundary was a period of important cratonisation, at which time rigid lithospheric plates possessing stable interiors developed (Windley, 1983). The early Proterozoic 'Olarian' Orogeny generated tectonic fabrics comparable in style to those present in Cenozoic collisional terrains (Le Fort, 1975; Shackleton and Ries, 1984) suggesting the crust deformed during the 'Olarian' Orogeny with similar properties to the present-day crust. However, in the absence of observable tectonic boundaries, the global scale processes responsible for the 'Olarian' Orogeny remain speculative.

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