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Excursion Guide C-2

Broken Hill Block

29 September - 5 October, 1990

by

B.P.J. Stevens, R.W. Page & S.S. Sun

Bureau of Mineral Resources, Geology and Geophysics
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Geochronology, Cosmochronology and Isotope Geology

**Seventh International Conference on Geochronology,
Cosmochronology & Isotope Geology**

ICOG 7

EXCURSION GUIDE C-2
BROKEN HILL BLOCK

Saturday 29 September - Friday 5 October 1990

Leaders:

B.P.J. Stevens, Geological Survey of N.S.W., Broken Hill, N.S.W.

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Bureau of Mineral Resources, Geology & Geophysics

Record 1990/53



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2. Excursion C-2 schedule

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<u>DAY 1</u>	<u>Saturday 29 September.</u> Leave Canberra by coach at 1400 hours, travel to Balranald, southern New South Wales (NSW), across part of the Palaeozoic Lachlan Fold Belt, and relatively flat-lying Devonian-Carboniferous sediments of the Darling Basin. Arrive Balranald ~2000 hrs. Overnight at Capri Motel.	17
<u>DAY 2</u>	<u>Sunday 30 September. Mungo National Park, World Heritage Area.</u> Leave Mungo ~1600 hours, complete journey to Broken Hill - arrive ~2000 hrs, and stay for next 5 nights at Mario's Motel.	17
<u>DAY 3</u>	<u>Monday 1 October</u> Overview of Broken Hill geology, geochronology, and isotopes. Outcrops of stratigraphic and petrological significance near Broken Hill City. Locality 1: Alma Gneiss Locality 2: Cues Formation Locality 4: Upper Cues Formation and Rasp Ridge Gneiss Locality 5: Banded Iron Formation (BIF) (* Lunch at Zinc Corporation twin lakes). Locality 6: Hores Gneiss (* View of Blackwoods South Mine open cut, operated by MMM). Locality 8: Gossan outcrop over Pb lodes of Broken Hill orebody Locality 10: Rasp Ridge Gneiss Locality 11: Sundown Group metasediments	18
<u>DAY 4</u>	<u>Tuesday 2 October</u> Geology and geochronology of Broken Hill Group - Yanco Glen, Southern Cross Mine, and Broken Hill Mines areas. (i) Yanco Glen area - morning (ii) Southern Cross mine area - afternoon (iii) NBHC oval - afternoon	22
<u>DAY 5</u>	<u>Wednesday 3 October</u> Mineralization and Pb and stable isotopes (i) Broken Hill orebody - morning (ii) Thackaringa Mines - afternoon (iii) Pyrite Hill (Cobaltian Pyrite) - afternoon (iv) Angus-Kintore area - afternoon (v) Egebeck feldspar quarry - afternoon	28 30 32 34 35
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<u>DAY 7</u>	<u>Friday 5 October</u> Travel to historic mining town of Silverton, art galleries, etc. Depart Broken Hill for Sydney. Excursion ends Sydney Airport.	37

SUPERGROUP	PARAGON GROUP	DALNIT BORE METASEDIMENTS		
		BIJERKERO METASEDIMENTS		
		CARTWRIGHTS CREEK METASEDIMENTS		
		KING GUNNIA CALC-SILICATE MEMBER		
	SUNDOWN GROUP			
	BROKEN HILL GROUP	PURNAMOOTTA SUBGROUP	HORES GNEISS	SILVER KING FORMATION
			FREYERS METASEDIMENTS	
			PARNELL FORMATION	
			ALLENDAL METASEDIMENTS	
		ETTLEWOOD CALC-SILICATE MEMBER		
THACKARINGA GROUP	RASP RIDGE GNEISS		HIMALAYA FORMATION	
	KYONG FORMATION	CUES FORMATION		
		ALDERS TANK FORMATION		
	ALMA GNEISS		LADY BRASSEY FORMATION	
	THORNDAL COMPOSITE GNEISS		MULCULCA FORMATION	
WILLYAMA	CLEVEDAL MIGMATITE		EDNAS GNEISS	
			REDAN GNEISS	

16268

Figure 1. Stratigraphic subdivision of the Willyama Supergroup.

1. GEOLOGICAL OVERVIEW

(a) GEOLOGICAL HISTORY AND GEOCHRONOLOGY

The Broken Hill Block, in far western New South Wales (Fig. 2) consists of highly deformed high grade metamorphic rocks of the Willyama Supergroup (Fig. 1 - inside front cover), and pre- and post-tectonic intrusives, all overlain unconformably by Late Proterozoic (Adelaidean) weakly deformed sediments. The geological history of the Willyama Supergroup has been summarized by Stevens (1986), and recently, further geochronological data have been acquired by Page & Laing (in prep.). The geological history of the Block is described in four tectonic stages, and the following summary of this history is detailed in Tables 1 to 5.

Reconnaissance Sm-Nd results on various gneisses indicate depleted mantle model ages of 2300-2100 Ma, which McCulloch (1987) interprets as ages of separation from the mantle, or mixed ages averaging material contributed from Archaean and Proterozoic sources. Our reinterpretation of such depleted mantle evolution (given on page 15) actually makes these model ages about 300 Ma older, but neither interpretation is of any stratigraphic relevance.

Deposition of the Broken Hill Group occurred at 1690 ± 5 Ma, the only primary age yet established for any part of the Willyama Supergroup (Page & Laing in prep.). These rocks were metamorphosed to amphibolite and granulite facies and deformed twice at 1600 ± 8 Ma, in the Olarian Orogeny. A third deformation with accompanying retrograde metamorphism occurred soon after. Before 1570 Ma, retrograde schist zones had formed, some with associated kyanite- and staurolite-bearing metamorphic assemblages. The transitional tectonic stage commenced at 1490 ± 40 Ma, with the emplacement of Mundi Mundi type granites and minor muscovite pegmatites.

Between 1490 Ma and 800-1100 Ma, the presently exposed rocks were elevated from 13 to 20 km below the surface, to surface and near surface levels. During the epicratonic stage (1100-500 Ma), continental and shallow marine sediments of the Adelaide System plus minor basalt were deposited in grabens or half-grabens on Willyama basement. Substantial erosion of the Willyama Supergroup occurred. Alkaline ultramafic plugs and dykes were intruded at 561 ± 7 Ma, and a thermal pulse at 520 ± 20 Ma (reset mica ages) marks the Delamerian Orogeny. This was accompanied by low grade metamorphism, re-activation of retrograde schist zones, intrusion of dolerite plugs, dykes and zoned pegmatites, and gentle folding of the Adelaidean rocks. Peridotite stocks and dykes may have accompanied the ultramafic intrusions at 561 ± 7 Ma, or the dolerite intrusions at 520 ± 20 Ma. During the cratonic stage (500 Ma to present), faulting occurred, fluorite-bearing veins and siderite-rich Pb-Ag veins formed. At about 280 Ma, either a thermal event occurred, or substantial erosion dropped the temperature of the presently exposed rocks to less than 100°C . Between 280 Ma and the present there was substantial weathering, and significant uplift and erosion. Silcrete and ferricrete were formed locally, possibly in the Oligocene. Specific events of uplift and erosion probably occurred in the Palaeocene to Mid Eocene and Late Miocene to Pliocene. These left the Broken Hill Block in its present state, a series of slightly uplifted, tilted and incised sub-blocks, with adjacent alluvial fans.

The Willyama Supergroup contains the Broken Hill Pb-Zn-Ag orebody and abundant minor deposits. The top of the orebody was removed by erosion and it is possible that other orebodies have been eroded away. The main period of erosion of potentially ore-bearing Willyama Supergroup was between 1490 Ma and 1100 Ma. Substantial erosion also occurred between 800 Ma and 600 Ma, between 530 Ma and 280 Ma, or at about 280 Ma, and at intervals during the Cainozoic. It seems likely that the Broken Hill orebody was partly eroded at 280 Ma, and possibly also during the Cainozoic.

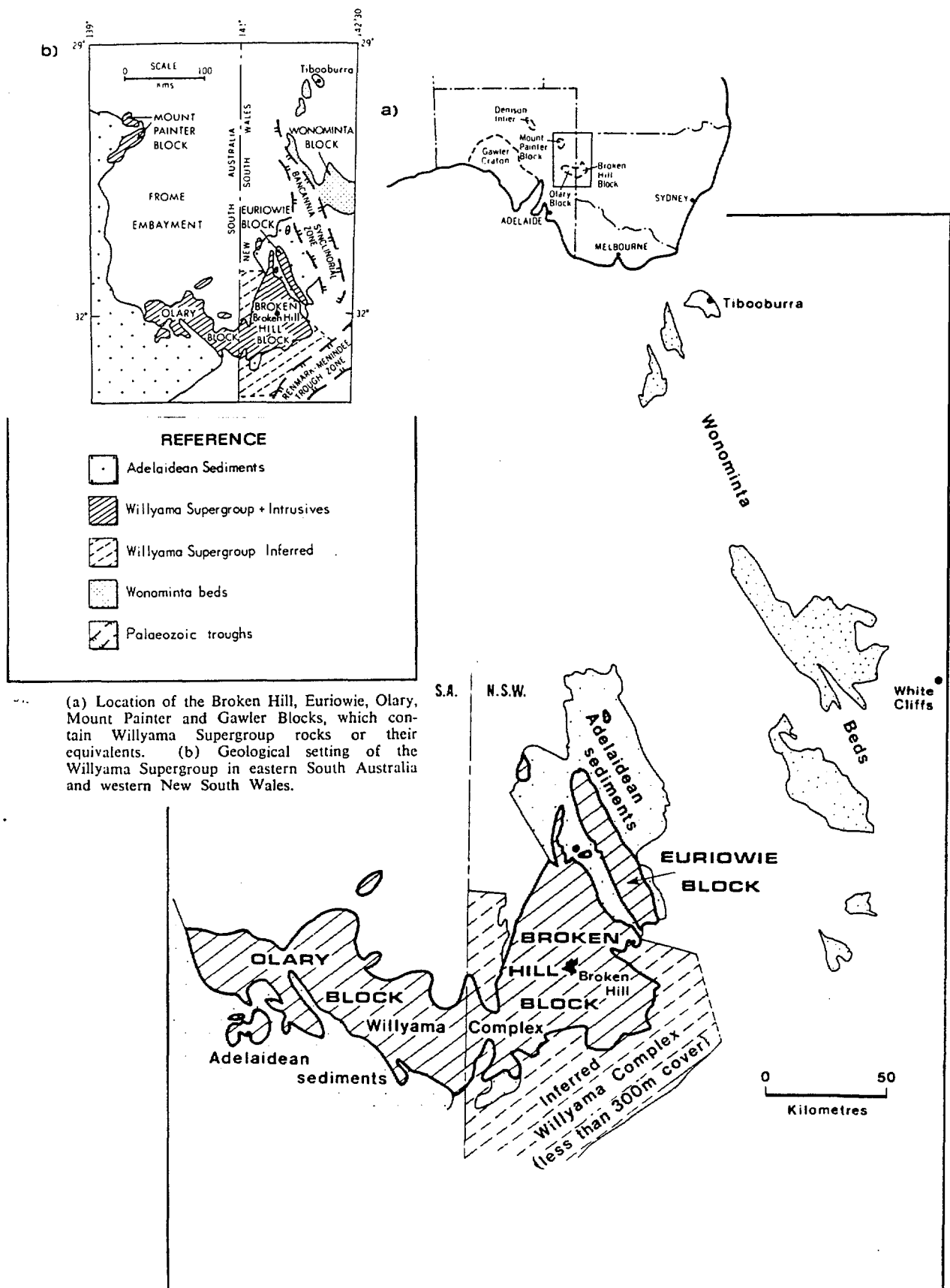


Figure 2. Major exposures of the Willyama Complex (now Willyama Supergroup) in New South Wales and South Australia.

Table 1 Precratonic history of the Broken Hill Block (modified after Stevens, 1986)

	Event	Age	Major relevant data
1.	Possible separation of crustal material from the mantle	2100-2300 Ma	Sm-Nd model ages (McCulloch & Hensel 1984; McCulloch 1987)
2.	Deposition of Broken Hill Group sedimentary-volcanic sequence	1690±5 Ma	U-Pb age from zircons (Page & Laing in prep.)
3.	Olarian orogeny. High grade metamorphism accompanied by deformations D ₁ and D ₂ and anatexis. Central and southern area T = 750-800°C, P = 5-6 kb equivalent to depth of burial of 16-20 km. Northern area T = 580°C, P = 3-4 kb equivalent to a depth of 10-14 km.	1600±8 Ma 1659±21 Ma - 1661±35 Ma - 1663±9 Ma -	U-Pb age from zircons (Page & Laing in prep) - Rb-Sr age (Pidgeon 1967); - Pb-Pb age (Reynolds 1971); - U-Pb age from zircons (Gulson 1984); metamorphic assemblages (Phillips 1978, 1980), structural analysis (Marjoribanks <i>et al</i> 1980; Glen <i>et al</i> 1977)
4.	Olarian orogeny. Emplacement and crystallization of anatectic melts, continuing during 5a and 5b		Deformation history (Stevens 1978a; Marjoribanks <i>et al</i> 1980). Metamorphic history and melting (Phillips 1978, 1980; Corbett & Phillips 1981; Stevens & Stroud 1983).
5.	Olarian orogeny? Deformation D ₃ after peak metamorphic grade; retrograde minerals, including muscovite, biotite and local sillimanite grew in schistosity S ₃ . Retrograde schist zones and pseudomorphous semi-regional retrogression may have been initiated by this time.	~1600 Ma	Deformation history (Willis 1976; Glen <i>et al</i> 1977; Marjoribanks <i>et al</i> 1980), Sr isotopes (Plimer 1976).
6.	Rocks near the orebody cooled to below about 600°C.	~1595 Ma	Closure of U-Pb systems in monazite (Gulson 1984; Page & Laing in prep.).
7.	Emplacement of zoned pegmatites, after 5. (includes some pegmatites at Yanco Glen, Euriowie, Kantappa).		Field relationships (Lishmund 1982; Brown <i>et al</i> 1983a).
8.	Retrograde schist zones and pseudomorphous retrogression active. Staurolite, kyanite, chloritoid-bearing assemblages formed. Southern area T = 550-600°C, P = 5-5 kb equivalent to a depth of 16-18 km.	~1595-1570 Ma	Metamorphic history and interpretation of microtextures (Chenhall 1973, 1976; Corbett & Phillips 1981).
9.	Cooling below 500°C.	1570 Ma	Hornblende ⁴⁰ Ar- ³⁹ Ar spectra (Harrison & McDougall 1981).
10.	End of precratonic stage.	1490±40 Ma	Emplacement of Mundi Mundi type granites (Pidgeon 1967).

Table 2 Transitional tectonic history of the Broken Hill Block (after Stevens 1986).

	Event	Age	Major relevant data
1a.	Emplacement of muscovite-bearing pegmatites (Broken Hill City area).	1490±40 Ma	Rb-Sr (Pidgeon 1967).
1b	Emplacement of Mundi Mundi type granites in N and NE. P≥ 4 kb, equivalent to a depth of 13 km or more.	1490±40 Ma	Rb-Sr (Pidgeon 1967). Depth from Hyndman (1981).
2.	Elevation of presently exposed rocks from depth to surface and near-surface levels. Northern areas-granites elevated from at least 13 km to surface and partly eroded. T drops from about 560°C (granite crystallization) to ambient temperature.		Temperature and pressure estimates during prograde, retrograde metamorphism (Table 1) and granite emplacement (above). Deposition of Adelaidean rocks on unconformity at 800-1100 Ma.
3.	Termination of transitional stage.	800-1100 Ma	

Table 3 Epicratonic history of the Broken Hill Block (after Stevens 1986)

	Event	Age	Major relevant data
1.	Partial or complete cover by thin terrestrial quartz sand sheet (Lady Don Quartzite).	est. 1100 Ma or 802±10 Ma	Adelaidean history (Cooper <i>et al</i> 1978; Preiss & Forbes 1981; Fanning <i>et al.</i> 1986).
2.	Local uplift and erosion of quartzite to form conglomerate (Christine Judith Conglomerate).		As above.
3.	Partial cover by basalt and shallow marine sediments (remainder of Poolamacca Group).	1076±34 Ma, or 802±10 Ma	As above
4.	Hiatus in deposition, area probably uplifted, some erosion probable.		As above
5.	Uplift and substantial erosion of Broken Hill Block, accompanying deposition of Torrowangee and Farnell Groups. Probable block-faulting of the Block and related deformation of cover rocks.	about 800 Ma to about 600 Ma	As above
6.	Emplacement of plugs and dykes of alkaline ultrabasic rocks; pyroxenites, jacupirangites, possibly also peridotites.	561±7 Ma	K-Ar age on hornblende (Harrison & McDougall 1981).
7.	Thermal pulse, resetting of isotope systems in many rocks and minerals, T approximately 350°C Low grade metamorphism of Willyama Supergroup, deformation in schist zones, possibly some pseudomorphous 'retrogression'. Partial recrystallization of alkaline intrusives.	520±4 Ma Possibly continued locally until 458 Ma	Rb-Sr, K-Ar age data (Binns Miller 1963; Richards & Pidgeon 1963; Pidgeon 1967; Harrison & McDougall 1981; Etheridge & Cooper 1981).
8.	Probably same time as 7. Delamerian orogeny; folding and low grade metamorphism of Adelaidean rocks, deformation of unconformity.		Stratigraphic correlations with South Australia (Thomson 1969; Scheibner 1976; Cooper <i>et al</i> 1978; Forbes & Pitt 1980)
9.	Possibly also during 7, intrusion of dolerite plugs and dykes, possibly also peridotite. These show some alteration, possibly metamorphic, during 7.	Possibly between 560 and 500 Ma	Field relationships (Stroud <i>et al</i> 1983)
10.	Emplacement of some zoned pegmatites (including some in Thackaringa area), possibly same time as 7, but later than the dolerite dykes	About 500 Ma	Field relationships (Lishmund 1982; Stroud <i>et al</i> 1983), K-Ar ages (Binns & Miller 1963; Pidgeon 1967)

Table 4 Cratonic history of the Broken Hill Block.

	Event	Age	Major relevant data
1	Faulting at some stage after schist zone movements (i.e. after 520 Ma thermal pulse). TP conditions suitable for brittle fracture.	< 520 Ma	Field relations Barnes 1975, 1980, 1988).
2	Copper-quartz vein at Paragon mine		Field relationships (Barnes & Stevens 1975; Fenton-Corbett 1978)
3	Siderite rich Thackaringa type Pb-Ag veins formed.		Field relationships (Barnes 1975, 1980), fluid inclusions (Dong <i>et al</i>)
4	Probably substantial erosion, perhaps glacial. T cooled below approximately 100°C.	~280 Ma	Fission track date on apatite (Harrison & McDougall 1981), field data (Dun 1891; Flint <i>et al</i> 1980; J. Morton pers. comm.).
5	Weathering, perhaps minor uplift.		
6	Probable uplift and erosion.	Eocene	Sedimentation history, Lake Frome area (Callen 1977).
7.	Some probable silcrete and ferricrete formation.	Oligocene	Analogy with Tibooburra (Morton 1982) and South Australia (Wopfner 1974)
8.	Uplift and erosion to form alluvial fans. Probable block-faulting.	Pre-30 000 BP	Age estimate for alluvial fans (Wasson 1979).
8a.	Human habitation of the region.	From ~40 000 BP	Carbon isotope dating (Bowler <i>et al</i> 1970).
9.	Minor erosion.	To present	Incision of alluvial fans (Wasson 1979)

Table 5* Summary of geochronological data from Rb-Sr, K-Ar and Pb-Pb systems: Pidgeon (1967)¹, Shaw (1968)¹, Reynolds (1971)¹; Harrison and McDougall (1981)²; Etheridge and Cooper (1981)³, Sm-Nd dating (McCulloch & Hensel 1984)⁴, zircon, sphene, monazite, apatite U-Pb dating (Gulson 1984)⁵, zircon and monazite U-Pb work (Page & Laing, in prep.)⁶.

Age	Event
<u>New data:</u>	
1690 ± 5 Ma	Deposition of the Broken Hill Group. ⁶
1600 ± 8 Ma	High grade metamorphism of the Broken Hill Group. ⁶
<u>Previous data:</u>	
2100-2300 Ma	Postulated separation of crustal material from mantle. ³
1800 ± 60 Ma	Deposition (model Rb-Sr age) - Willyama Supergroup. ¹
1659 ± 21 Ma	High grade metamorphism in the 'Mine Sequence'. ¹
1661 ± 35 Ma	Pb-Pb whole rock age. ¹
~1595 Ma	Temperature fell below about 600°C, Broken Hill City area. ⁵
1570 Ma	Temperature fell below about 500°C. ² Cooling at a rate of 3°C per Ma ¹ (or 10°C per Ma, considering new data. ⁶)
1490 ± 20 Ma	Mundi Mundi Granite emplacement. ¹
1494 ± 20 Ma	Muscovite pegmatites emplaced (samples from near Broken Hill City dated).
561 ± 7 Ma	Ultramafic plus (nepheline pyroxenite) emplaced. ¹
520 ± 40 Ma	Thermal pulse, temperature rose to about 350°C in some places, resetting some biotite and muscovite isotope systems. ¹
~460 Ma	Last Rb-Sr isotopic redistribution within schist zones. ³
~280 Ma	Region cooled below approx. 100°C, either as a result of slow cooling following the 520 Ma event, or after a minor thermal event closer to 280 Ma. ¹

*Note: All ages referred to in this guide employ decay constants advocated by Steiger and Jager (1977). Some of the data here attributed to Harrison and McDougall (1981) are adjustments of earlier work. See their paper or this text for original references.

(b) STRATIGRAPHY

The early Proterozoic stratigraphic sequence was first formally described by Willis *et al.* (1983), defined by Stevens *et al.* (1983), and has been modified by Stevens *et al.* (1988):

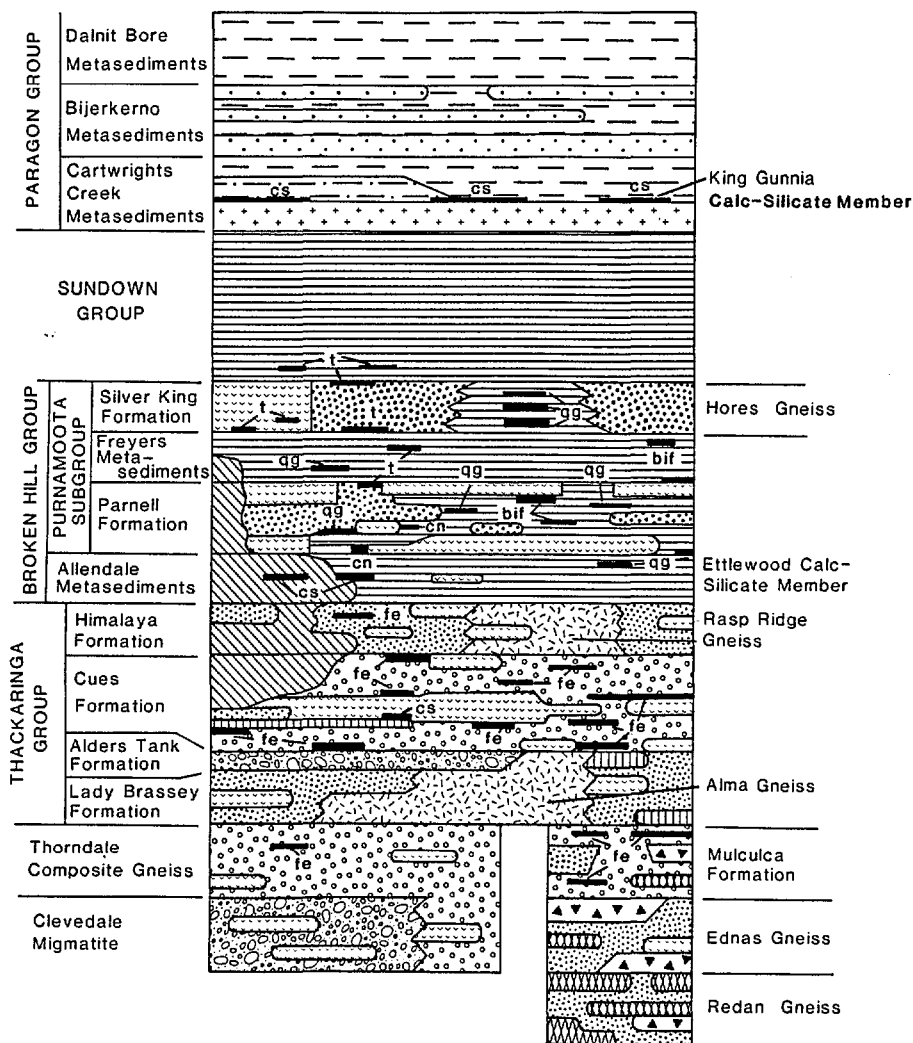
"The Willyama Supergroup has an estimated total thickness of 7-9 km, with neither top nor basement exposed. No unconformities have been recognized in the sequence. The Supergroup was deposited in a deepening environment, passing upward from sandy facies to more shaley and fine sandy facies, and from interpreted bimodal felsic/mafic volcanics, to non-volcanic facies.

The metasediments have been interpreted as shelf sediments overlain by deeper water turbidites and minor contourites. Recently they have been reinterpreted as shallow marine, with the quartzo-feldspathic gneisses interpreted as fluvio-deltaic arkoses.

In this paper the sequence to the top of Thackaringa Group is interpreted as mainly fluvio-deltaic and lacustrine. The Broken Hill Group and Sundown Group are interpreted as shallow marine. The Paragon Group may have comprised shelf muds overlain by delta-front and lacustrine sediments, in turn overlain by deeper-water fine-grained turbidites."

Further information is presented in Figures 1 and 3.

There has been considerable debate concerning the origin of several of the rock types within the Willyama Supergroup. Recent contributions to this debate include Willis *et al.* (1983), Wright *et al.* (1987), Haydon and McConachy (1987), Vernon and Williams (1988), Stevens *et al.* (1988) and Page & Laing (in prep.). Various interpretations are shown in Table 6.



METASEDIMENTARY ROCKS		OTHER ROCK TYPES	
	Graphitic Pelitic to psammopelitic rocks		Quartz-feldspar-biotite-garnet('Potosi' type)gneiss
	Fine grained feldspar-rich psammite		Quartz-feldspar-biotite('granitic')gneiss
	Fine grained graphitic psammite		Leucocratic quartz-feldspar rich rock and intermixed pegmatite
	Chistallite-bearing pelitic rocks		Leucocratic gneiss
	Non-graphitic pelitic to psammitic metasediments, calc-silicate nodules common		Finely layered sodic plagioclase-quartz rock
	Metasedimentary composite gneiss and migmatite		Sodic plagioclase-quartz-magnetite gneiss
	Quartzo-feldspathic composite gneiss and migmatite		Amphibolite and basic granulite
	Bedded calc-silicate rock		Sodic plagioclase-quartz-amphibole rocks
	Variably layered to non-layered calc-silicate rock		
	Quartz-gahnite rock, Mn garnet-rich rocks, Pb-Zn sulphide ore		
	Fine-grained Mn garnet-magnetite-quartz-apatite rock		
	Quartz-magnetite, quartz-Fe sulphide ± Fe garnet rocks		
	Tourmaline-rich rocks		

Compiled by B.Stevens 1989

Figure 3. Generalized stratigraphic sequence for the Willyama Supergroup in the Broken Hill Block, NSW.

Table 6. Interpreted depositional environments of the Willyama Supergroup summarized from recent papers

	Willis <i>et al.</i> (1983)	Wright, Haydon and McConachy (1987)	Stevens <i>et al.</i> (1988)
Paragon Group	Deep-water deposition from turbidites + suspension; extensive contourite sands.	Deep-water sediments.	Shelf muds overlain by delta front sand-silt, shallow lacustrine sands, deeper fine turbidites.
Sundown Group	Distal(?) to medial turbidites + proximal massive sands in moderate to deep fan system.	Shelf sediments overlain by deep-water sediments.	Shelf muds and silts with storm-surge sands + shallow marine sheet sands.
Broken Hill Group	Deeper shelf, turbidites, some traction current deposition/reworking. Tholeiitic-calc-alkaline rhyodacites and oceanic tholeiites.	Shelf muds and silts with storm-surge sands, shallow marine sheet sands, overlain by fluviodeltaic arkose.	Shelf muds and silts with storm-surge sand, shallow marine sheet sands. Intercalated rhyodacitic + tholeiitic volcanics.
Thackaringa Group	Shallow marine shelf with bimodal felsic/basic volcanism, medial (to proximal) to volcanic source.	Shallow marine sediments with 3 major progradational fluviodeltaic arkose wedges.	Evaporitic lacustrine or coastal sabkha, with possible marine incursions in Cues Fmn. Felsic and mafic volcanics abundant.
Thorndale Composite Gneiss	Feldspathic sands and silts (volc. derived) with thin airfall felsic tuffs, thin mafic tuffs + intrusives relatively shallow shelf medial to volc. source.	Shallow marine sediments.	Fluvio-deltaic and lacustrine or sabkha environment in a low relief landscape.
Clevedale Migmatite		Progradational fluvio-deltaic wedge.	
Mulculca Ednas, Redan Formations	Not specifically considered		

(c) STRUCTURE AND METAMORPHISM

(after Stevens *et al.* 1988)

Structural history

The Willyama Supergroup in the Broken Hill Block shows evidence of three major episodes of folding, with minor subsequent folding, and further major deformation associated with retrograde schist (shear) zones and faulting (Marjoribanks *et al.*, 1980; Hobbs *et al.*, 1984).

The first deformation (D₁) produced very large reclined to recumbent isoclinal folds, with amplitudes of tens of kilometres. Very few small F₁ folds have been identified, but a prominent high-grade S₁ schistosity parallels bedding in most areas. Downward-facing F₂ and F₃ folds over substantial areas of the Willyama Supergroup have formed as a result of refolding of overturned limbs of F₁ folds. The Broken Hill orebody occurs in one of these areas of downward-facing folds. The second deformation (D₂) produced large and small folds, the largest being several kilometres in amplitude. The F₂ folds tend to be tight to isoclinal, with open hinges and axial planes dipping steeply to the NW. The S₂ axial plane schistosity is high grade, and very similar in grade to S₁. The third deformation (D₃) produced abundant small folds and some larger folds of significance on a regional scale. F₃ folds generally have near-vertical axial planes and a variably developed axial planar retrograde schistosity (S₃). Initial development of retrograde schist zones may have coincided with F₃ folding (Rutland and Etheridge, 1975). However, the common association of staurolite and kyanite with the schist zones and the lack of these minerals in the S₃ schistosity may suggest that the schist zones formed as a response to a separate and probably later phase of deformation.

Biotite analysed from several retrograde schist zones produced Delamerian Orogeny ages of 520±20 Ma (Pidgeon, 1967; Harrison and McDougall, 1971) and 460 Ma (Etheridge and Cooper, 1981), indicating extensive reactivation at that time. This agrees with field evidence of schist zone deformation of the Adelaidean unconformity, of post-tectonic Mundi Mundi-type granitoids, and basic/ultrabasic dykes (Stevens, 1986).

Retrograde schist zones are steeply dipping, planar or curvilinear zones, with a well developed generally intense schistosity, and a steeply pitching lineation, defined by retrograde minerals, notably micas and chlorite. They form an anastomosing network throughout the Broken Hill Block. In these zones, bedding in metasediments is strongly deformed and may be transposed or even destroyed. Many schist zones perform a similar structural function to a fault, with offset of units across the schist zone. However, deformation within a schist zone is largely ductile rather than brittle.

Faulting occurred within or at one margin of some schist zones in the Broken Hill Block (some of these faults contain Thackaringa-type Pb-Ag veins). Faults independent of schist zones are rare.

Metamorphism

The prograde metamorphism has been made described by Phillips (1980) and Phillips and Wall (1981), superseding work by Binns (1963, 1964). Prograde partial melting has been described by Downes and Wall (1984) and retrograde metamorphism was described by Chenhall (1973) and Corbett and Phillips (1981).

The prograde metamorphic path has been deduced from mapping zones of different grade (Fig. 4, Table 7). It is interpreted as a progression from andalusite+muscovite (lowest grade recognized) through a narrow interval of sillimanite+muscovite, to sillimanite+K-feldspar, to orthopyroxene+clinopyroxene+hornblende (i.e. hornblende-granulite grade).

Within the granulite zone, sillimanite and biotite are orientated parallel to S₁ and S₂ (Marjoribanks *et al.*, 1980) and it is concluded that these schistosities were formed during highest grade metamorphism. Laing (1977) suggested that S₂ formed at a slightly higher pressure (~0.5 kb higher) than S₁. Glen *et al.* (1977) suggested that prograde andalusite predated S₁, but this was disputed (Corbett, 1979; Corbett and Phillips, 1981). S₃ is a retrograde schistosity and is generally defined by muscovite, although sillimanite is present in some areas (Stevens, 1978b; Marjoribanks *et al.*, 1980).

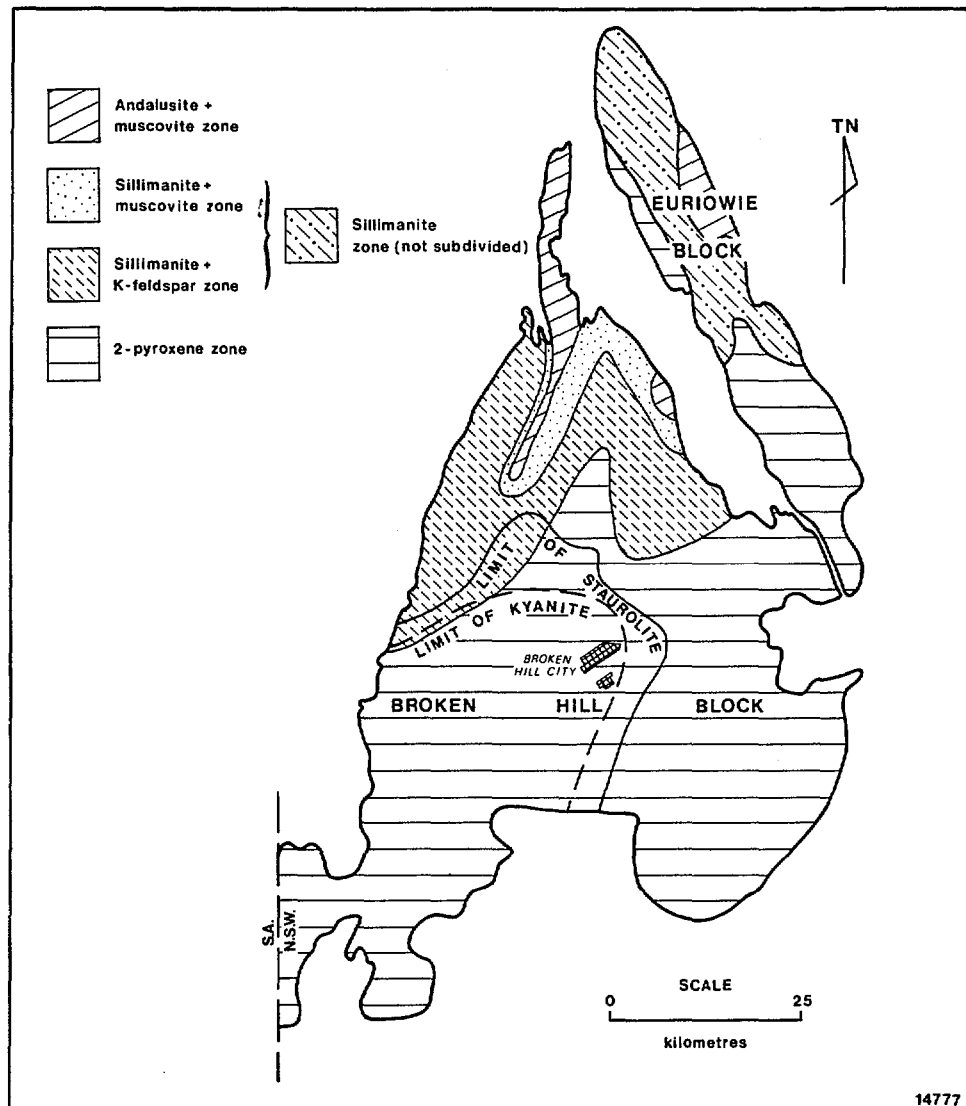


Figure 4. Prograde metamorphic zones in the Broken Hill and Euriowie Blocks (modified after Phillips 1980), overprinted by the approximate position of retrograde kyanite and staurolite (from Geological Survey of NSW mapping).

Retrograde schist zones and the extensive regional retrogression are characterized by mineral assemblages ranging from medium-pressure amphibolite to greenschist grade (Table 8). In the SW of the Broken Hill Block (Fig.4) kyanite, staurolite, garnet, and biotite are common retrograde minerals, chloritoid occurs in the northern and central areas and muscovite, sericite and chlorite are widespread. Retrograde andalusite has been recorded from the central part of the Broken Hill Block (Stevens, unpublished field observations).

Phillips and Wall (1981) concluded that there was a low-intermediate pressure prograde P-T path and nearly constant pressure retrograde path (Tables 7 and 8). This indicates that the heat source could not be related to tectonic thickening alone, but required an external heat source, such as deep crustal mafic magma. One problem with the metamorphic path interpretation is that it has not been conclusively demonstrated whether the staurolite- and kyanite-bearing assemblages are truly retrograde (i.e., formed during decline in temperature following prograde metamorphism), or formed during a later, separate metamorphic event (see discussion under "Structural History"). Studies on element partitioning in poikiloblastic minerals such as garnet are needed to resolve these uncertainties and provide accurate detail of the high-grade P-T path (see, e.g. St. Onge, 1987). Garnet grew at various stages of prograde metamorphism, and some additional growth occurred during retrograde metamorphism.

Table 7 Physical conditions during prograde metamorphism (largely after Phillips, 1980)

Zone	Distinctive assemblage	T (°C)	P_{total} (Kbar)	$a_{\text{H}_2\text{O}}$
1	Andalusite+muscovite	500-580?	3?	1.0
2	Sillimanite+muscovite	580?-680	4	1.0
3	Sillimanite+K-feldspar	680-760	4.5 ± 0.6	0.5-0.8
4	Orthopyroxene+clinopyroxene	760-800	5.2-6	0.3-0.6

Table 8 Retrograde metamorphic conditions (physical conditions estimated from data in Corbett and Phillips, 1981, and Miyashiro, 1973)

Area	Probable assemblage	T (°C)	P_{total} (kb)	$a_{\text{H}_2\text{O}}$
Southwest	Kyanite + staurolite + almandine + biotite + quartz + muscovite (+rare sillimanite)	550-600	5-5.5	1.0?
Central	Staurolite + almandine + biotite + quartz + muscovite (+rare andalusite)	550?	3-5?	1.0?
North and east	Chloritoid + muscovite + biotite (?) + chlorite (?) + quartz (+almandine?)	350-530	3-4?	1.0
General	Muscovite + chlorite + quartz (+almandine?)	300-500	?	1.0

(d) MINERAL DEPOSITS

The following summary is taken from Barnes (1988) from which much detailed description and further references are available.

"The Broken Hill Block contains many different types of mineralization. Using objective criteria including mineralogy, relationship to host rocks, host rock types and stratigraphic position, the following types have been recognized:

Stratiform deposits

Broken Hill type: lead-silver-zinc mineralization in quartz-gahnite rock, garnet-quartz rock and similar lode rock types and miscellaneous stratiform horizons related to Broken Hill type. These include garnet-quartz rock, banded iron formation, quartz-fluorite rock and other lode rock types with minor mineralization.

Ettlewood type: layered calc-silicate rock containing sulphides or base metals.

Corruga type: irregular garnet-quartz-epidote-amphibole rock containing scheelite or base-metal sulphides, including irregular quartz-garnet-epidote-amphibole rock similar to Corruga type but containing minor copper mineralization and no tungsten.

Sisters type: quartz-magnetite \pm iron sulphide rock containing minor copper mineralization.

Great Eastern type: granular quartz-iron sulphide (\pm garnet) rock containing copper and/or cobalt mineralization.

Big Hill type: pyrite (\pm cobalt) in plagioclase-quartz rock.

Stratabound deposits

Silver King type: base metal-bearing, grossly concordant quartz bodies or base metal disseminated in amphibolite.

Hores type: tungsten in quartz-muscovite-tourmaline pegmatite, or as disseminations within quartz-feldspar-biotite (\pm garnet) gneiss or tourmalinite.

Diamond Jubilee type: copper-gold mineralization in pyritic quartz lenses in migmatite.

Vein, multiple veins and stockworks

Thackaringa type: silver-lead bearing siderite quartz veins and copper-bearing siderite-quartz veins.

Mount Robe type: lead-silver-zinc-copper bearing quartz-fluorite veins.

Lead-bearing quartz veins.

Copper-bearing quartz veins, copper disseminated in schist zones.

Pyrite-bearing quartz veins with no base metals apparent, including laminated types.

Gold-bearing quartz veins.

Disseminations and massive, lenticular or irregular mineralization related to intrusive rock types

Waukeroo type: tin-bearing pegmatite.

Mulga Springs type: platinoid-copper-nickel occurrences in ultrabasic intrusive rock.

Iron Duke type: Magnetite-pyrite occurrences in granitic intrusive rock, or as veins or pods in metasediments.

Bakers type: pegmatitic and aplitic rocks containing radioactive minerals. Pegmatites containing base metals or rutile."

(e) Pb, Nd, AND STABLE ISOTOPE STUDIES IN BROKEN HILL

During the last 30 years many isotopic studies have been carried out on ores and other rocks from Broken Hill. When they are integrated with geological and other geochemical studies, they offer constraints on questions such as:

- (i) genetic relationship among coexisting different rock types and their tectonic environment.
- (ii) source material for different types of mineralization, i.e., crustal versus mantle, sedimentary versus igneous, or a combination.
- (iii) mineralization processes, heat source, transportation and concentration mechanisms.
- (iv) genetic relationship (if any) among various types of mineralization, e.g., are Thackaringa type Pb-Ag siderite-quartz veins products of remobilization of Broken Hill type stratiform Pb-Zn mineralization?

Overview of Pb isotope studies

Among others, Reynolds (1971) and Gulson *et al.* (1985) analysed Pb isotopes from stratiform and stratabound mineralization in the Broken Hill Block. Their data demonstrated small but significant differences between various styles of mineralization, but showed that particular deposit types have almost identical values at differing stratigraphic positions and widely spaced locations. This may be summarized as follows:

Broken Hill Main Lode samples have very homogeneous Pb isotopic compositions with an upper crustal Pb character, $^{206}\text{Pb}/^{204}\text{Pb} = 16.00 \pm 1$, $^{207}\text{Pb}/^{204}\text{Pb} = 15.39 \pm 1$, $^{208}\text{Pb}/^{204}\text{Pb} = 35.66 \pm 4$. Samples from the much smaller Pinnacles mine seem to have two groups of slightly different Pb isotopic compositions: 15.98 ± 1 , 15.38 ± 1 , 35.61 ± 4 and 16.00 ± 1 , 15.38 ± 1 , 35.63 ± 2 .

Other types of stratabound mineralization have slightly more radiogenic initial Pb isotopic compositions. The Pb isotope values for these stratiform and stratabound mineralizations suggest their formation from a homogeneous source area of crustal material. Small differences in the processes of formation of the deposits and minor variations caused by metamorphic remobilization may account for the small variations observed between deposit types.

However, galena leads from the Thackaringa veins have a considerably more radiogenic character than the Broken Hill Main Lode, with $^{206}\text{Pb}/^{204}\text{Pb} = 17.37$ to 17.90 (Cooper, 1970). It is interesting to note that Mount Isa (Queensland) Pb-Zn ores, formed at about the same time (~1680 Ma), have slightly more radiogenic Pb isotopic compositions: 16.06 - 16.11 , 15.43 - 15.45 , 35.76 - 35.83 (Gulson, 1986). The difference between Broken Hill and Mount Isa ore Pb is similar to the situation of Silurian volcanogenic and metamorphic-sedimentary hosted Pb-Zn massive sulphide ores within the Lachlan Fold Belt, covering a distance of ~2000 km from Victoria to northeast Queensland - these compositions are: 18.00 - 18.10 , 15.60 - 15.63 , 38.05 - 38.25 (Gulson, 1986; Richards, pers. comm.).

There have been several thousand Pb isotope analyses on Broken Hill ores and gossans undertaken in the last 10 years for major mining companies by SIROTOPE (an isotope consultancy, CSIRO Division of Exploration Geoscience, North Ryde, N.S.W.).

$^{143}\text{Nd}/^{144}\text{Nd}$ isotope studies

Four samples from the Clevedale Migmatite (the lowest exposed formation), overlying Thorndale Composite Gneiss, Alma Gneiss (Thackaringa Group) and Hores Gneiss (Broken Hill Group) have $E_{\text{Nd}} = -5$ at 1690 Ma, the time of mineralization (McCulloch, 1987; Sun, unpub.) suggesting a similar crustal source which has T_{DM} model age of 2500 to 2700 Ma (assuming $E_{\text{Nd}} = +4$). Pre-existing late Archaean to early Proterozoic crustal sources can be inferred for these rocks. This is consistent with conclusions based on SHRIMP U-Pb zircon work (Page and Laing, in prep.).

One amphibolite sample with MORB-type chemistry, $(\text{La}/\text{Sm})_{\text{N}} \sim 1.1$, $\text{Zr} \sim 70$ ppm, $\text{La}/\text{Nb} \sim 1.0$ (not an island arc basalt!) has $E_{\text{Nd}} = +1$ at 1680 Ma (Sun, unpub.). Thus the bimodal basalt and rhyolite association (e.g. Hores Gneiss) represents mantle and crustal melting, respectively, in a rift environment. The Potosi (?Hores) Gneiss sample reported in McCulloch (1987) has $E_{\text{Nd}} = -2.6$ at 1690 Ma, falling between the amphibolite (+1) and other felsic rocks (-5), and may represent a mixing product of the two sources.

¹¹B/¹⁰B isotope studies

Boron isotopic compositions for tourmalines from Broken Hill stratiform and stratabound mineralization are distinctively negative ($\delta^{11}\text{B} = -17$ to -23‰) suggesting involvement of non-marine evaporites in the origin of this mineralization (Slack et al., 1989). If so, it is natural to expect some sulphate and carbonate also derived from the evaporite sequence during mineralization.

¹³C/¹²C isotope studies

Broken Hill Main Lode calcite samples have quite homogeneous and low $\delta^{13}\text{C}_{\text{PDB}}$ values of $\sim -22\text{‰}$ (Dong et al., 1987) probably reflecting severe decarbonization through high grade metamorphism. In contrast, Thackaringa vein siderites have much higher $\delta^{13}\text{C}_{\text{PDB}} = -2$ to -7‰ .

³⁴S/³²S isotope studies

Sulphur isotope studies by Spry (1987) indicate that the S in the Broken Hill orebody ($\delta^{34}\text{S}_{\text{CDT}} = -3$ to $+7\text{‰}$) was derived from either: (a) inorganic reduction of seawater sulphate, leaching of evaporite sulphate and mixed with some magmatic S, or (b) low temperature biological reduction of sulphate from contemporaneous seawater.

Thackaringa-type Pb-Ag vein-type deposits have $\delta^{34}\text{S} = -8$ to $+17$ (Dong et al., 1987). Combined with studies of C, O and Pb isotopes (Both and Smith, 1975; Reynolds, 1971) these indicate that the veins could be derived from disseminated mineralization in the sequence, mixed with other components possibly derived from meteoric water or seawater (see below).

¹⁸O/¹⁶O isotope studies

The $\delta^{18}\text{O}_{\text{SMOW}}$ values estimated for the fluid responsible for Thackaringa vein mineralization generated at 180-200°C range from -4 to $+1\text{‰}$, suggesting a surface derived meteoric and marine origin (Dong et al., 1987).

Summary

An integrated interpretation of S, C, O, and Pb isotopic data is consistent with the idea that Thackaringa vein mineralization took place during a regional tectonic and thermal pulse at ~ 500 Ma ago, through circulation of surface derived fluids and leaching of ore-forming elements from the local country rocks, rather than simple remobilization of pre-existing stratiform Pb-Zn mineralization. For example, a Thackaringa vein at Consols cutting the Main Lode has $^{206}\text{Pb}/^{204}\text{Pb} = 17.4$ and $\delta^{13}\text{C} = -2\text{‰}$, very different from the Main Lode isotopic signature. However, some contribution, especially Ag from stratiform sulphide cannot be excluded.

For the Broken Hill type stratiform Pb-Zn mineralization, available Pb, Nd, B, and S isotopic data are consistent with a model of ensialic rifting, shallow marine environment, with intrusion and eruption of both mafic and felsic magmas in the vicinity at the time of mineralization. Hydrothermal circulation of heated marine water had leached ore-forming elements from the Pb-Zn rich sedimentary pile with felsic pyroclastic components. The present-day Salton Sea environment is an appropriate analogue for generation of Broken Hill stratiform Pb-Zn mineralization (e.g., McKibben et al., 1988).

2. Excursion C-2 schedule

DAY 1. Travel from Canberra to Balranald by coach.

DAY 2. Mungo National Park, World Heritage Area.

The park is about 150 km (2 hours drive) northwest of Balranald. The ICOG excursion will be in this area for most of Sunday 30th September, as it is a most interesting geomorphological and archaeological site, and was declared of World Heritage value in 1981. Our excursion visit will draw heavily on knowledge of a N.S.W. National Parks and Wildlife Service archaeologist (Mr Harvey Johnston), and an Australian Quaternary Association field guide written by Jim Bowler, Wilfred Shawcross, I. McBryde, J.W. Magee and J. Beaton.

Lake Mungo is one of several in the dry Willandra Lakes system of western NSW. No other area of inland Australia combines a record of past environmental and human history spanning the last glacial period as does the Willandra Lakes region. This chain of basins along the now abandoned course of the Willandra Billabong Creek provides a virtual tapestry of information into the past. Like windows in the otherwise monotonous uniformity of the western plains, they reveal a record of Late Quaternary events unparalleled in the detail of human and physical history available anywhere in Australia.

Lake Mungo is one of the earliest known sites of Aboriginal occupation in Australia. At present the most reliable radiocarbon ages put the maximum age of aboriginal occupation of the region at ~36,000 years. A series of less reliable ages pushes this back to about 40,000 years, but the dating of these older levels of occupation has proved problematic due to limitations of this technique. It is noted that recent research in the Kakadu area of northern Australia has successfully applied thermoluminescence (TL) dating techniques to sedimentary layers that contain aboriginal artefacts. These ages (50,000-60,000 years) are significantly older than any so far obtained from the Willandra Lakes. The application of TL dating in the Willandra Lakes is currently being planned, and may result in exciting new interpretations of the aboriginal antiquity of the region.

DAY 3. Overview of Broken Hill geology, geochronology, and isotopes - outcrops of stratigraphic and petrological significance close to Broken Hill

Introduction

The first excursion day in Broken Hill area will be spent inspecting outcrops near Broken Hill City. Because of the proximity to the major mines, these rocks have been the subject of much study, including several geochronological studies. The development of the mines and the city has obscured much of the outcrop, but good quality geological mapping is available from the 1920's, and much data are available from diamond drilling.

A summary of the stratigraphic subdivision is shown on the inside front cover (Fig. 1). Today we will see parts of the stratigraphic sequence extending from lower Thackaringa Group, through Broken Hill Group, to Sundown Group (at locations shown in Figs. 5, 6). The excursion progresses from the Broken Hill Synform, across the poorly defined Broken Hill Antiform (the Broken Hill orebody is located on the northwestern limb of this structure), into the Hanging Wall Synform, all F₂ structures. The Broken Hill orebody (to be inspected on the morning of day 4) occurs within Hores Gneiss of the Broken Hill Group.

The following notes are taken from Stevens (1988a).

Locality 1: Alma Gneiss. Follow Bonanza Street to airport gates, turn left and follow dirt road about 600 m to low rise. (See Figure 6 of Pidgeon, 1967 - Rb-Sr age 1635 ± 100 Ma).

The Alma Gneiss is a coarse grained quartz-feldspar-biotite gneiss with abundant very coarse feldspar megacrysts, some of which take the form of augen and others are more rectangular. The rock also contains some large garnet porphyroblasts. The rock has a very well defined gneissosity, probably F₁.

Within the gneiss there occur irregular, discontinuous wispy inclusions resembling xenoliths. These could be interpreted as:

- (i) xenoliths in an original intrusion,
- (ii) layers in the volcanic pile, disrupted during deformation,
- (iii) fragments of better sorted psammitic layers in a thick arkosic unit.

The fine grained layers which do not contain augen are essentially composed of quartz, calcic plagioclase with or without K-feldspar and biotite. In outcrop these layers appear darker than average gneiss.

Within the Alma Gneiss, there are cross-cutting mafic dykes, containing pyroxene, amphibole and/or plagioclase. They are probably about 560-500 Ma old. The Alma Gneiss forms the centre of the Broken Hill Synform and as such forms the lowest stratigraphic unit within the Thackaringa Group. At Broken Hill the sequence is overturned and is therefore younging downwards. The Alma Gneiss is spatially underlain (stratigraphically overlain) by Cues Formation and the Rasp Ridge Gneiss.

Origin: There are a number of possible origins for the Alma Gneiss and other "granite" gneisses in the area:

- (i) plutonic - a granitic intrusion before the onset of metamorphism or during D₁. The megacrysts in it support this origin (Vernon and Williams 1988).
- (ii) volcanic- a thick rhyodacitic unit comprising either ash flow tuffs or lava flows. The megacrysts could represent metamorphic overgrowths on smaller phenocrysts in the original volcanic.
- (iii) sediment - as a thick arkosic sediment. In this case the megacrysts would be purely metamorphic in origin.

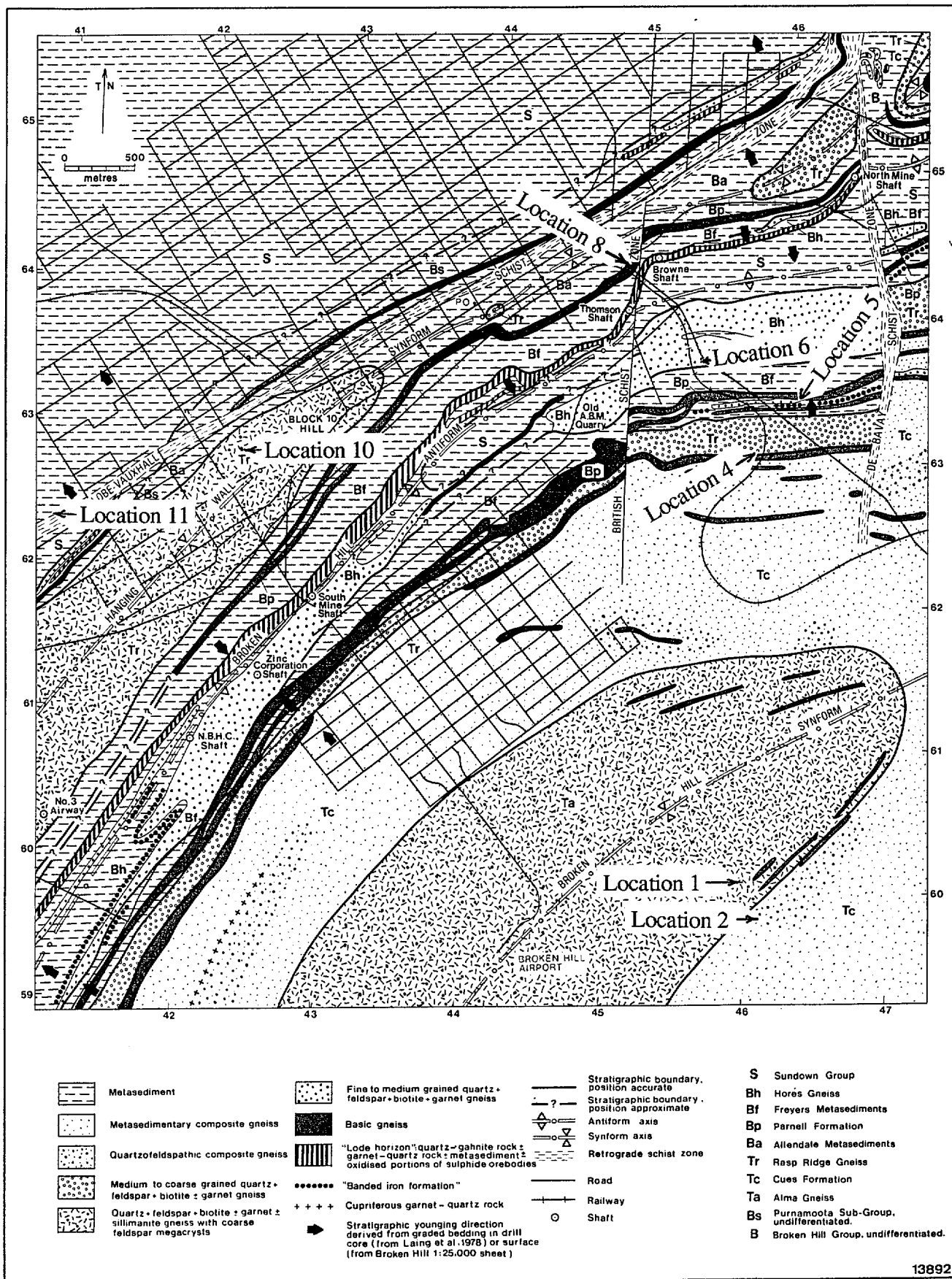


Figure 6. Simplified geology and stratigraphic interpretation of Broken Hill City area (from Brown *et al.* 1983b). Locality numbers 1, 2, 4, 5, 6, 8, 10, 11 refer to Day 3 excursion stops.

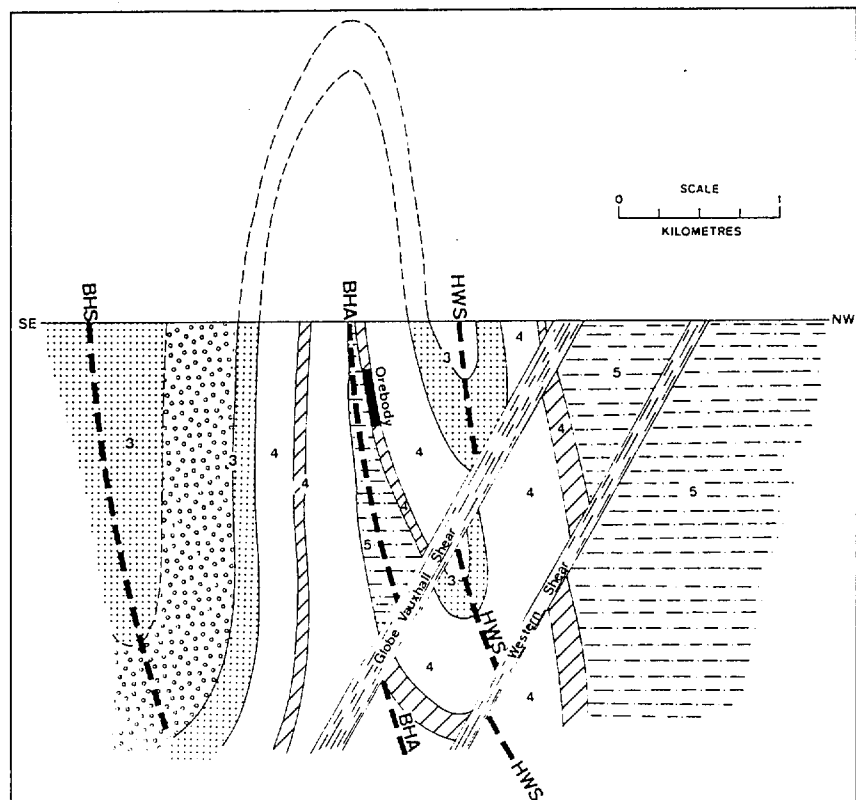


Figure 7(a) Schematic geological section through the Broken Hill mines area (after Laing 1980).

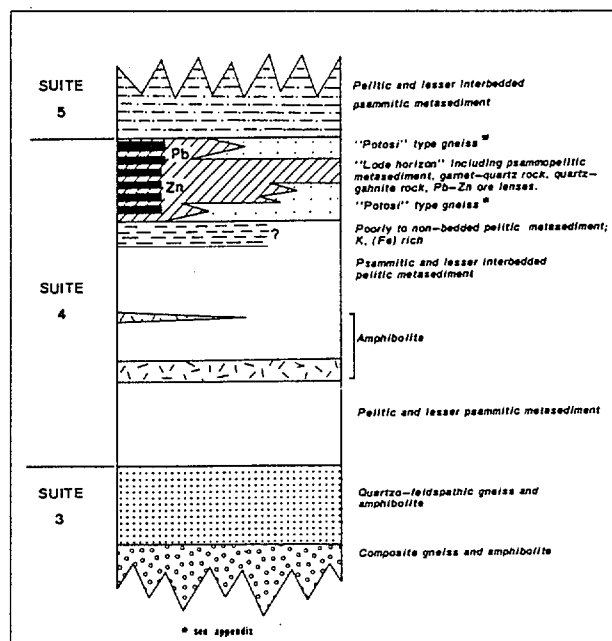


Figure 7(b) Stratigraphic sequence in the Broken Hill mines area.

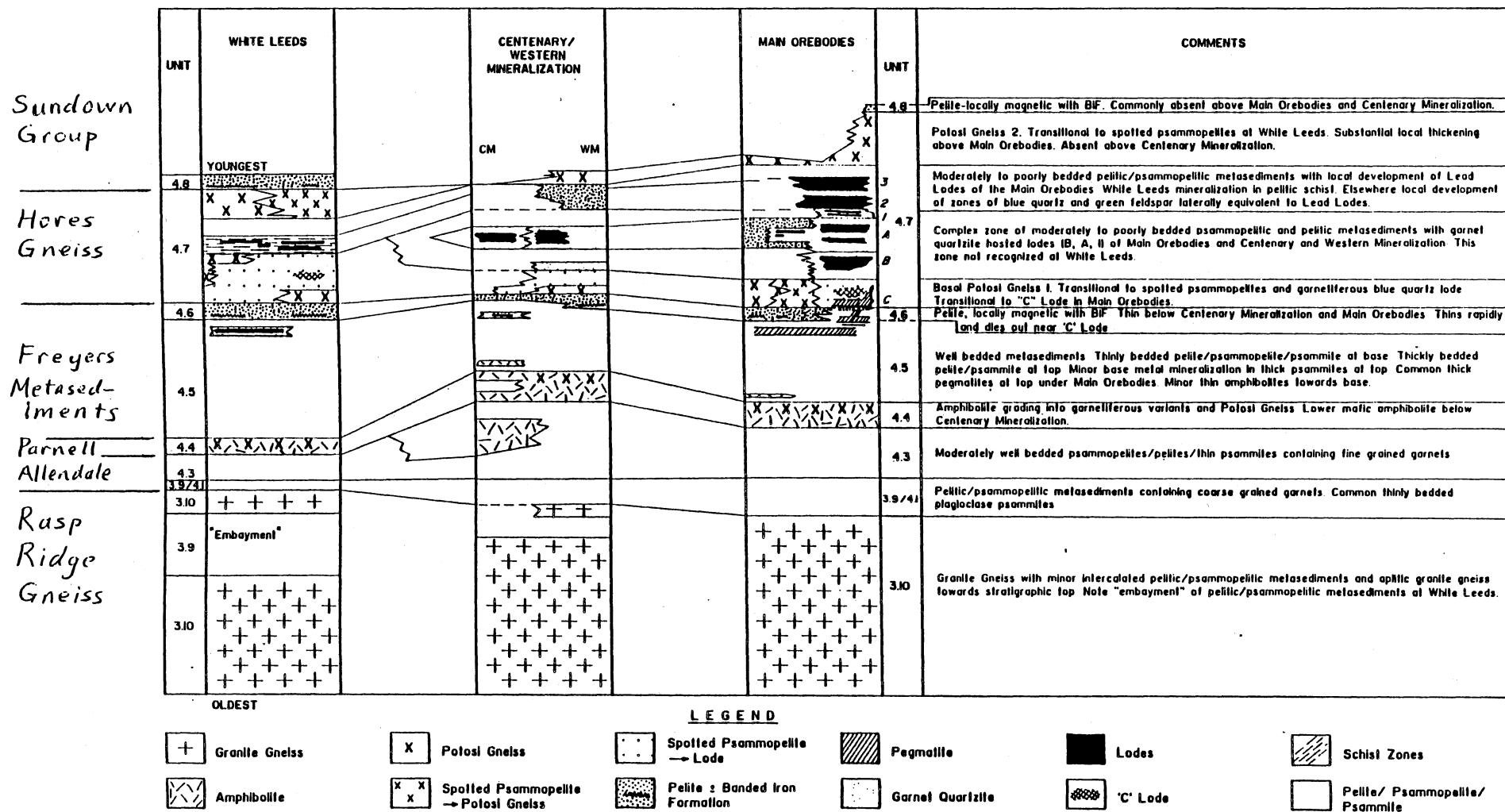


Figure 8. Comparative stratigraphic sections from White Leeds, Centenary Mineralization and Western Mineralization zones and the main orebodies, showing the relative thickness of units and facies relations (after Haydon and McConachy 1987).

Locality 2: Cues Formation. 500 metres east of locality 1.

The outcrop occurs just east of the Alma Gneiss. The Cues Formation here consists mostly of quartzo-feldspathic composite gneiss*. This gneiss is lithologically layered. Some layers are quartz-albite rich, others are rich in biotite, sillimanite, and garnet. The rock also contains concordant and discordant pegmatitic quartz-feldspar segregations.

Some of the quartz-albite layers and pegmatitic segregations contain pinitite (greasy grey alteration product of cordierite) and cordierite. The cordierite occurs as stubby hexagonal crystals, and as coarse dark blue-grey masses of grains.

Cues Formation hosts the Eastern Copper mineralization consisting of quartz and garnet rich rocks containing low grade copper mineralization.

Elsewhere Cues Formation contains abundant mafic gneiss, minor 'Potosi-type' quartz-feldspar-biotite-garnet gneiss, and quartz-magnetite rocks. Cues Formation has similarities with Parnell Formation in Broken Hill Group. Both Formations contain extensive minor mineralization.

Locality 4: Upper Cues Formation and Rasp Ridge Gneiss. The outcrop occurs in a railway cutting east of grain silos at the start of the Menindee Road. The cutting is very close to the Readymix quarry where Rasp Ridge Gneiss is being mined for aggregate. Look out for trains!! (This is 'lower granitic gneiss' locality BH1 of Gulson, 1984; discordant U-Pb zircon data, 5 fractions, indicated an age of 1704 ± 50 Ma).

Rasp Ridge Gneiss on this side of the Broken Hill orebody was once called the "Lower Granite Gneiss". At this locality Cues Formation is a metasedimentary composite gneiss (contains 10% to 50% pegmatitic and/or granitic material). The pegmatitic lenses here contain large garnets. Mineralogy of the pegmatite segregations tends to reflect that of the host rocks. The formation of these pegmatites and the garnets may be triggered by the reaction:
 biotite + sillimanite + quartz - K-feldspar + garnet + H₂O.

In the cutting, the composite gneiss contains psammitic metasediment rich in dark blue quartz, and containing thin veinlets of pegmatite, plus lenses of micaceous schist probably representing retrogressed sillimanite-rich pelite. The composite gneiss is very retrogressed, as indicated by abundant sericite and fine crenulations on schistosity surfaces.

Within the composite gneiss some remnant layering is interpreted as bedding. However the layering is parallel to retrograde schistosity and its origin is uncertain.

If you look carefully there is also a high grade schistosity oblique to layering. This is probably S₁, S₂ or S₃, predating the retrograde schistosity.

On the western end of the railway cutting there is a very good outcrop of Rasp Ridge Gneiss, consisting of medium to coarse grained quartz-feldspar-biotite gneiss with a very well developed gneissosity.

The boundary between the metasedimentary composite gneiss (Cues Formation) and the quartzo-feldspathic gneiss (Rasp Ridge Gneiss) is difficult to see in the cutting. The contact is better seen by climbing the embankment. Here the contact between quartz-feldspar-biotite gneiss (Rasp Ridge) and extensively retrogressed garnet bearing gneiss with very thin pelite lenses (Cues Formation) is occupied by a basic gneiss about 7 metres wide. Several other thin basic gneisses are present.

Origin: The Rasp Ridge Gneiss is interpreted by N.S.W. Geological Survey geologists as a pile of rhyodacitic lavas and/or ash flows and the intercalated mafic gneisses were either lavas or sills emplaced soon after deposition.

* The term "composite gneiss" refers to a lithologically layered rock containing between 10% and 50% pegmatitic or granitic segregations. Rocks containing >50% melt are referred to as migmatite.

Locality 5: "Banded iron formation" (BIF) Approximately 300 m northeast of locality 4, adjacent to North Mine lease fence.

This locality has poor outcrop and mainly consists of scattered float of BIF rock from the Parnell Formation, which here lies just above Rasp Ridge Gneiss, on the SE limb of the Broken Hill Antiform. BIF also occurs in Hores Gneiss in the Broken Hill area and thus very close to the Broken Hill orebodies. It is uncommon elsewhere.

At this locality there is no outcrop of any other rock types apart from scattered amphibolite float to the east. BIF in the Broken Hill area is a fine grained, well laminated rock consisting of quartz, magnetite, garnet and apatite. The garnet has a high spessartine (Mn) component.

The fine lamination in the BIF's is interpreted as bedding, and some BIF's show lenticular layering and occasional small slump structures. Occasional cross-bedding type features can be seen, but these could be tectonic in origin.

Origin: The N.S.W. Geological Survey agrees with the interpretation that these rocks were chemical sediments, perhaps with some reworking. They have also been interpreted as heavy mineral sands, such as beach sediments.

Locality 6: Hores Gneiss. Boulder-strewn outcrop adjacent to the Menindee Road, opposite the grain silos. (This is 'Potosi' locality BH6 of Gulson, 1984; discordant U-Pb zircon data, 5 fractions, indicated an age of 1635 ± 8 Ma; monazite $^{207}\text{Pb}/^{206}\text{Pb}$ age is 1580 Ma).

Hores Gneiss consists predominantly of 'Potosi'-type gneiss, a traditional local name for a medium to fine grained quartz-feldspar-biotite-garnet gneiss with abundant, evenly distributed, round garnet porphyroblasts. The rock contains orthoclase and plagioclase, which generally ranges from andesine to labradorite-bytownite. Gneissosity is generally well developed.

In most exposures 'Potosi'-type gneiss is significantly different from "granitic" gneiss which occurs in Rasp Ridge Gneiss and Alma Gneiss. The latter is generally coarser grained, and where it contains garnets, they are larger and tend to be concentrated in pegmatitic segregations. There are some outcrops where the two rocks are very similar.

In the Broken Hill mines area it is common to find biotite rims on the garnets in 'Potosi'-type gneiss. This is probably a retrograde reaction feature, due to reversal of the reaction: quartz + biotite + sillimanite --- K-feldspar + garnet + H₂O.

Another common but not distinguishing feature is the small pygmy quartz-feldspar rich veins which occur in the 'Potosi'-type gneiss.

Stratigraphic Position: In the Broken Hill mines area, Hores Gneiss includes 'Potosi'-type gneiss, metasediments, and the Broken Hill orebody with its associated quartz-gahnite and garnet rich lode rocks. The orebody occurs on the northwest limb of the F₂ Broken Hill Antiform. Hores Gneiss at locality 6 occurs on the southeastern limb of the Antiform, which is placed somewhere between here and the orebody. Its position has not been exactly determined. No significant mineralization has been discovered in Broken Hill Group in the southeast limb of the antiform.

Origin: The origin of 'Potosi'-type gneiss is still widely debated. The origins put forward range from igneous intrusions to volcanics, to shaley or arkosic sediments. The intrusive theory has been out of favour for many years. The N.S.W. Geological Survey preferred origin (also Laing *et al.* 1984) is that the rock was a non-welded rhyodacitic ashflow tuff.

Wright, Haydon and McConachy (1987) propose that the gneiss originated as thick arkosic sediments laid down in a deltaic environment. Page and Laing (in prep.) consider that zircon morphology and U-Pb isotopic systematics are consistent with a pyroclastic volcanic origin.

Locality 8: Gossan outcrop over the Pb lodes of the Broken Hill orebody. North side of Menindee road, opposite Thompsons shaft.

This is a bold outcrop of quartz-coronadite (Mn, Pb oxide) gossan with sericitized sillimanite schists on either side. The continuation of the gossan can be seen southwards across the road, leading towards Thompson's shaft. The outcrop is the expression of the Broken Hill lode within the British Schist Zone, a cross-cutting retrograde schist zone which deviates the trend of the Broken Hill orebody. The rock from which the gossan was derived was probably quartz-Mn garnet-rich, with minor lead-zinc mineralization. The main development of ore in this area is deeper. The host rocks are highly retrogressed metasediments containing narrow zones of pale sericite with quartz eyes. These zones represent highly retrogressed thin pegmatitic segregations.

Locality 10: Rasp Ridge Gneiss. Block 10 Hill. (This is 'upper granitic gneiss' locality BH11 of Gulson, 1984; discordant U-Pb zircon data, 3 fractions, indicated an age of 1688 ± 7 Ma; monazite $^{207}\text{Pb}/^{206}\text{Pb}$ age is 1600 Ma).

This hill shows the Rasp Ridge Gneiss within the hinge of the Hanging Wall Synform. The rock is a medium to coarse grained quartz-feldspar-biotite \pm garnet gneiss with a well developed gneissosity.

Small folds are locally abundant, with a variation from sinistral (S) folds on the eastern side, through M or W folds in the centre, to dextral (Z) folds on the western side. The sense of the folds is determined by viewing down the fold axis, which plunges to the southwest. There are very few sinistral folds, possibly because part of the eastern limb has been sheared off. The following structural elements can be seen: folded high grade schistosity/gneissosity (S_1), small pegmatite segregations in the axial planes (S_2) of F_2 folds, irregular layering, predating S_1 . The layering is defined by scattered finer grained quartz-feldspar-biotite gneiss with less well developed gneissosity. The origin of such layers is discussed under Locality 1, and is important in understanding the origin of the quartzo-feldspathic gneisses.

Locality 11: Sundown Group Metasediments. Wills Street outcrop. Drive SW along Wills Street, just past the last house; the road leads to the sewage works and garbage tip. The outcrop is on a prominent hill within the regeneration area. Walk from near the last house, diagonally up the hill. The small pavement outcrop occurs next to a single large mulga tree.

The outcrop shows an F_2 fold in well bedded metasediments. The metasediments include psammite, psammopelite and pelite (i.e. ranging from quartz-feldspar rich to sillimanite-biotite rich). Bedding is very well developed and some of the beds show subtle grading. After metamorphism the original sandy component of the beds still has a sandy texture and grain-size, while the originally clayey component is now represented by coarse sillimanite-biotite. The graded beds are interpreted as original turbidity current deposits with sandy bases and clayey tops. Bedding (S_0) is folded around the F_2 fold, and an axial plane schistosity (S_2) is defined by sillimanite-rich aggregates and biotite-rich aggregates.

Some other outcrops contain zoned calc-silicate nodules. These are very common in Sundown Group, are typically about 0.3 m across, and are interpreted as metamorphosed carbonate bearing concretions, formed during diagenesis.

DAY 4. Geology and geochronology of the Broken Hill Group - Yanco Glen, Southern Cross Mine, and Broken Hill Mines area.

Introduction

The purpose of this day's geology is to examine outcrops of different metamorphic grades within the middle sections of the Broken Hill Group, and discuss relatively recent geochronological information that has enabled determination of the stratigraphic age, as well as the age of high grade metamorphism.

In the Yanco Glen area, about 40 km north of Broken Hill, two horizons of 'Potosi' gneiss equivalent (Hores Gneiss and Parnell Formation) outcrop in lower metamorphic grade windows (middle amphibolite facies). Here, there are many preserved textural features that support the idea that these rocks were deposited as ash flow tuffs and reworked pyroclastics. Sites sampled for the recent study by Page and Laing (in prep.) will be visited in a walking traverse of about 2 hours. We return to the bus for lunch.

The afternoon will be spent looking at the same stratigraphic units of the Broken Hill Group at intermediate and high metamorphic grades as we move south, first to the Southern Cross mine area, and then closer to Broken Hill itself. The transition towards higher metamorphic grades is mirrored by changes in zircon morphology and U-Pb isotopic characteristics, although whole-rock geochemical changes are minimal.

(i) Yanco Glen area

The first stop will involve a walking traverse from the type section of Hores Gneiss, down the stratigraphy across Freyers Metasediments and Parnell Formation. One or more dykes of Mundi Mundi type granite will also be inspected. The geology of the area is shown in Figures 9 and 10, and the following notes are in part taken from Stevens (1988b):

Features: Cross-section through most of Broken Hill Group (B), near the type sections for Hores Gneiss (Bh) and Freyers Metasediments (Bf). Also good exposure of Sundown Group (S). A complete section through Sundown Group is possible here.

The rocks here are at relatively low metamorphic grade. In the east the rocks only attained andalusite grade, while in the west they are in the lower part of sillimanite grade. The isograd has never been accurately delineated, due to metastable persistence of andalusite into sillimanite grade, and to pervasive retrograde metamorphism which has altered most of the andalusite and sillimanite to sericite. One of the major features of the area is the stratabound tungsten mineralization and associated tourmaline (bedded tourmaline + quartz rocks).

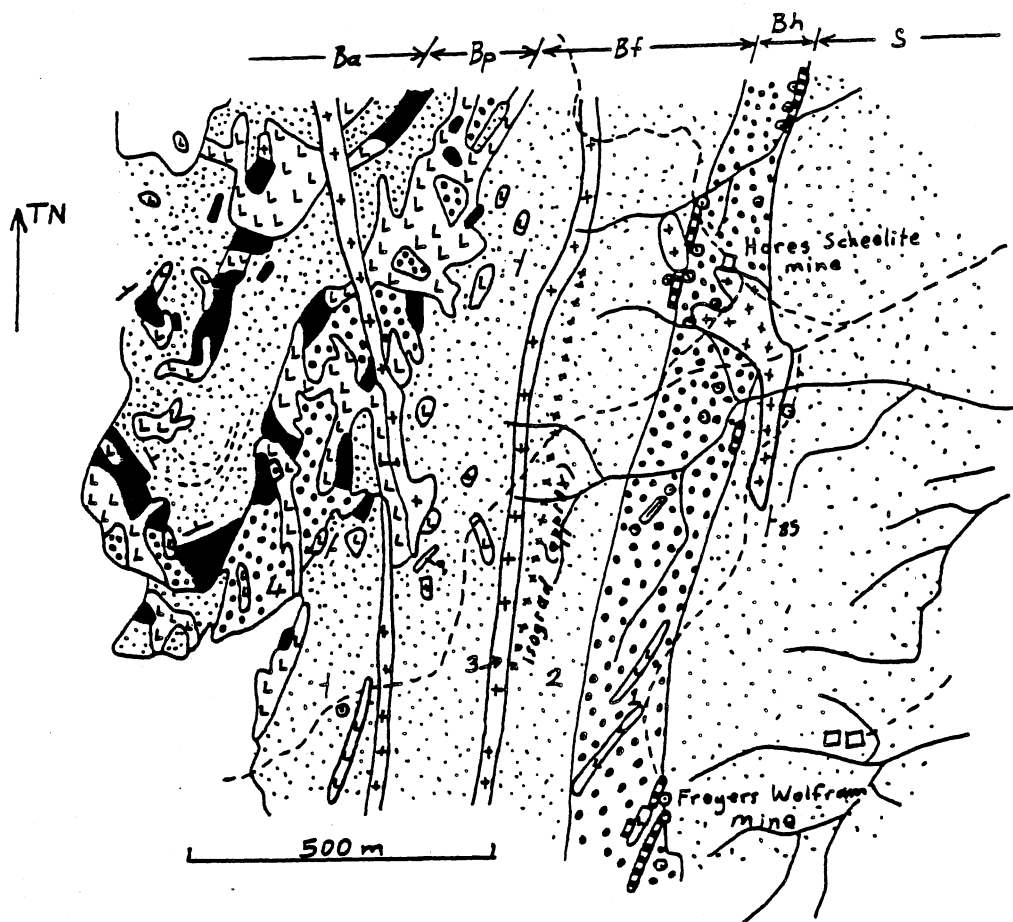
Tungsten Mineralization: Tungsten mineralization occurring in and adjacent to Hores Gneiss (Bh) and Parnell Formation (Bp), has been described by Barnes (1983), in the Hores mine area. The mineralization occurs in a variety of forms, including:

- disseminations in quartz + feldspar + biotite (\pm garnet) gneiss,
- coarse aggregates of scheelite and wolframite in quartz + muscovite + tourmaline pegmatoids,
- aggregates of scheelite in irregular quartz veining in tourmalinites.

Past production totals only several tens of tonnes, from each of three mines: Hores, Freyers and the Annandale mine. This has come mostly from the scheelite and wolframite-bearing pegmatoids. The area has been explored and drilled by C.R.A.E. in recent years.

The tungsten deposits are distributed over a strike length of more than 5 km (Fig. 11), and occur within and immediately adjacent to Hores Gneiss (Bh) and a similar gneiss unit within Parnell Formation (Bp). The main ore minerals are scheelite and wolframite. Minor amounts of pyrite and/or pyrrhotite occur in most deposits and arsenopyrite has been identified at Hores mine. Disseminated pyrrhotite occurs throughout much of the mineralized zone. Minor enrichment of Pb, Zn, Cu and As occurs with some of the tungsten deposits.

Tin Mineralization: Tin, in the form of cassiterite, has been mined from pegmatites distributed throughout an area 11km by 1-3km. The tin-bearing pegmatites occur within the Sundown and Paragon Groups and Hores Gneiss, but will not be visited on this traverse.









-  Mundi Mundi type granite (post -Orogenic).
-  Quartz + feldspar + biotite (\pm garnet) gneiss or schist.
-  Amphibolite.
-  Pegmatite with or without foliated granitoid (syn-orogenic).
-  Bedded metasediments (andalusite to the east, sillimanite to the west)
-  Tourmalinite

Figure 10. Detailed geology of Freyers mine traverse (Willis & Stevens 1989).

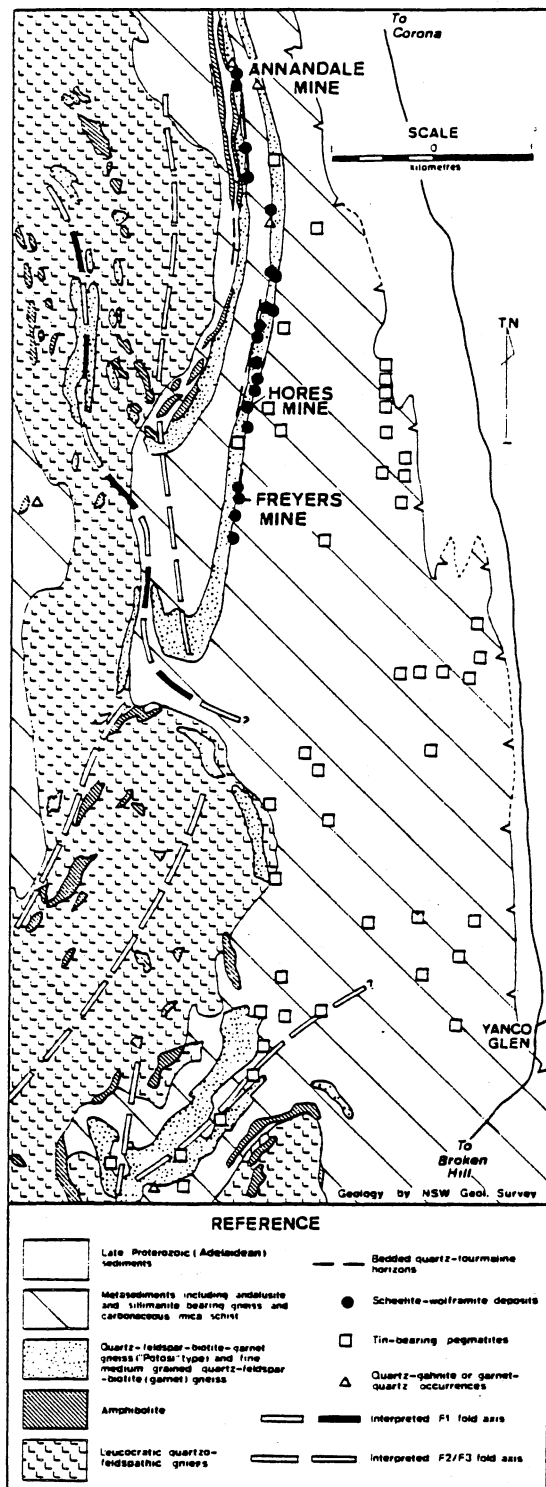


Figure 11. Generalized geological plan showing the tungsten and tin deposits of Yanco Glen area.

Yanco Glen area - geochronological summary (from Page & Laing in prep)

Geochronology of the Hores Gneiss - conventional U-Pb results

In an endeavour to determine the depositional age, conventional U-Pb zircon measurements using bulk fractions were initially undertaken by Page and Laing (in prep.) on Hores Gneiss samples from the lower metamorphic grade areas near Yanco Glen, as it was considered that younger metamorphic overgrowths would not be a problem. However, despite careful selection of euhedral, inclusion-free populations, these U-Pb data form a discordant fan-shaped array with a 200 Ma spread in apparent $^{207}\text{Pb}/^{206}\text{Pb}$ age. This suggested a major inheritance problem, and no useful age could be determined. Taken in isolation, these data would have been conventionally interpreted as indicating an igneous crystallisation age of about 1760 Ma.

Geochronology of the Parnell Formation & Hores Gneiss - ion microprobe U-Pb zircon results

Clear, zoned, elongate euhedral grains dominate the zircon population in a Parnell Formation felsic gneiss, but a small proportion have metamorphically corroded subhedral faces. Zircon U content ranges from 200 to 1000 ppm, and the majority of the zircon data is close to concordant. All twenty analyses fit a single $^{207}\text{Pb}/^{206}\text{Pb}$ grouping to within experimental expectations. Model 1 discordia regression yields a U-Pb upper intercept age of 1696 ± 6 Ma, interpreted as the igneous crystallisation age of the magmatic zircon population, and hence defining the stratigraphic age of the host volcanoclastic unit, the Parnell Formation.

The zircon morphology and U-Pb systematics for this sample substantiate field, petrographic and chemical arguments that the gneisses have an igneous precursor such as a rhyodacitic tuff, or reworked pyroclastic derived proximally from such a source. The euhedral nature and absence of abrasion are important, but alone are not conclusive features, as the same morphology is found in immature epiclastic environments. More substantive are the integrity and age coherence of the 1696 Ma zircon population, an expected pattern of primary igneous parentage.

Page and Laing (in prep.) sampled two other felsic gneisses (Hores Gneiss) 8 to 10 km southeast of, and 300 to 400 m stratigraphically above the Parnell Formation site. The rocks contain pale pink to virtually colourless zircons that are dominantly euhedral, slender or squat grains, and have mild internal zonation. Such morphology is again consistent with an igneous origin or an immediate to proximal source. A few percent of the population are structured grains containing cores, generally $30\text{--}50\mu$ across, and mantled by euhedral to subhedral zircon rims. Additionally, a few pitted grains, possibly of detrital origin or from a sedimentary lithic fragment, are present. The presence of structured zircon grains accounts for the inheritance that plagued the conventional multi-grain analyses.

The major group of ion microprobe analyses is the magmatic zircon component. These are generally clear, elongate, multi-faceted discrete grains that show little zoning. This simple structure is mirrored by consistent replicate analyses. This group of data has a weighted mean $^{207}\text{Pb}/^{206}\text{Pb}$ age of 1689 ± 5 Ma, interpreted as the igneous crystallisation age, a result that is indistinguishable from the age determined for the Parnell Formation, and renders strong support for considering it as the age of volcanism and a primary depositional age for the sequence.

The U-Pb data have an overall $^{207}\text{Pb}/^{206}\text{Pb}$ age dispersion from around 1700 Ma to 2700 Ma, with an average (geologically meaningless) age of 1740 Ma consistent with the conventionally analysed multi-grain data. Most of the 1000 Ma age spread is attributable to zircon xenocrysts or cores (2000 - 2700 Ma). It is not known whether the xenocrysts were inherited as discrete crystals, or whether they were part of an assemblage in flattened lithic fragments that are present in the gneisses. It is considered likely that the pattern of xenocryst ages reflects a complex igneous source(s) or a hybrid of xenocrystic contaminants, since there are a number of examples where xenocrysts are overgrown by younger zircon rims of the age of the principal 1690 Ma magmatic component.

Yanco Glen area location descriptions

Locality 1: Hores Gneiss (Bh on Figure 10).

This is the type section for Hores Gneiss, and is also a locality sampled for U-Pb zircon geochronology. The rock is a fine- to medium-grained quartz-plagioclase (An₂₅₋₄₀) - microcline-biotite gneiss or schist. Minor garnet is present in places. The gneissic layering is defined by flat lenticles of biotite.

The rock shows little or no bedding and contains scattered inclusions of metasediment. Laing *et al.* (1984) described minor lenticular "bedded" facies in the middle and upper portions. Within the massive facies, Laing *et al.* (1984) described euhedral to subhedral quartz phenocrysts with bipyramidal shapes, indistinct feldspar phenocrysts, and flattened aggregates of biotite similar to a eutaxitic texture. They interpreted the unit as "several massive, ash flow crystal tuffs, separated by deposition of minor laminated ashfall or subaqueous reworked tuffs."

Locality 2: Freyers Metasediments (Bf on Figure 10).

The interval between the Hores Gneiss (Bh) and Parnell Formation (Bp) is occupied by Freyers Metasediments, consisting of pelitic to psammitic metasediments, very similar to those in the Sundown Group (S) and Allendale Metasediments (Ba).

The pelitic rocks are schists consisting of prograde quartz, muscovite, biotite, andalusite / sillimanite \pm garnet. Our walking traverse crosses the mapped position of the andalusite / sillimanite isograd. The schists are strongly affected by retrograde metamorphism which has produced sericite, chlorite and chloritoid.

The psammitic rocks contain prograde quartz, plagioclase (\pm microcline), and biotite, with retrograde sericite and chlorite.

Locality 3: Mundi Mundi type granite intrusion.

The granite is composed of quartz, microcline, albite (An₀₋₈), muscovite and biotite. Small microcline phenocrysts are a typical feature. These granitic intrusions post-date all three major regional deformations. Elsewhere, this post-tectonic granite has a Rb-Sr whole-rock/muscovite age of 1490 ± 40 Ma (Pidgeon, 1967), and an $^{40}\text{Ar}/^{39}\text{Ar}$ muscovite age of 1507 ± 14 Ma (Harrison and McDougall, 1981). The granite is not thought to be the source of the tungsten, although it may have played a part in concentrating the tungsten.

Locality 4: Parnell Formation (Bp on Figure 10).

The walking traverse continues to a good exposure of a fine- to medium- grained quartz - feldspar-biotite gneiss (or schist) very similar to that in the Hores Gneiss. Adjacent to this are outcrops of amphibolite. The association of this or a similar quartz -feldspar-biotite gneiss and amphibolite are typical of Parnell Formation.

In some areas there is a gradation between gneiss and amphibolite. Both are relatively high in iron and there may be a genetic link. Willis *et al.* (1983) favoured contemporaneous felsic - mafic volcanism, whereas James (1987) suggested in situ differentiation of sills. The suggestion of Wright *et al.* (1987) that the gneiss represents an arkose, is not supported. This location is in the hinge of a large, north-plunging synform, the Paps Synform (Willis and Stevens, 1989). This structure is an inverted anticline and was interpreted by Corbett (1979) as an F₂ structure.

Pre-deformational pegmatites

On the traverse a large number of pegmatitic bodies will be seen. Most of these are simple quartz-feldspar \pm muscovite \pm biotite pegmatites, transgressive to bedding. To the north, there are larger, more complex bodies which contain faintly layered and folded leucocratic granitoid with pegmatite. Elsewhere, the larger bodies of granitoid and pegmatite also contain a leucocratic quartz -feldspar-biotite gneiss phase. These bodies were present during high grade deformation (Stevens, 1978a; Brown *et al.*, 1983a), and smaller bodies were emplaced parallel to F₂ and F₃ axial planes. No geochronological work has yet been undertaken on these rocks.

(ii) Southern Cross Mine Area

After lunch, we leave the Yanco Glen area, and drive south about 20 km, into higher grade rocks, again in the Broken Hill Group and stratigraphically equivalent to the rocks seen during the morning traverse.

The Southern Cross mine was developed on a small Broken Hill type Pb-Zn-Ag deposit within Freyers Metasediments, just above Parnell Formation. The excursion stop is designed only to inspect the Hores Gneiss stratigraphically above the mineralization.

The Hores Gneiss consists of quartz + feldspar + biotite + garnet gneiss disrupted by small pegmatitic veins and larger masses of pegmatite (shown in Fig. 12). Unlike the Yanco Glen location, Hores Gneiss here is distinctly layered. The layering is defined by variation in the proportions of quartz, feldspar, and biotite, and layers are from about 1 cm to 50 cm wide, similar to the scale of bedding in the enclosing metasediments. The rock is still considered to be of felsic volcanic origin, but consisted originally of multiple submarine debris flows, or reworked volcanic ash.

Southern Cross area - geochronological summary (from Page & Laing in prep)

(a) Conventional U-Pb zircon results

Conventionally measured bulk zircon fractions from the Southern Cross locality of the Hores Gneiss contain about twice the uranium of the Yanco Glen zircon populations, hence are even more discordant, and have a spread in $^{207}\text{Pb}/^{206}\text{Pb}$ age from 1640 to 1790 Ma (Page & Laing, in prep.). Inheritance compounded by multi-stage Pb loss again render these data of little value for unambiguous age determination.

(b) Conventional U-Pb monazite results

Honey-coloured, pitted and shapeless monazite grains were analysed from the same sample. Page & Laing's data are only a few percent discordant and the analysed fractions define model 1 discordia trend with upper and lower intercept ages at 1599 ± 9 Ma and 402 ± 200 Ma.

This age is in agreement with the pooled age of 1595 ± 7 Ma for sphene and three monazite analyses reported by Gulson (1984) for Potosi gneiss and Upper granitic gneiss samples in the Broken Hill mine sequence some 15 km to the south. The mine sequence monazites have similar $^{207}\text{Pb}/^{206}\text{Pb}$ ages from 1579 to 1599 Ma, even though one is much more discordant and appears to have undergone recent Pb loss. It appears that the Southern Cross monazites have suffered Palaeozoic Pb loss, broadly corresponding in time with ~480 Ma Delamerian biotite ages recorded in most gneisses.

Gulson (1984) could not distinguish whether the 1595 Ma monazite-sphene ages were post-1660 Ma cooling ages, or whether they were reflecting a separate amphibolite facies metamorphic event superimposed on what was then interpreted as the 1660 Ma major granulite event. Gebauer and Grunenfelter (1979) suggest that monazites reflect cooling ages from high temperatures, at least 600°C. This is consistent with the 1573 ± 10 Ma age and 500°C blocking temperatures for ^{40}Ar - ^{39}Ar hornblende results elsewhere in the Broken Hill Block (Harrison and McDougall, 1981). The concurrence of Gulson's (1984) and Page & Laing's monazite data provides support for the conclusion that the 1600 Ma age is related to the peak of high-grade metamorphism.

(c) Ion microprobe U-Pb zircon results

Page & Laing's (in prep.) U-Pb zircon data for this higher grade sample show a pattern similar to those of the lower grade Hores Gneiss samples, namely, a major population interpreted as magmatic, and various inherited components from 1780 Ma to 2600 Ma old. In the principal magmatic group, some of the analyses form a concordant or near-concordant group with a weighted mean $^{207}\text{Pb}/^{206}\text{Pb}$ age of 1665 ± 12 Ma. These data and the ten discordant data points give a poorly fitted discordia trend (MSWD 18.2) with a similar upper intercept age of 1668 ± 10 Ma, and a 'zero-age' lower intercept, 24 ± 40 Ma.

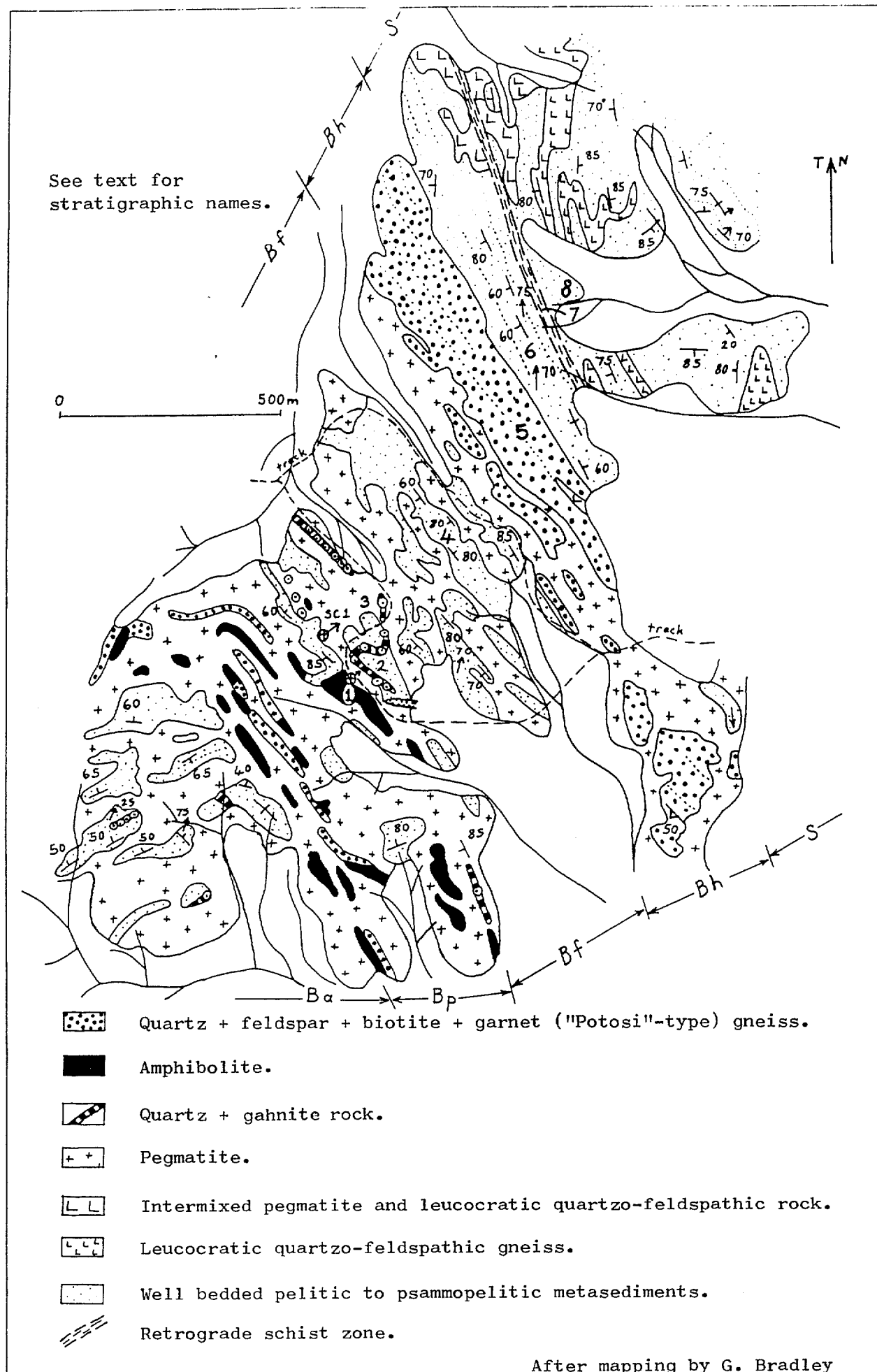


Figure 12. Southern Cross mine traverse (location 2 = main mine shaft; location 5 = Hores Gneiss sampling site).

It will be recalled that the 1600 Ma U-Pb monazite age from this sample indicates that it passed through 600°C blocking temperature at this time. Thus the zircons, even at upper amphibolite-granulite facies and incipient melting conditions, have basically preserved the integrity of their primary magmatic age history. The 1668 ± 10 Ma result is marginally younger than the 1680-1690 Ma depositional ages determined for the lower grade rocks near Yanco Glen some 25 km to the northeast. However, the Southern Cross data are a much more imperfect fit and of less credibility.

Ages of inherited grains present in the Southern Cross sample are comparable to the inherited ages found in the lower grade Yanco Glen samples - a group of nine analyses has a $^{207}\text{Pb}/^{206}\text{Pb}$ age of 1768 ± 17 Ma. One such xenocryst is a core with a euhedral, younger rim belonging to the magmatic population. A number of this 1768 Ma group are imprecisely measured, because of higher common Pb corrections, lower U and associated higher counting errors in the analyses. A second group has a $^{207}\text{Pb}/^{206}\text{Pb}$ age of 1838 ± 45 Ma, and a third discrete xenocryst group has a pooled $^{207}\text{Pb}/^{206}\text{Pb}$ age of 1894 ± 40 Ma. Older inherited grains between 1948 Ma (with a 1771 Ma rim) and 2584 Ma further mimic the inheritance patterns found in lower grade rocks.

(iii) NBHC Oval

The excursion drives back into Broken Hill to examine a garnetiferous felsic gneiss outcrop of the Hores Gneiss at granulite facies metamorphic grade ($T \sim 800^\circ\text{C}$). 'Potosi'- type gneiss, i.e., medium- to fine-grained quartz-feldspar--biotite-garnet gneiss of Hores Gneiss, forms outcrops close to the Broken Hill mines. This outcrop is only a few hundred metres from a Pasminco Mining underground shaft, on the western side of NBHC oval. This outcrop was sampled for U-Pb zircon geochronology in the Page & Laing study. (This is also 'Potosi' locality BH8 of Gulson, 1984; discordant U-Pb zircon data, 4 fractions, indicated an age of 1661 ± 18 Ma).

The gneiss is similar to those at the Southern Cross area, but layering is much less distinct. Although both outcrops are mapped as being within the granulite facies, metamorphic temperatures were probably higher at Broken Hill. This may have led to more biotite breakdown to produce more garnet, K feldspar and melt.

Granulite facies Hores Gneiss, Broken Hill mines area - geochronological summary (from Page & Laing in prep)

(a) Conventional U-Pb zircon results

The complex nature of zircons in this granulite facies grade, garnetiferous felsic gneiss outcrop (rounded to subhedral cores and metamorphic overgrowths) was recognised by Gulson (1984). His data from this locality are affected by partial resetting of the U-Pb systems at granulite facies, and have a narrow range in $^{207}\text{Pb}/^{206}\text{Pb}$ ages - 1599 Ma, and 1608 to 1638 Ma. Pooling of both Gulson's (1984) Hores Gneiss samples gave him an extrapolated U-Pb age of 1652 ± 8 Ma, but the apparent linearity camouflages any inheritance predictable from the zircon morphologies, and so evident in Page & Laing's data in lower grade gneisses. Until now, Gulson's (1984) and similar 1650-1660 Ma ages have been accepted as reflecting high grade metamorphism, but clearly these ages can only be regarded as maxima.

(b) New ion microprobe U-Pb zircon results

Pooling of the 43 ion microprobe analyses on 33 zircon grains (Page & Laing, in prep.) provides a blended age (weighted mean $^{207}\text{Pb}/^{206}\text{Pb}$ 1656 ± 4 Ma) similar to that reported by Gulson (1984), but it is clear from the complex morphology and individual spot isotopic signatures that such any such blend must be geologically meaningless. In this granulite terrane, the ubiquitous complexities of magmatic / inherited zircon evident in the lower grade rocks are compounded by the presence of new grain growth, as well as clear metamorphic overgrowths which produce the ovoid to rounded outlines that mantle older, corroded, magmatic and xenocrystic zircon cores. It is of interest that the presence of "rounded" zircons in this particular sample was cited as evidence to support a clastic sedimentary origin for the gneiss' precursor (Wright et al., 1987).

Amongst the more concordant analyses, Page & Laing (in prep.) find a clear bimodal distribution in $^{207}\text{Pb}/^{206}\text{Pb}$. The older group has U-Pb intercept ages of 1681 ± 14 Ma (lower intercept 146 ± 140 Ma). Although not as precisely determined as in lower grade samples, this age is within error of and enforces the magmatic crystallization ages found elsewhere in the Hores Gneiss. The rounded metamorphic rims have characteristically low Th/U and higher U compared to the magmatic centres and define a $^{207}\text{Pb}/^{206}\text{Pb}$ grouping with an age of 1600 ± 8 Ma. This is interpreted as the time of formation of these high-U zircon rims and a direct measure of the age of granulite facies metamorphism.

This age is in excellent agreement with Gulson's (1984) U-Pb monazite-sphene age of 1595 ± 7 Ma from granulitic gneisses at Broken Hill, and our 1599 ± 9 Ma U-Pb monazite age from amphibolite facies Hores Gneiss 15 km to the north near Southern Cross. It implies that the closure temperatures for U-Pb systems in zircon and monazite are very similar, or that post-granulite metamorphism cooling to below 600°C took place rapidly, within a few million years. This is in line with the Harrison and McDougall (1981) hornblende ^{40}Ar - ^{39}Ar plateau age that fixes post-metamorphic regional cooling to below 500°C by 1573 ± 10 Ma.

Xenocrysts analysed in this population are mantled by thick, high-U metamorphic rims formed in the 1600 Ma event. Two cores have late Archaean ages of 2570 Ma and 2721 Ma, and another two are about 1860 Ma old, a familiar xenocryst age found in the lower grade Hores Gneiss samples.

DAY 5 Mineralization and Pb and stable isotopes

(i) Broken Hill orebody

The Broken Hill orebody, near the top of Broken Hill Group, consists of a series of stacked lenses. Much recent work has concluded that the deposit is volcanic exhalative in origin, probably formed from seawater convected through the sequence, and driven by heat from high-level magma chambers. However, some features of the deposit are more appropriate to a sedimentary exhalative origin, and models have been proposed involving 'seismic pumping' of connate water, with ore deposition on or below the seafloor. Deposition may have occurred in a narrow NE-SW trending seafloor depression.

The Broken Hill orebody consists of 7 sulphide-bearing lenses, stacked one above the other, each having distinctive chemical and mineralogical characteristics (Johnson and Klingner, 1975; Plimer, 1979, 1984). There is a general increase in Pb/Zn ratio and Ag values stratigraphically upwards, though each lens is relatively homogeneous in metal ratios. The mineralogy of the ore lenses is complex, with ~300 primary and secondary mineral species identified (Worner and Mitchell, 1982). The main minerals in each lens are listed in Table I. We have given each lens simple lithological names to show its general character, for comparison with rocks found elsewhere in the district.

The stratigraphically lower lenses ('zinc' lodes) tend to have gradational boundaries with host rocks and are enclosed in garnet-quartz-rich metasediments, which may represent simple metamorphosed sandy sediments, but more probably included a substantial chemical SiO₂ and Mn component. A rock composed almost wholly of fine-grained, Mn-rich garnet ('garnet-sandstone') is associated with the stratigraphically upper lenses ('lead' lodes), but does not extend far from the orebody. The 'lead' lodes tend to be high in grade and have sharp boundaries with the host pelitic and psammitic metasediments.

Outcrops of quartz-gahnite rock extend NE and SSW more or less along strike from the Broken Hill lode, for a total distance of about 25 km. This rock probably represents an exhalite laterally equivalent to the 'zinc' lodes. Associated with this exhalite are small Broken Hill-type Pb-Ag-Zn deposits, containing up to 600,000 tonnes of sulphide mineralization. Downdip from the Broken Hill orebody, drilling has identified two more sulphide-bearing lenses (or groups of lenses): the Western Mineralization and the Centenary Mineralization. These contain respectively an inferred resource of 15 and 9 million tonnes of about 2% Pb, 3% Zn, 30 g t⁻¹ Ag (Haydon and McConachy, 1987).

Origin of the Broken Hill orebody

The origin of the Broken Hill orebody has been the subject of many theories (see Stevens, 1975, for review). In recent times there has been a consensus of opinion that the orebody is premetamorphic and syngenetic in origin, probably having formed as a result of exhalations onto the seafloor. The close association of the orebody with metavolcanics led Stanton (1972) to classify the deposit as volcanic exhalative. However, some features of the orebody are more suggestive of a sediment-hosted exhalative deposit (e.g., Gustafson and Williams, 1981; Phillips et al., 1985). These features include the huge size, the absence of a definite footwall feeder zone, the abundant Pb, Zn, and Ag, with low Cu values, and the metasedimentary nature of the immediate host rocks.

Haydon and McConachy (1987) and Wright *et al.* (1987) have rejected the syngenetic models, and propose an origin related to compactive expulsion of metal-bearing brines during accumulation of the sedimentary pile, and deposition in pore spaces and by diagenetic replacement of shallow marine sands.

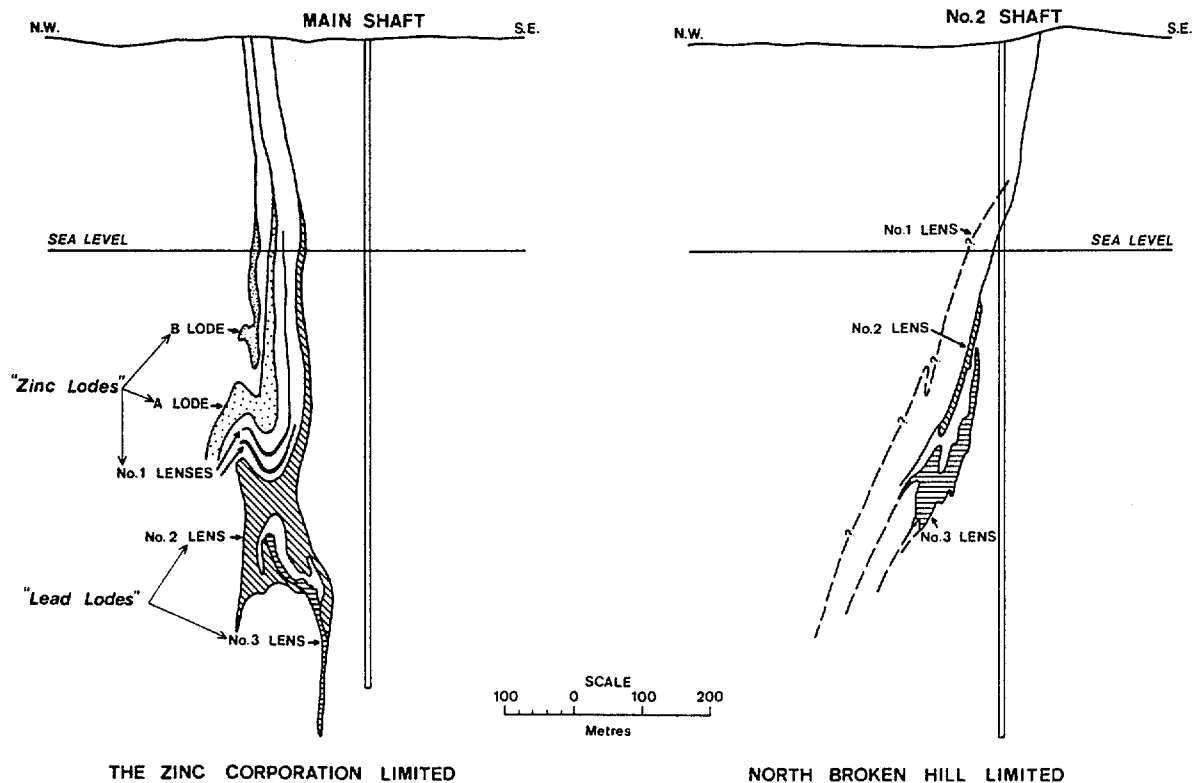


Figure 13. Geological cross sections through the Broken Hill orebody in the Zinc Corporation mine and North mine (Pasminco Mining).

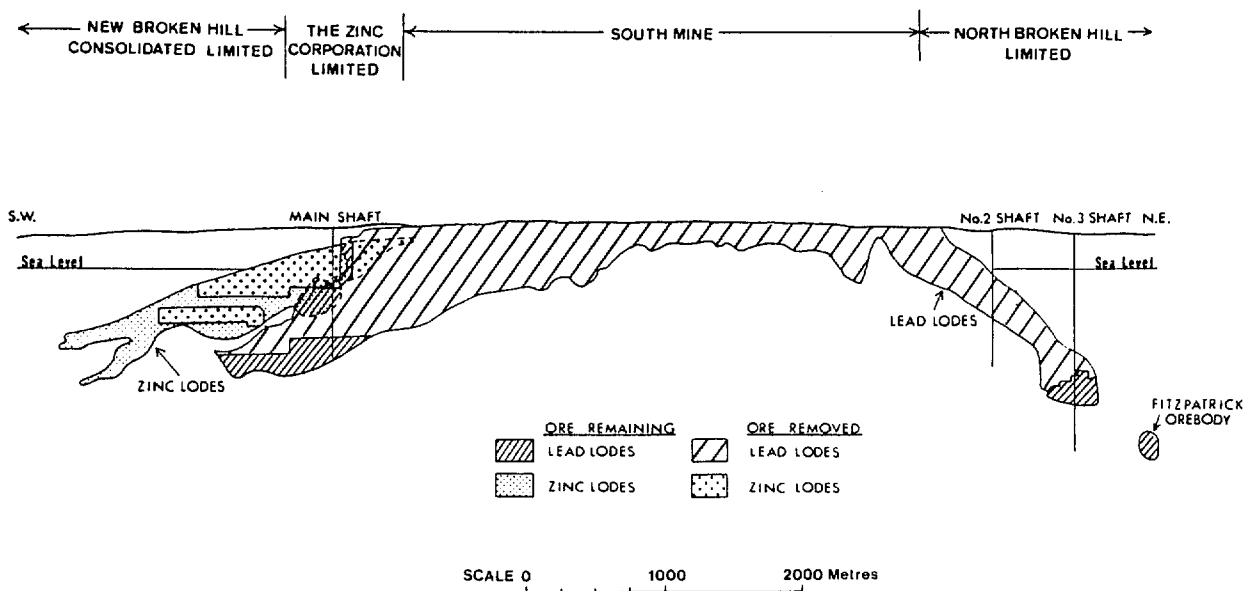


Figure 14. Longitudinal projection of the Broken Hill ore deposit showing areas mined out and ore remaining, dated 1979.

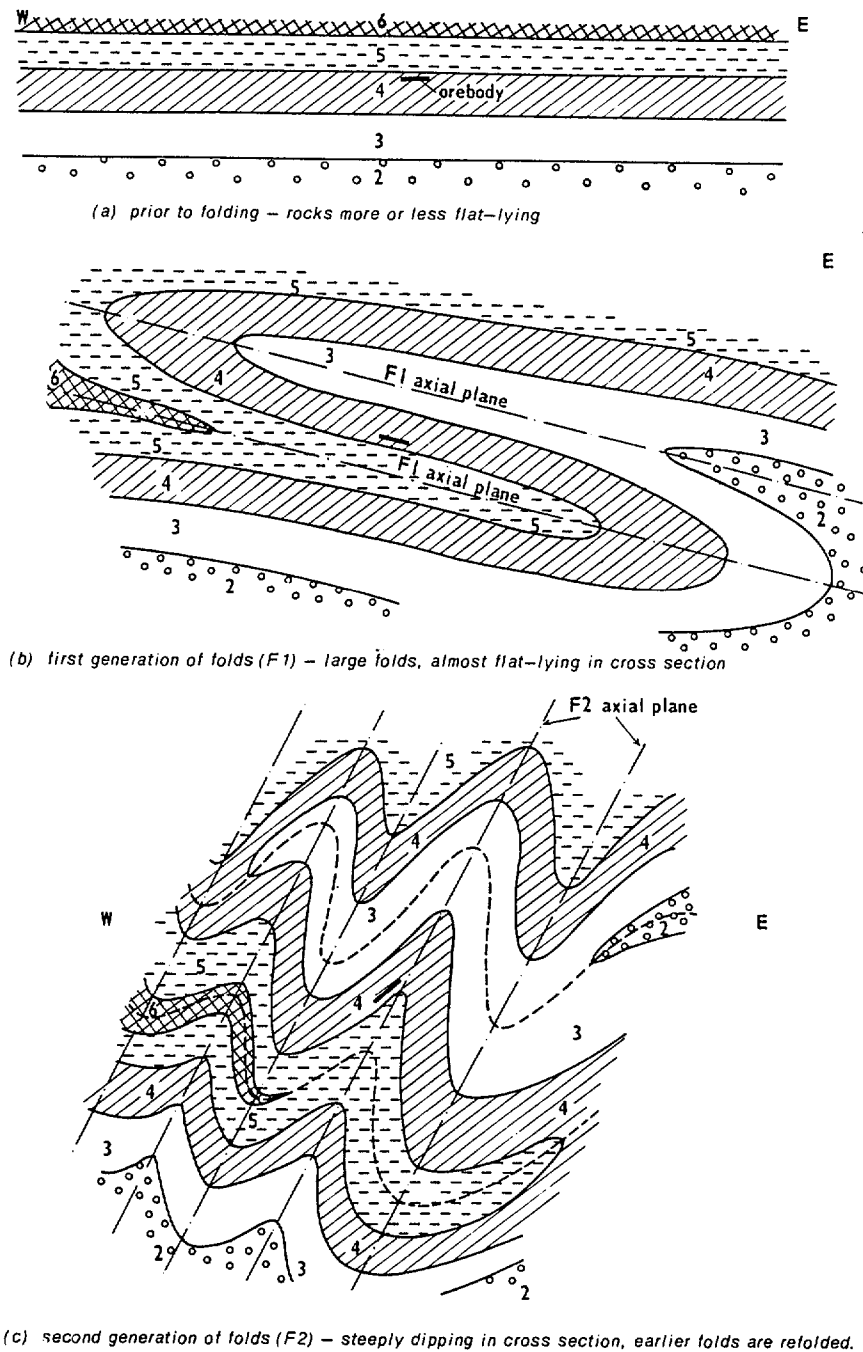


Figure 15. Diagrammatic representation of the first two generations of folding of rocks containing the Broken Hill orebody (from Worner and Mitchell 1982).

Table 9 Lithology, mineralogy and metal contents of ore lenses constituting the Broken Hill lode (from Stevens *et al.* 1988; in part after Plimer, 1984, and Mackenzie, pers. comm., 1986)

Ore lens	Rock types	Minerals	'Typical' mining grade		
			Pb (%)	Ag (g ^t ⁻¹)	Zn (%)
No. 3 lens northern	Sulphide-quartz-Mn-silicate-fluorite rock, rhodonite-sulphide rock, fine-grained garnet rock (adjacent).	Abundant:	15	300	13
		Minor:			
		Trace:			
No. 3 lens southern	Sulphide-quartz-Mn-silicate-fluorite rock, fine-grained garnet rock (adjacent).	Abundant:	11	200	15
		Minor:			
		Trace:			
No. 2 lens	Sulphide-calcite-CaMn-silicate rock, fine-grained garnet rock (adjacent).	Abundant:	14	100	11
		Minor:			
		Trace:			
No. 1 lens	Sulphide-quartz-calcite rock	Abundant:	8	50	20
		Minor:			
		Trace:			
A lode	Sulphide-MnCa-silicate-quartz rock, quartz-garnet rock.	Abundant:	4	40	10
		Minor:			
		Trace:			
B lode	Quartz-sulphide rock	Abundant:	5	40	17
		Minor:			
		Trace:			
C lode	Quartz-garnet-gahnite-sulphide rock.	Abundant:	2.5	20	5
		Minor:			

(not mined)

(ii) Thackaringa Mines

Geology (after Barnes 1988) - Thackaringa Area

The mines in the Thackaringa area occur as a distinct cluster in an area 5 km x 4 km situated just south of the Barrier Highway approximately 35 km west-southwest of Broken Hill. The density of ore-bearing veins exceeds that of other parts of the Broken Hill, Euriovie or Olary Blocks.

The major mines in the area are the Pioneer and Gipsy Girl, each having produced in excess of 10,000 tonnes of medium to high-grade ore. Most of the other named deposits are comparable in size with the numerous other well known Thackaringa type deposits in the Broken Hill Block. These have produced a few hundred kilograms to a few hundred tonnes of ore. The recorded figures are, however, incomplete, and in many of the mines, production was up to several times higher than recorded.

History

The discovery of argentiferous galena at Thackaringa in 1875 holds a special place in the history of the Broken Hill area. Before the discovery of ore, Thackaringa was a small settlement on the track from Terowie, South Australia, to Wilcannia on the Darling River. The settlement had a grog shop and many wagon teams would camp to spell at the Thackaringa Tank.

The Pioneer mine at Thackaringa was the first operating Ag-Pb mine in the Broken Hill district. Rich silver deposits were soon afterwards discovered at Umberumberka, in the Apollyon Valley, and elsewhere, and by the early 1880's small settlements and mining camps were spread throughout much of the Barrier Ranges.

Mineralogy

The mines at Thackaringa exhibited less substantial secondary enrichment either at the surface or near the water table than was recorded at Umberumberka, Apollyon Valley, Purnamoota and elsewhere. In those areas, records suggest that masses of enriched silver halides, predominantly chlorargyrite, occurred at the surface in rubbly ironstone gossan derived from leached siderite. Such masses were not reported at Thackaringa where galena commonly occurred at or near the surface.

The deposits at Thackaringa show several other minor differences when compared to Thackaringa type deposits elsewhere in the Block. The lodes at Thackaringa commonly contained minor amounts of secondary copper minerals which were reportedly silver-bearing. Observations suggest that such material probably derived from the weathering of tetrahedrite and other sulphosalts as well as from minor chalcopyrite. Field observations suggest that sulphosalts such as tetrahedrite, as well as quartz and sphalerite, are slightly more abundant in the mines at Thackaringa than in similar deposits elsewhere.

Host Rocks and Alteration

Host rocks are mainly composite gneiss, strongly foliated micaceous schist, minor amphibolite, plagioclase-quartz rock and layered calc-silicate rock and rare quartz-gahnite rock. The rocks in the entire mines area have been affected by hydrothermal alteration, retrogression and/or weathering. Coarse muscovite is present in many composite gneiss units and appears to be an overprint caused by a thermal pulse at 520 ± 40 Ma (Harrison and McDougall 1981). Hydrothermal alteration of host composite gneiss has resulted in sericitization of feldspars and other aluminosilicates, and a characteristic pale fawn to fawn-green colour is developed in the rocks. Microveinlets of siderite have formed stockworks in joints in gneiss adjacent to most veins. When these weathered, patchy ferruginous staining developed. Pervasive alteration is common, leaving only massive medium to fine-grained quartzitic layers unaffected. Rocks in the mines area at Thackaringa are not necessarily strongly retrogressed, but numerous narrow retrograde schist zones are present. The extensive alteration and weathering of the rocks, however, gives a first impression that retrogression is widespread.

Structure

Numerous siderite-quartz veins are present in the Thackaringa area but three main strike directions are apparent: (a) northeast, (b) south of east, (c) southeast. In addition, in the

main Pioneer, Gipsy Girl area, near-horizontal systems are present. The dominant easterly dip of the veins is overall, more shallow than the schistosity or bedding in the host rocks.

The strikes of the veins correspond approximately with:

- (a) The direction of the Mundi Mundi fault scarp and other major faults.
- (b) The approximate direction of the Thackaringa-Pinnacles retrograde schist zone.
- (c) The schist zone direction marking the offset of Mundi fault scarp immediately to the west of mines area. This is also the approximate direction of the Kantappa lineament, Pine Creek shear and Corona fault.

Pioneer and Gipsy Girl Mines

The main workings in the Thackaringa area are Pioneer (TM5) and Gipsy Girl (TM2) which lie adjacent to one another. Each mine worked shallowly dipping siderite "lodes" which varied from about 0.2 m to 2 m in thickness, in places regular, elsewhere pinching and swelling over short distances. The mineralogy of the veins was typical of those throughout the Thackaringa mines area, with a gangue of siderite and quartz containing dispersed "bunches" of cerussite, anglesite, galena and occasionally a little malachite.

The Pioneer mine worked semi-continuously from 1875 to 1892 and intermittently on a very small scale up until recent times. It contained numerous galena-bearing veins. Whether the veins in the Pioneer are folded, or simply arranged in such a way as to give the impression of folding is open to conjecture. The mined ore clearly did not follow a regular tabular course.

The Gipsy Girl mine, like the Pioneer, contains several veins. Underground inspection of the upper level and above of the Gipsy Girl mine around the No. 1 shaft showed that main workings follow a shallowly north dipping tabular vein which gently rolls, strike varying through 10° to 20° from the average. In places, vertical faults have offset the vein by over 1 m. Several small systems, some dipping vertically, some horizontal, are present. Some of these contain abundant galena while others contain little obvious mineralization.

(iii) Pyrite Hill - Cobaltian Pyrite

Geology (after Barnes 1988)

The Pyrite Hill deposit (TK234, TK238) consists of a sweeping arc of disseminated to massive pyrite in plagioclase-quartz rocks extending for over 1.2 km in length. Pyritic rocks occur over widths of several tens of metres but also lens out in places. The deposit was first described by Wynn (1961).

Workings at the northern end of Pyrite Hill comprise two vertical shafts about 20 m deep (TK234). The shafts are adjacent to a ferruginous zone in plagioclase-quartz rock. The presence of metasedimentary rocks on the dumps suggests that workings passed through the entire thickness of plagioclase-rock. Bulldozer costeans intersected the pyritic mineralization to the south of the shafts, but these have been subsequently rehabilitated covering good exposures.

At TK238, a shaft about 15 m deep follows a gossanous lens after massive pyrite within a zone of pyritic plagioclase-quartz rock. The gossanous material consists of very open honeycomb boxworks after very coarse pyrite. A breccia texture 5 m south of the collar of the shaft is probably a solution collapse breccia developed within a lens of massive pyrite.

The Pyrite Hill deposit has been extensively explored and the history and results of the work are documented in Simon (1981). The details of the recent assessment of resources at the prospect are currently confidential. The Pyrite Hill and Big Hill areas have been held under title by Central Austin Pty Ltd for many years. Possible tonnages of the Pyrite Hill deposit (reported by Department of Mineral Resources 1981) have been estimated as between:

- 23 million tonnes at 0.11% cobalt and 11.7% sulphur over an average width of 37 m and strike length of 1036 m, and
- 31 million tonnes at 0.09% cobalt and 9.9% sulphur over an average width of 50 m and strike length of 1036 m.

Big Hill Type cobaltiferous pyrite deposits in plagioclase-quartz rocks

General Characteristics

Plagioclase-quartz rocks occur throughout the Broken Hill Block (Brown *et al.* 1983a), dominantly in the Thackaringa Group (Willis *et al.* 1983). In many places, the plagioclase-quartz rocks contain disseminated to massive pyrite which is cobaltiferous in part. The major deposits of pyritic plagioclase-quartz rocks are at Big Hill and Pyrite Hill (also known as Pine Ridge or Thackaringa pyrite). Although the deposits represent an enormous resource, none is presently economically viable.

Cobaltiferous pyrite deposits in plagioclase-quartz rocks have been described in publications by Wynn (1961), Barnes and Stevens (1975), Plimer (1977) and Barnes (1980) and in numerous unpublished exploration reports. The plagioclase-quartz host rocks have been described by Vernon (1961, 1969), Plimer (1977) and Barnes (1980) and in numerous unpublished Geological Survey of New South Wales reports.

The plagioclase-quartz rocks are leucocratic, massive to well bedded, and composed essentially of sodic plagioclase (albite-oligoclase) (up to 100%), quartz (up to 70%), magnesian biotite, and in places, pyrite. Accessory minerals include muscovite, rutile, zircon, sphene, magnetite, sillimanite, apatite, pyrrhotite, chalcopyrite, sphalerite, and chlorite (Plimer 1977, Brown *et al.* 1983a). Vernon (1969) noted that the pyrite-bearing rocks are generally devoid of biotite.

Mineralization in the plagioclase-quartz rocks takes several forms, with one type grading to the next. Most commonly, pyrite occurs as disseminated single grains in thin trains parallel to bedding. With higher pyrite contents, the pyrite forms highly elongate lenses, in places composed of massive pyrite. The massive pyrite lenses are dominantly conformable, but in several localities, transgressive masses have been observed. Mobilization of pyrite into coarse-grained pyritic veins also occurs in places. Deformation of massive pyrite has resulted in the formation of pyritic breccias in several areas.

Origin

The origin of pyritic mineralization in plagioclase-quartz rocks is intimately related to the origin of the host rocks. The plagioclase-quartz rocks exhibit field relationships and structures typical of sedimentary rocks but have an unusual mineralogy and chemistry. Postulated precursors for the rocks include metasomatically altered metasediments (Brown 1922, Vernon 1961), metamorphosed arkoses (Thomson 1955), metamorphosed sediments of "unusual" composition (Condon 1959, Coombs 1965), metamorphosed soda rhyolitic and keratophyric tuffs (Stevens 1975, Stanton 1976d), and metamorphosed, analcimized airfall tuff (Coombs 1965, Plimer 1977, Stevens *et al.* 1980).

Brown *et al.* (1983a) and Willis (1984) reviewed the possible origins of the plagioclase-quartz rocks. Brown *et al.* (1983a) favoured a keratophyric tuff progenitor, but also considered analcimized airfall tuff as a possibility, while Willis (1984) concluded that the rocks were analcimized volcanics altered under alkaline conditions in an evaporitic, lacustrine, or transitional marine setting.

The pyrite, and in places magnetite, in and associated with the plagioclase-quartz rocks, are stratigraphically controlled, dominantly concordant, and are considered to have been deposited contemporaneously with the surrounding rock (e.g. Plimer 1977, Barnes 1980). Plimer (1977) concluded that the high Co/Ni ratios of the deposits were in accord with a volcanogenic origin. He further suggested the sulphide mass at the Thackaringa pyrite deposit is enclosed by a metamorphosed alteration zone marked by increasing Rb/Sr, Rb/K₂O and MgO towards the massive sulphide.

The massive pyrite lenses in plagioclase-quartz rocks may have formed from iron-rich exhalations associated with keratophyric volcanism. Stanton (1976, p. B230) suggested that quartz-magnetite horizons represent:

"an early phase iron-rich sea-floor hydrothermal episode linked specifically with the keratophyric phase of volcanism"

and Barnes *et al.* (1983, p. 312) noted that:

"the qm [quartz-magnetite] rocks represent only part of an iron-rich association which includes qm rock, qf [granular quartz-iron sulphide] rock, some qg [quartz-gahnite] rocks and pyritic plagioclase-quartz rocks, and an association of magnetite and iron sulphide with minor copper and cobalt mineralization".

Overview

The association, if any, of the iron-rich mineralization concentrated in the Thackaringa Group with the lead, zinc and tungsten-rich mineralization in the Broken Hill Group remains unclear. The presence, in places, of gahnite (or at least green spinel), and minor lead, zinc and/or tungsten, suggest a relationship, as does the stratigraphic interpretation of the Pinnacles ore body as being in the Thackaringa Group. However, the fundamental chemical characteristics of the mineralization in the Thackaringa Group are as different to those of mineralization in the Broken Hill Group as the rocks are different. This strongly points to a change of the nature of stratiform mineralization in parallel to the change of the geological environment. Studies of the Pb isotope ratios of pyrite from the Pyrite Hill deposit (Gulson *et al.* 1985), show that the Pb in this deposit is highly radiogenic with ²⁰⁶Pb/²⁰⁴Pb ratios being in the range from 16.6 to 50, and thus substantially different from Pb in Broken Hill type deposits. These results, however, reflect high U/Pb ratios in the rocks, and do not necessarily prove that Pb in the two different types of deposit was initially different.

The iron-rich mineralization has equivalents in the Olary Block to the west of Broken Hill. Quartz-magnetite-barite horizons (e.g. Perryhummock), finely disseminated magnetite in finely layered albitite (e.g. Waukaloo), and magnetite layers in plagioclase-quartz rock (e.g. 1 km west of the Dome Rock mine) all represent slight variants of the types of mineralization found in the Broken Hill Block, and indicate that the processes operating to form these types of rocks also occurred in the Olary areas. By comparison, Broken Hill type mineralization and its associated zinc and manganese-rich siliceous horizons are almost totally absent in the Olary Block.

Willis *et al.* (1983) have suggested that deposition of the Willyama Supergroup took place in a deepening marine environment in a rift setting. Some similarities with the East African rift can be seen. It is possible that the environment of deposition of the soda-enriched rocks and iron-rich mineralization of various types occurred in relatively shallow, restricted basins in a shallow marine analogy of the soda-rich lakes of the East African rift.

(iv) Angus - Kintore area

A small cluster of Broken Hill type occurrences is situated between the Hillston and Spar Ridge fault/schist zones to the east of Egebek feldspar quarry (Fig. 16). Two very distinct levels of mineralization occur in the area, one in Cues Formation and the other in Parnell Formation.

The Angus mine (CC41) lies about 700 m south of the Egebek schist zone. The Angus mine area has been described in detail by McManus (1963) and Cowan (1975) and its mining history is documented in Dickinson (1972). The mine was worked from 1880 to 1890 and from 1925 to 1926, and produced about 400 t of run-of-the-mine ore, with at least 184 t averaging 35% Pb and 1200 g/t Ag (Dickinson 1972). The dimensions of the worked out ore shoot are approximately 0.6 m by 1.8 m by 61 m, and a pillar from the 58 m level gave an assay of 26% Pb, 965 g/t Ag, 16.5% Zn, and 0.24% Cu (McManus 1963).

Ore minerals include abundant galena, sphalerite, pyrite/pyrrhotite and less chalcopyrite, cerussite, anglesite, malachite, covellite, marcasite, pyrrargyrite, rutile, ilmenite and haematite.

The lode rock types at the mine are comparable with those in the Southern Cross and Parnell mines in the northern Broken Hill Block. They comprise typical granular quartz-gahnite rock including garnet-rich varieties and numerous textural variants. Biotite and feldspar (some green) are common and, in parts, the lode rocks appear to grade into the pelitic hosts. Some material resembles sheared vein quartz but contains scattered, irregular lumps of granular garnet.

The immediate host rocks to the mineralization are metasediments and retrograde micaceous schists, but 'Potosi-type' gneiss and mafic gneiss are adjacent, and are particularly strongly developed along strike to the south.

An interesting feature of the mine is that, apart from the southernmost 10 to 20 metres, where surface workings are present, the surface indications of mineralization are poor; yet a significant amount of ore has been won from a narrow shoot.

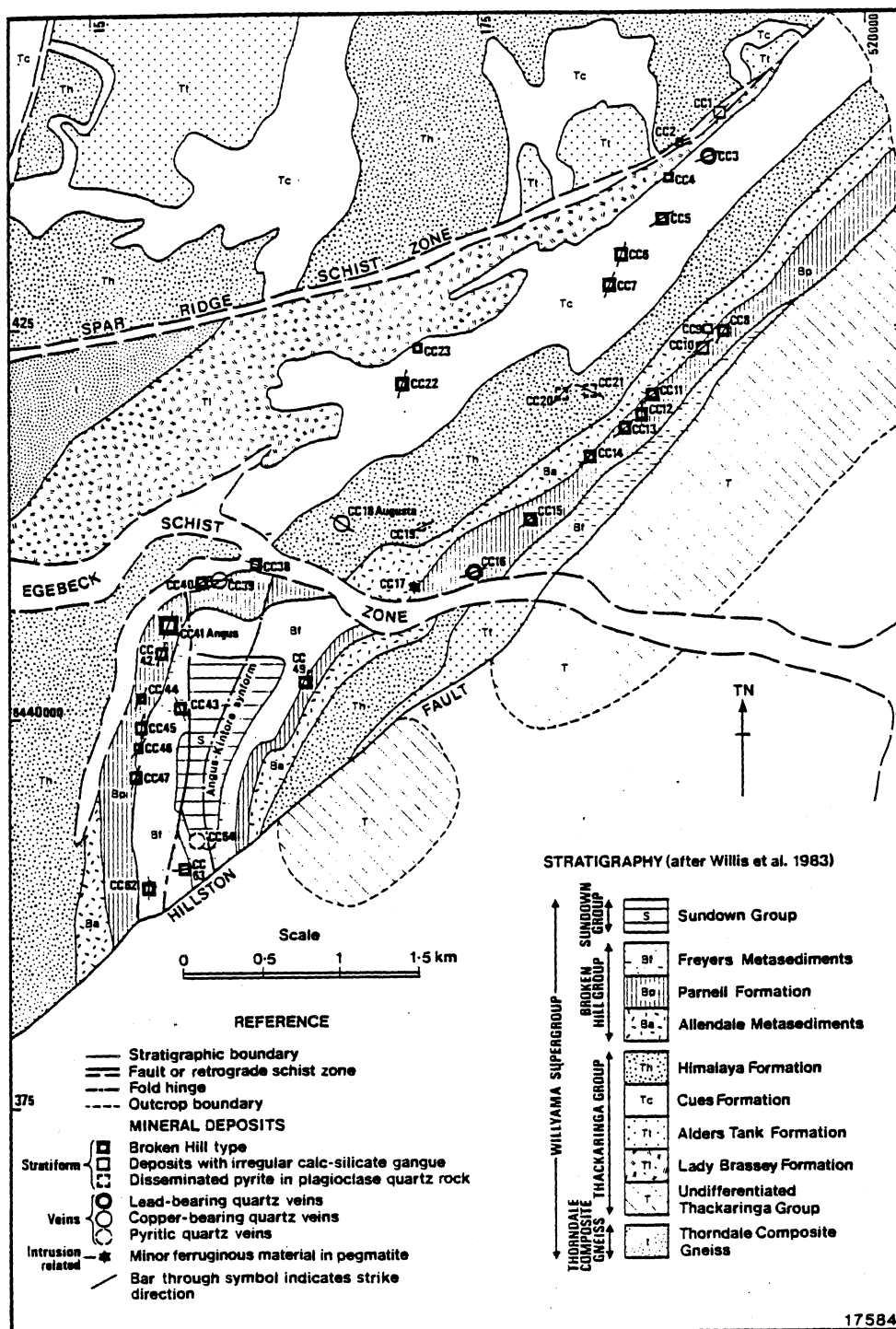


Figure 16. Mineral deposits in the Angus-Kintore area .

(v) Egebek Feldspar Quarry (from Lishmund 1982)

The mine will be visited on the ICOG excursion if time allows. It has been the largest producer of feldspar in the State, but no mica or quartz production has been recorded, and only a minor amount of beryl has been won from the deposit.

Geology

The Egebek pegmatite is over 200 m long by up to 50 m wide, striking east-west and dipping approximately 60° south. Predominant country rocks in the vicinity are amphibolite and quartz-plagioclase-biotite gneiss and schist, with lesser amounts of layered quartz-feldspar rocks ('aplite') and coarse retrograde mica schist.

The rocks are only moderately affected by retrogressive metamorphism except in the immediate vicinity of the pegmatite contacts, where the gneiss grades into a coarse quartz-sericite schist, particular along the footwall where the zone of schist is up to 25 m wide. The amphibolite appears to have been comparatively resistant to such alteration. The coincidence of the retrograde schist with the margins of the pegmatite is considered to be due to the emplacement of the pegmatite within a retrograde shear zone rather than to contact metamorphic effects.

The pegmatite comprises the following zones:

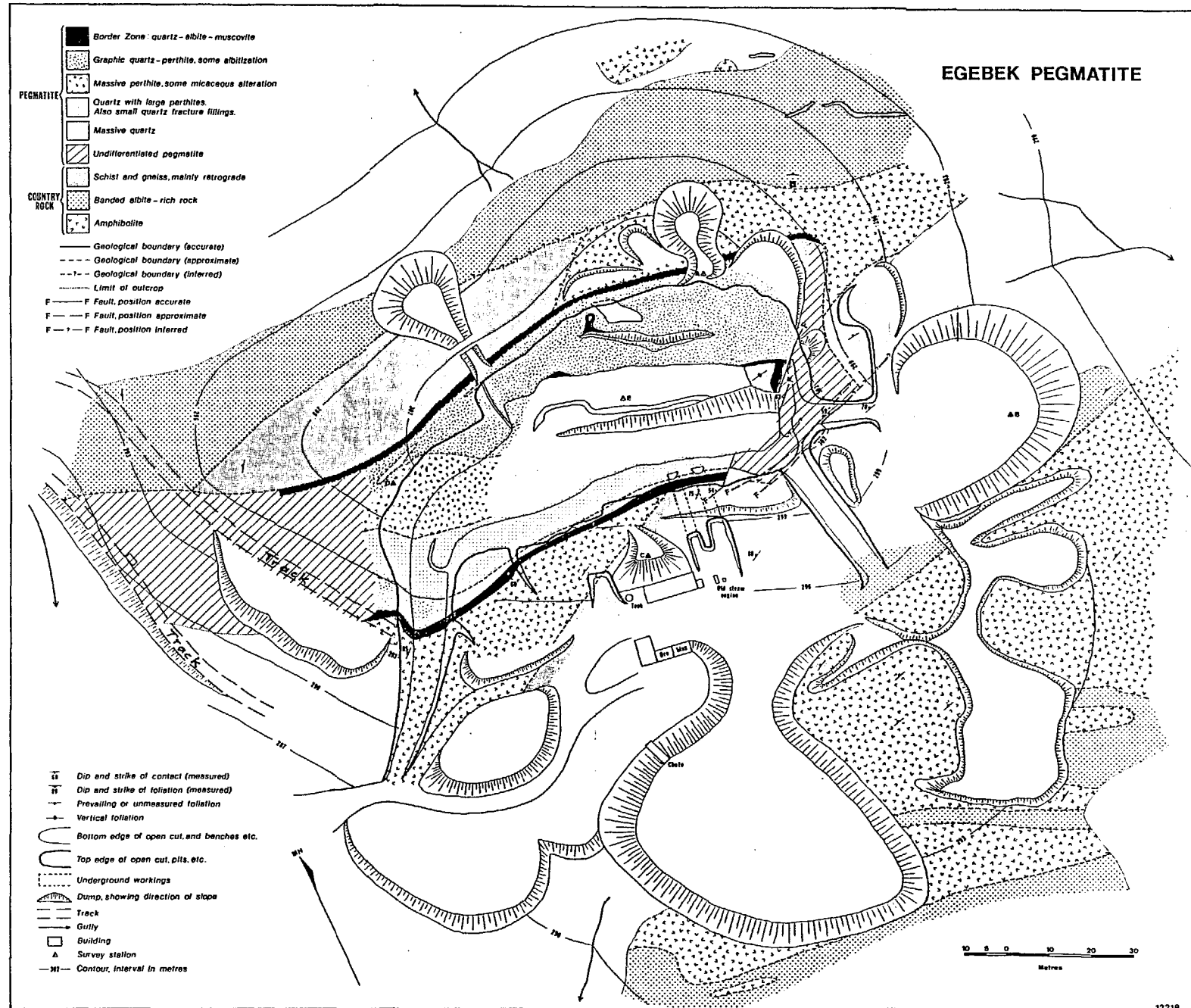
- a) A border zone up to 2 m wide consisting of quartz and albite-oligoclase, frequently graphically intergrown, and muscovite. The muscovite occurs as small crystals and as long, bladed crystals averaging between 50 mm and 0.1 m long and up to 3 m long with joints radiating inwards from the contact. Small, optically continuous relics of microcline occur in the plagioclase of this zone.
- b) An intermediate zone up to 15 m wide of pinkish to off-white coarse microcline-albite perthite, with some large, massive perthite crystals, approximately 25 per cent by volume of graphic quartz intergrowths, and interstitial quartz. The grain size in this zone averages approximately 0.5 m, and muscovite is virtually absent.
- c) A zone up to 15 m wide of off-white to pinkish-white coarse microcline-albite perthite with a grain size of up to 0.5 m. This material only occurs in the northern half of the pegmatite.
- d) A central zone of massive whitish quartz with scattered coarse white perthite crystals up to 2 m wide. Quartz veining in the outer zones of the pegmatite probably formed at the same time as this central zone, as did the small quartz veins which occur north of the pegmatite and contain large pink perthite crystals and some graphic perthite. Tonkin (1969) noted that these veins also contain small amounts of ilmenite, arsenopyrite, apatite, and possible sphalerite.

Texturally the minerals of these zones are similar to those of the other zoned pegmatites of the area. The perthite contains unusually small amounts of albite, and exhibits microscopic fractures and zones of recrystallization and sericitization. An analysis given by Tonkin (1969) shows the plagioclase of the perthite to be almost pure albite.

In comparison to other zoned pegmatites of the area, the Egebek pegmatite is only sparingly albitized, and a correspondingly minor amount of beryl (a total of less than 1 tonne) has been won from the deposit, despite the large scale of the mining operations. Apatite, rather than manganapatite, has been reported to occur in the albitized portions in association with beryl.

Since about 1970 the deposit has been operated by Quality Earths Pty. Ltd., who have made some efforts to remove overburden from the southern wall of the quarry. However, only minor production has been recorded. Considerable further reserves undoubtedly exist in this deposit, but the cost of removing large quantities of overburden present might be sufficiently high to prevent large-scale extraction of feldspar at current prices. Also, on the basis of past production, only limited amounts of beryl could be expected to occur in the deposit.

Figure 17. Geology of the Egebeck Pegmatite (from Lishmund 1982).



DAY 6 Metamorphism, deformation - relative and absolute timing, and major problems remaining for geochronology

The morning will be spent examining a few key outcrops of structural significance in and around Broken Hill, and a discussing some of the major isotopic and geochronological problems in the Broken Hill Block. Outcrops to be visited include Round Hill (D₂ structures and syn-D₂ pegmatites) and ABM quarry (D₃ or D₄ later folds with axial plane pegmatites). We hope to be accompanied by Ken Hickey, from James Cook University of North Queensland, Townsville.

Overview

Despite the large number of geochronological studies applied to the Broken Hill Block over the past 30 years, there are significant gaps in our knowledge of the geological history. Some of the major problems that could be addressed with geochronological techniques in the future include:

1. The age of deposition of stratigraphic units other than the Hores Gneiss.
2. Separation of the age of each of the metamorphic and deformational events.
3. History of the retrograde schist zones.
4. Ages of the various granitic intrusives. Only the Brewery Well Stock and two dykes have been studied previously.
5. Age range of the Adelaidean sequence.
6. Ages of the cumulate peridotite and serpentinite bodies.
7. Ages of the hornblendite, pyroxenite and dolerite dykes and stocks. One has been previously dated.
8. Ages of the deformed leucocratic granitoids, and the various generations of pegmatites.
9. Age of the Thackaringa type Pb-Ag-siderite veins.
10. Age of the Broken Hill orebody gossan.

Page and Laing (in prep.) have recently determined the depositional age of part of the Broken Hill Group (Hores Gneiss and Parnell Formation) from U-Pb zircon studies. This style of geochronology needs to be applied to other units, especially probable metavolcanic units in the Thackaringa Group and older gneisses, to determine the age range of the entire sequence. Such study would also provide important information on the nature of the quartzofeldspathic gneisses (were they sediments, volcanics, or intrusives?), and the relative amounts of new Proterozoic crustal growth versus recycled Archaean crust.

Future Sm-Nd and (?)U-Pb dating of the amphibolites and mafic granulites could be particularly useful, because these have probably been derived directly from the mantle, with no crustal reworking or contamination.

Page and Laing (in prep.) have determined an age of 1600 ± 8 Ma for the granulite grade metamorphism. The question remains as to which of the two deformation (D₁ and D₂) have been dated, or has the closure of the U-Pb zircon system been dated during cooling after D₂? Another unanswered question concerns the age of D₃. It may be possible to determine a timing for this deformational framework by U-Pb zircon dating of pegmatites in the axial planes of F₁, F₂, F₃ folds, or to obtain age limits by dating of pegmatites folded by F₁, F₂ or F₃ folds. It may also be possible to date minerals which crystallised during particular deformations. Less reliable would be dating of whole rocks dominated by one schistosity (D₁, D₂, D₃).

DAY 7 **Travel to historic mining town of Silverton, art galleries, etc.
Depart Broken Hill for Sydney. Excursion ends Sydney Airport.**

Silverton

The 'ghost town' of Silverton lies 23 km northwest of Broken Hill. Its formation as a township followed the discovery of silver-lead-zinc ore in 1875-1876 at Thackaringa. With the opening of the Pioneer mine at Thackaringa, prospectors gradually moved into the district, many of them from South Australia, following the decline of the copper fields in that state.

The initially small village (beside Umberumberka Creek) was given the name of Silverton in 1883. By the end of that year the population was about 250. The peak population reached about 3,000 in 1885-1886. By this time, however, the small pockets of high grade ore had become exhausted, and there was a wholesale exodus of miners and their families to the newly discovered Broken Hill mining field. (The original Broken Hill leases were pegged out in 1883, but the main lode was not located until 1885, when the famous Broken Hill Proprietary Company Limited was formed. The BHP Company ceased to operate in Broken Hill in 1939). The number of Silverton's inhabitants decreased to 1700 by 1888. The population now numbers less than 100.

Broken Hill City Art Gallery, etc

Founded in 1904, it is the oldest Regional Gallery in NSW. The gallery has a magnificent collection of Australian art with regular changing exhibitions. It is home of the famous 'Silver Tree'.

There are numerous other galleries, craft shops, and mining memorabilia in Broken Hill. Perhaps one of the better known is the Pro Hart Gallery. This gallery is in an extended house in suburban Broken Hill, and houses one of Australia's most exciting private art collections.

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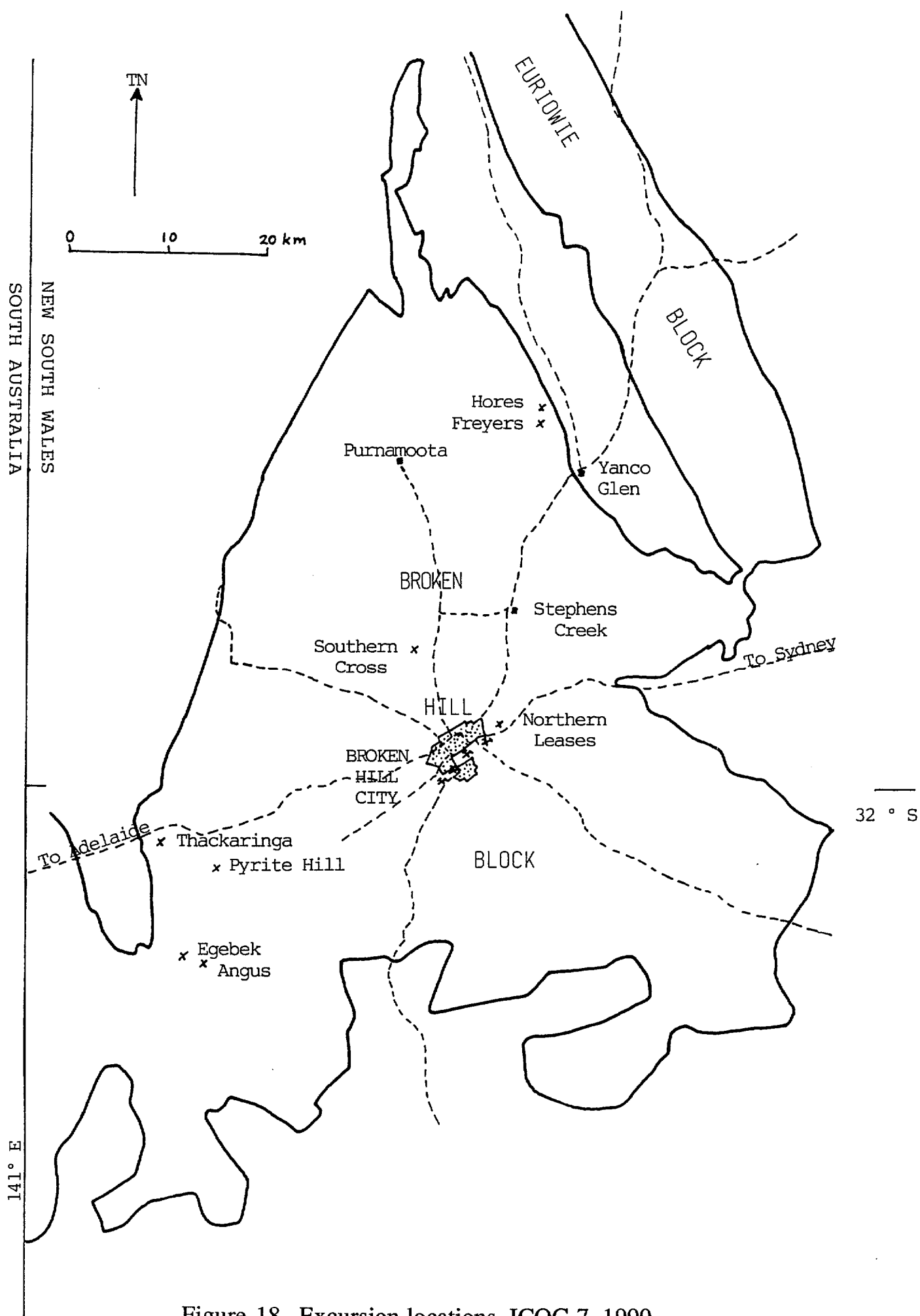


Figure 18. Excursion locations, ICOG 7, 1990.