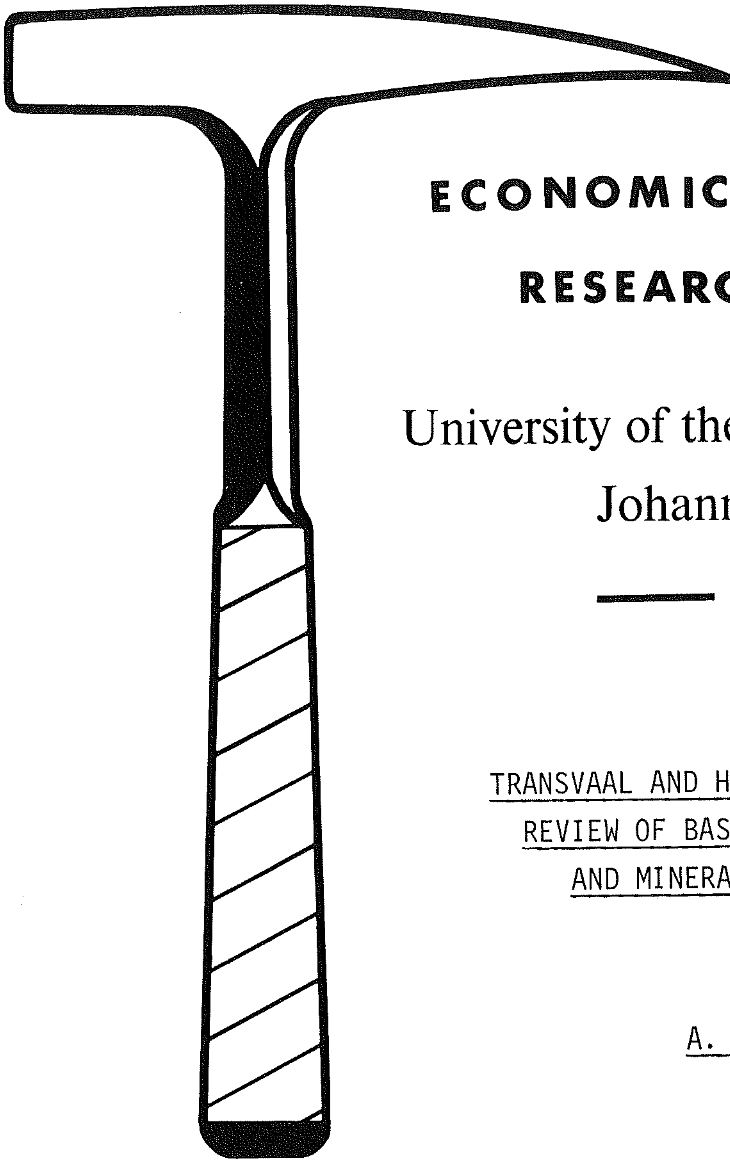

ECONOMIC GEOLOGY RESEARCH UNIT

University of the Witwatersrand
Johannesburg

TRANSVAAL AND HAMERSLEY BASINS - REVIEW OF BASIN DEVELOPMENT AND MINERAL DEPOSITS

A. BUTTON

INFORMATION CIRCULAR No. 107

UNIVERSITY OF THE WITWATERSRAND
JOHANNESBURG

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by

A. BUTTON
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<u>TRANSVAAL AND HAMERSLEY BASINS - REVIEW OF BASIN DEVELOPMENT AND MINERAL DEPOSITS</u>

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TRANSVAAL AND HAMERSLEY BASINS – REVIEW OF BASIN DEVELOPMENT AND MINERAL DEPOSITS

SYNOPSIS

The Transvaal Basin (in Southern Africa) and the Hamersley-Nabberu basins (in Western Australia) show a number of remarkable parallels. They are of roughly the same age. They have the same geotectonic setting. Each is divided into a basal volcanic and clastic unit, a chemical sedimentary unit, and an upper clastic unit. Stratigraphic relations, lithologies, and depositional environments within each of these divisions are similar. The basins have a number of important mineral deposits in common, including iron, manganese, and crocidolite asbestos. Some mineral deposits, now known in only one of the basins, may well be found in the other basin as exploration proceeds.

The parallel behaviour of the basins suggests a uniform tectonic history over a large portion of the Gondwana Supercontinent. Continental reconstructions that place the western margin of Australia against the African-Madagascan unit are favoured on geological grounds.

INTRODUCTION

The early-Proterozoic (2000 to 2500 million year old) sedimentary basins of the world are repositories of a wide range of valuable minerals, and produce a large proportion of the world's gold, uranium, iron, manganese, blue asbestos (crocidolite), and amosite. Prominent among these basins are those situated on the ancient shield areas of southern Africa and Western Australia. Comparisons of these basins has resulted in the recognition of remarkable parallels in basin development and mineral deposits. Similarities are nowhere more striking than those shown by the Transvaal Basin (southern Africa) and the Hamersley Basin (Western Australia)[1]. This paper reviews these two basins, and their mineral deposits, with a view to arriving at a generalized understanding of processes of sedimentation and ore formation. Such a synthesis will hopefully be applicable to similar basins on shield areas around the world, where preservation is such that critical relations may not have been recognized.

CONTINENTAL SETTING OF THE BASINS

In southern Africa, the strata of the Transvaal Basin are preserved within the limits of the Archaean tectonic unit known as the Kaapvaal Block. Two principal structural basins are present, an easterly one in the Transvaal, and a westerly basin in the northwestern Cape, extending into Botswana (Figure 1).

In Australia, the formations that comprise the Mount Bruce Supergroup are preserved in a single structural basin, referred to as the Hamersley Basin[2]. The Hamersley Basin is situated entirely upon the Archaean tectonic unit known as the Pilbara Block. Recently, the Nabberu Basin, a depository of similar age and general character, has been delineated around the northern and northeastern periphery of the Yilgarn Block[3,4] (Figure 1).

Dr Andrew Button received his degrees at the University of the Witwatersrand, Johannesburg. His research has centred on the stratigraphy, sedimentology, and mineral deposits of Proterozoic basins in southern Africa, particularly the Transvaal Basin. In 1974, he spent three months in the field in Western Australia, collecting data for a first-hand comparison of the Hamersley and Transvaal basins. He is currently employed as a Senior Research Fellow at the Economic Geology Research Unit, University of the Witwatersrand.

Important similarities are seen between the basement blocks of the basins. They are composed of greenstone belts, preserved in larger volumes of granitic rock, the ages of which are generally in excess of 3000 m.y.[5,6]. A suite of younger granitic intrusives has been recognized in both blocks. Those on the Kaapvaal range in age from 2880 to 2550 m.y.[5], while their counterparts in the Pilbara have been dated at 2670 ± 95 m.y.[7].

The Archaean blocks of both continents are surrounded by younger metamorphic mobile belts. The Kaapvaal Block is truncated along its northern margin by the Limpopo Belt, the principal metamorphic event of which has been dated at 2690 m.y.[8]. To the south, it is bounded by the 1100 m.y. Namaqua-Natal Belt, while on the east it abuts against the Mocambique Belt. In the latter belt, an earlier 1200 m.y. metamorphism has been overprinted by events dated between 700 and 450 m.y. ago (T. N. Clifford, *personal communication*, 1975). The Kheis Province (2900 to 2500 m.y.) truncates the Kaapvaal Block on its western side[9].

In Australia, the Pilbara and Yilgarn blocks are separated by the Gascoyne Province (1730 ± 240 m.y.)[6]. These units are truncated along the western margin of the continent by the Darling Fault System. Crystalline rocks within and adjacent to this zone have been dated at 1040 m.y. (Northampton area) and in the range 750 to 450 m.y.[6]. It is considered possible that a linear metamorphic province, here tentatively referred to as the Darling Province, extends down the length of the western margin of Australia. Finally, the Pilbara Block is bounded on its eastern margin by the Paterson Province, a belt of folded sediments intruded by 600 m.y. old granites[10].

In summary, the regional geological, tectonic and geochronological setting of the Hamersley and Transvaal basins is very similar. Not only do the geological styles of the Archaean blocks show many parallels[11], but there is also a degree of correspondence of rock ages within the circumcratonic mobile belts.

AGE OF THE BASINS

The Transvaal Basin frequently rests unconformably upon the Ventersdorp Lava (Figure 2), a volcanic unit

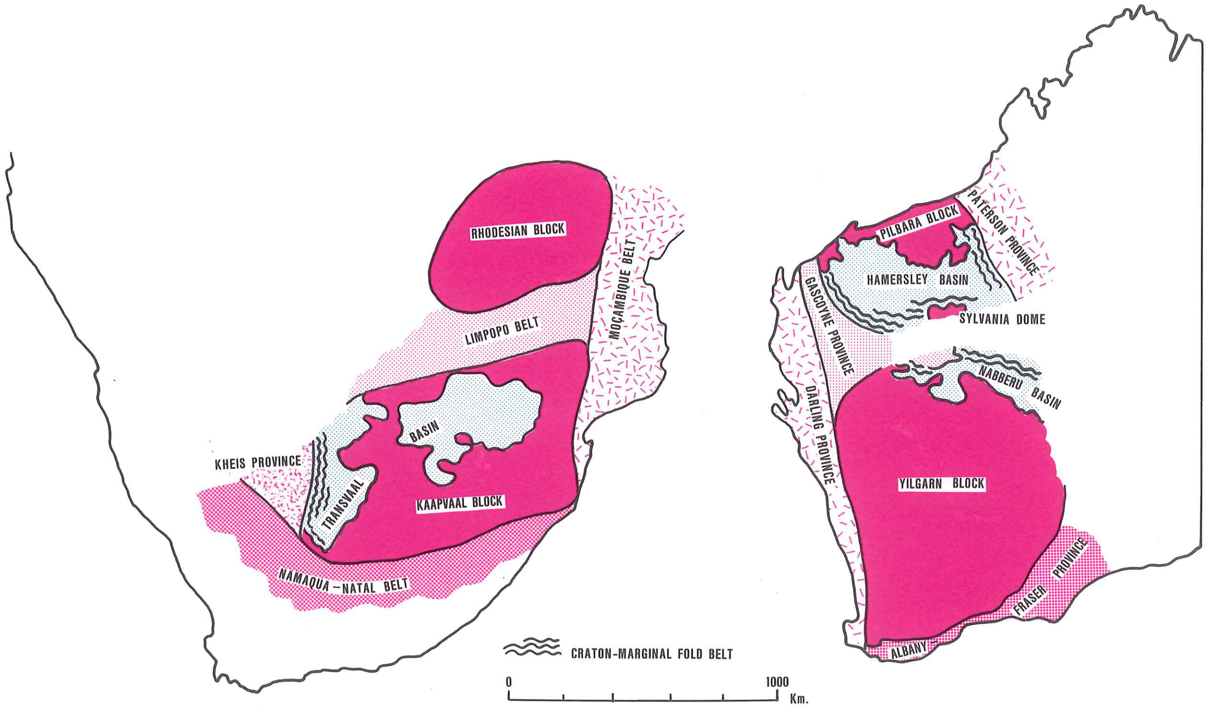


FIGURE 1 Setting of the Transvaal, Hamersley, and Nabberu basins on the African and Australian continents.

previously thought to be about 2300 m.y. old[12]. Geochronological work in progress indicates a much older age, somewhat in excess of 2600 m.y. (A. J. Burger, *personal communication*, 1975). A volcanic unit within the Pretoria Group (uppermost unit of the Transvaal Supergroup) has been dated at 2224 $\pm$ 21 m.y. (D. Crampton, *personal communication*, 1972), while underlying shales are 2263 $\pm$ 85 m.y. old[13]. In the northwestern Cape, a lava in the Olifantshoek Group that rests unconformably on rocks of the Transvaal Supergroup, has been dated at 2070 $\pm$ 90 m.y.[14]. The Transvaal strata are certainly older than 2095 $\pm$ 24 m.y., since they are intruded by the layered mafic rocks of the Bushveld Complex of that age[13]. Granitic rocks of the Bushveld Complex have been dated at 1954 $\pm$ 30 m.y.[15], a figure that has been recalculated at 1870 $\pm$ 190 m.y.[13]. A further date on the Bushveld granite has been given as 1780 $\pm$ 166 m.y.[13]. In summary, Transvaal sedimentation probably commenced around, or slightly before, 2300 m.y. ago, and ceased around 2100 m.y. ago.

Sediments of the Mount Bruce Supergroup rest on a dolerite dyke that has been dated at 2345 $\pm$ 105 m.y. (J. Blockley, *personal communication*, 1974). This dyke may be a feeder for early basalt flows, in which case this date represents the onset of basin filling. Otherwise it represents a maximum age for the Hamersley Basin. The Fortescue is intruded along its basal contact by the Gidley Granophyre, dated at 2196 $\pm$ 26 m.y.[16], while an acid igneous rock interlayered in the Fortesque has been dated at 2190 $\pm$ 100 m.y.[6].

The Woongarra Volcanics in the Hamersley Group have been dated at 2000 $\pm$ 100 m.y.[6,17]. Recent work[18] suggests deposition of Weeli Wolli shales (in the Hamersley Group) at about 2200 m.y. ago. The Wyloo Group was intruded by the Boolaloo Granodiorite at about 1720 m.y. ago[19]. Within the Wyloo, an 1850 m.y. old siltstone has been recorded[19], an age that is now considered unreliable. Acid igneous rocks interbedded in the Wyloo have been dated at 2020 $\pm$ 165 m.y.[6].

The deposition of the Mount Bruce Supergroup had definitely started about 2200 m.y. ago, and may have started as early as 2350 m.y. ago. There is no firm estimate for the cessation of deposition, but it was probably in the range 2200 to 2000 m.y. ago. There is thus a degree of overlap between the depositional ages of the Transvaal and Mount Bruce supergroups. Bearing in mind the errors and uncertainties inherent in isotopic dating, it can be stated that the two basins could be essentially of equal age.

The age of the recently discovered Nabberu Basin is uncertain. It rests on an Archaean basement, and is overlain unconformably by glauconite-bearing arenites dated at 1685 $\pm$ 34 m.y.[4]. It is considered to be an equivalent of the Hamersley Basin[4,20].

SIZE OF THE BASINS

The two structural depressions that constitute the Transvaal Basin have a combined area of about 250 000 square kilometres[1]. On the basis of isopach studies of units within the basin, it has been estimated that the basin may originally have been twice this size[21]. The exposed portion of the Hamersley Basin comprises 150 000 square kilometres[52], the Nabberu Basin having an area of 60 000 square kilometres[20]. If account is taken of the eroded edges of the basins in Western Australia, plus the fact that a significant portion of the basins is probably developed under cover of younger basins, they may well have had a total area approaching that of the calculated figure for the Transvaal Basin.

The Transvaal Basin is filled by up to about 12 km of sediments and volcanics[21], equivalent figures for the Hamersley[2] and Nabberu[20] basins are 15 km and 6 km respectively.

Geometrically, the basins are gentle warps on a subcontinental scale. They represent gently subsiding continental regions with plan-view dimensions of about 100 times their maximum downwarp dimension.

STRUCTURAL STYLE OF THE BASINS

A range of deformation styles is to be seen in the strata of

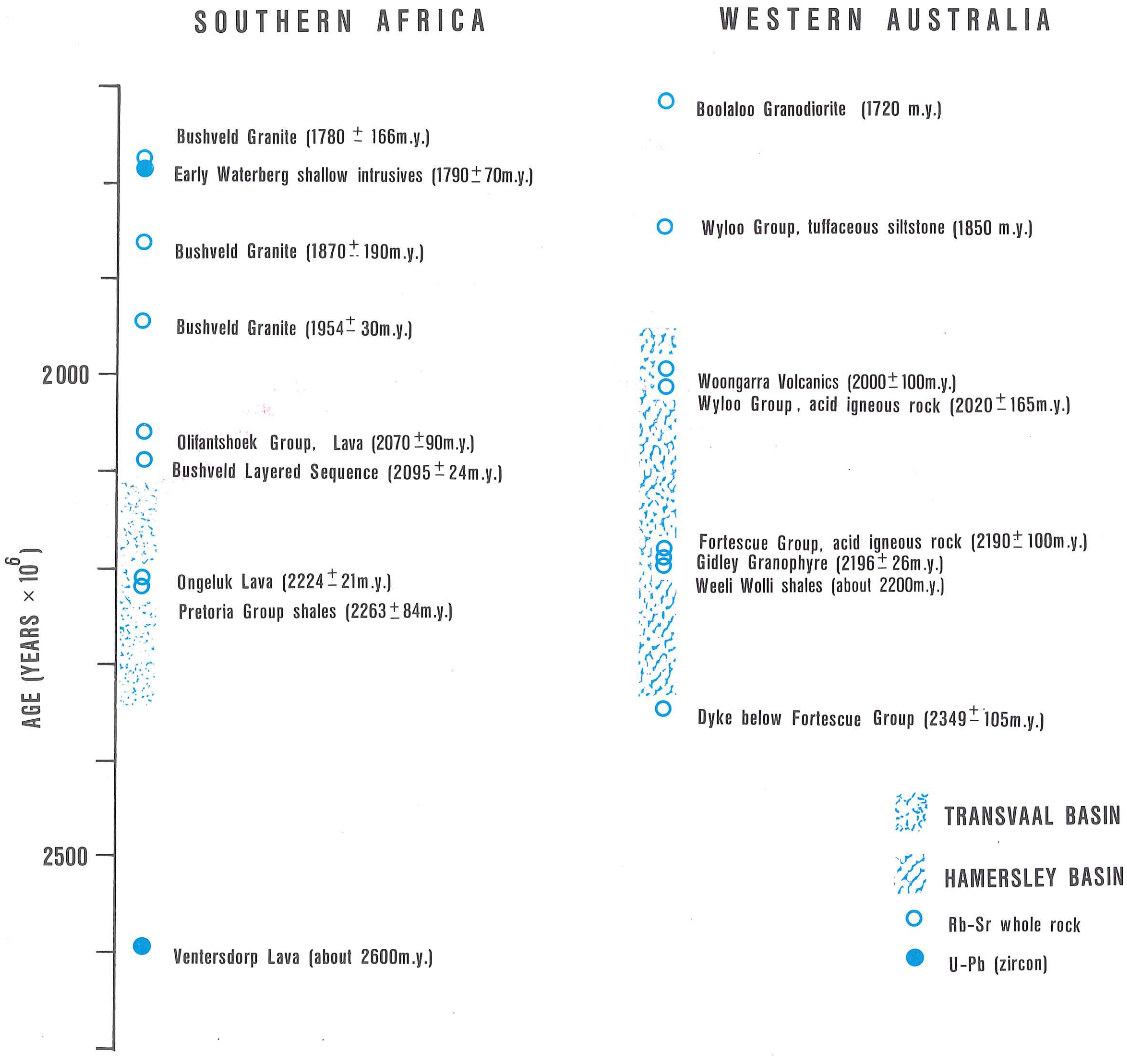


FIGURE 2 Diagrammatic summary of the geochronology of the Transvaal and Hamersley basins.

the Hamersley, Nabberu, and Transvaal basins. These early-Proterozoic successions are homoclinal and very gently deformed over large areas, generally in the interior or heartland of the cratons. Craton-marginal fold belts can be discerned in both continents (Figure 1). In southern Africa, the Transvaal strata become successively more strongly folded as the western margin of the Kaapvaal Block is approached. Similar relations can be seen in the Hamersley Basin, which becomes more intensely deformed as the Paterson and Gascoyne provinces are approached (Figure 1). The axes of folds in the craton-marginal tectonic belts tend to parallel the margins of the craton.

Within the craton interiors, local structural disturbances are seen, and can often be related to the configuration of the granite-greenstone basement. Some linear greenstone belts can be shown to have undergone tectonic rejuvenation during the Proterozoic[21,22], resulting in linear fold-belts in the blanket of sedimentary cover.

Mild, concentric-style deformation over non-linear greenstone belts represents a further tectonic pattern. In the Marble Bar-Nullagine region (Figure 12), mapping by Noldart and Wyatt[23] clearly indicated the superimposition of Proterozoic synclines over Archaean greenstone synclinoria. Similar observations were made by Kriewaldt and Ryan[24] in the vicinity of Pilbara (Figure 12). In the Transvaal Basin, the axes of major synclinal features are frequently situated over Archaean greenstone belts[25].

GROSS STRATIGRAPHIC SUBDIVISION

The Proterozoic units under discussion fall naturally and easily into three major subdivisions. They frequently commence with a *basal volcanic and clastic unit*, which grades upwards to a *chemical sedimentary unit*, the latter being overlain unconformably by an *upper clastic unit* (Table 1). The basal volcanic and clastic unit is not developed in parts of the basins, being overstepped by the chemical sedimentary unit (Figure 3). Locally, the latter may also be missing, being truncated by the overlying upper clastic unit.

THE BASAL VOLCANIC AND CLASTIC UNIT

Both the Transvaal and Mount Bruce supergroups commence with an assemblage of volcanics and sediments, here termed the *basal volcanic and clastic unit*. The assemblages show a number of similarities, but also some marked differences, which are summarized in Table 2.

FIGURE 3 Schematic diagram of the gross-stratigraphic subdivision of the Transvaal and Hamersley basins.

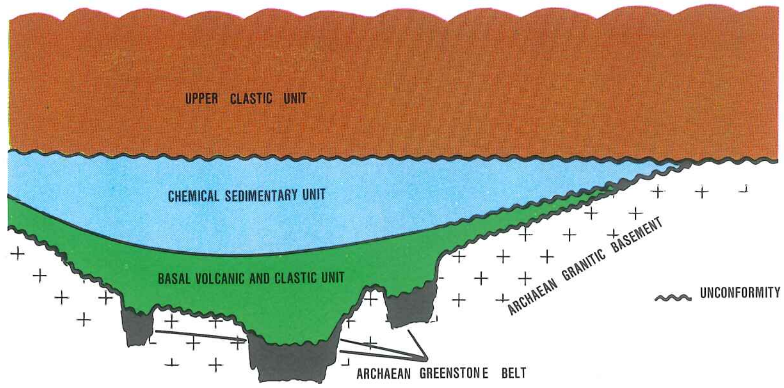


TABLE 1
GROSS STRATIGRAPHIC SUBDIVISION OF THE EARLY-PROTEROZOIC BASINS

	Hamersley Basin	Nabberu Basin	Transvaal Basin*	
	Mount Bruce Supergroup	Not named	Transvaal Supergroup	Griqualand West Supergroup
Upper Clastic Unit	Wyloo Group, Manganese Group	Present, not named	Pretoria Group	Postmasburg Group
	Unconformity	Unconformity	Unconformity	Unconformity
Chemical Sedimentary Unit	Hamersley Group	Yelma Sandstone, Frere and Windidda Formations	Chuniespoort Group	Campbell and Griquatown groups
	Local Unconformity	Unconformity	Unconformity, except near basin axis	Unconformity
Basal Volcanic and Clastic Unit	Fortescue Group	Not preserved	Wolkberg Group	Not preserved

*Nomenclature recommended by the South African Committee for Stratigraphy[26].

One of the most striking parallels between the basins involves the topographic and tectonic control exerted by the greenstone belts (see Table 2). The importance of braided stream deposition, and of volcanism on a marginal-marine platform, in both basins, is noteworthy.

THE CHEMICAL SEDIMENTARY UNIT

The *chemical sedimentary unit* comprises the Hamersley Group of the Mount Bruce Supergroup, and the Chuniespoort and Campbell-Griquatown groups in the Transvaal Basin (see Table 1). The unit is characterized by the almost total absence of allochthonous coarse clastic rocks, and by the predominance of chemical sediments, including carbonates, iron formation, and chert. The basal formations of the Nabberu Basin can also be accommodated in the chemical sedimentary unit. Table 3 synthesizes some of the most important characteristics of this unit in the two basins.

In the Transvaal Dolomite, cycles of iron enrichment in carbonates have been related to depositional structures indicative of the presence of barriers in the basin[40]. Iron formation is thought to have been deposited in an environment barred from the open ocean by wave-built banks of detritus, both of intraclastic breccia and of oolites. Such structures are common at the top of the Transvaal dolomites[40], and are also seen in the overlying iron formations[41,42]. Layers of intraclastic breccia are found at the top of the Wittenoom Dolomite (Figure 9c), and within carbonate lenses in the Brockman Iron Formation[90].

The iron formations in Australia and South Africa have been intensively studied[2,43,44,45,46,47,48,49,50]. Comprehensive reviews are given by Trendall[1,51], and by Beukes[33].

Grubb[46] and Ayres[47] have studied the paragenesis of minerals in the Dales Gorge Member of the Brockman

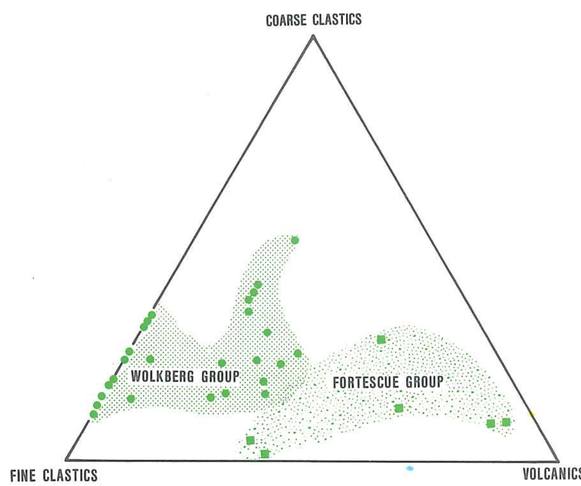


FIGURE 4 Lithological triangle for the Wolkberg and Fortescue groups.

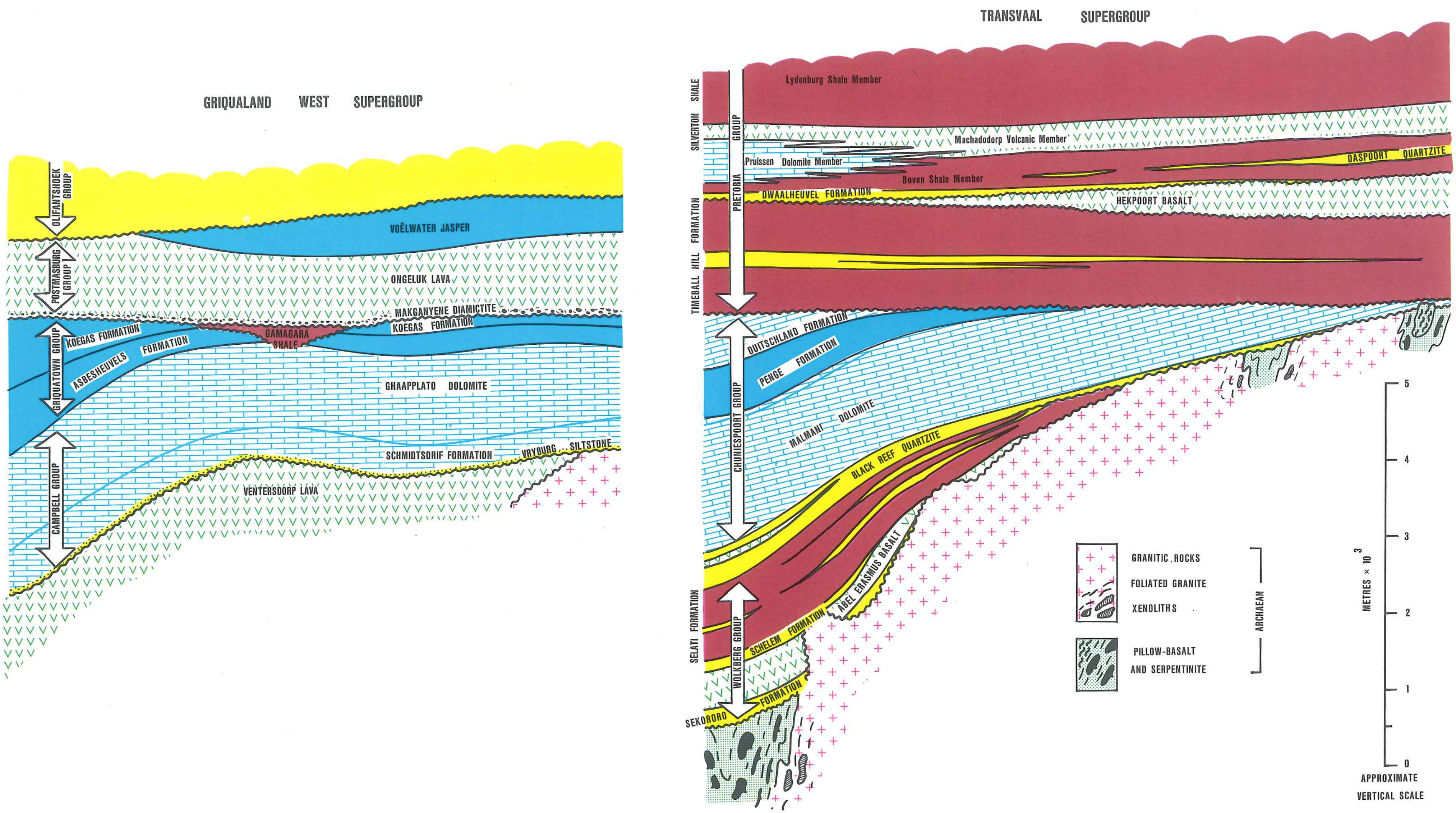
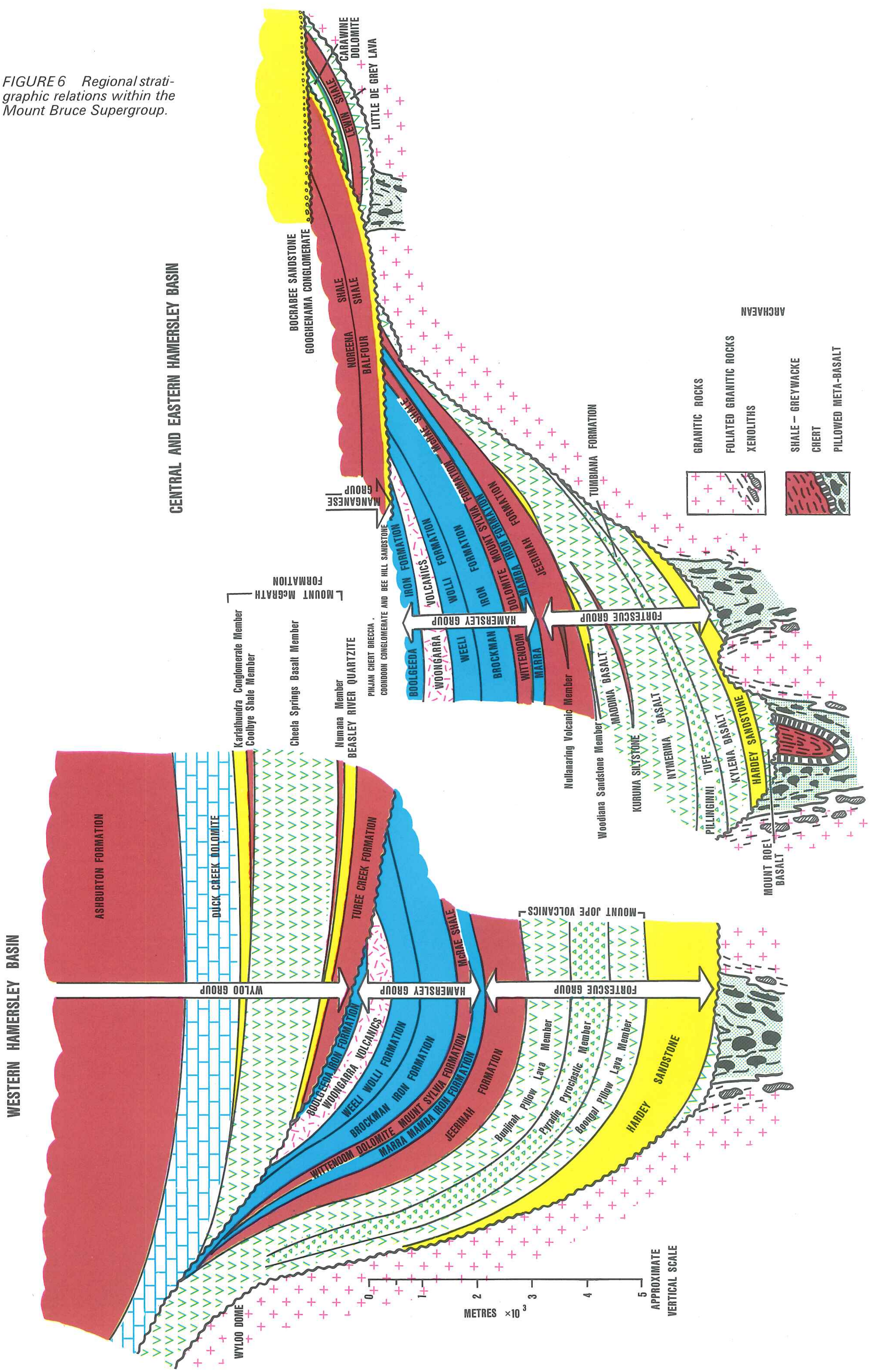


FIGURE 5 Regional stratigraphic relations within the Transvaal Supergroup.

FIGURE 6 Regional stratigraphic relations within the Mount Bruce Supergroup.



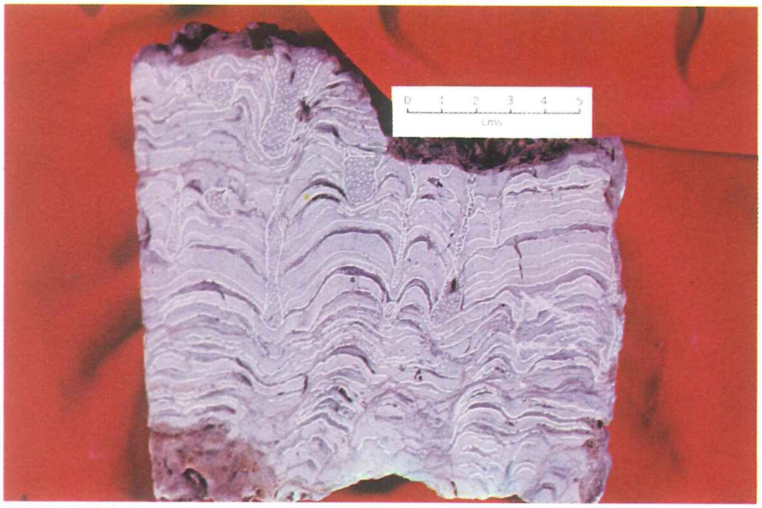


FIGURE 7 (a)


FIGURE 7 (b)

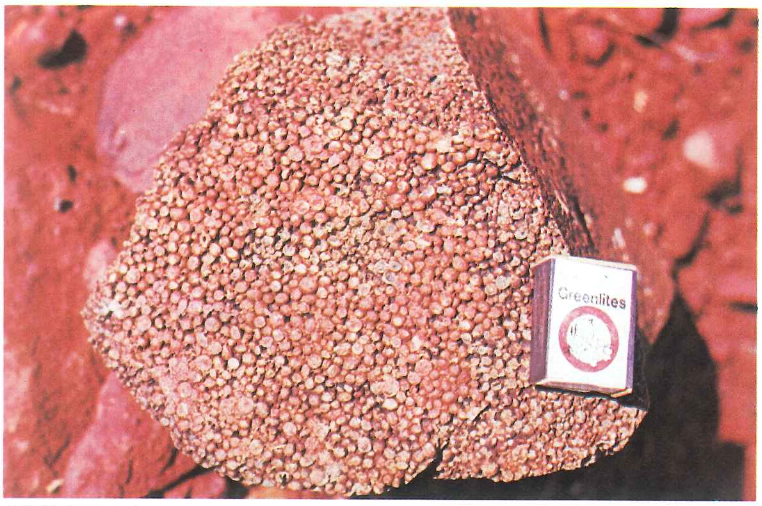


FIGURE 7 (c)


FIGURE 7 (d)

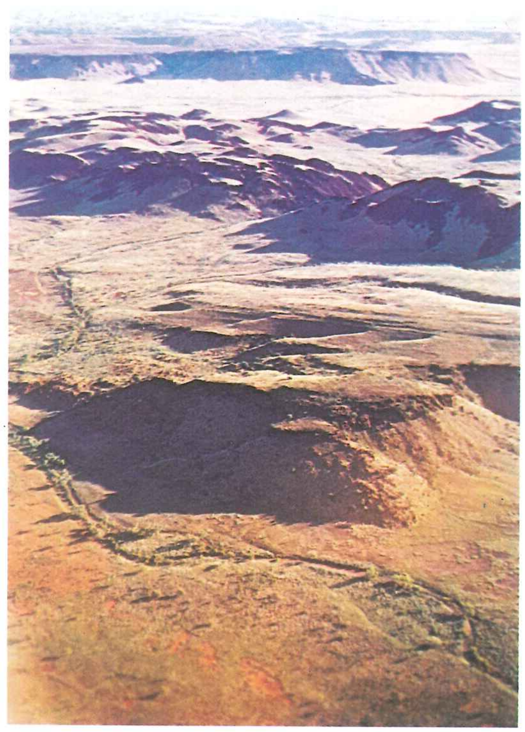


FIGURE 7 (e)

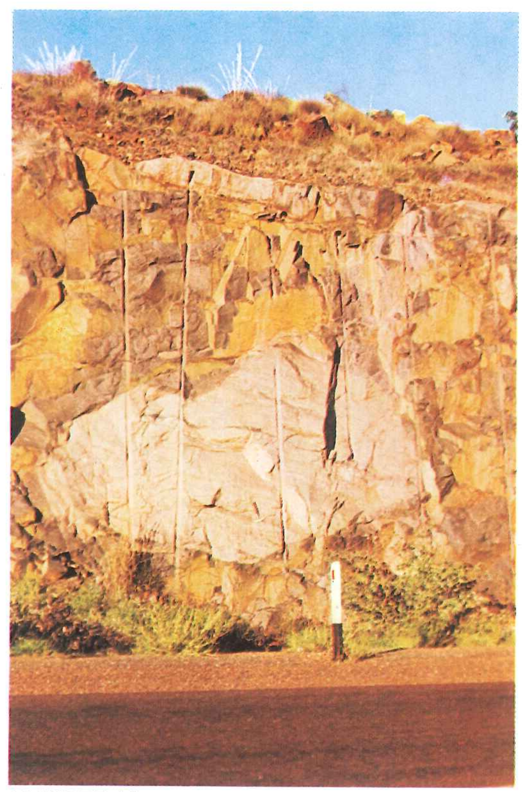


FIGURE 7 (f)

TABLE 2
BASAL VOLCANIC AND CLASTIC UNIT – COMPARATIVE ATTRIBUTES

<table>
<tr><th></th><th>TRANSVAAL BASIN</th><th>HAMERSLEY AND NABBERU BASINS</th></tr>
<tr><td>Name of Unit</td><td>Wolkberg Group</td><td>Fortescue Group</td></tr>
<tr><td>Thickness</td><td>0-2 000 metres[25], maximum thickness along a linear trough overlying a greenstone belt (Figure 5)</td><td>320-4 250 metres[27,28]; thickest in Mt. Bruce sheet area[27], thins towards eastern margin of Hamersley Basin[28].</td></tr>
<tr><td>Areal Extent</td><td>Restricted to axial portion of Transvaal Basin[25].</td><td>Restricted to Hamersley Basin</td></tr>
<tr><td>Regional Stratigraphic Relationships</td><td>Conformably overlain by chemical sediments in axial region of basin; elsewhere chemical sediments overstep the Wolkberg Group (Figure 5).</td><td>Comformably overlain by chemical sediments in the Hamersley Basin; overstepped by chemical sediments in the Nabberu Basin[3].</td></tr>
<tr><td>Control on Basin-filling by Archaean Basement</td><td colspan="2">1. Archaean granitic batholiths stood out as broad, fairly regular topographic highs[24,25,29] (Figures 5 and 6), while greenstone belts formed depressions and valleys. Within greenstone belts, thick quartzites, cherts, iron-formations and rhyolites formed topographic spines; meta basalts and greywacke-shale units formed valleys.
2. Earliest units (volcanic and sedimentary) are restricted to valleys, and wedge out against highs[24,25,29,30]. Units become laterally more continuous stratigraphically upwards.</td></tr>
<tr><td rowspan="4">Lithology</td><td colspan="2">1. Basaltic extrusives and pyroclastics, arenites, agrillites and some chemical sediments (dolomite and chert).</td></tr>
<tr><td>2. Fine- and coarse-clastics, some basaltic lava (Figure 4).</td><td>Dominated by volcanics and fine-clastics (Figure 4).</td></tr>
<tr><td>3. Arenites are felspathic subgreywackes at base, become cleaner upwards.</td><td>Arenites are felspathic subgreywackes at base.</td></tr>
<tr><td colspan="2">4. Volcanic rocks are basaltic, with higher FeO than Phanerozoic tholeiites[21,29].
5. Stromatolitic dolomites (Figure 7a) are developed between flows[29,38,39].
6. Shaly formations are frequently rich in carbon.</td></tr>
<tr><td>Vertical Succession</td><td colspan="2">Volcanics and coarse-clastics predominate at base, finer-clastics predominate near top.</td></tr>
<tr><td>Depositional Environments</td><td>Braided-stream arenites and conglomerates near base; marginal-marine volcanism (some pillows and stromatolites between flows); coarsening-up argillite-arenite depositional cycles, some due to deltaic progradation[21].</td><td>Braided-stream and alluvial fan arenites and conglomerates[90], with discernible channelling (Figure 7b), followed by volcanism on a marginal-marine platform (pillow basalts, pisolitic tuffs[149], Figure 7c), and stromatolitic carbonates[29], followed by offshore-marine deposition (shale and pillow-basalt of the Jeerinah Formation, Figure 7d).</td></tr>
<tr><td>Intrusive Sills</td><td>Rare, of mafic composition, related to Bushveld Igneous Complex</td><td>Thick and extensive Cooya Pooya Dolerite[24,32] (Figure 7e). Acid intrusives include Gidley Granophyre[16] (Figure 7f), and Bamboo Creek Prophyry[23].</td></tr>
</table>

FIGURE 7(a) Algal stromatolite in dolomite and chert, between lava flows in the Wolkberg Group.

(b) Conglomerate-filled scour-channel in Hardey Sandstone, southeast of Marble Bar, W. Australia.

(c) Pisolitic tuff in the Tumbiana Formation, east of Nullagine, W. Australia.

(d) Pillowed basalt in a flow in the Jeerinah Formation near Newman, W. Australia.

(e) Areal view of the Cooya Pooya Dolerite sill (black-topped hills, middle-ground), looking south, near Roeburne. Archaean granite seen beneath ledge closest to camera.

(f) Xenolith of Archaean gneiss in the Gidley Granophyre, near Dampier, W. Australia.

TABLE 3
CHEMICAL SEDIMENTARY UNIT – COMPARATIVE ATTRIBUTES

	TRANSVAAL BASIN	HAMERSLEY AND NABBERU BASINS
Name of Units	Chuniespoort and Campbell-Griquatown groups.	Hamersley Group, chemical group not named in Nabberu Basin.
Thickness	Chuniespoort Group >3 000 metres[21]; Campbell-Griquatown groups >3 200 metres[33].	Hamersley Group 1 867-2 160 metres[2]; chemical sediments in Nabberu Basin 3 000 metres[3].
Areal Extent	Developed over entire extent of the basins (Figures 5 and 6).	
Regional Stratigraphic Relationships	1. Thickness-changes gradual. 2. Unconformably overlain by Pretoria and Postmasburg groups (Figure 5).	1. Thickness-changes gradual, except near Wyloo Dome (Figure 6). 2. Hamersley Group unconformably overlain by Wyloo and Manganese groups (Figure 6); Nabberu chemical sediments unconformably overlain by an upper clastic unit[3,4].
Control on Basin-Filling by Archaean Basement	Influence on chemical unit not marked. Thickest sedimentation is in linear troughs[2,35], which are parallel to, and superimposed on, greenstone-belt trends. Palaeotopographic effects locally important, where chemical sediments rest on the basement[36,37].	
Lithology – General	1. Carbonates (dolomite, some limestone), iron formation, carbonaceous shale, minor tuff and arenites. Acid extrusives in Hamersley Basin. 2. Carbonates dominant in Transvaal Basin. 3. Arenites developed at base of chemical pile in Transvaal, Hamersley[90], and Nabberu basins[3,4].	2. Iron formation dominant in Australian basins.
Carbonate Units	1. Algal stromatolites, of widely varying types and sizes (Figure 9a) are prominent throughout carbonate sections. 2. Algal structures become less obvious as the transition zone of carbonate to iron formation is approached (Figure 9b). 3. Oolite and intraclastic breccia layers (Figure 9c) are common to the carbonate sections. 4. In chert-poor carbonate sections, silica frequently appears as blebs of crystaline quartz. 5. Away from the iron formation transition, cherts are found in bedded or cross-cutting replacement bodies. (Figure 9a) 6. Near the iron formation transition, banded cherts occur as nodules, pods and lenses (Figure 9b). 7. Primary limestones and carbonaceous shales are preferentially developed in the carbonate-iron formation transition zones. 8. During dolomitization, Mn^{2+} and Fe^{2+} cations were introduced along with, and proxy for, Mg^{2+} in the dolomite lattice[21,105]. 9. The average Fe^{2+} concentration in carbonates increases upwards towards the iron formation transition zone[40]. 10. Major cycles of iron-enrichment found in carbonate section[40].	10. Cycles may be present, but not documented.
Iron Formation Shifts	1. Carbonaceous shales and mudstones make up a large fraction of the iron formation piles. 2. Iron formations (except those in the Nabberu Basin) are micro-, meso-, and macro-banded (Figure 9d). 3. Sedimentation units show great lateral continuity; macrobands are continuous over 85 000 square kilometres[2,52], meso- and microbands have been correlated over a distance of 300 kilometres[2]. 4. Iron formation is composed of mixed or mono-mineralic layers of quartz, magnetite, hematite, stilpnomelane, riebeckite, minnesotaite and carbonates (siderite, ankerite, ferrodolomite, dolomite and calcite) with minor apatite, pyrite, felspar, carbon and barite[2,33].	
Vertical Succession	Carbonate formations (with minor iron formation) predominate at base of sections, and grade upwards, through a zone rich in carbonaceous shale, to iron formation[26,33,35,40].	
Tectonic Environment	Extremely stable cratonic platforms with very low relief[2,21,116].	
Depositional Environments	Carbonates deposited on shallow shelf-seas in a spectrum of environments, including lagoonal, sub-inter-, and supratidal[35,53,54,55,56,57,58,59]. Carbon isotopes are similar to those of contemporary marine carbonates[60,61,63]. Iron formation deposited in highly saline evaporitic basins behind barriers or shoals of carbonate intraclastic breccia and oolite[33,40]. Source of iron probably large oceanic reservoir of ferrous cations[62]. Spherical structures (5-40 microns in diameter) found in iron formation[63] suggest micro-organisms played a role in iron formation deposition. Carbon in iron formation carbonates is isotopically light (-9 to -11 per mil.), and confirms micro-organism activity in restricted basins[63].	Iron formation deposited in basins 50 to 250 metres deep, containing 10-20 ppm Fe, with bottom-currents less rapid than 1 metre/sec.[2].
Volcanism	Minor tuffaceous units in carbonate and iron formation[35,45].	Thick and extensive rhyolitic extrusive (Woongarra Volcanics) in Hamersley Group[2]. Tuffaceous and shard-bearing shales occur in Wittenoom Dolomite[90] and iron formations[2,44,64,150].
Intrusive Sills	Basic sills common to the chemical sedimentary units of Transvaal and Australian basins.	

TABLE 4
UPPER CLASTIC UNIT – COMPARATIVE ATTRIBUTES

<table>
<tr><th></th><th>TRANSVAAL BASIN</th><th>HAMERSLEY AND NABBERU BASINS</th></tr>
<tr><td>Name of Units</td><td>Pretoria and Postmasburg groups.</td><td>Wyloo and Manganese groups; upper clastic groups of Nabberu Basin not named[4].</td></tr>
<tr><td>Thickness</td><td>Pretoria Group>7 000 metres[21]; Postmasburg Group>2 200 metres[26].</td><td>Wyloo Group>9 900 metres[2]; Manganese Group >540 metres[65].</td></tr>
<tr><td>Areal Extent</td><td colspan="2">Inferred to have been developed over entire extent of basins.</td></tr>
<tr><td>Regional Stratigraphic Relationships</td><td colspan="2">Rests unconformably on, and sometimes oversteps, the chemical sedimentary unit (Figures 5, 6, and 12)[23,28,34,43,65,66,67].</td></tr>
<tr><td>Lithology</td><td colspan="2">1. Dominated by shaly sediments, incorporate smaller volumes of arenite, carbonate, iron formation, tillite-like sediments and volcanics.
2. Basal unconformity frequently marked by a chert breccia (Figure 9e), derived by chemical weathering of underlying cherty dolomites.
3. Shaly formations show evidence of re-sedimentation, including flute and groove-casts (Figure 9f)[68,69].
4. Arenaceous formations alternate cyclically with the shaly units (Figures 5 and 6).
5. Stromatolitic carbonates form subordinate units in these clastic-dominated successions[21,33,34].
6. Volcanic units are well-represented, and tend to be basaltic or intermediate in composition. Minor acid volcanism has been reported[34,70].</td></tr>
<tr><td>Vertical Succession</td><td colspan="2">1. Not well-defined; a cyclical alternation of garillite and arenite is common, punctuated by periods of volcanicity and chemical sedimentation.
2. Cycles are typically progradational, of both coarsening- and fining-up types[21,71,72,90].</td></tr>
<tr><td>Tectonic Environment</td><td colspan="2">Subsiding margin of land-mass, supplied with copious volumes of sediment.</td></tr>
<tr><td rowspan="2">Depositional Environments</td><td colspan="2">1. Marine and marginal-marine tide-dominated clastic depositional systems are most common[21,71,72,73].
2. Clearwater carbonate sedimentation during periods of, or in areas with, reduced clastic input.</td></tr>
<tr><td>3. Glacial sediments (including fluvioglacial, glacio-lacustrine and glacio-marine) are developed[144].</td><td>3. No glacial sediments reported to date.</td></tr>
<tr><td>Intrusive Sills</td><td>1. Differentiated mafic sills, related to the Bushveld Igneous Complex, very common.
2. Sills intruded mainly along arenite-garillite contacts.</td><td>1. Mafic sills present in Nabberu[4] and Hamersley[28,65,90] basins.
2. Some sills follow arenite-garillite contacts[90].</td></tr>
</table>

TABLE 5
CLASSIFICATION OF ORE DEPOSITS IN TRANSVAAL AND HAMERSLEY BASINS

CLASS	MINERALS PRODUCED
Syngenetic (mechanical sedimentary)	Gold (pyrite, osmiridium, uraninite), Silica
Syngenetic (chemical sedimentary)	Manganese, Oolitic ironstone, Limestone, Copper?
Diagenetic and load metamorphic	Dolomite, Crocidolite Asbestos, Amosite Asbestos
Metamorphic	Chrysotile Asbestos, Andalusite, Marble
Supergene	Iron, Manganese
Low-temperature hydrothermal	Fluorite (lead, zinc, vanadium)
Intermediate- and high-temperature hydrothermal	Gold (copper, bismuth, scheelite), Lead-Zinc-Silver, Tin

Iron Formation, Western Australia. An original gel is thought to have crystallized to a mixture of quartz, siderite, greenalite, hematite, and stilpnomelane[46,47]. Stilpnomelane may have formed from a montmorillorite precursor, which, in turn, may have been derived from a volcanic glass[46]. Magnetite formed during diagenesis, from hematite and by decomposition of siderite[47]. Minnesotaite rosettes grew from greenalite during low-grade burial metamorphism[46,47]. Riebeckite formed by soda metasomatism of pre-existing stilpnomelane or quartz-iron oxide mesobands, and is frequently found as radiating needles around magnetite grains. Experimental work[46] indicated that crocidolite growth is favoured by an abundant supply of Na^+ and Fe^{2+} cations, combined with low pH and Eh conditions. Crocidolite was synthesized in the temperature range 110-350 °C. Ayres[47] concluded that the Dales Gorge Member had been subjected to temperatures of around 300 °C and pressures of around 4 to 6 kb.

Trendall[52] has established a cyclicity to microbanding in the iron formation of the Weeli Wolli Formation. Stripes within chert mesobands have a cyclical recurrence of 23 microbands. Microbands are thought to represent an annual cyclicity, so that stripes could represent double sunspot cycles.

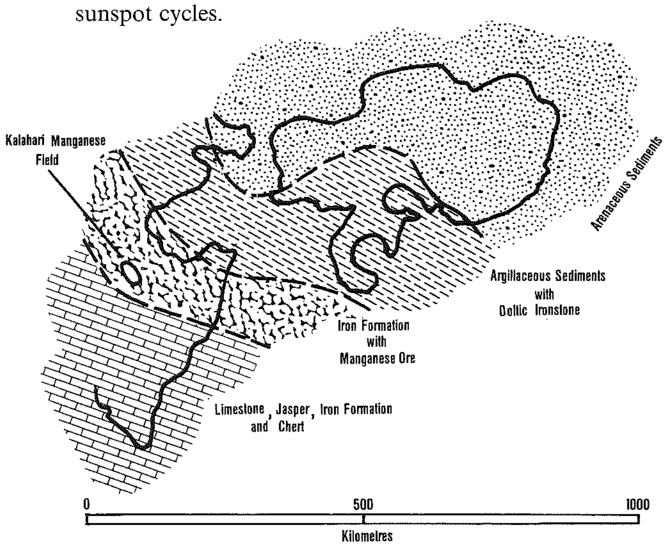


FIGURE 8 Regional facies-change in sediments immediately above the Hekpoort Basalt-Ongeluk Lava in the Transvaal Basin.

THE UPPER CLASTIC UNIT

The *upper clastic unit*, in both the Hamersley and Transvaal basins, comprises principally shaly rocks, with cyclically-interbedded arenaceous units, volcanic formations, and some chemical sediments (see Table 4).

The most striking similarities between the upper clastic units of the basins involves their great thicknesses (up to 10 km) and their dominantly marine nature. In some cases, facies changes can be made out on a regional scale in the upper clastic unit. One of the best examples is from the Pretoria-Postmasburg groups (Figure 8). The Ongeluk Lava, and its correlatives in the Transvaal, known as the Hekpoort Basalt, can be used as a time stratigraphic datum. The sediments immediately above the lava change dramatically across the Transvaal Basin[143], from nearshore arenites in the north and northeast, to subaqueous shales with oolitic ironstone lenses (in the western Transvaal and Botswana), to alternating banded iron formation, banded manganese formation, and limestone, in the northern Cape[33,88].

MINERAL DEPOSITS IN THE TRANSVAAL, HAMERSLEY, AND NABBERU BASINS

The Transvaal and Hamersley basins are important producers of base and industrial minerals. The Transvaal Basin, for example, produced about 19 per cent[145] of the world's manganese ore in the year 1973, while the Hamersley Basin currently accounts for 6 per cent of global iron ore[145]. The Malmani Dolomite contains some of the world's largest fluorite reserves[131], while iron formations in the Transvaal Basin are the sole producers of crocidolite (Cape Blue) and amosite asbestos.

The more important ore deposits in the basins are described and classified. An attempt is made to emphasize the major controls on mineralization, in the hope that these

FIGURE 9(a) Cross-cutting chert in light-coloured dolomite, Malmani Dolomite, near Badplaas, S.E. Transvaal.
(b) Banded and podded chert in ferruginous dolomite (orange) and primary limestone (grey), Wittenoom Dolomite, at Wittenoom, W. Australia.
(c) Intraclastic breccia at the top of the iron-rich Wittenoom Dolomite, at Wittenoom, W. Australia.
(d) Mt. Stevenson, Western Australia, showing macrobanding in the Dales Gorge Member of the Brockman Iron Formation (uppermost series of ledges) and the Bruno's Band iron formation, Mt. Sylvia Formation (prominent in middle ground).
(e) Chert breccia at base of Pretoria Group, south of Johannesburg, S. Africa.
(f) Flute casts at base of greywacke bed in the Ashburton Formation, Wyloo Group, W. Australia.


FIGURE 9 (a)


FIGURE 9 (b)


FIGURE 9 (c)

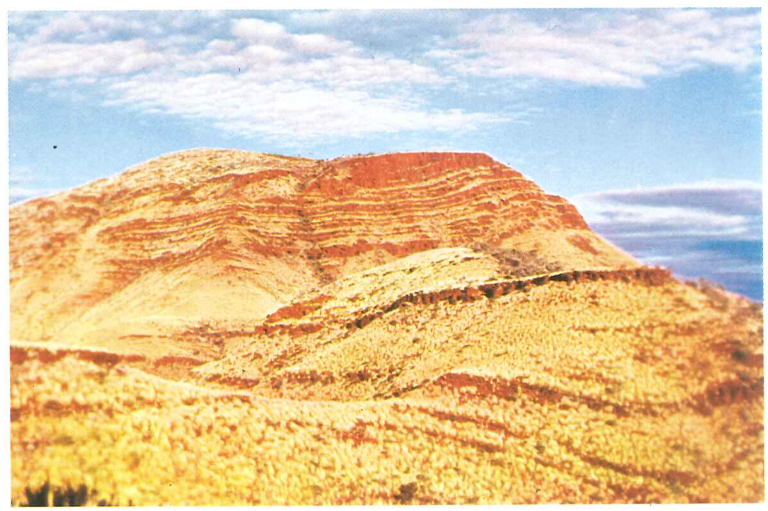


FIGURE 9 (d)


FIGURE 9 (e)


FIGURE 9 (f)

FIGURE 10 (a)

FIGURE 10 (b)

FIGURE 10 (c)

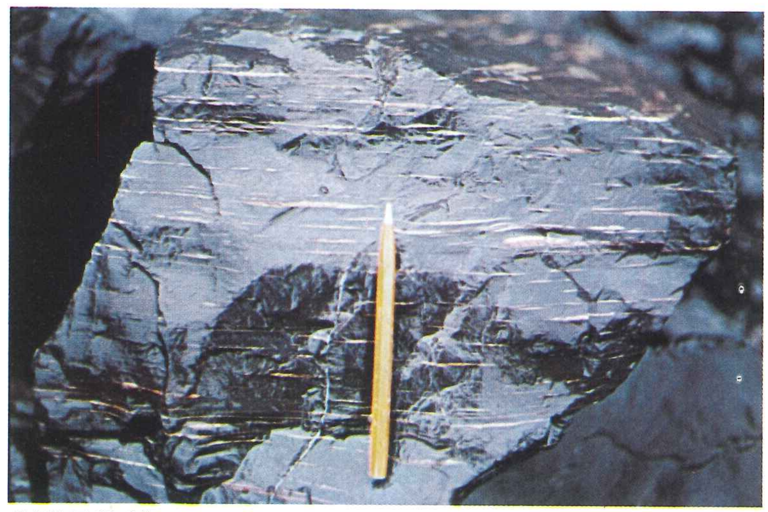


FIGURE 10 (d)

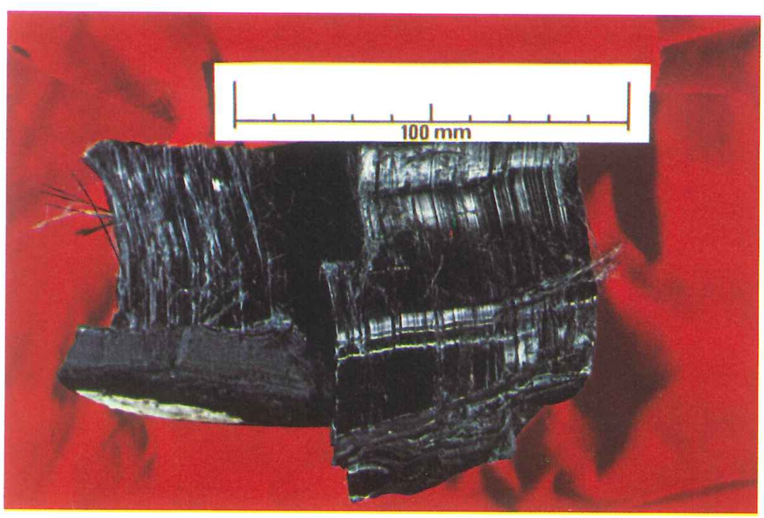


FIGURE 10 (e)

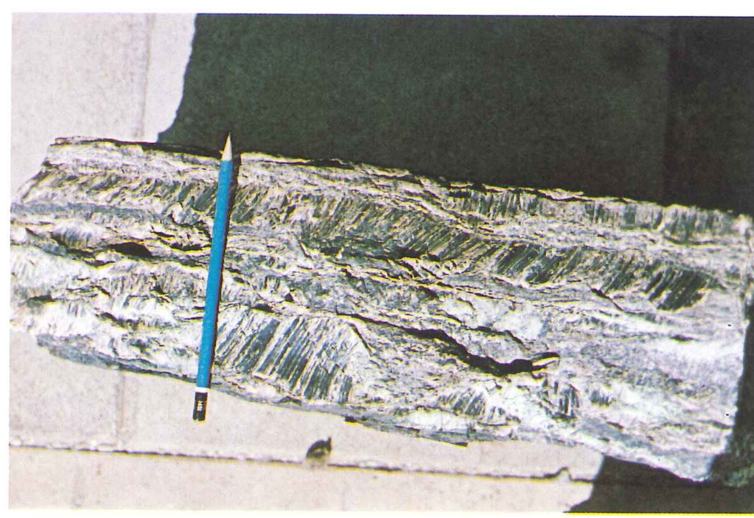


FIGURE 10 (f)

may be applicable to exploration both within these basins, and within analogous basins around the world.

CLASSIFICATION OF ORE DEPOSITS

Ore deposits are classified here according to the dominant mode of their formation. Seven broad classes are recognized (Table 5). The classification is subjective, and cannot accommodate the ideas of all investigators on all deposits. It represents an attempt to synthesize the best available data on the basins studied.

SYNGENETIC MECHANICAL DEPOSITS

Gold (Pyrite, Osmiridium, Uranium)

Auriferous conglomerates are encountered in the basal volcanic and clastic units of both the Transvaal and Hamersley basins. The workings are small and subeconomic, being restricted to the immediate vicinity of auriferous deposits in the underlying Archaean formations. Known workings include the Pennyfather Mine in the Wolkberg Group[75,76], and the Beatons Creek and Just-in-Time (Figure 10a) workings in the Fortescue Group[23] (see Figures 11 and 12).

Over a large portion of the Transvaal and Nabberu basins, the chemical sedimentary unit rests directly on an older Proterozoic or Archaean basement. In such situations, a veneer of clastic sediment is developed along the unconformity. The conglomerates in the clastic veneer are generally auriferous where they rest on older gold-bearing formations.

The most extensive mining of such conglomerates (Figure 10b) took place in the central Transvaal (Figure 11), where the basal clastic unit (the Black Reef Quartzite) rests on the auriferous Witwatersrand conglomerates[36,77,78]. In the principal mine (Government Gold Mining Areas, on the East Rand), 27 million tonnes of ore were extracted with a grade of between 4,5 and 16 gm/tonne of Au[36]. In addition, considerable quantities of pyrite (1,8 million tonnes) and osmiridium were recovered. Locally, the Black Reef also carries some uraninite[36,79]. Minor quantities of sphalerite, galena, chalcopyrite, and carbon are developed[77,78,117] in the conglomerate matrix. The economic mineral assemblage in the Black Reef was derived directly from the underlying Witwatersrand rocks, being concentrated by the marine transgressive front that marked the start of the period of chemical sedimentation. Reconstitution of mineral phases has resulted in the appearance of some hydrothermal features in the conglomerates[117].

Proximity to the Witwatersrand auriferous conglomerates, and palaeotopography, are the major controls on distribution of mineable bodies (Figure 13). Ore-bodies are found along ancient valleys, some of which follow Witwatersrand shale beds or pre-Black Reef dykes[36].

Silica

The orthoquartzitic units of the Transvaal Supergroup are quarried at a number of localities for their silica content (Figure 11). If the need arose, the equivalent rocks in the Hamersley Basin, such as the Beasley River Quartzite, could probably be exploited in a similar way. The purest arenites are those deposited on tide-dominated shallow-marine platforms.

FIGURE 10(a) Auriferous conglomerate at base of Fortescue Group, Just-in-Time workings, near Marble Bar. Conglomerate rests on Archaean rhyolite.
(b) Black Reef conglomerate, with boulders of Witwatersrand quartzite and conglomerate, and a matrix rich in buckshot pyrite.
(c) Cross-bedded oolitic ironstone, Timeball Hill Formation, Pretoria Group, east of Lydenburg, S. Africa.
(d) Banded manganese ore with pink-weathering calcareous streaks, Mamatwan Mine, Kalahari Manganese Field, S. Africa.
(e) Crocidolite fibre in Asbesheuwels Formation, from Koegas area, S. Africa.
(f) Amosite asbestos in the Penge Iron Formation, S. Africa.

SYNGENETIC CHEMICAL DEPOSITS

Oolitic ironstones

Lenticular beds of oolitic ironstone are extensively developed in the Timeball Hill Formation, near the base of the Pretoria Group[80]. Greatest development is in the area of Potchefstroom, Pretoria and between Badplaas and Machadodorp (Figure 11). Ironstone occurs in lenses, up to 8 metres thick, set in a section of marine shales, often in association with orthoquartzite units. The ironstones are composed of closely-packed oolites, generally consisting of a quartz core surrounded by concentric layers of chamosite, ankerite, kaolinite, magnetite, hematite, lepidocrocite, and goethite[81]. Sedimentary structures in the ironstone include cross-bedding (Figure 10c), ripple marks, and, rarely, mud cracks. On a regional scale, ironstone is best developed near the feather-edge of major quartzite bodies in shale formations[21]. It is thought that the ironstone facies-belt coincides with a zone of mixing of reduced, iron-rich, deep oceanic waters and oxygenated, near-shore waters.

Reserves of oolitic ironstone in the Pretoria Group are large (over $4{,}5 \times 10^9$ tonnes at 45 per cent Fe)[80]. The ores were exploited early in this century, but have been abandoned in favour of high-grade, massive hematite deposits. At least one bed of ironstone occurs in the Turee Creek Formation, Wyloo Group[90], being found in the transition zone at the base of the Beasley River Quartzite.

Limestone

Extensive deposits of primary limestone are developed in the carbonate successions of the Campbell Group and Malmani Dolomite[35,82]. Limestone tends to be best developed near the top of the carbonate successions, immediately beneath the overlying iron formation. It is preserved in large-scale lenses, up to 130 metres thick, and traceable on strike for tens of kilometres. The lenses are truncated laterally and vertically by transgressive dolomitisation fronts. The grade of the limestone varies. Quarries south of Danielskuil in the northern Cape (Figure 11), are currently producing limestone with greater than 96,5 per cent $CaCO_3$.

No primary limestones are presently being mined in the Wittenoom or Carawine Dolomites of the Hamersley Group. Thin lenses of primary limestone are developed near the top of the Wittenoom Dolomite[90], and could possibly supply modest tonnages of limestone.

Cupriferous shales

Chalcopyrite-bearing shales are developed over a wide area in the Jeerinah Formation, Fortescue Group. Surface enriched ores were mined on a very small scale near the Wanna Munna Flats[83,84] (Figure 12). Despite intense regional prospecting, no payable deposits have been outlined. Although pyritic shales are known from the Wolkberg Group, none are known to be cupriferous.

Manganese

In the east Hamersley Basin, shaly sediments of the Manganese Group contain appreciable amounts of manganese[85,161] (Figure 12). The Noreena Shale (Figure 6), which is the uppermost unit in the Manganese Group, assays between 0,4 and 10 per cent Mn. The underlying Balfour Shale is also manganiferous. The Noreena Shale contains discoidal nodules of braunite, which are thought to have formed during diagenesis, by precipitation of manganese around a nucleus of quartz or clay. The manganese in the shale is considered to be a primary component of the rock[85].

Some of the largest reserves of manganese in the world (conservatively estimated at over 8 000 million tonnes)[88] are found in the Kalahari Manganese Field, about 100 km north of the Postmasburg region (Figure 11). In this general locality, a lava in the Postmasburg Group (the Ongeluk Lava) is overlain by a succession of chemical sediments, principally iron formation[86,87,88]. Within the basal 100 metres of iron formation, up to three layers of primary manganese ore (Figure 14) are developed over a strike-length of over 50 km. The latter are manganiferous and calcareous sediments. They are bedded, sometimes pseudo-oolitic, and are frequently streaked by thin wisps of a white carbonate (Figure 10d). The lowest manganese layer is up to 25 metres thick, and is developed about 30 metres above the Ongeluk Lava (Figure 14).

In the Kalahari Manganese Field, all but one of the deposits is covered by younger sediments, including calcrete and wind-blown sands. Beneath this cover, supergene-enriched derivatives of the primary ore are encountered, and have been mined. In at least one deposit (Figure 14), it has been shown that a supergene enriched cap fingers out, with depth, to the primary manganese sediment[89]. However, the bulk of the ores mined are not appreciably modified by surficial processes. The ores are mineralogically complex, especially since they are locally intruded and metamorphosed by bostonitic dykes and sills. The principal manganese minerals are braunite, bixbyite, rhodocrosite, hausmannite, and jacobsite[88].

The original sediment probably consisted of 'oolitic' carbonate in a matrix of gelatinous manganese and iron hydroxide, manganese- and iron-carbonate, and, in places, hydrous silicates of magnesium and iron[88]. Diagenesis resulted in the crystallization of wad, cryptomelane, braunite, jacobsite, rhodocrosite, and calcite. A suite of derivative minerals were formed by subsequent metamorphism, by supergene, and by hydrothermal activity.

The major control on the development of mineralization appears to be regional sedimentational environment (Figure 8). Manganese sediments were deposited in a distal facies belt, far removed from regions of detrital influx. A similar environment can be inferred for the manganiferous Noreena Shale. The manganese was probably held in solution (as Mn^{2+}) in the ancient sea-water, and was precipitated by physico-chemical changes in the environment. The deposits could represent a purging of Mn^{2+} from sea water, brought about by the onset of more oxidizing conditions.

DIAGENETIC AND LOAD METAMORPHIC DEPOSITS

Dolomite

Dolomite, which is considered to have replaced a primary limestone soon after deposition[21], is quarried from a number of localities in the Malmani Dolomite in the central Transvaal (Figure 11). A stratigraphic unit, about midway in the Malmani Dolomite succession, is exploited. The unit, which is characterized by absence of chert, reaches a thickness of up to 200 metres. The quarried thickness is less, being confined to a sub-unit with a very low proportion of SiO_2.

Dolomite is not quarried in the carbonates of the Hamersley Group. The Carawine Dolomite in the eastern Hamersley Basin consists of a succession of chert-rich and chert-poor dolomites[90]. If needed, it is possible that some of the chert-poor units could yield material of the requisite grade.

Crocidolite asbestos

The iron formations of the Transvaal and Hamersley basins contain the world's only reserves of crocidolite. Crocidolite (Figure 10e) is the fibrous form of the soda amphibole, riebeckite. It is found in the Marra Mamba, Brockman, and Boolgeeda formations of the Hamersley Group[2,91,92,93], and in the Penge, Asbesheuwels, and Koegas formations of the Transvaal Basin[48,49,50,94,95,96,97,98,99].

Production of crocidolite in Australia has ceased owing to indifferent grades. A total of 155 000 tonnes of fibre has been produced[2] since 1933. In South Africa, mining continues at a high level, a production of over 138 000 tonnes being recorded for the year 1973[100].

In Australia, mining of crocidolite fibre was essentially restricted to the area south of Wittenoom (Figure 12), where units in the Dales Gorge Member of the Brockman Iron Formation were exploited. In the northern Cape, crocidolite has been mined at places over a strike length of 500 km[48] (Figure 11). Fibre is developed at five principal levels[48], four of them in the Asbesheuwels Formation, one in the Koegas Formation (Figure 5). Relatively unimportant amounts of crocidolite are mined in the Penge Formation in the Transvaal (Figure 11).

A great deal has been written (much of it conflicting) on both the origin of riebeckite and on the mechanism of crocidolite fibre development. In summary, South African investigators believed that riebeckite was the diagenetic product of a primary sediment, termed *proto-riebeckite*. Cilliers and Genis[48] were of the opinion that this material was an attapulgite-like clay, while Hanekom[49] regarded it as a volcanic ash. In Australia, Trendall and Blockley[2] have shown that iron formation and riebeckite were derived from a common precursor sediment. They believe that those parts of the precursor that had been relatively uncompressed were preferred pathways for migrating soda-rich liquids, which metasomatically converted the precursor to riebeckite. The microscopic work of Grubb[46] suggested that riebeckite formed diagenetically, through sodic metasomatism of stilpnomelane. However, Ayres[47] showed that riebeckite also formed by metasomatic replacement of quartz-iron oxide mesobands. Investigators in both basins have documented the growth of riebeckite needles around magnetite[46,47,48].

Cilliers and Genis[48] and Genis[99] believed that crocidolite fibres formed in a band of proto-riebeckite, adjacent to a layer of magnetite. The magnetite crystals provided a constant number of growth-points per unit area, a feature essential to the orientation of fibre. In layers of proto-riebeckite where magnetite is absent, this material was thought to have crystallized to an assemblage of disoriented riebeckite needles, known locally as *mass fibre*. Their work has to some extent been superseded by that of Australian investigators. Trendall and Blockley[2] have shown that crocidolite grew in dilatant sites formed as a response to two opposing stresses. Fibre growth is thought to have been within magnetite layers, the chemical con-

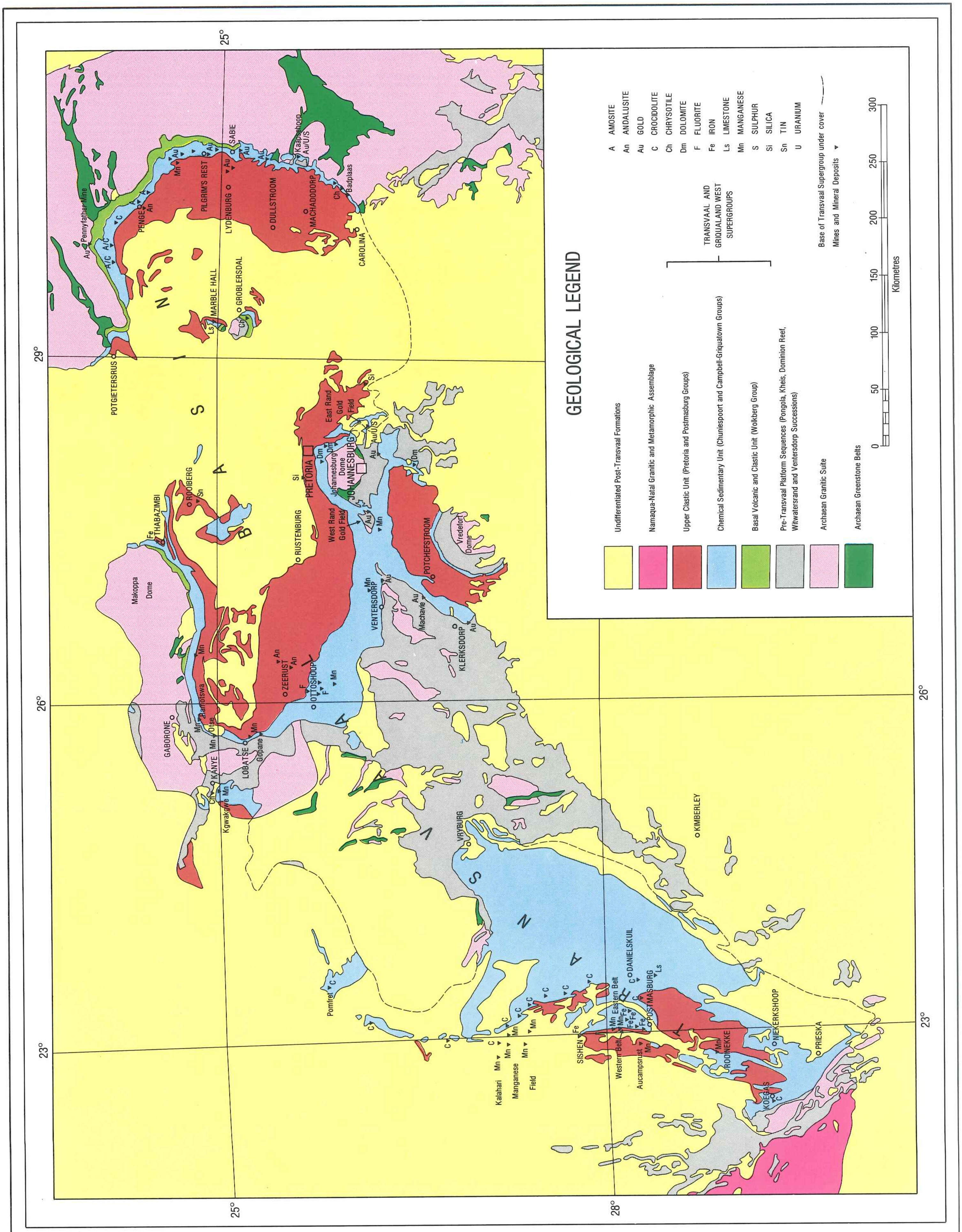


FIGURE 11 Generalized geological map of the Transvaal Basin (modified after the 1:1 000 000 map of the Geological Survey of South Africa).

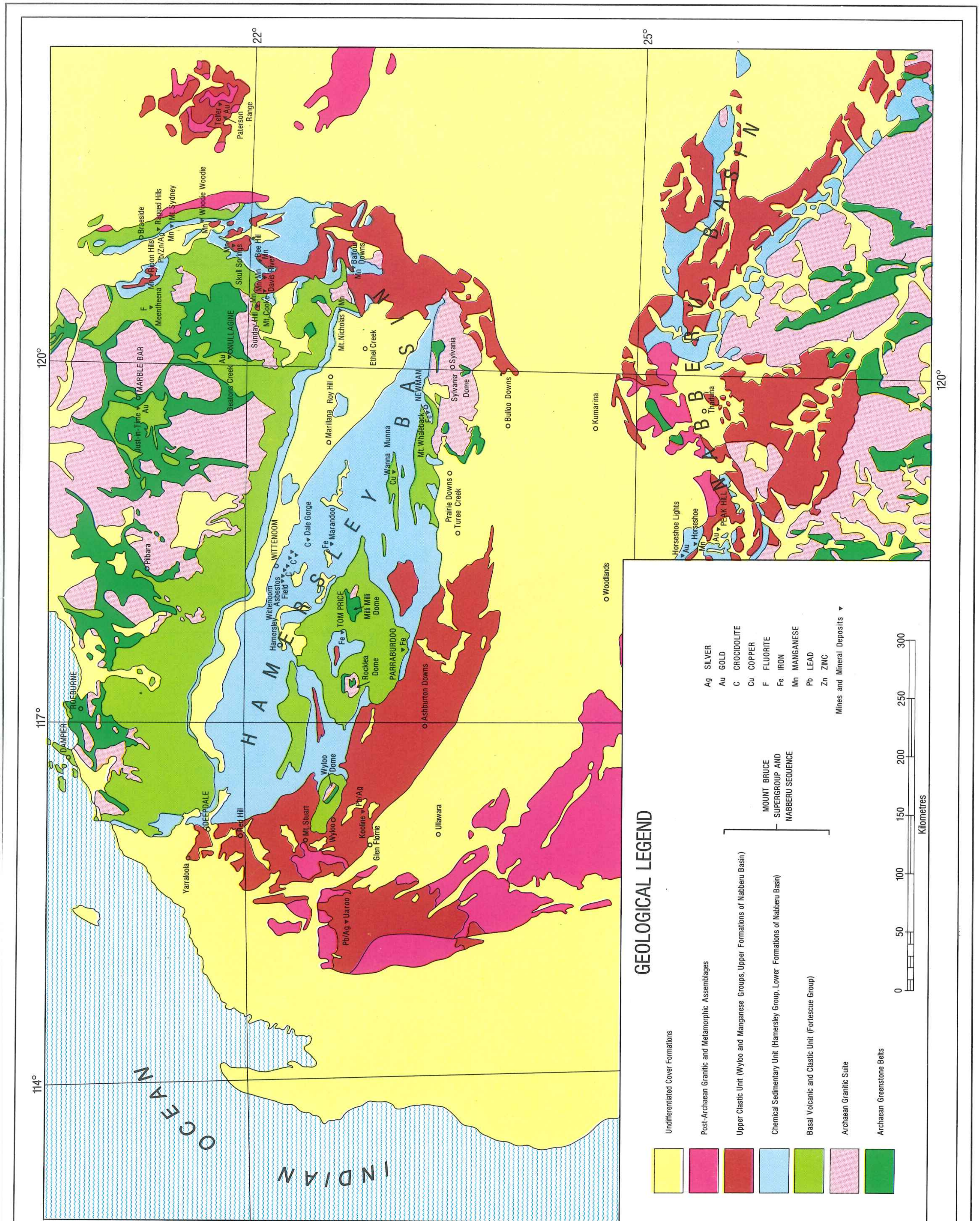
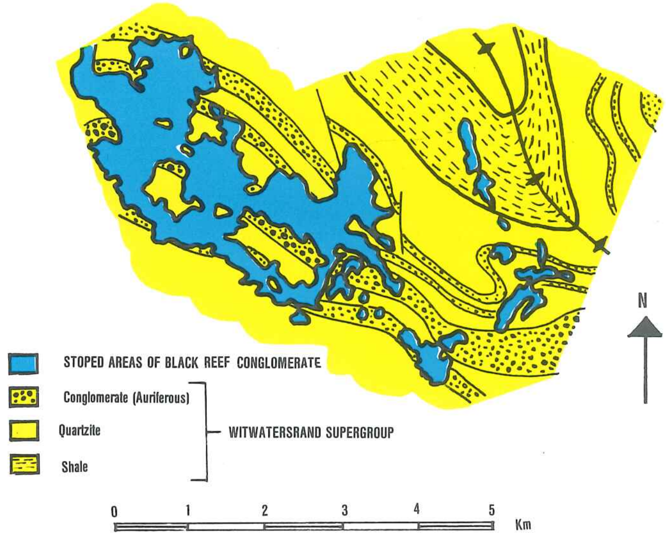


FIGURE 12 Generalized geological map of the Hamersley and Nabberu basins (modified after 1:2 500 000 map of the Geological Survey of Western Australia, and after maps in Trendall and Blockley[2], Horwitz[4] and De la Hunty[28,65]).

FIGURE 13 Map of distribution of mineable auriferous conglomerates in the Black Reef, Government Gold Mining Areas Consolidated, Modder Deep Levels and Geduld Proprietary Mines (modified after Papenfus[36]).



stituents being derived from the adjacent iron formation. Grubb[46] stressed that crocidolite was preferentially developed in intraformational breccias, which are inferred to have been more permeable to migrating sodic brines than the surrounding iron formation.

Structural control on the development of crocidolite ore-bodies is also well-established in the northwestern Cape[48,49,50]. Here, exploitable deposits are frequently stacked one above the other in the axial zones of folds. This characteristic has been extensively and successfully used during exploration for unexposed deposits.

In summary, there appears to be three fundamental controls to crocidolite fibre development:

- only parts of the basin where sodic brines were present contain crocidolite, so that large areas are barren,
- stratigraphic control is marked, and depends on layers amenable to replacement[2] and horizons that are relatively permeable[46],
- structural control is important, and depends on the presence of low-stress environments[2,46] in the axial zone of folds[48,49,50] and in dilatant sites formed by opposing stresses[2]. Logically, structure would also be expected to be important in the way in which it affected migration of the sodic brines.

Amosite

Amosite (Figure 10f) is the fibrous polymorph of the iron amphibole, grunerite[97]. It is mined in the Penge Iron Formation in the northeastern Transvaal (Figures 5 and 11). Production for the year 1973 was about 96 000 tonnes[100]. The geological setting and mode of occurrence of amosite are similar to those of crocidolite[94,95,96,97,98,101,102,103]. When traced towards the north and west in the eastern Transvaal, amosite-bearing iron formation grades laterally to iron formation in which crocidolite predominates[98].

The lateral change from crocidolite- to amosite-bearing iron formation was seen, by Cilliers[103], as a manifestation of palaeosalinity in the ancient depository. However, it has been noted[21] that the amosite-bearing iron formation occupies a fairly unique stratigraphic position, in that it

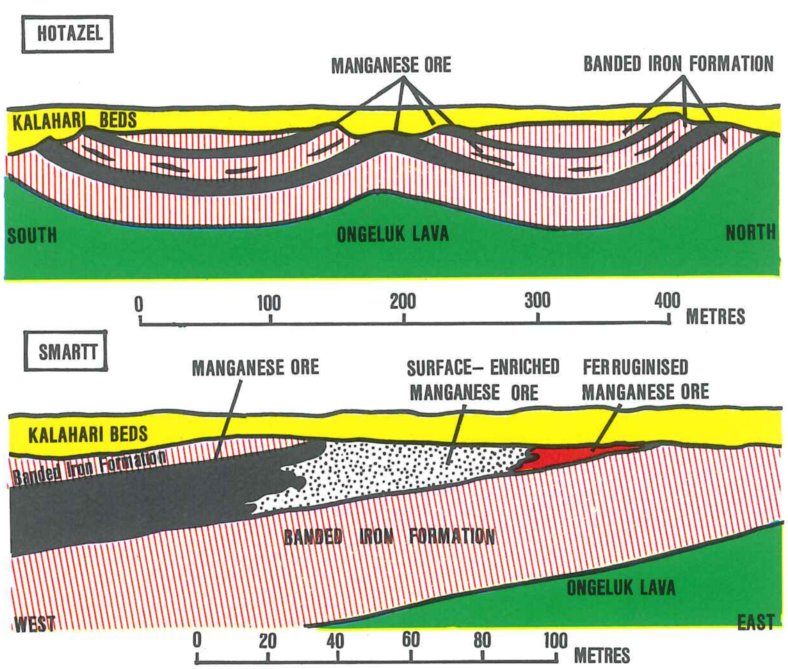


FIGURE 14 Cross-sections through the Hotazel and Smartt mines, Kalahari Manganese Field (modified after Boardman[89]).

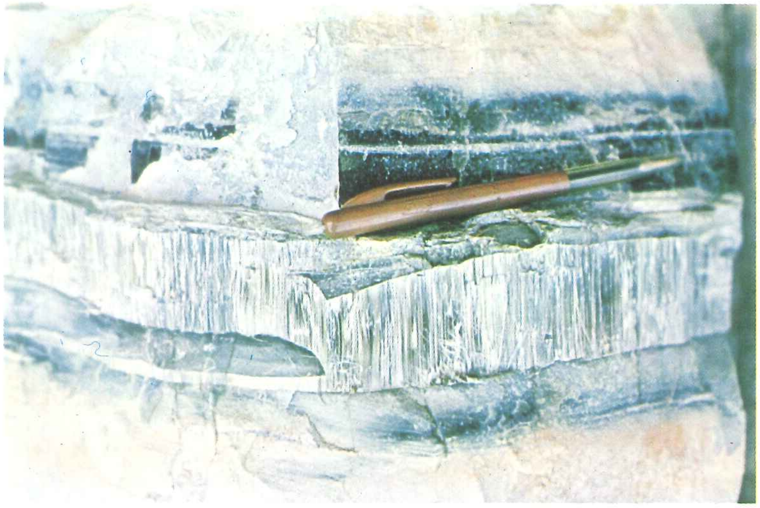


FIGURE 15 (a)


FIGURE 15 (b)


FIGURE 15 (c)


FIGURE 15 (d)


FIGURE 15 (e)


FIGURE 15 (f)

sub-outcrops beneath the pre-Pretoria Group unconformity (Figure 5). It is thought that the era of pre-Pretoria weathering may have leached soda from crocidolite, leaving amosite as the leached product. The lateral change from one asbestos type to the other could be due to proximity to an intraformational weathering surface.

Amosite has not been recorded from the Hamersley Basin. If the analogy with the Transvaal Basin is used, it could conceivably be present in the basin marginal areas, where the Marra Mamba and Brockman iron formations are truncated by the unconformities developed at the base of the Wyloo and Manganese groups.

METAMORPHIC DEPOSITS

Chrysotile asbestos

High-quality chrysotile asbestos (Figure 15a) has been mined on a small scale in numerous localities in the Transvaal Basin[21, 94, 104], the largest deposits being developed in the Badplaas area (Figure 11). The fibre typically occurs at the upper contact of mafic sills intrusive into the Malmani Dolomite. Smaller deposits are found adjacent to dykes. The controls on fibre-development are fairly simple. In the first instance, an intrusive is required to supply heat to drive the metamorphic reaction of dolomite + silica + water → serpentine + calcite. Magnesia is supplied by dolomite, while silica is derived from chert in the dolomite. Water is thought to be provided by the sill itself, and accounts for the fact that major deposits are limited to the upper surfaces of sills, the expected locus of accumulation of volatiles[21].

The upper metamorphic aureole of a sill is usually 1 to 2 metres thick, and consists of the assemblage serpentine, chrysotile, talc, and lime-rich carbonate. The control of chert is seen by the fact that only those sills intruded into chert-bearing dolomite are associated with fibre. Secondly, serpentine pseudomorphous after chert is common, and is seen as serpentine layers, laminae, and pods, duplicating the structure in chert[21].

No such chrysotile occurrences have been reported from the Hamersley Basin. They are likely to be present where mafic sills intrude cherty phases of the Wittenoom and Carawine dolomites.

Andalusite

Large tonnages of andalusite are developed, and are being exploited, in the hornfelses in the aureole of the Bushveld Complex around Zeerust and near Penge (Figure 11). Alluvial and eluvial concentrations have been worked for many years in the western Transvaal. More recently, open-pit quarrying of partially decomposed hornfelses has been undertaken at a number of localities. At present, production is of the order of 55 000 tonnes of andalusite per annum[100].

FIGURE 15(a) Chrysotile fibre and serpentine in Malmani Dolomite, S. Africa.
(b) Contact of siliceous manganese ore and dolomite, Eastern Manganese Belt, northeast of Postmasburg, S. Africa.
(c) Siliceous manganese ore, Eastern Manganese Belt, northeast of Postmasburg, S. Africa.
(d) Banded ferruginous manganese ore (formed by manganization of Gamagara Shale), Western Manganese Belt, between Sishen and Postmasburg, S. Africa.
(e) Banded hematitic iron ore, formed by hematization of Banded Iron Formation, Sishen, S. Africa.
(f) Anticlinal fold in McRae Shale (black) overlain by hematized Dales Gorge iron formation (shale macrobands are lighter-coloured stripes seen near base of iron formation), Tom Price orebody, W. Australia.

Andalusite-bearing veins in the Wyloo Group have been recorded by Daniels[74]. It is possible that mineable concentrations of andalusite could be found adjacent to major mafic intrusives into the shaly sediments of the Hamersley and Nabberu basins.

Limestone

Calcareous marble, developed largely as a result of de-dolomitization of the Malmani Dolomite[146], is quarried at Marble Hall in the central Transvaal (Figure 11). The de-dolomitization was effected by thermal metamorphism related to the Bushveld Igneous Complex, which surrounds the sediments.

SUPERGENE DEPOSITS

Manganese in dolomite host

Occurrences of manganese found associated directly with the dolomite of the Malmani and Campbell units tend to be low-tonnage deposits[87]. They are widely scattered, but are best developed in regions of comparatively lower rainfall and flatter topography, principally in the western Transvaal (Figure 11), between Johannesburg and Zeerust. Most deposits are situated near the top and the base of the dolomite, where the Mn content of the dolomite is highest.

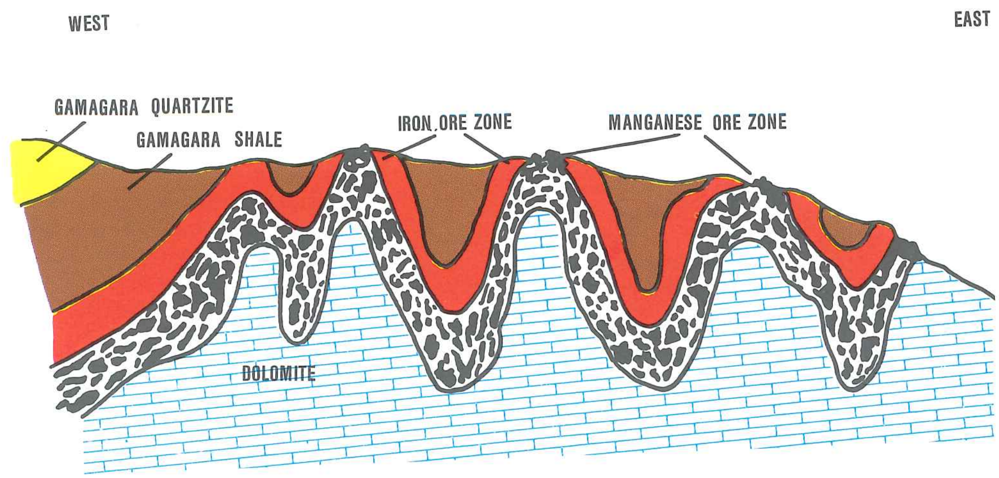
Mineralogically, the ores consist of pyrolusite, psilomelane, and manganiferous earth. They were formed during the present cycle of erosion, by solution of manganese-bearing dolomite and the precipitation of manganese oxides. Minor deposits of this general type are associated with the Wittenoom and Carawine dolomites[43,161]. The manganese deposits of the Horseshoe area, Nabberu Basin (Figure 12), are said to have been derived from manganiferous sediments[157,162], probably including dolomite. The region has produced about 560 000 tonnes of intermediate-grade (42 per cent Mn) ore[162].

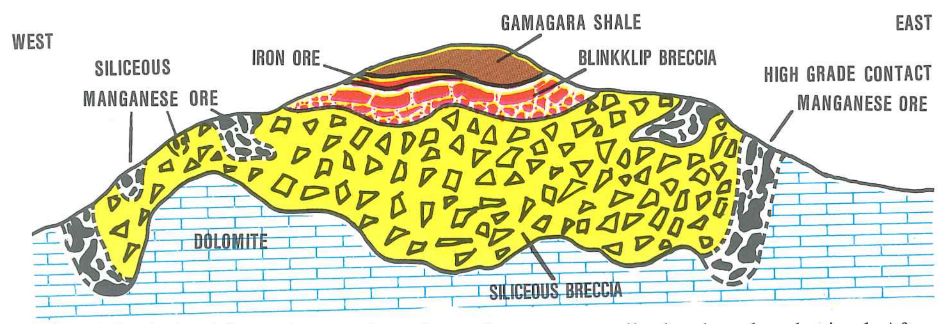
Manganese in chert breccia host

A well-defined class of manganese deposit is one associated with the basal unconformity of the upper clastic unit. Such deposits are found where the unconformity rests on manganese-rich dolomite (Figure 15b) and are frequently associated with chert breccia (Figure 9e), which represents the residual material left on the unconformity by a period of chemical weathering. Manganese deposits of this general type have been described from the east Hamersley Basin[106,161] (Figure 12), from the 'Eastern Belt' of the Postmasburg region of the northern Cape (Figure 11)[87,89], and from a few scattered localities in the Transvaal[21,87]. The Otse deposit in Botswana occurs in a chert breccia overlying the Malmani Dolomite.

The Australian deposits are found immediately below or within the Pinjan Chert Breccia, the basal unit of the Manganese Group[106,162]. Occurrences of this type are found in the Ripon Hills, at Mt. Sydney, Woodie Woodie, Skull Springs, Ant Hill, Mt. Cooke, and Sunday Hill (Figure 12). Those in the northwestern Cape occur in a similar position relative to a siliceous breccia known locally as the 'manganese marker', which outcrops in a discontinuous, arcuate, belt of hills east of, and extending between, Postmasburg and Sishen (Figure 11). The manganese ores tend to be of a high grade, but individual deposits tend to be small (a few thousand tonnes), irregular in shape and difficult to evaluate[89] (Figure 16). The principal manganese mineral is braunite, silica (mainly as chert fragments) is the main impurity (Figure 15c).

FIGURE 16
Cross-sections of the manganese deposits of the Postmasburg area. Top diagram – Western Manganese Belt. Lower Diagram – Eastern Manganese Belt (modified after Boardman[89]).





The manganese was almost certainly derived from the underlying dolomite, which contains up to 6 per cent Mn[105]. Ore formation is probably related to at least two periods of weathering. In the first (which coincides with the unconformity between the chemical sedimentary unit and the upper clastic unit), insoluble manganese, together with chert rubble, were left on the surface of erosion. Subsequently, during a post-Proterozoic weathering period, circulation of meteoric waters in this zone has resulted in the concentration of manganese immediately below, within, or above the chert breccia. In Australia, this latest period of concentration certainly preceded deposition of Permian tillites[106].

Mining has indicated that this type of deposit has no great persistence in depth (Figure 16). The manganese ore generally passes downward to an earthy material carrying chert clasts[89].

Manganese in shale

Along the Gamagara ridge, which runs due north-south between Postmasburg and Sishen in the northwestern Cape (Figure 11), the shaly sediments of the Gamagara rest on manganese-rich, chert-poor dolomite, without the development of a large thickness of intervening chert breccia (Figure 16). The shaly sediments above the unconformity have been extensively manganized, and result in a number of orebodies, known collectively as the 'Western Belt' ores[89]. The original sedimentary textures and structures can frequently be made out in the ore (Figure 15d). Manganized conglomerates are present immediately above the dolomite, but the bulk of the ore is derived from shale[89,107,108,109,110]. The dominant ore mineral is bixbyite. The ores are of a lower grade than those associated with chert breccia, being contaminated by varying amounts of iron. They are, however, larger tonnage deposits, and are more easily developed and mined. After some 11 million tonnes had been mined up to 1964, Boardman[89] calculated that at least 18 million tonnes, at over 30 per cent Mn, remained. At Kgwakgwe, in Botswana (Figure 11), manganiferous shales at the base of the Malmani Dolomite have been enriched to ore-grade material[147]. A reserve of 181 000 tonnes of ore has been calculated.

At Gopane, in the Western Transvaal, manganese mineralization is developed over a strike length of 16 km, a short distance above the base of the Timeball Hill Shale[148] (Figure 11). The orebody is 1 to 5 m thick, and comprises nsutite, pyrolusite, and cryptomelane. This mineral belt extends over the border, into eastern Botswana, occurring in the Lobatse and Ramotswa areas. It appears to be a surface enrichment of a manganiferous protore.

Many of the deposits in the east Hamersley Basin are situated in a setting analogous to that of the Postmasburg Western Belt occurrences. Manganized shales near the base of the Manganese Group have been recorded[23,106,161].

As in the case of the ores associated with the breccias, the ultimate source of manganese is in the underlying dolomite. Manganized sediments are limited to regions where the unconformity rests on dolomite. The mechanism of mobilization, transport, and replacement by manganese is not understood, but is likely to involve meteoric solutions[87,89]. The persistence in depth of this type of manganese deposit has not been firmly established. It may transpire that the basal Gamagara shale has a high primary manganese content, and that the ores of the Western Belt represent surface enrichments of this protore. A comparable situation exists in Australia, where the manganiferous Noreena Shale has been enriched locally to give rise to supergene manganese deposits, such as the ore at Balfour Downs[106] (Figure 12). In the Ripon Hills, surface enrichment of ferruginous and manganiferous shales has resulted in ferruginous manganese bodies, averaging 6 metres in thickness[106]. Relict bedding, after the shale, can be made out. Some 18 million tonnes of ore, with a grade of 19,4 per cent Mn and 25,9 per cent Fe have been proved, with an additional 45 million tonnes inferred[112].

Manganese in banded iron formation

Manganese enrichments in banded iron formation are known from the northwestern Cape and from the Hamersley Basin. They tend to be low-grade and low-tonnage deposits, and have not been mined on a large scale. Manganese concentrations in the Marra Mamba Iron Formation are known over extensive areas[43] in the Hamersley Basin, and include the Mount Nicholas deposits in the east Pilbara region[106] (Figure 12). Near Tom Price, a mineralized zone up to 1,5 m thick in the Marra Mamba contains over 40 per cent Mn[43]. Manganese enrichments in iron formation are known from the Rooinekke area of the northern Cape[87] (Figure 11). Orebodies are up to 3 m thick. The principal ore mineral is psilomelane. The ore is of low grade, seldom carrying more than 35 per cent Mn. Production up to 1953 was 45 000 tonnes. The manganese represents a surface enrichment in iron formation. Manganized zones in stratiform breccias in banded iron formation are known in the Korannaberg[87], northeast of the Kalahari manganese field.

Hematitic iron ore in an iron formation host

High-grade iron ores, in iron formation hosts, represent one of the economically most-important type of deposits in the chemical sedimentary unit. Many billions of tonnes of such ore are developed in the Hamersley Basin[163], while the iron formations in the Transvaal Basin contain a few hundreds of millions of tonnes of enriched ore.

In South Africa, hematite orebodies are developed in the Penge Iron Formation at Thabazimbi, and in an iron formation at the base of the Gamagara succession in the northwestern Cape (Figure 15e) near Sishen (Figure 11). In the former locality, high-grade hematite ore is encountered in the lower portions of the iron formation (Figure 17) resting on a shale a short distance above the Malmani Dolomite[80,113,114,115]. The iron formation dips fairly steeply to the south, and is repeated by a series of strike faults. With increasing depth, the ore tends to finger out to unmineralized iron formation[115], and into a banded hematite-calcite rock. Supergene processes are thought to be primarily responsible for the enrichment. However, the effects of hypogene processes were also considered

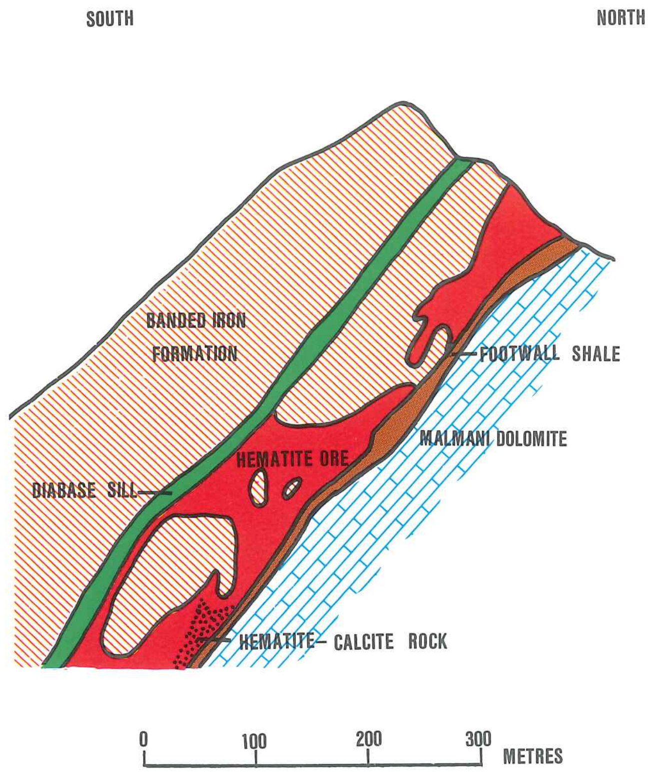


FIGURE 17 Cross-section of Thabazimbi iron ore deposit, northwestern Transvaal (modified after Strauss[115]).

important[110,114,115]. Strauss[115] was of the opinion that only those iron formations that were chemically conditioned by hypogene processes related to the faulting were amenable to replacement by meteoric fluids.

In Australia (Figure 12), high-grade, low-phosphorous hematite is mined at Newman (where the Whaleback Orebody has a reserve in excess of 1000 million tonnes at 64 per cent Fe)[118], at Parraburdoo[165] (695 million tonnes at 60 to 64 per cent Fe) and at Tom Price[164] (450 million tonnes at 64 per cent Fe, plus 136 million tonnes at 58 per cent Fe). Numerous other bodies, somewhat higher in phosphorous, have been drilled out, but are not being mined at present. They include[119] Rhodes Ridge (907 million tonnes, > 61 per cent Fe, 0,12 per cent P), Koodaideri (656 million tonnes at 62 per cent Fe, 0,13 per cent P, and 1062 million tonnes at 56 per cent Fe, 0,12 per cent P) and the Mt. Brockman area (402 million tonnes).

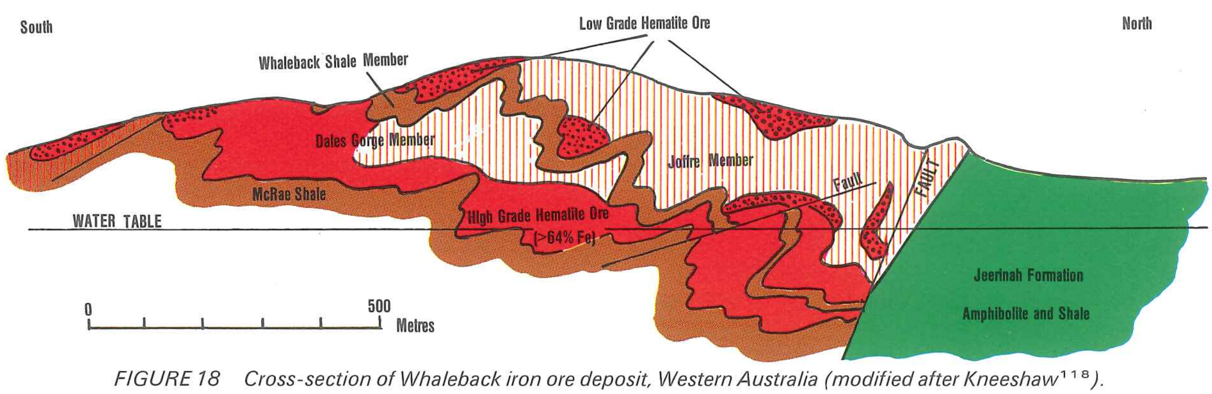


FIGURE 18 Cross-section of Whaleback iron ore deposit, Western Australia (modified after Kneeshaw[118]).

The majority of this ore is developed within the Dales Gorge Member of the Brockman Iron Formation (Figure 18). At Parraburdoo, ore is also mined in the Joffre Member. The shale macrobands in the Dales Gorge Member (Figure 9d, 15f) give rise to the principal impurities in the orebodies. Gamma logging[120] of boreholes during exploration and development, has assisted greatly in the blocking out of orebodies. The individual shale and iron formations can be recognized by their characteristic gamma log profiles.

A number of factors appear to influence development of hematite orebodies in iron formation, and include the following:

- stratigraphy – certain units are preferentially hematized, such as the Dales Gorge Member, owing to their chemical and physical characteristics, as well as the fact that they are sandwiched between shale bands, which acted either as aquifers or confining barriers to mineralizing fluids[64].
- folding – enriched iron formation is frequently encountered in the axial regions of synclinal structures[43]. For example, in the cross-section of the Whaleback orebody[118], maximum development of hematite ore is in synclines (Figure 18). The effects of structure are also seen in the fact that the essentially unfolded portions of the Hamersley Basin contain few enriched hematite occurrences.
- faulting – the presence of strike faults appears to be critical to the development of large hematite orebodies. The Tom Price, Parraburdoo, Whaleback, and Thabazimbi deposits dip into, and are truncated by, steeply dipping strike faults (see Figures 17 and 18). The presence of faults appears to have facilitated the establishment of a plumbing system for the circulation of the large volumes of fluid needed to effect enrichment.

Field evidence thus points to the enrichment of iron formation through some metasomatic process. Blockley[121] has shown that the Dales Gorge Member undergoes a 50-per-cent reduction in thickness when traced into the Tom Price ore-body, a figure that corresponds fairly closely with the proportion of chert in the Dales Gorge. Enrichment could involve removal of chert with simultaneous hematization of iron silicates and carbonates. Hypogene metasomatic fluids are frequently regarded as the mineralizing agents. However, high-grade hematite deposits in iron formation almost invariably finger out to unaltered rock with depth, pointing to a supergene origin for the hematizing fluids.

There is a growing body of evidence that suggests a Proterozoic age for the period of hematization. At Tom Price, for example, MacDonald and Grubb[64] have distinguished two periods of lateritization, separated by a period of diagenesis. The first and most intense is regarded as the period during which enrichment occurred. Palaeomagnetic studies[122] indicated a middle Precambrian age for iron enrichment in Australia. Geological evidence in South Africa supports this conclusion. Hematized iron formation clasts are found in the Gamagara basal conglomerate in the Postmasburg-Sishen area[123].

The balance of evidence thus suggests that enrichment took place during the early- to middle-Proterozoic, through the agency of circulating meteoric waters associated with a period, or periods, of weathering. The pathways taken by circulating meteoric fluids were directed by structural and stratigraphic controls. The circulating groundwaters must have been particularly suited to dissolving, and holding in solution, large quantities of silica. They may have been partly of connate origin, representing the diagenetic dewatering effluent of the iron formation gel.

Banded hematite-goethite iron ore in an iron formation host

Iron ore of the banded hematite-goethite type is best developed in the upper unit of the Marra Mamba Iron Formation[166] (Figure 6). The ore is soft and outcrops in low hills or is covered by surface drift. At depth, it is a well-banded ore (Figure 20a). It is thought to have been derived from an iron formation by the replacement of iron silicates by goethite and of magnetite by hematite. Under the hand lens, goethite is seen to be pseudomorphous after a fine-grained aggregate of a platy mineral, probably an iron silicate[90].

At least one large body of Marra Mamba ore has been drilled out at Marandoo (Figure 12) comprising 250 million tonnes[112] at $>$ 63 per cent Fe and 0,06 per cent P. A further 150 million tonnes is estimated to be present. Other large orebodies are developed at Mining Area 'C', southeast of Marandoo[166], and at Newman. No Marra Mamba type ore is known in South African iron formation. It may well be present and have gone unrecognized.

Hematitic iron ore in conglomerate, breccia, and shale host

Between Sishen and Postmasburg, in the northern Cape (Figure 12) deposits of high-grade hematite are found in the Gamagara succession, immediately above the plane of unconformity that separates the chemical sedimentary unit from the overlying upper clastic unit (Figure 19). Some of the ore is present as enrichment in iron formation, but the majority is in hematized shale, conglomerate, and breccia[124]. The largest deposits are around Sishen, where reserves have been estimated at close to 4000 million tonnes at $>$ 60 per cent Fe[125].

Stratigraphically, the low-phosphorous hematized sediments are localized within the basal few hundred metres of the Gamagara Formation, which rests on a topographically-irregular erosion surface cut across gently-folded iron formation and dolomite. Where the erosive surface cuts chert-bearing dolomite a chert breccia is developed. Elsewhere, the unconformity is generally mantled by a thin conglomerate. The Gamagara Group commences with iron formation and shale, which are thickest in north-south troughs. A conglomeratic phase follows, and is overlain by aluminous (pyrophyllite and diaspore-bearing) shale, passing up to ferruginous shale, to impure arenite, and to clean quartzite (Figure 19). The basal iron formation of the Gamagara is represented by a sedimentary breccia in places, thought to have formed by slumping into solution cavities in the underlying dolomite[123]. This breccia is known as the Blinkklip Breccia.

Any of the basal ferruginous sediments of the Gamagara may become hematized. Hematization is most intense, but is not restricted to, regions where the Gamagara strata overlie iron formation of the chemical sedimentary unit. The enriched sediments retain their structure, so that four texturally distinct types of ore can be distinguished being derived from conglomerate (Figure 20b), breccia, iron formation, and shale. Laterally, the hematized sediments finger out into unaltered rocks. In addition, inclusions

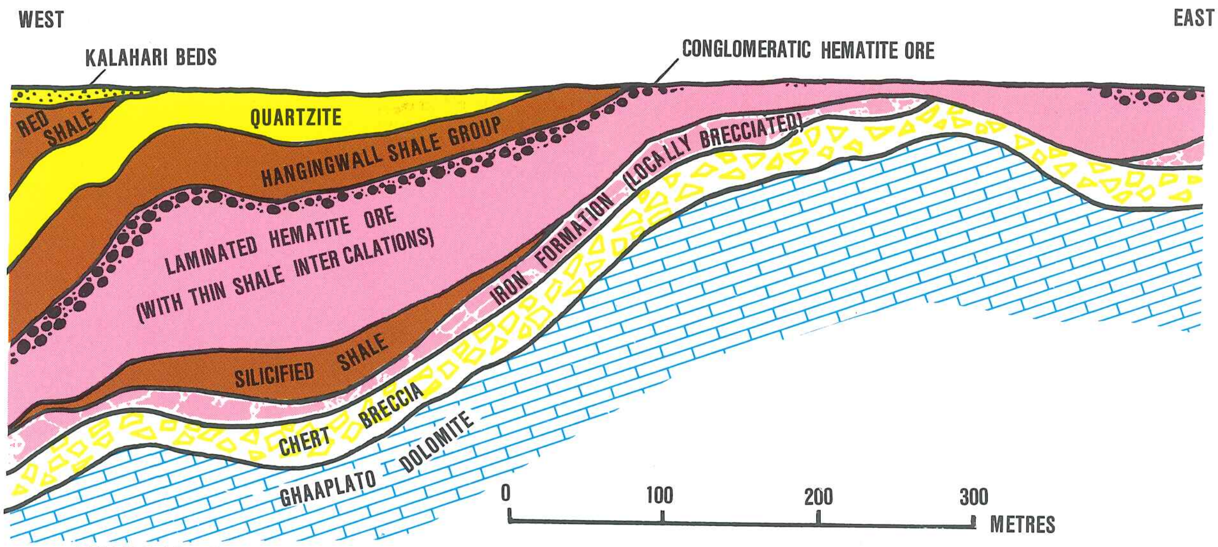


FIGURE 19 Cross-section of iron-ore deposits at Sishen, northwestern Cape Province (modified after Strauss[124]).

and beds of unenriched sediment are frequently encountered in the ore.

The origin of the ores is still open to debate. The fact that those Gamagara sediments that rest on iron formation are extensively hematized suggests that, in some way, the iron is derived from the underlying formations and is redeposited in favoured sites in the overlying rocks. The rocks that are hematized are probably those that are chemically amenable and that were relatively porous. It is suggested that circulating meteoric waters (fossil groundwaters[125]), associated with one of the erosive periods post-dating the Gamagara, were probably the agents of hematization. The sediments that were hematised were rich in iron, consisting in part of the clastic debris from the older Griquatown iron formations. The period of hematization dates back at least to the pre-Karroo era, since glaciated pavements on hematite have been recorded[123].

The generalizations developed in the Sishen area appear to apply in the Hamersley Basin. Where the Wyloo Group rests on the chemical sediments of the Hamersley Group, a hematized conglomerate occurrence is recorded[34] in the vicinity of the Wyloo Dome (Figure 12). The conglomerate, a member of the Mount McGrath Formation, outcrops over a distance of 2440 metres. An unhematized shale parting within the conglomerate is recorded. The enriched conglomerate contains in excess of 65 per cent iron in places.

LOW TEMPERATURE HYDROTHERMAL DEPOSITS

Fluorite (lead, zinc, vanadium)

Deposits of fluorite, associated with Pb, Zn, and V, have long been known to occur in the western Transvaal (Figure 11). The occurrences are located near the top of the shallow-dipping Malmani Dolomite, within about 100 metres of the unconformably-overlying Pretoria Group. Until fairly recently, mining was restricted to small-tonnage vein, pipe, and replacement deposits in dolomite[126,127,128,129,130,131], and residual concentrations of fluorite found with wad in a rectangular array of joint-controlled solution depressions.

Mineralization occurs scattered over a strike-length of about 60 km, the fluorite occurrences being preferentially located near the western boundary of the mineralized belt. A regional control on mineralization probably involves a dense banded chert, which coincides with the top of the Malmani Dolomite, and the overlying impermeable Pretoria Group shales. These are thought to have formed barriers to ascending fluids, which were forced to move laterally beneath this cap. On a more local scale, depositional structures in the dolomite exerted an important control on ore deposition. Relatively massive dolomites are barren or weakly mineralized. By contrast, dolomites that show well-defined bedding planes (frequently ornamented by algal structures of various types (Figure 20c) and clastic-textured dolomites were preferentially mineralized.

The origin of the fluorite is being debated at present. Some investigators[129] believe that the fluorite is a primary deposit, mainly on the basis of the very delicate layered dolomite-fluorite rocks found in places. However, the cross-cutting relation of mineralization to stratification leaves little doubt that the deposits are of a replacement type, probably low-temperature hydrothermal. The Bushveld Complex is the source most frequently called upon to supply the fluids. However, juxtaposition of the Bushveld and the dolomite, as at Zeerust, is repeated in other places in the Transvaal Basin, while the fluorite mineralization apparently is not. A second feature taken as evidence against a Bushveld origin for the fluids is the fact that fluorite replaces Bushveld-age metamorphic minerals in the dolomite[127]. An unexposed Pilanesberg-related alkaline complex (ca 1300 m.y. old) is considered to be a more likely source.

The reserves of fluorite (proved and indicated) in the Ottoshoop area are large, and have been estimated at 100 to 150 million tonnes of easily accessible fluorite-bearing dolomite with $>$ 15 per cent CaF_2[131].

No fluorite occurrences have been recorded in the chemical sedimentary unit of the Hamersley Basin. The analogy with the Transvaal Basin is used to suggest that the Carawine Dolomite, beneath the impermeable cover of Pinjan Chert Breccia and Manganese Group Shales, might be a favoured venue for such deposits. In addition, Pb–Zn deposits of the Mississippi Valley type are frequently found beneath unconformities, where the zones of


FIGURE 20 (a)


FIGURE 20 (b)


FIGURE 20 (c)


FIGURE 20 (d)

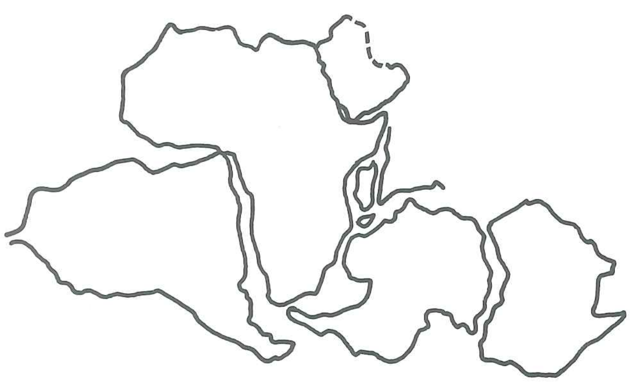


FIGURE 20 (e)

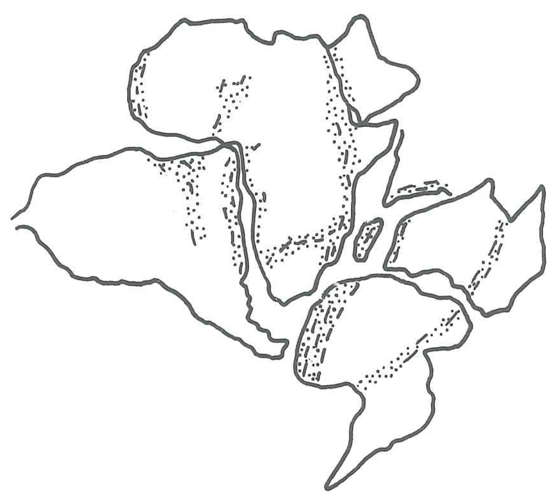


FIGURE 20 (f)

enhanced porosity afforded by cave-fill breccias has resulted in the localization of low-temperature epigenetic mineralization[132].

Fluorite-bearing vein systems have recently been discovered in the Meentheena region (Figure 12), southeast of Marble Bar[133]. The veins cut the Mount Roe Basalt, near the base of the Fortescue Group. As yet no large-scale production has taken place.

The case-history of the fluorite deposits in the Transvaal might be used to advantage in the Hamersley Basin. In the Transvaal, cross-cutting vein deposits in dolomite were known for almost a century before stratiform replacement bodies were mined. It is considered entirely possible that stratiform replacements might be found in the vicinity of the Meentheena vein deposits (Figure 12), in the carbonates of the Tumbiana Formation, Fortescue Group (Figure 6).

INTERMEDIATE AND HIGH-TEMPERATURE HYDROTHERMAL DEPOSITS

Gold

Uneconomic auriferous vein deposits are found in both the Fortescue and Wolkberg groups[32,34,98]. Auriferous vein deposits are known from numerous localities in the Wyloo Group, particularly in the Ashburton valley (Figure 12), where alluvial mining has taken place[74]. Several thousand ounces have been recovered.

Auriferous hydrothermal veins reach their maximum development in the Pilgrims Rest-Sabie-Lydenburg area of the eastern Transvaal (Figure 11), where the bulk of the gold was won, over a hundred-year period, from quartz 'reefs' in the Malmani Dolomite. Total estimated production[146] from the field was about 6 million ounces. Some of the bodies mined were situated in the lower part of the Pretoria Group. The most significant producers were stratiform quartz bodies. Smaller amounts were won from cross-cutting veins (known locally as leaders), blows (sausage-like swells in stratiform quartz veins), and impregnations[134,135,136,137,138,139].

The major control on ore localization was the presence of planes of intrastratal movement (bedding plane thrust faults) at numerous levels through the succession. In arenite and carbonate units, bedding slip took place along thin shale bands. In arenite-argillite alternations, it took place at lithological contacts. Evidence for intrastratal movement includes the presence of offset dykes, of slickensided surfaces, and of non-penetrative cleavage adjacent to the plane of movement.

The principal stratiform quartz sheets can be followed for up to 10 km along strike. They are enriched in north to northeast-trending paystreaks, along the crests of gentle anticlinal warps[137,138,139].

FIGURE 20(a) Banded hematite-geothite iron ore, Marra Mamba Iron Formation, Newman, W. Australia.
(b) Hematite ore, formed by enrichment of ferruginous conglomerate, at Sishen, N. Cape.
(c) Bedded fluorite ore, in Malmani Dolomite near Ottoshoop, W. Transvaal. Fluorite weathers positively, and accentuates tepee structures in dolomite.
(d) Block of quartz-sulphide ore with carbonaceous shale fragments, from the Bevets Reef, Pilgrims Rest area, S. Africa.
(e) Smith-Hallam fit of Gondwanan continents (after Smith and Hallam[153]).
(f) Piper's fit of Gondwanan continents (modified after Piper[154]).

Mineralogically, the reefs comprise early-phase quartz, carbonates, and pyrite, with scheelite, arsenopyrite, pyrrhotite, sphalerite, and galena[136], together with platy fragments of brecciated shale (Figure 20d). These early minerals were shattered by a second period of bedding plane movement, before final introduction of gold with chalcopyrite, bismuthinite, tetrahedrite and galeno-bismutite. Small amounts of silver, copper, bismuth, and pyrite have been recovered along with the gold.

The deposits are generally considered to be epigenetic mesothermal[136]. A variety of sources for the hydrothermal fluids has been postulated, and include the Bushveld Complex, some 80 km west of the deposits. However, the juxtaposition of the Complex and the Transvaal strata is far more widespread than the mineralization. Secondly, the mineralization can be shown to postdate a north-northeast-trending dyke system that is of Bushveld age or younger. No satisfactory source for hydrothermal fluids is presently known.

A lateral secretion origin for the gold has been favoured by some investigators[137]. Some support for this idea has recently been obtained from a geochemical study of shaly sediments near the base of the Transvaal Supergroup in an area far removed from economic mineralization. A shale near the base of the Malmani Dolomite, over 100 km away from the nearest known mineralization, was found to carry 0,1 p.p.m. Au[140], while shales near orebodies contain up to 0,2 p.p.m. Au.

No gold deposits on the scale of those in the Transvaal Basin are known within the confines of the Hamersley Basin. The Paterson Range deposits at Telfer (Figure 12) show some similarities, being stratiform sulphidic orebodies developed in minor shaly beds in a quartzitic succession, with the best values being found along anticlinal axes[141]. The age and stratigraphic affinities of the host sediments of the Paterson Range deposits have not been firmly established. They could be equivalents of units within the Mount Bruce Supergroup.

The auriferous deposits of the Peak Hill-Horseshoe Lights region (Figure 12), in the Nabberu Basin can probably be included under this heading. The gold is found in quartz vein systems or is disseminated in decomposed (kaolinitised) iron formation, quartz-mica, and chlorite schist[157]. Nearly 300 000 ounces of gold have been produced from the region, principally from Peak Hill. The inclusion of the Peak Hill beds in the Nabberu succession is open to question, since Horwitz's map shows them as being Carpentaian (middle-Proterozoic) in age.

Lead, zinc, and silver

In the Braeside region of Western Australia (Figure 12), quartz vein systems cutting Fortescue basalts have been mined for Pb, Zn, and Ag[142] and produced 3216 tonnes of lead. One of the largest veins was mined at Ragged Hills (Figure 12), which produced nearly all of the quoted tonnage.

Other veins cutting Duck Creek Dolomite and the Ashburton and Capricorn formations (all in the Wyloo Group) carry lead, copper, silver, and barite[34,69,74]. These attain their greatest development in the Kooline and Uaroo-Range districts[142] (Figure 12). Some of the veins are in metamorphozed and migmatized representatives of the Wyloo Group. In addition to vein deposits, Blockley[142] mentions one stratiform replacement body.

TABLE 6
LONGER TERM PARALLELS IN STRATIGRAPHIC DEVELOPMENT OF W. AUSTRALIA AND SOUTHERN AFRICA

SOUTHERN AFRICA	WESTERN AUSTRALIA	APPROXIMATE AGE (m.y.)	REMARKS
Umkondo Group	Bangemall Group	1 100	Stratiform copper occurrences in both basins
Pilanesberg alkaline intrusives	No major alkaline intrusives	1 300	Probable source of stratiform fluorite in Malmani Dolomite
Waterberg-Olifantshoek Groups	Bresnahan-Mt. Minnie Groups	1 500-2 200	Coarse, fluvial sediments in fault-bounded troughs
Bushveld Complex	Boolaloo Granodiorite, layered intrusive in Nabberu Basin	1 700-2 200	In Australia, may include mafic complex between Hamersley and Nabberu basins[159].
Pretoria and Postmasburg Groups	Wyloo and Manganese Groups	2 000-2 250	Contain major manganese concentrations
Chuniespoort and Campbell-Griquatown Groups	Hamersley Group	2 000-2 300	Contain major iron and crocidolite deposits
Wolkberg Group	Fortescue Group	2 200-2 350	No major ore deposits
Ventersdorp Group	? Fortescue Group	2 300-2 600	Top part of Ventersdorp succession grouped with Transvaal Basin[158].
Witwatersrand and Dominion Reef successions	No known equivalent	2 600-2 800	Major Au-U metallogenic epoch
Pongola Supergroup	No known equivalent	3 000	
Archaean greenstone belts	Archaean greenstone belts	2 700-3 400	Similar depositional and tectonic history

Tin

Hydrothermal tin deposits have been emplaced in Pretoria Group arkoses and shales in the Rooiberg area, Transvaal[151,152] (Figure 11). In this region, the Pretoria sediments form a roof-pendent in Bushveld granitic rocks. Ore-bodies are located in cross-cutting fractures and in stratiform replacement bodies in arkose. Hydrothermal solutions probably represent the fluid fraction driven off the Bushveld granitic suite during cooling. Lodes in the Transvaal sediments have produced over 3500 tonnes of metallic tin[160].

CONCLUSIONS

Parallels in basin development

There are a number of striking similarities between the early-Proterozoic Hamersley Basin of Australia and the Transvaal Basin in southern Africa.

- □ Within the limits of presently-available geochronology, the basins are of the same age.
- □ Gross stratigraphic relations are analogous, a basal volcanic and clastic unit is overlain (often unconformably) by a chemical sedimentary unit, followed (again unconformably) by an upper clastic unit.
- □ Depositional environments evolved similarly. In the basal volcanic and clastic unit, earliest deposition appears to have been essentially fluvial, and was followed by sedimentation and volcanism on a marginal-marine platform. The chemical sedimentary units include carbonates, deposited on an unrestricted marine shelf, and iron formation, precipitated in a restricted arm of an epeiric sea. The upper clastic unit is essentially an assemblage of marginal-marine progradational cycles, punctuated by episodes of volcanism and of chemical sedimentation.
- □ Magmatic events terminated sedimentation, and include the mafic and acid phases of the Bushveld Complex, and, in Australia, the Boolaloo intrusive suite, and differentiated mafic bodies in the Nabberu Basin[4].

These parallels are best explained by the basins developing more-or-less contemporaneously, on a common continental block, in which various regions were subjected to the same tectonic, climatic and atmospheric history.

Parallels in mineral deposits

A number of classes of mineral deposits are common to the basins, and include the following:

- ★ Mechanical sedimentary gold concentrations, found along unconformities in the vicinity of older, underlying vein or conglomeratic gold deposits.
- ★ Oolitic ironstones, which are developed along the edges of marine sand bodies in shaly formations.
- ★ Primary limestones, found in large-scale, cross-cutting lenses beneath banded iron formations.
- ★ Primary manganese deposits, developed in the upper clastic units, in relatively deep, quiet water, away from active sources of clastic input.
- ★ Crocidolite asbestos, restricted to provinces (probably regions of higher salinity during deposition) in banded iron formations, and concentrated by stratigraphic and structural factors.
- ★ Supergene manganese deposits (where the manganese can be traced back to divalent manganese in carbonate

formations), concentrated in a chert-breccia, shale or iron formation host during periods of weathering.

★ Hematite in iron formation, developed (during Proterozoic weathering) at favoured levels in banded iron formation, often immediately above shaly layers and in regions of structural disturbance, particularly strike faulting.

★ Hematite in ferruginous conglomerate, breccia and shale (the detrital products of iron formation weathering), formed by supergene enrichment of iron-rich sediments.

★ Hydrothermal gold in stratiform sulphidic sheets, located along lithological contacts and enriched along anticlinal structures.

Some ore deposits are apparently developed in only one of the basins. These include

☆ Stratiform fluorite (and minor lead-zinc) orebodies found near the top of the Malmani Dolomite.

☆ Amosite asbestos, developed where crocidolite units sub-outcrop beneath an intraformational unconformity.

☆ Banded hematite-goethite ores, developed by surface enrichment of silicate-oxide facies iron formation.

These constitute attractive exploration targets in the basins in which they are apparently not developed.

Longer-term parallels in stratigraphic development in W. Australia and Southern Africa

Similarities in stratigraphic development are not limited to the Transvaal, Hamersley and Nabberu basins. Table 6 summarizes parallel events in the two continents, and brings out areas of apparent non-parallel behaviour. Similarities in Archaean greenstone belts have been described elsewhere[11]. There are no known Pongola- or Witwatersrand-age and style sediments in Australia. Only a small fraction of the perimeter of the Witwatersrand basin outcrops. It is conceivable that a Witwatersrand-age basin could be developed beneath the Hamersley. Experience in South Africa has shown that basins of Witwatersrand preservation tend to be developed below synformal structures in the Transvaal cover. Consequently, a Witwatersrand equivalent in Australia, if developed, might be sought beneath the Hamersley Basin, along the regional syncline south of the Hamersley Range.

The uppermost units of the Ventersdorp succession have been grouped with the Transvaal Basin[158]. The Ventersdorp, in part, could have a parallel in the Fortescue Group. The Transvaal, Hamersley, and Nabberu basins are intruded by gabbroic and granitic complexes. A major gravity anomaly, situated between the Hamersley and Nabberu basins[159], has been interpreted as being due to a basaltic intrusive, and could be of Bushveld age and type.

The coarse clastic formations of the Waterberg-Olifantshoek and Bresnahan-Mt. Minnie groups are remarkably similar in lithology and tectonic style[90]. They were deposited in fault-controlled basins. Much of their clastic fill was derived by weathering of the Transvaal and Hamersley basins.

The Umkondo Basin (in southeastern Rhodesia) and the Bangemall Basin (in Western Australia) are of similar age. The former is filled mainly by fluvial sediments, while the latter is essentially marine. In both continents, there is a major stratigraphic hiatus separating these units from the oldest of the Phanerozoic formations.

Implications for Gondwanaland

At present, there are no widely accepted reconstructions for the Gondwana super-continent. The relative positions of Africa-S. America and of Australia-Antarctica are firmly established. However, the original configuration with respect to Africa, Antarctica, Australia, and India present greater problems. In the Smith-Hallam fit[153], the west coast of Australia is not juxtaposed to any other continent, being shown as a free interface (Figure 20e). This coast shows strong evidence of rifting in the Darling fault-system, an array of tensional gravity faults. This fact, together with the straightness of the continent margin suggests that Western Australia must have been adjacent to another straight-edged Gondwanan fragment. The eastern coast of Madagascar is considered to be a likely counterpart, a notion supported by the Pan-African (450 to 700 m.y.) type basement in the two regions. Previous reconstructions of the pre-drift Madagascar-Africa relation are probably incorrect. Förster[156], on the basis of a study of Karroo-age basins, has suggested that there has been no post-Karroo movement between Africa and Madagascar.

It has been shown that there is a remarkable degree of correspondence in the development of the Transvaal and Hamersley basins, both in time and in geological style. Parallels can also be seen in older and younger units. These facts suggest that the basins were developed near to one another on a common crustal fragment, and that regional stratigraphic similarities are a response to a common tectonic history. It is thus suggested that there was a much more intimate relation between the Australian and African continent than suggested by the Smith-Hallam fit[153]. A reconstruction that juxtaposes the Darling and Mocambique provinces is favoured. The reconstruction of Piper[154] is close to the one envisaged, and could be modified by leaving Madagascar in its contemporary position (Figure 20f). Piper's positioning of India, off the northern coasts of Western Australia, is supported by palaeocurrent measurements in the Kimberley Basin[155].

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