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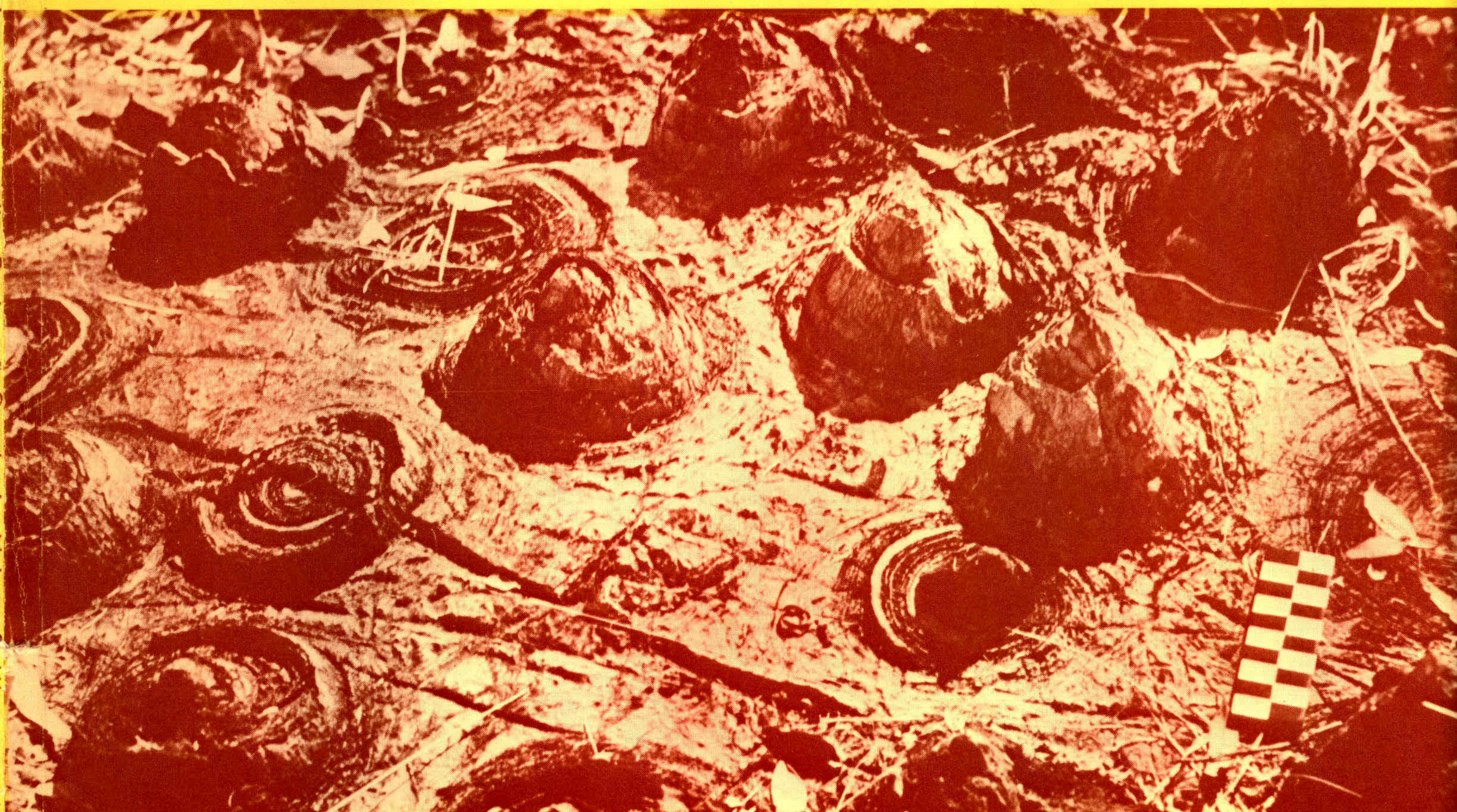

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Front Cover:

Stromatolites from the Tooganinie Formation, 10 km NNW of old Tawallah homestead, Bauhinia Downs 1:250 000 Sheet area, McArthur Basin, Northern Territory. Some of the conical columnar stromatolites (*Conophyton* sp.) have weathered out to give an impression of what they looked like during growth.

Work in the McArthur Basin will intensify this year with the start of BMR's multi-disciplinary McArthur Basin project. In this the evolution of the basin will be studied, using a variety of approaches. The data obtained will be applied to the genesis of, and exploration for, ore deposits in the region.

Photograph: M. R. Walter

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Implications of Australian seismic and gravity measurements for the structure and composition of the upper mantle

J. C. Dooley

In a previous paper densities of crustal layers were inferred from seismic refraction surveys in Australia and surrounding marine areas. These indicated substantial variations in crustal mass. As the free-air gravity field does not show anomalies corresponding to these, it is inferred that compensating mass variations must occur in the upper mantle. Sub-crustal mantle densities, inferred from P_n velocities, in general do not provide the required mantle mass distribution; however in some parts of the continent observed increases in seismic velocity at depths of 60 to 100 km suggest density changes which would lead to approximate compensation at about 130 km depth, corresponding to the top of a low-velocity layer suggested by surface wave studies.

Marine crustal masses are reasonably close to a common value, but the wide variation of P_n velocities implies a corresponding variation of densities which would counteract this compensation if they persisted in depth. It is suggested that the P_n velocities represent comparatively thin layers, and that deeper density changes occur so that compensation takes place at 80 to 100 km, at the top of the sub-oceanic asthenosphere.

The West Australian shield has the highest crustal mass, and also the highest P_n velocity, which implies a further relative increase in mass with depth. If the sub-shield mantle is assumed to consist of refractory peridotite with a relatively low density corresponding to its P_n velocity, the discrepancy in crustal mass with respect to the other areas is reduced with increasing depth, but is still not eliminated at depths less than about 160 km.

This suggests that the sub-shield mantle above this depth has enough strength to support the differential pressure associated with the excess crustal mass. This conclusion is in accordance with other evidence, suggesting that sub-shield or sub-continental mantle differs from sub-oceanic mantle to depths of several hundreds of kilometres, and hence that the return flow compensating for plate-tectonic motions cannot take place at depths of 100 to 200 km, as often supposed.

Introduction

In the theory of plate tectonics as originally proposed, and in the form of the theory most widely accepted currently, it is postulated that the outer shell of the earth or lithosphere consists of a number of rigid plates in relative motion with each other; these are formed by cooling of material extruded at the mid-ocean ridges, and they sink into the mantle at subduction zones, mainly at ocean trenches. The process of extrusion and subduction and accompanying plate motions requires a return flow of material at depth in the opposite direction to the plate motions. The return flow is postulated to take place in a world-wide asthenosphere, which has the properties of viscous behaviour and very little strength, for geological periods of time of the order of millions of years. The asthenosphere also acts as a zone of decoupling between the lithospheric plates and the deeper mantle.

The lithosphere is generally believed to be about 75-100 km thick (Le Pichon, 1968; Isacks *et al.*, 1968; Morgan, 1968; Green & Liebermann, 1976; Bottinga & Allegre, 1976), and the asthenosphere is taken to extend to about 160 to 200 km depth, where an increase in seismic velocity to about 8.7 km/s commonly occurs. The seismic velocities in the asthenosphere are presumed to be lower than those in the mantle below and the lithosphere above, which makes its range of depth and velocities difficult to define.

Because the asthenosphere by its nature cannot withstand significant stresses over geological periods of time, it is expected that if lateral mass variations occur in some part of the lithosphere, the asthenosphere will flow so that on a broad scale the resulting hydrostatic pressure is equalized, i.e., that isostatic compensation takes place at the base of the lithosphere (if not at some higher level).

The gravity field of the Earth shows only relatively small free-air or isostatic gravity anomalies on a broad scale, particularly in the stable parts of the Earth. This implies that isostatic compensation does occur, though the depth at which it occurs, and the degree to which compensation is local or regional, cannot be determined uniquely from gravity data alone.

Seismic refraction surveys provide data on crustal velocities and layer thicknesses. These data have been used, in conjunction with an empirically based density-velocity relation, to estimate a density-depth structure for the crust, and hence a pattern of crustal mass variation, over Australia and surrounding marine areas (Dooley, 1976). This is specified as the deficiency in mass per unit area of a standard crustal column with zero elevation, with respect to mantle material of 3.32 t/m^3 extending to sea level. This column is considered to be in isostatic equilibrium with the actual crust if its free-air residual anomaly were zero; i.e., the residual anomalies are assumed to represent small departures from isostatic equilibrium, which are corrected for in calculating the standard crustal column.

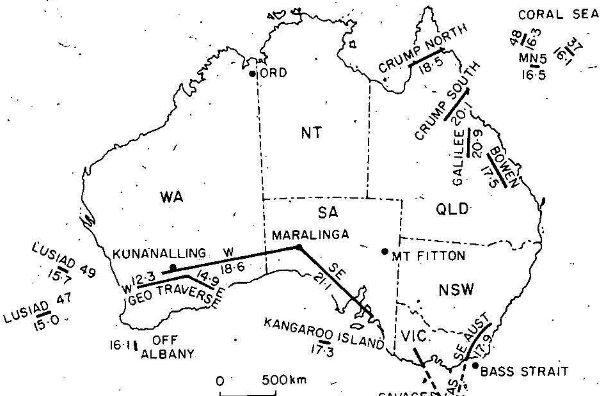

Figure 1. **Location of seismic refraction surveys and values of crustal mass deficiency (modified from Dooley, 1976).**

The crustal mass deficiency (CMD, Figure 1) is lowest (12.3 kt/m²) in the shield area of Western Australia, and highest (up to 21 kt/m²) in northeast Queensland. Marine values range from about 15 to 17 kt/m².

The variation over the Australian continent if uncompensated would give rise to isostatic anomalies of about 300 mGal; as free-air anomalies averaged over broad areas are a good approximation to isostatic anomalies, variations of about this magnitude should occur in the free-air field averaged over say 3° × 3° or 5° × 5° areas; the maps prepared by Dooley (1974) show variations of only about 60 to 70 mGal in the regions concerned. Most of this variation is accounted for by spherical harmonics of degree 16 or less, generally supposed to be due to deep mantle density variations. Thus one expects to find a mass distribution below the crust providing nearly complete compensation for the crustal mass variation. The objective of this paper is to investigate some features required for a suitable lithospheric mass distribution, and the implications for the depth of the asthenosphere.

Sub-crustal lithospheric mass distribution

The density of the mantle immediately below the crust was estimated from the measured seismic velocities (Dooley, 1976, Tables 1 & 2). On the assumption that this density is representative of the material for some depth into the mantle, the accumulation of mass with depth beneath each standard crustal column can be calculated. Again this mass has been referred to that of a standard mantle with density 3.32 t/m³; if the actual mantle is lighter than the standard, the mass deficiency, denoted by M, will increase beyond the CMD value with depth; if the actual mantle is heavier, M will decrease with depth, according to the formula.

$$M(z) = M(H) + (3.32 - \varrho_m)(z - H) \quad \ldots (1)$$

where z is depth below sea-level.
H is depth to base of the crust.
ϱ_m is mantle density estimated from P_n velocity.

In Figure 2 (Continental) and Figure 3 (Marine) the CMD values are plotted against H for each survey area. The CMD values used here (Table 1 and Figure 1) differ slightly from those given in Figure 2 and Tables 1 and 2 of Dooley (1976); the latter were corrected for free-air gravity anomaly to produce a hypothetical standard crust representing isostatic equilibrium conditions. Here the CMD is calculated for the actual crustal mass, without the gravity correction. Using this as the starting point, the mass deficiency in the mantle is plotted as a function of depth in accordance with (1).

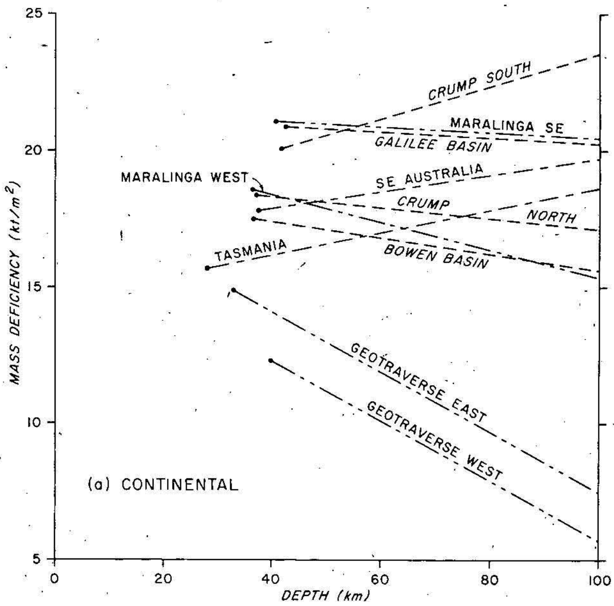

Figure 2. Mass accumulation with depth based on P_n velocities—continental.

The mantle density need not remain constant with depth, so that Figures 2 and 3 represent a hypothetical situation. The velocity-density empirical relations are generally supposed to hold, within the limits of their accuracy, for variations caused by temperature and pressure, and to a large extent for variations in rock type. An exception to the latter is the systematic change with mean atomic number shown by Birch (1961), to be discussed further below. The effects of increasing temperature and pressure are in opposite directions; the net effect depends on the temperature gradient, and is small for the range of depths discussed here. For the part of the lithosphere below the crust, it is assumed for the present that change of density with depth is the same for all sites, so that we may take the straight lines in Figure 2 to give a reasonable representation of the relative mass deficiencies at any depth z in the lithosphere, assuming no change of composition with depth.

Abbreviation	*Survey*	*H* km	*M(H)* kt/m²	P_n km/s	ϱ_m t/m³
Continental					
GTW	Geotraverse west	39.7	12.3	8.34	3.43
GTE	Geotraverse east	32.6	14.9	8.34	3.43
MW	Maralinga west	36.2	18.6	8.16	3.37
MSE	Maralinga southeast	40.4	21.1	8.00	3.33
SEA	Southeast Australia	37.5	17.9	7.85	3.29
TAS	Tasmania	27.6	15.7	7.84	3.28
BB	Bowen Basin	36.3	17.5	8.08	3.35
GB	Galilee Basin	42.2	20.9	8.00	3.33
CRS	Crump south	41.4	20.1	7.79	3.26
CRN	Crump north	36.9	18.5	8.04	3.34
Marine					
L47	Lusiad 47	10.0	15.0	7.87	3.29
L49	Lusiad 49	11.3	15.7	8.28	3.41
ALB	Albany offshore	11.9	16.1	8.07	3.34
KI	Off Kangaroo Island	11.5	17.3	8.27	3.41
MN5	Coral Sea MN5	18.8	16.5	(8.07	3.34)
CS48	Coral Sea 48	12.9	16.3	8.23	3.40
CS37	Coral Sea 37	18.0	16.1	8.45	3.46

Table 1. CMD values and mantle densities

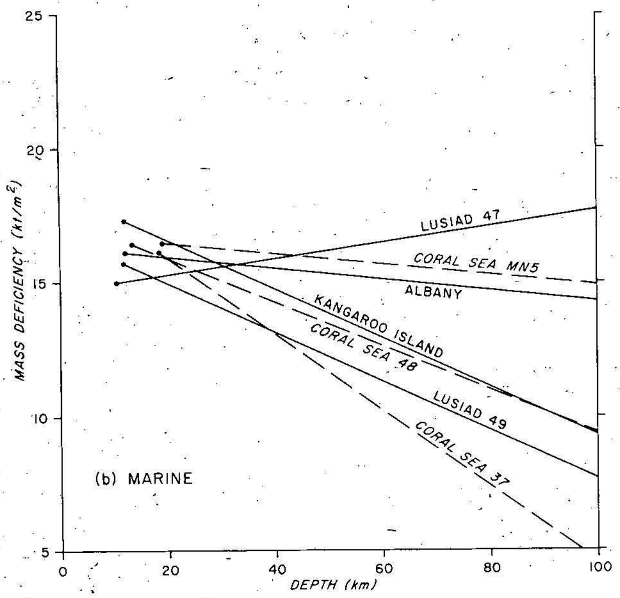

Figure 3. Mass accumulation with depth based on P_n velocities—marine.

If isostatic compensation for the crustal mass were to occur at some depth z_c, then locus of M on the graphs in Figure 2 should converge, at least approximately, towards a common value at z_c.

The continental data in Figure 2 fall into three groups—those with CMD above 20 kt/m², those between 15 and 20 kt/m², and those below 15 kt/m². The CMD for the marine data (Figure 3) lie between 15 and 17.3 kt/m², but the graphs diverge significantly for depths over 30 km. There is no apparent tendency to universal convergence within or between any of these groups, even bearing in mind that with the inaccuracies in determining the mass deficiencies, a difference of 1 kt/m² or so could hardly be taken as a serious discrepancy. We will discuss each group separately.

1. Continental middle mass group (CMD 15-20 kt/m²)

Crump North and Bowen Basin graphs are nearly parallel and separated by 1 to 2 kt/m²; Maralinga West is between those to 90 km or so. But SE Australia and Tasmania graphs, with their low velocities, cut across these. Some degree of convergence could be postulated at about 60-70 km. However Muirhead *et al.* (1977) found a P velocity increase to 8.36 km/s in southeastern Australia at a depth of 100 km. If SE Australia and Tasmania curves were to 'bend' at 100 km depth and follow approximately the slope shown for SE Australia in Figure 4, they would intersect the CRN and BB curves at about 130-140 km. As Goncz & Cleary (1976) find a low-velocity layer at about this depth from surface wave studies, this would therefore seem to be an appropriate level for isostatic compensation.

2. Continental low mass group (CMD >20 kt/m²)

All three traverses here are single-ended profiles and therefore open to some doubt for reliable velocity determinations, although in the case of Maralinga SE the length of the profile precludes interpretation of a substantial dip causing an erroneous apparent velocity. Finlayson *et al.* (1974 in their TASS model 2A, applicable to central Australia and South Australia-Victoria, show an increase to 8.18 km/s at about 60 km depth; with this the MSE curve could approach agreement with the central group at depths greater than 100 km, as shown in Figure 4. It is possible that a similar high velocity layer exists under northern Queensland, which could similarly affect the CRS and GB graphs, if the low masses indicated for these profiles are realistic. I know of no evidence either for or against such a layer in this area.

3. Marine group (15-17 kt/m²)

These profiles show reasonably consistent CMD, suggesting that isostatic compensation at the base of the crust should be almost complete. However the wide range of P_n velocities, most of them fairly reliably determined, is surprising; they show no discernible geographic pattern. On the hypothesis that they represent a corresponding range of densities, the divergent graphs in Figure 3 show that if they represent conditions to a depth of even 40 or 50 km under each profile isostatic imbalance would be re-introduced.

One way of explaining this situation is to postulate that at least some of the measured velocities represent comparatively thin sub-crustal layers—perhaps about 10-15 km thick—and that compensating velocity/density changes occur between this layer and the top of the asthenosphere, which is generally postulated at a depth of about 80-100 km under the oceans (Green & Liebermann, 1976).

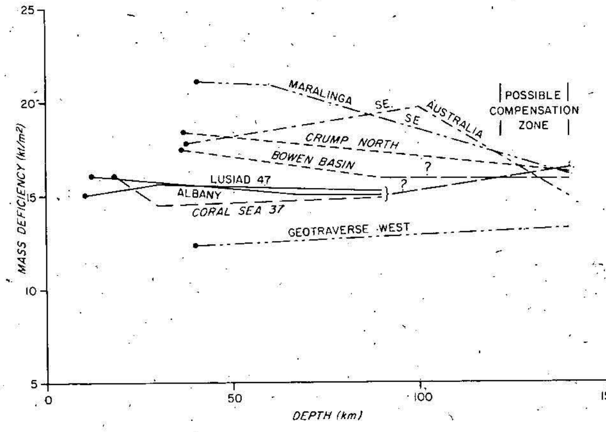

Figure 4. Revised mass accumulation with depth for selected profiles.

The oceanic and continental areas must be in isostatic equilibrium with each other. If the middle continental group as discussed above is representative of continental isostasy, then the target for the marine profiles should be about 15 kt/m², i.e., the denser sub-crustal material for L49, KI, and CS37 and 48, should be underlain by lower density material. Figure 4 shows graphs for three of the marine curves illustrating one way of achieving balance in this way; the details of the model are not intended to be definitive. Green & Liebermann (loc cit, Figure 6, p. 71) show a density variation with a broad minimum near the top of the asthenosphere, rather than a discrete change.

4. Continental high mass group (Geotraverse east and west)

The two graphs for the southwestern shield area of Western Australia stand well apart from the other continental graphs, with striking divergence with depth. The crustal structure is well determined by reversed profiles (Mathur, 1974), and velocities are high throughout, implying high densities—yet the crust is not particularly thick. The mantle density based on the P_n velocity is also high, so that M decreases rapidly with depth.

To bring these graphs into accord with the other continental masses, i.e., to establish isostatic balance, low density material is needed somewhere in the section. A low velocity/density layer in the shield would not be detected by seismic refraction, but this could not contribute more than about 0.5 to 1.0 kt/m^2 to the CMD. Low heat-flow values in this area (Sass, Jaeger & Munroe, 1976) indicate that high temperatures cannot be a cause of lower densities in the upper mantle here than under other parts of the continent; in fact, low density—velocity crustal layers are more plausible under Eastern Australia than under the shield.

We now examine whether compositional differences can be invoked to explain some of the required density variations. Birch (1961) has derived a series of empirically based velocity-depth relations, depending on the mean atomic number of the rock (Figure 5). High atomic numbers are generally associated with high iron content and give a higher density for a given seismic velocity. The velocity/depth relation used by Dooley (1976) is also shown in Figure 5, and corresponds to a mean atomic number of about 21.5 in the range under consideration. For the sub-shield mantle, a lower mean atomic number is required to give a lower density for the same seismic velocity.

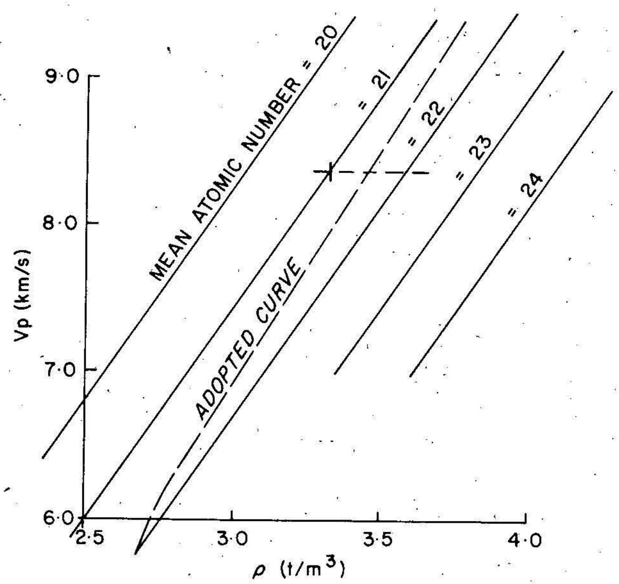

Figure 5. **Birch's density-velocity relations, together with relation used by Dooley (1976)**

According to the pyrolite model for the upper mantle (Ringwood & Green, 1966; Ringwood, 1975) the mantle immediately underneath shield areas consists of a refractory residue of dunite or peridotite whose mean atomic number is about 21, which is about the lowest that can be postulated for any reasonable mantle rocks. This would permit a density of about 3.31, and reverse the downward slope of the Geotraverse curves on Figure 2, for a slight upward slope; the initial discrepancy in CMD of about 5 kt/m^2 relative to the middle continental group would be reduced but not eliminated. D. H. Green (pers. comm.) confirms this low-density limit, which is appropriate for a composition of olivine Fo_{93} + enstatite Mg_{94}.

The high seismic velocities under the shield must persist to a substantial depth in the mantle, as the teleseismic travel-time residuals to shield stations are early by about 2 to 2.5 s compared with stations in southeast Australia (Cleary, 1967; Everingham, 1969). Only about 0.5 s of this difference can be accounted for by the crustal models. The P_n velocity differential of 0.5 km/s would have to persist with depth for about 200 km below the crust to explain the rest of the difference. This makes it very difficult to postulate a low-velocity layer within this depth range beneath the shield.

As it seems difficult to 'bend' the Geotraverse graphs upwards any further, we enquire whether the other graphs can be bent downwards so as to close the gap between them at a reasonable depth. Eclogite has a mean atomic number of 22 or more, and has been proposed by some petrologists as forming an important constituent of the lithosphere; in fact some propose that it comprises virtually the whole of the sub-crustal lithosphere, particularly in the oceanic regions (Ito & Kennedy, 1970; Kennedy & Ito, 1972). However, Green & Ringwood (1967, 1972), and Bottinga & Allegre (1976) have pointed out serious objections to this hypothesis; a summary of the arguments is given by Ringwood (1975). A partially eclogitic sub-oceanic mantle is discussed by Green & Liebermann (1976) as a possibility; it would have a higher density for a given seismic velocity, and would enable the marine curves in Figure 4 to be bent down towards the amended Geotraverse curves; however Ringwood & Green (1966), and Ringwood (1975), give reasons why the eclogitic content of sub-continental lithosphere must be minor, so it seems unlikely that the continental curves under the lighter crust could be bent so as to converge towards the shield curves at depths of less than about 160 km.

Discussion

Clark & Ringwood (1964) drew attention to similar mass balance discrepancies between shields and oceans; they pointed out that they could be accounted for by an average systematic difference from their models of .006 t/m^3 extending to a depth of 400 km, which was not considered serious. This would make a difference of 2.4 kt/m^2. However a difference of .06 t/m^3 would be required for a layer 40 km thick for the same effect; a systematic difference of this order, in addition to that already considered, seems unlikely, particularly as the obvious reasons for changing the density distribution suggest changes in the wrong direction.

Hales & Doyle (1967) concluded from body wave travel times that a crustal mass imbalance equivalent to about 4 to 5 kt/m^2 exists between the eastern and western parts of USA, requiring compensating masses to a substantial depth in the mantle.

It is concluded that a reasonable model can be constructed such that an approach to isostatic balance might be attained at depth of 130-140 km under eastern Australia, and at lesser depths under the oceanic crust; hence in these areas the existence of an asthenosphere with its top at these depths is possible; the bottom of such an asthenosphere would presumably be at about 160 to 200 km depth, where higher seismic velocities have been found by Muirhead *et al.* (1977), Finlayson *et al.* (1974), and Denham *et al.* (1972).

However, under a large area in the West Australian shield it is difficult to construct a lithospheric model such that mass balance can be achieved above 160 km depth, and the existence of an asthenosphere above this depth seems improbable. This conclusion is supported by several other lines of evidence; for example the surface wave studies of Goncz & Cleary (1976), the low heat flow (Sass *et al.*, 1976) combined with the high melting temperature of the dunite or peridotite beneath the shields (Clark & Ringwood, 1964), and evidence quoted by Jordan (1975b) from differential travel times of S and ScS waves.

The conclusion drawn from mass balance alone must be regarded as suggestive rather than conclusive. The argument depends on acceptance of the refraction results, the velocity-density relations, and the pyrolite model for the mantle. It could be argued that any or all of these are not known with sufficient accuracy to warrant a firm conclusion; however the most probable causes of departures have been shown to act in the wrong direction for restoring isostasy at a shallow depth.

Denham *et al.* (1972) found a P velocity increase to 8.6 km/s at a depth of about 160 km under central Australia. A lithospheric root extending to about the same depth under the shield may not entirely preclude compensating return flow for the plate motions from taking place above 200 km depth. However mechanical difficulties would be expected in postulating flow deflected around the root.

The mass balance argument is seen as another link in the chain of evidence supporting the conclusions reached by Jordan (1975a), based on studies of free oscillations, seismic body-wave travel times and surface waves, geothermal depth profiles, and petrological considerations, and of King (1976), based on P velocity variations, that the mantle under shield areas translates coherently with the plate motions to depths of some hundreds of kilometres. Jordan concludes that an alternative theory, with convection flows throughout the larger part of the mantle, seems more probable.

Acknowledgements

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Skylab photography for geological mapping

C. Maffi and C. J. Simpson

Skylab spacecraft stereoscopic photography of the Alice Springs and Snowy Mountains regions of Australia was studied by conventional photogeological techniques to assess its usefulness in geological mapping.

In the arid Alice Springs region, which has well exposed sedimentary rocks and relatively simple structures, broad rock units can be differentiated and correlated, and rock trends, joints and folds interpreted with the same accuracy as that shown on the 1:500 000 scale geological map of the region. The distribution of Cainozoic travertine and other surficial materials can be interpreted with sufficient reliability to allow up-dating of 1:250 000 scale geological maps.

In the more humid Snowy Mountains region, where the geology-to-morphology relationships are complex and varied, little lithological information can be obtained: only Tertiary volcanic rocks and alluvium can be identified and outlined with confidence. The Skylab photographs proved more useful for structural interpretations: faults, lineaments and joint trends can be detected. Several circular structures can be related to features of igneous origin. Statistical analysis of linear features revealed a direct relationship between known structural trends and linear features annotated on low resolution Skylab photographs.

Introduction

In December 1970 the US National Aeronautics and Space Administration (NASA) invited world scientists to put forward proposals for the analysis and interpretation of earth resources data acquired by the Skylab manned spacecraft. The Skylab program provided the opportunity to study survey-quality vertical photographs taken from an altitude of approximately 434 km and returned to earth for processing. This was an advance on the hand-held photography from the Gemini and Apollo spacecraft, and differed from the imagery later to become available from the unmanned earth resources technology satellite ERTS-A (now Landsat-1) which would view the earth from about 915 km altitude and telemeter the data to earth.

In response to the invitation the interdepartmental Australian Committee for ERTS (ACERTS) forwarded a proposal for participation, which was accepted by NASA. The Australian proposal requested the acquisition of Skylab Earth Resources Experimental Package (EREP) photography from both the Multispectral Camera System S190A (a bank of six 70 mm cameras containing a variety of films and filter combinations—see Table 1) and the Earth Terrain Camera S190B (a 458 mm focal length, high resolution 126 mm format camera). Site selection for photography gave priority to test areas already nominated for evaluation under the Landsat-1 program. This resulted in Skylab photographic targets being approved for Mount Isa (priority 1), Kalgoorlie, Alice Springs, and the Snowy Mountains (equal priority 2).

The unmanned Skylab spacecraft (SL1) was launched on 14 May 1973, into a 50-degree inclined circular orbit which resulted in a 5-day repeating ground track. During the three manned missions Skylab 2 (SL2) 25 May—21 June 1973, Skylab 3 (SL3) 28 July—25 September 1973, and Skylab 4 (SL4) 16 November 1973—8 February 1974, the astronauts operated the EREP cameras over Australia on two occasions.

During SL3, Track 13 was photographed with both camera systems on 12 August 1973. Figure 1 shows the extent of coverage by the S190A system; within this the S190B camera covered a narrower central strip. Terrain photography was obtained in the Alice Springs and Snowy Mountains areas, but the remainder of the track was extensively cloud-covered. Track 13 was photographed again on 15 December 1973 during SL4. Photography was acquired over Alice Springs, but additional photography over the Snowy Mountains was cancelled owing to 100 percent cloud cover observed by the crew.

S190A—*Multispectral Photographic Camera*

Focal length: 152 mm; negative size: 70 mm; negative scale 1:2 860 000

Film No.	*S190A Film Type*	*Filter bandwidth, μm*
25	Infrared Aerographic black and white (EK2424)	.7 to .8
26	Infrared Aerographic black and white (EK2424)	.8 to .9
27	Aerochrome Infrared colour (EK2443)	.5 to .88
28	Aerial colour (high-resolution SO-356)	.4 to .7
29	PAN-X aerial black and white (SO-022)	.5 to .6
30	PAN-X aerial black and white (SO-022)	.6 to .7

S190B—*Earth Terrain Camera*

Focal length: 458 mm; negative size 126 mm; negative scale 1:948 000

Film type: Aerial colour (SO-242) high definition
Filter: No. 5 neutral density.
Bandwidth .4—.7 micrometres.

Table 1. Skylab EREP photographic data

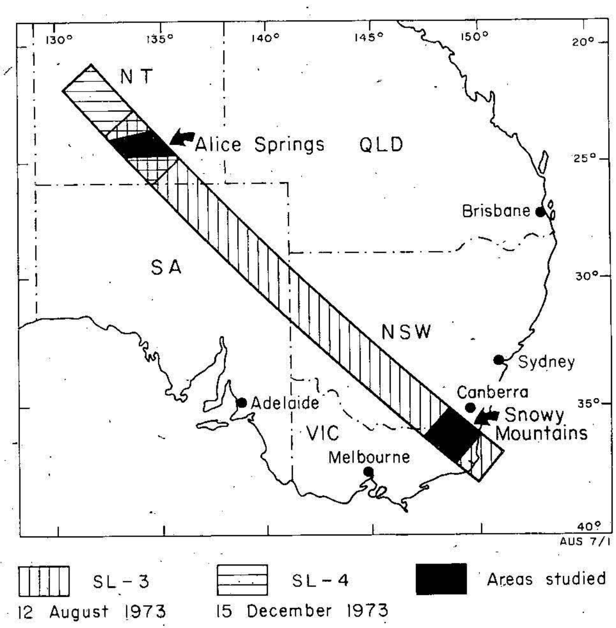


Figure 1. Skylab EREP photographic coverage of Australia

Early generation photographs taken during the missions were received from NASA during the period 18 December 1973 to 16 January 1975. Copies were issued to co-investigator groups to evaluate the use of the photography for forestry, land classification, geology and map production. The results of the investigations were compiled into a final report (Lambert, 1975) which was despatched to NASA in December 1975.

The following article is based on the final report to NASA and covers the BMR geological investigations of the Snowy Mountains area by C. Maffi and the Alice Springs area by C. Simpson. Subsequent information from field work and computer analysis of linear features is also incorporated.

To keep the geological evaluation of Skylab as objective as possible, examination and interpretation of the EREP photography was carried out initially without reference to available ground data. However, each interpreter already had some familiarity with the general geology of the area he was studying.

Conventional principles of photogeological interpretation were applied in the examination of the photography. During interpretation attempts were made to differentiate,

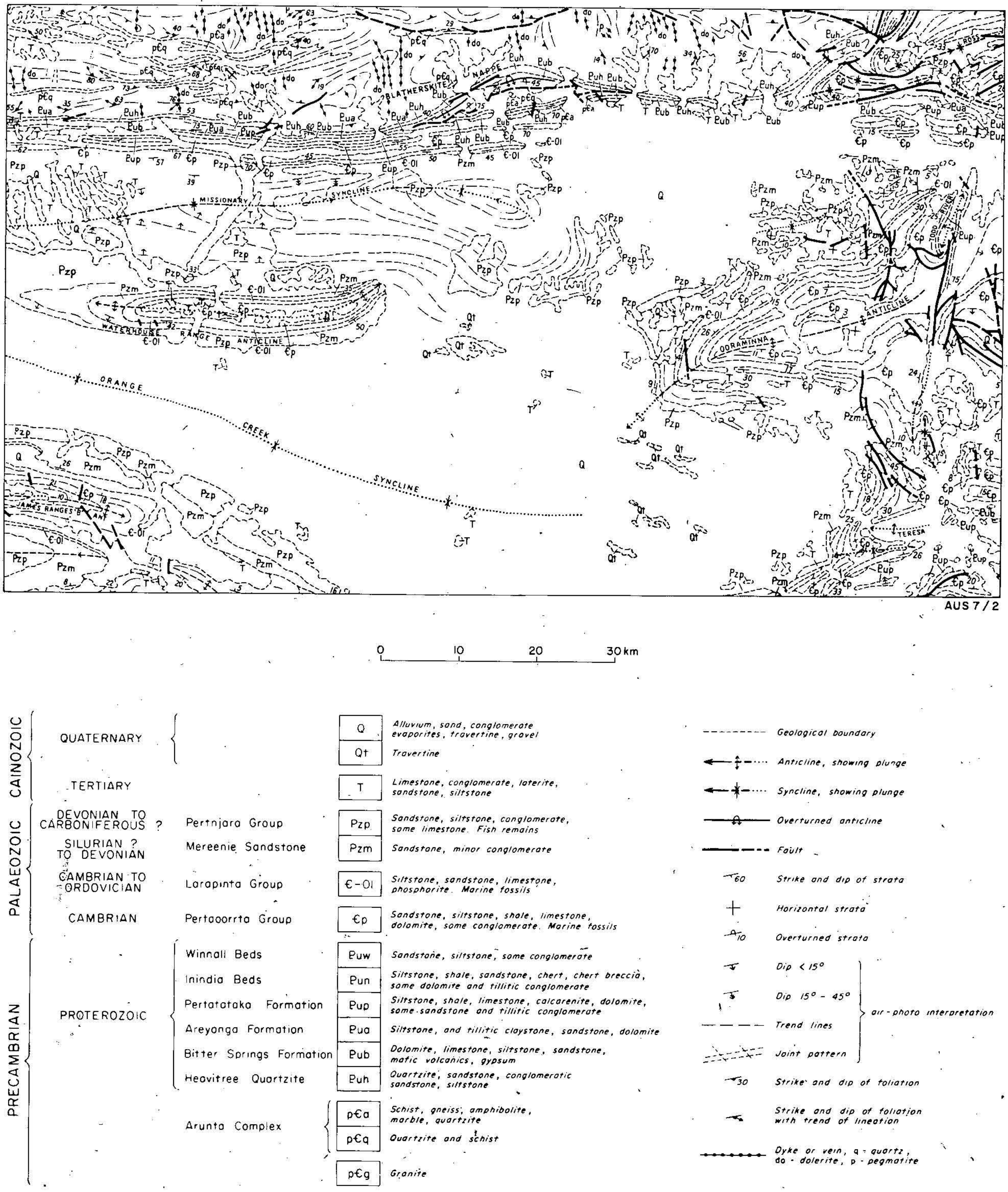


Figure 2. Alice Springs area, published geology

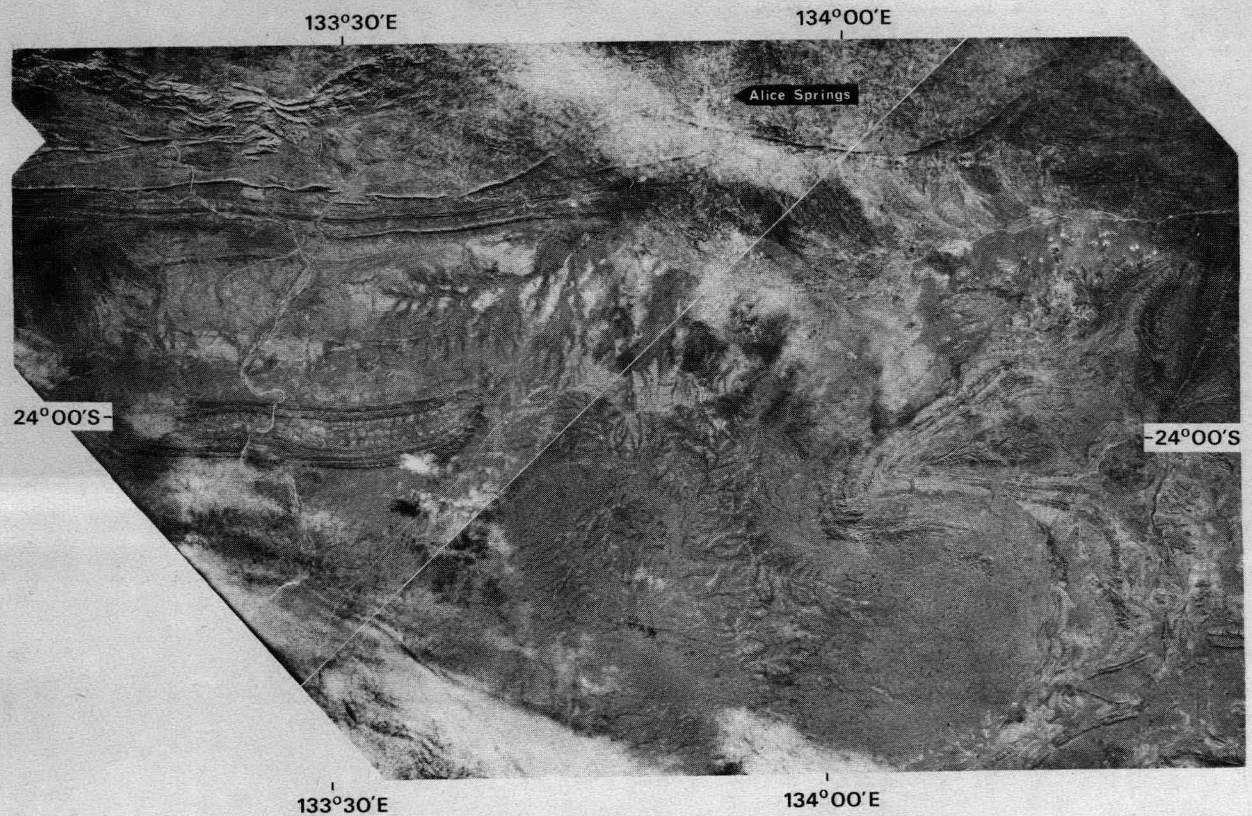


Figure 3. **Alice Springs area—part mosaic of S190B/RL84 frames 123, 124**

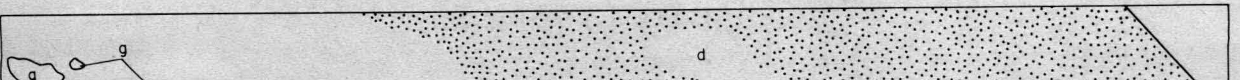


Figure 4. **Cainozoic geology from S190B photography**

QUATERNARY: a—stream alluvium; b—colluvium, alluvium, active depositional fans; c—aeolian sand; d—undifferentiated sand, soil; e—travertine.
TERTIARY: f—sediment (sandstone, siltstone); g—gravel conglomerate, fan detritus.
PRE-CAINOZOIC: h—undifferentiated.

delineate and correlate rock units and identify rock structures such as trends (foliation in metamorphics, bedding in sediments), folds, faults, joints and dykes. Interpretation was carried out on positive transparencies; illuminated by fixed intensity (fluorescent tube) light tables. Mirror stereoscopes with built-in 1 x and 1.8 x magnification and accessory 3 x and 8 x magnification binoculars were used. Major differences between the Skylab and interpretation and map data were further checked against other available ground data and vertical air photography at 1:83 000 scale or larger.

Alice Springs area

Skylab photography of approximately 8500 km^2 in the vicinity of Alice Springs was studied in detail. The area available for study was part of an irregularly shaped cloud gap and is illustrated in Figure 3. Skylab (SL3) photography from both the Multispectral Camera System (S190A) and the Earth Terrain Camera (S190B) was studied, but because the latter was far superior the report that follows relates mainly to observations from the S190B photography.

Photography from Skylab 4 (SL4) was also acquired over the region studied, but was not evaluated because of extensive cloud cover. It was noted that the terrain detail in cloud gaps was clearer than on the SL3 photography.

The study area was selected as representative of an arid environment. Alice Springs in the central north of the area has an average annual rainfall of 252 mm, which mostly falls between October and March. Because of the sporadic nature of rainfall there is no definite growing season. Vegetation ranges from grassland or shrubland to low woodland in which acacias are the most common trees and shrubs. Spiny plants and succulents common in overseas arid areas are not important (Perry *et al.*, 1962).

Major drainage throughout the area illustrated in Figure 3 consists dominantly of consequent streams which are part of a regional internal drainage network. Subsequent streams are well developed in areas of sedimentary rocks. The central part of the area is occupied by sand and alluvial plains at elevations between 540-590 m a.s.l. Aeolian dune development increases to the southeast.

Shadow effects on Figure 3 allow some appreciation of the topography. To the east and west of the plains, folded Palaeozoic sediments display well-developed strike valley, cuesta and hogback morphology, with peaks up to 200 m above plain level. The northern part of the area consists of an east-west-trending zone of ranges and hills within which arid erosion processes have developed excellent rock exposures. Folded quartzites of the Blatherskite Nappe (Figure 2) form crests up to 700 m above plain level, whereas most of the crystalline and metamorphic rocks of the ranges have subdued relief.

General geology

The area investigated covers part of the Amadeus Basin, originally an east-west-trending intracratonic depression approximately 800 km long and 200 km wide, within the relatively stable Australian Precambrian Shield. The crystalline basement comprises orogenically deformed igneous and metamorphic rocks known as the Arunta Complex. The basement rocks are unconformably overlain by the Amadeus Basin sequence of Adelaidean (Late Proterozoic) to Devonian sediments, which have been deformed by epeirogenic and orogenic movements. The distribution of the main rock types as shown on Figure 2 is based on Wells *et al.* (1970). The 1:250 000 scale mapping (Cook, 1968, 1969; Quinlan & Forman, 1968; Wells, 1969) was concerned primarily with the sedimentary basin, and lithological subdivision of the Arunta Complex was not attempted. Similarly only broad subdivision of Cainozoic surficial units was attempted.

Results

Structure. In the metamorphic terrain of the Arunta Complex in the northwest of the areas studied (Figure 3), the strike of metamorphic foliation can be mapped on S190B photography to the accuracy shown on published 1:250 000 scale maps. Foliation dip direction can be determined in only a few places, generally where its influence on topography can be detected by stereoscopic viewing.

Within the outcropping Proterozoic and Palaeozoic sedimentary sequences bedding traces and strike direction can be readily identified. This is primarily due to the effects of erosion on rocks of different resistance. Since different rocks of the area often display different natural colours the colour photography is more useful for detecting bedding than panchromatic copies.

Dip direction and estimation can be determined in areas of well-developed cuestas and hogbacks, although the small scale of the Skylab photographs affects reliability. Some large dip slopes are in the order of 1 km wide, but the more common size is in the range 200 to 500 m, which is represented by distances of 0.2 to 0.5 mm on the original S190B photography. With conventional aerial photography the vertical exaggeration (V/H) of the stereoscopic models is always greater than 1 (usually between 3 to 4 for 1:50 000 scale photographs). This substantially aids determination of dip and slope angles in the low dip ranges, but prohibits reliable estimation of high dip angles. Skylab photographs possess the unusual quality of having a vertical exaggeration of less than 1. The airbase/focal length ratio is only one sixth of that of 1:50 000 scale aerial photographs, and calculations of the author's perception of vertical exaggeration based on the Fichter method (Fichter, 1954) show that the vertical exaggeration of the S190B photography is about 0.6. While this results in the slope and dip angles on S190B appearing more natural than on conventional photographs, dip angle estimates are poor for angles less than 20°, but reliable in the intermediate and high dip ranges.

Since strike and dip directions can be readily determined the positions of fold axial traces could be interpreted. With the exception of the axis of Orange Creek Syncline—which could not be positioned because of cloud cover over the southern limb—all fold axes on Figure 2 can be independently identified and accurately positioned from Skylab photography.

Rock exposures throughout the region studied do not contain any extensively developed joint systems. The jointing that is present can be mapped on S190B photography in equivalent detail to that shown on published 1:250 000 maps of the area.

Detection of faults was not as successful as expected. Some transgressive faults in well-exposed terrain could be definitely identified. Faults such as those 10 km north of Teresa anticline in the southeast of the area (Figure 2) could be inferred, but do not display sufficient photo evidence to allow positive identification. None of the strike or near-strike faults (e.g., near Blatherskite Nappe, Figure 2) could be detected.

No new faults of major significance were identified, although some new faults were located in the Arunta Complex rocks in the northeast of the area.

Numerous photo lineaments were detected by employing the techniques of both vertical stereoscopic viewing and low-angle monoscopic viewing. However since only a limited area was available for study and problems arose from the presence of scattered cloud and cloud shadows, no intensive lineament study was undertaken.

Most lineaments were detected throughout the plain areas of Quaternary deposits (Figure 2). The lineaments do not correspond with any structures on published maps and they are believed to be expressions of mega-joints. Where lineaments can be traced through well-exposed Proterozoic and Palaeozoic sediments there are no detectable dislocations of the bedding, which suggests that most lineaments are unlikely to be expressions of faults. Similar observations were noted during studies on Landsat-1 lineaments of the Alice Springs area (Maffi *et al.*, 1974).

The S190A panchromatic film 29 (Table 1) proved best for detecting lineaments. Approximately twice as many lineaments were detected on the Skylab S190A photography as on Landsat imagery of the same area at the same scale. This can be attributed largely to the greater resolution of Skylab photography. Less than 5 percent of the Skylab lineaments coincide in whole or part with Landsat lineaments. In some places fence lines could be identified on Skylab because of marked vegetational and/or tonal differences on either side of the fence. Where tonal differences are less marked fence lines may be mapped as lineaments.

Numerous dolerite and pegmatite dykes intrude the Arunta Complex. At least 50 percent of the dolerite dykes shown on Figure 2 could be independently identified and annotated in whole or part because of their width (up to 25 m), high colour contrast, and transgressive nature. Dolerite dykes in areas of dense topographic shadows or with trend directions similar to the surrounding geology cannot be reliably detected. Light-toned porphyry dykes do not have sufficient width or tonal contrast to be identified.

Rock-type discrimination. Regions of Precambrian Arunta Complex metamorphics (Figure 2) can be reliably differentiated on S190B photography from Proterozoic and Palaeozoic sediments. Owing to hardness differences and tonal contrast, the distribution of the quartzite and schist unit within the Arunta Complex can be annotated, but no further reliable subdivision of the metamorphics was possible. Some areas of different metamorphic rock types can be recognized, but the boundaries between such areas can seldom be annotated continuously.

The Proterozoic and Palaeozoic sediments cannot be differentiated from one another by photogeological criteria alone. Throughout the sedimentary terrain it is generally possible to photo-interpret bedding and dip information and different rock criteria, thus allowing reliable subdivisions of, and correlation between, individual exposures. As with conventional aerial photography, photo-interpretation subdivision into exactly the same units as shown on published maps would not be possible without additional field data. However, once unit boundaries have been established at key locations, extensive preliminary subdivision of the sedimentary sequence throughout the area can be done on S190B photography with little additional ground data.

The geologic and geomorphic information about Cainozoic surficial materials that can be recognized on S190B photography was greater than expected. For this reason additional emphasis was placed on evaluating the reliability of photo-interpretation of seven subdivisions of Cainozoic surficial materials.

The Skylab photo-interpretation map (Figure 4) was prepared at photo scale (1:474 000) and was initially compared against 1:250 000 scale published maps. Although the published geology of Figure 2 naturally shows less information than the 1:250 000 scale maps from which it was generalized, some information (e.g. travertine) represents the outcrop distribution from all publications. As Skylab photographs were annotated at a small scale the map of the interpretation (Figure 4) must also be regarded as generalized and does not represent the maximum amount of information that can be interpreted. Some boundary differences noticeable between Figures 2 and 4 are due to generalization during compilation of both data sources.

The attempt to differentiate pre-Cainozoic rocks (Figure 4) from younger rocks was reasonably successful. Differentiation was more accurate where topographic differences were greatest, e.g., between sand plains and strike ridges. An area of disagreement between published and interpreted geology occurs along the northwestern edge of the Waterhouse Range Anticline. Examination of 1:25 000 scale colour aerial photographs taken in 1973 shows that although the area marked as Pertnjara Group (Figure 2) does contain rock outcrop, it is dominantly sand-covered and in this respect the Skylab Cainozoic interpretation of that area as undifferentiated sand and soil (Figure 4) is more accurate.

Two early Cainozoic units were interpreted. Their age, relative to other units, was judged on the basis that both units are unconformable on older rocks and both occur as remnants of more extensive deposits. In the northwest of the area (Figure 4) remnants of fan deposits were interpreted from position and morphology. Comparison with the Tertiary rocks of Figure 2 shows that approximately 70 percent of the unit was correctly identified on Skylab and that some boundary positions could be improved by the use of the space photographs.

In the central and eastern portions of the area a flat-lying unconformable sedimentary unit was delineated. In general there is poor agreement between interpreted Tertiary sediments (Figure 4) and outcrops of Tertiary sediments from the published geology (Figure 2). Reference to published 1:250 000 scale maps (Wells, 1969; Cook, 1969) shows that at the larger scale the outcrops of Tertiary sediments are subdivided into two separate types of rocks: silcrete; and freshwater sediments consisting of chalcedonic limestone, sandstone, siltstone and claystone. When compared against these subdivisions essentially all the Tertiary sediments interpreted from Skylab photography correspond to the freshwater sediments.

With the exception of the sediments 5 km northwest of Teresa Anticline, all other areas of Tertiary sediments of Figure 2 that were not detected on Skylab photography correspond to Tertiary silcrete. Non-detection of the sediments near Teresa Anticline was due to the presence of trends parallel to the pre-Cainozoic rocks; and the absence of light-toned scree and alluvium, which is characteristic of the other areas designated as flat-lying sediments. North of Ooraminna Anticline the interpretation of Mereenie Sandstone (Figure 2) as flat-lying Tertiary sediment is due to cappings of Tertiary silcrete over the Mereenie.

Areas interpreted as travertine from Skylab colour photography correlate well with the known areas of travertine shown on Figure 2. It was possible to interpret from Skylab a far greater distribution of travertine than had been previously shown on published maps. Limited field inspection was subsequently carried out along the Stuart Highway (the fine white line on Figure 3 extending from near Alice Springs past the eastern end of the Waterhouse Range Anticline). Light-toned areas crossed by the highway and interpreted as travertine were found to consist of pale brown fine sandy soils containing travertine and/or calcareous sand. Areas of very bright reflectivity that show as white scattered specks adjacent to the highway are excavations that invariably contained soils or weathered outcrop with high travertine content.

It has not been established whether travertine is the sole cause of high reflectivity in the areas examined. However correlations do indicate that despite the scale, the Skylab S190B colour photography allows more rapid and reliable detection of outcrop with high travertine content than can be interpreted from conventional (1:50 000 and 1:80 000 scale) panchromatic photography.

Skylab photography has subsequently been used for delineating travertine in sand plain, and the results will be incorporated into the Alice Springs 1:100 000 scale map sheet. The ability to detect and map Cainozoic travertine on Skylab photography has benefits of possible economic significance since travertine is a potential source of secondary uranium mineralization (Ivanac & Spark, 1976).

Interpretation of Skylab photography indicates that the distribution of Quaternary aeolian sand and stream alluvium can be mapped in considerable detail. Interpreted aeolian sand includes all areas of recognizable dune development. To the south of Ooraminna Anticline an extensive area of reticulate dunes can be identified on Figure 3 by the dark speckled pattern of vegetated swales. Individual dune crests can be identified by the lighter tone of the mobile sand. The reticulate dunes are up to 12 m high and consist of braided sand ridges or connected smaller dunes (Perry *et al.*, 1962).

Stream alluvium (Figure 4) was differentiated on the basis of texture and position relative to drainage channels. Areas of surficial material which could not be classified as either aeolian sand or stream alluvium were classified as undifferentiated sand and soil. The latter unit is shown by conventional photographs to be mostly sheetwash alluvium. There is sufficient information on Skylab photographs to differentiate most areas of sheetwash alluvium from active stream alluvium.

Where colluvial fans are immediately adjacent to high topographic features the boundary between surficial material and pre-Cainozoic outcrop is difficult to interpret. Areas of alluvium and colluvium associated with presently active depositional fans could not be consistently differentiated from aeolian sand or stream alluvium.

Comparison of S190A with S190B photography

Features categorized on 1:500 000 scale S190B photography were examined stereoscopically on 1:1 000 000 S190A photography with 3 x and 8 x magnification.

As set out in Table 2 the ability to map geological features on S190A photography (Table 1) was graded as good (G), fair (F), poor (P), or not detectable (ND) when compared to the S190B photography, which was regarded as optimum.

Poor results from films 25 and 26 (black and white IR) can be attributed in part to excessive film density and grain. Both the colour and false colour IR films (27 and 28 respectively) contain significant grain effects which are visible on 3 x enlargement. Because of the different film defects mentioned above no meaningful comparison can be made. An overall comparison of the films (irrespective of defects) based on interpretation of the fourteen geological features examined would rate them in decreasing order of utility as: 27, 28, 29, 30, 25, 26.

In general the colour and false colour IR photographs allowed more reliable geological interpretation than any of the black and white films.

Snowy Mountains area

Topography and physiography

The Snowy Mountains (Figure 5) form a plateau which, in several places, rises about 1800 m a.s.l. and which tops 2230 m at Mt Kosciusko, the highest mountain in Australia. The eastern and western slopes of the plateau are deeply dissected. The Murray River system drains the western slopes; the point where it flows out of the area is 265 m a.s.l. The eastern slopes are flanked by the southeastern New South Wales Tablelands, of 1300 to 730 m elevation. North of the tablelands, the rugged Brindabella-Bimberi Range rises to 1900 m at Bimberi Peak, and the Tinderry Mountains reach 1600 m. The southern margin of the tablelands is deeply incised by the drainage system of the Snowy River, whose lower point in the area is about 200 m a.s.l.

The climate ranges from temperate highland type at Cooma to alpine mountain type on the Snowy Mountains. The average rainfall is 558 mm at Cooma, and 2343 mm at Charlotte Pass, near Mount Kosciusko (Bureau of Meteorology, 1975).

General geology

The oldest rocks exposed in the area are Ordovician and Silurian sandstone-shale sequences (Figures 6 and 7), and some rocks belonging to the Ordovician metamorphic belt of Victoria. The deformation of these rocks is due to several mainly compressive tectonic events which started at the end of the Ordovician (Benambran Orogeny) and continued intermittently until the Carboniferous.

Thick sequences of middle to late Silurian acid volcanics with minor interbedded sediments are distributed in north-south-trending belts which are bounded by granite batholiths of late Silurian to early Devonian age. The intrusive rocks are present in the horsts of horst-and-graben structures, whose predominantly meridional orientation

SL3/S190A Films— *Spectral Range—micrometres*	*25* *.7-.8*	*26* *.8-.9*	*27* *.5-.88*	*28* *.4-.7*	*29* *.5-.6*	*30* *.6-.7*
a—stream alluvium	P	P	F	F	P	P
b—colluvium, alluvium, active depositional fans	ND	P	P	F	G	P
c—aeolian sand	ND	ND	F	P	F	ND
d—undifferentiated sand, soil	P	P	G	F	P	P
e—travertine	ND	ND	G	G	ND	F
f—Tertiary sediments	ND	ND	P	P	ND	P
g—Tertiary gravel, conglomerates, fan detritus	P	P	F	F	F	F
h—pre-Cainozoic boundary	P-F	P	G	P	F-G	F
Archaean rock subdivision	P	P	P	P	P	P
dykes	P	P	P	F	F	F
faults	P	P	F	F	F	F
bedding	F	P	G	G	G	G
dips	P	P	F	F	G	G
fold axes	F	P	F	G	G	F

Table 2. Mappability of features on S190A photography compared with S190B (G—Good, F—Fair, P—Poor, ND—Not detectable)

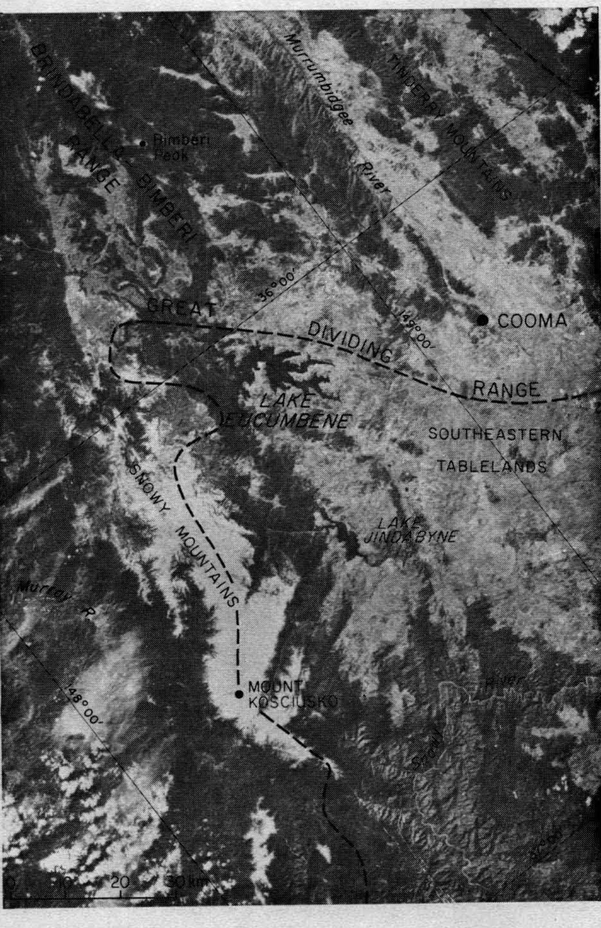


Figure 5. The Snowy Mountains area

was probably controlled by east-west, mainly extensional, forces during the Silurian and followed by later compressive forces, culminating with the mid-Devonian Tabberabberan Orogeny. East of the Great Dividing Range the structural style consists of fold belts separated by north-south-trending near-vertical faults.

Devonian volcanics, possibly extruded along the major longitudinal faults, crop out in the grabens. Ultramafic rocks crop out in a northerly trending belt which extends for about 50 km outside the area. In the west of the area (A7 in Figure 7), Devonian molasse-like sandstones crop out in a narrow meridional syncline, formed during the Kanimblan Orogeny of Early Carboniferous age. Tertiary volcanic rocks and clastic rocks are scattered in the central part of the area; south of Cooma, the volcanics cover several hundred square kilometres. Many of the Siluro-Devonian faults were rejuvenated by the Late Tertiary Kosciusko uplift. Cainozoic deposits cover the floors of some of the present valleys.

The known dominant structural trends in the area are

(a) North: Silurian to mid-Devonian trend associated with the horst-and-graben structures.
(b) Northwest: trend developed after the emplacement of the granite, probably during the Tabberabberan Orogeny.
(c) Northeast and east: right-lateral transcurrent faults active during the Tabberabberan Orogeny, rejuvenated in the Mesozoic and Cainozoic.

Rock-type discrimination

It can be seen from Figure 7 that in some places differences in lithology correspond with differences in vegetation, relief and texture. Examples of this are: the difference between intrusives and Silurian volcanics in the area E1-F2; the differences between intrusives and Ordovician sediments in the eastern and in the southern corners of the photograph; and the difference between Tertiary volcanics and intrusives in the area JK10.

Differences like these were observed in all types of Skylab photography studied. The problem is that they can be seen and used to trace boundaries only over relatively short distances; beyond, these differences either disappear, or do not correspond with lithological boundaries.

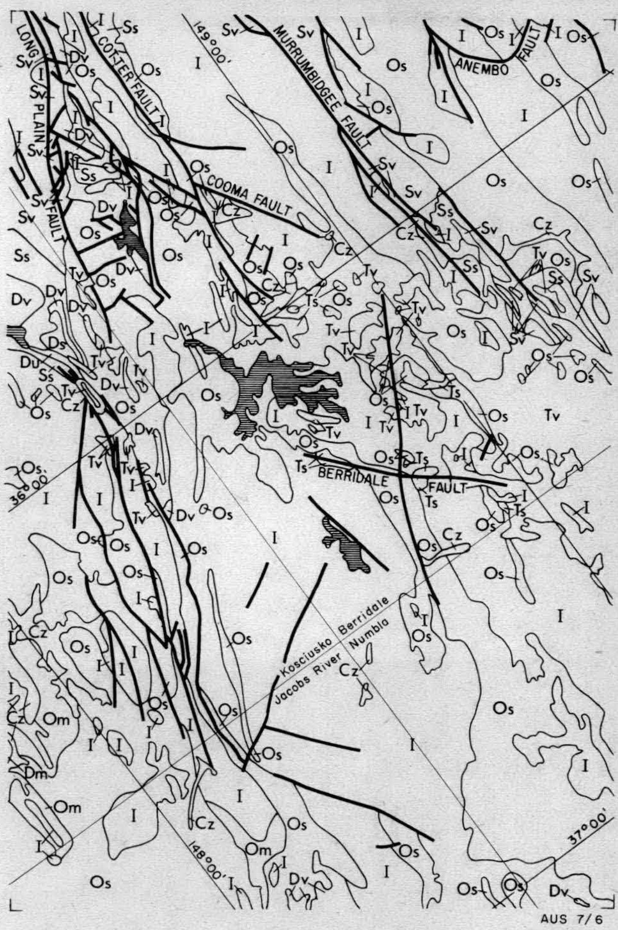
In many places different rock types are represented with similar characters, like, for example, intrusives, Ordovician sediments and Silurian volcanics in the northern corner, or intrusives and Ordovician sediments in the area EF15. In other places the same rock types are represented with different characters, for example intrusives at C1 and at E2, Ordovician sediments at I12 and I-J16. These inconsistencies hinder lithological photo-interpretation in most of the area. Tertiary volcanics are the only rock type that exhibit a fairly uniform photogeological character. Problems similar to those described above were encountered in the interpretation of photographs from all film types.

Photo-interpretation of the true colour film 28 (Table 1) is slightly easier than that of the other films, because of the natural appearance of the terrain. On black and white IR film with a near-IR filter (film 25), alluvium is easy to map because of the high reflectivity of its vegetation cover, mainly grass. The same film type with a far-IR filter (Film 26) gives a similar response, but with poorer contrast. The colour IR film 27 is the best for mapping alluvium and Tertiary volcanics: with few exceptions alluvium is imaged in reddish orange and Tertiary volcanics in a particular hue of green. Panchromatic film, either with a green-yellow filter (film 29) or with a red filter (film 30), provides good discrimination between forest (dark tone) and non-forest (light tone).

On photographs from the high resolution camera (S190B), landform elements can be studied in greater detail than on those from the low resolution camera (S190A). This led to the detection, in some places, of patterns related to rock type. However these patterns are uniform only over small areas: they can be used locally for rock-type identification, but not to extrapolate such information to other areas, nor to map lithological boundaries.

In forested areas, bare and isolated rock outcrops as small as about 30 m across could be detected on high-resolution photographs, because their light tone contrasts sharply against the dark tone of the trees. On low-resolution photographs, the smallest rock outcrop detected in the same area was about 100 m across. In grassland areas the detectability of isolated rock outcrops depends on relief and texture differences; the smallest outcrops detected on S190B were 500 m across, and on S190A 1 km across.

The results reported above are somewhat expected. Interpretation of air photographs at 1:50 000 and 1:85 000 scale did not give much better results, probably because of the complicated structural setting of the area and of the man-made alterations to the natural vegetation. Even worse results were obtained from Landsat-1 images at 1:1 000 000 scale: the characteristic hue of the Tertiary volcanics on Skylab colour IR photographs does not appear on Landsat-1 images, even when observed through a colour additive viewer, and the patterns related to rock type in high resolution Skylab photographs are not visible on Landsat-1 images.



Cz *Cainozoic*
Ts *Tertiary sedimentary rocks*
Tv *Tertiary volcanic rocks*
Ds *Devonian sedimentary rocks*
Dv *Devonian volcanic rocks*
Du *Devonian ultramafic rocks*
Ss *Silurian sedimentary rocks*
Sv *Silurian volcanic rocks*
Os *Ordovician sedimentary rocks*
Om *Ordovician metamorphic rocks*
I *Intrusive rocks*
Boundaries
Faults
Lakes
0 10 20 30 km

Figure 6. Snowy Mountains area, lithological map (redrawn from Pogson, 1972)

Figure 7. Comparison between lithological map and part of Skylab photograph S190A Film 29, frame 181

Faults

Continuous and discontinuous linear features expressed by strong, deeply incised traces in the land surface, or accompanied by dislocation of geological or geographical features, were interpreted as faults (Figures 8 and 9).

A comparison between the number of faults shown on the 1:250 000 geological map and the number of faults detected by interpretation of satellite pictures for the area covered by Figure 9 is made in Table 3.

The faults interpreted from satellite images were also compared with those shown in the 1:100 000 Geological Sheets Tantangara and Berridale. As expected, most of the mapped faults shorter than 10 km do not appear in the satellite interpretations: the detection of such small features is not the purpose of satellite imagery. Therefore, Table 4 was compiled considering only faults of at least 10 km length.

Origin	*Length ≥ 10 km*	*Length < 10 km*	*Total*	*Detected on S190A*	*Not Detected on S190A*	*New faults from S190A*	*Detected on S190B*	*Not Detected on S190B*	*New faults from S190B*
1:250 000 geological map	26	39	65	22	43	30	29	36	114
Landsat-1	48	26	74	30	44	22	50	24	93
S190A	48	4	52						
S190B	72	71	143						

Table 3. Number of faults in area covered by Figure 9

	Length ⩾ 10 km	*Detected on S190A*	*Not detected on S190A*	*New faults from S190A*	*Detected on S190B*	*Not Detected on S190B*	*New faults from S190B*
1:250 000 geological map	16						
1:100 000 geological map	22	12	10	4	12	10	17
Landsat-1	14						
S190A	16						
S190B	29						

Table 4. Number of faults ⩾ 10 km in the Tantangara-Brindabella area

Figure 8. Faults from S190A

Figure 9. Faults from S190B

The most significant points shown by Tables 3 and 4 are

(i) Many more faults were interpreted from S190B than from any other type of image.

(ii) When the faults shorter than 10 km are excluded from computation, the number of faults interpreted from each type of satellite picture is greater than that of faults shown in the 1:250 000 geological map; and the number of S190B faults is even greater than that of the faults shown in the 1:100 000 geological maps.

(iii) Approximately the same number of known faults were detected on S190A and on S190B photographs. Many more new faults were interpreted on the latter, probably because the high resolution makes it easier to recognize the faults among all linear features: in fact about 50 percent of the S190B faults are shorter than 10 km.

(iv) The number of faults interpreted from Landsat-1 over the entire area is about 1.4 times that of faults from S190A, but only about 0.5 times that of faults from S190B; if only faults longer than or equal to 10 km are considered, the number of faults is the same for S190A and Landsat-1. Almost 70 percent of the Landsat-1 faults were also interpreted on S190B photographs.

A comparison between faults from the lithological map of the area (Figure 6) and those from S190A (Figure 8) shows that

(i) There may be continuity between the Long Plain Fault and one of the faults mapped along the western slopes of the Snowy Mountains (AB on Figure 8).

(ii) The northern half of fault CD coincides almost exactly with the Cotter Fault, but the southern half diverges from it and corresponds with the boundary between intrusives and Ordovician sediments.

(iii) Fault EFG coincides with the Murrumbidgee Fault from E to F. Part FG suggests that the Murrumbidgee Fault may extend southward, under the Tertiary volcanics.

(iv) Fault HI partly coincides with the Cooma Fault but it extends beyond it for almost 60 km in a southeast direction.

(v) Part JK of fault JKL coincides with a mapped fault; part KL is new.

(vi) Faults MN (Berridale Fault), OP, QR and ST are examples of interpreted faults which coincide almost exactly with mapped faults.

(vii) Almost all the known faults which were not detected on Skylab photographs are shorter than 10 km.

Linear feature analysis

The term linear feature is used here to indicate a natural alignment, continuously expressed by landform, vegetation and/or colour, which presumably reflects a subsurface phenomenon. The annotation was carried out, both monoscopically and stereoscopically, on colour photo-

Figure 10. Linear features from S190A annotated without magnification

Figure 11. Linear features from S190A annotated with 3x magnification

graphs. To investigate both regional and local phenomena, the S190A photographs were annotated first without magnification (Figure 10), then with 3 x magnification (Figure 11). To evaluate the potential of high resolution the S190B photographs were annotated only with 3 x magnification (Figure 12).

The linear features were classified into eight azimuth classes of 22°30′ amplitude. Class 1 is north ± 11°15′; the other classes follow in a clockwise direction.

Using the lithological map (Figure 6) as a guide, generalized boundaries were traced to separate broad lithological units (Figures 13, 14 and 15), and the areas so obtained were lettered (Table 5). The linear features of each area in each azimuth class were then counted. Finally polargraphs were drawn, showing (for each area and for the total area) the percentage of linear features in each azimuth class (Figures 13, 14, and 15). To emphasize trends, the same percentages were plotted on opposite sides of the polargraphs. No polargraph was made for areas containing less than 10 linear features. Circular features were not included in the statistical analysis.

Areas	*Main rock type present*
I	Tertiary volcanic rocks
A, C	Silurian volcanic rocks
D, F, G, J, M	Ordovician sedimentary rocks
B, E, H, L, N	Intrusive rocks
K, O	Intrusive rocks and Ordovician sedimentary rocks

Table 5. Lithological units used in linear feature analysis

Straight and slightly curved linear features. In the azimuth distribution of linear features from S190A, annotated without magnification (Figure 13), the Palaeozoic trends (north and northwest) are well represented in the polargraph of the total area and in many polargraphs of lithological units. The Mesozoic and

Figure 12. Linear features from S190B annotated with 3x magnification

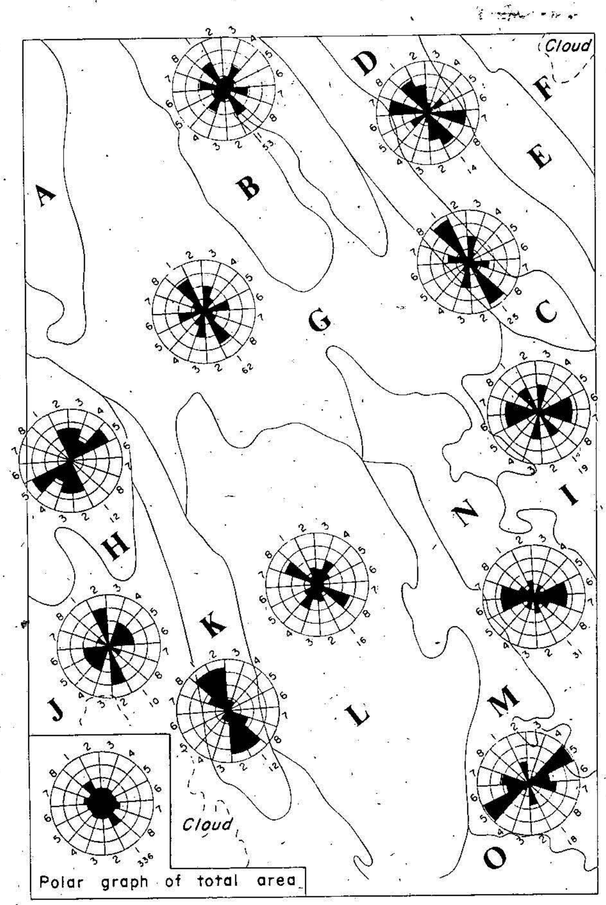


Figure 13. Azimuth distribution of linear features from S190A annotated without magnification

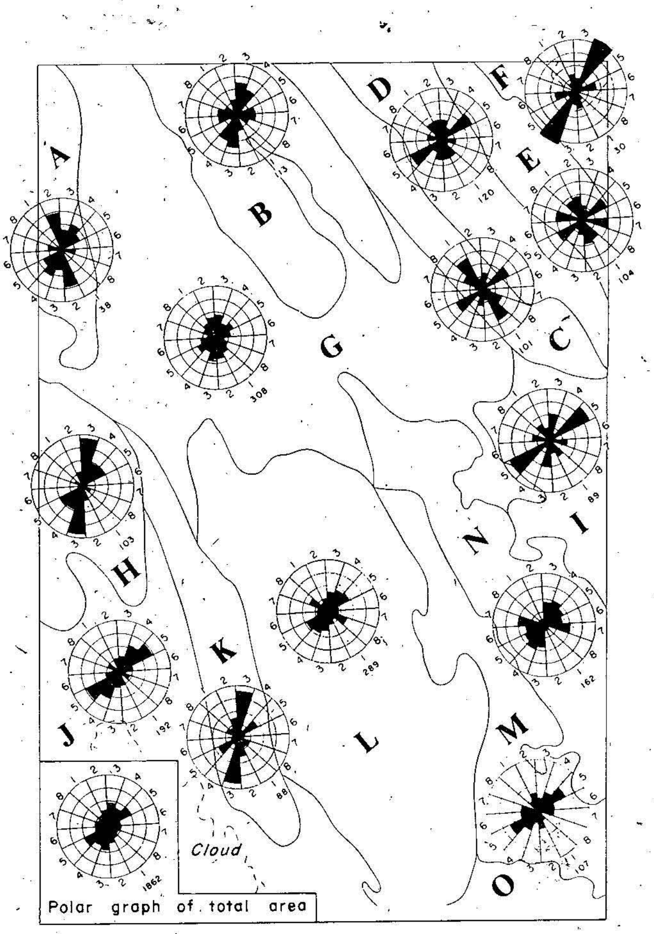
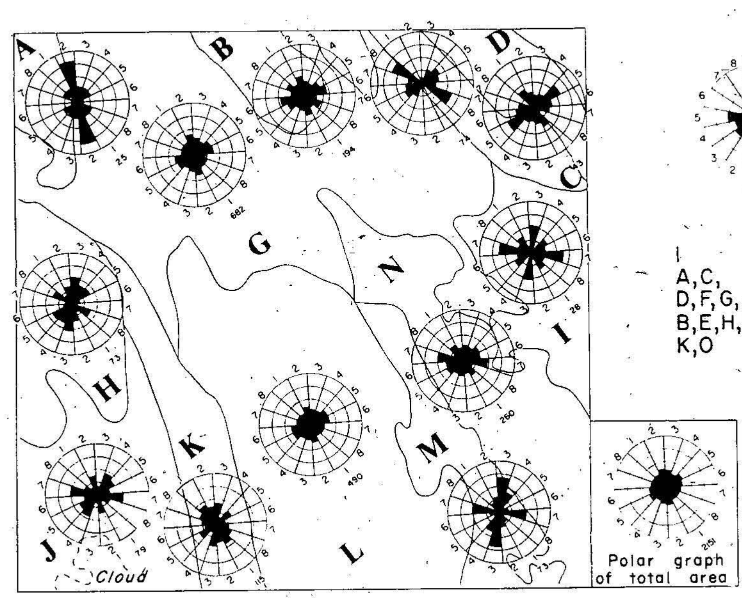


Figure 14. Azimuth distribution of linear features from S190A annotated with 3x magnification



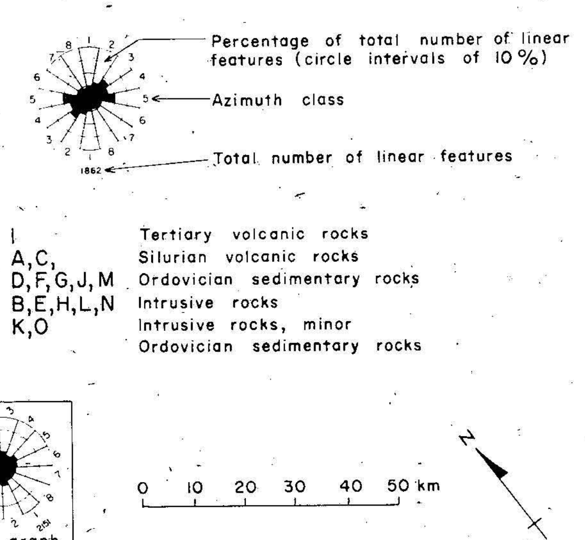


Figure 15. Azimuth distribution of linear features from S190B annotated with 3x magnification

Cainozoic trends (east and northeast) are present in some of the polargraphs of lithological units, but are not well represented in the polargraph of the total area. No similarity is visible between polargraphs of units having similar rock type, age, and history. The Tertiary volcanics (polargraph I) show the dominant trends of Silurian volcanic rocks (polargraph C, classes 1, 3, and 7) and of Ordovician sedimentary rocks (polargraph G, classes 1, 3 and 6); this may indicate that many linear features of the Tertiary volcanics are inherited from underlying rocks.

In the azimuth distribution of linear features from S190A, annotated with 3 x magnification (Figure 14), the polargraph of the total area clearly indicates a dominance of the east and northeast Mesozoic and Cainozoic trends. The polargraphs of intrusive rocks H and K are similar to each other; so are those of Ordovician sedimentary rocks D and M. Again, the Tertiary volcanics seem to have inherited features from underlying rocks.

Because of the higher resolution it was expected that the azimuth distribution of linear features from S190B, annotated with 3 x magnification, would show relationships similar to or better than those described above. Instead, the polargraph of the total area is unexpressive and no relationship could be found between polargraphs of the lithological units. The annotation had been made by the same interpreter and with the same method as for the linear features from S190A photography; it was concluded that either the relationship between linear features from S190A and geology was fortuitous, or the linear features from S190B had been flooded with spurious data introduced with high resolution, or possibly that data-handling errors had been made during their analysis.

To explore these possibilities the linear features from S190B were analysed again by computer. The co-ordinates of both ends of each linear feature were recorded on magnetic tape by use of a Gradicon digitizer on-line with a HP 2100 computer. The digital data were then analysed using program FAP31 (Fracture Analysis Program, Version 3, Part 1) run on a CYBER 76 computer. It classifies the linear features of each group into azimuth classes of any amplitude (in this case, 8 classes of 22°30′ each); calculates number, total length and average length of linear features in each azimuth class; transforms these data into percentages, and makes the calculations necessary to prepare polargraphs representing these percentages. A Calcomp 936 drum plotter was used to draw the polargraphs.

Three analyses were carried out: of all linear features annotated; of all linear features longer than 1 km; and of all linear features longer than 2 km. Analysis 2 eliminated about 10 percent of the linear features and analysis 3 about 60 percent. Further filtering was not attempted because it could have reduced the representativity of the sample.

The polargraphs were compared to each other by inspection, and again they failed to show any relationship between geology and azimuth distribution of linear features.

The results of the analysis of all linear features are similar to those of the previous analysis; the presence of significant data-handling errors can thus be excluded. The elimination of all linear features shorter than or equal to 1 km did not significantly change the azimuth distribution. The elimination of all linear features shorter than or equal to 2 km changed the azimuth distribution, but did not significantly change the results. The analysis of linear feature length gave approximately the same results as that of linear feature number. The average lengths of linear features were approximately the same in each direction class.

Having thus excluded from S190B linear feature analysis the possibilities of data handling errors and flooding by spurious data, it remains possible that the relationships noted between geology and azimuth distribution of linear features from S190A photographs were fortuitous. If this is so it does not invalidate the overall method since statistical analysis of linear features has been proved to be effective in geological investigation by many workers, in many areas. But it does indicate that great care should be taken in the use of linear features analysis, particularly in areas of complicated geological history and structure.

Circular features. The nature of circular features annotated on Skylab photographs (Figure 12) was investigated by use of conventional air photographs and geological maps.

Circular feature 1 is a large ring dyke. Circular feature 2 is formed by a granite body at the centre, surrounded by a circular ridge of hornfels. The two semi-circular features at 3 have the same composition as 2; originally they were part of a unique circle which was then disrupted by a left-lateral wrench-fault (Wyborn, in prep.). The northwestern quarter of circular feature 4 is visible on air photographs and coincides with the curving boundary between late Ordovician metamorphic rocks and late Silurian intrusive rocks in the Tantangara 1:100 000 geological map (Owen *et al.*, 1974). The remainder of the feature is unexplained. Circular feature 5 is a stream segment displaced by a landslide, clearly visible on air photographs. Feature 6 appears to be formed by circular lineaments on S190A photographs (Figures 10 and 11), but on S190B (Figure 12) the same feature is composed of short straight segments. On air photographs the area is crossed by a complex pattern of weathered joints, but two concentric rings formed by topographic features can be seen. The feature coincides with the Tara Granodiorite, a late intrusion in the Berridale batholith (Chappell & White, 1976). The complex circular feature 7 is perfectly visible on air photographs. The three northernmost rings are remains of Tertiary volcanic centres; the others are the result of small multiple intrusions which have been dated as Jurassic by McDougall & Wellman (1976). Features 8 and 9 are clearly visible on air photographs. Both are formed by curving granite ridges; probably they are the effect of late intrusions in the batholith, as feature 6.

Comparison of Skylab photography with Landsat-1 imagery

Fifth generation Landsat-1 imagery of the Alice Springs and Snowy Mountains areas was examined to compare the geological information content with that of Skylab photography. Evaluation involved examination of individual Landsat bands at various magnifications and of colour composite images produced with a I^2S additive viewer.

In the Snowy Mountains region the S190A black and white, and true colour, photographs, have about the same information content as Landsat-1 imagery. The colour IR photographs from S190A and true colour photographs from S190B have slightly more information content (respectively, the characteristic colour of Tertiary volcanics and, possibly, patterns related to rock types). Both S190A and S190B photographs contain more detailed structural information than Landsat imagery.

In the arid terrain of the Alice Springs area it was found that while some geological features could be recognized on Landsat the overall mappability compared to S190B photography is inferior in all respects and would be classified as very poor or not detectable (cf. Table 2). The superior data obtainable from Skylab is attributed to the combination of increased resolution and stereoscopy.

Conclusions

Evaluation of Skylab high-resolution (S190B) photography of the arid terrain in the Alice Springs region indicated that the differentiation and correlation of broad rock subdivisions, rock trends, joints, and fold axial traces can be interpreted with an accuracy equivalent to that shown on the 1:500 000 scale published map of the area. Although only the major transgressive faults and dykes can be recognized, the overall geological information content is such that Skylab photography could assist in the programming and execution of reconnaissance geological mapping. Travertine distribution can be more readily mapped than on larger scale panchromatic photography, and the photo-interpretation of Quaternary surficial materials is sufficiently reliable to allow extensive updating of 1:250 000 scale geological maps.

In the more vegetated terrain of the Snowy Mountains the interpretation of S190A photographs by conventional photogeological methods provided little lithological information because of the complex and variable relationships between geology and morphology; only the Tertiary volcanic rocks and alluvium could be identified and outlined with confidence in many places. On S190B photographs patterns related to rock types are visible in some places and can be used locally for rock-type identification but not to map lithological boundaries. The Skylab photographs are useful for structural interpretation, particularly in the detection of faults, lineaments and joint trends. In this area the interpretation of conventional aerial photography at 1:50 000 and 1:85 000 scale does not produce significantly better results. All Skylab photographs examined contained more geological information than 5th generation Landsat-1 images, because of higher resolution and of stereoscopy.

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The mineral potential of the Arunta Block, central Australia

A. J. Stewart and R. G. Warren

The Arunta Block is the mass of Precambrian basement rocks in the southern part of the Northern Territory of Australia. It comprises an early Proterozoic (or older) discontinuous sequence of sedimentary and volcanic rocks that were multiply deformed and initially metamorphosed 1800-1700 m.y. ago, and numerous granite masses that intruded the metamorphic rocks from 1700 to 1000 m.y. The metavolcanic rocks are concentrated in the lower part of the sequence, and the sedimentary rocks become more mature and better differentiated towards the top of the sequence. One carbonatite and a mantle-derived intrusion of kimberlitic affinity are located near a major crustal lineament in the east of the Block.

Mineral occurrences as presently known are small and in general uneconomic; only one small mine was operating in 1976. The occurrences can be grouped into the following types: 1—Stratabound: copper-lead-zinc in metasediments in the lower and middle parts of the sequence; 2—Pegmatitic: mainly copper, tin, tungsten, and tantalum derived from granite, and mica in pegmatites formed by partial melting of metasediments; 3—Metasomatic: tungsten, molybdenum, and minor copper in calc-silicate rocks adjacent to granite; 4—Hydrothermal: gold in a zone of late Palaeozoic deformation and retrogressive metamorphism, and fluorite-barite veins in zones of late Palaeozoic warping; 5—Magmatic: very minor copper, nickel, and chromium, in mafic and ultramafic rocks; and 6—Weathering: manganese and uranium in superficial Phanerozoic rocks. The mineral occurrences are areally distributed in two zones which are directly related to the distribution of major rock-types in the Block. The stratabound occurrences in the lower part of the sequence, magmatic occurrences, mica pegmatites, and hydrothermal gold deposits are located in the southern part of the Block; the stratabound occurrences in the middle part of the sequence, metal-bearing pegmatites, metasomatic occurrences, and hydrothermal fluorite-barite veins are located in the north. In terms of future prospects, stratabound base-metal lodes in the lower part of the sequence, metasomatic tungsten, and superficial uranium are the most likely candidates for economic success. Diamonds, rare earth elements, and niobium, as yet undiscovered, are possibilities along or near the major lineament in the east of the Block.

The Arunta Block shows marked geological resemblances to The Granites-Tanami, Tennant Creek, and Willyama Blocks in Australia, and to the Precambrian rocks of the Baltic and East African regions. All these regions are economically mineralized to some degree, and this, together with its own mineralization, suggests that the Arunta Block holds some potential for economic deposits. How much is a matter for further exploration and assessment.

Introduction

The Arunta Block is the extensive region of igneous and metamorphic rocks in the southern part of the Northern Territory of Australia, between Barrow Creek in the north and Alice Springs in the south (Figure 1). This report is a review of available data on mineral occurrences of potentially economic value in the Arunta Block, apart from water resources, construction materials, and fuels, which are not considered. With the exception of the study by Warren (1974, 1975) on the Oonagalabi base-metal occurrence, there has been no detailed work on any mineral of economic interest in the Arunta Block. Accordingly, this report presents a synthesis of the presently available data in unpublished company reports, and in the reports of the Aerial Geological and Geophysical Survey of North Australia, the Bureau of Mineral Resources (BMR), and the Geological Survey of the Northern Territory (GSNT). This report also includes a summary of the geology of the Arunta Block (Shaw *et al.*, in prep., Stewart *et al.*, in prep.) and a review generalized from published literature on the geology of some other regions similar to the Arunta Block. Where the data warrant it, we have speculated on the origin and control of some of the mineral occurrences; such speculations are offered only as possible working hypotheses.

There are no major economic deposits yet known in the Arunta Block; tonnages of identified resources are shown in Table 1, but to date all are subeconomic. The total known tonnages of identified base-metal resources are about 330 000 t (tonnes) of copper (about two years' output from Mount Isa), 370 000 t of lead, and 7000 t of zinc. At the time of writing (October, 1976), only one small mine—Molyhil (tungsten and molybdenum)—is producing ore from the Arunta Block. A lone gouger is working at the Arltunga Goldfield. Three other ventures—Jervois and Home of Bullion (both copper) and Jericho (tungsten)—are under 'care and maintenance'. Until recently the Yuendumu Mining Company, operated by aboriginals, produced copper ore from one lode in the Mount Hardy field, but the operation is no longer economic. The Company is now quarrying road aggregate and facing stone from the Vaughan Springs Quartzite at the base of the Ngalia Basin sequence, 3 km south of Yuendumu. Uranium has recently been discovered in sedimentary rocks adjoining and overlying the Arunta Block, and is being evaluated. Sales of mineral specimens, gems, and ornamental rocks are an important part of the tourist trade in Alice Springs.

Geology

The Arunta Block measures about 1000 km east-west and 400 km north-south, and is basement to several basins of shallow-marine sediments of Late Proterozoic to Palaeozoic age (Figure 1). The Block is geologically very complex, because of its history of multiple deformation, episodic metamorphism, and widespread granitic intrusion, but essentially it consists of early Proterozoic or older sedimentary and volcanic rocks which were complexly deformed, metamorphosed, and intruded by granite during the mid-Proterozoic (Carpentarian). Later events include an episode of migmatization in the southern part of the Block during the late Proterozoic (Adelaidean), and widespread thrust-faulting and associated retrogressive metamorphism in the late Palaeozoic. For simplicity of presentation, the

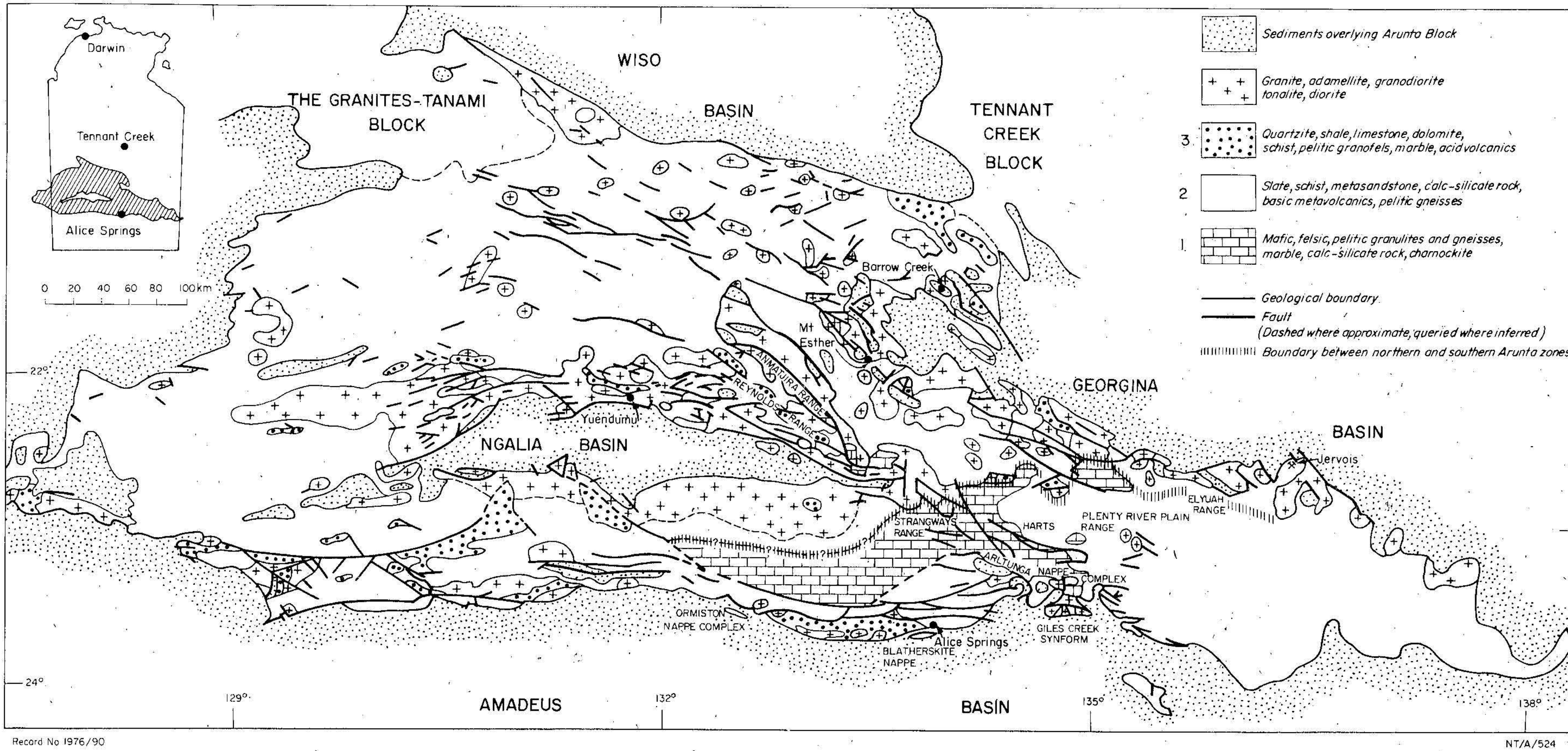

Figure 1. Generalized geological map of Arunta Block, showing major stratigraphic subdivisions and granite. Compiled from geological mapping, airphoto interpretation, and aeromagnetic interpretation by BMR, 1956-1976. Inset map shows location of Arunta Block in Southern part of Northern Territory.

Status	*Tonnes of ore (x10³)*	*Grade of ore (%)*	*Tonnes of metal*	*Mine**	*Reference***
Copper					
Measured	1753	0.3—4.1	5 260—71 870	J	A
Measured	3085	3.07	94 710	J	B
Measured	3.05	12—24	370—730	H	C
			100 340—167 310		
Indicated	635	3.07	19 500	J	B
Indicated	ca 30	6	ca 1 800	H	C
			ca 21 300		
Inferred	420	2.56—3.42	11 000—14 400	J	B
Inferred	4 170	3.1	129 270	J	B
Inferred	12.2	15	1 830	H	C
Inferred	30.5	4	1 220	H	C
			143 320—146 720		
Total identified copper resources = 264 960—335 330 tonnes of metal					
Lead					
Measured	3.05	2—3	60—90	H	C
Indicated	ca 30	2	ca 600	H	C
Inferred	30.5	2—3	610—920	H	C
Inferred	12.2	Not stated	Unknown	H	C
Inferred	3350	8—11	286 000—368 500	J	D
Total identified lead resources = 287 270—370 110 tonnes of metal					
Zinc					
Measured	12	5.7	680	J	E
Measured	3.05	1	30	H	C
			710		
Indicated	204	?2	?4080	J	E
Indicated	3.05	5—10	150—300	H	C
			4230—4380		
Inferred	87	2	1740	J	E
Total identified zinc resources = 6680—6830 tonnes of metal					
Bismuth					
Inferred	3350	0.054—0.073	1800—2400	J	D
Gold					
?Inferred	7.4	0.00023	0.017	W	F
Silver					
Inferred	3350	0.0052—0.033	170—1100	J	D

Table 1. Known tonnages of identified subeconomic resources of base and noble metals in some deposits in Arunta Block.

*** J—Jervois; H—Home of Bullion; W—White Range**

**** A—Sydney Stock Exchange, 1973; B—Goldner *et al.*, 1974; C—Sullivan, 1953; D—Elliott, 1974; E—Holmes, 1972; F—Hossfeld, 1937a.**

metamorphic rocks are grouped into three divisions (Figures 1 and 2). The rocks assigned to each division are tentatively regarded as chronological or stratigraphic correlatives.

The first division (Figure 2) consists essentially of granulites of mafic, felsic, and pelitic compositions; the first two types include chemical equivalents of basic and acid volcanics (Shaw *et al.*, in prep.). In the Harts and Strangways Ranges, the granulites are succeeded by metapelitic and cordierite-rich gneisses, marble, and calc-silicate rock of the amphibolite facies. These rocks are separated from the granulites by a major stratigraphic break.

The second division consists of greenschist facies slate, schist, and metasandstone (including Lander Rock Beds and Mount Stafford Beds; Shaw & Stewart, 1975), calc-silicate rock, and associated intermediate and basic flows or sills. In the Harts Range, these rocks pass into amphibolite-facies equivalents (including Irindina Gneiss and Harts Range Group of Joklik, 1955), and to granulite-facies equivalents in the Reynolds Range. As a whole, the metasediments of the second division show a higher degree of sedimentary maturity than those of the first, and there is a smaller proportion of meta-igneous rock. The two divisions are everywhere in discordant contact, but whether the discordance is a metamorphosed fault or a metamorphosed unconformity has not yet been determined.

The third division lies with angular unconformity on the second, and shows an even greater degree of sedimentary maturity; it consists of weakly metamorphosed sedimentary rocks, including orthoquartzite with a basal conglomerate, shale, lenses of limestone and dolomite, and sills and a lopolith of granitic porphyry. It is almost everywhere at greenschist facies, but in the eastern part of the Arunta Block, both the second and third divisions are generally at amphibolite grade. In the Reynolds Range, in the northwest of the Block, the second and third divisions can be traced southeastwards from low-greenschist metasediments through a retrograde zone to granulite-facies rocks.

Large elongate syntectonic granite batholiths and smaller equant post-tectonic plutons intrude the three metamorphic divisions. Granitic rocks are uncommon in the southeastern part of the Block; a few small syntectonic intrusions are present, and a diorite-tonalite-granite complex with associated ultramafic hypabyssal intrusions has also been recognized (Shaw *et al.*, in prep.). Smaller plutons unrelated to the granites include a late Proterozoic basic intrusive complex (the Mordor Complex) with ultramafic differentiates of kimberlitic affinity, and a carbonatite (the Mud Tank Carbonatite) of similar age. Dolerite dykes and plugs cut all the units except some post-tectonic plutons; some dolerites are progressively metamorphosed to granulite-facies assemblages, some are retrogressively metamorphosed to greenschist facies, and still others are unmetamorphosed.

The Arunta Block is cut by numerous major faults which trend mainly west-northwest in the east of the Block, and west-southwest in the west, forming an arc convex to the north (Figure 1). Also prominent in the east is a major gravity lineament—the Woolanga Lineament—which trends north-northwest for 300 km (Anfiloff & Shaw, 1973). Many major faults coincide with or diverge from this Lineament, and the Mordor Igneous Complex and Mud Tank Carbonite are located near it (Figure 1).

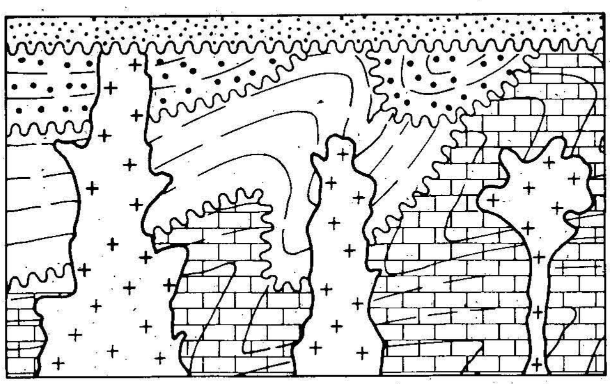

Figure 2. Schematic diagram of relationships between major stratigraphic divisions of Arunta Block; reference as for Figure 1.

Shortly after the episode of migmatization in the south of the Arunta Block, Late Proterozoic shallow-marine sediments were laid down near and over much of the Block.

Deposition began with the Heavitree Quartzite of the Amadeus Basin to the south of the Block (Wells *et al.*, 1970), and its correlative the Vaughan Springs Quartzite of the Ngalia Basin, which overlies the central part of the Block. The Heavitree Quartzite was conformably succeeded by dolomite, limestone, shale, and evaporites of the Late Proterozoic Bitter Springs Formation, and this was followed by tilloid, shale, red-beds, orthoquartzite, carbonates, and evaporites during the remainder of the Proterozoic and early Palaeozoic. Deposition in the Amadeus Basin finished with molasse conglomerate and sandstone of the Devonian Pertnjara Group. The sequence in the Ngalia Basin is in general sandier and thinner than that in the Amadeus Basin (Wells *et al.*, 1972).

The northern margins of both Basins became the site of major overthrust faulting during the Late Devonian and/or Early Carboniferous Alice Springs Orogeny. At Arltunga, in the southeast of the Arunta Block (Figure 1), several nappes—the Arltunga Nappe Complex—comprising cores of Arunta basement rock and envelopes of Heavitree Quartzite and Bitter Springs Formation were transported southwards for some tens of kilometres, mainly by low-angle thrust-faulting and sliding; ductile deformation took place under conditions of increased metamorphic grade in the root zone of the nappes (Stewart, 1971a; Shaw *et al.*, 1971; Stewart *et al.*, 1976). Other thrust nappes formed in the Ormiston and Alice Springs areas (Figure 1—Marjoribanks, 1975; Stewart, 1967). Along the northern margin of the Ngalia Basin, the late Palaeozoic movements took place along north-dipping thrust-faults (Wells *et al.*, 1972).

A program of isotopic dating of rocks of the Arunta Block began in 1972. Preliminary results (Black, 1975) suggest two widespread episodes of regional metamorphism throughout the Block; the first, of granulite grade, at about 1800 m.y., and the second, generally of amphibolite grade but reaching granulite in the centre, at about 1700 m.y. Woodford *et al.* (1975) have recognized a third episode, also of granulite grade, at about 1400 m.y. in the Strangways Range. Most granites date at about 1700 m.y., but intermittent granitic intrusion continued to about 1000 m.y. The Mordor Complex is dated at 1210 m.y. (Langworthy &

No	*Name*	*Lat (S) Deg. min.*	*Long (E) Deg. min.*	*Element(s)*	*Type**	*Notes*
1	Jervois	22 40	136 16	Cu, Pb, Zn	Str	Estimated production 500-1000 t Cu, Bi, W associated.
2a	Bonya	22 44	136 03	Cu	Peg	Estimated production 50-100 t Cu.
2b	Jericho	22 42	136 06	W	Met	Production several tonnes W.
2c	Samarkand	22 44	136 04	W	Met	
2d	Marrakesh	22 41	136 05	W	Met	
2e	Tashkent	22 41	136 09	W	Met	Stockpiled ore being milled at Molyhil (3) (1976).
2f	City of Medina	22 41	136 06	W	Met	
2g	White Violet	22 44	136 05	W	Met	
3	Molyhil	22 44	135 45	W, Mo	Met	Operating (1976). Grade estimated from production figures 0.6% W.
4	Jinka district	22 43	135 47	F, Ba	Hyd	Estimated resources 370 000 t ore at 39.6% CaF_2 (Gourlay, 1974)
5	Perenti	22 31	135 02	Cu	Hyd	
6	Delmore Downs	22 30	134 53	W	Peg	
7	Delny	22 34	134 53	W	Peg	
8	Bundey River	22 25	134 48	Ta, Bi	Peg	Bismuthinite assays 0.005% U, greisen 0.022% U (Daly & Dyson, 1963).
9	Utopia	22 12	134 26	Ta, Bi	Peg	Weakly radioactive.
10	Home of Bullion	22 31	134 10	Cu, Pb, Zn	Hyd	Production ca 1000 t Cu. Galena contains Ag.
11	Home of Bullion district	21 30	134 04	Cu	?	No details known.
12	Barrow Creek district	21 28	133 47	Sn, Ta, W	Peg	Several small occurrences.
13	Anningie	21 41	133 06	Sn, Ta	Peg	Production ca 27 t concentrate. Greisen assays 0.024% U_3O_8 (Daly & Dyson, 1963).
14	Mount Peake	21 31	133 05	Pb	Peg	Quartz vein in amphibolite. Galena assays 279 g/t Ag.
15	Waldron's Hill	20 45	132 29	Au	Hyd	Quartz-carbonate in metadolerite and hornfels; assays 5g/t Au (Anon., 1941).
16a	Reward	22 11	132 49	Cu, Pb, Zn	Str	Estimated production 8 t Cu. Max. assays: 0.016% Cu, 0.03% Zn (Anon., 1967).
16b	—	22 13	132 47	Cu, Pb, Zn	Str	Max. assays 0.009% Cu over 1.5 m, 0.046% Pb and 0.072% Zn over 0.6 m (Anon., 1967).
17	Mount Allan	22 13	132 10	Sn	Peg	Estimated production 1 t Sn. Ta associated.
18	Aileron	22 39	133 17	Au	Hyd	Quartz veins in retrograde schist. Production 0.03 kg Au.
19	Mount Boothby	22 37	133 20	W	Peg	Production 0.4 t W.
20	Brookes Soak	22 07	132 10	W	Peg	Position approximate. Production ca 0.5 t concentrate.
21	Coniston	22 07	132 34	Sn	Peg	Greisen in albite-quartz rock.
22a	Mount Stafford	22 02	132 34	Sn	Peg	
22b	Mount Stafford	22 03	132 36	Sn	Peg	
23	Double Dams	22 07	132 16	Ta	Peg	
24	Double Dams	22 07	132 13	W	Peg	Production 0.05 t W.
25	Patty Well/Stuart Bluff +	22 47	132 51	Fe	Hyd	Hematite-quartz veins in granite and Vaughan Springs Qtzt. F. assoc.
26	Pine Hill	22 11	132 47	Au, Cu	Hyd	Quartz vein in schist. Assays: 6.14 g/t Au, 4.91 g/t Au.
27	Ingellina Gap	22 09	132 49	W	Peg	No details known: position approximate.
28	Barney's +	22 19	132 46	Fe	?	Earthy limonite lenses in schist.
29	Woodforde River +	22 33	133 06	Fe	?	Limonite lens in marble. Assays 0.0375% Zn.
30	White Hill Yard	22 29	133 07	Cu	Hyd	One grab sample assayed 5% Cu.
31	Lander	22 09	132 48	Cu	Hyd	Estimated production 10 t Cu.
32	Wolfram Hill	22 03	131 19	W	Peg	Production 90 t wolframite.
33	Mount Hardy district	22 07	131 33	Cu	Peg	Estimated resources 12 200 t ore at 3-4% Cu, 56 g/t Ag (Grainger, 1968).
34	Rock Hill	22 11	131 46	Cu	Peg	Estimated production 5 t Cu.
35	Jubilee Silver King	22 07	131 11	Cu, Pb	Peg	Bi associated. Assays: 11-14% Cu, 16-55% Pb, 140-1490 g/t Ag.
36	Vaughan Springs	22 11	131 19	F, Ba	Hyd	Cu, Pb associated.
37	Clark	22 02	131 01	Cu	Peg	Estimated production 10 t Cu.
38	Buger Creek	22 07	130 40	Cu	Hyd	
39	Djagamara +	22 12	131 17	Fe	Str	Banded iron formation.
40	Patmungala	22 13	131 12	Cu	Hyd	Estimated production 1 t Cu.
41	Wilson's Find	21 59	130 41	W	Peg	Production 2 t concentrate. Also called Mt Singleton Wolfram Mine.
42	Tom Braun's	23 05	133 52	Cu	Mag	
43	Mueller Creek	23 01	134 04	Cu	Mag	
44	Copper Queen	23 09	134 40	Cu	Met	
45	Selin's	23 05	134 42	Cu	Mag	
46	Virginia	23 04	134 40	Cu	Mag	
47	Arthur Pope's	24 05	135 27	Cu	Mag	
48	The Pinnacles	23 09	134 14	Cu	Met	Estimated production 20 t Cu. Au, Ag, Bi associated.

No	Name	Lat (S) Deg. min.	Long (E) Deg. min.	Element(s)	Type*	Notes
49	Sliding Rock	23 19	134 12	Cu	Str	
50	Turner's	23 19	134 13	Cu	Mag	Au associated.
51	Paddy's Jump-Up	23 32	134 37	Cu	Mag	
52	Gecko	23 18	134 09	Cu, Pb, Zn	Str	Ag associated.
53	Rankin's	23 17	134 07	Cu, Pb, Zn	Str	Assays 4-16% Cu.
54a	Glen Helen	23 26	132 15	Cu	Peg	
54b	Glen Helen	23 27	132 17	Cu	Peg	
55	Stokes Yard	23 27	132 06	Cu, Pb, Zn	Peg	Ag associated. Assays on core: 0.85% Cu, 0.08% Pb, 0.22% Zn.
56	Oonagalabi	23 07	134 52	Cu, Pb, Zn	Str	Assays: 1% Cu and 1.6% Zn over 40 m.
57	Johnnie's Reward	23 08	134 13	Cu, Pb, Zn	Str	
58	Edwards Creek	23 01	134 01	Cu, Pb, Zn	Str	Assays at surface: up to 3.6% Cu, 4.7% Pb, 4.5% Zn.
59	Harry Bore	23 12	133 56	Cu, Pb, Zn	Str	Assays: Cu and Pb very low, up to 9.5% Zn (surface and core).
60	Red Rock	23 03	133 46	Cu, Pb, Zn	Str	Assays of core: 0.25% Cu, 0.69% Pb, 1.62% Zn over 16.5 m.
61	Woolanga Bore	23 07	134 13	Pb	Str	Galena in forsterite marble.
62	Johannsen's Mine	23 14	134 05	Cu, Pb, Zn	Str	Production 3.57 t phlogopite. Core assays up to 3.3% Zn.
63	Winnecke goldfield	23 19	134 17	Au	Hyd	Production 37.5 kg Au recorded, 375 kg estimated.
64	Glankroil	23 18	134 21	Pb	Peg	Estimated production 10 t Pb, 50-100 kg Ag. Galena assays 5000 g/t Ag.
65	White Range	23 28	134 46	Au	Hyd	Production 363 kg Au. Cu associated.
66a	Wheal Fortune	23 25	134 48	Au	Hyd	
66b	Wheal Mundi	23 24	134 47	Au	Hyd	Production 10.8 kg Au.
67a	Wipe Out	23 24	134 45	Au	Hyd	Production ca 6 kg Au.
67b	Jenkins	23 23	134 45	Au	Hyd	(Production ca 6 kg Au.)
68	—	23 24	134 44	Au	Hyd	Minor workings west of Wipe Out. Pyrite absent.
69	Round Hill	23 25	134 45	Au	Hyd	
70	Claraville	23 25	134 43	Au	Hyd	Production 0.7 kg Au.
71	Arltunga	23 26	134 42	Pb	Peg	Ag and Bi associated.
72	Hale River +	23 26	135 01	Cu	?	Au associated.
73	Tommys Gap	23 37	134 38	Cu	?Peg	Production ca 1 t Cu, 0.3 kg Ag (Shaw, 1967). Hydrothermal?
74a	Inkamulla Dome	23 05	135 12	Mo	?Met	No details known.
74b	Inkamulla Dome +	23 03	135 09	W	?Met	In calc-silicate rock; no details known.
75+	—	22 29	131 01	Fe	Wea	Ironstone capping on marble.
76+	—	23 02	133 47	Cu	?	
77+	—	23 03	134 24	Cu	?	
78+	—	23 04	134 26	Cu	?	
79	Arltunga goldfield	23 27	134 39	Au	Hyd	Production 2 kg Au recorded, much more estimated.
80	Yarraman	22 39	135 58	Cu	Mag	
81	King's Legend	22 47	136 06	Cu	Mag	Estimated production 5-10 t Cu.
82	Ivy	21 24	133 57	Sn	Peg	
83	Watt Range	21 26	133 55	W	Peg	Bi associated.
84	Neutral Junction	21 31	133 58	W	Peg	
85	Haasts Bluff	23 26	131 57	Cu	Mag	
86	—	22 33	134 57	Cr	Mag	Talc schist; assays up to 0.6% Cr.
87	Xanten	22 41	136 04	Cu	Mag	Estimated production 5-10 t Cu.
88	—	22 13	132 44	Mn	Wea	Laterite. Cu, Pb, Zn also present.
89	Mordor Complex	23 27	134 27	Cu, Ni, Cr, U, Th	Mag	Ultramafite assays 0.3% Cr. Albitite assays 2.88% U, 0.98% Th (Kostlin, 1971).
90	—	23 12	134 13	Diamond	Mag	One diamond (0.0002 carat = 0.00004 g) in stream sediment.

Table 2: List of mineral occurrences in Arunta Block

* Str = stratabound, Peg = pegmatitic, Met = metasomatic, Hyd = hydrothermal, Mag = magmatic, Wea = weathering.
\+ Not mentioned in text; described in Warren *et al.* (1974).

Black, in prep.), and dating of the Mud Tank Carbonatite is in progress. The late Proterozoic migmatization in the southern part of the Block has been dated at 1076 m.y. (Marjoribanks & Black, 1974), and this date sets an older time limit for the beginning of subsequent deposition in the Amadeus Basin. The retrogressive metamorphism that accompanied the late Palaeozoic Alice Springs Orogeny has been dated at 342 and 319 m.y. (Carboniferous) at Arltunga (Armstrong & Stewart, 1975). The Alice Springs Orogeny was also accompanied by local melting and pegmatite emplacement in the eastern part of the Harts Range (Black, *op. cit.*).

Mineral occurrences

Introduction

The Arunta Block has produced mainly copper, gold, tin, and tungsten, small amounts of other metals, and mica, in total worth about $10 million (total production at early 1976 prices). Mineral occurrences in the Block, together with their locations, elements present, genetic type in the classification of Lindgren (1933) as modified by Park & MacDiarmid (1964), and notes on production, etc., are listed in Table 2. The mineral occurrences are plotted in Figure 3, and have been assigned to the following genetic categories: 1—stratabound (and/or stratiform), 2—pegmatitic, 3—metasomatic, 4—hydrothermal, 5—magmatic, 6—weathering.

Stratabound (Figure 3-1)

These are base-metal occurrences containing copper, lead, zinc, and in some cases small amounts of bismuth, gold, and silver. The content of zinc equals or exceeds that of copper. They can be grouped into two types—the Jervois type and the Oonagalabi type.

The **Jervois type** (1, 16a-b)* are located in the northern part of the Arunta Block (henceforth referred to as the northern zone) in dominantly pelitic metasediments of Division 2. The Jervois lodes themselves (1) are the largest in the Arunta Block, and contain copper, lead, zinc, silver, and minor bismuth; tungsten is present in the hanging wall

***Number in parenthesis refer to locations of occurrences in Figure 3 and entries in Table 2.**

above the base-metal lodes (Watson, 1975). The lodes are lenticular (Holmes, 1972), and lie along a synform in metapelitic and calc-silicate rocks. Fluorite and scheelite occur in a small intrusive plug in the axial zone of the synform. Metamorphic facies of the country rocks is high greenschist or low amphibolite (Robertson, 1959; Morgan, 1959). Ore grades are listed in Table 1. Watson (1975) suggested a two-stage process for the genesis of the Jervois lodes: syngenetic deposition of sulphides in reef carbonates (or in sabkha carbonate ooze—Warren, 1974), followed by migration of the base metals in brine along faults to the lode positions.

The Reward prospect (16a) is a small subsurface group of three steeply dipping weakly mineralized zones in sericite schist, biotite-sericite schist and sericite quartzite of Division 2 (Anon., 1967). The sulphides present are pyrite, chalcopyrite, and sphalerite. At the surface, the prospect is marked by a hydrothermal quartzose lode containing pyrite, chalcopyrite, galena, and their oxidation products in a sericitic shear zone (Warren *et al.*, 1974).

Weakly mineralized carbonaceous schistose meta-siltstone (16b) is present in the subsurface 5 km southwest of the Reward prospect. Intermittent films and fractures in the rock are filled with pyrite, chalcopyrite, and sphalerite over a width of about 36 m. The longitudinal extents of both subsurface prospects are not known. They are currently (October 1976) under investigation by GSNT.

The **Oonagalabi type** occurrences (56, 57, 58, 59, 60, 61, 62; probably also 49, 52, 53) are all located in the southern part of the Block (henceforth, the southern zone) in rocks of Division 1. They are characterized by a distinctive lithological assemblage of three adjoining rock-types, all of them mineralized. They are: (i) forsterite marble, accompanied by calcium minerals such as diopside; (ii) gneisses containing abundant magnesium and aluminium, and characterized by anthophyllite, cummingtonite-gedrite, Mg-Al spinel, enstatite, and sapphirine; and (iii) quartz-magnetite rock, which occurs everywhere except at Oonagalabi itself (Warren *et al.*, 1974; 1975). A fourth rock-type, para-amphibolite, is also present in the mineralized zone in some occurrences. The mineralized rocks lie at the stratigraphic break (possible unconformity) between the two subdivisions of Division 1 of the Arunta Block. Primary economic minerals present in the occurrences are chalcopyrite, sphalerite, and galena (generally confined to the marble).

Fine to coarse-grained phlogopite is a characteristic constituent of the mineralized rocks of the Oonagalabi type, and at Johannsen's Phlogopite Mine (62) this mineral occurs as very coarse books in cordierite-feldspar gneiss and forsterite marble. The phlogopite was mined during World War II.

Small amounts of native gold occur with the sulphides at Oonagalabi (Warren *et al.*, 1975) and Johannsen's Phlogopite Mine (Stillwell, 1943).

The origin of the Oonagalabi type of deposits is not known. They resemble the Orijärvi and Lampinsaari deposits of Finland, and these are both regarded as having been formed by metasomatism, namely, of felsic and aluminous granulites and marble by igneous solutions at Orijärvi (Eskola, 1914; 1950), and of dolomite and basic volcanics by igneous or syngenetic (connate) solutions at Lampinsaari (Kahma, 1973). However, the stratabound nature of the Oonagalabi occurrences and the absence of igneous rocks in their vicinity suggests a sedimentary origin, possibly as a marine sequence of shale overlain by bituminous (and metalliferous) evaporitic dolomite and chert, the whole subsequently metamorphosed. Warren (1974) suggested a syngenetic origin by weathering of pre-existing rock together with simultaneous precipitation of base-metals from groundwater in the weathering profile. Weathering of a mixed terrain of silicate and carbonate rocks by nearly stagnant groundwater of neutral to slightly alkaline pH and reducing Eh could produce an assemblage of magnesium and aluminium clay minerals such as montmorillonite, palygorskite, and possibly also kaolinite and magnesite (Lukashev, 1958 translated 1970, p. 155; Deer, Howie & Zussman, 1962, p. 241) whereas potassium, most of the sodium, calcium, iron, and silicon would be taken into solution. Evaporation of the groundwater would precipitate the calcium, iron, and silicon as calcrete and a ferruginous silica pan above the water-table, whereas the soluble alkalies would remain in solution and eventually be removed by groundwater flow. In this way, the three contrasting rock-types characteristic of the Oonagalabi deposits could be formed. The conditions for such a weathering profile to develop would need to be: a fairly average overall rainfall to decompose the rocks, a low floral content in the soil to prevent the groundwater from being too acid, a landscape of low relief and poor drainage to hinder removal of cations produced by decomposition of the rocks (except alkalies), and to allow formation of clays, and seasonality of the rainfall to allow evaporation of the groundwater and deposition of calcium, iron, and silicon. Such conditions would not have been dissimilar from those that prevailed during mid-Tertiary time in inland Australia, where long-continued weathering of an old landsurface approaching a peneplain produced vast tracts of calcrete, silcrete, and laterite over a kaolinitic leached zone. The main difference would have been the paucity of plant life during the early Proterozoic, resulting in nearly neutral groundwater that enabled Mg-clay to precipitate, as well as kaolinite.

Pegmatitic (Figure 3-2)

Minerals of economic interest are present in granitic pegmatite or quartz veins—mostly in the northern zone—where they contain copper, lead, tin, tantalum, tungsten, bismuth, uranium, and lithium. In the southern zone, the pegmatites contain beryllium, uranium, thorium, rare earth elements, and mica. Many of the pegmatites have been mined by small syndicates in the past, but none is currently being worked.

Copper occurrences (2a, 33, 34, 35, 37, 54, 55, 73) are generally near granite in metapelitic schist or phyllite of Division 2. The country rocks, however, also include calc-silicate rock, granitic gneiss, amphibolite, and basic metavolcanics. The lodes are small, and consist of assemblages of chalcopyrite, pyrite, and galena—and their corresponding secondary and oxidized equivalents—in pegmatite or quartz veins which are commonly slightly discordant to the foliation of the country rock. The absence of mica in the veins indicates that they are not metamorphic segregations from the micaceous country rock schist or gneiss. The common occurrence of granite near the pegmatite and quartz vein coppers suggest that the veins and the copper in them originated from the granites.

Lead (14, 35, 55, 64, 71) occurs as galena in small quartz or pegmatite veins in both the northern and southern zones of the Arunta Block. The veins are emplaced in a variety of country rocks, including biotite gneiss, felsic schist, sericite schist, granitic gneiss, amphibolite, and calc-silicate rock. The galena in all the deposits is argentiferous. At Jubilee Silver King, the galena is largely replaced by chalcocite, and what remained of the galena has altered to anglesite and a small amount of native silver (CSIRO, 1957).

The tin prospects in the Arunta Block are situated in the northern zone (Figure 3), and consist of cassiterite in pegmatite and greisen. Six small prospects (12, 13, 17, 21, 22, 82) are known; all lie in an east-northeast-trending zone of small faults of various orientations which crosses the west-northwest trend of the major faults in the Arunta Block (Figure 1). The tin-bearing pegmatites intrude metapelitic schist of Division 2, and in all cases granite crops out a few kilometres nearby. Calc-silicate rock and quartzite accompany the schist at the Mount Allan Tin Mine (17); the tin-bearing pegmatite at this locality is heavily kaolinized.

Tantalum (8, 9, 12, 13, 23) is found only in the northern zone, and occurs as tantalite in pegmatites intruded into metapelitic schist and gneiss of Division 2. Some of the tantalum occurs with tin in the tin zone that extends from Yuendumu to Barrow Creek, but it also forms small concentrations away from this zone, and in these it is accompanied by bismuth. The tantalite is commonly weakly radioactive (8, 9, 13) (Daly & Dyson, 1963).

Tungsten (7, 12, 19, 20, 24, 27, 32, 41, 83, 84) generally occurs as wolframite in pegmatitic segregations or quartz veins in the border zones of granites in the northern zone of the Arunta Block; some are known in granite well away from its margins. At all these occurrences the wolframite-bearing granite is surrounded by metapelitic schist and sandstone of Division 2. The occurrence at Delmore Downs (6) consists of wolframite disseminated in metapelitic gneiss near granite. The wolframite-bearing granites themselves include representatives of both the earlier syntectonic batholiths and the later porphyritic plutons.

Small quantities of bismuth minerals are known in some pegmatites in the northern zone (8, 9, 35, 83), where they accompany tantalum, copper, lead, and tungsten. A small amount of bismuthinite occurs with galena and pyrite in vein quartz (71) in the southern zone.

The lithium minerals elbaite, spodumene, and lepidolite occur in pegmatite a few kilometres east of the Anningie tin field (13) (Pontifex, 1965). Beryl is present in several pegmatites in the Harts Range (Joklik, 1955).

Grains of a uraniferous silicate are present in radioactive gossan (36) on strike with a quartz vein that cuts granite 55 km west of Yuendumu (Warren *et al.*, 1974; Ivanac & Spark, 1976). Uranium, thorium, and rare earth elements are present in monazite, samarskite, and betafite in several pegmatites in the Harts Range (Joklik, *op. cit.*). Biotite gneiss of Division 1 north of the Plenty River Plain contains up to 0.016 percent Th (Mannoni *et al.*, 1971).

Muscovite was mined from 1888 to 1961 from numerous pegmatites in the Harts Range and Plenty River Plain (Figure 3) (Joklik, 1955). A total of 1660 t was produced (Gourlay, 1965). The mica-rich pegmatites fill cross-cutting fractures in mica-rich metapelitic gneisses of the middle-amphibolite metamorphic facies. The gneisses form the outer part of a large dome of metamorphic rocks—the Harts Range Group—and are assigned to Division 2. The inner part of the dome consists of non or poorly micaceous felsic gneisses, and pegmatites cutting these rocks are poor in mica (Joklik, *op. cit.*). Hence the pegmatites are regarded as partial melts originating in the nearby country rocks. The best muscovite came from zoned pegmatites containing oligoclase. The last mines could not compete with imported mica, and were abandoned in 1961 when the Commonwealth Mica Pool ceased operation.

Metasomatic (Figure 3-3)

Metasomatic tungsten occurrences (1, 2b-g, 3) are in general larger than those of the pegmatite type described above. One—Molyhil (3)—is currently being worked (1976), but it has not been drilled and reserves are unknown. The tungsten occurs as scheelite in layers in calc-silicate rock of Division 2. Bowen *et al.* (1972) found that the scheelite in the Bonya Mineral District (2b-g, immediately east of the Jinka Granite) is generally restricted to within 400 m of granitic pegmatites that cut the calc-silicate rocks, and Molyhil is situated in a roof pendant of calc-silicate rock in the west of the Jinka Granite. It seems that the tungsten has been metasomatically introduced from this granite, and when we recall that the pegmatitic tungsten lodes all occur in or near granites that are surrounded by schist and sandstone—but not by calc-silicate rock, it appears that the calc-silicates have acted as a sink for tungsten that became concentrated in the late magmatic fraction of the granite. Where the tungsten-bearing granites were surrounded by non-calcareous schist and sandstone, the tungsten remained in the residual part of the magma, and crystallized as wolframite.

Molybdenite occurs with the scheelite at Molyhil (3), and is being stockpiled in mill tailings. Molybdenite (74a) occurs in felsic gneiss in the eastern part of the Harts Range (Warren *et al.*, 1974), but details of the occurrence are not known.

The two copper occurrences classed as metasomatic consist of copper sulphides in calc-silicate rock (44) or in quartz veins in calc-silicate marble (48) of Division 1 in the southern zone (Shaw, 1970; Warren *et al.*, 1974). Both deposits have been worked by small syndicates, but are now abandoned.

Hydrothermal (Figure 3-4)

Gold produced in the Arunta Block came from the White Range goldfield (65) in the eastern part of the southern zone; smaller amounts came from the nearby Arltunga goldfield (79), from the Wheal Fortune (66a) and adjacent mines north of the White Range, and from the Winnecke goldfield (63) 40 km west of White Range.

The White Range, Arltunga, and Winnecke goldfields are situated in the central and western parts of the Arltunga Nappe Complex. At White Range, the lodes were quartz-pyrite-chalcopyrite bodies that filled tension joints and fissures in the metamorphosed Heavitree Quartzite; the gold was contained in the pyrite, or in limonite near the surface, where oxidation had taken place (Hossfeld, 1937a). At Winnecke the gold was mined from similar oxidized quartz-pyrite veins in Heavitree Quartzite and schist of the Bitter Springs Formation, but chalcopyrite was generally absent (Hossfeld, 1940). The nature of the gold lodes west of Arltunga is not known with certainty; veins observed during geological mapping of the area by BMR in 1971 are similar to those in the Winnecke goldfield. The auriferous lodes in the Arunta basement rocks north of the White Range (66a-b, 67a-b, 68, 69, 70) were generally quartz-pyrite veins, but some also carried abundant calcite and/or siderite, and some were composed of quartz and calcite without pyrite (Hossfeld, 1937b).

The time of formation of the auriferous lodes in the metamorphosed Heavitree Quartzite is indirectly dated at 322 m.y. (Carboniferous) on muscovite of sample 206 in Stewart (1971b), which comes from one of many quartz 'blows' that fill irregular fissures in the metamorphosed Heavitree Quartzite of the White Range-Arltunga area. Warren *et al.* (1974) suggested that the gold in the White Range lodes may have been introduced by mobilization during Devonian-Carboniferous time of older lodes in the adjoining Arunta basement rocks to the north. However, the basement rocks of the Arunta Block north of White Range are known to have undergone substantial retrogressive metamorphism during the Carboniferous (Stewart, 1971a, 1971b; Shaw *et al.*, 1971; Armstrong & Stewart, 1975)—calcic plagioclase altered to epidote, white mica (muscovite and paragonite) and calcite, hornblende altered to epidote and calcite, biotite altered to chlorite, and quartz

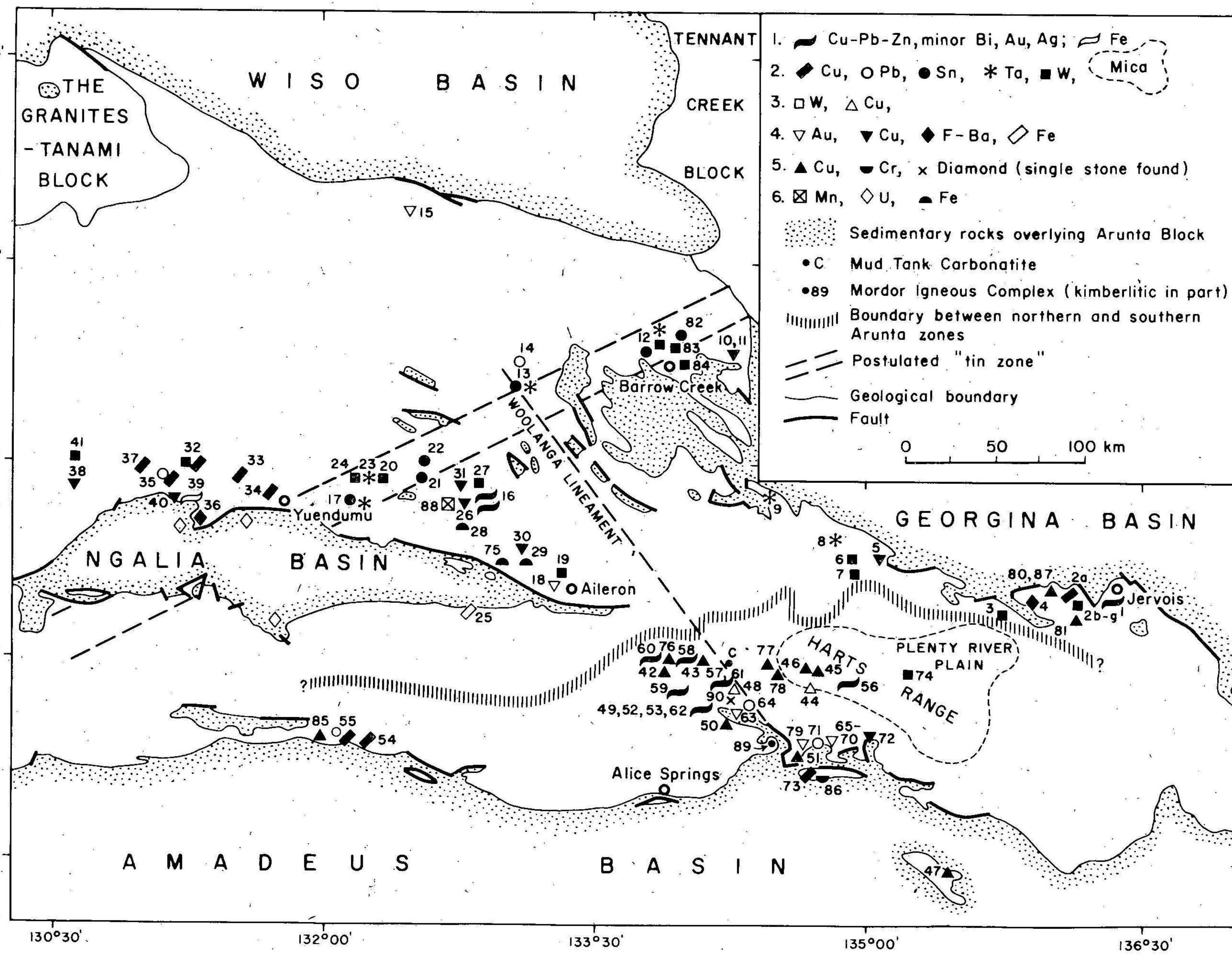

Figure 3. Distribution of mineral occurrences in Arunta Block; categories 1 to 6 explained in text. Orientation of elongate metallogenic symbols has no structural significance.

was extensively recrystallized. Hence, we now believe that the abundance of carbonates in the auriferous lodes in the Arunta basement rocks north of White Range indicates that these lodes are hydrothermal concentrations, in fissures, of silica and carbonate that were mobilized during the retrogressive metamorphism, and hence are also of Devonian to Carboniferous age. The origin of the lodes by retrogressive metamorphism is also supported by the existence of several veins of pyrite epidosite (pyrite-epidote-quartz rock) noted during mapping of the region by BMR in 1968.

Gold (15, 18, 26) also occurs in the northern zone in fault zones which cut a variety of rocks, including metapelitic schist and gneiss, metasandstone, metadolerite, hornfels, and granite.

Seven hydrothermal copper occurrences (5, 10, 16a, 30, 31, 38, 40) are located in fault or shear zones generally in metapelitic schist of Division 2; at White Hill Yard (30) the metapelitic country rocks are at high amphibolite or low granulite facies. All the occurrences are in the northern zone. Copper minerals present include chalcopyrite, bornite, pyrite, galena, and chalcocite, and are commonly accompanied by vein quartz or quartz stringers. At Home of Bullion (10), sphalerite is a major constituent and the lodes occupy parallel shear zones (Hossfeld, 1937c; Sullivan, 1953) which are one half of a complementary set of shear planes symmetrically disposed about the axial planes of the macroscopic folds in the area. Presumably the lodes formed by mobilization and deposition of ore shortly after folding. Both in metal content and nature of surrounding country rocks the Home of Bullion lodes resemble the stratabound lodes of the Jervois type described above, and so may be derived from such an orebody at depth.

Fluorite and smaller amounts of barite are major constituents of certain hydrothermal veins which cut some of the granites in the northern zone. The largest veins—in the Jinka mineral district (4)—cut the Jinka Granite east and west of the Elyuah Range in the east of the Arunta Block (Figure 1), and consist of quartz-fluorite-barite and minor hematite, malachite, azurite, and galena. Hill (1972) regarded the veins as telethermal to epithermal. Some of the Jinka veins also cut the lowest unit of the Proterozoic sequence in the Elyuah Range (Hill, *op. cit.*), and so are considerably younger than the Jinka Granite. The mineralogically similar Vaughan Springs fluorite prospect (36) cuts granite 55 km west of Yuendumu, and is on strike with a fault in the lower part of the nearby late Proterozoic sequence of the Ngalia Basin. The prospect is currently (October 1976) being assessed by GSNT. Small quartz-fluorite veins (not plotted in Figure 3) cut granite in the Anmatjira Range (Stewart *et al.*, in prep.) and porphyritic granite immediately south of Mount Esther (Offe, in prep.).

Magmatic (Figure 3-5)

Numerous small occurrences (42, 43, 45, 46, 47, 50, 51, 80, 81, 85, 87) of copper sulphides or their oxidized equivalents are disseminated in lenses or layers or concentrated in shears or joints in metamorphosed basic rock. All but two (81, 87) are in the southern Arunta zone, and few have been mined. They are probably small concentrations localized during initial crystallization of the rock, or during later recrystallization and deformation. Traces of copper and nickel sulphides are present in monzonite and melamonzonite of the Mordor Igneous Complex (89) (Kostlin, 1971), and are currently (1976) being investigated by GSNT (Barraclough, 1975). The Mordor Complex also contains uranium and thorium silicates (including brannerite and uranophane) in various plagioclase-rich rock-types (Kostlin, *op. cit.*). Chromium occurs in ultramafic differentiates of the Mordor Complex (Langworthy & Black, in prep.), and in two small exposures of talc schist (86) at the western end of the Giles Creek Synform (Shaw *et al.*, in prep.). The schist forms part of a unit of basic metavolcanics, and is considered to be metamorphosed ultramafic igneous rock.

Weathering (Figure 3-6)

Manganiferous laterite has formed on carbonate rocks at a number of localities in the Arunta Block, particularly in the northwest, where laterite (88) on limestone and dolomite of Division 3 contains up to 58 percent Mn (Stewart *et al.*, in prep.).

Uraninite and carnotite occur in several areas in Devonian and Carboniferous lacustrine sandstones of the Ngalia Basin (Ivanac & Spark, 1976) and Amadeus Basin, and in Quaternary calcrete overlying or flanking the Arunta Block. The discoveries are currently (1976) being prospected and evaluated. A BMR survey of part of the northwestern Arunta Block in 1958 found that the granites in this area are notably radioactive (Carter, 1960), and prospecting of some of these granites has shown that in places they have up to 10 times the average uranium content for granite, and in faults and shear zones up to 150 times the average for granite (Davies, 1973; Paltridge, 1973). An airborne survey over the Alcoota 1:250 000 Sheet area (north of the Harts and Strangways Ranges—Figure 1) detected anomalous uranium radiation from two areas of granite (Wyatt, 1974). These data, and the occurrence of uranium in pegmatites at several localities in the Arunta Block (described above), indicate that the Arunta rocks are the likely source of much of the uranium in the over-lying sediments.

Gemstones and mineral specimens

Coarsely crystalline mineral specimens are obtained from the pegmatites and metamorphic rocks of the Harts Range, and faceted gemstones of zircon, garnet, cordierite, and smoky quartz have been cut from material from the Mud Tank Carbonatite, the Harts Range, and elsewhere. A single small diamond (90) was found 10 km southwest of the Woolanga Lineament (Figure 3) in 1973 (Stracke, 1974).

Comparisons with other areas

Shaw & Stewart (1975) have drawn attention to the marked lithological similarities of the Arunta Block to its two tectonic neighbours, The Granites-Tanami Block (Blake & Hodgson, 1975; Blake *et al.*, in prep.) and the Tennant Creek Block (Crohn, 1975; Le Messurier, 1976; Mendum & Tonkin, in prep.). In both these regions there is a lower pelitic sequence (Tanami complex and Warramunga Group, respectively) of siltstone, shale, micaceous quartz sandstone, greywacke, and minor basic volcanic rocks, all metamorphosed to lower greenschist facies, which correlate with Division 2 of the Arunta Block. These rocks are unconformably overlain by cleaner sedimentary rocks (Pargee Sandstone and Hatches Creek Group respectively) comprising quartzite, sandstone, conglomerate, and acid volcanics, correlated with Division 3. The sequences in both regions are intruded by granites dated at between 1800 and 1700 m.y. (Page *et al.*, 1976; Riley, 1968; Crohn, *op. cit.*). Hematite quartzite, garnet-mica gneiss, grunerite-garnet gneiss, and plagioclase gneiss intruded by acid to basic igneous rocks 30 km west-southwest of Tennant Creek may be basement to the Warramunga Group (Mendum & Tonkin, *op. cit.*; Crohn, *op. cit.*), and hence may be correlated with Division 1 of the Arunta Block. An equivalent of Division 1 is not known in The Granites-Tanami Block. The Warramunga Group at

Tennant Creek is host to high-grade gold deposits in conformable lenticular ironstone bodies, and to copper-gold-bismuth lodes in steeply plunging ironstone bodies in the cores of zoned pipes of hydrothermally altered and metasomatized metapelite (Le Messurier, 1976; Large, 1975). Quartz veins in metapelitic rocks of the Tanami complex were worked for gold from 1900 to 1960.

The Arunta Block also shows similarities to the Willyama Block, around Broken Hill. The succession in the Willyama Block comprises phyllite, slate, metapelitic schist and gneiss, calc-silicate rock, banded iron formation, quartz-feldspar gneiss, feldspathic gneiss, and amphibolite, formed by the metamorphism of siltstone, shale, sandstone, impure dolomite, and basic sills (Thomson, 1975). The assemblage resembles Division 2 of the Arunta Block, and, as in the Arunta, the metamorphism and accompanying synorogenic granites are dated at 1700 m.y., followed in this area by emplacement of pegmatite at 1560 m.y. and post-orogenic granite at 1520 m.y. (Thomson, *op. cit.*). The sequence at Broken Hill itself—the Mine Sequence—is interpreted as a conformable assemblage of basic and acid volcanics, shale, and quartzite metamorphosed to high amphibolite-low granulite facies (Johnson & Klingner, 1975). Several of the rock-types in the Mine Sequence, particularly the sillimanite gneiss and Potosi Gneiss, show marked resemblances to the Lander Rock Beds and Mount Stafford Beds, and the Irindina Gneiss (respectively) of the Arunta Block. The Broken Hill area is Australia's major producer of silver, lead, and zinc; the metals occur in tightly folded sulphide orebodies in the Mine Sequence, and are now generally regarded as syngenetic in origin (Johnson & Klingner, *op. cit.*).

Outside Australia, the Arunta Block is similar lithologically, stratigraphically, and temporally to parts of the Precambrian of the Baltic region (notably Sweden and Finland) and East Africa.

The oldest rocks in Sweden are gneisses of Archaean age, and these are basement to the unconformably overlying Svecofennian rocks (Magnusson, 1960). The latter is a thick sequence of basic to acid volcanics, detrital sediments, and calc-silicate rocks which were folded and metamorphosed at about 1950 m.y. (Geijer, 1963), and which are similar to those of Division 1 of the Arunta Block. Unconformably overlying the Svecofennian rocks are phyllite, greywacke, and slate of the Elvaberg Series and Upper Phyllite Series (Geijer, *op. cit.*), and these correspond lithogically to Division 2. Unconformably above these rocks are conglomerate, quartzite, slate, limestone, dolomite, and basic volcanics of the Karelian (Magnusson, *op. cit.*; Geijer, *op. cit.*), which corresponds lithologically to Division 3. The Svecofennian, Upper Phyllite Series, and Karelian rocks are all intruded by granites dated at 1850-1750 m.y. (Magnusson *et al.*, 1960), which is the same age as the early granites of the Arunta Block. The Svecofennian volcanics are host to numerous stratabound base-metal deposits, such as those in the Skellefte region (Rickard & Sweifel, 1975), which are similar to the Oonagalabi type of the Arunta Block.

Similar rocks to the Swedish sequence are present in Finland, but here the Svecofennian and Karelian are considered to be equivalents (termed Svecokarelide), because they both overlie basement of Archaean age, and proof of unconformity between the two is lacking (Simonen, 1960; Eskola, 1963; Kahma, 1973). Almost all the economic ores in Finland are in the Svecokarelide rocks, and include numerous stratiform base-metal deposits in the 'Main Sulphide Ore Belt' (Kahma, *op. cit.*), some of which are similar to the Oonagalabi type in the Arunta.

In East Africa, Archaean rocks of the Nyanza-Tanganyika Shield are unconformably overlain to the southwest by the Proterozoic Ubendian Belt of metapelite, basic metavolcanics, calcic granulite, migmatite, anorthosite, and charnockite, intruded by large synorogenic to post-orogenic granites (Pallister, 1971); the Ubendian rocks are dated at about 1800 m.y. (Pallister, *op. cit.*), and correspond lithogically in a general way to Divisions 1 and 2 of the Arunta Block. These rocks are unconformably overlain in the east by undeformed sandstone, dolomite, and basalt (the Abercorn Sandstone and Plateau Series of Zambia), and in the northeast by sediments of the Kibaran-Burundian-Karagwe-Ankolean belt, comprising metapelite and quartzite of low metamorphic grade; these sediments correspond lithologically to Division 3. The Abercorn Sandstone and Plateau Series are intruded and metamorphosed by granite dated at 1725 m.y.; the metasediments of the Kibaran-Burundian-Karagwe-Ankolean belt have yielded a single isotopic date of 1185 m.y. (Pallister, *op. cit.*), and are intruded by granites which are mined for beryllium, and are the source of alluvial tin and tungsten (Saggerson, 1962). The late Proterozoic episodes of metamorphism and granitic intrusion have their counterparts in the southern part of the Arunta Block (Marjoribanks & Black, 1974), described above in the section on Geology. The Proterozoic rocks of East Africa produce small amounts of copper, cobalt, tin, tungsten, and 15 percent of the world's beryllium (Unesco/ASGA, 1969). Carbonatites related to the East African Rift System have been worked for niobium. The major economic mineral of the region as a whole is diamond, which occurs in many kimberlite pipes of Mesozoic age in Tanzania, but in economic amount in only one, the Mwadui pipe (Edwards & Howkins, 1966), which produces 3 percent of the world's diamonds (Unesco/ASGA, *op. cit.*).

Discussion

Metallogenesis

As noted by Warren *et al.* (1974), the various types of mineral occurrences in the Arunta Block are distributed in two distinct geographic zones (Figure 3), which also differ geologically. The southern zone includes almost all the rocks of Division 1; rocks of Divisions 2 and 3 are generally metamorphosed to middle amphibolite facies; and granites are few and small. Metallogenically, the southern zone includes the stratabound base-metal occurrences of the Oonagalabi type, which are found only in rocks of Division 1; pegmatites are characterized by beryllium, uranium, thorium, rare earth elements, and abundant mica, and originated by partial melting of amphibolite-facies metasediments of Division 2; numerous magmatic occurrences of copper are located in metabasic rocks of Division 2, which are relatively more abundant in the southern zone; and hydrothermal gold lodes are restricted to the southern zone, where late Palaeozoic reactivation of the Arunta Block was most intense and penetrative. The northern zone, in contrast, is characterized by an almost total absence of rocks of Division 1; rocks of Divisions 2 and 3 are generally metamorphosed only to greenschist or low-amphibolite facies; and granites are large and numerous. Metallogenically, the northern zone includes a different type of stratabound base-metal occurrence, the Jervois type, which is found in rocks of Division 2, accompanied in a few places by compositionally similar hydrothermal derivatives (Home of Bullion, Reward); the pegmatites are characterized by the presence of copper, tin, tungsten, tantalum, and bismuth, and originated from the abundant granite masses; metasomatic deposits of tungsten are located near granite in this zone; and hydrothermal veins of fluorite and barite are present only in this zone. Occurrences formed by weathering—uranium and manganese—are found in superficial rocks of both zones. It thus appears that, in general, metal occurrence in the Arunta Block is closely related to rock-type, although other factors, such as faulting, deformation, and weathering, are also involved. These processes, following on from sedimentation and granite emplacement, allowed movement and concentration of some of the economically desirable elements.

The metallogenic history of the Arunta Block began during the accumulation of basic and acid volcanics and generally immature sediments of Division 1, when base metals were concentrated in the Oonagalabi stratabound occurrences, possibly during a time of still-stand and emergence. After more mature sediments of Divisions 2 and 3 had accumulated, folding, regional metamorphism, and partial melting led to the concentration of mica, uranium, and thorium in complex pegmatites and copper in ortho-amphibolite. Subsequent emplacement of large granite masses in the northern zone was accompanied by injection of simple pegmatites containing copper, tungsten, tantalum, and bismuth, presumably the residual elements from the granite magmas (cf. Tauson, 1974), and by metasomatism of calcareous country rocks to scheelite-bearing calc-silicate assemblages. The granites also brought with them uranium and tin, and epeirogenic movements that occurred towards the end of granite emplacement facilitated the concentration of these elements into fault zones. Further faulting led to the formation of small hydrothermal lodes of gold and copper.

The Arunta Block than became tectonically less active for about 800 m.y., although it was never quiescent in the classical sense of a stable craton, and at the end of this period downwarping initiated shallow-marine sedimentation in late Proterozoic basins around and over much of the Block. By Devonian-Carboniferous time, orogenic uplift halted marine deposition, and led to rapid erosion of the uplifted area and deposition of thick non-marine sandstone and conglomerate above the marine sequence. Eventually the erosion reached Arunta basement rocks, and allowed transport and deposition of uranium in the non-marine sediments. The late Palaeozoic orogeny culminated in thrust-faulting and folding of both basement and sedimentary cover, and the basement rocks were sufficiently heated to reset isotopic mineral dates throughout much of the Block (Black, 1975), mobilize fluorite and barite into fissures in basement and cover rocks of the northern zone, and metamorphose basement and the lowermost cover rocks to greenschist facies assemblages in the southeast of the Block, thereby mobilizing and concentrating gold into hydrothermal fissure fillings. In the Harts Range, the late Palaeozoic heating was sufficiently intense to form pegmatitic partial melts (Black, *op. cit.*). Finally, long-continued weathering and erosion during much of the Mesozoic and Cainozoic enabled further movement and concentration of uranium to take place in the late Palaeozoic non-marine sediments and in late Cainozoic superficial calcrete.

Future prospects

The mineral commodities of greatest potential value in the Arunta Block are base metals (copper, lead, and zinc), gold, and tungsten. Economic base-metal deposits of the Oonagalabi type may yet be discovered in Division 1 of the Arunta Block, and if so will probably contain small amounts of bismuth, gold, and silver as well. However, there is no evidence at present that any further occurrences will be larger than those already known. The rocks of Division 2, in which the economically paramarginal base-metal lodes at Jervois and Home of Bullion are situated, crop out across the whole northern zone of the Arunta Block, and the presence of three small prospects of the same type within 5 km of one another between the Reynolds and Anmatjira Ranges may signify the existence of further deposits there. The same rocks are also host to two other common types of copper occurrence, namely hydrothermal and pegmatitic. However, the latter are derived from granitic source rocks, and so further occurrences of this type are unlikely to be large. Basic igneous rocks are not a likely source of large magmatic copper deposits, unless a very large basic rock mass is found in which extensive segregation has taken place; the Riddoch Amphibolite in the Harts Range Group is very large, but has only a few small copper concentrations in it. Diorite and tonalite in the Giles Creek Synform in the southeast of the Block may warrant examination for low-grade copper deposits, and in fact two very small copper occurrences are known here, consisting of partly oxidized chalcopyrite in quartz and quartz-calcite veins (Shaw *et al.*, in prep.). Both veins cut metamorphosed basic volcanic rocks which are intruded by the diorite-tonalite-granite complex, but copper minerals are not known in the plutonic rocks themselves.

The easily mined gold deposits in the White Range, Arltunga, and Winnecke areas have been exhausted, and the other areas affected by Devonian-Carboniferous tectonism and metamorphism along the southern margin of the Arunta Block are not known to contain gold. Detailed investigations in these areas, namely, the eastern part of the Arltunga Nappe Complex by Khan (1972) and Shaw *et al.* (1971), and of the Ormiston Nappe Complex by Marjoribanks (1975), have shown that, in contrast to the central and western parts of the Arltunga Nappe Complex (Stewart, 1971a; Shaw *et al.*, 1971), penetrative deformation and greenschist metamorphism were restricted to the immediate vicinity of thrust faults, whereas the bulk of the rock between the faults was largely unaffected by penetrative processes. A similar situation prevails at Alice Springs itself, where movement of the Blatherskite Nappe took place along a single thrust fault (Stewart, 1967). As gold has never been discovered in these particular areas it appears that the formation of the gold deposits at White Range, Arltunga, and Winnecke was the result of the penetrative nature of the deformation and greenschist facies metamorphism in the latter areas. If this is so, it seems unlikely that gold is present in the Ormiston Nappe Complex, the Blatherskite Nappe, the eastern part of the Arltunga Nappe Complex, or in the area of extensive thrust-faulted Arunta basement and Heavitree Quartzite southeast of the Arltunga Nappe Complex (Figure 1). However, the large area of infolded Arunta basement and Heavitree Quartzite 50 km west of the Ormiston Nappe Complex has not yet been studied in detail, and if extensive penetrative deformation and low-grade metamorphism have taken place there, this area may be prospective for small gold lodes. In the other main area of Carboniferous tectonism—the northern margin of the Ngalia Basin—the movement took place along discrete thrust faults, and associated low-grade metamorphism was restricted in extent; the probability of discovering gold there is low. The area of Tertiary sediments north of the Winnecke and White Range goldfields, between the Arltunga Nappe Complex and Harts Range (Figure 1), may warrant prospecting for alluvial gold. Mapping of the biotite isograd in the large areas of greenschist facies rocks of Divisions 2 and 3 of the northern Arunta Zone may lead to additional discoveries also, as gold is localized along the biotite isograd in some other areas—e.g., the Lachlan Geosyncline of New South Wales (Warren, 1972).

After the base and noble metals, tungsten is the most likely metal to be present in significant quantity in the Arunta Block. Calc-silicate host rocks and granitic source rocks of the types known at the Molyhil mine are common throughout the northern zone of the Block, and so further economic deposits of tungsten may be present in that region. Molybdenum may also be present in any further discovery of this type.

Tin exhibits some degree of structural control, although this is only an empirical observation as yet. If the tin zone is a real tectonic lineament, other tin deposits may be located along it, but they will probably be similar in size to the presently known uneconomic occurrences. Tantalum and tungsten may be associated with any further tin occurrences.

Economic amounts of fluorite and barite may be present in veins around the margins of the Georgina and Ngalia Basins, which overlie the Arunta Block, or in veins intruding the base of the basin sequences themselves.

The entire Pertnjara Group (Devonian) of the Amadeus Basin, and its lithological counterpart in the Ngalia Basin—the Mount Eclipse Sandstone (Carboniferous)—are prospective for uranium. In addition to these formations, basins of Tertiary 'deep alluvium' in the northern Arunta zone contain up to 250 m of unconsolidated gravel, sand, clay, and coal seams (Morton, 1965; O'Sullivan, 1973; Shaw & Warren, 1975; Stewart, in press; Offe, in prep.), derived from the radioactive granites and surrounding country rocks, and so these basins may be prospective for stratiform uranium deposits.

In addition to those commodities that have been obtained from the Arunta Block in the past, other commodities may prove to be present in economic amounts. Chief among these are diamond from kimberlite, and niobium and rare earth elements from carbonatite. The proximity of the Woolanga Lineament (Figure 3) to both the Mud Tank Carbonatite and the Mordor Igneous Complex, which has chemical similarities to kimberlite, indicates the deep-seated nature of the Lineament, and suggests the possibility that true kimberlites and other carbonatites containing niobium and rare earth elements may have been emplaced elsewhere along or near the Lineament. The occurrence of a single diamond in the vicinity of the Lineament strengthens this possibility.

Conclusions

The Arunta Block, on present evidence, is a region of small uneconomic lodes of copper, lead, zinc, gold, tin, tungsten, bismuth, mica, fluorite, and a few rarer metals such as tantalum and molybdenum. In the northern part of the Block, most of the lodes, including copper, tin, tungsten, bismuth, tantalum, and molybdenum, are derived from granites, and so further occurrences are unlikely to be large. Sedimentary uranium derived from the granites is currently being evaluated, but whatever the results of the present assessments are, the predicted increase in demand (Hanrahan, 1975) will enhance the value of the occurrences in the future. In the southern part of the Block, the potentially most valuable lodes are the stratabound base-metal occurrences of the Oonagalabi type. Little exploration has been done to test the subsurface extensions of any lodes in the Arunta Block.

Geological mapping of the Arunta Block to date has shown it to be lithogically, stratigraphically, and temporally similar to a number of other Precambrian shield areas. In Australia, it closely resembles the Tennant Creek Block, which until 1975 produced 8000 t of copper, 6 t of gold, and 350 t of bismuth each year (Large, 1975), although copper production is now halted (October, 1976). The Arunta Block also resembles The Granites-Tanami Block, which produced about 550 kg of gold between 1900 and 1960 (Blake *et al.*, in prep.). The Willyama Block (Broken Hill area) is similar to the rocks of Division 2 of the Arunta Block; the Broken Hill area itself has produced 30 million t of combined silver, lead, and zinc, and a further 15 million t remain to be extracted (Johnson & Klingner, 1975). Outside Australia, the Arunta Block markedly resembles the Precambrian rocks of the Baltic region, where stratabound base metals are mined from rocks corresponding to Division 1' of the Arunta Block, and also the East African region, where tin, tungsten and beryllium are produced from granites which are geochemically similar to those in the Arunta Block. While recognizing that lithological character is only one of many factors that control the economic concentration of minerals, it does appear on present evidence that the Arunta Block holds some potential for economic deposits of these commodities. How much can be determined only by further exploration in the region.

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Quasicyclammina gen. nov. and *Thalmannammina* (Foraminiferida) from the Paleocene of Papua New Guinea

D. J. Belford

The new genus *Quasicyclammina* is described from the Lagaip Beds of upper Paleocene age in the Wabag area, Papua New Guinea; it is placed in the subfamily Cyclammininae of the family Lituolidae. This new genus has an agglutinated test wall, slightly asymmetrical test, short internal longitudinal partitions, and an asymmetrical interiomarginal aperture. Three species are described, *Q. breviseptum* sp. nov., *Q. compressa* sp. nov. and *Q. inflata* sp. nov., separated on the number of the chambers in the outer whorl and on the maximum diameter/thickness ratio.

A new species of the genus *Thalmannammina*, *T. anfracta*, is also described.

Introduction

The foraminifera described in this paper were obtained from samples collected during geological mapping of the Wabag area, Papua New Guinea, in 1963, by the Bureau of Mineral Resources; the specimens have been obtained from grey calcareous mudstones of the Lagaip Beds. The geology of this area was described by Dekker & Faulks (1964), and also by Dow *et al.* (1972). Sample localities are shown in Figure 1, and details of the measured sections in Figures 2 and 3. Planktonic foraminifera from these samples were described by Belford (1967); benthonic foraminifera are abundant but have not yet been studied. An internal structure was evident in the specimens here referred to *Quasicyclammina* gen. nov., clearly shown in specimens infilled with pyrite, but could not be related to that of any described genera. Specimens here referred to the genus *Thalmannammina* were studied initially to examine the wall structure of associated agglutinated forms which were infilled with pyrite; it was later decided to include them in the paper.

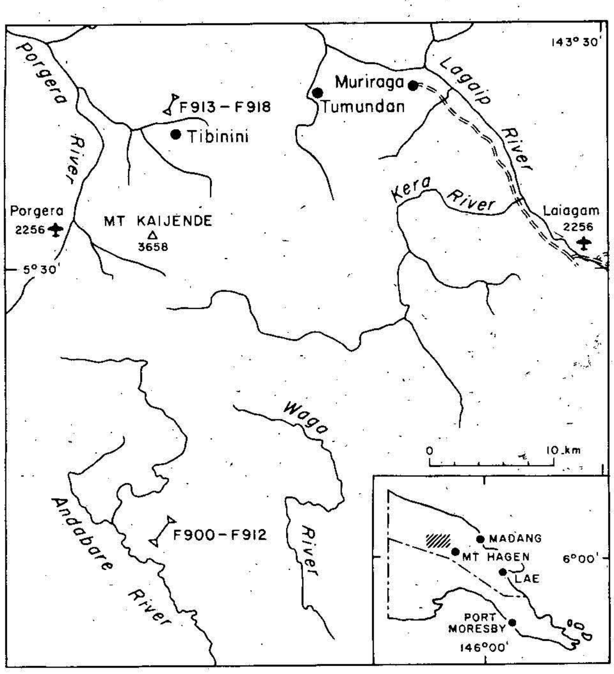

Figure 1. Locality map.

All figured specimens and thin sections are deposited in the Commonwealth Palaeontological Collection (CPC), Bureau of Mineral Resources, Canberra. Additional unfigured material is deposited in this collection, and also in the ESCAP Fossil Reference Collection (E.) held at BMR. All measurements given are in millimetres.

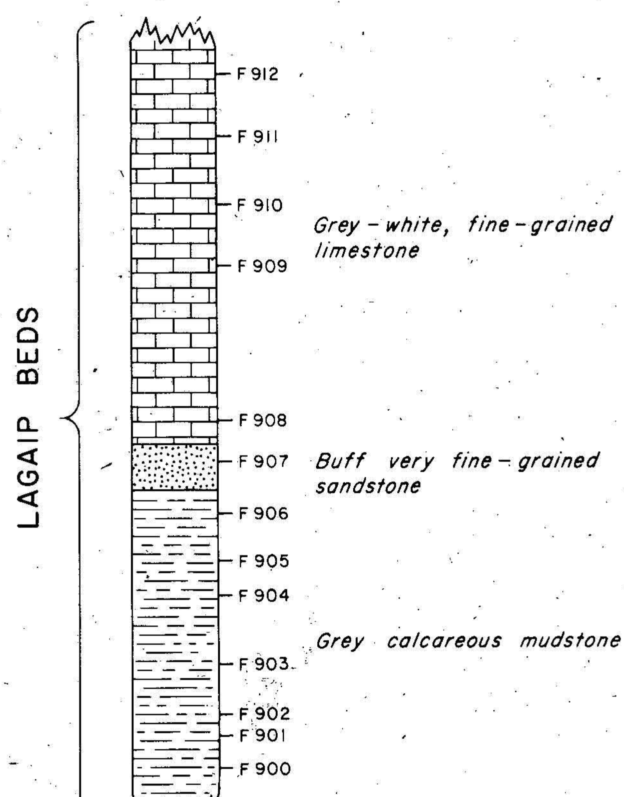

Figure 2. Section near Andabare River. This section, here drawn correctly, was inverted by Dekker & Faulks (1964) and Belford (1967); it is now known to have been measured on a limb of an overturned anticline.

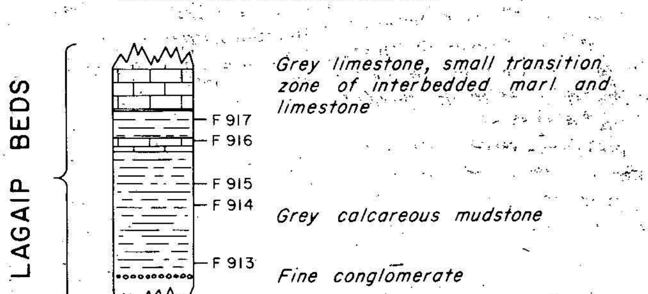

Figure 3. Section at Tibinini.

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Systematic descriptions

Family Lituolidae de Blainville, 1825
Subfamily Cyclammininae Marie, 1941
Genus Quasicyclammina gen. nov.

Type species: Quasicyclammina breviseptum sp. nov.

Description: Test involute, asymmetrical, interior with short irregularly inserted longitudinal partitions extending from test wall into upper part of chamber lumen, strongly developed only in outer whorl; test wall agglutinated with siliceous cement, wall and septa simple in structure. Aperture interiomarginal, asymmetrical.

Remarks: Taylor (1965) discussing Victorian Lower Tertiary "*Cyclammina* faunas" described a series of preservation stages resulting from replacement by pyrite. The internal structure of the Papua New Guinea specimens is more regular than that of the specimens illustrated by Taylor, is restricted to longitudinal partitions and is considered to be an original test structure. Taylor (*op cit.*) also referred to asymmetry of the final chamber, but considered this to be caused by distortion of the test. The Papua New Guinea specimens are also asymmetrical, but again this is regarded as an original test feature. Quilty (1974) recorded specimens referred to *Cyclammina* cf. *incisa* (Stache); these specimens also have a slight asymmetry, suggested by Quilty to be a primary feature and not a preservation phenomenon. These specimens are true *Cyclammina*, having an alveolar wall more complex than that of the Papua New Guinea specimens. The morphology of the present specimens indicates that a new genus is required to accommodate them.

The longitudinal partitions developed in *Quasicyclammina* gen. nov. vary in length, in thickness, and in direction of insertion into the chamber lumen. Although longitudinal partitions occur in early whorls they are not strongly developed, and can be observed clearly only in the outer whorl. Only rarely do adjacent partitions coalesce at their inner ends, and no true reticulate, labyrinthic or alveolar internal structure is formed. The irregular inner chamber wall, in conjunction with the longitudinal internal partitions, may result in apparent tubular extensions of the chamber ending just below the outer chamber wall; this appearance is often particularly evident in specimens infilled with pyrite.

The asymmetry of the test is slight but distinct, and is shown by different development of the umbilical depression on each side of the test, and by the asymmetry of the interiomarginal aperture. The test wall in all known species of *Quasicyclammina* gen. nov. is constructed of quartz grains and is smoothly finished, with a large proportion of siliceous cement.

Quasicyclammina gen. nov. appears to be closer to the genus *Mesoendothyra* Dain 1958 than to any other genus placed in the subfamily Cyclammininae. *Mesoendothyra* has an early plectogyral coil, tending to a planispiral asymmetrical test in the outer whorl; *Quasicyclammina* approaches planispiral development throughout, being only slightly asymmetrical. The wall of *Mesoendothyra* was originally described as having broad pores, perpendicular to the surface of the chamber (*fide* Ellis & Messina, Catalogue of Foraminifera, 1940, *et seq.*), and by Loeblich & Tappan (1964) as coarsely alveolar. The redrawn vertical section illustrated by Loeblich & Tappan (Figure 144, 6a-b) shows what could be interpreted as broad irregular extensions from the outer chamber wall, well developed only in the outer whorl, with narrow (?tubular) openings ending just below the outer chamber wall; the wall does not show the alveolar structure developed in other genera of the Cyclammininae. The difference in wall structure between *Mesoendothyra* and *Quasicyclammina* seems to be one of degree only, with the internal extensions in *Quasicyclammina* being more widely spaced and regularly developed, and having more clearly the appearance of incomplete longitudinal partitions. Banner (1970) discussed in detail the genera of the family Spirocyclinidae. Axial sections of specimens of *Quasicyclammina* gen. nov. resemble *Alveolophragmium (Reticulophragmium)* as figured by Banner (*op. cit.*, Plate 4, Figure 4); *Quasicyclammina* lacks the alveolar hypodermis seen in equatorial sections of *Alveolophragmium* (*Reticulophragmium*) and is also asymmetrical, not planispiral.

Horizontal sections of rare specimens give indications that traverse partitions are developed (see Figure 6, P). The structure of these specimens resembles that of the specimen figured by Banner (1970 Plate 13, Figures 1, 1a) as *Cyclammina* cf. *elegans* Cushman & Jarvis, but no septal areal apertures are present. Other Papua New Guinea specimens have an irregular wall in equatorial section (Figure, 6, 0). The short extensions into the chamber lumen are not as regularly developed as are the longitudinal partitions, and may result from partial solution of the chamber wall and replacement by pyrite; specimens of this kind have regularly developed longitudinal partitions. The inner whorls of the specimens shown in Figure 6, P, have a smooth inner wall, not yet having been affected by solution and replacement. Infilling by pyrite alone does not necessarily produce an appearance of traverse partitions, and it seems that partial solution of the test wall is also necessary. I have observed the same effect in specimens of the genus *Triplasia* (Belford, in press).

Taylor (1965) described the development of a cancellate wall structure in specimens which he referred to the genus *Haplophragmoides*, from Victorian Lower Tertiary deposits; these specimens previously had been referred to the genus *Cyclammina* (Chapman, 1904; Chapman & Crespin, 1930, 1932; Crespin, *in* Raggatt & Crespin, 1955). Several preservation stages were figured, with advancing solution and replacement of the test by pyrite; no horizontal sections of the Papua New Guinea specimens show as regular a structure as that figured by Taylor in his text figure 2c, which gives the appearance of a series of short transverse partitions. The preservation features discussed by Taylor were suggested to result not from infilling by pyrite, but from secondary alteration of the pyrite, causing chemical reactions which result in dissolution of the foraminiferal test. However the specimens illustrated by Taylor (1965, p. 146, figures 2 a-c) are re-interpreted by Ludbrook (in preparation) as an ontogenetic series of a new species of *Cyclammina*. Quilty (1974) recorded well preserved specimens, not affected by secondary alteration, from Tasmanian Tertiary beds, which he referred to *Cyclammina* cf. *incisa*; Taylor's specimens of *Haplophragmoides* cf. *incisa* were placed in synonymy.

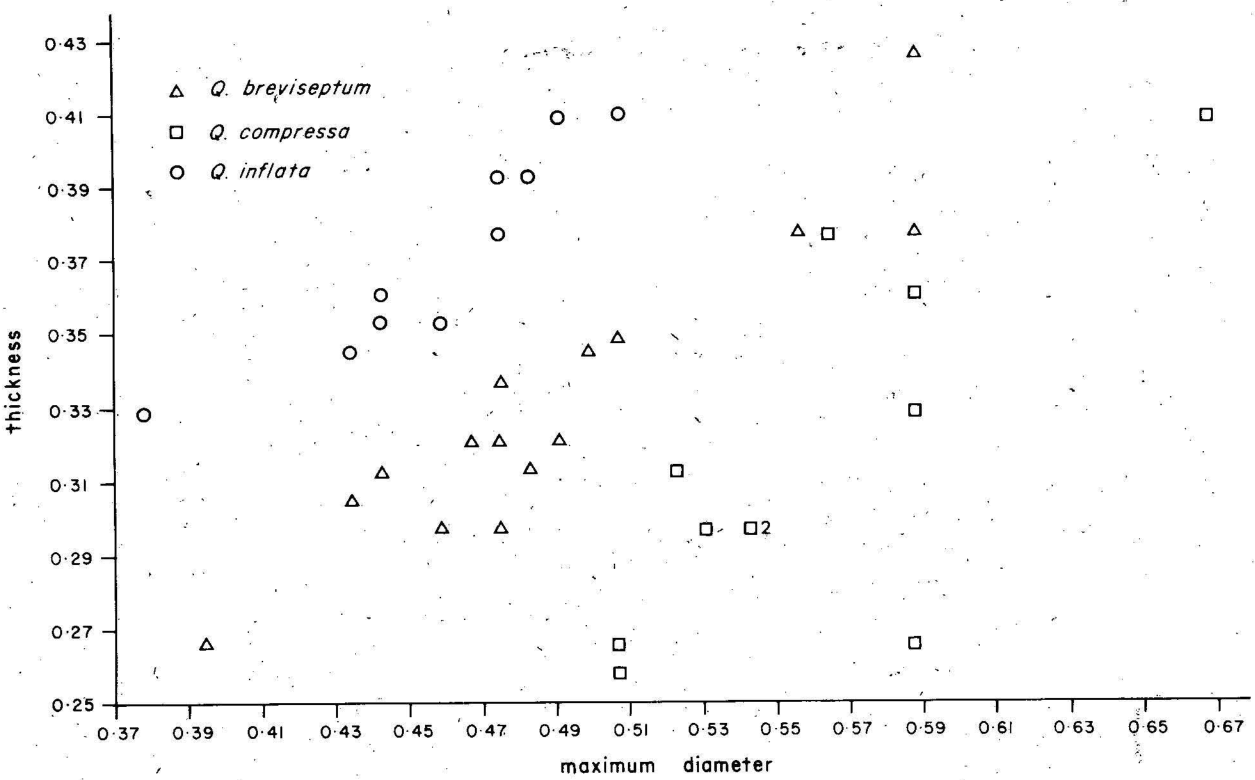

Figure 4. Graph of thickness against maximum diameter for species of *Quasicyclammina*.

Calcareous foraminifera have been dissolved from one Papua New Guinea sample, F. 902, and these forms are represented only as ?glauconite casts. No secondary alteration of pyrite, resulting in dissolution of agglutinated foraminiferal tests, has been observed.

The longitudinal partitions observed in the specimens from Papua New Guinea are believed to be an original test structure, as they are a constant feature of all specimens, irrespective of the state of test preservation. The regularity of their development also is thought to support this interpretation, as against the occasional and irregular occurrence of apparent transverse partitions.

In an attempt to remove pyrite from the test interior, some specimens of *Quasicyclammina* gen. nov. were broken and the fragments treated with nitric acid and potassium chlorate (Schulze's solution). Specimens treated in this way were examined with the scanning electron microscope to observe the geometry of the internal partitions, but the results are inconclusive. Other infilling material, presumably siliceous, not removed in the treatment process, obscures the detailed wall structure.

The cement in the test of species of *Quasicyclammina* gen. nov. is either siliceous or has become silicified during the process of fossilization. N. H. Ludbrook (in preparation) noted that in the species *Cyclammina incisa* the alveolae, chamber lumina and septal areal apertures are lined with organic material which is assumed to act as cement in the chamber and septal walls; the nature of the organic cement is not known for any species. In *C. complanata* the alveolae are lined with pseudochitin. No organic material has been observed in tests of *Quasicyclammina*, and material of this kind is unlikely to have survived fossilization. The genus *Asanospira* Takayanagi, 1960 was described as having siliceous cement; Leoblich & Tappan (1964) placed this genus in the synonymy of *Haplophragmoides*, and suggested that the cement is possibly a replacement product.

SPECIES	SAMPLE NUMBER				
	Andabare section			Tibinini sect.	
	F 902	F 903	F 904	F 914	F 915
Quasicyclammina breviseptum	X	X	X		
Quasicyclammina compressa	X	X	X	X	
Quasicyclammina inflata	X	X			X
Thalmannammina anfracta	X	X	X		X

Figure 5. Distribution of species.

The species *Haplophragmoides retrosepta* (Grzybowski) was thought to be possibly referable to the genus *Quasicyclammina*. Dr A. von Hillebrandt forwarded some specimens of this species which he (1962) recorded from the Paleocene. However, the slight asymmetry seen in some specimens of *H. retrosepta* is caused by distortion of the test, and I cannot detect any longitudinal partitions in the specimens.

The specimens referred to *Quasicyclammina* gen. nov. occur in sediments interpreted as shallow water deposits. Benthonic foraminifera, including both agglutinated and calcareous forms, are abundant, and the benthonic/planktonic ratio is about 80/20. Genera of benthonic foraminifera occuring include *Gavelinella*, *Anomalinoides*, *Heterolepa*, *Dentalina*, *Nodosaria*, *Neoflabellina*, *Gyroidina*, *Frondicularia*, *Praebulimina*, *Bolivina*, *Melonis*, *Eouvigerina*, *Quadrimorphina*, *Textularia*, *Dorothia*, *Ammodiscus*, *Spiroplectammina*, *Glomospira*, *Verneuilina*, *Clavulina* and *Gaudryina*. The sediments containing the recorded fauna are interpreted as having been deposited on the continental shelf, in water depths between 50 and 100 metres.

Quasicyclammina breviseptum sp. nov.

(Figure 6, A-P)

Material examined: 38 specimens.

Derivation of name: From the Latin, *brevis*, short and *septum*, wall, partition, referring to the internal structure.

Diagnosis: A species of *Quasicyclammina* with 8-9 chambers in the outer whorl and a maximum diameter/thickness ration ranging from 1.39 to 1.61.

Description: Test closely coiled, biumbilicate, slightly asymmetrical, involute, 8-9 chambers in outer whorl, increasing only slowly in size as added. Circular in outline, equatorial periphery slightly lobate, axial periphery broadly rounded. Chambers with short longitudinal internal partitions extending from chamber wall into upper part of chamber lumen, extending for a maximum distance of half chamber height; partitions vary in length, in thickness and in direction of insertion, only rarely coalescing at inner ends. Ratio of maximum diameter to thickness ranges from 1.39 to 1.61. Sutures broad, indistinct, smooth or very slightly depressed, straight. Test wall agglutinated, smoothly finished, of quartz grains with large proportion of siliceous cement, structure of wall and of septa simple. Aperture an elongate interiomarginal, narrow, slightly asymmetrical slit.

Dimensions	*Maximum Diameter*	*Minimum Diameter*	*Thickness*
Holotype	0.60	0.51	0.38
Paratype A	0.48	0.38	0.32
Paratype B	0.47	0.39	0.32

Occurrence: Holotype (CPC. 16932), paratypes A to C (CPC. 16933 to 16935) and thin sections (CPC. 16936 to 16940) from sample F.902, in a section near the Andabare River, Wabag 1:250 000 Sheet area, Papua New Guinea; also occurs in samples F.903 and F.904 in this section. Unfigured paratypes are deposited in the Commonwealth Palaeontological Collection under number CPC. 16941 and additional specimens and thin sections are deposited in the ESCAP Fossil Reference Collection held at the Bureau of Mineral Resources under numbers E.636 to E.640.

Remarks: The species of *Quasicyclammina* gen. nov. described in this paper are distinguished by the number of chambers in the outer whorl, and by the ratio of maximum diameter to thickness. This ratio for each of the three species described is shown graphically in figure 4. *Q. breviseptum* sp. nov. and *Q. inflata* sp. nov. each have 8-9 chambers in the outer whorl, but *Q. breviseptum* is more compressed than *Q. inflata*, the maximum diameter/thickness ratio ranging from 1.39 to 1.61 for *Q. breviseptum* as against 1.15 to 1.30 for *Q. inflata*.

Type level: Late Paleocene (planktonic foraminiferal zone P. 4).

Type locality: Sample F.902, in a section on the Andabare River, Wabag 1:250 000 Sheet area, Papua New Guinea.

Quasicyclammina compressa sp. nov.

(Figure 6 Q-S; Figure 7 A-G)

Material examined: 22 specimens.

Derivation of name: From the Latin *compressus*, pressed together, squeezed, referring to the high maximum diameter/thickness ratio.

Diagnosis: A species of *Quasicyclammina* with 10-13 chambers in the outer whorl and a maximum diameter/thickness ratio of most specimens ranging from 1.64 to 2.00.

Description: Test closely coiled, biumbilicate, slightly asymmetrical, compressed, involute, 10-13 chambers in outer whorl, increasing only slowly in size, axial periphery broadly rounded. Chambers with longitudinal internal partitions, not well preserved, extending from chamber wall into upper part of chamber lumen, varying in length, in width and in direction of insertion, only rarely coalescing at inner ends. Ratio of maximum diameter of test to thickness of most specimens ranges from 1.64 to 2.00. Sutures indistinct, straight. Test wall, agglutinated, smoothly finished, of quartz grains with large proportion of siliceous cement, structure of wall and of septa simple. Aperture interiomarginal, an elongate narrow slightly asymmetrical slit.

Dimensions	*Maximum Diameter*	*Minimum Diameter*	*Thickness*
Holotype	0.60	0.51	0.35
Paratype A	0.55	0.46	0.30
Paratype B	0.54	0.46	0.30

Occurrence: Holotype (CPC. 16942) from sample F. 914, in a section at Tibinini, Wabag 1:250 000 Sheet area, Papua New Guinea; paratypes A and B (CPC. 16943 and 16944) and thin section CPC.16946 from sample F.902 in a section near the Andabare River, Wabag 1:250 000 Sheet area, Papua New Guinea; thin section CPC. 16945 from sample F.903 in the same section. Also occurs in sample F.904 in the Andabare River Section. Unfigured paratypes are deposited in the Commonwealth Palaeontological Collection under numbers CPC. 16947 and 16948; additional specimens are in the ESCAP Fossil Reference Collection held at the Bureau of Mineral Resources under number E.641.

Remarks: Q. compressa sp. nov. is distinguished from the other described species of *Quasicyclammina* by the greater number of chambers in the outer whorl and by the compressed test. As noted, for most specimens the maximum diameter/thickness ratio falls within the range 1.64—2.00; one specimen has a ratio of 1.50.

Type level: Late Paleocene (planktonic foraminiferal zone P. 4).

Type locality: Sample F.914, in a section at Tibinini, Wabag 1:250 000 Sheet area, Papua New Guinea.

Quasicyclammina inflata sp. nov.

(Figure 7 H-Q)

Material examined: 14 specimens.

Derivation of name: From the Latin *inflatus*, swollen, referring to the low maximum diameter/thickness ratio.

Diagnosis: A species of *Quasicyclammina* with 8-9 chambers in the outer whorl and a maximum diameter/thickness ratio ranging from 1.15 to 1.30.

Description: Test closely coiled, biumbilicate, globose, slightly asymmetrical, involute, 8-9 chambers in outer whorl, increasing only slowly in size as added; equatorial periphery smooth, axial periphery broadly rounded. Chambers with short longitudinal internal partitions extending from chamber wall into upper part of chamber lumen, varying in width, in length and in direction of insertion, extending for 1/3 to 2/3 of the height of chamber, only rarely coalescing at inner ends. Ratio of maximum diameter of test to thickness ranging from 1.15 to 1.30. Sutures broad, limbate, smooth, straight. Test wall agglutinated, smoothly finished, of quartz grains with large proportion of siliceous cement, structure of test wall and of septa simple. Aperture interiomarginal, an elongate narrow slightly asymmetrical slit.

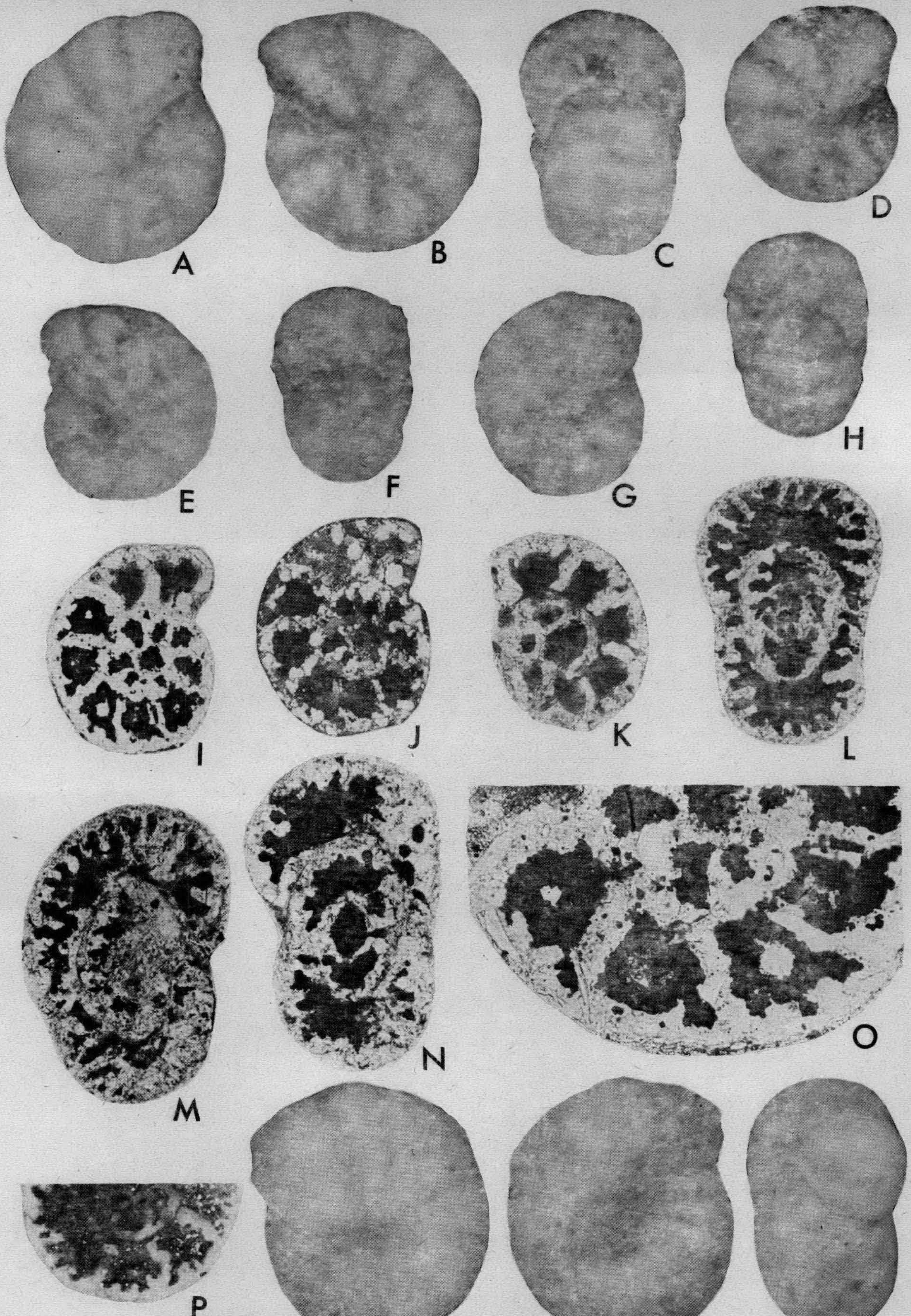

Figure 6. *Quasicyclammina breviseptum* gen. et sp. nov. A—C Holotype, CPC. 16932; A, B, opposite sides; C, edge view. All x 80. D—F Paratype A, CPC. 16933; D, E, opposite sides; F, edge view. All x 80. G, H Paratype B, CPC. 16934; G, side view; H, edge view. Both x 80. I, J Equatorial section, CPC. 16936; I, ordinary light, showing irregular inner test wall; J, crossed nicols, showing granular test wall. Both x 100. K Equatorial section, CPC. 16937, showing irregular inner test wall, x 100. L—N Axial sections, CPC. 16938 to 16940, showing longitudinal partitions of chambers and slight asymmetry of test; all x 100. O Part of equatorial section illustrated in fig. I, CPC. 16936, x 250. P Polished surface of paratype C, CPC. 16935, showing apparent small transverse partitions; x 100. *Quasicyclammina compressa* gen. et sp. nov. Q—S Holotype, CPC. 16942; Q, R, opposite sides; S, edge view. All x 80.

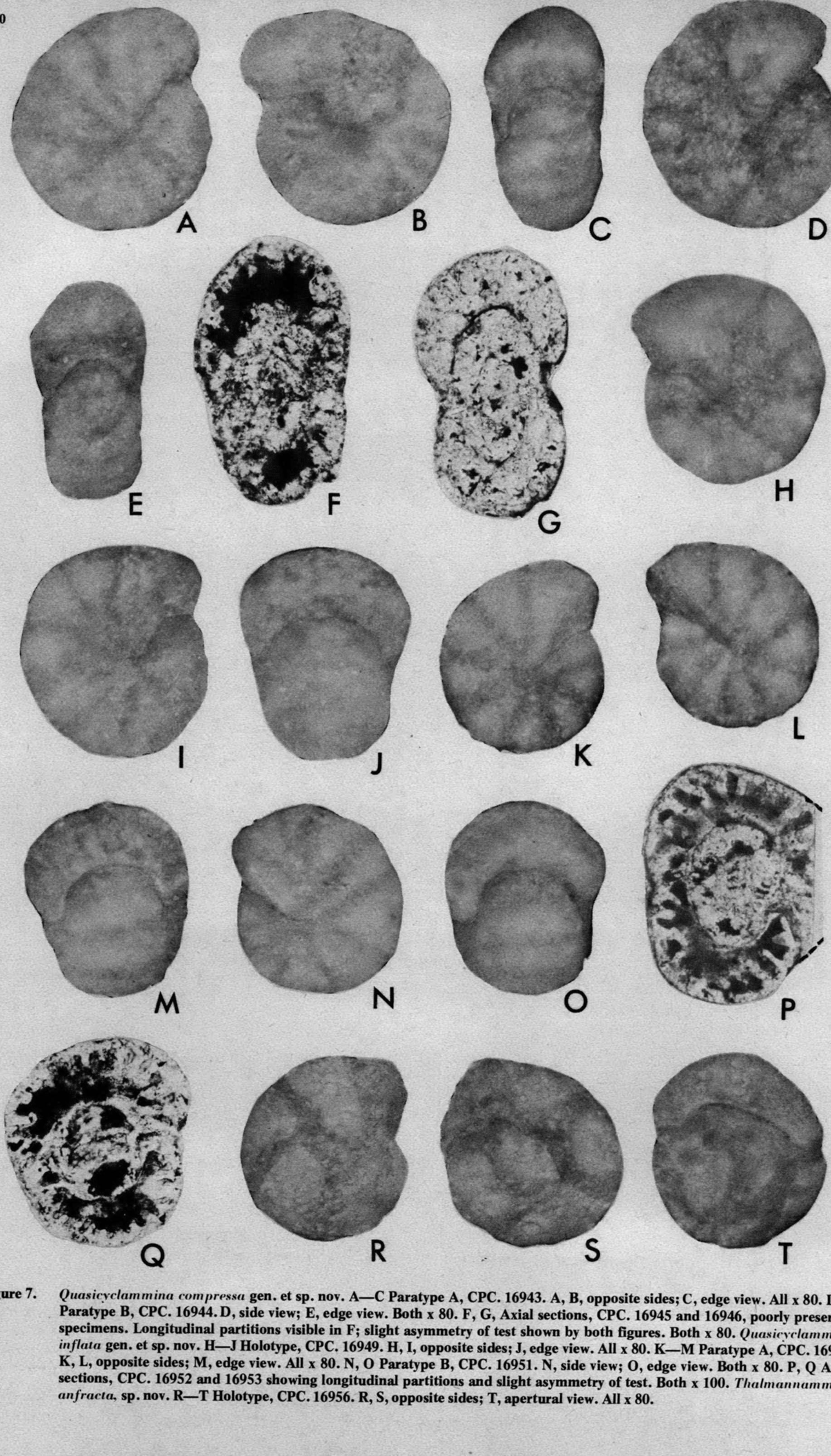

Figure 7. *Quasicyclammina compressa* gen. et sp. nov. A—C Paratype A, CPC. 16943. A, B, opposite sides; C, edge view. All x 80. D, E Paratype B, CPC. 16944. D, side view; E, edge view. Both x 80. F, G, Axial sections, CPC. 16945 and 16946, poorly preserved specimens. Longitudinal partitions visible in F; slight asymmetry of test shown by both figures. Both x 80. *Quasicyclammina inflata* gen. et sp. nov. H—J Holotype, CPC. 16949. H, I, opposite sides; J, edge view. All x 80. K—M Paratype A, CPC. 16950. K, L, opposite sides; M, edge view. All x 80. N, O Paratype B, CPC. 16951. N, side view; O, edge view. Both x 80. P, Q Axial sections, CPC. 16952 and 16953 showing longitudinal partitions and slight asymmetry of test. Both x 100. *Thalmannammina anfracta*, sp. nov. R—T Holotype, CPC. 16956. R, S, opposite sides; T, apertural view. All x 80.

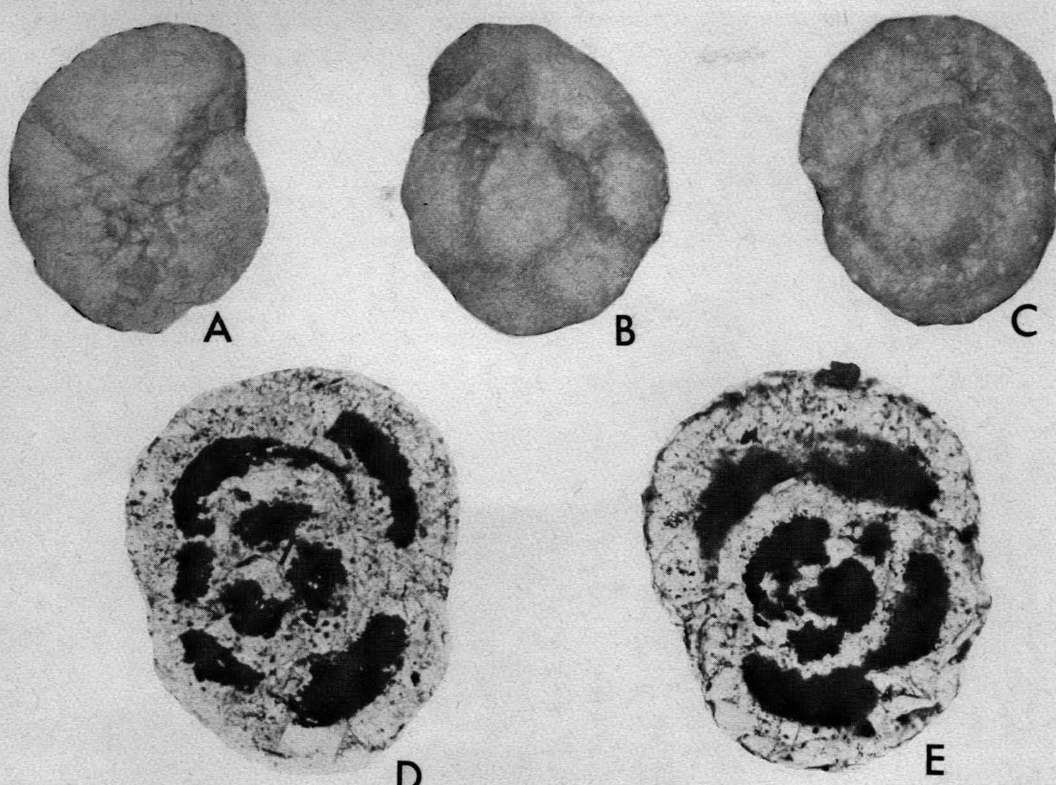

Figure 8. ***Thalmannammina anfracta*, sp. nov. A—C Paratype, CPC. 16957. A, B, opposite sides; C, apertural view. All x 80. D, E Thin sections, CPC. 16958 and 16959, showing streptospiral coiling and simple wall structure. D, cut perpendicular to apertural face; E, in plane of apertural face. Both x 100.**

Dimensions	*Maximum Diameter*	*Minimum Diameter*	*Thickness*
Holotype	0.51	0.46	0.42
Paratype A	0.48	0.41	0.40
Paratype B	0.48	0.42	0.38

Occurrence: Holotype (CPC. 16949) and thin section (CPC. 16952) from sample F.902 in a section near the Andabare River, Wabag 1:250 000 Sheet area, Papua New Guinea. Paratypes A and B (CPC. 16950 and 16951) and thin section CPC. 16953 from sample F. 903 in the same section. Also occurs rarely in sample F.915, in a section at Tibinini, Wabag 1:250 000 Sheet area. Unfigured paratypes are deposited in the Commonwealth Palaeontological Collection under numbers CPC. 16954 and 16955, and additional specimens are in the ESCAP Fossil Reference Collection held at the Bureau of Mineral Resources under number E.642.

Remarks: Q. inflata has the lowest maximum diameter/thickness ratio of the three species of *Quasicyclammina* recognized in the present material and is separated from *Q. breviseptum*, which also has 8-9 chambers in the outer whorl, on this feature.

Type level: Late Paleocene (planktonic foraminiferal zone P.4).

Type locality: Sample F.902, in a section near the Andabare River, Wabag 1:250 000 sheet area. Papua New Guinea.

Subfamily HAPLOPHRAGMOIDINAE Maync, 1952

Genus *Thalmannammina* Pokorny, 1951

Type species: Haplophragmium subturbinatum Grzybowski 1897; original designation.

Thalmannammina anfracta sp. nov.
(Figure 7, R-T; Figure 8, A-E)

Material examined: 25 specimens.

Derivation of name: From the Latin *anfractus*, bending, winding, referring to the coiling of the test.

Diagnosis: A species of *Thalmannammina* with a globose test, 5 to 6 visible chambers, agglutinated roughly finished test wall, and elongate interiomarginal aperture.

Description: Test streptospiral, tightly enrolled, globose, 5 or 6 chambers visible, increasing only slowly in size as added. Sutures broad, limbate, smooth. Test wall agglutinated, roughly finished, of quartz grains with siliceous cement, structure of wall and of septa simple. Apertural face broad, low; aperture interiomarginal, an elongate narrow slit.

Dimensions	*Maximum Diameter*	*Minimum Diameter*	*Width across apertural face*
Holotype	0.48	0.41	0.41
Paratype A	0.53	0.44	0.45

Occurrence: Holotype (CPC. 16956), paratype (CPC. 16957) and thin sections (CPC. 16958 and 16959) from sample F.902, in a section near the Andabare River, Wabag 1:250 000 Sheet area, Papua New Guinea; also occurs in samples F.903 and F.904 in this section and in sample F.915 in a section at Tibinini, Wabag 1:250 000 sheet area, Papua New Guinea. Unfigured paratypes are deposited in the Commonwealth Palaeontological Collection under number CPC. 16960, and additional specimens are in the ESCAP Fossil Reference Collection held at the Bureau of Mineral Resources under number E.643.

Remarks: The streptospiral coiling and simple wall structure of *T. anfracta* sp. nov. are clearly shown in thin sections. Slight irregularities of the inner test wall may be present, possibly caused by partial test solution and replacement by pyrite. In comparison with the type species, *T. subturbinata* (Grzybowski), *T. anfracta* has a more globose test, broader limbate and smooth sutures, and a broader apertural face. Pokorny (1951) gave the stratigraphical range of *Thalmannammina* as Upper Cretaceous to Eocene; Loeblich & Tappan (1964) gave the range as Eocene to Recent, extending the upper limit because they considered the genus *Recurvoidella* Uchio 1960 to be a synonym of *Thalmannammina*. This Papua New Guinea occurrence indicates that the time of first appearance of the genus is at least late Paleocene.

Type level: Late Paleocene (planktonic foraminiferal zone P. 4).

Type locality: Sample F.902, in a section near the Andabare River, Wabag 1:250 000 Sheet area, Papua New Guinea.

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The 1974 wet-season flooding of the southern Carpentaria Plains, northwest Queensland

C. J. Simpson & H. F. Doutch

In January 1974 aerial observations were made of the very severe flooding which occurred in the low-gradient plains country adjacent to the southern Gulf of Carpentaria. Floodwaters were derived from two sources, the extensive river channel network throughout the plains mostly carried silty water which originated from hinterland regions, while the plains surfaces were flooded with clear water derived from local rainstorms. Runoff of clear storm water caused active erosion around peripheries of planar interfluves on the clay plains. There was generally no flood-water erosion or deposition in the sandy plains. Flooding was extensive on tidal mudflat areas, particularly behind beach ridge remnants which inhibited runoff. Despite the severity of flooding, the overall lack of erosion and overbank flooding suggests that landforms of the fluviatile plains were developed under conditions of greater runoff than prevail during normal wet-season flooding. The major landform features were probably developed in the Late Pleistocene and have not been substantially modified since then.

Introduction

The region bordering the southern Gulf of Carpentaria (the Gulf) contains an area in excess of 70 000 km^2 (i.e. greater than Tasmania) of very low gradient plains which are subject to seasonal flooding. Floodwaters are derived from direct runoff from the plains, and from several major intermittent river systems which rise in the hinterlands to the southwest and southeast, drain through the plains, and converge towards the southeastern corner of the Gulf. Depending on the severity of the inconsistent seasonal flooding, homesteads may be isolated by the swollen rivers for days or weeks.

From the beginning of November 1973 to early January 1974, steady rain (probably averaging in excess of half a metre) fell throughout the Carpentaria Plains. Normanton for example received 488 mm on 24 rain days in that period and 292 mm in the first 14 days of January 1974. The subsequent floods that occurred throughout the Gulf plains during January-February 1974 were the worst in memory. Prior to 1974 the most severe floods since settlement of the region occurred in the summer of 1869-70 when 'the entire site of Burketown was under water' (Bauer, 1959). The 1974 floods may have reached higher levels than those of 1869-70, as data on the early floods are sketchy.

Weather patterns of the Gulf region are dominated by the northwest monsoons and the southeast trades, which result respectively in pronounced wet and dry seasons. More than 80 percent of the total wet-season rainfall usually falls in the period December to March (Perry *et al.*, 1964). Throughout the area shown in Figure 1 the average annual rainfall increases from south to north within the range 497 mm at 'Canobie' station homestead to 958 mm at Normanton. Absolute values of overall wet-season runoff are not known; however, the volume of fresh water discharged into the shallow environment of the Gulf of Carpentaria during flooding is sufficient to cause significant sea-water dilution. Monroe (1972) reports that the effects of salinity dilution from normal December-March 'wet' season rain are not overcome until June or July.

The first systematic regional geological mapping of the region was undertaken as part of the Carpentaria and Karumba Basins Survey in 1969-1974 by a joint party from the Bureau of Mineral Resources and the Geological Survey of Queensland. For obvious reasons field operations were conducted during dry seasons of each year and wet season conditions were not observed. Although various authors (Whitehouse, 1944; Twidale, 1966) have discussed drainage systems of the region, virtually no published data exists on the effects of flooding and its relation to geomorphology of the Gulf country.

When it became apparent in January 1974 that exceptional floods were imminent in the Gulf region arrangements were made to carry out aerial observations. Flood peak in the Norman River system reached Normanton on 26 January 1974. The following report is based on aerial observations of flood phenomena on 13, 14 and 15 January and Landsat imagery of 7, 10 and 27 February. Despite the fact that the aerial observations were made 11-13 days before the flood peak at Normanton the flooding was then far in excess of normal seasonal flooding. At the time of the survey local opinion in Normanton regarded the flooding as worse than anything in the preceding 23 years.

The objectives of the aerial survey were twofold. Firstly to examine flood phenomena which may relate to an understanding of past and present geomorphological development and lithostratigraphy of the Late Cainozoic fluviatile plains. Second to observe the effects of high rainfall and flooding that may influence the identification and interpretation of features observed on Landsat (ERTS) satellite imagery of flooded or wet terrain, and their corresponding appearance on 'dry' season satellite imagery and air photography.

Aerial observation and photography was carried out over that region of the southern Carpentaria Plains bounded by 'Esmeralda', 'Canobie', Burketown and 'Galbraith' (Figure 1). The region between Georgetown and 'Wrotham Park' (to the east of the area shown in Figure 1) was also examined but is not discussed.

Aerial photography

During the three days of aerial observation more than 300 photographs were acquired with hand-held 35 mm format cameras. The photographs may be examined in BMR by arrangement with the Director.

The following Kodak films were used; Panatomic X—processed to negative; Ektachrome X, Kodachrome II, and Ektachrome Infrared (with Wrattan 12 filter) processed to positive. The latter film was used to record the infrared reflection of water and vegetation features to assist interpretation of Landsat false-colour infrared images. Most of the photographs were taken through open windows and many multiple photographs from different altitudes and attitudes were obtained. Photograph quality suffered as a result of intermittent rain and overcast cloud conditions. Many of the colour infrared transparencies proved to be

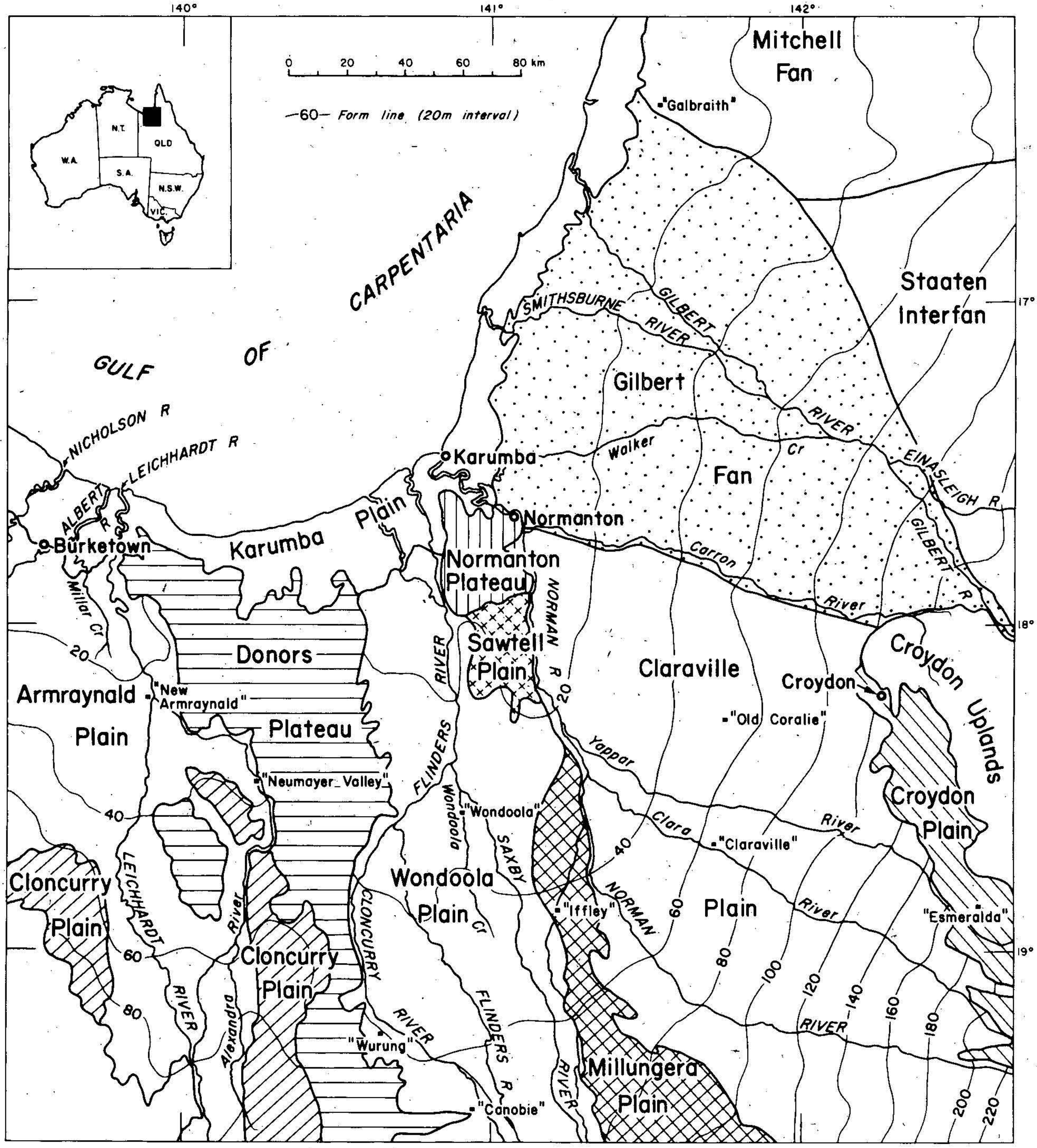

Figure 1. Major drainage, and distribution of physiographic units of the southern Carpentaria Plains.

overexposed. This was probably due to the authors' inability to reliably determine the amount of infrared radiation penetrating the overcast cloud, although exposure variability problems reported with Ektachrome Infrared can not be discounted.

Colour film was better than panchromatic or infrared for recording general flood phenomena. It was particularly valuable for recording the distribution and colour differences of silty floodwater. Of the two varieties of colour film used Ektachrome X showed better colour rendition and haze penetration in the overcast conditions. Colour infrared film was superior for delineating the distribution of silty freshwater plumes within the Gulf. None of the films used during aerial observations proved useful for recording the existence of clear floodwater unless sun reflection was present in the photograph.

Flood assessment using Landsat imagery

Part of the 1974 flooding in the Gulf was imaged by the Landsat 1 satellite and scenes subsequently examined with the aid of an I²S additive colour viewer were; 1564-23562 and 1564-23564 (7 Feb. 1974), 1567-00074 (10 Feb. 1974), 1584-00014 (27 Feb. 1974). Despite extensive cloud cover the Landsat imagery proved to be a valuable supplement to the data acquired from aerial observation. Landsat flood imagery contains information on water movement and its geomorphic implications than cannot be obtained from aerial observation, dry season aerial photographs, or topographic maps. By correlating flood observations with the Landsat imagery it is possible to delineate areas of clear water and subdivide waters with different concentrations of sediment load.

The data from aerial observations combined with available Landsat imagery over the Gulf region allow the establishment of interpretation keys to assist assessment of any flood imagery acquired by future Landsat satellites. The authors do not wish to digress on interpretation of Landsat flood imagery. Sufficient to note that the information content of timely Landsat flood imagery, especially involving low gradient terrain and clear floodwater, would be an invaluable historical document for authorities involved in land use and regional development planning.

The southern Carpentaria Plains

The southern Carpentaria Plains can be differentiated into several large, fluviatile plains which may differ in surface composition, morphology and gradient. Grimes (*in* Smart *et al.*, in preparation) discusses the physiography of the region, and Grimes & Doutch (in preparation) discuss in detail the development of the fluviatile deposits of the plains.

All the plains are characterised by very low gradients. The Wondoola Plain (Figure 1) is the flattest plain in the Gulf country with a gradient of about 1 in 3000. It occupies a topographic low between the uplands and the plateaus, and rivers occur within broad valleys in the plain.

The Wondoola and Armraynald Plains are composed of heavy textured clays (blacksoil) which support mid-height perennial grasses and sparse trees. The Claraville, Millungara, Croydon and Cloncurry Plains sustain similar grass cover but are dominated by sandy soils, and low, moderately dense woodlands. Along the western side of the Croydon Uplands distributary piedmont fans have developed on the Claraville Plain, particularly in the floodout zones of the Clara and Yappar Rivers (Figure 1).

The section of coastal plain (Karumba Plain of Twidale, 1966) which flanks the southeastern part of the Gulf consists predominantly of tidal mud flats. The coastal zone between the Norman River and the Nicholson River (to the west) contains the widest expanse of tidal flats fringing the Gulf. In some areas the flats extend inland for 20 km or more, their low relief broken only by discontinuous remnants of Holocene and Pleistocene beach ridges paralleling the coast and rising 4-6 m above the plain level. The nature and origin of the beach ridges have been discussed by Smart (1976).

The floodwaters

From aerial observation it soon became apparent that the floodwaters throughout the Carpentaria Plains could be differentiated into two types derived from different sources. Water from local rainstorms was accumulated as a sheet of clear water across the plains. During aerial observation the presence of the clear water could be readily determined only by sun reflection (Figure 2), and then only in the immediate vicinity of the reflected sun image. Although it is not apparent on Figure 3, the dark-toned grassed surfaces are covered with clear water. Clear stormwater is referred to as 'dumped' since the low gradient of the terrain results in very slow sheet-flood drainage away from the areas of accummulation.

In contrast to the dumped water, the major rivers entering the plains contained discoloured silty floodwater, shown by the light tones in Figures 2 and 3. The discoloured water is regarded as imported, since most of the water and impurities is derived from the highland catchments outside the area investigated. Only those rivers which have appreciable catchment areas outside of the plains contained very silty floodwater. This applies to the Leichhardt, Cloncurry, Flinders, Gilbert and Einasleigh Rivers (Figure 1). In the plains tract imported silty water was introduced into many smaller river systems via overflow channels which interconnect almost all the major rivers. Due to the vast catchment area of the plains and the higher rainfall towards the coast, the floodwaters that ultimately reach the Gulf contain a greater proportion of dumped than imported water.

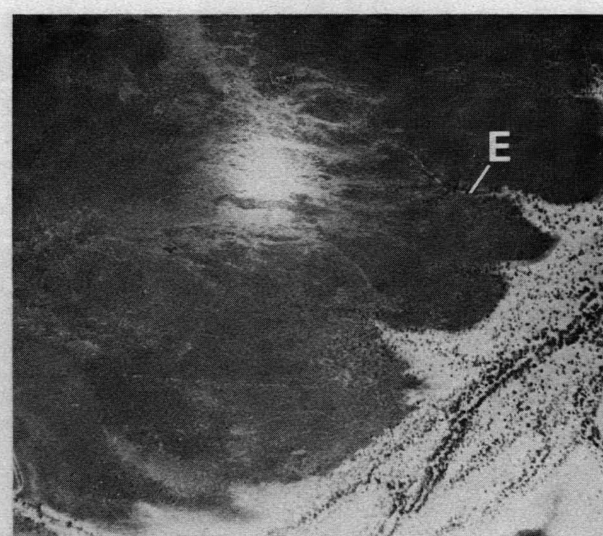

Figure 2. Clear 'dumped' stormwater (shown by sun reflection) on the grassed plain, and silty 'imported' floodwater in the drainage system.

Flooding in the river systems

At the time of observation the Gilbert and Einasleigh River systems (Figure 1) were contributing very silty water to the major drainage channels on the Gilbert Fan. Throughout the fan incised channels, especially the main channels of the Gilbert River, were coping with the volume of silty water and there was negligible overbank flooding. A similar situation existed in the braided Cloncurry and Flinders River system north of 'Canobie' where the greatest quantities of silty imported water were observed. Newspaper reports indicate that overbank flooding (particularly in the Gilbert River) became more common some days after our observations were made. However, at the time of observation the floods were regarded as exceptionally severe, and the region was still receiving abnormal rainfall.

The best examples of flooding in channels were observed in the braided Cloncurry River (Figure 3). The anastomising streams of Figure 3 appear to be flowing arbitrarily across the relatively treeless plain; however comparison of flood observation data with the vertical airphotograph coverage of 1966 shows that the silty water is contained in a drainage system consisting of active and abandoned channels. In this context the active channels are those which transport the normal seasonal runoff. They are incised, with non-vegetated sandy or muddy floors, and can be recognized by relatively dense tree growth along both banks (A in Figure 3). In contrast, the abandoned channels are comparatively broad, shallower, grassy floored channels, that are watercourses only during flood periods. They consist of segments of meandering and braided

Figure 3. The braided Cloncurry River (looking upstream near 'Wurung').

streams, may contain lagoons, and represent relict channel positions abandoned during stream migration within the plain. They sustain fewer trees, which are scattered along the complete course (B on Figure 3).

Classical levee banks and related flood deposits are not well developed and over most of the plain the interfluve represents the highest topography. The edges of the planar interfluve surfaces can be recognized by erosion scolloping (E on Figure 3), which show that the silty water was below the general plain level. Rising floodwater in the active channels initially overflows into the abandoned channels, and little overbank flooding onto the plain surface occurs until the abandoned channel system is full. Minor discharge onto the plain surface may occur via partially blocked abandoned channels that act as chutes. Sediment deposition on the plain is likely in segments of abandoned channels in which the flow of silty water is greatly reduced or stopped by channel blockage (e.g. D on Figure 3). Infilling of abandoned channels probably progresses slowly by this process. The rates of infilling would be reduced if newly deposited sediment was remobilized and flushed into active channels by stormwater runoff from the plains when local rainfall occurs during flood recession.

Although a considerable quantity of silty imported flood water was entering the Wondoola Plain via river systems which head in the hinterlands, only minor silty water discharge (C on Figure 3) onto the plain was occurring at the time of observation. Under these abnormal flood conditions the active and abandoned channels, although full, could generally cope with the volume of floodwater, representing both introduced silty water and water derived from local rainfall. During normal wet-season flood conditions overbank discharge onto the plain surface is unlikely to occur. Within the overall channel network the active channels which carry intermittent runoff can be regarded as misfit. Dury (1959) considers that misfit streams result from a general change in runoff. Flood observations suggest that the channel system in the Wondoola Plain was formed under conditions of greater runoff than exist today.

The only observed major discharge of silty water onto the plains surface was from the Alexandra River which develops a large ephemeral lake during flooding. The lake is the white (silty water) area in the top left of Figure 4. Silty lake water is derived from the Leichhardt River via the Alexandra River, which acts as a flood overflow channel. Discharge from the river is contained behind the Donors Plateau in a depression resulting from recent tectonic warping (Twidale, 1966).

In the left foreground of Figure 4 imported silty water is moving along normally abandoned channels of the Alexandra River. The dark border along the eastern edge of the silty water is an accumulation of clear stormwater draining from the interfluve. At the time of photography silty water was backed up along the Alexandra River for more than 5 km south of the lake. Figure 5 shows the ephemeral lake from the west. The treeless light-toned water area is believed to represent the standing water that remains after floods recede below outflow level. The broad expanse of light-toned silty water on either side of the tree-lined outlet channel (Alexandra River) resulted from local overbank flooding.

Further downstream from this point the combined effects of clear water inflow from the plains, and valley constriction and deepening—where the river cuts through a corner of the Donors Plateau—resulted in silty floodout water being re-confined to the river channel. Where the Alexandra River (A on Figure 6) reaches its confluence (C) with the Leichhardt River (L), floodwaters, although high, were not spreading overbank onto the plain surface. Clear water covered the plains flanking the Leichhardt and Alexandra Rivers in Figure 6.

The narrowing of the Leichhardt River towards its confluence with the Alexandra River is due to accommodation of floodwater by sudden deepening of the river channel downstream from the 12 m high Leichhardt Falls (Figure 6). The falls represent a significant erosional nick-point initiated by eustatic sea level drop (Ingram, 1972).

As the silty channel floodwater approached the coast it was progressively diluted by the inflow of clear stormwater. In the Gulf plains both the volume of clear water present, and the somewhat immiscible behaviour of silty and clear water were significant factors both in preventing sheet flooding of silty water onto the plains surface, and returning any floodout to the channels.

The only ground observations of silty floodwater were made at Normanton. No measurements of silt content were attempted although the diluted nature of the floodwater was noticeable. All streams draining the Millungera, Claraville and Croydon Plains flow into the Norman River upstream of Normanton. The large quantity of clear dumped water entering the Norman River system resulted in extensive dilution of silty water derived from the Clara River and

Figure 4. View downstream along the tree lined Alexandra River near 'Neumayer Valley' (circled).

Figure 5. View upstream along the Alexandra River to its ephemeral lake.

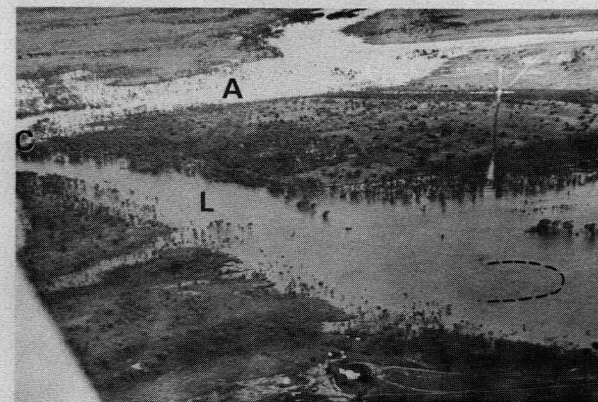

Figure 6. View east over 'New Armraynald' at the confluence (C) of the Leichhardt River (L) and Alexandra River (A). The broken line marks the approximate position of the 12 m high Leichhardt River Falls.

from flood overflow channels of the Flinders-Saxby Rivers system. Although the Norman River at Normanton appeared silty, the silt content as judged visually from the air, and from Landsat colour analysis, was significantly less than that of the Cloncurry-Flinders and Leichhardt River systems. This agrees with comments in the report by Cardno & Davies (1968) on the investigations of a damsite on the Norman River 25 km upstream of Normanton. They note that siltation was not expected to be great, and that during times of flood the water had been observed to carry very fine particles which were almost entirely in colloidal suspension.

Flooding on the plains

Clean dumped stormwater was present over most of the Gulf plains. The wide distribution and depths of clear water on the plains was unexpected. Previous work (Twidale in Perry *et al.*, 1964; Twidale, 1966) suggests that wet-season runoff rates are high because of the lack of vegetation cover resulting from the dry summer season. While this applies in elevated terrain (hence the abundance of silty imported water) observation did not show it to be the case on the interfluves of low-gradient plains. Muddy water trails, created in clean water by walking cattle, indicated that the overall movement of clean water across the plain surface was slow.

The quantity of clean water accumulated on the Gulf plains demonstrated that sheetflow erosion of the surfaces of plain segments (as distinct from the edges) was very minor. At the end of the dry summer months bare clay soil is often exposed between grass tussocks on the clay plain. The very minor quantities of discoloured dumped water in these areas suggests that erosion of bare soil by rain impact was also negligible. It is possible that the first rains of the wet season (at the beginning of November 1973 in this case) produced some impact erosion. Resulting muddy water could have been removed by normal sheet flow before aerial inspection. However the development of a cover of water on the plain surface would rapidly suppress effects of rain impact whether this caused erosion or compaction (Leopold *et al.*, 1963).

Some sediment presumably deposits from silty water on the plain surface. Any deposits would be very thin for, as judged by colour, silty water discharged onto the plain was noticeably diluted by mixing with clean water. In some places (C on Figure 3) flow patterns of silty water within clean water indicated that clean water movement on the plain can re-channel diluted silty water back into the main river-channel system.

The surface of the Gilbert Fan was extensively covered with clear stormwater which was finding its way towards the coast via the many relatively shallow distributary streams present throughout the fan. The virtual absence of silt discoloration of the clear water throughout the fan indicated that erosion by dumped water movement was negligible.

Similar conditions existed on the Claraville Plain. There the surface of the plain was extensively covered with clear water, and most of the numerous drainage channels in the plain and distributary fans were running full or overflowing with clear water. Some erosion of channel banks was noted.

Additive colour analysis of the four spectral bands of Landsat scene 1564-23564 (imaged 23 days after the reconnaissance) showed that the Clara River was the only drainage system in the Claraville Plain to be carrying significantly discoloured water. Figure 7 (part of Band 6 of the Landsat scene) shows the floodout of light-toned silty water from the Clara River in the vicinity of 'Claraville'. The dark-toned areas along channels and on interfluves are clear water.

All streams heading in the Uplands carried some silty water; however on reaching the plains the waters were rapidly diluted. As determined from the satellite image the overall proportion of silty water relative to clear water was comparatively minor. The lack of silt could be attributed to the sandy lithologies of the headwaters region. However the Flinders River which heads in the same rock material carried very silty water into the plains. The authors' consider that the difference in silt content is due to the Flinders having a much larger headwater catchment outside the Carpentaria Plains.

The vast quantities of clear water runoff observed throughout the Claraville Plain showed that the prevailing flood conditions were not modifying the distributary fan deposits except for some erosion of the channels developed in them. It is concluded that the distributary fans of the Claraville Plain were developed in conditions of greater runoff than currently occurs either in normal, or severe, wet-season floods.

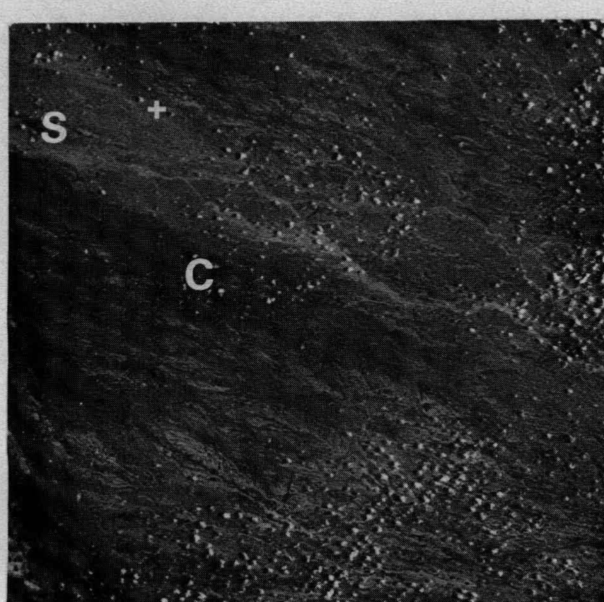

Figure 7. Silty water (S) floodout from the Clara River near 'Claraville' (+). Clear water (C) is dark-toned. (Part of Landsat image 1564—23564—6 at 1:1 000 000 scale).

Flooding on the tidal flats

While virtually no overbank flooding occurred within the plains, aerial observation showed that the main river systems in the Karumba Plain all displayed overbank flooding. The major river tracts within the Karumba Plain develop sinuous meanders in the tidal zones and overbank flooding occurred when rivers reached these regions. At the time of observation the tidal flats and adjacent terrain were completely flooded. Figure 8 illustrates the overbank flooding of silty water from the Albert River system. Loops of the main river channel of the Albert River can be traced by the distribution of denser mangrove growth. In the background of the figure similar flooding can be seen along the meander zone of the Saltwater Arm of Millar Creek.

Figure 8. View east across the tree lined Albert River and flood-bound Burketown.

The flooding of the tidal flats resulted in the remnants of Holocene beach ridges, and associated higher ground, becoming islands. This is illustrated in Figure 9, the inland (southeasterly) view from the coast at a point 7 km west of the Flinders River mouth. The presence of chains of these remnants in the vicinity of major river outlets inhibited runoff and resulted in temporary damming of the floodwaters on the tidal flats. Such damming and subsequent raising of the water level on the coastal plain behind the beach ridges will result in increased deposition of suspended material from inflowing silty floodwater, erosion of the remnant beach ridges adjacent to the outflow gaps (Figure 9), and reduction of the inflow of tidal water. Water tonal differences in the centre and foreground of Figure 9 give some idea of flood outflow, and distribution of silty (light-toned) and clearer (darker toned) water.

Water on the coastal plain may be derived from four sources: flood-out from the major river systems; dumped clear water accumulated locally, and by runoff from the adjacent terrain; and tidal saltwater inflow. The overall effect of the latter was not known and could not be determined from aerial observation. At the time local opinion in Normanton expressed the belief that no tidal water was encroaching upstream in the Norman River system.

Twidale (1956) considered that severe seasonal flooding is consequent upon the combined effects of monsoonal rain and the higher tides developed by the northwesterly winds.

Figure 9. Inland (southeasterly) view across the flooded Karumba Plain 7 km west of the Flinders River mouth.

While some of the floodwater on the tidal flats near the coast was reasonably clear most of the more inland floodwater on the coastal plain was silty and discoloured. This floodwater must have originated from flood-out of the major river systems and/or local runoff erosion of the northern flanks of the Donors Plateau. Some rainfall impact erosion cannot be totally discounted but seems unlikely due to the extensive water cover.

Deposition of silt is likely to be associated with the overbank flooding of silty river water onto the tidal flats; however at the time of observation the impression was obtained that the bulk of suspended silt was being carried through the plains of the southern Gulf to the sea. During seasonal flooding sediment deposition in the Karumba Plain will be determined by locally prevailing meteorological conditions, particularly tide levels. Air-photographs show limited domains of meander belt, point-bar and flood-out deposits which, although affecting less than 5 percent of the Karumba Plain, seem to account for most of the fluvial deposition on the coastal plain west of Normanton.

Floodwater erosion

It was difficult to ascertain from the air what erosion of the river channels within the plains occurs during flooding. While some scouring and deposition occurs in the active channels (i.e. the young short-lived alluvial deposits of Doutch *et al.*, 1972) neither aerial observation nor previous field work provided evidence of erosion within abandoned channels.

Although direct sheetflow erosion on the plains surface was negligible the most active erosion observed resulted from the movement of dumped stormwater. Erosion occurs along the peripheries of planar interfluves where dumped water drains to the lower level of adjacent either active, or abandoned channels. This has resulted in the formation of gullies or scarps adjacent to channels. Rates of peripheral erosion will be controlled by water volume, and elevation differences between the planar interfluve edge and the water level in adjacent waterways. Thus erosion of interfluve edges is virtually independent of flooding within adjacent channels. High-flood levels in channels can reduce or even temporarily stop erosion by virtue of the reduced elevation difference between water level and plain level.

Small dendritic drainage tributaries, such as E in Figure 2, that are present along the edges of the grassed interfluves, are typical of the gullying that has developed around the edges of planar interfluves with relatively slow lateral runoff of dumped stormwater. With increased sheet runoff the peripheries of interfluves are actively eroded into scalloped scarps (E in Figure 3). In areas of high sheet runoff the plain, or interfluve, periphery develops as an active retreating scarp (breakaway) and discrete drainage-ways are not as significant for the movement of water. This type of scarp is illustrated at E in Figure 4, adjacent to the main river course. The long term effect of such scarp retreat will be widening of the valleys adjacent to the main watercourse with associated reduction in the incidence of overbank flooding onto the plain surface. The valley-in-valley structures which result from such scarp retreat are common throughout the Carpentaria Plains and are believed to represent conventional pediplanation erosional processes.

One instance of gully erosion resulting solely from concentration of sheet flow was observed in the Dingo Creek branch of Wondoola Creek at 'Wondoola'. Figure 10 shows light-toned silty creek water resulting entirely from active channel erosion. Dingo Creek catchment lies within an interfluve of the Wondoola Plain and is fed only by clear stormwater. Although not obvious the surface of the plain shown in Figure 10 is covered with clear water. Among the processes of present day dissection of the Wondoola Plain this type of gully erosion is minor compared to scarp erosion.

Previous work (Simpson, 1973) noted that the Walker Creek channel on the Gilbert Fan was in an erosive phase. The Walker Creek main channel connects to the Gilbert River by a chute which allows floodwater into the creek system well below the overbank flood level. Observations from the air, and study of Landsat imagery, showed that the quantity of introduced silty water that entered the system caused sheet flooding in a strip up to 5 km wide on either side of the shallow Walker Creek main channel. In these rather exceptional circumstances it is possible that silt may be deposited on the plain adjacent to the creek while the excessive water volume causes erosion within the Walker Creek main channel.

Figure 10. Upstream along Dingo Creek near 'Wondoola'.

Discussion

Aerial observations during 13, 14, 15 January combined with studies of Landsat flood imagery of 7, 10 and 27 February 1974 showed that virtually the whole of the Carpentaria Plains country had some floodwater cover and that clear water was more widespread than silty water. Most of the silty water originates in the hinterlands and is restricted to major river-channel systems during its passage through the plains.

In the clay plains the introduced silty water is diluted by considerable inflow of clear stormwater runoff. Consistent dilution of silty water along the length of the rivers presumably contributes to transport of suspended sediment to the coastal plain with only very limited deposition en route. Deposition of sediment may occur when silty water is discharged from channels onto the plain or into floodout areas such as the tidal flats of the Karumba Plain.

Doutch *et al* (1970) concluded from field work that the riverine plains are in an erosive phase, and this was confirmed during the flood reconnaissance. The most active erosion observed, however, results from stormwater runoff around the peripheries of planar interfluves, and flooded river systems apparently do not contribute significantly to the erosion processes other than to transport the detritus. Landsat imagery confirmed that of the rivers reaching the southern Gulf region the Cloncurry-Flinders-Saxby system contributes more silty water than any other. The lack of any significant sediment deposits at the mouths of these streams suggests that the overall sediment load entering the Gulf is not very great.

The vast quantities of clear water runoff on the Carpentaria Plains were best observed in the Claraville Plain, where most of the incised channels were either full or overflowing with clear water. While some deposition of sediment may be expected where eroding streams reach the plains the quantity and distribution of clear floodwater which is not eroding or depositing implies that most of the detrital fan deposits on the Claraville Plain were created under different conditions of runoff than operate today.

A similar conclusion was reached after examination of flooding on the Wondoola Plain. There it was observed that even during abnormal flooding the existing stream-channel network, although full of floodwater, could generally cope with the large volume with only limited overbank discharge onto the plain surface. Accommodation of floodwater is attributed mainly to the existence of the abandoned channels which help to contain the overflow from active channels. Within this type of drainage system normal wet-season flooding can be regarded as underfit. From the observations it was concluded that the major fluviatile landforms of the Carpentaria Plains were formed under conditions of greater stream activity than currently prevails.

The present-day, relatively decreased stream activity could have resulted from eustatic, tectonic or climatic changes. The authors consider that climatic change is the most probable cause. Eustatic changes are only likely to reduce stream activity during sea transgression across planar regions. Nick-points in major river systems on the north of the southern Carpentaria Plains (Ingram, 1972) confirm that the present-day sea level of the Gulf has dropped relative to the general surface level of the plains. The nick-points probably relate to a higher sea-level stand (of at least 5-6 metres) about 120 000 years BP which has been postulated by Smart (1976).

Tectonism could have reduced stream activity if it resulted in reduced stream gradient. Twidale (1966) considers that drainage types on the Wondoola Plain suggest uplift of the region immediately south of the Carpentaria Plains (i.e. the Selwyn upwarp).

It thus appears that climatic change is the most likely cause of the present-day comparatively reduced stream activity in the region. Palaeoclimatological work by Kershaw & Nix (1975) suggests a period between 7000 and 11 000 years BP that was generally wetter than today, but beyond that, back to at least 60 000 years BP, rainfall was less. While some surface features of the region may have been modified during the wetter period it is unlikely that the comparatively short time-span of 4000 years was sufficient to actually develop the main landforms of the Carpentaria Plains. It is more likely that they were developed earlier, under conditions of increased rainfall which must have occurred at least before 60 000 BP.

Some indications of the age of major river systems draining into the Gulf can be deduced by the distribution and configuration of beach ridges shown on the map of the geology of the Carpentaria, Karumba and part of the Laura Basins (Smart *et al.*, in preparation). The curvature of beach ridges into existing river mouths shows that the positions of major river exits and deltaic fan fronts, into the Gulf, have not substantially altered since the development of the Pleistocene beach ridges. Smart (1976) inferred the age of the ridges to be of the order of 120 000 years old.

It is concluded that the present-day normal wet season, and more irregular major flooding that occurs throughout the southern Carpentaria Plains, has very little erosional or depositional effect on the landforms of the region. It seems likely that the major landforms were developed in the Late Pleistocene under wetter conditions than currently prevail and that since formation they have not been substantially modified.

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The discovery of Miocene vertebrates, Lake Frome area, South Australia*

Richard H. Tedford[1], Michael Archer[2], Allan Bartholomai[2], Michael Plane, Neville S. Pledge[3], Thomas Rich and Patricia Rich[4], and Rod T. Wells[5].

This report announces the discovery of a diverse vertebrate fauna from exposures of the Namba Formation in the southern Frome Embayment (Tarkarooloo Basin), South Australia. The fluvio-lacustrine Namba Formation can be divided into two informal members based on regional lithological changes. The lower member bears Balcombian-Batesfordian (medial Miocene) pollen floras representing subtropical rainforest and adjacent savanna habitats. The top of the lower member yields the Pinpa Fauna of aquatic and terrestrial vertebrates including fish, turtles, crocodiles, two genera of dasyurids and seven genera of diprotodontan marsupials and a platanistid porpoise. The base of the upper member contains a similar vertebrate fauna (Ericmas Fauna) but includes a platypus and, significantly, diprotodontid marsupials which are the dominant large mammals in the contemporaneous Ngapakaldi Fauna of the Lake Eyre basin.

Introduction

In 1885 Ralph Tate (1886, pp. 54-55) noted the occurrence of aquatic vertebrate remains from a well 'near Lake Hurd, north of Billeroo trig, in the basin of Lake Frome', where 'they occurred in a stratum of sharp white sand underlying a clay which is reported to me to have embedded in it stems of mulga. The location of Lake Hurd has passed into obscurity but the occurrences of turtle, crocodile and fish remains in an angular sand matrix, were confirmed nearly 90 years later by the work reported below.

Study of the Cainozoic rocks of the Frome Embayment of the Great Artesian Basin by Roger A. Callen of the Department of Mines, South Australia resulted in the rediscovery of vertebrate fossils there in 1970. In 1971 and 1973 the authors obtained collections from Miocene and Pleistocene deposits southeast of Lake Frome. The National Museum, Victoria, assisted by an Australian Army contingent, obtained further materials from this area in 1974.

The outcrop stratigraphic studies of Callen and Tedford have been augmented by subsurface data collected by the Department of Mines, South Australia from its own drilling program and that of the several companies prospecting for uranium in the basin. These data have been synthesized in a detailed analysis of the Tertiary sedimentary history of the southern Frome Embayment (the Tarkarooloo Basin) by Callen (1975a). The Cainozoic stratigraphy and depositional environments have been summarized by Callen (1975b; 1976, & in press), and Callen & Telford (1976b). The following conclusions about the Tertiary deposits and environments are more fully developed in the works cited.

Acknowledgements

We are particularly grateful to Roger A. Callen, Mines Department, South Australia, for his interest and advice and for allowing us access to his detailed stratigraphic study of the Lake Frome area in advance of its publication. Our field assistant in 1973, Mr Richard Brown, rendered invaluable service. Mr Paul F. Lawson of the South Australian Museum again provided incomparable assistance in the preparation and logistics for the field, and in many other ways assured the success of our work. Station owners and managers in the area kindly gave access to their properties and other courtesies, especially Mr and Mrs Buddy Napier of Frome Downs. We are grateful for the support given our work by the directors and boards of trustees of the institutions we represent and to the National Science Foundation for Grant GB 18273X to Tedford. Mr Raymond Gooris skillfully prepared the figures and Mrs Janice Quinter typed the manuscript.

Stratigraphy

A diverse fauna of aquatic and terrestrial vertebrates has been obtained from the upper part of the fluvio-lacustrine Namba Formation, a newly recognized lithostratigraphic unit restricted to the Frome Embayment. The Namba Formation rests unconformably on the Paleocene-Eocene fluviatile Eyre Formation and extends onto older rocks around the basin margins and across pre-Namba basement uplifts within the basin (Figure 1). Its lower contact is exposed in a limited area on the western side of the basin where post-Miocene faulting has been active. The Namba Formation is divisible into two members that can be recognized over most of the Tarkarooloo Basin. The lower member is characterized by grey and black sandy clays composed predominantly of smectite, interbedded with laminated silt and fine to medium-grained cross-bedded sands, especially toward the basin margins. The upper member is disconformable on the lower, a zone of alunite is sometimes found in the top of the lower member near the contact, and the smectite clays of the lower member change sharply to an illite-kaolinite assemblage characteristic of the green clays of the upper member. Laminated fine sand and silt and cross-bedded stream-channel deposits are more common in the upper member. Both members contain lacustrine dolomite and associated palygorskite claystones. Dolomites were more extensively developed over the Tarkarooloo Basin during the deposition of the upper member, especially at its base. Such lacustrine and low energy fluviatile environments were eventually succeeded by red-coloured coarser clastics and a reappearance of smectite in the Willawortina Formation which intertongues with the uppermost Namba Formation (see legend, Figure 1). Restriction of the poorly sorted clastics of the Willawortina Formation to the western side of the basin indicates that they represent alluvial fans contributed by a rising Flinders Range and accompanying shift in climate toward drier environments in this region.

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[1] **The American Museum of Natural History, Central Park West at 79th Street, New York.**
[2] **Queensland Museum, Gregory Terrace, Brisbane 4000, Queensland.**
[3] **South Australian Museum, North Terrace, Adelaide 5000, South Australia.**
[4] **National Museum of Victoria, Russell Street, Melbourne 3000, Victoria.**
[5] **School of Biological Sciences, Flinders University, Bedford Park 5042, South Australia.**

* **Paper presented at the 25th International Geological Congress, Sydney, August, 1976.**

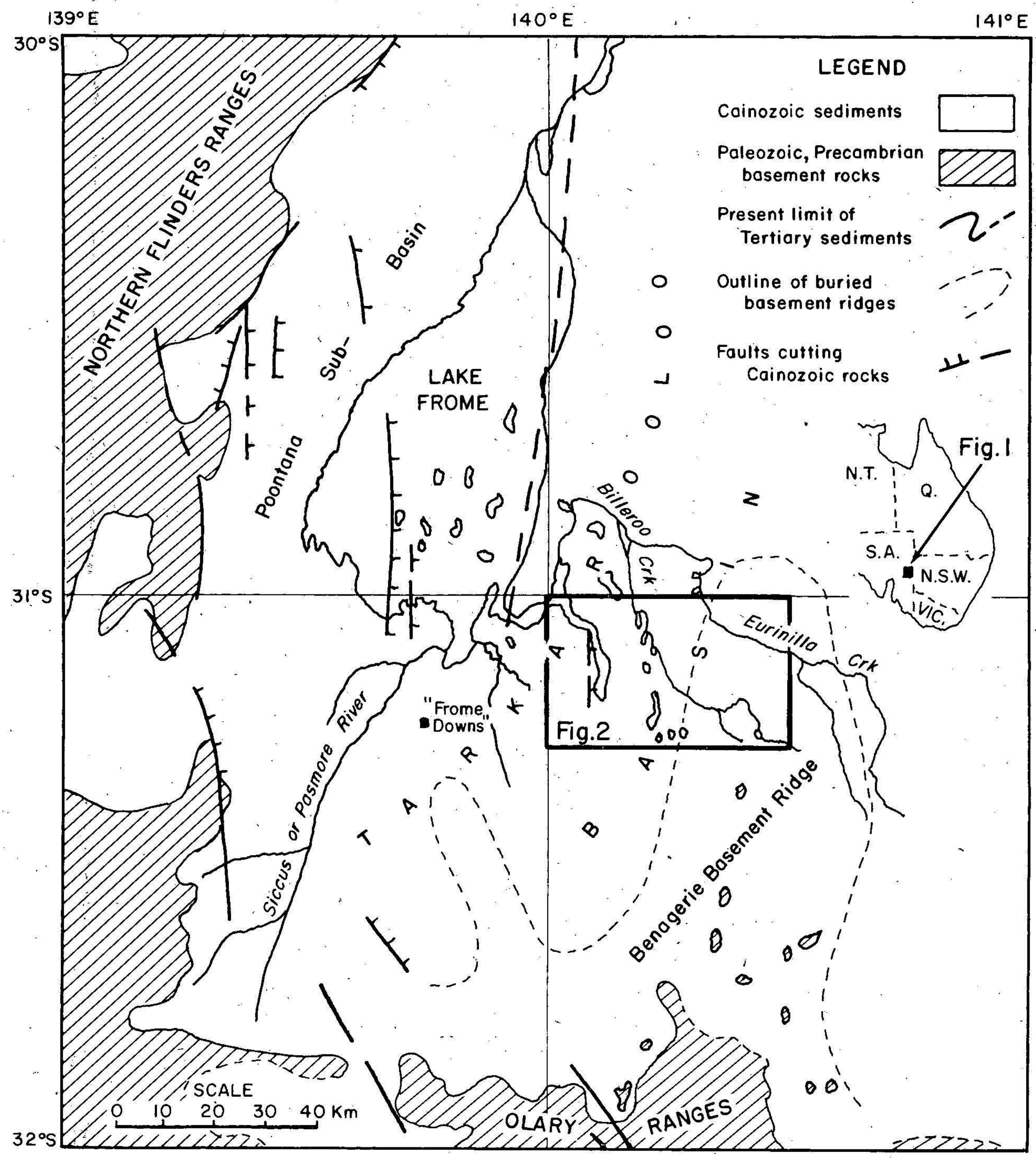

Figure 1. Location of southern Frome Embayment, and its relationship to the Cainozoic Tarkarooloo Basin margin and structure. Namba Formation and overlying Quaternary fluviatile sediments form scattered exposures where revealed by deflation and the action of streams that penetrate the latest Quaternary-Holocene sand sheets and dunes. West of Lake Frome in the Poontana Sub-Basin the Willawortina Formation forms virtually the only surface outcrop of Tertiary rocks. It interfingers with the uppermost Namba Formation just east of the Passmore River. Data from Callen (1975a).

Palaeontology

Outcrops of the Namba Formation at Lakes Namba, Pinpa, and Yanda, and along Billeroo Creek, 35-45 km east and southeast of Lake Frome, appear to include the intraformational contact (Figure 2). Green claystones and dolomitic claystones at the top of the lower member produced a locally abundant vertebrate fauna termed the Pinpa Fauna. These rocks are disconformably overlain by a regionally traceable sequence of thin-bedded fine to medium-grained sands which were deposited in point-bars and overbank sheets on a scoured surface cut in the lower member. The more limited vertebrate assemblage from these basal sands of the upper member is termed the Ericmas Fauna. The Pinpa and Ericmas Faunas are dominated by aquatic vertebrates including ray-finned fish (catfish are represented here), lungfish, chelid turtles, crocodiles and river-dwelling platanistid porpoises. The latter provides clear evidence of external drainage of the Frome Embayment—possibly southward into the Murray Basin, at that time experiencing its greatest Tertiary transgression. In addition to the aquatic forms common to both

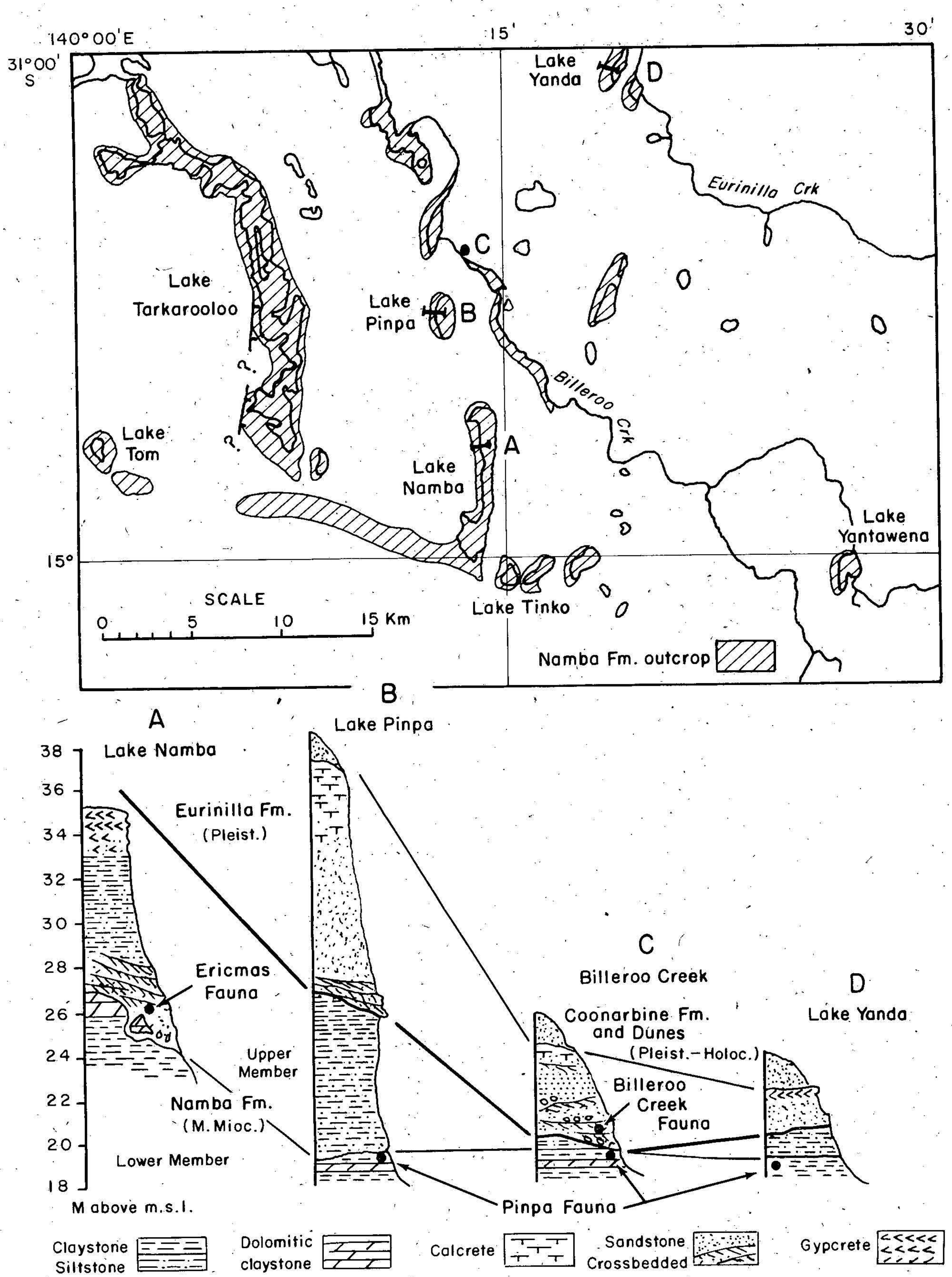

Figure 2. **Map and stratigraphic sections showing outcrops of Namba Formation in the Eurinilla 1:63 360 sheet area (From Callen, 1975a, and original observations).** Columnar sections at vertebrate fossil sites show mutual stratigraphic relationships of Miocene faunas and a Pleistocene assemblage. Stratigraphic nomenclature after Callen, 1975b. Sections A and B were directly levelled using a barometer with ± 2 m. accuracy; Section C was projected to a nearby similarly levelled point and section D is unlevelled.

faunas, a single platypus tooth (*Obdurodon insignis* Woodburne & Tedford, 1975) one of the two known teeth representing the earliest recorded monotremes, occurs in the Ericmas Fauna. Bird remains are abundant in the lower member, especially water birds including flamingos, cormorants, ducks, geese, rails and the stone curlew.

The terrestrial vertebrates of the Pinpa Fauna include meiolanid turtles, lizards, and a variety of marsupials, most of which are new taxa of generic and higher rank and hence cannot be more precisely listed at the present time than as follows: Dasyuridae (2 species), ?Wynyardiidae (1 species), Vombatoidea (2 species), Phascolarctidae (1 species), Petauridae (1 species), Ektopodontidae (1 species) and Burramyidae (1 species). This fauna is especially noteworthy for the lack of diprotodontids and macropodids and the diversity of terrestrial vombatoids, and arboreal wynyardiids, koalas and small phalengerids. Terrestrial vertebrates are rare in the younger Ericmas Fauna, but a palorchestine diprotodontid close to the Miocene genus *Ngapakaldia* occurs along with a vombatoid of modern type. Remains of a koala and pseudocheirine petaurid in the Ericmas Fauna are clearly related to their Pinpa counterparts, but they appear to be specifically distinct, implying that the intraformational contact records a significant time gap as well as change in environment of deposition.

The following notes will indicate the morphology and relationships of some of the Pinpa Diprotodonta as far as analyses have been taken at the moment. More complete descriptions are in preparation.

1. ?Wwnyardiidae: partial skeletons are present, but unfortunately the one skull available lacks precisely those areas necessary for close comparison with the Tasmanian *Wynyardia.* Close correspondence in the limbs provides the main evidence for the tentative indentification and confirms that these animals were syndactylous. Complete dentitions establish their diprotodonty and show an interesting stage in the development of bilophodont upper molars, in which the labial ends of the lophs are formed from the large stylar cusps b, c and d (Figure 3A). The paracone and metacone take up a median position on the developing lophs. The lower dentition is completely lophodont and very macropodine in appearance (however, the mandibular ramus bears no masseteric canal).

2. Vombatoidea: one species (genus A) is represented by most of a skeleton (the only specimen found in the entrapment position so common among the *Ngapakaldia* skeletons in the Lake Eyre Basin) including a crushed skull but no lower jaw. The other and larger form, (genus B), is represented by crushed skulls, rare jaw fragments and fragments of the skeleton. These are the most abundant large mammals, about wombat-size and a little larger and very wombat-like in the limbs. The delto-pectoral crest of the humerus is not so expanded as in the fossorial living wombats, but otherwise the comparisons are striking. These were heavy-bodied terrestrial animals, diggers but probably not burrowers. Many of the cranial features are also wombat-like, including the phylogenetically important exclusion of the alisphenoid from the auditory cavity through expansion of the squamosal. Dentally these forms are dissimilar: both have the same dental formula including three upper incisors, one canine, a premolar and four molars, but the smaller more wombat-like form shows greatly enlarged central incisors. Behind the fluted sectorial premolar its cheek teeth are brachyodont, root-bearing bilophodont teeth that incorporate the stylar cusps into the crown pattern in a manner very similar to the unworn teeth of living wombats (Figure 3B). The larger form has low crowned selenodont cheek teeth (Figure 3C), molariform premolars and a short-crowned, tightly grouped upper incisor battery and ankylosed lower jaw symphysis. In these features it is koala-like, but the resemblance stops there.

The Pinpa ?Wynyardiid and the vombatoids indicate the ways in which stylar cusps were incorporated into complex molar patterns in the Diprotodonta. This evidence reinforces the contention of Winge (1941), Ride (1971), and Archer (1976b), that selenodont molar patterns resembling those of the peramelids and phascolarctids, with their large stylar cusps and a median valley separating the paracone and metacone, represent the structurally primitive dental pattern among the Diprotodonta.

3. Phascolarctidae: the Pinpa koala is different from *Perikoala* of the Ngapakaldi Fauna and seems more closely related to the living genus than any of the Tertiary genera so far described. It shows an early stage in molarization of M_1 and enlargement of the posterior molars (Figure 3D).

4. Petauridae: a small pseudocheirine is the most abundant mammal in the Pinpa Fauna and congeneric forms are also present in the Ericmas and Ngapakaldi faunas. Interestingly, its dentition suggests an intermediate phase in the development of a bunodont-phalangerid type of dentition from a selenodont one.

5. Ektopodontidae: a single cheek tooth resembles undescribed material from the Etadunna Formation which demonstrates the phalangeroid bilophodont affinities of this family, originally attributed to the Monotremata.

6. Burramyidae: a large *Cercartetus*-like form is present and also appears to be represented in the Etadunna Formation. This taxon demonstrates the antiquity of the bunodont trituburcular type of cheek tooth thought by many to be the primitive pattern among the Diprotodonta, but considered here to be a modification of the primitive selenodont plan.

Age and palaeoecology

Pollen floras from the lower member of the Namba Formation in the Poontana Sub-basin (Figure 1) record subtropical rainforest vegetation including *Nothofagidites* (but no species diagnostic of high temperatures) and abundant grass pollen, suggesting riparian forests with savannas on the better drained interfluves. Very similar floras are present in Batesfordian-Balcombian deposits in Victoria (Muddy Creek Marl) and South Australia (Munno Para Clay) and these comparisons establish the maximum age for the vertebrate assemblages that occur higher in the Namba Formation (W. K. Harris, pers. comm., 1973). These stages are approximately medial Miocene in age, roughly 14-16 million years BP (Ludbrook, 1973).

The Namba Formation faunas have a different composition to the approximately contemporaneous Ngapakaldi Fauna (see Stirton, Tedford & Woodburne, 1968) from the Etadunna Formation in the Lake Eyre Basin 350 km to the northwest of Lake Frome. This correlation is best supported by the presence of four congeneric taxa (a large vombatoid and three small phalangeroids) in the Pinpa Fauna and the Ngapakaldi Local Fauna from the stratotype of the Etadunna Formation. Ngapakaldi local faunas from lakes Pitikanta and Ngapakaldi are dominated by palorchestine diprotodontids and to a lesser extent kangaroos that strongly contrast with the Pinpa assemblage with its abundant large vombatoids, koalas and ?wynyardiids. These faunal differences are believed to at least partly reflect the ecological contrast between the inland Lake Eyre Basin of internal drainage and the coastal Lake Frome Basin that maintained access to the sea in medial Miocene time. The pollen floras obtained from the two basins are very similar in composition and can be used to support the correlation provided by the mammals. However, they imply

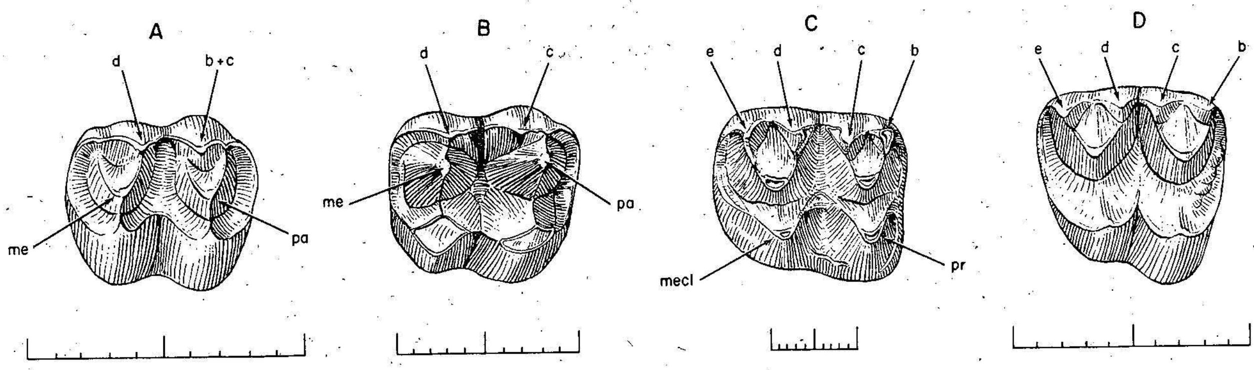

Figure 3. Comparative occlusal views of right upper second molar of four Pinpa Fauna diprotodontans to show importance of stylar cusps in crown pattern. All drawn to the same size, actual sizes indicated by 1 cm. bars. A ?Wynardiidae, QMAM 178, reversed; B. Vombatoidea, gen. A, QMAM 168; C. Vombatoidea, gen. B. QMAM 181; D. Phascolarctidae, QMAM 255. Stylar cusp nomenclature follows Archer, 1976; me, metaconid; mecl, metaconule; pa, paracone; pr, protocone.

little difference in environment at least during the early phases of deposition of these medial Miocene sediments. The Etadunna Formation as exposed (Stirton, Tedford & Miller, 1961), and especially as revealed by drilling in the Lake Eyre Bore 20 (Johns & Ludbrook, 1963), is very similar in lithology to the Namba Formation, except for the dominance of carbonates. Black smectite-rich clays with a ferruginous horizon and alunite as in the lower member of the Namba Formation constitute only a very thin sequence of the base of the Etadunna Formation in Bore 20 (revised log Callen, 1975a). If the clay mineral and attendant lithological changes can be related to synchronous regional environmental change then most of the Etadunna Formation, particularly that containing the Ngapakaldi Fauna, may be more precisely equated with the upper member of the Namba Formation. Such a correlation is also suggested by the presence of the platypus and diprotodontid in the Ericmas Fauna. If this hypothesis is correct the Pinpa Fauna may be older than most of the Ngapakaldi Fauna. For the moment, however, we must conclude that the faunal differences observed between the medial Miocene assemblages of the Lake Frome and Lake Eyre basins may be the result of contrasting ecologies and/or significant age differences.

Despite these uncertainties, the presence of diprotodontids and kangaroos in the Ngapakaldi Fauna of the Lake Eyre Basin suggests an early stage in the development of a marsupial assemblage typical of later Cainozoic time. In contrast, the Pinpa Fauna in the Lake Frome Basin contains a peculiar assemblage of terrestrial and arboreal diprotodont marsupials that probably represent survivors of rainforest inhabiting assemblages of the medial Cainozoic. The Pinpa marsupials are thus exceedingly interesting for they present us with novel morphological combinations that enlarge our concept of the diversity of the Australian Diprotodonta.

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Investigation of hot gas emissions from Koranga volcano, Papua New Guinea, in 1967

C. J. Pigram*, R. W. Johnson, and G. A. M. Taylor

Hot emissions of mainly sulphur dioxide and carbon dioxide took place from a mound in Koranga open cut, near Wau, following a landslide at the end of May, 1967. Rocks of the Holocene volcano, Koranga, are exposed in the open cut. The emissions lasted about three months, and ceased on 13 August after another landslide removed the active mound. During the period of activity, recorded temperatures ranged up to 680°C; no anomalous seismic or tilt phenomena were recorded. The cause of the activity is not known, but it is thought that the high temperatures and gases may have been the result of the spontaneous combustion of reactive sulphides and carbonaceous material present in the altered rocks of Koranga volcano.

Introduction

On 22 May, 1967, the Goverment District Office at Wau, Papua New Guinea, received a report of the appearance of hot ground and emissions of gas following a landslide in the Koranga open cut, about 1 km northwest of Wau township (Figures 1 & 2). Because these events took place in an area occupied by a Holocene volcano, and because thermal activity had not previously been reported from the area, the appearance of hot ground and gas was viewed with concern, and a volcanological investigation was carried out. Some inhabitants in Wau were fearful that the emissions were preliminary signs of an imminent volcanic eruption, and one of the principal objectives of the investigation was to advise the local authorities of the significance of the event; and to recommend any necessary precautionary measures.

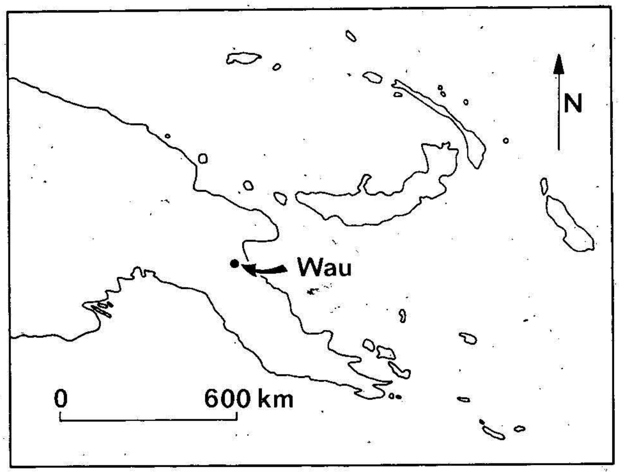

Figure 1. Papua New Guinea and location of Wau.

The late G. A. M. Taylor, and R. G. Horne, assisted by R. F. Heming, maintained observations for almost three months. Temperatures and tilt were measured, and collections of gases, sublimates and rocks were made. Observations started on 2 June; activity was last observed on 13 August shortly before a further landslip took place.

In this account, the geology of Koranga volcano is briefly described, a summary is presented of the observational data on the 1967 thermal activity held in one of Mr Taylor's files in Canberra, and the cause of the emissions is discussed.

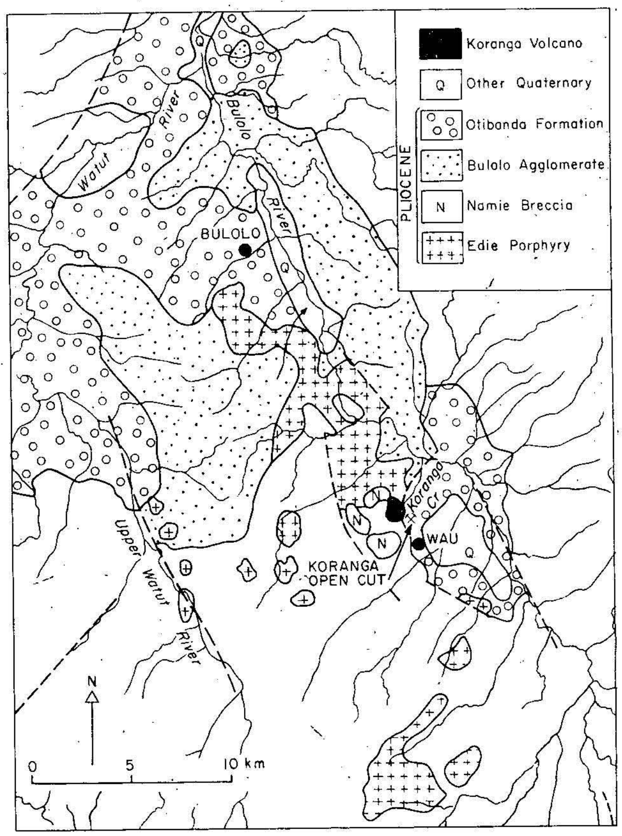

Figure 2. Geological sketch map of the Wau-Bulolo area, adapted from Dow *et al.* (1974). Rocks older than Pliocene are shown blank. Faults shown as dashed lines. Solid circles represent townships.

Geology

Koranga open cut is an eastward-facing amphitheatre-like depression on the southeastern side of Koranga volcano. The oldest exposed rocks are Pliocene auriferous sediments of the Otibanda Formation (Plane, 1967) which, according to Dow *et al.* (1974), are unconformably overlain by the rocks of Koranga volcano (Figure 2).

The volcanic rocks of Koranga cover about 1 sq. km on a low broad ridge that overlooks Wau township. Pervasive thermal alteration had destroyed many of the primary characteristics of the rocks, but the volcano appears to consist of a lava flow, or flows, overlying volcaniclastic deposits. The rocks are thought to be dacitic or rhyolitic, although to the writers' knowledge no unaltered rocks have been chemically analysed. The rocks contain pyrite, and traces of gold were discovered during drilling operations in 1959. Recently, P. L. Lowenstein (pers. comm., 1975) found

* C. J. Pigram, Geological Survey of Papua New Guinea, P.O. Box 778, Port Moresby, Papua New Guinea

Figure 3. Koranga Open Cut from the east in 1967.

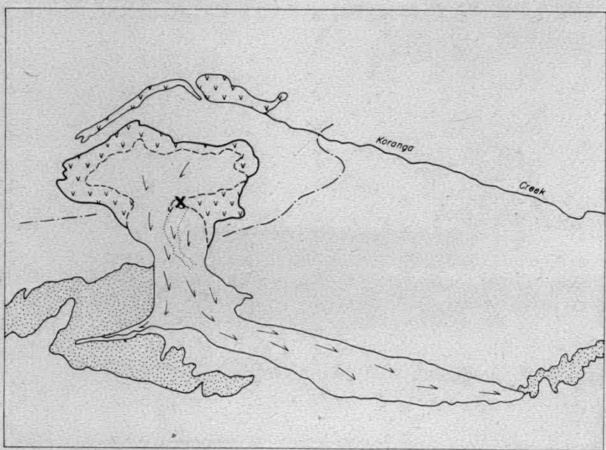

Figure 4. Explanation of features shown in Figure 3. Prominent outcrops of Koranga volcanic rocks are shown by the v-pattern; those of the underlying sediments are shown stippled; approximate base of Koranga volcano indicated by dot-dash line (drawn by D. B. Dow, 1974). The half-headed arrows indicate approximate directions of flow of mudflow units formed by slips from the wall of the Open Cut. The two dotted lines show the probable edges of the upper part of the landslip produced in May, 1967, when the gas emissions—shown by the cross—appeared at the head of the slip.

highly pyritized and carbonized wood within boulders of volcanic rocks in the open cut.

At Koranga, the sediments of the Otibanda Formation are mainly lacustrine conglomerate and interbedded cross-laminated sandstone lenses (Plane, 1967). D. B. Dow (pers. comm., 1974) reported that beds of coarse arenites in the open cut contain pyrite and carbonized logs up to 20 cm across and 30 cm long, and that in Anderson's Creek, about 1 km northwest of the open cut, sluicing operations in 1960 revealed the base of the Koranga volcano which was seen resting on '. . . several metres of fairly unconsolidated sand and sandy gravel. Near the base of these beds was a highly pyritic carbonaceous sand which, from memory, contained about 20 percent pyrite and a small proportion of carbonized plant remains'.

During the Pliocene, explosive dacitic volcanic activity led to the formation of the Bulolo Agglomerate which blocked an old course of the Bulolo River north of Wau, and formed the lake in which part of the Otibanda Formation was deposited (Figure 2; Dow *et al.*, 1974). The late-stage emplacement of high-level stocks and dykes (Edie Porphyry) and diatremes (Namie Breccia) associated with this igneous activity is thought to have introduced most of the mineralization of the Morobe goldfield. Koranga open cut is one of several mining sites in the Morobe goldfield, which was discovered in 1922 when gold was first panned from the mouth of Koranga Creek (Figure 2).

Old solfatara-like deposits of sulphur and siliceous sinter had been reported from Koranga before 1967. Widespread deposits of sulphur were also observed in the open cut in 1974, when sulphur was especially common at the top ends of recent landslips, suggesting the deposits formed very recently—that is, after the 1967 gas emissions.

Gas emissions in 1967

Location

The hot ground and gas emissions of 1967 were in a mound at the head of the landslip which had taken place in May (Figure 3 and 4). The mound was in the centre of the open cut, at the southern end of a spur that projected from the northern rim. The mound had steep slopes, and the strongest gas activity and highest temperatures were always centred at the upper end of the mound where the rock (breccia) was fracturing and moving away from a stable wall of material that was not part of the initial landslide. With movement of the slide the hot material appeared to be spread over a distance of about 10 m.

Temperatures

Temperatures appeared to change rapidly at some points on the mound, because of the movement of the landslip material, and because pressurized vents were absent. To localize temperature readings as much as possible so that trends could be detected, two four-feet lengths of two-inch galvanized water pipe were driven into the mound—one at the top, the other at the bottom. Hard wooden points fitted into the lower opening of the pipes prevented rubble from entering the pipes during penetration of the mound. Numerous quarter-inch holes drilled in the lower halves of the pipes acted as entry points for the gases in the mound, so that the pipes acted as chimneys. Many of the recorded temperatures were outside the range of mercury-in-glass thermometers, and mercury/gallium-in-quartz thermometers (upper limit of 1200°C) were therefore used. These instruments were later supplemented with a thermo-couple probe-type instrument.

Temperatures recorded in the two pipes, A and B, are plotted in Figure 5. At the upper measurement point A, the highest temperature was 640°C, recorded at the beginning of June, but by the end of the month temperatures had declined to about 300°C. Throughout July, temperatures at A stayed in the range 240-325°C, but on 5 August they rose abruptly to 420°C, and thereafter declined slightly until activity ceased on 13 August. Temperatures at the lower measurement point B were lower than those at A; they never exceeded 350°C, and recording ceased after 24 June when temperatures dropped below 70°C.

From 31 July measurements in other parts of the mound, using the thermocouple-probe, indicated that temperatures were much higher than those at points A and B, as shown by C in Figure 5. During the next two weeks, these temperatures ranged up to 580°C. Furthermore, on 13 August, just before landslide movement transported the active mound into the valley below, a temperature of 680°C was recorded in a crevice revealed by clearing away about 60 cm of surface rubble from the top of the mound.

It seems probable, therefore, that despite the declining course of temperature changes shown at measuring points A and B, high temperatures were maintained in the mound throughout the period of activity. A and B were therefore probably not stationary points of measurement, and the apparent decline in temperature can be attributed to migration of the heat centre away from the measuring points in the mound or, alternatively, to movement of the points away from the heat source. A few days before the gas emissions ceased, a pronounced increase in the rate of landslip took place, and pipe A moved to a point about 25 m below the top of the mound.

Gas compositions

The Koranga gases formed white drifting emissions at the summit of the active mound (Figure 6). They were visible during the heat of the day, and smelt strongly of sulphur dioxide. Collections of gas were made on six days in June by bubbling about 18 litres of gas through 250 ml. of 1N potassium hydroxide (KOH) solution. These solutions were analysed for the acid gases and it was shown that the gases consisted almost entirely of sulphur dioxide and carbon dioxide.

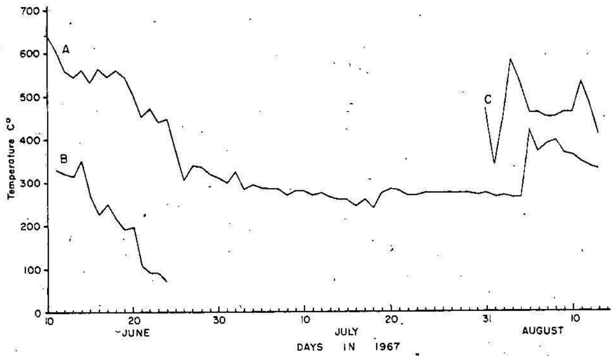

Figure 5. Temperatures recorded at Koranga Open Cut in 1967. A and B constructed from daily temperature measurements in pipes at top (A) and bottom (B) of the active mound, using mercury/gallium-in-quartz thermometers. Temperatures recorded by the thermocouple-probe in other parts of the mound are indicated by C.

Significant quantities of water vapour were not detected in the field, which is surprising in view of the fact that the gas emerged from landslip material which was capable of moving as a mud flow. However, as the first gas samples were not taken until 9 June, eighteen days after the activity was first reported, it is clear that with temperatures as high as 600°C it would not take long for the mound to dehydrate. In the field, minor amounts of hydrogen sulphide were thought to be present, but they were not detected by later analysis.

Compared to the compositions of gases and vapours collected from fumaroles and solfataras of known volcanic origin, the Koranga gases are unusual, as they contain high proportions of sulphur dioxide, but little, or no, water vapour and hydrogen sulphide (cf. Macdonald, 1972, p. 323-29).

Sublimates

During the period of gas emission, crystals grew on the surface of the mound and on the galvanised-iron pipes used for temperature measurement. Several samples were collected, and these were later examined spectrographically.

Six samples were found to consist dominantly of iron sulphates, or aluminium sulphates, or both. Two other samples were altered rocks, stained by iron sulphide (and possibly carbonaceous matter). Two of the sulphate samples collected from the pipes contained zinc, and it is probable that these formed by reaction of the galvanised iron with the sulphur dioxide.

Seismicity and acoustics

A portable seismometer was used during the investigation. No anomalous local seismic events indicative of a moving body of magma appear to have been recorded. Recorded earth tremors were probably induced by landslipping. Between 11 and 14 August, the rate of landslip was observed to have increased, and continuous underground sub-explosive noises were noticed in viscous clayey areas where movement was rapid.

Tilt

A tiltmeter was installed in the open cut 300-400 m from the active mound, and a consistent movement downslope was indicated from the beginning of June until 14 August. This corresponded with the general direction of slippage in the open cut, and was thought to be indicative of the build-up in movement that led to the major slip which removed the hot mound.

Discussion

The cause of the 1967 gas emissions is not known. However, the observations recorded above suggest that the high temperatures were almost certainly not a direct result of a body of magma beneath the volcano, but rather may have been produced by a series of near-surface exothermic chemical reactions involving sulphides and carbonaceous materials, or carbonates, or both.

Figure 6. Gas emissions from the active mound, showing drum aspirators used in fruitless attempts to collect gas samples late in the investigation.

The following points argue against a direct volcanic origin for the high temperatures and gas emissions at Koranga.

1. The life of the emissions was governed by landslides; gas appeared after a major landslip in May, and disappeared in August after another slip had removed the active mound.
2. The compositions of the gases were apparently unlike those normally recorded at volcanic fumaroles and solfataras—they were characterized especially by an apparent absence of water vapour.
3. Seismic, tilt, and acoustic observations gave no indication of the presence of a magma body beneath the open cut.

The production of high temperatures, gases and iron sulphates has been noted in mines and stock piles of ore in many parts of the world, and ascribed to spontaneous combustion (e.g. Harrington *et al.*, 1923; Hewett, 1968; Lukaszewski, 1969). By analogy, therefore, it is proposed that the Koranga landslip of May 1967 allowed access of oxygen to reactive pyrite and carbonaceous material either in the altered rocks of Koranga volcano, or—less likely—in the underlying sediments. The pyrite and carbonaceous material were spontaneously ignited, producing sulphur dioxide, carbon dioxide and high temperatures and, because the fuel source and supply of oxygen were maintained, the exothermic reaction continued unabated until the landslip in August cut off the air supply. An alternative possibility for the formation of the carbon dioxide is by attack of carbonate minerals in the altered rocks of Koranga by acids produced during combustion of the sulphides (see Lukaszewski, 1969).

The possibility that combustion was triggered off by an input of geothermal (i.e. volcanic) heat has been considered. However, it seems likely that the effects of a significant thermal input would have been noticeable over a much greater area than that occupied by the active mound, and we therefore favour the concept that the 1967 activity resulted essentially from non-volcanic chemical reactions involving the oxidation of ore.

Oxidation undoubtedly took place under special and complex conditions. No further activity has been reported since 1967, despite the fact that reactive material is exposed in the open cut. However, the presence of solfatara-like deposits in the open cut may indicate that similar activity had taken place both before and after the 1967 event, but was not observed or reported.

Acknowledgements

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Magnesite-bearing calcrete near Gosses Bluff, Northern Territory

A. T. Wells

Small nodules and tabular bodies of practically pure micro-crystalline magnesite up to a few centimetres across occur in late Cainozoic calcrete around Gosses Bluff. The calcrete underlies an area of about 15 km² and the magnesite constitutes somewhat less than 1 per cent of the outcrop. The bedrock in the area of calcrete is impact breccia of the Gosses Bluff structure. The superficial weathered products of these breccias constituted a suitable host rock for the calcrete because of their inherent permeability and their position in

topographically low areas. The source of magnesium carbonate was most likely in the Late Proterozoic and Palaeozoic dolomites and magnesian limestones exposed to the north in the MacDonnell Ranges.

Petrographic evidence from the random samples of calcrete collected at Gosses Bluff suggests that the history of the deposit commenced with invasion of magnesium carbonate rich waters and formation of small bodies, probably of a metastable hydrate of magnesite which later reverted to the stable phase.

A period of sub-aerial dessication ensued and caused disintegration of the nodules and production of cracks and voids. Phreatic water enriched in calcium carbonate invaded the deposit; voids were lined with fibrous calcite, smaller cracks were completely filled, and at the same time the magnesite was replaced, in part, by calcite. The larger voids were subsequently filled by calcrete which consisted of a mixture of disintegrated breccia fragments, chiefly quartz, feldspar and quartzite grains, with the addition of a minor proportion of magnesite grains incorporated from the nodules; and an abundant matrix of calcite.

There is scant reference to magnesite in calcretes elsewhere in Australia, possibly because magnesite is not readily distinguished in some fine-grained calcretes.

Introduction

Magnesite in sediments is not common; described modes of occurrence include weathering of magnesium silicate rocks, dolomite and dolomitic limestone, primary precipitations in playa lakes, apparently primary deposits in thick marine evaporites, in ephemeral lakes bordering lagoons where metastable phases have transformed during diagenesis and similar transformations in the process of formation of magnesites of hydrothermal and metamorphic origin.

Throughout the Amadeus Basin magnesite occurs as small incrustations on outcrops of Adelaidean Bitter Springs Formation and on float material in alluvium probably derived from weathering products of ultramafic basement rocks there. This paper records its presence in calcrete in the Gosses Bluff area.

The occurrence of magnesite as an unbedded superficial deposit in this environment is inconsistent with the described modes of occurrence and has apparently received scant attention. To the author's knowledge magnesite has rarely been reported in Australian calcrete. This paper may help to stimulate interest in recording magnesite in surface environments and in the interpretation of their formation. Information on its origin at Gosses Bluff may indicate where richer, possibly economic deposits might have accumulated elsewhere in the continent.

Occurrence

Calcrete bodies containing small nodules and tabular bodies of magnesite crop out in the plain outside, but adjacent to, the ring-shaped central uplift of the Gosses Bluff impact structure in the western part of Missionary Plain about 165 km west of Alice Springs, Northern Territory (Figure 1).

The rocks forming the Bluff and underlying the adjacent plain up to 11 km from the centre of the Bluff consist of brecciated rocks, mainly middle Palaeozoic sandstone; the brecciation is thought to be the result of extra-terrestrial impact in the Early Cretaceous (Milton *et al.*, 1972). The calcrete underlies an area of about 15 km^2; of this about 10 km^2 of calcrete is situated in the outer zone to the west and southwest of Gosses Bluff and the remaining 5 km^2 is scattered over the remainder of the outer zone. The calcrete is exposed in stream channels, forms low outcrops in the thin spread of aeolian sand that underlies the plain (Figure 2), and occurs as joint fillings in, and crusts on, outcrops of breccia. The magnesite nodules in the calcrete are irregular in shape and size but are generally no more than a few centimetres across (Figures 2, 3). It is estimated that they constitute somewhat less than 1 percent of the outcrops of calcrete in the 45 localities examined (Figure 1). No magnesite was found in the small calcrete bodies and selected rock samples within the central pound of the Bluff and only about half of the sampled calcrete bodies surrounding the Bluff appear to be magnesite-bearing (Figure 1). In all the localities where magnesite is present it appears to be closely associated with impact breccia, or with areas where impact breccia is thought to be at shallow depth.

The widespread occurrence of magnesite in the calcretes was first confirmed by X-ray diffraction studies. The results of major element analyses of 13 samples of magnesite-bearing calcrete are given in Table 1; their locations are given in Figure 1. Compared to world-average calcretes (Goudie, 1973, p. 18) the Gosses Bluff samples are deficient in CaO, SiO_2, Al_2O_3 and Fe_2O_3, but greatly enriched in MgO. High-magnesian calcretes are reported from Archers Post, Kenya (op cit., p. 21) but their mineralogy is unknown.

Petrography

The host calcrete consists of quartz and feldspar grains and sandstone fragments in a matrix of mostly fine with some coarse-grained calcite.

The magnesite is microcrystalline (Figure 4; crystallites about 0.002 mm across), mostly homogeneous, and contains rare quartz and feldspar grains and, in a few places, fragments of impact breccia (Figure 5). It is veined and partly replaced by microcrystalline to fine-grained calcite (Figures 5, 6, & 7), and some nodules are fragmented, the matrix being microcrystalline calcite, in places incorporating quartz and feldspar grains. Fractures in some magnesite nodules are filled with microcrystalline calcite crowded with quartz and feldspar grains and small fragments of magnesite, and commonly have a selvedge of fibrous calcite (Figure 6). Some calcite veins cut across both magnesite nodules and incorporated breccia fragments. Partial staining of the magnesite, particularly around vugs and cavities (Figure 4), is probably a weathering feature owing to the introduction of iron minerals from groundwater.

Origin

Bedded magnesite deposits in sedimentary rocks are unusual and reported occurrences in calcrete are rare. It is generally believed that because of their great solubility magnesium carbonates are uncommon under surface conditions. None of the described occurrences appear to be in any way consistent with the mode of occurrence in the unbedded superficial calcrete at Gosses Bluff. Magnesite deposits of any size are nearly always formed by the decomposition of mafic or ultramafic rocks of which serpentinite is the most common. Some bedded deposits in sediments are known in Australia, chiefly in South Australia, but the details of the occurrences are not known. Johns (1963) recorded high-magnesium carbonate content in Pleistocene armorphous limestone but it would seem that it occurs combined in dolomite in the 'kunkar' ('travertine'). It would appear that the hydro-magnesite recorded from recent carbonate sediments in ephemeral, lagoonal lakes by Von der Borch (1965), Aldermann (1965) and Aldermann &

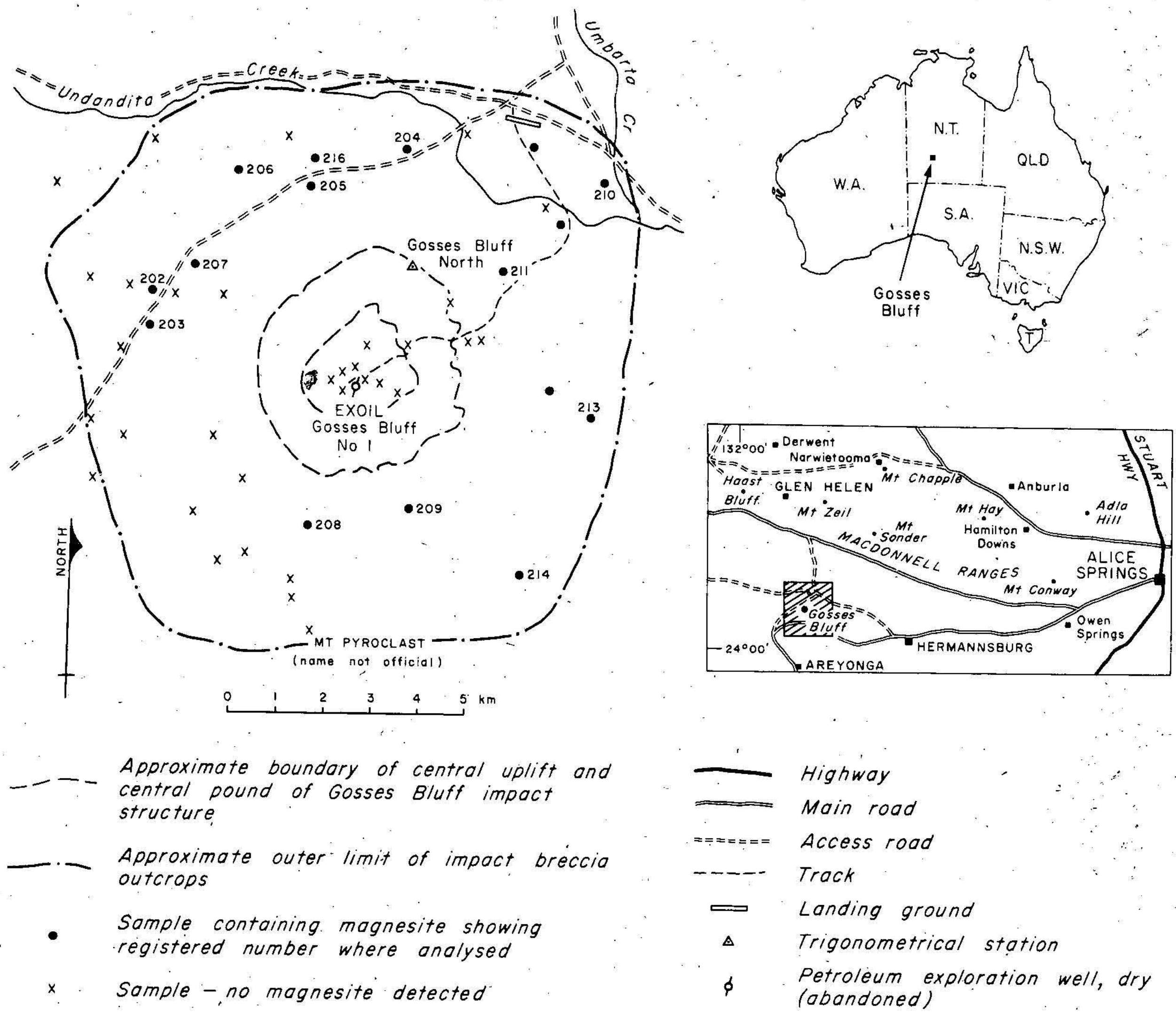

Figure 1. Sketch map showing location of sample sites at Gosses Bluff.

Sample No.	202	203	204	205	206	207	208	209	210	211	213	214	216
SiO_2	6.6	17.7	6.0	5.1	2.7	2.1	2.3	4.6	6.1	11.5	1.7	5.2	1.1
TiO_2	0.02	0.09	0.03	0.03	0.01	0.00	0.01	0.00	0.05	0.04	0.02	0.05	0.00
Al_2O_3	0.53	1.44	0.59	0.53	0.24	0.06	0.30	0.12	.0.93	0.91	0.42	0.88	0.21
*Fe_2O_3	0.22	0.60	0.30	0.29	0.07	0.01	0.14	0.05	0.43	0.35	0.15	0.28	0.08
MnO	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.
MgO	18.2	19.8	26.5	37.8	28.6	42.6	39.5	45.0	23.3	4.4	39.8	27.6	45.9
CaO	31.2	21.1	21.8	7.5	21.1	6.0	11.0	3.75	24.8	43.6	10.2	20.0	2.15
K_2O	0.15	0.42	0.16	0.16	0.06	0.01	0.09	0.03	0.29	0.32	0.10	0.28	0.05
P_2O_5	0.04	0.04	0.04	0.03	0.05	0.02	0.02	0.01	0.06	0.10	0.03	0.04	0.01
Loss on ignition	43.9	39.2	45.9	48.4	47.6	50.8	49.4	49.4	44.9	39.2	49.8	45.9	51.2
Total	100.9	100.4	101.3	99.8	100.4	101.6	102.8	103.0	100.9	100.4	102. 2	100.2	100.7

* Total iron as Fe_2O_3; n.d. not detected; Na_2O detected, but not determined; all sample numbers prefixed 70500.

Table 1. Silicate analyses of magnesite-bearing calcretes by X-ray fluorescence

Analyses by J. W. Sheraton, BMR.

Considerable difficulty was experienced in the preparation of homogeneous fusion discs for sample numbers 70500207, 208, 209, 213 and 216 and probably accounts for the unacceptably high totals for these analyses. This is attributed to their unusual compositions, particularly the high MgO contents. The results for these samples should therefore be treated with extreme caution.

Von der Borch (1961), together with aragonite, are the precursors of dolomite and magnesite.

Equilibrium phase diagrams for the relations between calcium and magnesium carbonates at 25°C and one atmosphere total pressure (A. B. Carpenter *in* Schmitt 1962, *in* Garrels & Christ, 1965) suggest that magnesite cannot be deposited together with calcite over a very wide range of CO_2 pressure and Ca/Mg ratios. This supports the proposal that deposition of carbonates at Gosses Bluff took place by the action of two periods of groundwater invasion; the first with magnesium carbonate-enriched water and the second enriched in calcium carbonate.

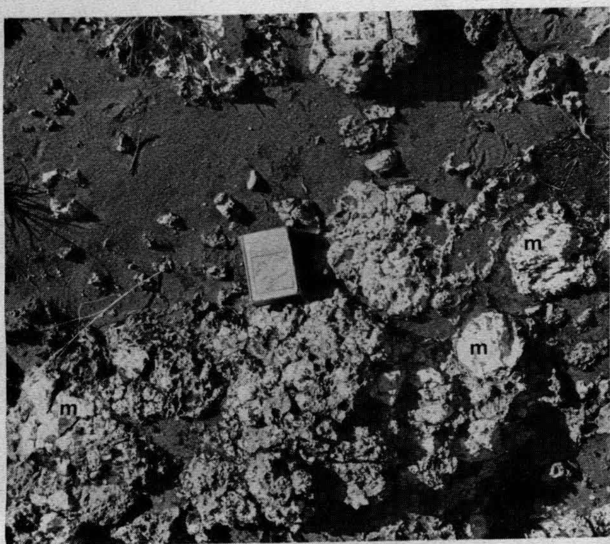

Figure 2. Spherical and irregular nodules of magnesite (m) in calcrete outcrop, partly obscured by aeolian sand, on the western side of Gosses Bluff.

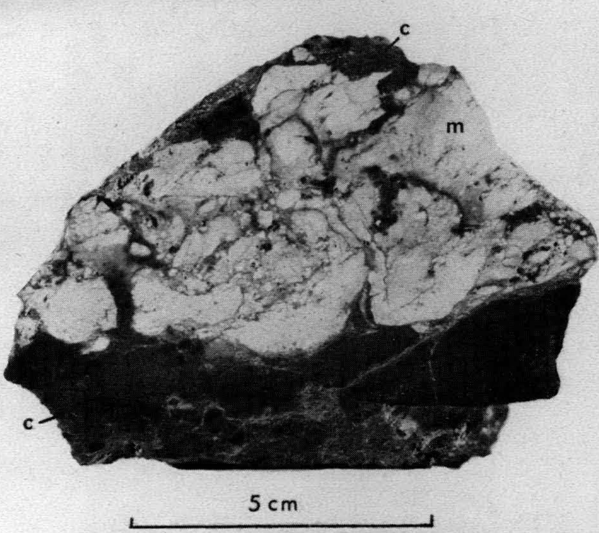

Figure 3. Polished section of nodular magnesite (m) in calcrete (c). Angular fragments of impact breccia in contact with white magnesite nodules at base of specimen.

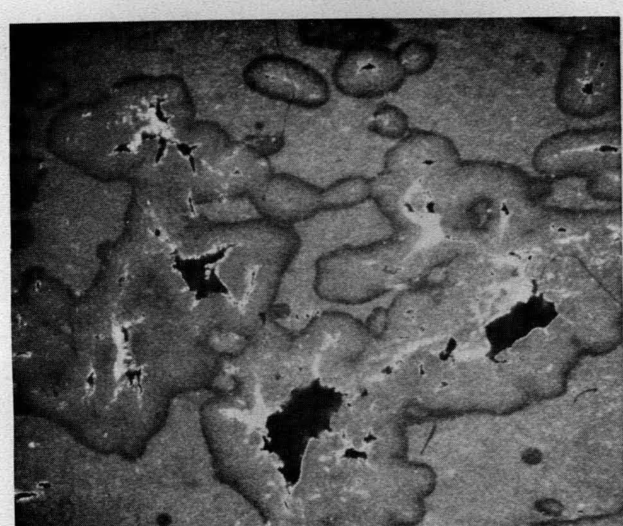

Figure 4. Staining of microcrystalline magnesite around vugs partly filled by calcrete. 13X.

Figure 5. Irregular bodies and veins of coarse grained calcite transecting magnesite and included quartzwacke fragment from impact breccia. Thin planar calcite veins replacing magnesite. 12X.

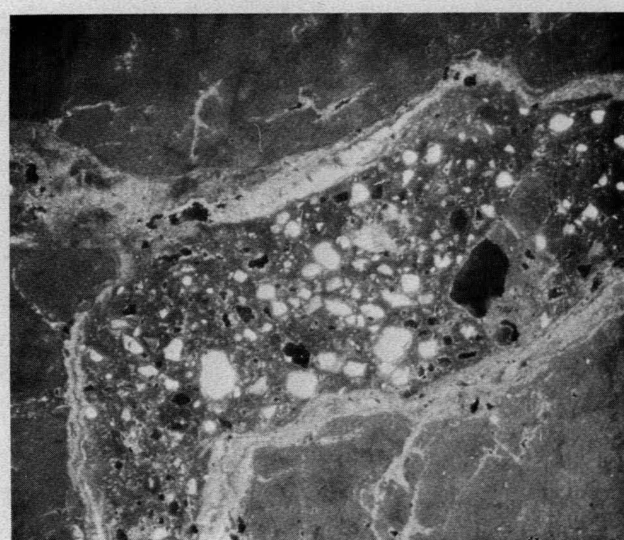

Figure 6. Calcrete filled fracture in magnesite nodule with selvedge of fibrous calcite. Microcrystalline calcite in thin veins replacing magnesite. 13X.

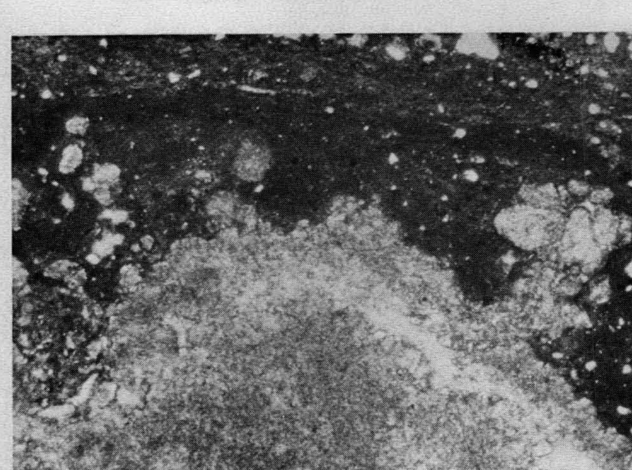

Figure 7. Detail of contact between magnesite nodule and darker toned microcrystalline calcite and included quartz grains of the calcrete matrix. Globules of magnesite emanating from margin of nodule indicate replacement 29X.

Krauskopf (1967) considers that because magnesite is probably generally formed by slow alteration of one of the hydrated carbonates, then precipitation is controlled by the solubility product of a hydrate which is about 500 times that of calcite. This product is only ever exceeded in closed systems where there are elevated temperatures of arid environments. Another influence is the pH of the water; Von der Borch (1965) for instance reports high pH in the lakes of the Coroong area, South Australia caused by aquatic plants.

The conditions favouring magnesite precipitation laid down by Langmuir (1965): that is the lack of aqueous circulation, concentration of carbonates at shallow depths, subjection to diurnal temperature changes, and subsequent loss of CO_2 caused by exposure to sun and elevated temperatures, appear to be consistent with the environment that would normally be expected for the deposition of calcrete deposits, and similarly the calcrete and magnesite deposits at Gosses Bluff.

Conclusion

The magnesite apparently formed as nodules and small tabular bodies in sandy soils which developed in and on breccia in topographically low areas in Late Cainozoic time. Cementation and partial replacement of the nodules then took place during an influx of calcium carbonate-rich waters. Subsequent erosion has exposed the magnesite-bearing calcrete.

The magnesium could have originated from weathering of the few dolomite-bearing rocks in the breccias, but, more likely, was derived from stream water draining the thick beds of magnesian limestones and dolomites in the MacDonnell Ranges to the north, drained at the present day by Undandita Creek and its tributaries. Similar rock types in the Gardiner Range to the south of Missionary Plain could also have provided a source of magnesium.

Presumably the magnesium-rich solutions were concentrated in topographically low areas underlain by the more unconsolidated breccia, and magnesite was formed during drier phases of the climate. The later and more widespread calcrete was probably a response to a change in the chemistry of groundwater, and to probably wetter conditions, although its precipitation would still require dry climatic phases.

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Preliminary studies on the Cape Leeuwin manganese nodule deposit off Western Australia

L. A. Frakes[1], N. F. Exon, and J. W. Granath[2]

In 1970 a large deposit of ferromanganese nodules was discovered on the floor of the Indian Ocean southwest of Cape Leeuwin by the research vessel USNS *Eltanin*. This discovery, which was based largely on bottom photographs from about 20 stations, was discussed by Frakes (1975) and Kennett & Watkins (1975, 1976). The photographs suggest that the deposit spreads, nearly continuously, over 900 000 km², and cores showed that the nodules are essentially confined to the sediment surface.

Kennett & Watkins (op. cit.) pointed to the abundance of ripple and scour marks and current-formed lineations on the present surface, and of extensive disconformities in the cores, as evidence of strong present and past bottom currents in the region. They suggested that the current action had resulted in very low sedimentation rates, which had allowed the nodule field, named by them (1976) the "Southeast Indian Ocean Manganese Pavement", to develop.

[1] **Department of Earth Sciences, Monash University, Melbourne;**
[2] **Department of Earth Sciences, Monash University, and State University of New York, Stony Brook.**

In early 1976 the authors used the research vessel HMAS *Diamantina* for a 10-day cruise in the region to sample the nodules in order to study their chemistry and mineralogy. During the cruise 9 stations were occupied, 8 of them successfully (Figure 1), and about 2000 nodules were recovered from the sea bed. The apparatus used was a light box dredge on the ship's hydrowire, which had a breaking strain of about one tonne. Although an attempt was made to reoccupy *Eltanin* photographic stations, it should be noted that positioning was by celestial navigation, so errors of up to 10 km are possible.

Bulk chemical analyses using the atomic absorption method were carried out in 14 whole individual nodules by the Australian Mineral Development Laboratories in Adelaide. Duplicate analyses were performed for all stations where enough nodules were available (Stations 4-9). The results for the major metals are listed in Table 1.

Analyses of two other nodules from the region, collected by *Eltanin*, were presented by Noakes & Jones (1976). The stations are shown in Figure 1 and the major metal percentages respectively are: 35.35°S, 108.22°E, Fe 14.0, Mn 14.8, Ni 0.26, Cu 0.12, Co 0.18; 40.55° S, 114.53°E, Fe 5.2,

Station	*Position*	*Water Depth (m)*	*Nodule diameter (cm)*	*Average values for major metals (%)*					
				Fe	*Mn*	*Ni*	*Cu*	*Co*	*Ni + Cu + Co*
2	40°03′S, 114°10′E	4700	1	5.5	16.2	0.90	0.48	0.055	
3	41°53′S, 113°57′E	4300	1-3	9.4	20.2	0.79	0.42	0.065	1.27
4	37°57′S, 103°09′E	5000	1.5-8	10.2	18.2	0.68	0.34	0.110	1.13
5	37°00′S, 102°55′E	4700	1.5-10	9.2	20.1	0.72	0.41	0.125	1.25
6	36°00′S, 102°00′E	4800	1.5-8	9.8	18.1	0.63	0.36	0.13	1.12
7	35°54′S, 99°03′E	4300	1.5-4	10.3	18.5	0.66	0.31	0.15	1.12
8	34°58′S, 98°58′E	4350	1.5-4	8.7	19.7	0.75	0.41	0.16	1.32
9	34°38′S, 101°00′E	4650	1.5-4	11.9	16.0	0.44	0.22	0.15	0.81

Table 1: Station data and chemical analyses

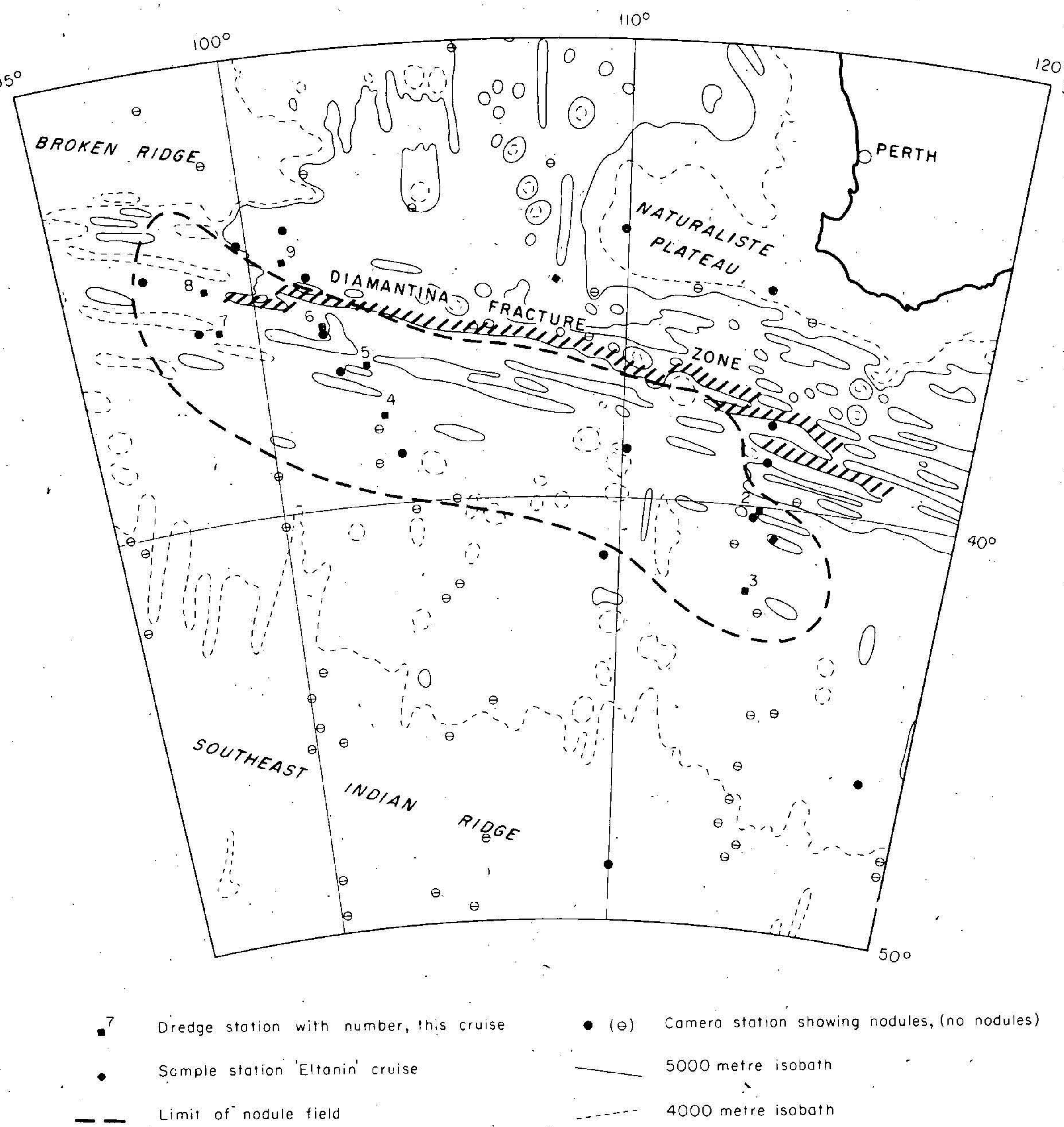

Figure 1. **Map of the Cape Leeuwin manganese nodule field. Dashed line outlines field. Hatched area represents the southern margin of the Diamantina Fracture Zone.**

Mn 9.1, Ni 0.41, Cu 0.35, Co 0.04. The first nodule came from north of the Cape Leeuwin deposit, and the second nodule from the extreme east of the deposit.

Distribution and nodule morphology

The *Eltanin* bottom photographs indicate that the nodule field is 1600 km long by 500 km wide, and extends west-northwesterly from about 40°S, 116°E, to about 35°S, 98°E (Figure 1). It lies on an apparently featureless seafloor on the gently inclined northern flank of the Southeast Indian Ridge, in water depths ranging from 4200 m to 5100 m, and terminates to the north against the highly irregular Diamantina Fracture Zone. To the south the field grades into nodule-free sediment at about the position of the 4300 m isobath. At the extreme eastern end of the field bottom photographs show manganese coatings on rocky outcrops. The deposit is surrounded by calcareous ooze, except in the area of the Diamantina Fracture Zone, where ferruginous muds abound. The nodules themselves lie on a plain of light reddish-brown nannoplankton ooze, in which rare foraminifera show signs of dissolution.

About 80 percent of all photographs taken in the field show nodules on the seafloor. The deposits occur as carpets of subspherical nodules, which have amalgamated to form crusts in places. On most multiple-camera stations all photographs reveal nodules, indicating that the bottom cover is extensive and only rarely interrupted by patches without nodules. At least one station shows no nodules at all, suggesting that the patches can be larger than 10,000 m^2 (the area sampled by an average multiple-camera station).

The nodules recovered ranged from less than 1 cm to more than 10 cm across (Figure 2), but at individual stations the range is commonly much less (Table 1), and the majority of the nodules are 3-4 cm in diameter. Manganese nodules from the Cape Leeuwin deposit are somewhat less variable in size than those from the various Pacific provinces. Few bottom photographs show either carpets of small nodules, or fields in which the size ranges of nodules are large.

Most of the Cape Leeuwin nodules belong to the botryoidal class of Margolis & Burns (1976), consist of several major and minor lobes (Figure 2), and are formed of concentric shells. In most cases the lobes are approximately randomly oriented, giving the nodules a sub-spherical shape, and an abundance of tiny hemispherical protuberances less than 1 mm across give a granular surface texture. The rough surface, and the deep indentations between lobes, have frequently trapped calcareous ooze from the substrate on the lower hemisphere of individual nodules, enabling their former orientation to be determined.

Chemistry and mineralogy

The bulk chemical analyses, determined by atomic absorption methods, are summarized in Table 2. Subsequent analyses carried out at Monash University, using both atomic absorption and X-ray fluorescence techniques, generally agree with the initial results. However, nickel values tend to be slightly higher.

Metal	*Mean (%)*	*Standard deviation (%)*	*Range (%)*
Fe	9.01	1.76	5.5-12.0
Mn	18.40	1.64	15.7-20.2
Ni	0.68	0.04	0.44-0.90
Cu	0.37	0.03	0.22-0.48
Co	0.13	0.01	0.06-0.16

Table 2: Average concentrations of major metals in all 14 nodules.

Additional information from the initial analyses includes average values for Pb (0.053%), V (0.041%), Ti (0.048%), Au (approx. 0.01 grams/tonne) and Pt (approx. 0.04 grams/tonne). Gold and platinum were determined from wet chemical assays.

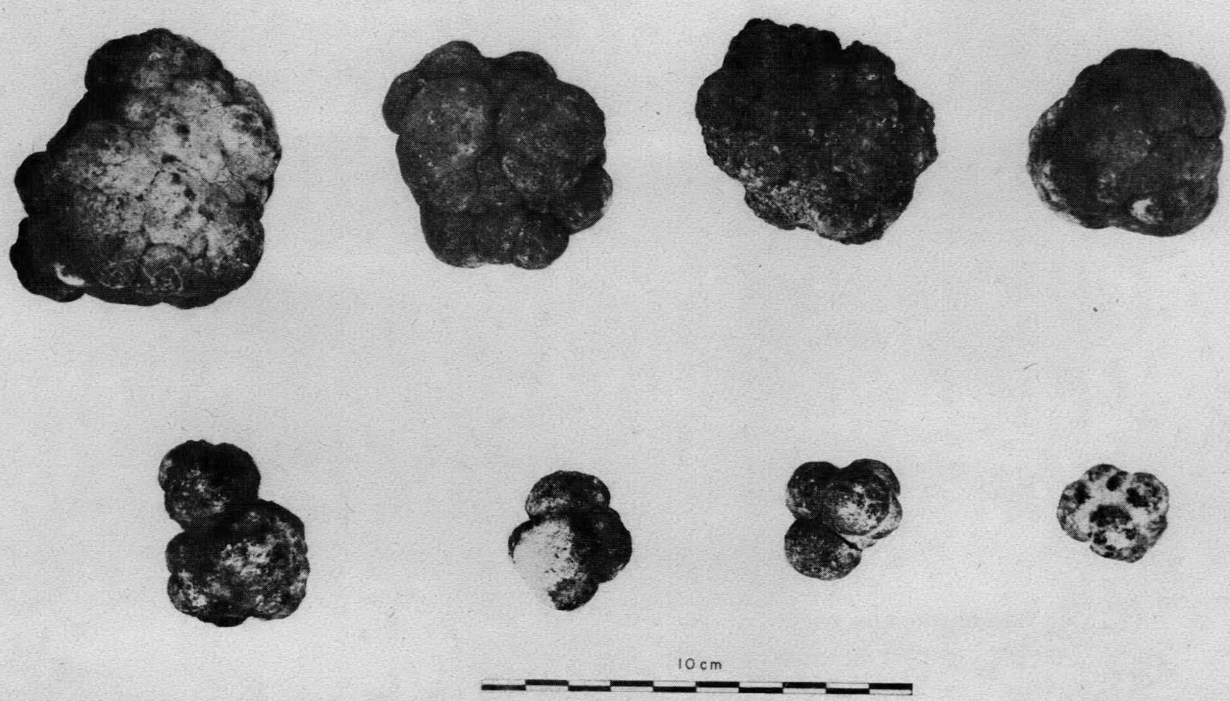

Figure 2. Photograph illustrating the range of sizes and shapes of nodules recovered from the Cape Leeuwin field.

Between-station, or geographical, variability in nodule chemistry is much greater than within-station variability, as indicated by analyses of three nodules from a single dredge haul. Metal content variation within a given station is less than one-fifth of total variation over the field. Hopefully, additional surveys could define the size of areas over which critical changes of chemistry take place—at present we can state only that such areas must be larger than the area traversed by a typical dredge haul.

Mineralogical studies of the nodules are in progress at Monash University using X-ray diffraction and transmission electron microscope methods. As the nodules were not stored in seawater after collection, they have doubtless undergone some mineralogical alteration due to dehydration. The principal mineral identified thus far is todorokite, but birnessite and other related phases have also been detected. Cronan & Tooms (1968) showed that high proportions of todorokite in nodules from the Indian Ocean were associated with high nickel and copper values.

Discussion

The *Eltanin* and *Diamantina* cruises have shown that there are substantial nodule deposits over some 900 000 km² of deep ocean southwest of Australia, ranging from 500 km to 1500 km from the shore (Figure 1).

The commercial interest in manganese nodules depends on their combined nickel, copper and cobalt contents, and especially on their nickel and copper contents. Combined contents of 2½ per cent or more are considered commercially significant in the richest deposits yet known, those of the northeast Pacific Ocean (Granville, 1975). Our best combined value of 1.43 percent falls short of the best Pacific values, but it is encouraging to note that values of 3.05 per cent and 2.27 percent have been recorded at a similar latitude further east in the Great Australian Bight (Noakes & Jones, 1976, Table 3), although no large nodule field has been delineated in that area. Comparison of average metal values for the Cape Leeuwin deposit with average values for the Pacific (Table 3), shows that combined values are comparable with those of most Pacific areas, and that nickel plus copper values are higher than those in all Pacific areas, with the exception of the northeast and central Pacific.

It is widely accepted that high Mn:Fe ratios are associated with high nickel and copper values and low cobalt values (e.g. Margolis & Burns, 1976), and this certainly seems to apply to the Australian region as a whole (Noakes & Jones, 1976), and to our results (Table 1). Our data indicate significant enrichment in nickel and copper over the general situation for manganese nodules in the Indian Ocean (Table 3), and support the conclusion of Noakes & Jones (1976) that nodules near Australia are much richer in nickel and copper west of 135°E than east of that longitude.

Area	*Ni*	*Cu*	*Co*	*Combined Ni + Cu*	*Combined Ni + Cu + Co*
Cape Leeuwin Field	0.68	0.37	0.13	1.05	1.18
Western Indian Ocean	0.32	0.10	0.36	0.42	0.78
Eastern Indian Ocean	0.51	0.33	0.15	0.84	0.99
Baja California	0.10	0.07	0.01	0.17	0.18
Western Pacific	0.56	0.39	0.40	0.95	1.35
Northern Pacific	0.42	0.29	0.14	0.71	0.85
South Pacific	0.43	0.19	0.60	0.62	1.22
Northeast Pacific	1.08	0.63	0.19	1.71	1.90
Central Pacific	0.96	0.31	0.16	1.27	1.43

Table 3: Average percentages of important metals in nodule provinces (after Cronan, 1972)

Far too few samples have been collected for any reliable assessment of the mineral potential of the Cape Leeuwin deposit to be made. However, the information now available justifies further investigations, which will be carried out as the opportunity arises. The apparent general flatness of the seafloor is a favourable feature of the Cape Leeuwin deposit.

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Reef growth, southern Great Barrier Reef—preliminary results

P. J. Davies, J. F. Marshall, D. Foulstone, B. G. Thom[1], N. Harvey[2], A. D. Short[3], and K. Martin[4]

Introduction

The reefs of the Capricorn-Bunker Group in the southern Great Barrier Reef were the focus of a Bureau of Mineral Resources survey in September-October 1976. Subaerial and submarine exploration of seven reefs was conducted (Figure 1). The objectives of the expedition were:

1. To define the depth, shape and origin of the surface on which the present reefs rest.
2. To determine the effects of the present-day hydrologic regime on the growth of the reefs.

[1] **B. G. Thom, Department of Geography, University of Sydney, Sydney, N.S.W. 2006.**

[2] **N. Harvey, Department of Geography, James Cook University of North Queensland, Townsville, Qld 4811.**

[3] **A. D. Short, School of Earth Sciences, Macquarie University, North Ryde, N.S.W. 2113.**

[4] **K. Martin, Queensland Institute of Technology, Brisbane, Qld 4000.**

3. To define the time framework of modern growth.
4. To study the physical and chemical changes involved in the reef lithification processes.
5. To estimate the potential for metal accumulation of reef sediments and to determine the time of removal and deposition of metals in the carbonate sequence.

The M.V. *Escape* was chartered from Gladstone to provide the platform for field studies. Shallow seismic refraction, echo profiling, underwater investigations using SCUBA, underwater coring, current, wave and water monitoring studies, and sediment sampling of lagoons were the principal field operations.

Eighty-eight shallow seismic refraction traverses, each 120 m in length, were conducted using a Huntec FS-3 facsimile seismograph with a hammer or detonator sound source, and two subminiature land geophones or one pressure-sensitive hydrophone. The profiles cover windward and leeward algal ridges, cays, and in one case a lagoon and a lagoonal patch reef (One Tree Reef). This paper records field data and observations with the major emphasis placed on data relating to the morphologic growth of reefs. No attempt is made at this stage to present evidence relating to lithification or to processes and products of metal accumulation.

Morphology

Subreef morphology

A marked change in seismic velocity is present below all the reefs studied. The depth of the seismic discontinuity varies from 7-20 m from the present surface. Beneath some reefs, e.g. Fairfax, there is little variation in depth, but beneath others, e.g. One Tree Reef, the seismic discontinuity is higher beneath the windward edge than beneath the leeward edge. At One Tree Reef, the seismic discontinuity is deepest beneath the deep part of the lagoon.

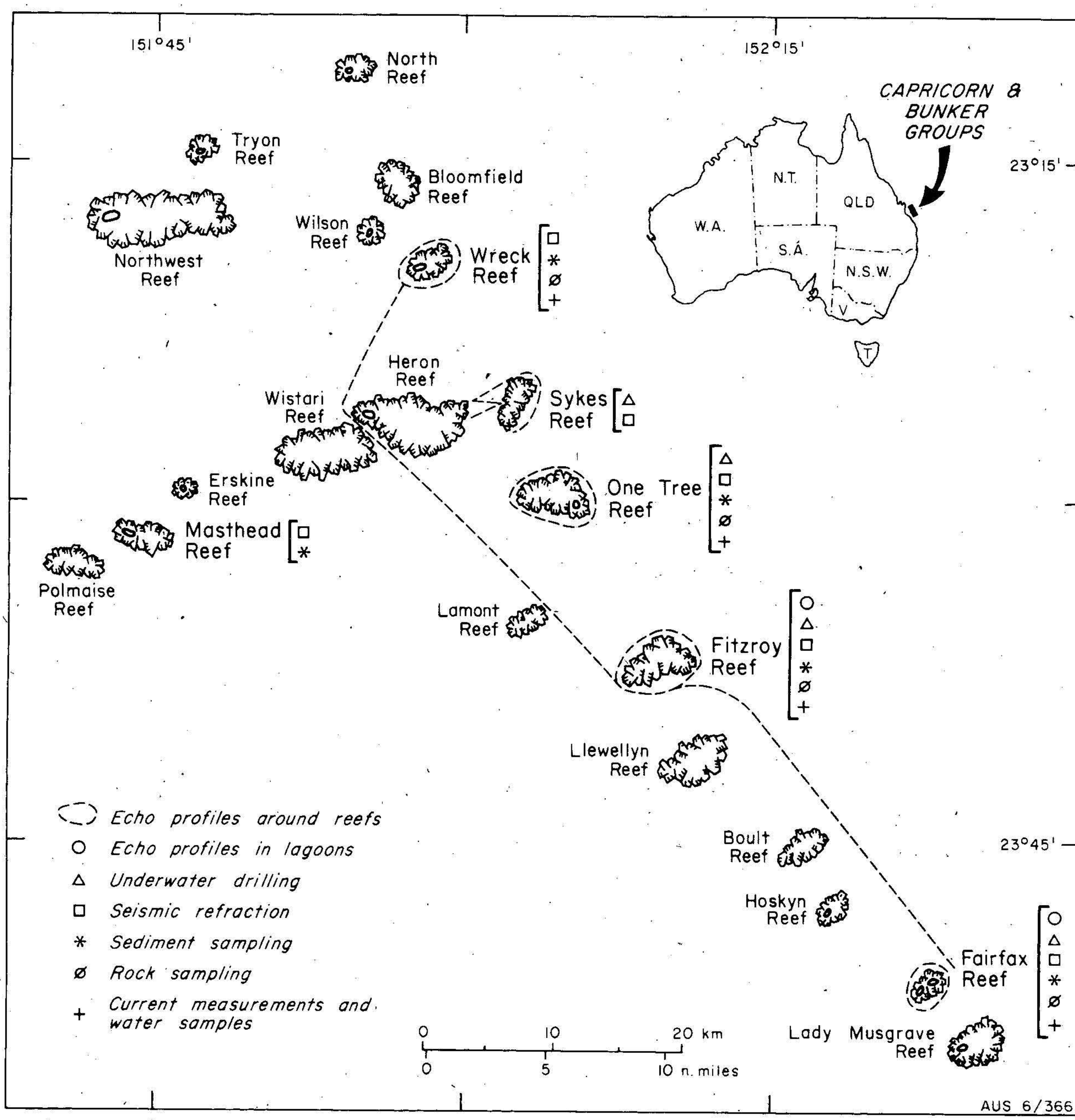

Figure 1.

Windward margins

Water depths are deeper and submarine slopes generally steeper close to windward margins than along any other margins. Depths of 30 m occur within 100-200 m of the reef crest, e.g. the southern end of One Tree Reef. The most prominent windward feature of many reefs is a scarp, the top of which varies in depth from 10-15 m. Vertical scarps 5-20 m high are common and extend for several kilometres parallel to the reef edge. Between the top of the scarp and the reef crest, a pavement sloping at 10-40° predominates. Such pavements are either extremely irregular hard limestone surfaces exhibiting a relief of 1-2 m, or are dissected by smooth bottomed channels which 'hang' on the scarp face. On the south side of One Tree Reef, a cave occurs in this top surface at a depth of 10 m and extends downwards through the rock, opening out at the base of the scarp at a depth of 30 m. The hard limestone pavement above the scarp is predominantly covered by encrusting corralline algae, but interspersed clumps of tabular *Acropora* up to 40 cm high and subdued growth forms of *Favia* and *Platygyra* also occur. The rock surface is swept clean of sediment; however, sand and rubble accumulations occur localized in patches in enclosed basins, or as lag gravel concentrates on the floors of 'hanging valleys'. Sand and reef-rock rubble occur as sheet deposits, or talus fans, at the foot of the scarp.

Seawards of the base of the scarp there is a decrease in gradient, and the sea bottom flattens out to a relatively constant depth at about 60 m. However, a 'moat' parallels the windward side of some reefs. Off the southern side of One Tree Reef there is a broad moat at a depth of 53-57 m with an outer ridge at 45-50 m. The moat is replaced westwards by a marked change of slope at 55 m. On the southern windward corner of Fairfax Reef, the moat occurs in a depth of 30 m.

Spur and groove features exhibiting a relief of 2-3 m occur along select portions of windward edges. At Fairfax, the grooves are cut partly in the limestone pavement. Frequently both ends of the grooves are blind. However, extension of the grooves across the algal flat is seen as a process of backward extension by the formation of scour pools. Along the windward margins of most reefs, much larger features occur interspersed with the smaller features described above. Deep channels cut into both the present reef edge and the limestone platform have a relief of as much as 10 m.

On the southern side of Fitzroy Reef, a broad platform extends out from the edge of the reef. The platform varies in depth from 20 m at the western end to 35 m at the southeast tip. The seaward edge of the platform is marked by a rim standing 10-20 m above the floor of the platform. From the top of the rim, the sea bottom falls away very steeply to a depth of 60 m.

Leeward margins

Slopes on leeward margins are not as steep close to the reef as are their windward counterparts; the steep leeward slope of Fairfax Reef is an exception. In most cases the leeward slope contrasts markedly with the morphology described above for windward sides. The overall leeward slope is generally less than 20°. Seawards of the leeward reef crest, the reef fronts show strongly developed spur and groove structures, which give way to submerged coral pinnacles, ridges and mounds out to a depth of 20 m. Commonly large detached patch reefs rise vertically for 10-15 m from a sandy/coral rubble bottom. The sand is rippled in less than 5 m water depth, but in deeper water, the sandy bottom is characteristically hummocky as a result of shrimp burrowing. Fan-like concentrations of rubble fining seawards extend into deeper water from the surge channels which are clearly acting as transportation pathways. Coralline algae, an abundance of corals, sponges, gorgonians and soft corals, a much greater species diversity and a variety of growth forms, provide a marked contrast with the windward edges. Overhangs, tunnels and caves also contain abundant calcifiers. The growing framework is highly porous and easily detached.

Lagoonal patch reefs and walls

Reef growth in Fitzroy and One Tree Lagoons was studied to determine the properties of the reef rock. Two sites were studied, (a) vertical faces of patch reefs, and (b) the lagoon-facing walls of the leeward reef flat. In both cases, slopes are vertical to a depth of 10 m. The lagoon-facing wall of the leeward reef flat at Fitzroy exhibits in places a 100 percent coral cover, frequently of *Montipora* colonies up to 2 m in diameter. Overhangs and caves are common in both patch reefs and leeward walls. Collapse of the overhangs, especially on the leeside of patch reefs, and of the windward-facing leeward wall is an active process of lagoon infill and growth of both patch reefs and leeward wall. Recolonization on the collapsed material appears to be rapid, and growth occurs vertically towards the surface. This frequently involves continued growth of collapsed branching species in a different direction.

Drilling results

Twenty cores of up to 300 mm long of *in situ* reef rock were recovered from windward and lagoonal sites using a hand-operated pneumatically powered drill. The depths below the surface varied from 10-20 m at windward sites, and down to 10 m at lagoonal sites. Lagoonal cores were generally unrecrystallized white coral/algal material, while cores of the limestone platform on the windward reef slope were extremely hard, well cemented, partially recrystallized and stained brown. All cores are being prepared for dating.

Current, wave, and water monitoring

Preliminary results indicate that outside and around the reefs tidal flow reverses with flood and ebb. Maximum velocities up to 80 cm sec^{-1} were observed. The tidal currents are fairly uniform in flow through the water column. However, the very rough bottom and groove—buttress formations on the reef edge generate eddies within 1-2 m of the bottom and within 30 m of the reef edge, which significantly lowers net current velocity and causes local reversals in direction. A significant amount of current energy is therefore expended on the reef edge and bottom.

Water velocities during flooding tides on windward reef flats average 25 cm sec^{-1}. This onshore flow continues through the ebb although velocities decrease to 5 cm sec^{-1}. On leeward reef flats the flow is predominantly off the reef. However, the flow of water on to the windward reef and off the leeward reef is greatly increased during southeasterly winds. Measurements were conducted before and after spring tide conditions. In addition small waves generated in shallow lagoons (Fairfax, Wreck) put much sand and silt into suspension. This material is carried over the leeward edge and deposited in leeside situations.

In the leeward Fitzroy channel the dominant flow was out of the lagoon for 9 hours, with maximum velocities to 70 cm sec^{-1}, with a shorter 3 hour flood into the lagoon. This suggests that most water flows in over the windward reef and out on the leeward side.

Lagoon sedimentation

One hundred bottom-sediment samples were collected from the large lagoon at Fitzroy Reef. The lagoon is approximately triangular in plan, and it has an area of some 6 km^2. The lagoon has an average depth of 8 m and nowhere exceeds 12 m. Large, generally circular patch reefs up to 200 m in diameter grow to the surface from the lagoon floor in many parts of the lagoon, but particularly near the western margin. Much of the lagoon floor is also covered by smaller coral patches which rise several metres above the surrounding bottom. The western margin of the lagoon is marked by an abrupt shallowing onto the algal rim at the reef edge. The northeast, east and southeast sides shallow more gradually and grade into a reef flat and then to the algal rim on the windward edge of the reef. This more gradual shallowing is due to the presence of a prograding sand wedge which is building out from the eastern side of the reef into the lagoon. Predictably the lagoonal sediments are generally coarsest on the eastern side of the lagoon being mainly medium to coarse sands, whereas fine sands and silts are typical of the western lagoonal sediments.

Discussion

Reef studies in the last ten years have focussed on a dichotomy of opinion as to the principal controls on modern reef growth. Maxwell (1968, 1976) has asserted that organic growth is the principal factor operative in determining reef morphology. Alternatively, Bloom (1973), and Purdy (1973) suggest that substrate control is the principal factor affecting growth and morphology. Several recent publications on reefs from the southern Great Barrier Reef (Davies, 1974; Kinsey & Davies, 1975; Davies *et al.* 1976) have favoured the second hypothesis, which may be stated in two parts (1) the present position of reefs results from their specific localization on favourable parts of a shallow, older, eroded, karst surface, and (2) the morphology of the karst surface is inherited by, and reflected in, the shape of the present day reefs.

We believe that data within the body of this paper add weight to the hypothesis in the following ways: seismic profiling has shown the reefs to be underlain by a distinct seismic discontinuity at shallow but variable depths. A similar discontinuity at Heron Island (Davies, 1974) has been shown to coincide with an unconformity, where unaltered marine carbonates rest on highly recrystallized limestone which has the appearance of having undergone massive subaereal solution. SCUBA investigations described in the present work show the modern reef to be growing on an extremely hard recrystallized dissected limestone pavement, while both SCUBA and bathymetric studies show a steep scarp edge to this limestone pavement, especially around the windward margins. Clearly, the modern reefs are localized on high spots on the limestone pavement. Three lines of evidence show how present reef shapes are determined to some degree by the configuration of the substrate off which they grow. (1) reef extension along windward margins is inhibited by the steep scarp face. (2) the depth of lagoons is related to the depth of the seismic discontinuity, and (3) present day spur and groove structures have been localized, to some degree, by grooves in the limestone substrate.

Davies *et al.* (1976) have suggested that one other factor, in addition to substrate, has affected reef growth and shape, namely interactions with the wave regime. In the present study, hydrological experiments on different reefs have shown the dominant direction of water movement across the reefs is from windward to leeward, a condition which is intensified during strong southeast weather. It is to be expected therefore, that sediment carried in suspension will move in the same direction, a conclusion supported by the presence of graded prograding sand sheets encroaching into the lagoons, and the ephemeral shingle storm deposits on the windward flats, which migrate gradually leewards during succeeding storms. These conclusions support previous suggestions made for a reef in the northern Great Barrier Reef (Limer Expedition 1975 Team, 1976). In addition SCUBA observations show negligible sediment accumulation on windward edges, this contrasting strongly with observations of abundant autochthonous and allochthonous sedimentation on leeward edges. We believe that windward edges act as sediment sources, while lagoons and leeward edges are sediment sinks. Predominant reef growth is therefore on the leeward side, while lagoon configuration is determined by the rate of infill, and the depth to the karst platform.

Acknowledgements

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Environmental and urban geology in Australia: workshop meeting of government engineering geologists, November, 1976

Compiled by G. Jacobson*

Environmental and urban geology is an expanding field in which the government geological surveys are inevitably becoming more involved. Throughout the world, pressures for urban development and the exploitation of resources are coinciding with a growing awareness of threats to the environment. Phillip (1976) has recently reviewed the status of environmental geology in Australia, and indicated its development particularly in relation to land-use planning. Several papers in the 25th International Geological Congress held at Sydney in August 1976, described geological contributions to environmental management in Australia. These papers included reports of the urban geology of Sydney (Burgess, in press); the environmental geology of the Western Australian coastal limestone (Gordon, 1976); landslides affecting urban development in Tasmania (Knights & Matthews, 1976); engineering geology for subdivisional planning in South Australia (Selby, 1976); environmental geological mapping for land-use planning in Queensland (Hofmann, 1976); geological aspects of the pollution of coastal lagoons in New South Wales (Albani & Brown, 1976); and quarry reclamation problems in Victoria (Bowen, 1976).

Interest aroused at the Congress led to a workshop meeting of government survey geologists concerned with environmental and urban geology being held in Canberra, 15-17 November 1976. Participants included W. S. Chesnut and I. Wallace (New South Wales Geological Survey); K. G. Bowen and J. L. Neilson (Victorian Geological Survey); G. W. Hofmann (Geological Survey of Queensland); J. Selby (South Australian Geological Survey); P. C. Stevenson (Geological Survey of Tasmania); E. G. Wilson, G. Jacobson, P. D. Hohnen, P. H. Vanden Broek, G. A. M. Henderson and R. C. M. Goldsmith (BMR); J. C. Braybrooke (SMEC); and other Commonwealth government personnel.

At the meeting, government activity in environmental and urban geology was reviewed; abstracts of these reviews are given below, and illustrate the wide range of investigations in this field currently being undertaken by the geological surveys. The meeting included discussion of specific problems encountered in environmental geology investigations (see below); and a field inspection of the urban geology of Tuggeranong, A.C.T.

Review of activities

New South Wales *W. S. Chestnut & I. Wallace*

Investigations in urban and environmental geology are carried out mainly by the Geological Survey of New South Wales, Department of Mines.

*** With contributions from the Geological Surveys of New South Wales, Queensland, South Australia, Tasmania, Victoria and Western Australia.**

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The Geological Survey of New South Wales provides advice to Government on geological matters relating to land use planning and environmental protection.

Land use planning in New South Wales is essentially carried out by the Planning and Environment Commission and local government bodies. Advice is provided on request to these organizations.

The type of advice given includes:—

1. Maps showing the distribution of known and potential extractive resources.
2. Maps showing potential sites for future extraction.
3. Maps showing engineering and natural hazard constraints.
4. Projected requirements for extractive resources.
5. Potential effects of extractive development on the environment.

Some difficulty has been experienced in establishing the most effective means of presenting geological data to the planner and in communication of ideas.

The importance of extractive resources to urban development and the effect of mineral extraction on the environment are aspects which require close liaison between the geologist and planner.

Various sections of the Geological Survey of New South Wales are involved in preparation of advice for land use planning and environmental protection. These mainly include the Engineering and Marine Section (concerned with the identification of geological conditions, hazards and processes which affect an area), the Non-Metallics Section (dealing with low to moderate cost extractive resources), the Coal Section (in defining potential areas of coal extraction affecting future development), and to a lesser extent, the Metallic Minerals Section.

A number of other government departments and instrumentalities e.g. Department of Main Roads, provide advice on environmental geology in more specific or localized areas.

Queensland *G. W. Hofmann*

The Queensland Geological Survey has an Urban and Environmental Geology Section with an establishment of 8 geologists and 4 technical assistants under the direction of a Principal Geologist. This section carries out geological resource assessment and hazard identification for land-use planning in Queensland. These activities are not supported by legislation but have been commenced to meet an obvious need for information within the expertise of the Geological Survey.

Reconnaissance surveys are made to locate potential deposits of quarry rock, gravel, sand and clay; these deposits are categorized into (a) major or significant resources, (b) resources of long-term interest, and (c) sterilised resources and resources whose extraction would have a severe environmental impact. Four surveys have been completed on a local authority basis and are available as unpublished Records 1975/1, 1975/27, 1976/2, and 1976/19, accompanied by maps at a scale of 1:100 000.

Protection of any deposits can be provided under local authority planning schemes, but is rarely considered by the responsible authority. The extraction of gravel, sand, and most rock is controlled on private land by the local authority, on Crown and public land by the Forestry Department, in non-tidal streams by the Irrigation and Water Supply Commission, and in tidal streams and coastal waters by the Harbours and Marine Department.

A pilot study of urban land capability in a rapidly developing local authority area has been completed in 1976. Maps at a scale of 1:50 000 show geological units, geomorphology and selected slope categories, known landslide and flood areas, deposits of construction materials, hydrogeology, and potential urban land capability based on a combination of physical constraints.

Other activities of the Geological Survey relating to environmental geology include contributions to interdepartmental land-use studies; contributions to, and assessments of, environmental impact studies; and documentation of geological features of interest to the public.

Engineering geological work includes site investigations for public projects; slope stability inspections of specific landslides; and groundwater investigations for town water supply.

The survey's marine-geological work includes the study of recent coastal processes in Moreton Bay and its vicinity.

South Australia *M. N. Hiern & J. Selby*

Mining and quarrying in South Australia, including workings for the production of construction materials, are conducted under the provisions of the Mining Act, and the Mines and Works Inspection Act. This legislation which is administered by the Department of Mines, includes the establishment of an Extractive Areas Rehabilitation Fund for the restoration of extractive mineral workings and provides powers for the Chief Inspector of Mines to order the preparation of development and rehabilitation programmes for all mining operations.

The Geological Survey Branch of the Department provides an in-house service to the Mining and Registration Branches as well as being the principal advisor to other Government Departments on geological and mineral resource matters.

The environmental work carried out by the Department focuses on three main areas:

- ensuring that exploration and mining are conducted on a sound environment-conscious basis;
- providing engineering and mineral-resource data for land use planning and management purposes;
- rehabilitating mine and quarry workings.

Construction materials resources of metropolitan Adelaide are being systematically assessed by mapping and drilling (Hiern, 1975) to define areas which should be zoned for extractive industry. This work will be extended to include the main provincial towns.

Appraisal of barite and other industrial mineral resources in environmentally sensitive areas like the Flinders Ranges is being carried out.

Studies by the Australian Mineral Development Laboratories have been sponsored to solve special problems caused by the accumulation of fine tailings from washing of construction sands and the contamination of surface waters from an abandoned pyrite mine.

Geological advice given to the State Planning Authority includes inspection of subdivisions for slope stability, drainage problems and foundation conditions.

Site investigations and mineral resource evaluation have been carried out for the Monarto Development Commission. Special studies have also been completed for the Redcliffs Scheme and for a proposed new Northern Power Station, as part of their environmental impact studies.

Over 30 metropolitan waste-disposal sites have been assessed for surface and groundwater pollution potential.

Tasmania *P. C. Stevenson & V. M. Threader*

The Engineering Geology and Groundwater Section of the Geological Survey of Tasmania has responsibility for the provision of geological information used in the planning, design and construction of engineering structures, and for geological information in the location, estimation and winning of groundwater resources. The location and estimation of sands, clays aggregates and non-metallic minerals is within the field of the Economic Geology Section.

The Engineering Geology Section consists of a Supervising Geologist, two Senior Geologists and four Geologists, with a Geophysicist attached as an allied specialist. The interests of the staff cover a wide field related to specific Tasmanian problems, with the aim that interests will overlap between two or more officers. For instance, the interests in rock-face stability are the usual concern of three persons, clay-slope stability is within the field of three persons, one or two of whom are also in the rock-face group. Less allied subjects show correspondingly less overlap.

As a service section the fields of interest are not rigidly defined, but change with changing demand. Until five years ago the emphasis was mainly on dam sites, but this has faded away and now slope stability is a major preoccupation. Reviewing reports written in the last two years the following topics are common: the geology of the River Derwent in connection with the construction of a second crossing; the measurement of vibration in rocks, soils and water due to blasting and heavy vehicles; the routing of pipelines in scenic areas; the location of aggregate resources and minimization of impact of quarries; dams for amenity and town water supply; the mapping of expansive clays and associated damage prevention; the location and planning of cemetery sites; the location and planning of waste disposal sites; advice on groundwater drainage; and above all mapping and analysis of the geology of slope stability. In this last field detailed advice is requested by local authorities, real estate agents, solicitors, vendors and buyers of land. This is a very time-consuming part of the section's activity. A more general vein of urban mapping for engineering and planning purposes has arisen out of this.

The use of geophysics in most aspects of engineering geology is notable in Tasmania. The Engineering Geology section is closely allied with the geophysical specialist and most of the field observations and interpretations are done by the geologists themselves. The design of the survey is a cooperative effort between the geologist and the geophysicist, who is on hand to assist in observation and interpretations, but the close contact between geology and geophysics so necessary to effective use is ensured by allowing this to occur within the mind of the geologist, who is then aware of the quality and limitations of his own observations and interpretations. Longer and more specialized surveys are the preserve of the geophysicist who then uses geologists to assist as observers.

The Geological Survey Economic Section employs one geologist responsible for non-metallic minerals, construction materials and coal investigations. Geological work in the extractive industries includes geological advice to operators if and when required. A register of construction materials is maintained with details of individual pits and quarries, results of tests on materials, and notes on geology, suitability of materials and an estimate of reserves. A 1:100 000 atlas of these localities is also kept. Reports on the non metallic mineral resources of 1:50 000 map sheets are included in Explanatory Notes to the geological maps.

Victoria *J. L. Neilson & K. G. Bowen*

Within the Victorian Geological Survey responsibility for environmental geology is shared between the Engineering

Geology, Environmental Geology (Land Conservation Council), Groundwater and Mineral Resources Sections.

Activities supported by legislation include extractive industry surveys, groundwater pollution studies and land-use studies.

(a) Extractive Industry surveys

Protection of any deposits located can be provided by zoning under the Town and Country Planning Act. However the responsibility to provide the protection rests with the Responsible Authority.

Recent work includes the Dingley-Heatherton and Cranbourne sand surveys; Melbourne western and northern suburbs basalt survey; Axedale clay survey; and the Lang Lang survey.

(b) Groundwater

Some current projects are:

(i) Basalt waters west of Melbourne are polluted by salts including sulphate, phenolic substances and surfactants, and to a lesser extent heavy metals. Following a recent hearing, disposal of further liquid industrial waste is to be prohibited at Sunshine from March 1977. Any new waste disposal sites and tips are referred to the Survey.

(ii) Experimental sub-surface treatment of polluted groundwater.

(iii) Controlled extraction of water from the Western Port Basin and the possibility of artificial recharge using treated sewage effluent.

(iv) Pollution of groundwater by whey in western Victoria.

(v) Salinity problems in irrigation areas of the Riverine Plains.

(c) Land Conservation Council

The Survey is one of several departments represented on the Land Conservation Council and a geologist is engaged full time in this work. The Council studies public land and makes recommendations regarding land use including reservation of areas for mining, extractive industry and groundwater recharge, and protection of exploration rights.

Activities of the Geological Survey that are not supported by legislation include:

(a) Engineering geology investigations for major public projects as requested. Examples are the Lower Yarra bridge and the Melbourne underground rail loop.
(b) Engineering geological mapping of urban areas. Examples are the map of Central Melbourne which is widely used by foundation engineers; maps of growth corridors for Melbourne (in progress); and maps of regional growth centres. With the latter it is difficult to assess the extent to which advice is considered by planners.
(c) Slope stability problems where requested by local government authorities. Examples are specific landslips at Portland, and regional studies of landslip prone areas in South Gippsland.

Western Australia *E. R. Biggs*

The Geological Survey of Western Australia has produced urban geology maps of the areas in and around Perth, depicting on separate sheets the geology, land utilization and the distribution of clay, silica, dimension stone and aggregate, water and limestone. After the appointment of two environmental geologists, a new Urban Geology series was instigated, expanding this coverage to the north and south of Perth and in the Pilbara in the Dampier-Roebourne areas. These maps are based on the National Grid and include text panels with additional data alongside the geological map on single sheets. All the urban geology maps are at 1:50 000 scale and, except for preliminary sheets, in colour.

Studies of resources, supply and demand of industrial minerals in the environs of Perth have been undertaken and more are planned. Geological information for planned urban development corridors have been carried out for studies made by the Town Planning Department.

Environmental and rehabilitation conditions are formulated to lessen adverse impacts of mining on the environment in Western Australia.

The Survey is participating in multidisciplinary studies into the effects of bauxite mining and wood-chipping on the ecology, especially groundwater salinity, in the forested southwest of the State. It was represented on the technical sub-committee of the Conservation Through Reserves Committee, a body convened to evaluate, review and report on the requirements for National Parks and Reserves in Western Australia.

Federal Territories

In the Australian Capital Territory, BMR carries out environmental and urban geology investigations on behalf of the planning authority (National Capital Development Commission) and the construction authority (Department of Construction).

Geological studies have been undertaken for urban planning of the new town areas of Tuggeranong and Gungahlin (Hohnen, 1974; Jacobson, Vanden Broek & Kellett, 1976). The information has been presented to planners in the form of thematic maps at a scale of 1:25 000 including bedrock geology, surficial geology, soils, groundwater, excavation and foundation conditions, and geological constraints. Geophysical surveys and augering have been used extensively in these investigations. Larger scale, more detailed, investigations have been undertaken of proposed town centres where high-rise buildings are planned. Urban geology maps of the developed areas of Canberra are being prepared at 1:10 000 scale.

Detailed geological investigations are being undertaken of existing and proposed landfill sites for refuse disposal in the A.C.T. and leachate monitoring systems are being established. Detailed investigations are also continuing in groundwater seepage problem areas affecting the development of residential land. Groundwater levels are monitored to assess the effect of the remedial drainage works in these areas. Another groundwater study is being carried out to assess effects of the re-use of sewage effluent for irrigation.

Geological studies for urban planning of the new town of Darwin East have been carried out by BMR in collaboration with the Mines Branch, Department of the Northern Territory (Vanden Broek, 1975).

Notes on discussion

Specific aspects of environmental geology that were discussed at the meeting included the legislative and administrative framework in which geologists work; problems of communication; geological aspects of extractive resources; urban geological maps; and the use of geophysics in urban geology.

Legislative and administrative framework

The legislative and administrative framework for geological work is different in each State, and the State Geological Surveys have different roles in their studies of extractive resources, geological hazards and groundwater pollution.

Communication

The universal problem of geologists working in the field of environmental and urban geology is that of communication. It is necessary to communicate concisely and clearly with planners, engineers and laymen. Consequently a good deal of attention is paid to the presentation and ease of interpretation of geological data. Examples are the specialized maps of hazard zoning and resources zoning prepared for planners in some areas. Each map has its own cartographic problems—how to define zone boundaries, how to make the map intelligible to non-geologists, how much area to cover and at what scale, etc.

Extractive resources

Pressures for the use of extractive resources are evident in all urban areas, and geologists are deeply involved in assessing resources for land-use planning. There is concern for the future supply of construction materials in many cities. Deposits of construction materials need to be reserved for future use, and extractive industry should be recognized as a valid land use. Resource management is not at present adequately catered for by legislation. The reclamation of quarries and pits is a concern in many areas.

Urban geology maps

There is a trend towards the publication of systematic series of large-scale geological maps of urban areas. In Victoria a detailed map of the Central Business District of Melbourne has been published at 1:5000 (Brumley, 1974) and other geological surveys plan similar series. At present this kind of map compilation is in the experimental stage; there is no uniformity of scale or presentation; and there is little feedback from engineers and planners as to the usefulness of the maps.

A problem experienced by the compilers of these urban geological maps is the difficulty of obtaining bore data and other geological information from private sources such as engineering consultants. Consequently, the geological information forming a basis for map compilation varies both in quality and availability.

Use of geophysics

There is an increasing use of geophysics in urban geology investigations. However, there is a need for better geological interpretation of geophysical data, and for closer co-operation of geologists and geophysicists.

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Book Reviews

History and Role of Government Geological Surveys in Australia.

Edited by R. K. Johns; published by the South Australian Department of Mines. 111 pp, 1976.

Price: $3, obtainable from the State, and Northern Territory, Geological Surveys; and BMR..

Today, Geological Surveys are a feature of government science and technology in practically every country in the world, and nowhere is the development of those surveys more closely tied to that of their country than in Australia.

Gold was the mainspring of Colonial Government action in the formation of the Geological Surveys, but their birth and growth in the various Colonies (States since Federation in 1901) have not been without trauma, as is neatly illustrated by R. K. Johns and his fellow contributors in this book.

The State Surveys, the Northern Territory Survey, and the Federal Bureau of Mineral Resources, Geology and Geophysics, each form the subject of a chapter. The history of each survey is covered, albeit very condensed, from its inception to the present day. Each chapter contains numerous snippets about the surveys and their personalities, and the whole is liberally sprinkled with photographs of the cast.

The first Survey, that of Victoria, was inaugurated in 1856, and the others followed as important new mineral discoveries were made or as the Colonial Governments acceded to public and economic pressures.

In the early days, great contributions were made by a few dedicated individuals, working within limited budgets and with little technical support. Of the more notable personalities mentioned in this book, A. R. C. Selwyn, who was to make such a great contribution to Australian geology both directly and indirectly through the geologists he trained, arrived in Victoria, from Great Britain in 1852, to be attached to the Surveyor General's Department at an annual salary of £500. Selwyn's classic clash of interests with the Secretary for Mines ended in 1869 with his resignation and the temporary disbanding of the Victorian Survey.

It is interesting to note that in 1910 the Victorian Government rewarded the Survey for its work in opening the Wonthaggi coalfield the previous year by building a Geological Museum.

The setting up of the New South Wales Geological Survey in 1875 was followed in the next year by the opening to the public of the Geological and Mining Museum, and, as a welcome example of government farsightedness, we are told that in 1879 the Government purchased the private collection of the Reverend W. B. Clarke, "The Father of Australian Geology".

In 1879 R. Logan Jack became Government Geologist for Queensland, which position he held for 22 years. Between 1879 and 1880 he 'undertook a traverse of Cape York Peninsula from south to north, undergoing the rigors and dangers of travel in unknown country during the wet season, and facing the hostility of aboriginal inhabitants. During a surprise night attack on the camp he was speared through the neck. In spite of a painful wound he completed the trip to Somerset, meticulously mapping the geology, topography and river system'.

For the first year of the South Australian Geological Department set up in 1882 under the Commissioner of Crown Lands and Immigration, £1300 was voted for expenditure. The value of mineral production for that year is recorded as £460 000. The man appointed to the new position of Government Geologist was H. Y. L. Brown, a Canadian, and student at the Royal School of Mines in London. He came to South Australia in 1882 and worked there practically unaided until he retired in 1912. His achievements as an explorer-geologist have become legendary and it has been said of him that 'no single geologist has made such extensive personal contributions to the growth of our knowledge of Australian geology'.

It was H. Y. L. Brown who, as Government Geologist for Western Australia from 1870 to 1872, said 'The colony is extraordinarily rich in lead, silver, copper, iron, plumbago and many other minerals . . .' and who recommended several areas for gold prospecting, some of which ultimately proved to be auriferous.

In 1896 Gibb Maitland became Government Geologist for Western Australia and it is he who is responsible for surely the most delightful anecdote in this book; that which relates his employment of the notorious bushranger, 'Captain Starlight', who, having presumably retired from his illegal activities and using the name Major Pelly, established a reputation as a reserved and courteous civil servant, whose services to the Geological Survey were held in high regard by Maitland.

Survey activity throughout Australia has always been closely connected with the Mining Industry and, therefore, with the state of the economy. Intense mining activity has in the past engendered intense Survey activity, although in the mineral boom of the late 1960s many Survey staff were lost to the private sector, drawn by lucrative offers in the fight for geological expertise.

Meanwhile new horizons are opening. Environmental geology and the geology of the continental margin are just two of the new interests of the Geological Surveys. One enormous and vital task can be undertaken only by Geological Surveys —the assessment of the nation's total mineral resources, without which government economic policy moves in a partial vacuum. The realization of this has been slow. This book should ensure that the efforts of many of those who have participated in this realization or who have helped others attain it will not go unrecorded.

Those who are interested in the history of the Government Surveys in the broader context of Australian Geological Sciences as a whole will find Branagan & Townley (1976) a good complement to this book.

Branagan, D. F., & Townley, K. A., 1976—The Geological Sciences in Australia—a brief historical review. *Earth Science Reviews*, **12**, 323-346.

I. M. Hodgson

Walter, M. R. (Editor), 1976—**Stromatolites.** Developments in Sedimentology, 20, 771 + 18 pp, Elsevier, Amsterdam.

Price: Dfl259; in Australian approximately $91

The book is concerned with a study of all aspects of stromatolites. Following the introduction, the second chapter describes field and laboratory techniques, including biological techniques, and discusses methods of classification. It seems likely that more will be heard of the computer-based qualitative image-analysis methods of classification. Abiogenic structures —calcretes, cave deposits, and geyserites—that may mimic the form of stromatolites, are described in the following chapter; it seems an early stage to do so. Thereafter biology is introduced in several contributions that describe extant stromatolite-building organisms, discuss their evolution, and review their organic geochemistry. The chapter emphasizes most clearly, through microbiology and geochemistry, today's multidisciplinary approach to the field.

Chapter 5 is given over to fabric and microstructure; of particular value is a lengthy treatment of the origin and development of cryptalgal fabrics. It is the Editor's belief that the study of stromatolites is essentially one of morphogenesis, the subject of the next chapter. Hamelin Pool at Shark Bay remains the most diverse assemblage of modern stromatolites, and a condensed version of morphogenesis from there is of value. So too is the discussion of the factors controlling the morphology of Riphean stromatolites from Russia, considered to depend both on taxonomic composition and environment.

The use of stromatolites in Precambrian biostratigraphy remains controversial: contributions to Chapter 7 include a statement of the Russian view on their application to the Riphean, a thoughtful critique on intercontinental correlation, and a word of caution to be applied before assigning geological age solely on the basis of stromatolites. The ghost of the dogma that stromatolites are marine intertidal forms must surely rest with the assembled documentation in Chapter 8, recent models for interpreting stromatolitic environments: documented not only from the marine intertidal, but also in ephemeral carbonate lakes, in sabkhas, in nearshore algal mounds of a salt lake, from freshwater algal marsh, in bioherms in a freshwater lake, and from within hot-spring sediments.

Chapter 9 discusses features in the tectonic, atmospheric, hydrological and biological evolution of the earth which must be considered when using the present to interpret the past; and concludes that the present is not the past, that application of recent data to ancient rocks must be done in the full understanding of the state of evolution at that particular time. Chapter 10 describes the use of stromatolites in palaeoenvironmental and basin analysis in a number of wide-ranging examples. This chapter is headed stromatolites in basin analysis, and it would seem that some part of it could more logically have been taken in the previous, paleonvironmental, chapter.

Chapter 11, dealing with the mineralization, lists mineral deposits associated with stromatolites, and also ranges broadly over biological processes and mineral deposition. The final chapter reveals available information on using stromatolitic lamination to provide evidence on the length of day, and thus the speed of the Earth's rotation, through geologic line. Without wishing to be pejorative it would appear that this approach has yet to yield much. Contributions to the conference on 'Biological clocks and changes in the Earth's rotation' at Newcastle-upon-Tyne in 1974 came for example largely from molluscs, corals, and geophysical and astronomical data.

There are four appendices: a glossary of terms, a table of time ranges of Precambrian stromatolites, a listing of available translations, and a subject index to the bibliography. The glossary is useful but could be better organized: a broader introduction; the handful of terms in the table at the end could easily have been incorporated into the glossary itself; while some of the features presented in a graphical summary of attributes are, like the 1969 origin, too small for the uninitiated to follow. The bibliography cites the references from the individual papers, and also several hundred additional stromatolite references.

The Editor took as his terms of reference that the field was a burgeoning, increasingly interdisciplinary one in which there was much unassimilated new information. He wished to balance reviews of established work with reports on new methods and research; and aimed to reflect the present state of knowledge accurately while producing a book useful to both the specialist and the new specialist.

Contribution to the book was by invitation. Three-quarters of the 42 contributors are from the USA or Australia, the balance from Russia, Canada, South Africa, France, and Belgium. Many of the papers are either on the Recent or from the Precambrian. (Additional interest in the field can be gauged from the program and contributions to the international symposium on Fossil Algae at Erlangen, Germany in October 1975—many of whom were Europeans working on Phanerozoic material.)

I believe that the book is timely and that it's aims have been achieved. I congratulate M. R. Walter, the Editor, on his achievement.

The book is essentially error-free and well produced. I believe, however, that the calibre of photographic material supplied as copy warrants the publisher choosing a finer screen than that used in the book. I would also enter a plea to the publisher that in a book of this sort a more individual dust-jacket be developed within the overall series.

The book is very strongly recommended to anyone directly involved or peripheral to the field. How well it will sell may, however, depend on how individuals, even institutions, face up to the cost.

J. F. T.

Johnson, R. W. (Editor), 1976—**Volcanism in Australasia.** 406 + 16 pp. Elsevier, Amsterdam. Price: Dfl 60, approximately $A22.20

Volcanism in Australasia is a handsome volume consisting of a collection of papers in honour of the late G. A. M. Taylor.

Tony Taylor, as he was always known, joined the Bureau of Mineral Resources in 1950 and worked as a volcanologist, mainly in Papua New Guinea, until his untimely death from a heart attack in 1972 while engaged in field work on Manam volcano. This volume, edited by R. W. Johnson, contains some 28 papers covering a broad spectrum of topics volcanological, together with a memorial to Tony Taylor written by Dr N. H. Fisher.

Naturally many of the papers have been written by colleagues of Tony Taylor, and, appropriately, nearly two-thirds of the contributions are concerned with aspects of the geology and geophysics of the volcanic areas and volcanoes in the Papua New Guinea region.

As noted by many of the authors this region is one of considerable complexity, although in broad terms it can be thought of as the zone of interaction between the Indo-Australian and the Pacific lithospheric plates. In detail several smaller plates are identified from the seismicity and the geometry. The complexity no doubt arises from the oblique convergence of the two major plates and the collision with, and choking of, a subduction zone by the continental mass of the southern part of Papua New Guinea at the leading edge of the Indo-Australian plate.

Johnson's paper on the volcanic arc at the southern margin of the Bismarck Sea highlights these points. He distinguishes a western arc, with no presently identifiable Benioff zone beneath it, and an eastern arc extending through New Britain which has a Benioff zone associated with it. This paper sets the scene for the six papers that follow in which descriptions are given of individual volcanoes of the South Bismarck Sea region, including accounts of many of the more recent eruptions together with appropriate maps and photographs, some in colour.

In addition petrographic descriptions and chemical analyses are provided in many cases, and show that tholeiitic basalt and low-silica andesite predominate. Similar information also is given for Bagana, one of the andesitic volcanoes on Bougainville.

The two papers by Whitford and Nicholls on Quaternary volcanism in the western Sunda arc in Java and Bali provide a wealth of new information on a region that appears to be geotectonically much simpler than northern Papua New Guinea. Whitford and Nicholls confirm and greatly extend previous work that had indicated that the K_2O content of rocks with the same SiO_2 content increases regularly with increasing depth to the well-developed Benioff zone under Java; they conclude that the magmas were derived from the mantle wedge above the Benioff zone.

In the second paper Nicholls and Whitford demonstrate that basaltic andesite and andesite are the dominant rock types in the western Sunda arc volcanoes and that the range of composition of the lavas can be accounted for mainly by crystal fractionation of more mafic primary olivine tholeiite magmas derived from partial melting of mantle peridotite.

A most useful summary is given by C. D. Branch of the life cycle of andesitic stratovolcanoes and the common association of porphyry copper deposits with intermediate to acid subvolcanic stocks within these volcanic edifices. In addition Branch notes that favourable environments for deposition of lead, zinc and gold, mercury and sulphur deposits may occur associated with these stratovolcanoes.

Because of the tectonic complexity of the Papua New Guinea region perhaps it is not surprising that there is considerable volcanic activity that is not readily fitted into models of magma generation related to subduction zones at convergent plate margins.

D. E. Mackenzie presents much petrographic and geochemical information on 16 late Cainozoic volcanic centres, mainly stratovolcanoes, that are found scattered through western Papua New Guinea where the crust is decidedly continental in character. Basaltic rocks ranging from high-K shoshonitic types to low-K types are dominant in 11 of these centres, whereas andesites, with high to moderate K contents are most abundant in the other volcanoes. The absence of any presently identifiable Benioff zone under this region leads Mackenzie to suggest that the magmas were derived from the low velocity zone in the upper mantle as a consequence of uplift subsequent to plate collision and crustal warping.

Pain and Blong map and describe a number of late Quaternary tephras in the vicinity of Mount Hagen and Mount Giluwe, two of the volcanoes considered by Mackenzie. Likewise Quaternary peralkaline rhyolites of the D'Entrecasteaux Islands situated off eastern Papua cannot be readily understood in terms of a convergent plate margin setting and are more typical of regions of crustal extension and rifting; in his paper describing these rocks I. E. M. Smith suggests that the tectonics of this region are indeed of the latter kind.

Johnson, Wallace and Ellis describe and geochemically characterize an unusually wide range of volcanic rocks from islands situated to the northeast of New Ireland. Rocks range from basanites, tephrites, olivine nephelinites through to alkali basalts, trachyandesites and quartz trachytes. The authors are unsure as to whether these rocks are related to a down-going lithospheric slab, for which evidence is lacking, and tentatively canvas the possibility that the volcanic chain is related to an isostatically controlled fault zone.

A number of geophysical studies are to be found in the volume including a description of seismic surveillance of volcanoes in Papua New Guinea (Myers), an aerial thermal infrared survey of the Rabaul Caldera (Perry and Crick), a crustal structural study by Finlayson *et al.* using explosion seismology techniques across the Papuan Ultramafic Belt in the vicinity of Mt. Lamington, which erupted catastrophically in 1951, and stress release estimates for a submarine eruption in northern Tonga (Latter).

Clarke and Cole summarize observations made over a number of years on the active volcano of White Island in the Bay of Plenty, New Zealand, and Nairn *et al.* describe the pyroclastic eruptions of Ngauruhoe volcano in central North Island, New Zealand in January and March, 1974.

Some attention is given to mainland Australia with a review paper by Ewart, Mateen and Ross on the mineralogy and chemistry of the Tertiary central volcanic complexes adjacent to the coast in northern New South Wales and southern Queensland; Stephenson and Griffin describe some basaltic lava flows that have travelled more than 80 km from their sources in the northern Queensland late Cainozoic volcanic provinces, and McKee and Thomas present results of a gravity survey across a small volcanic complex in the Newer Volcanics province of western Victoria. Bultitude provides the first comprehensive account of the Antrim Plateau Volcanics, a sequence of tholeiitic flood basalts of probable Cambrian age which crop out over a large area of northern Australia.

The volume is well produced with over 180 illustrations in the form of maps, photographs and diagrams of many kinds, together with some 29 tables about half of which list major element chemical analyses of volcanic rocks; typographic errors are few.

In summary, Volcanism in Australasia is a volume containing a wealth of new information and data on a wide variety of broadly volcanological topics. This book will be especially useful to, and welcomed by earth scientists who are concerned with island arc regions of the world, and it will remain an important reference work for many years to come.

Ian McDougall

Research School of Earth Sciences,
Australian National University,
P.O. Box 4, CANBERRA 2600.

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