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STRATIFORM COPPER IN CYCLIC SEDIMENTS OF THE LATE PROTEROZOIC BURRA GROUP, WILLOURAN RANGES, SOUTH AUSTRALIA

by

N.J. ROWLANDS[1] **& O.N. WARIN**[1]

(6 figures and 4 tables)

RESUME.- Le Groupe de Burra, la deuxième plus ancienne unité stratigraphique du Supergroupe Adelaide, du Proterozoïque supérieur de l'Australie du Sud, renferme à plusieurs endroits au travers de l'état, des teneurs anormales en cuivre distribuées de façon stratiforme. Cependant, ces indices de cuivre stratiforme diffèrent à plusieurs points de vue des indices mieux connus situés dans les Assises de Callanna, sous-jacentes, et dans le Groupe sus-jacent, celui d'Umberatana.

Les sédiments du Groupe de Burra sont typiquement cycliques et pourraient se comparer avec des dépôts de périodes pluviales (lacustrine highstands). Régionalement, le cuivre stratiforme se retrouve à la transition verticale entre les sédiments siliciclastiques de style "blanket" et les couches de sédiments à carbonate stromatolytique et des boues hétérolitiques.

Cet article traite principalement de sédiments cuprifères du Burra dans les Monts Willouran. Dans cette région, les sédiments du Burra se sont formés originalement dans trois bassins distincts qui doivent leur origine à un léger rifting. Nous décrivons le gîte de cuivre stratiforme de Warra afin d'illustrer le milieu de déposition de ces roches qui sont l'objet de ce type de minéralisation cuprifère stratiforme. Par la suite, à l'exemple d'un cas type d'exploration, nous élaborons une méthode qui permet de reconnaître et d'évaluer les milieux sédimentaires (lesquels peuvent être des indications pour le cuivre) dans les sections verticales du Burra. Finalement, nous proposons un modèle de minéralisations cuprifères stratiformes dans les sédiments du Burra en fonctions de paramètres reliés au profil vertical de ces sédiments.

La présence de cycles bien distincts et bien formés dans les sédiments du Burra nous a conduit à penser en terme d'association sédimentaire. Cette façon nous a par la suite démontré les avantages pratiques au point de vue exploration ainsi que la validité scientifique d'interpréter les faciès cuprifères en relation avec les sédiments qui leur sont stratigraphiquement voisins. Ce mode de raisonnement fut aussi étendu aux indices de cuivres dans les strates sous-jacentes du Callanna et celles sus-jacentes du Groupe Umberatana, dont aucune ne montre des cycles aussi évidents, mais dans lesquelles des associations de faciès cuprifères sont discernables. Les résultats de ces travaux ont permis d'identifier une gamme de milieux sédimentaires propices à des minéralisations cuprifères stratiformes dans l'Adelaidien. En premier lieu viennent les sabkhas et les dépôts arides de playas (lowstands) dans le Callanna; puis les dépôts paraliques cycliques ou les dépôts lacustres de périodes pluviales (highstands) dans le Burra; et finalement, les progradations deltaïques dans l'Umberatana.

Nous sommes clairement en présence ici de variations dans le thème du cuivre stratiforme; on y trouve des variations de salinité (avec lesquelles Paul BARTHOLOME était bien familier); une variation hydrologique; et une variation biologique. A date, nous admettons ne pas avoir identifié le thème.

ABSTRACT.- The Burra Group, the second oldest stratigraphic unit of South Australia's Late Proterozoic Adelaide Supergroup, contains anomalous copper in the stratiform mode in many locations throughout the State.

However, the stratiform copper occurrences in the Burra Group differ in style in significant ways from the better known occurrences in the underlying Callanna Beds and overlying Umberatana Group.

1 *Utah Development Company, 197 Main Road, Blackwood, South Australia 5051.*

Burra Group sediments are typically cyclic and invite comparison with lacustrine highstands. Regionally, the stratiform copper in the Burra Group occurs at the vertical transition from blanket style siliciclastics to mixed blankets of stromatolitic carbonate and heterolithic muds.

Cupriferous Burra sediments in the Willouran Ranges are the main subject of this paper. Burra sediments in the Willourans were formed in three initially discrete basins which resulted from gentle rifting.

The Warra Warra stratiform copper occurrence in the Camp Basin is described to illustrate the depositional environment for host rocks to this mode of stratiform copper mineralization.

A method of recognition and ranking of sedimentological environments (which may be clues for copper) in Burra vertical profiles is then developed as an exploration case history. From this work, a model of stratiform copper occurrences in Burra sediments is postulated in terms related to the vertical profile of the host sediments.

The well-developed, clearly distinguishable cycles within the sediments of the Burra Group have forced us to think in terms of sedimentary association. This, in turn, revealed both the practical exploration advantage and the scientific validity of interpreting the copper facies by reference to its neighbour in the stratigraphic sense. This same thinking has been carried over into the consideration of copper occurrences in the underlying Callanna Beds and overlying Umberatana Group, neither of which show the same strong cyclicity, but in both of which copper facies associations can be discerned. The outcome has been the recognition of a spectrum of stratiform copper host-rock environments in the Adelaidean. Firstly there are sabkhas and playa lowstands in the Callannas, then cyclic paralic, or even lacustrine highstands in the Burra, and finally deltaic progradations in the Umberatana.

Clearly, we have here a set of variations on the stratiform copper theme; we have a saline variation (with which Paul BARTHOLOME was intimately familiar); a hydrological variation; and a biological variation. We admit to not yet having been able to discern the theme.

INTRODUCTION

The Adelaide Supergroup (PARKIN, 1969; ROWLANDS, 1973; PREISS *et al.*, in press; VON DER BORCH, in prep.) is a thick sequence of shallow water sediments of Late Proterozoic age. It consists of four tectono-sedimentary cycles (Groups) which, from the base upwards are the Callanna Beds, the Burra Group, the Umberatana Group and the Wilpena Group.

The repositories in which the Adelaide Supergroup sediments were laid down were formed as a consequence of the slow and gentle progressive development of a three-arm rift system (VON DER BORCH, in prep.).

Stratiform copper occurrences, mineralization and anomalism are stratigraphically and geographically widespread throughout the Supergroup (ROWLANDS, 1973, 1974; ROWLANDS *et al.*, 1978b). This paper describes stratiform copper environments in the Burra Group using the Willouran Ranges area (fig. 1) as an example.

The stratigraphy of the basal Burra (Rischbieth, Tarlton and Warra Warra Beds of fig. 1) is discussed in general terms as being an ancient system comparable with cyclic sedimentation in a humid lacustrine environment such as the Green River Formation (SURDAM & WOLFBAUER, 1975; SURDAM & STANLEY, 1979). The Warra Warra (fig. 1) copper prospect is then used as an example of stratiform copper fixation at a regional stratigraphic interface between siliciclastics below and chemical, carbonaceous and biogenic sediments above.

This stratigraphic level occurs anywhere within the top two-thirds of the Tarlton Beds and the lower portion of the Warra Warra Beds (fig. 1 and 2) in the more terrigineous and submergent component of shallowing-upwards cycles.

Utah Development Company has drilled this stratigraphic level at five geographically separate localities in the Willouran Ranges and in four localities elsewhere in the Supergroup. This drilling has resulted in 75 "positive signals" (i.e. more than 0.5 metre-percent in the primary zone). The vertical profiles with which these positive copper signals are associated have been processed by an empirical method to establish sedimentological anomalies for stratiform copper mineralization. The processing has been based on our analysis of vertical profiles on granulometry (LOMBARD, 1972 and NICOLINI, 1962, 1964 and 1970).

Comparison is made between a model for stratiform copper in the Burra Group and models for this commodity in the Callanna Beds and basal Umberatana

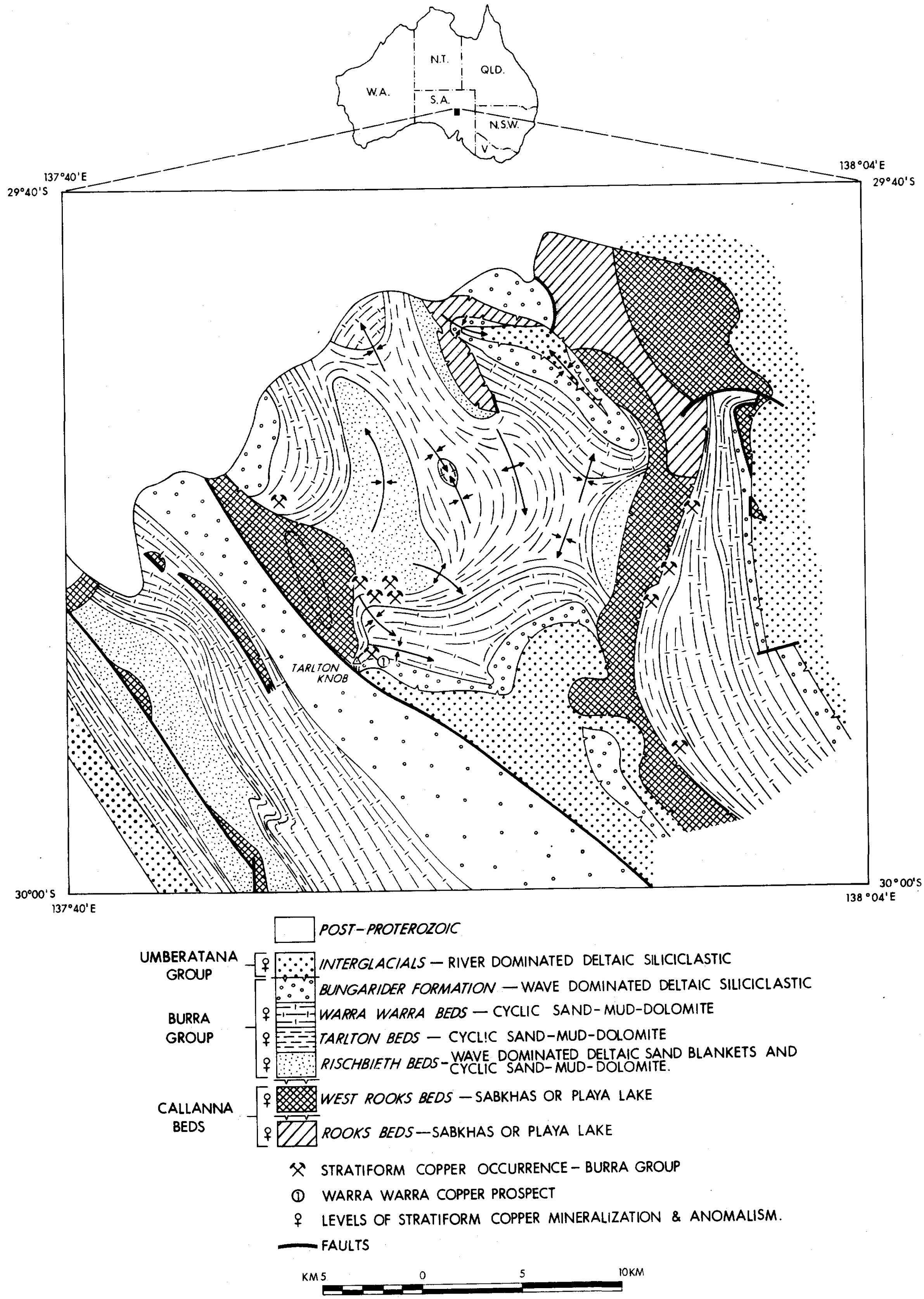


Figure 1.- Geological & Geographic Placefix, Willouran Ranges, South Australia

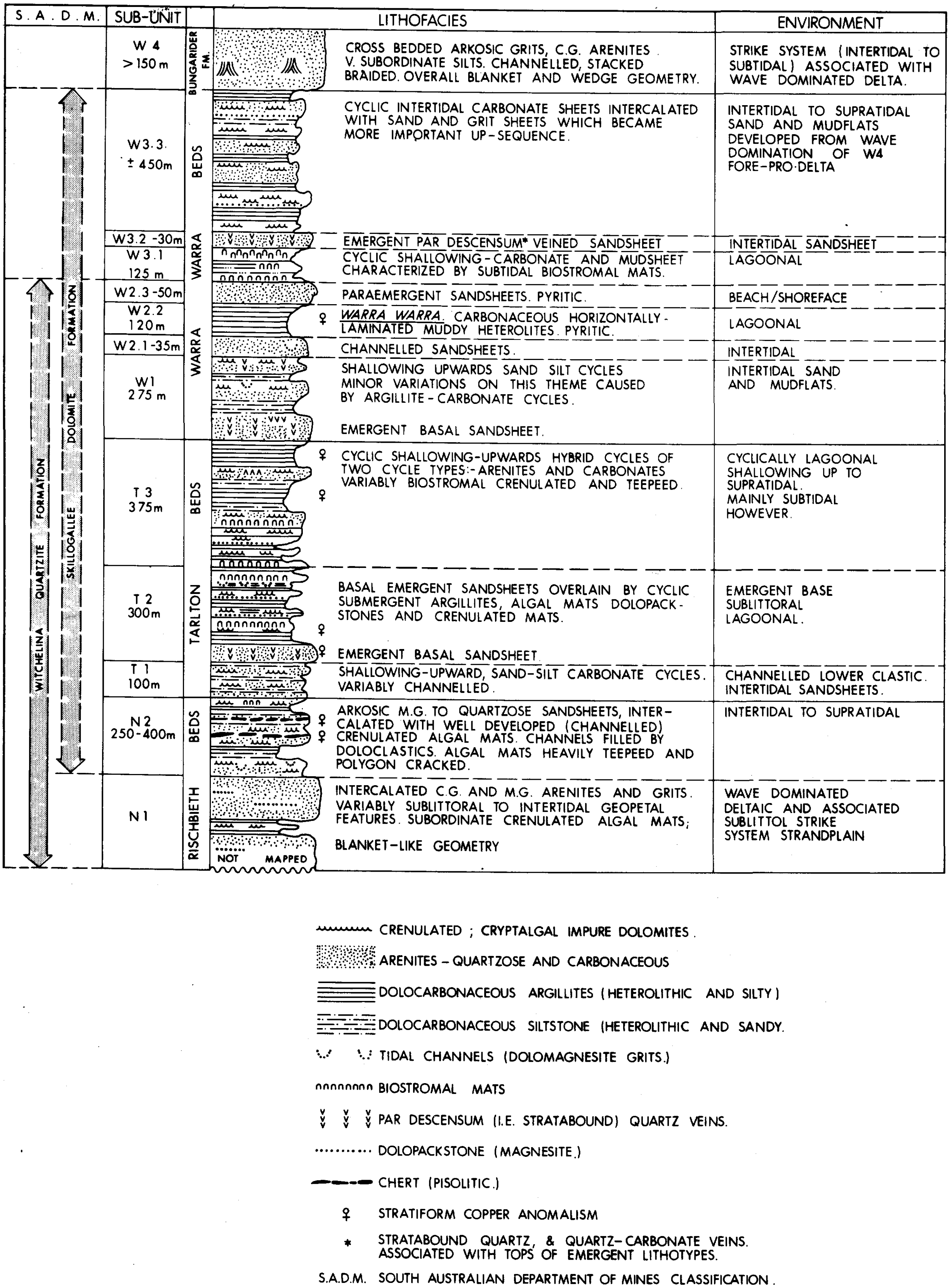


Figure 2.- Vertical Profile Basal Burra Group

Group (Interglacials). These three stratigraphic levels (fig. 1) contain stratiform copper in three different depositional associations (ROWLANDS, 1974). In the oldest (Callannas), it is the salinity within a hypersaline facies tract which controls the copper mineralization (ROWLANDS *et al.*, 1979b). In the Burra depositional association, it is palaeobiology (stromatolites) at a clastic-chemical interface. In the youngest (basal Umberatana) depositional association, the stratiform copper occurs in delta-associated clastic weges where palaeohydrology seems to have been an important control of mineralization (RAYNER & ROWLANDS, 1979, in prep.).

STRATIGRAPHIC SETTING OF COPPER MINERALIZATION

BURRA GROUP VERTICAL PROFIL

The stratigraphy under consideration is shown in figure 2. This shows the Burra Group starts with siliciclastics of a wave-dominated deltaic system with associated sublittoral strike-system strandplain (N1). This gives way to cyclically deposited siliciclastics, carbonaceous muds and stromatolitic dolomites (N2 to W3). Burra sedimentation terminated with a return to siliciclastic blankets (W4) of paragenesis similar to N1.

We have correlated the Rischbieth, Tarlton and Warra Warra Beds with the Skillogalleee and Witchelina Formations of PARKIN (1969), and PREISS *et al.* (in press) to provide a regional perspective with the rest of the Adelaide Supergroup.

The cyclically intercalated mix of siliciclastics, muds and algal dolomites in N2 to W3 of figure 2 are the main focus of this paper. The sediments N1 to W3 were laid down in three discrete basins in the Willouran Ranges (fig. 3). No stratiform copper mineralization is known from the western (i.e. Nor'west-Tarlton West) basin. The East Rooks basin contains both stratiform copper *sensu stricto* and occurrences of the peneconcordant type at the T2 level. Several levels (shown in fig. 2) and different geographic localities host stratiform copper occurrences in the Camp (or central basin). One of these is the Warra Warra copper prospect. Mining here between 1888 and 1920 produced 1300 tons of ore grading 15-38 °/o copper from a secondary accumulation at the stratigraphic level of W2. Mineralization in the primary zone consists of isotropic and stratiform disseminations of pyrite, chalcopyrite and bornite in decreasing order of abundance. Soil geochemistry shows a linear copper anomaly 1.8 km long and 30 to 100 m wide with a background of 10-15 ppm Cu and an anomaly threshold of 75 ppm Cu. Drilling suggested a minimum tonnage of 10 million tonnes averaging 0.3-0.7 °/o Cu at the W2.2 level.

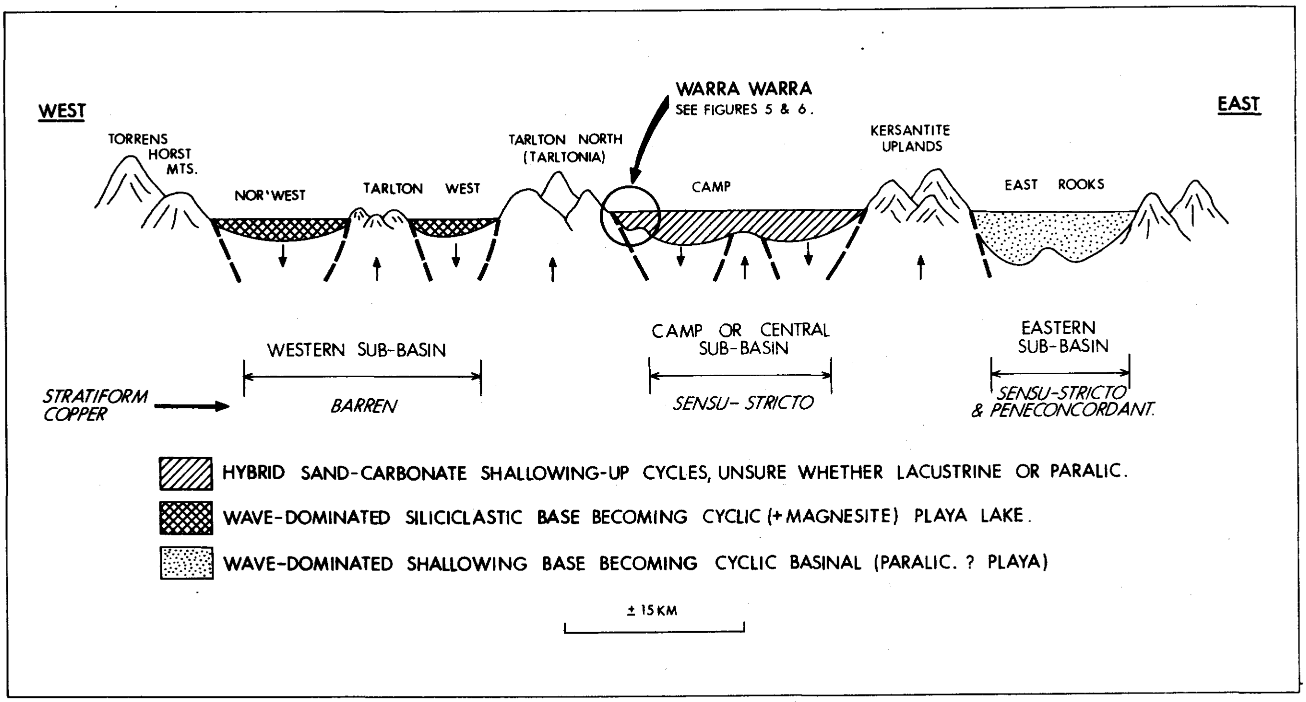


Figure 3.- Burra Receptacle - Geometry and Nomenclature

ANATOMY OF BURRA CYCLICITY, CAMP BASIN

Both the dolomite and the terrigineous components of the Burra sediments from N2 to W3 show shallowing-upward cyclicity. These shallowing-upward terrigineous and carbonate cycles have been spliced into each other in varying degrees at different levels in the stratigraphy. The result has been a hybrid sand-mud-carbonate shallowing-up cycle, which is shown in idealized format in figure 4. In this hybrid cycle, the shallowing-up terrigineous components are B2, B3, B4 and parts of C1. The shallowing-up carbonate cycle components are A, B1, and parts of C1 and C2. Locally (e.g. top of W2.3), a C3 (or terrestrial carbonate) unit is developed.

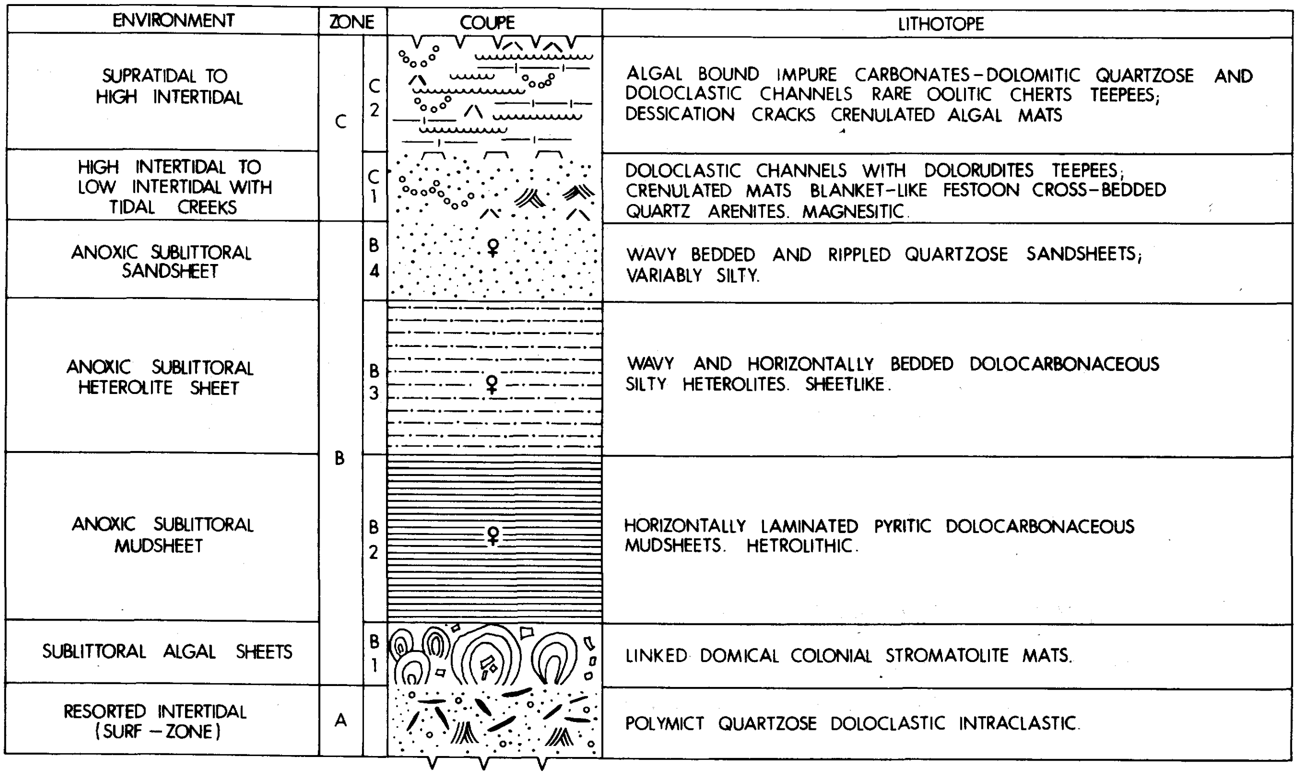
Naturally, there are many variations on this cyclic theme between N2 and W3. These variations have been caused by changes in siliciclastic input rates with time, including decreases to zero, and by the geographic position with respect to the edge of the Camp basin.

Geometrically, the N2 and W3 cyclically intercalated carbonate-sand-muds are uniform blankets. Such a combination of lateral persistence and cyclicity is usually ascribed to either advance and retreat of seas (paralic systems), or to fluctuations in climatic conditions between pluvial highstands and arid lowstands (lake systems). We are unsure whether the Camp basin cycles are evidence of a lacustrine or paralic system. The Western basin was sedimented by a wave-dominated delta, which resulted in blanket siliciclastics. This was followed by hypersaline siliciclastics (fringing a playa lake) and cyclic dolomite-magnesite-arenite-muds of an ephemeral lake system. The East Rooks basin saw, firstly, an wedge-like siliciclastic development on a fluvial braid-plain; then a hypersaline siliciclastic sabkha; then a river-dominated delta.

We think the Burra sediments in the three basins (fig. 3) represent deposition in a central gulf-graben (paralic style sediments) with flanking grabens receiving sediments from ephemeral lacustrine systems.

PETROGRAPHICS OF N2 TO W3 COMPONENTS

The petrography of the lithotopes which compose the Burra shallowing-upward cycle shown in figure 4 is as follows :



♀ COMMONLY HOST TO STRATIFORM COPPER ANOMALISM/MINERALIZATION

Figure 4.- Shallowing upward Burra Cycle

a) Clastic Lithotope

i) Siliciclastics (B3/B4 and C1 of figure 4)

These consists of submergent and para-emergent quartz arenites. The distinction between the two is made on geopetal features - wavy-bedded and massive for the submergent; festoon cross-bedded, rippled, *par descensum* veins (1) and mud-cracked for the para-emergent ones.

Petrographically though, the siliciclastics are virtually identical. They are black to dark grey quartz arenites varying in grain size from coarse through to fine sands. Bedding is usually on a scale of 5mm to 4cm. These sands are invariably grain-supported. The para-emergent ones are subrounded to rounded and well-sized. The submergent ones are subangular and often have authigenic quartz overgrowths. Both the emergent and para-emergent siliciclastics have an average 7-10 o/o potash feldspar and 7-10 o/o plagioclase feldspar. The feldspars seem to be a mix of authigenic and detrital. The para-emergent arenites have (locally) up to 10 o/o lithic fragments. Carbonaceous dust is ubiquitous throughout intergranular areas and within some feldspars (hence authigenic inference !). Minor components include carbonate grains, intergranular micas and detrital tourmaline. In the N2 and W1 (fig. 2) portions of the stratigraphy, some of these siliciclastics are distinctive by virtue of numerous, single authigenic dolomite crystals. Authigenesis has been inferred from the fact that the carbonate encloses quartz and feldspar grains. Generally these siliciclastics contain varying concentrations of disseminated euhedral pyrite, with more pyrite noted (7 o/o) in the submergent arenites.

ii) Carbonate Clastics (C1 and C2 on figure 4)

The carbonate clastics consist of dolomagnesitic packstones of intraclastic para-emergent origin, and channelled gravelitic and conglomeratic dolo-magnesitic detritus of tidal or ephemeral creek genesis. These channels characteristically occur as multistoried stacks.

They range from coarse sand or grit of dolomite grains; through rudites and gravelites of the same composition; to the same rocks with a magnesite component as well as a quartz sand component.

Macroscopically, this lithotope is a varigrained, granular rock. Microscopically, it consists of vaguely bedded, usually loosely-packed (i.e., matrix-rich) aggregates of sub-rounded to rounded and rounded-tabular grains, granules and pebbles. Clasts consist of dark grey cryptocrystalline dolomite, paler grey microcrystalline dolomite, grey arenite, white magnesite and/or dolomagnesite, and black argillite. Accessory detrital quartz sand averages 7-10 o/o. The matrix usually makes up 30-50 o/o of the carbonate clastic lithotope and is usually a crystalline mosaic of calcic-dolomite.

These rocks are of intraclastic and channel paragenesis. Some channels (base of N2; base of W1) are part of a well-developed tidal creek system, cut into inter- and supra-tidal algal bound carbonate mats of C2-type. Such features as cross-beds, pebble lag, channel-edge stopes, and chute sands have been logged in this carbonate-clastic lithotope. One channel in N2 is 30m wide by 3m thick and is exposed sinuously over 70m. This channel is stacked with other tidal creek channels.

b) Fine Terrigineous Lithotope (B2 and some B3 of figure 4)

This consists of carbonaceous argillites (or shales) and silty/sandy carbonaceous heterolites. The latter are a hybrid mix of the carbonaceous shale and the siliciclastic lithotope. The carbonaceous argillite or shales consist of ultrafine carbonaceous material, clays, and fine dolomite. Overall the shales are best described as dolocarbonaceous.

These rocks are characterized by 1-10 o/o pyrite in the form of extremely fine-grained disseminations. Both emergent (mudcracks, intraclasts, desiccation polygons) and submergent (horizontal laminations) subspecies of this lithotope are observed.

c) Carbonate Lithotope (in B1 and C2 of figure 4)

This is a carbonaceous impure (argillaceous, silty or sandy) dolomitic limestone facies. It is characterized by a fluted and etched weathering surface and is black where fresh. On the average, it consists of extremely fine near-black layers (60 o/o) averaging 5mm in thickness, with intercalated, generally thinner microcrystalline quartz-silt mosaics. The black layers are diffuse microcrystalline dolomite, dusted with carbonaceous material. There are several subspecies of the carbonate lithotope. These include submergent massive calc-dolomites, submergent biostromal calc-dolomites, para-emergent crenulated algal mats, para-emergent desiccated and intraclastic algal mats, and emergent cryptalgal groundwater-dominated dolomites with such features

(1) Stratabound discordant quartz, and quartz carbonate veins.

as teepees, healed teepees, mudcracks, and magnesitic intraclasts. There is a siliceous variation on this carbonate lithotope in N2 and W2.2. It consists of fine-grained black microcrystalline chert which has a widespread lateral persistence. Such blanket-like cherts are thought to be supratidal and may even be palaeosols.

The C1 lithotype is also variably cherty. A different interpretation for the origin of chert in this mixed carbonate-clastic lithotope is needed. The possibility of it replacing original sulphate is ruled out for the Camp Basin stratigraphy because of the lack of other evidence of palaeosalinity. In these cherts, up to 10 o/o of the chert consists of minute euhedra of magnesite and dolomite. Accessories are carbonaceous dust and sericite. The cherts occur as nodules, blebs and enterolithic bands. We think the model that explains these cherts is replacement of carbonate, which occurred in mixing zones between meteroic groundwater and Camp Basin depocentre connate waters.

Relatively porous and permeable shoreline sediments (B4–C2 type) which prograded over depocentre sediments of relatively low porosity/permeability (B1–B3 type) gave a groundwater mixing zone effectively confined to a narrow interval above these contrasting sedimentary suites. This mixing produced a narrow zone of silicification.

THE WARRA WARRA STRATIFORM COPPER PROSPECT

The geology and geometry of the Warra Warra Beds (figs 1 and 2) is shown in figure 5. The stratigraphy of the Warra Warra Beds at the Warra Warra copper prospect is :

W1 (5–140m) : This unit consists of stacked shallowing-up sand-carbonate cycles shown in figure 4, usually without the B1 component, but with well-developed C2 components. The arenites present in W1 are of the B4 and C1 type. Well-developed (tidal ?) channels are preserved in the C1 clastics of the W1 cycles. As "Tarltonia" is approached (figure 6), "A" intraclastic grits and mudchip conglomerates increase and give way shorewards to coarse calc-rudites.

W2 - WARRA WARRA CUPRIFEROUS LEVEL

These beds are divided into three units as follows :

W2.3 Hangingwall arenites : emergent
W2.2 Cupriferous & pyritic arenites : submergent
W2.1 Footwall clastics : emergent.

W2.1 - (0–40m) : This unit represents a clastic footwall for the main cupriferous horizon. It is composed

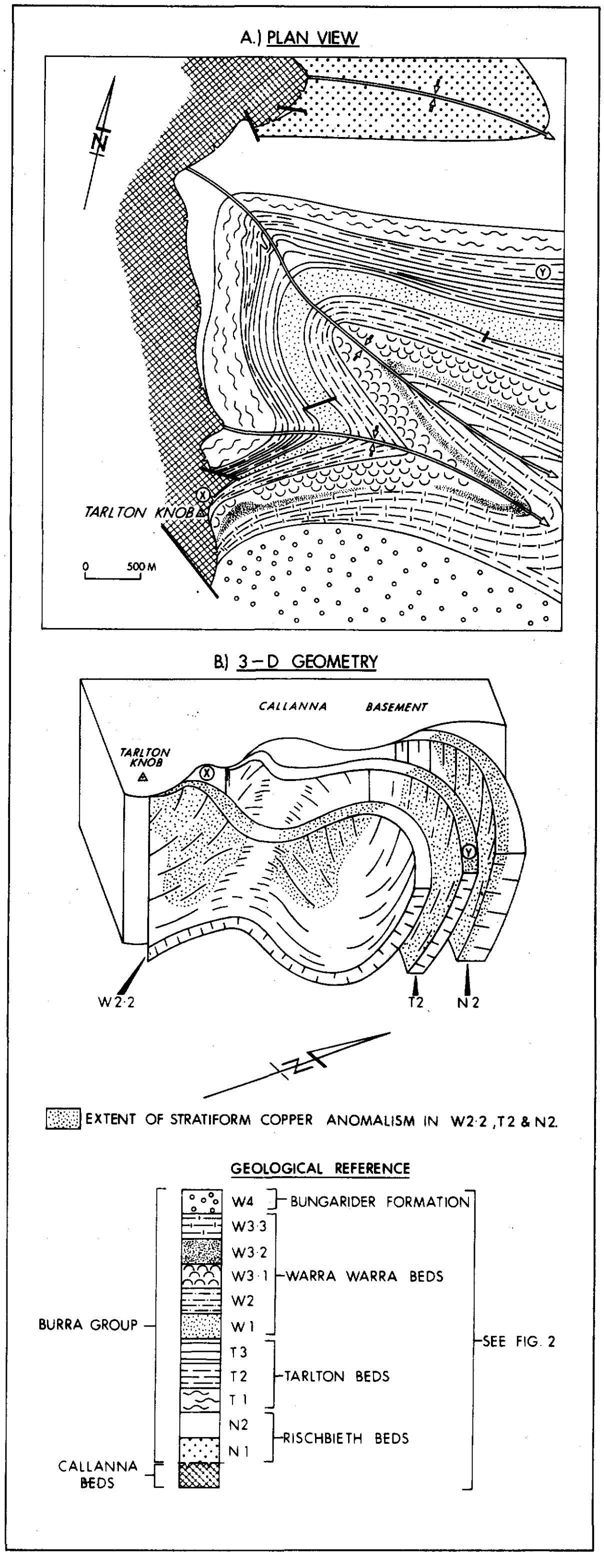


Figure 5.- Warra Warra Copper Prospect, Geology & Geometry

primarily of sub-components B3, B4 and C1 (fig. 4). Geopetal features especially characteristic of this level are intraclastic calc-grits and calc-rudties, bevelled ripples, rill marks, spectacular desiccation cracks and trough-oriented crossets in lenticular arenites. These features all point to an emergent siliciclastic facies being deposited synchronously with emergent muds. The upper part of W2.1 is characterized by disseminated pyrite.

W2.2 (10–40m) : This is the Warra Warra stratiform copper horizon. The average thickness in the prospect area is 30m. It has been divided into six sub-units as follows :

SUBDIVISION OF W2.2 COPPER UNIT

W2.2	W2.2.6	Non-sulphidic, feldspathic arenite (4–14m). (C1).
	W2.2.5	Cupriferous dolocarbonaceous arenites of B3 type (7-9m).
	W2.2.4	Siliceous arenite locally green chert (2m). (C2).
	W2.2.3	Pyritic dolocarbonaceous (ex-saline ?) arenites (2-7m). (C1).
	W2.2.2	Cupriferous carbonaceous arenites of B4 type (3-5m).
	W2.2.1	Black pyritic chert and chertified arenite (0.25-3m) (C2).

The W2.2 stratigraphic unit is a fine to medium-grained dolocarbonaceous heterolithic submergent siliciclastic of B3 and B4 type (as in fig. 4). It does contain some local evidence of emergence.

W2.3 (0–100m) : This is a medium-grained pyritic horizontally laminated quartzose arenite with desiccation cracks indicating its partly emergent paragenesis (i.e. of C1 type in fig. 4). It thins markedly towards Tarltonia (fig. 6) and oversteps W2.2 in this direction.

W3 : This section has been divided into (fig. 2) a basal unit (W3.1) consisting of shallowing-upward cycles with submergent stromatolites at their base (fig. 4), overlain by an emergent siliciclastic unit (W3.2), which is in turn capped by shallowing-upward, largely intertidal cycles (W3.3) (i.e. devoid of B1 to B4 components). The W3 unit is characterized by its dolomitic nature, its stromatolitic nature and its sedimentary cyclicity. A whole range of stromatolite morphologies have been recorded in this unit (generalized in fig. 6). The most common form is linked domical mats (inferred to be submergent), followed by crenulated mats (inferred to be para-emergent or intertidal). Single algal heads (classified as small bioherms in fig. 6) are much more restricted in their development. These small bioherms are up to 25cm high and 50cm wide. Near the palaeo-shoreline (i.e. Tarltonia in fig. 6) large (3m high by 3m in diameter) linked dominical colonial bioherms are associated with channel calc-rudites.

Individual B1 (fig. 4) stromatolite beds are never thicker than 1-3m. Submergent paragenesis for the linked domical mats and biohermal heads is inferred from : their height; their high degree of vertical inheritance; the absence of marked erosive surfaces on algal head crests; an A-type (fig. 4) footwall; and a B2-type (fig. 4) hangingwall.

Intraclastic dolo-rudites and dolo-gravelites are common in W3.1 and W3.3. They are ascribed the following paragenesis : desiccation and cracking of a mat or bioherm on exposure, followed by resorting of the desiccated clasts (by tidal currents ?). Oncolites are common in some channels near the bioherms.

PALAEOGEOGRAPHY OF WARRA WARRA COPPER PROSPECT (fig. 6)

The Callanna Beds were uplifted and moderately deeply eroded before the onset of Burra sedimentation. From the rates of thinning of sediments towards Tarltonia (e.g. W2.2 thins from 40m to 10m in ± 1.8km, figs. 5 and 6), these pre-Burra uplands must have been quite rugged.

The basal Burra paralic (or lacustrine) water body encroached on the Warra Warra copper prospect area (figs. 1 and 5) from the east and northeast. This transgression finally halted with its shoreline oriented roughly north-south and passing through Tarlton Knob (fig. 1). The T2 rudites near Tarlton Knob (fig. 6) represent a braided fluvial plain over which W1 and W2.1 were transgressively deposited. Further sinking and transgression resulted in the submergent W2.2 copper event, followed by an emergent siliciclastic period of sedimentation (W2.3).

In W3 time most clastic input ceased; this cessation coinciding with a bloom in algal growth in the shallowing Warra Warra repository. By W3.3 time, shallowing had resulted in an emergent style of carbonate sedimentation which became covered by blanket-style siliciclastics in W4 time. The siliciclastic beds resulted from arenites being fed into a strike system (e.g. strandplain) as a result of wave-domination of a delta.

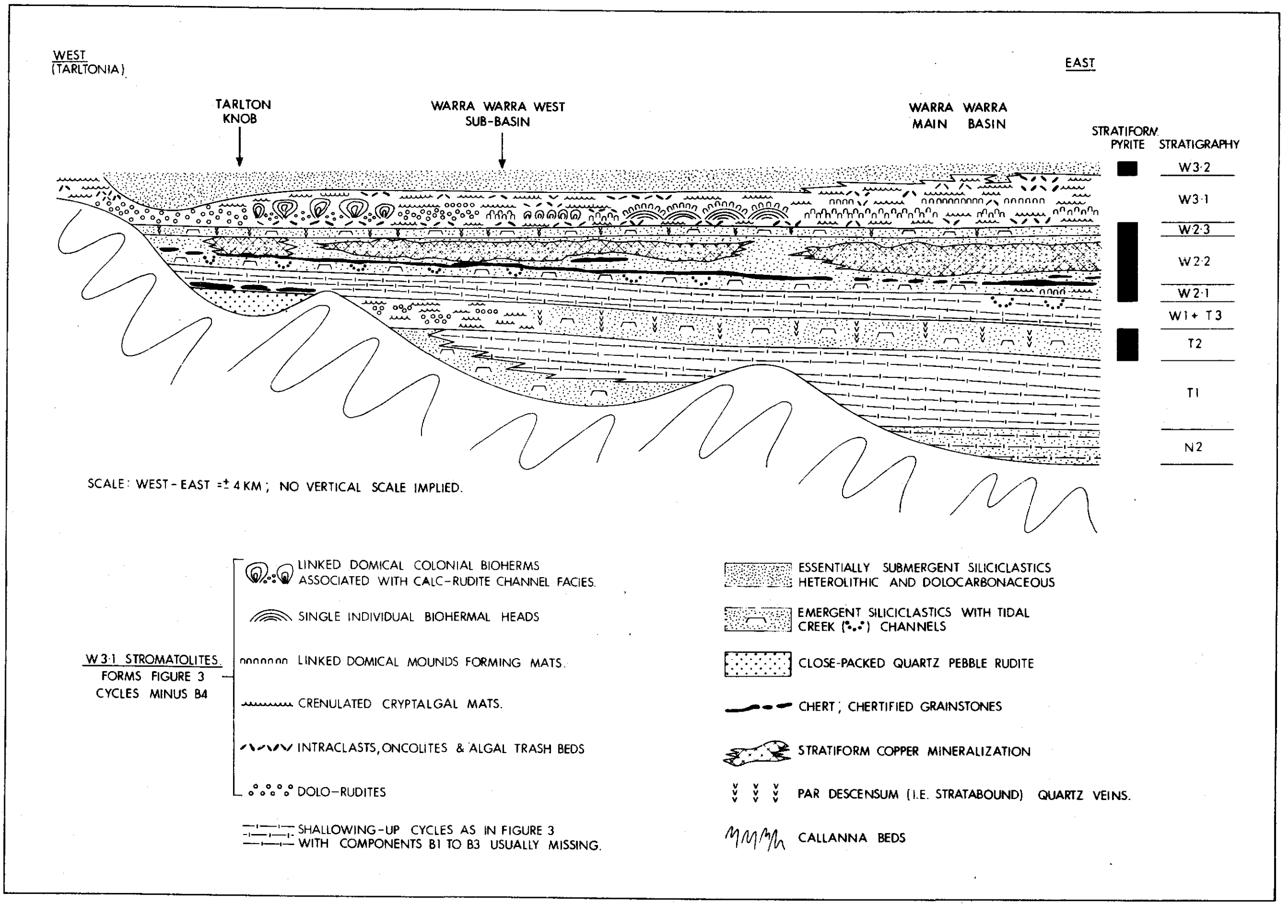


Figure 6.- Palinspactic Section Warra Warra Copper Prospect

TOWARDS A MODEL FOR STRATIFORM COPPER

In an attempt to associate above background copper assay values with a vertical profile subtype, we used Lombard's idea (LOMBARD, 1972; NICOLINI, 1962, 1964, 1970) of translating rock sequences into numerical sequences. This is done by associating each recognizable lithotope with an integer selected on the basis of the lithotope granulometry. The resulting classification of a stratigraphic sequence by integer class is called a Lombard curve which, when plotted graphically, becomes a "previsionelle" diagram (NICOLINI, 1962, 1964). Regretably, this simplifying technique is little used by Anglo-Saxon geologists.

In essence, a sedimentary sequence can be broken down into palaeoenergy domains by compiling previsionelle diagrams. We compiled previsionelle diagrams for drill holes into the Burra sediments and classified the Lombard curves on these diagrams into the 8 subtypes shown on Table 1.

Three types of sequence were mineralized with stratiform copper. These, together with their hangingwall and footwall variations are shown on Table 2.

From this table :

a) Twenty-four percent of the copper signals were hosted by negative sequences, with the most common hangingwall and footwall to this anomalism being a positive sequence.

b) Thirty-three percent of the copper signals were hosted by positive sequences, most commonly bracketed by negative sequences.

c) Forty-three percent of the copper signals were hosted by an I-sequence, with the most common footwall being a positive sequence and the most common hangingwall being a negative sequence.

Table 1.- Specification of Vertical Profile - Classification Criteria

1. Lombard Curve Subtypes

Submergent I-sequences
Emergent I-sequences
Steeply sloped positive sequences
Moderately sloped positive sequences
Flatly sloped positive sequences
Steeply sloped negative sequences
Moderately sloped negative sequences
Flatly sloped negative sequences

2. Definition of "Normal" Vertical Sequence

Negative Sequence Positive Sequence I-Sequence	deviations from this sequence were classified as TRUNCATIONS

3. Definition of Interruption Points on Lombard Curves

i) On a positive sequence	=	Negative blips
ii) On a negative sequence	=	Positive blips
iii) On a submergent I-sequence	=	Negative blips
iv) On a paraemergent I-sequence	=	Positive blips

4. Definition of a Positive Copper Signal

Taken as 0.5 m $^{o}/o$ in the primary zone.

5. Sequence Definition

i) I-Sequences : defined by vertical continuity of the Lombard Curve of over 15 m in any one integer class (non-variant energy domain).

ii) Positive Sequences : defined by continuous passage of the Lombard Curve to higher classes (diminishing energy domain).

iii) Negative Sequences : defined by continuous passage of the Lombard Curve to lower integer classes (increasing energy domain.

iv) These three sub-types were classified in one of 8 Lombard sub-types (as per "1" above); and subclassified as "normal" ("2" above); truncated or interrupted ("2" & "3" above).

v) 75 Burra "positive copper signals" were then associated with their host vertical profile to produce table 2.

Table 2.- Outcomes for Analysis of Cupriferous Vertical Profiles - Burra Group

	o/o Total of Positive Cu signals
a) Negative Sequence as stratiform copper host :	
Footwall I-sequence; hangingwall I-sequence	1.6
Footwall I-sequence; hangingwall positive sequence	4.7
Fottwall positive sequence; hangingwall positive sequence	15.6
Footwall positive sequence; hangingwall I-sequence	2.1
	24.0 o/o
b) Positive Sequence as stratiform copper host :	
Footwall I-sequence; hangingwall I-sequence	2.1
Footwall I-sequence; hangingwall negative sequence	10.9
Footwall negative sequence; hangingwall negative sequence	12.1
Footwall negative sequence; hangingwall I-sequence	7.8
	33.0 o/o
c) I-sequence as stratiform copper host :	
Footwall positive sequence; hangingwall positive sequence	12.5
Footwall positive sequence; hangingwall negative sequence	19.6
Footwall negative sequence; hangingwall negative sequence	3.1
Footwall negative sequence; hangingwall positive sequence	7.8
	43.0 o/o

d) No. of positive signals in dataset = 75

d) Table 2 also shows that these classification criteria were applied to the Lombard Curves of 75 stratiform copper prospects in the Burra Group.

e) In summary, the most common Burra host sequence profile type for stratiform copper is :

	Lombard Curve Type	Depositional Association (Table 3)
Hangingwall	Steep Negative Sequence	Braided channel sands
Host	I-sequence	Stillstand sand or cyclic submergent heterolite (2)
Footwall	Steep positive sequence	Cyclic emergent heterolites & blanket carbonates.

We can therefore state that this is a model vertical profile for a stratiform copper system anywhere in the Burra Group. Furthermore, steep positive footwalls should ideally be thin, and steep negative hangingwalls should be terminated by interruption or truncation (as defined on Table 1). Of the 75 stratiform copper intersections (defined on Table 1; classified on Table 2; and idealized in the above model vertical profile) forty-three percent were hosted by I-sequences. Furthermore, sixty-eight percent of these mineralized Burra I-sequences were of the subtidal type. Eighty-nine percent of these cupriferous subtidal I-sequences were wholly clastic; the remaining eleven percent were of a mixed chemo-clastic type. None were of the wholly chemical type.

(2) Heterolite : rock consisting of small scale (less than 1 cm) intercalations of sand, silt and shale.

Table 3.– Depositional Associations, Late Proterozoic Stratigraphy, Willouran Ranges

STRATIGRAPHIC LEVEL	CALLANNA BEDS						BURRA GROUP: WEST SUB–BASIN	BURRA GROUP: CAMP SUB–BASIN							BURRA GROUP: EAST ROOKS SUB-BASIN	UMBERATANA GROUP	
SEDIMENTARY ASSOCIATION \ STRATIGRAPHIC SUB-UNIT	R	WR	BS	WU	EC	H	NW	W	T	N	F	E	WW	TW	ER	B	W4
ENTROPIC CLASTIC WEDGE	●	●	●	●	●	●											
RIVER-DOMINATED DELTAIC															●	● ♀	
WAVE-DOMINATED DELTAIC							●			●					•		●
STILLSTAND SAND	●					•	×	• ♀	• ♀	• ♀		•	• ♀		•	● ♀	•
LABILE WEDGE ARKOSE			•	• ♀					•			●		•	●		
BRAIDED CHANNEL SAND				×			•	•	• ♀	• ♀	•	•	●	•		•	•
EPHEMERAL CREEK DOLOCLASTICS							•	•	•	•		•	×	×			
BLANKET LIMESTONES	● ♀						●							●	●		
BLANKET DOLOMITES		• ♀		● ♀			●	●	•		●	•	●	•	●	•	
RANDOM PATCH CARBONATES										•			×				
CARBONATE BANKS	●			•													
CYCLIC SUBMERGENT HETEROLITES		●	• ♀	●	•			● ♀	● ♀	• ♀	● ♀	×	• ♀	•	●		
CYCLIC EMERGENT HETEROLITES	● ♀			•	•	•	●	●	●	●	●	●		•	●		
SULPHATE SABKHA	● ♀	● ♀	●	●	•		•	•							• ♀		
CHLORIDE SABKHA	●	● ♀	●	•	●	●									×		
SILICICLASTIC SABKHA	•							• ♀	•	•		×	×		• ♀		
COORONG (LACUSTRINE)							●	●	●	●	●	●	×	•	×		

● SIGNIFICANT • MINOR × INFERRED ♀ CUPRIFEROUS SEDIMENTARY ASSOCIATION IN WILLOURAN RANGES

		STRATIGRAPHY	FORMATION NAME	
UMBERATANA GROUP		B		
BURRA GROUP	ER + NW	W = F = TW	WARRA WARRA BEDS	SEE FIGURE 2
		T = WW	TARLTON BEDS	
		N	RISCHBIETH BEDS	
CALLANNA BEDS		WR, BS, WU	WEST ROOK'S BEDS	
		R, EC, H	ROOK'S BEDS	

Table 4.– Characteristics of Stratiform Copper Levels – Adelaide Supergroup – Willouran Ranges

Stratigraphic Level	Description of Strati-form Cu Interface	Hinterland Behaviour	Dominant Cu Control	Host Association Geometry	Association Cyclicity	Association Type
Umberatana (Interglacials)	Clastic–laminite	Accelerating Uplift	Hydrology	Lentiform wedges	None	Dip system
Basal Burra	Clastic–chemical	Pivotal from accelerating to decelerating	Biology (algal)	Blanket–like	Multistoried fig. 4 cycles	Humid strike system
Callannas	Clastic–evaporative	Stable	Salinity	Blanket–like & lentiform	Stacked arid humid phases	Arid strike system

SUMMARY OF THE BURRA STRATIFORM COPPER HOST MODEL

We can say therefore :

1. The host horizon is a quiescent sublittoral clastic stillstand.
2. The immediate footwall is a fining-upward and shallowing upward cycle, i.e. an "uplap regression" that surely has to be read as a desiccating lake.
3. The immediate hangingwall is a coarsening-upward and emergent siliclastic (locally containing displacive salines), a prograding regression, with confusing paralic overtones.
4. The regional hangingwall is a stromatolitic impure dolomite. Sedimentary associations (figs. 2, 4 and Table 3) suggest this lithotope could have resulted from lacustrine highstands (SURDAM *et al.*, 1975 and 1979).
5. The regional footwall is a blanket-like, once permeable, usually labile siliciclastic. Sedimentary associations (figs. 2, 4 and Table 3) suggest this lithotope is due to strike feeding by wave domination of small deltas.

DEPOSITIONAL SPECTRUM FOR STRATIFORM COPPER HOST ROCKS

With this stratiform copper model for the Burra in mind, we would like to examine stratiform copper depositional systems in the Callanna Beds and Umberatana Group for comparison. Although all three groups host stratiform copper (ROWLANDS *et al.*, 1978b); the respective host associations are quite different.

This is illustrated in Table 3 in which those depositional associations that are known to host stratiform copper mineralization are indicated. This mineralization is in the range of 0.3 o/o Cu to 4.4 o/o Cu in the primary zone. It is mainly chalcopyrite and is associated with pyrite. Mineralized thicknesses range from 5 to 35 metres.

A full description of the sedimentary associations in Table 3 is given in the Appendix.

It now becomes clear that copper occurs at a different type of interface in each of the three groups. We have summarized the copper models to show their differences in Table 4 :

a) Callanna Stratiform Copper Model

Copper mineralization in the Callanna Beds occurs at a **clastic-evaporative** interface representing the change from stillstand sands, or labile wedge arkoses (Table 3) to sabkhas. The majority of Callanna sedimentation was in sabkhas and/or playa lakes (ROWLANDS *et al.*, 1979). The Callanna Beds in the Willouran Ranges represent a zone across which a pro-grading sabkha belt left cupriferous levels (Table 3).

The Callanna Beds depositional association (Table 3) is one which equates with the evaporite-associated stratiform metalliferous deposits of RENFRO (1974). As such it is a strike system.

b) Burra Stratiform Copper Model

Copper mineralization in the Burra Group occurs at a regional **clastic-chemical** interface, representing the change from wave dominated sand blankets to cyclic (non-saline) algal lake (or at times paralic) sediments. The blanket-like geometry of both the underlying and cupriferous Burra sediments points to it being a strike system, albeit a different strike system than the Callanna cupriferous event.

The fact that the Burra stratiform copper occurrences sit athwart a clastic chemical interface representing cessation of siliciclastic input from a hinterland that was in a decelerating uplift phase is also fundamental to mineralization at this level.

c) Umberatana Stratiform Model

Copper mineralization in the Umberatana Group (the "Interglacials" type of ROWLANDS, 1978b) occurs at a **clastic-laminite** interface representing the change from a river-dominated delta to prodelta and shelf muds.

This interface marks the conclusion of the surge of fluvio-deltaic activity of the first great Adelaidean ice age. The copper at this level is a dip system characterized by straight non-entrenched elongate multistoried and multilateral sands and gravels with a siliciclastic overbank facies.

CONCLUDING REMARKS

The three stratiform copper models above are a saline strike system, a non-saline strike system, and a dip system. We think they must represent a continuous spectrum for stratiform copper host-rock depositional environments, and it is interesting to speculate why copper fixation moved across this spectrum with geological time.

As explorationists we have to discover the great simplifying inferences that rationality tells us should underlie the present disposition of orebodies and mineral occurrences. We seek a fundamental understanding, a grasp of some underlying pattern in the hope that this will enable us more easily to answer the vexing daily question of "where ?"; where to undertake the next reconnaissance, where to take the next set of geochemical samples; where to put the next drill hole ? We have, on a previous occasion, gently chided some of our profession for a too great concern for answering the question "why" in relation to orebodies, and suggested that, at the present state of geological knowledge, pattern recognition (gitology) in relation to orebodies is the more appropriate methodology (ROWLANDS *et al.*, 1978b).

As data accumulates, however, the recognition of pattern becomes a more complex matter, and we find in the instance here described, that while we feel confident in the recognition of prospective patterns at the detailed level, we can claim no such security at those larger, grander scales that produce memorable epilogues to paper such as this.

At the scale of an individual outcrop, for example, the disposition of copper will clearly reflect lithology or a single fine stratigraphic unit, while at the scale of a particular prospect, the copper will be trapped in a sedimentary rock association, and at the scale of a basin, it may be a series of such associations whose links to each other (as in the case here illustrated) appear tenuous and ill-defined. However, at the scale of the world as a whole, the distribution of copper in stratiform deposits would appear to be overwhelmingly dominated by position in the time scale.

Put in a slightly different way, we have a heirarchy of scales and a heirarchy of influences. For the 1 metre of stratigraphy of the single outcrop, the influence of lithology dominates. Somewhere between the 1 metre section and the 1 km thick section of sediment, other influences dominate, but a series of sedimentary rock associations, which can be described in some detail and can be placed by analogy in reasonably well understood modern sedimentary environments, are clearly more prospective than others. At larger scales again (100 km of section, say), the control is very clearly one of time.

For the active explorationist who is constrained by the realities of an exploration budget, the key issues are generally in which basin shall I look, and where in the chosen basin shall I concentrate my efforts. Both choices fall in that part of our heirarchy of influences which are most equivocal.

If the choice of "which basin ?" has already been made by engineering, political or other parameters, or by the serendipity and the dart-throwing skill of the Exploration Manager, the explorationist in charge of the project is now confronted by the second, even more difficult choice of "where within the basin ?" The most basic consideration of a process that takes copper from a hinterland and places it in sheet-like bodies in a pile of sediments in a depository suggests that four parameters must be significant :

1. The metal content of the source area.
2. The weathering and erosion history of the source area.
3. The palaeogeography of the depository.
4. The physical, chemical and biological conditions at various places within the depository.

The single unifying thread of at least the first three of these parameters is "Energy", and it has been consideration of this factor that led us to attempt the "energy-processing" (Lombard curves and previsionelle diagrams) of the Burra cupriferous profiles in this paper.

The choice of energy dependent variables as the ones to be measured is not of course taken lightly, nor is it final. Not all the influences present at the time of copper deposition are kind enough to leave a legible record for the hard pressed explorationist. Climate was almost certainly a very powerful influence, but it leaves only a very indistrinct and broad sedimentary record. The sedimentary provenance and its intrinsic copper richness is also an extremely difficult parameter to determine in any way that is useful - after all, the "provenance" rocks that provided the copper presumably finished up as sediment in the basin along with the copper they once contained.

We have described the shift with time of copper fixation through a spectrum of depositional environments, as the South Australian Adelaidean was deposited and the localization of copper took place in specific sedimentary rock associations in the Callanna Beds, and in the Burra and Umberatana Groups. We do not feel able to offer an explanation of this phenomenon and can only ask for input from others who have analagous results, or who can help to coax the fundamental controls from beneath their camouflage of more flamboyant detail-scale metallotects.

We have here presented three variations on a stratiform copper theme : a saline variation (in the Callanna Beds), a biological variation (in the Burra Group), and a hydrological variation (in the Umberatana Group). We admit that we have not been able fully to discern the theme and we suggest that part of the reason may be a too great adherence to Lyell's dictum that the present is key to the past. We clearly do not have good present day analogues of these copper depositing systems.

We know that Late Proterozoic was characterized climatically by marked perturbations of rainfall and temperature (including ice ages), that it was characterized tectonically by rifted intracratonic basins, and that it was broadly a period of transition biologically and (?) atmospherically.

In view of recent speculation linking Pleistocene temperature and other changes to the earth's traversing an inhomogeneous galaxy (see for example GRIBBEN, 1977), maybe we should be seeking a fundamental framework in the new cosmology.

Perhaps after all we should seek our theme in the music of the spheres.

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APPENDIX - Description of Table 3

The sedimentary associations on this table are explained as follows :

Entropic Clastic Wedge Association : This applies to wedge-shaped, sub-sheeted exotic breccia facies. It is an olistostrome with sedimentary and basic igneous olistoliths generated by catastrophic, episodic graben-floor foundering in Callanna time.

River-Dominated Deltaic Association : This consists of lenticular sediments of cratonic interior derivation which (in contrast to the entropic clastic wedge association) thicken in the direction of sediment transport and the direction of reduction of average particle size. It is best developed in the basal Umberatana Group, where gravelites of this association host stratiform copper mineralization. This is the only dip-system, depositional association in the Willouran Ranges associated with stratiform copper.

Wave-Dominated Deltaic Association : This has produced blanket arenites by wave-domination feeding the deltaic arenites along strike. Its development is confined to the base of the Burra (N1 fig. 2 and tab. 3). It is not a host stratiform copper for anywhere in the area shown in figure 1. However, it does form a permeable, sometimes labile footwall close to mineralized levels in the Burra Group.

Stillstand Sand Association : This has the same geometry as the wave-dominated deltaic association, but is characterized by mature well-winnowed arenites representing reworking along strandlines.

It shows (tab. 3) significant volumetric development in the Callanna Beds, where it is barren; significant volumetric contribution to the Umberatana Group where it is a stratiform copper host; and minor development in the Burra Group where it is only cupriferous in the Camp (fig. 3) Basin (e.g., W2, fig. 6).

Labile Wedge Arkose Association : This depositional association consists of lenticular arenites, rudites and litharenites in the classical regional-scale I-sequence position of a Lombard curve (NICOLINI, 1970). A good example of it is shown developed in T2 in figure 6 infilling a palaeovalley near Tarltonia. This association hosts stratiform copper mineralization in the "WU" analogues of the Callanna Beds (tab. 3). Elsewhere, it is barren.

Braided Channel Sand : Although this depositional suite has a similar lithology to the stillstand sand, it has a different geometry in that it consists of multiple, clean, festooned-and-stacked lenticular arenite wedges. Its only significant development (tab. 3) is in the "WW" facies of the Tarlton Beds (fig. 2) of the Burra Group where it is barren. However, its minor development (tab. 3) in the T2 and N2 units (fig. 2) is host to stratiform copper mineralization.

Ephemeral Creek Doloclastics : This sedimentary association is developed only in the Burra Group. It is not mineralized anywhere in the Willouran Ranges. It represents parts of the C1 and C2 lithotopes in figure 4.

Blanket Limestones : This association shows major development in parts of the Burra and in the "R" subunit of the Callannas (tab. 3). This latter unit is host to stratiform copper mineralization in an impure limestone.

Blanket Dolomites : This depositional lithotope shows significant volumetric contribution to the Burra Group and (locally) to the Callanna Beds stratigraphic make-up. The association hosts stratiform copper in the "WR" and "WU" facies of the Callannas (tab. 3). Both blanket carbonate associations include laminated, cryptalgal and algal textures. The major development of this association in the Burra Group at Warra Warra (figs. 5 and 6) permits significant palaeogeographic interpretations. At Warra Warra it forms the main hangingwall to the cupriferous stillstand sands and cyclic submergent heterolites of W2.

Carbonate Banks : This association (tab. 3) is only a major component of the "R" unit of the Callanna Beds. It is inferred to be of offshore shoaling paragenesis, barren and dolo-calcareous.

Cyclic Submergent & Emergent Heterolites.

These two associations comprise the major portion of the Burra Group stratigraphy. They are cyclically intercalated blanket-like sands-muds-carbonates, an idealized cycle of which is shown in figure 3. They are characterized by being dolomitic, carbonaceous, and algal in all three Burra sub-basins (fig. 3). The East Rooks basin has the additional characteristic of a saline overprint, while the Western basin is magnesitic and lacks the submergent component.

Stratiform copper is hosted by the submergent heterolite cycles (tab. 3) in shales, sands and dolosilts in the Burra. In the Callannas, the submergent heterolite hosts stratiform copper in the "BS" unit, while the "R" unit contains emergent cycles which host stratiform copper.

Various Sabkhas : This evaporite association is a volumetrically significant component (tab. 3) of the Callanna stratigraphy only. It hosts stratiform copper mineralization as shown on table 3. The siliciclastic sabkha association includes cherty rocks which table 3 shows are cupriferous in the Warra Warra and Rischbieth Beds (figs. 2, 5 and 6).

Coorong (Lacustrine) : This depositional system represents a humid lacustrine phase. It is characterized by abundant dolomite and magnesite and cyclically emergent geopetal features. It is fairly widely developed in the Burra Group and nowhere mineralized.