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Front cover

In the account of the British Australian and New Zealand Antarctic Research Expedition, 1929-31, Sir Douglas Mawson recalls that on the afternoon of 18 February 1931 'a large party went ashore in the motor launch landing upon a rocky point to be known henceforth as Cape Bruce. There the flag was raised and cheers given for H.M. the King. The rocks proved of great interest, representing a wonderful variety of crystalline schists and gneisses'.

The site is marked by a plaque, and in the photograph a gravity reading is being made at this locality, which is in MacRobertson Land.

Photograph: L. E. Macey

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Kenneth Allison Townley: an appreciation

The first issue of the BMR Journal of Australian Geology and Geophysics was published recently. On 23 April 1976 Kenneth Allison Townley died as the result of a heart attack, at Woking, England. Thus began, as Ken passed on, an enterprise which will be associated with him forever in the minds of his colleagues. For it was Ken's aim as he approached retirement that a BMR journal should provide an additional outlet for scientific papers by Bureau officers. It is therefore both fitting and sad that a tribute to Ken should appear in this second issue: fitting because of his role in establishing the Journal; sad because it was planned that he should be honoured in his lifetime by an appreciation in an early issue of the Journal.

The Journal exemplifies two of Ken's deepest professional concerns: firstly the need for communication—between colleagues in BMR, between earth scientists generally, and between scientists and the public; and secondly the desire that the Bureau have, and be seen to have, a high sense of purpose and to be a vital productive organization with pride in its work and results. In his professional life Ken set himself and his colleagues high standards in values and conduct. He believed that personal integrity was of the utmost importance. He was warm and kind, but if the occasion demanded he would speak out forthrightly. His keen, quick intelligence and humour showed in the wit of his polished speech and in his stylish, economical writing.

Ken gave generously of his time and energy to many activities related to his profession. He was an active member of the Professional Officers Association, and prepared and presented the geologists' salary case to the Arbitration Commission in the early 1960s; he gave innumerable talks on geology to schools, led local geological excursions, and addressed university graduands on geology, and BMR in particular, as a career. He conducted report-writing courses within the Bureau, and presented similar courses to State Geological Surveys. He contributed greatly to the Geological Society of Australia of which he was a foundation member; he was a member of the Education Committee, and member of Council and Editor of the Society's Journal for three years. Latterly his interest concentrated on science editing. He was a member of the European Association of Earth Science Editors (Editerra), and of the Association of Earth Science Editors (AESE); he took a leading role in establishing Editeast—an association of science editors in southeast Asia and Oceania; he was appointed foundation President of Editeast in November 1975. Ken was also a member of the Australasian Institute of Mining and Metallurgy from 1954.

Ken Townley graduated with Honours in Geology from The Royal College of Science, London University, in 1938, and after a period as a demonstrator at Imperial College he took up a lectureship at Liverpool University. War broke out shortly after and he worked in radar, first as a civilian and then in the Army, attaining the rank of Captain. After the war he was engaged in intelligence work relating to radioactive minerals.

BMR was established in 1946, and soon became active in the search for radioactive minerals. Ken's experience in this field led to his recruitment early in 1950. He carried out field work in the Harts Range and at Rum Jungle in 1950, and in 1951 and 1952 led parties which started the large task of mapping the Precambrian of northwestern Queensland, covering an area from south of Mount Isa to the Nicholson River.

In June 1952, he was appointed editor of the Geological Section publications, a newly created position. Thus began Ken's main work with the Bureau, for it was in the field of reporting and publishing the results of Bureau investigations, with the attendant tasks of training personnel, preparing material for publication, and contract administration that Ken made his deepest impact. However, he did not confine himself to a narrow field of activity. He was constantly in demand as a teacher both within the Bureau and beyond it, and his written and oral dissertations in his own inimitable style have helped many of his colleagues to communicate. His report-writing notes, written many years ago, are still turned to by authors.

Ken remained with the Geological Branch until 1970, latterly in the position of Assistant Chief Geologist (Geological Services), a position which included not only his expanding editorial duties but direction of the work of the Geological Drawing Office, Map Editing and Compilation, Engineering Geology, Mineral Resources reports, and the Museum.

When the Publications and Information Section of the Operations Branch was established Ken moved to the position of Section Head and thereby became the Bureau's Editor-in-Chief. Despite ill health in recent years, he maintained a vigorous and innovative approach to his work, and his last years with the Bureau were devoted to a thorough reappraisal of the publications system. To overcome problems of long delays in publication, costs, and the ever-growing demands on storage, he proposed changes to provide a quicker outlet for the shorter scientific papers, and so the BMR Journal of Australian Geology and Geophysics was born. In addition, he made recommendations which will lead to some of the Bureau's information being published in microform.

On 24 December 1975, Ken retired from the Australian Public Service on grounds of invalidity, after 26 years service. He was then 60 years old, having been born at Swinton, near Manchester, England, on 1 September 1915.

Ken's interests and energies were by no means restricted to his professional life, and he contributed generously to community and cultural activities in Canberra. In line with his concern for communications, he was active in educational matters: he was the first president of the Lyneham Parents and Citizens Association and was president of the A.C.T. Council of P. and C. Associations from 1970 to 1973. He also served on the government-appointed Committee on Education in the A.C.T. He was a leading member of the Society of Friends and was chairman of the Canberra branch of Australian Frontier. Music played an important part in Ken's life, and that of his family; he shared in the founding of the Canberra Chamber Music Society and often held musical evenings at his home. He was also a foundation member of the Wine and Food Society.

Officers and former officers of BMR will remember Ken for his warmth and humour, for his concern for others, for his steadfast insistence on the highest professional standards, for his ability to help others to express clearly their spoken and written thoughts, and for his loyalty to the Bureau.

Characteristically, Ken had no intention of retiring quietly. He had plans to do consulting work, particularly in the fields of editing and training in report-writing, after a several-month visit to Britain via Japan and U.S.S.R. Ken and his wife Winifred were able to share three months of travel and visiting old friends and old places together before he died in the midst of an active life.

Our sympathy goes out to Winifred, their children, and grandchildren.

E. K. C.

The geochemistry of Lake Frome, a playa lake in South Australia

J. J. Draper and A. R. Jensen

Lake Frome, a large playa in southeast South Australia, lies at the centre of an internal drainage basin. Sediments and brines in the lake were studied to determine if the movement of fluids and sediments into an internal drainage basin in an arid environment could concentrate metal ions through evaporation or the action of sulphate reducing bacteria. Secondary objectives were the study of continental brines, playa sedimentation, and mound springs.

Stratigraphic analysis based on samples from a series of shallow auger holes shows that over the last 17000 years medium to fine sand accumulated on the margins of the lake and mud in the centre. The sediment has issued from streams entering the lake on all but the eastern sides, mainly in delta fans. Three informal stratigraphic units were recognised—upper and lower sandy units, and a muddy unit which is regarded as a lateral equivalent. A salt crust up to 20 cm thick overlies the clastic sediment in the centre of the lake.

At the time of the survey about 10 per cent of the lake was covered with water. Both surface and subsurface waters are hypersaline (26 to 34 percent) and characterized by high concentrations of sodium and chloride ions. The major ions have probably been derived from marine sediments. No enrichment of minor elements was detected in the brines, but lead appears to be leached from the sediments as soluble chloride complexes.

Clastic sediments from the lake have been analysed for major and minor elements. Statistical analysis of the results indicates that the upper and lower sands are geochemically similar and that they differ from the muds, which have higher concentrations of organic carbon and certain minor elements. There is no evidence of concentration of metal ions although manganese appears to have been concentrated on the surface of the lake by algae.

Mound springs in the northeastern part of the lake differ from those of the southeast in composition of the mound and the water. The composition of the water reflects mixing of artesian water with lake brines.

Introduction

Lake Frome is situated in the southeast of South Australia (Fig. 1). An expedition led by Captain E. C. Frome reached the shores of the lake in 1843. At that time the lake was assumed to be connected to Lake Torrens around the northern end of the Flinders Ranges (Frome, 1889; Henderson, 1925). When it was established in 1862 that the lake was a separate entity it was named after Frome. A description of the lake was provided by Madigan (1929), who saw it during his epic aerial reconnaissance into central Australia.

The lake is a large playa; it is approximately 100 km long, 45 km wide and covers an area of some 2700 km^2; the lowest part of the lake is approximately 2 m below sea level. It lies at the centre of a closed drainage basin of some 400 000 km^2. Part of this is occupied by small playas or salt pans, but most of the surface area drains towards Lake Frome. Short, steep gradient streams enter the lake from the west (Figs. 2 and 3); the Flinders Ranges, in which peaks rise more than 1100 m above sea level, are less than 30 km away. The Olary Ranges lie south of the lake. A number of streams, of which the Passmore is the largest, drain northwards towards the lake, but many of them do not reach it. One channel drains southwards from Lake Callabonna. There is little runoff from the area east of the lake, which is essentially flat and covered by longitudinal dunes and saltpans.

The dry climate of much of South Australia is controlled by a succession of anticyclones, moving from west to east. During summer northerly winds dominate the weather carrying hot dry air from the desert regions into South Australia; during winter, cool moist air is borne by southerly winds into the southern areas. Prevailing winds over the lake blow from the northeast in summer and the southwest in winter. The average rainfall is 100-125 mm, most of which falls in winter. However, rainfall shows appreciable fluctuations due to random summer thunderstorms over small areas, and also from the periodic southward extension

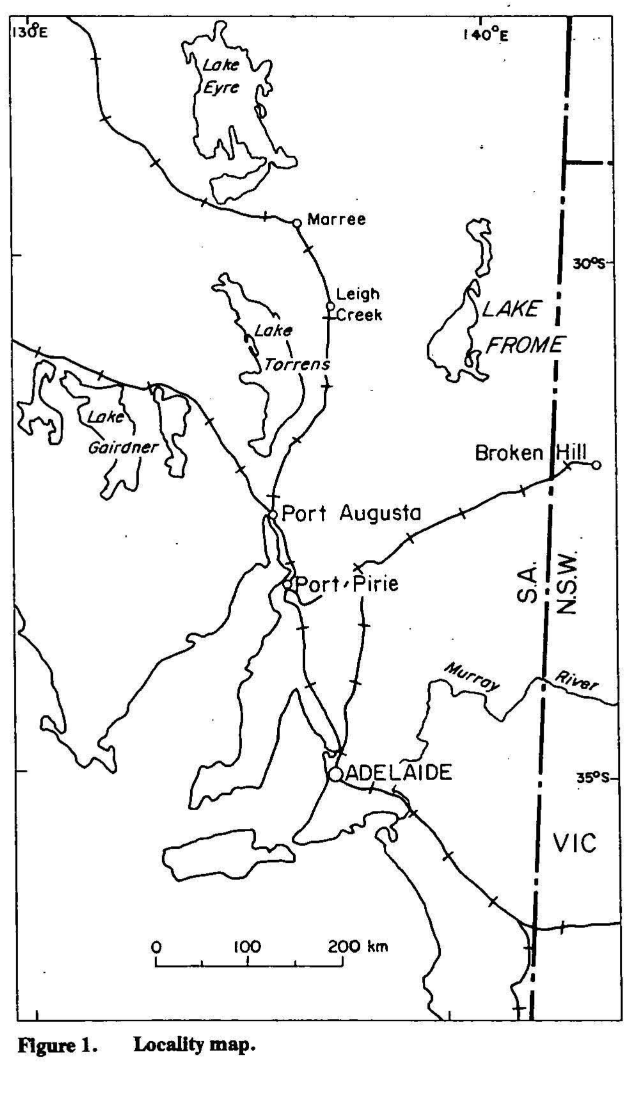

Figure 1. Locality map.

of the monsoon belt. Extrapolation suggests an annual mean maximum temperature of 24-25°C, and minimum of 11-12°C. The normal annual evaporation rate is in excess of 2200 mm.

Water is supplied to the surface of the lake by direct precipitation, surface runoff from the surrounding catchment areas, and by the upward movement of groundwater.

An outline of the groundwater hydrology of the area around Lake Frome has been provided by Ker (1966). The lake lies in the Frome Embayment near the southwestern margin of the Great Artesian Basin. Flowing bores tapping Mesozoic aquifers exist east of the lake and subartesian bores tapping the same aquifers exist between the lake and the Flinders Ranges to the west. The mound springs in the eastern part of the lake probably represent a natural outlet for waters of the Great Artesian Basin. Aquifers also exist at shallow depths in the overlying Tertiary and Quaternary sequences around and beneath the lake; the intake beds crop out in the Flinders and Barrier Ranges. Ker (1966) suggests that water in the shallow aquifers moves from intake areas (mainly in the Flinders Ranges) towards Lake Frome with an accompanying increase in salinity.

Surface waters were encountered during the present survey in the deepest parts of the lake around the islands (Fig. 4), at the mouths of some creeks on the western shoreline, and in the mound springs in the eastern parts of the lake. Elsewhere, the water table lay at depths ranging from 10 cm to several metres below the surface. Historical observations of water in the lake are few. Frome (1899) and Madigan (1929) both report that the surface was dry, Frome also observing dust storms on the surface. Water was observed during the seismic survey in 1970 (Austral United Geophysical, 1970) and it was seen to migrate rapidly under the influence of wind over the surface of the lake. An abnormally wet period commenced just prior to our survey of the lake and has continued since that time. In September 1973 about 10 percent of the lake was covered with water; eight months later about 75 percent was covered.

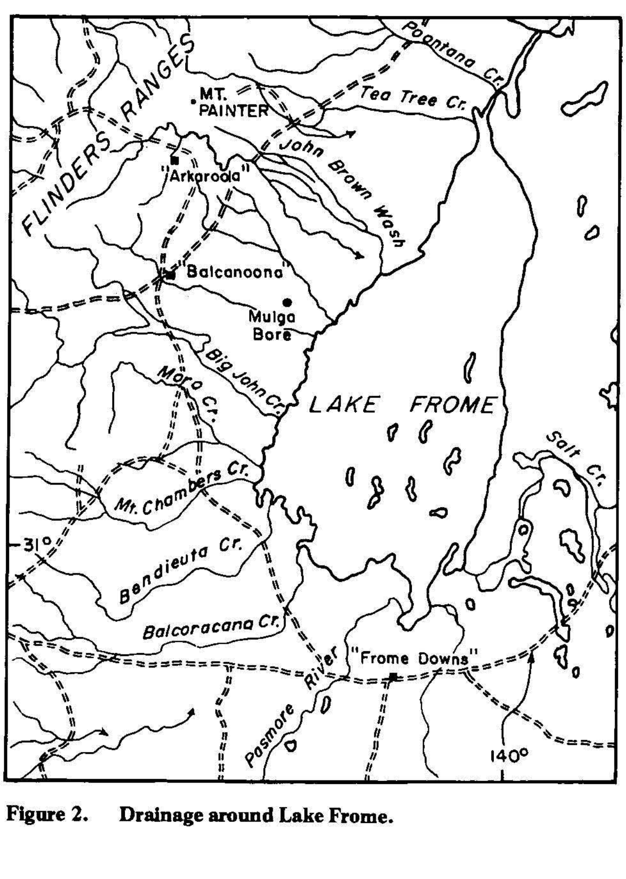

Figure 2. Drainage around Lake Frome.

The only examination of the lake itself was as part of a larger study of seven Australian playas (Krinsey *et al.*, 1968), but only one sample site was involved on Lake Frome. It is of considerable relevance to note that mining companies are currently prospecting for uranium in Tertiary sediments in areas beyond the limits of the present-day lake, and several important discoveries have been made (Callen, 1974). Callen also provides a detailed account of the geology of the area. A principal object of the present survey was to determine if the movement of fluids and sediment into an internal drainage basin in an arid area could concentrate metals such as zinc, copper, lead and uranium, through evaporation or the action of sulphate-reducing bacteria, and to determine factors influencing the spatial distribution of these elements. Lake Frome was selected because of its moderate size, its relatively simple drainage pattern, and its proximity to areas of known mineralization. Secondary objects were the study of continental brines, the study of sedimentation in a playa to aid in the recognition of such environments in the geological column and, lastly, the investigation of the springs on the eastern side of the lake.

Field work was carried out in the spring of 1973, working from a base camp at Mulga Bore (Fig. 2). In addition to field observations, 58 shallow auger holes were logged. Analyses were subsequently carried out on 130 sediment samples and 25 brine or water samples. The water samples were filtered in camp. All the chemical analyses were carried out by the Australian Mineral Development Laboratories (AMDL) in Adelaide.

A fuller report of the investigation of Lake Frome is to be found in Draper and Jensen (in prep.).

Acknowledgements

We wish to acknowledge the aid received in this investigation from Dr J. M. Bowler of the Australian National University and Mr R. A. Callen of the South Australian Mines Department. We benefited greatly from discussions held during the joint field operations and in the ensuing period.

Mr Callen, together with Messrs J. B. Firman, and B. G. Forbes, introduced us to the regional geology of the area in the early stages of the project. We would also like to thank Dr C. Downes and Mr A. D. Haldane for their advice on aspects of geochemistry, and Mr W. Mayo for advice on statistics and computing. Oilmin N. L. kindly granted permission to use groundwater uranium analyses from the Mount Painter area.

Surface features

A contour map of the lake surface has been prepared from theodolite traverse data (Austral United Geophysical, 1970), supplemented by field observations (Fig. 4). The contours shown lie below a zero datum of M.S.L. at Port Adelaide. The lake contains a large number of islands; most of these are in the south, where the bed of the lake is lowest. The islands are cliffed and terraced; this results from wave erosion. They are composed of gypsiferous quartz sand dunes developed on a clay surface.

Around the margin of the lake, features include transverse and longitudinal dunes, false spits and bars, beach deposits, and delta fans.

Delta fans have formed at the mouths of larger streams, particularly on the western side of the lake (Fig. 5). Major and minor channels, and interchannel areas, can be distinguished. The Munyallina Creek fan, described below, illustrates these sub-environments.

Figure 3. **ERTS photograph showing Lake Frome and the Flinders Ranges.**

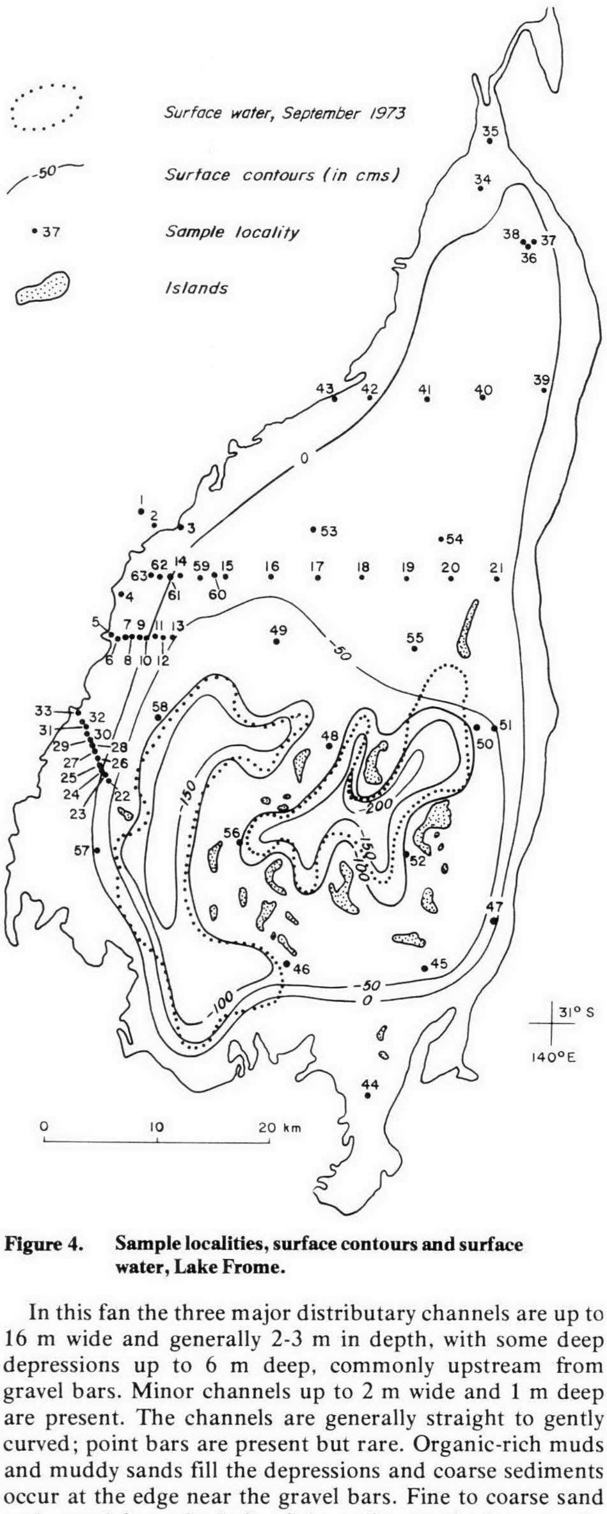

Figure 4. Sample localities, surface contours and surface water, Lake Frome.

In this fan the three major distributary channels are up to 16 m wide and generally 2-3 m in depth, with some deep depressions up to 6 m deep, commonly upstream from gravel bars. Minor channels up to 2 m wide and 1 m deep are present. The channels are generally straight to gently curved; point bars are present but rare. Organic-rich muds and muddy sands fill the depressions and coarse sediments occur at the edge near the gravel bars. Fine to coarse sand and gravel form the bulk of the sediment, the largest pebbles noted being 3-4 cm. A thin crust covers some of the sediment. Interchannel areas are well vegetated with clumps of bushes, around the bases of which fine to medium-grained, moderately well sorted aeolian sand is trapped. Deflation areas contain pebbles, many of which appear to be derived from local pre-existing sheet gravels. Flood debris obscures much of the interchannel areas. Salt pans are developed as large, flat areas peripheral to, but sometimes within, the delta fans. The sediment in the pans is poorly laminated slightly carbonaceous sandy silt with lenses of cross-laminated medium sand. Surface features consist of mudcracks and wind blown and flood debris.

Small isolated banks of gravel are scattered along the western margin adjacent to fans. They are generally close to the shore, but extend out into the lake for up to 1.5 km. At this distance the bank observed consisted of an evenly distributed layer of gravel up to 10 cm thick overlying 10 cm of fine sand which in turn overlay another gravel layer. The gravel is not dispersed around the banks and appears to be in situ.

Beyond the shoreline, the fans spread out and channels are almost non-existent with a maximum depth of 10 cm; the flat sandy surface with discontinuous salt encrustation is broken only by clumps of vegetation (halophytic phreophytes) which help to outline the fan shape. Interbedded medium sand and clay with some carbonaceous layers constitute the sediment although some gravel-sized particles are evenly and sparsely distributed, decreasing in quantity away from the shore. The fan sediments eventually merge into the lake sediments.

Isolated groups of mound springs are present on the eastern side of the lake (Fig. 10). The two northern groups are composed of fine clastic material, the three southern groups are composed of carbonate.

The clastic sediment mounds (Fig. 6) have a carbonate-cemented crust of up to 20 cm. This crust consists of calcite, quartz, and aragonite. Mounds range in height up to 2 m, and may be circular or elliptical. The mounds may carry some halophytic phreophytes. The largest elliptical mound is about 15 m long and 5 m wide. The smooth surface of this mound is broken by several small carbonate cones 20 cm high, and the interior of the mound consists of dark near liquid mud. Water is seeping out of some of the mounds and flowing from the carbonate cones. Algae grow in the moist areas of the mounds. Fig. 7 shows the north easterly group of mounds, surrounded by a halo of salt 90 m across.

Further south, the carbonate mounds are about 50-60 cm high, 1-2 m wide, and roughly circular. About 10 mounds lie within an area of several hundred square metres, separated by muddy lake sediment containing tufa fragments. The mounds are formed of tufa and also a greenish, more compact carbonate with concretionary layering. The tufa consists of aragonite and calcite, 30 percent each, and dolomite and quartz 20 percent each; the more compact rock is composed of 50 percent calcite, 45 percent dolomite, 5 percent quartz, and a trace of aragonite. Solution channels, small calcareous pinnacles, and a pustular calcareous crust are developed on the mounds. Water flows from some of the mounds. Others contain water standing above the level of the lake floor. Algae is associated with flowing water.

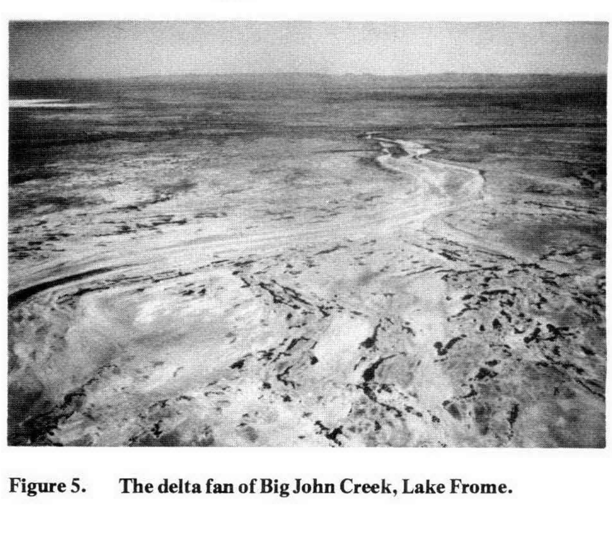

Figure 5. The delta fan of Big John Creek, Lake Frome.

The height of mound springs depends on piezometric surfaces and spring flow (Reeves, 1968); too high a head or too great a flow removes clastic or deflated material rather than trapping it. The height of the piezometric surface of the water in the springs has not been measured but in all cases flows are no more than several litres per hour. Water levels in many mounds are at present below the top of the mound, indicating a fall in effective piezometric surface. Numerous artesian water bores are in use in the area (Ker, 1966) and lowering may have been caused by wastage of water from these bores and slow replenishment of aquifers. Local graziers report a decrease in flow of 25 to 50 percent over the past 30 to 40 years (Callen, 1974).

Clastic sediment mound springs probably form by the accumulation of wind blown clastic sediment through a combination of moisture and algal entrapment. Vegetation once established probably aids the stabilization. If stabilization did not occur, erosion could remove the clastic material and leave a carbonate core. If the flow of the spring slowed down or stopped completely, the subsequent loss of moisture would make the mound more susceptible to deflation. There is no evidence that the southern mound

Figure 6. Clastic sediment mound springs.

springs ever had a clastic sediment mound and they may have built up merely by inorganic and/or algal precipitation. The role of the algae in the formation of the mounds is not known. They may merely be attracted to a moist environment or they may play an important role in trapping and precipitation processes. Algae can build quite large mounds in a lake environment (Scholl, 1960). Petrographic examination of the carbonate shows no layering and evenly sized (0.006-0.01 mm) randomly arranged crystals. Although algal filaments are present they are randomly distributed. It would appear therefore that inorganic precipitation is most important.

The age of the mound springs relative to the time of formation of the lake cannot be determined. The mounds will react differently in full lake phases and the differences in mineralogy and rock type in the southern springs may reflect such external differences. The clastic sediment mounds must have formed in a dry phase, the fine sediment being transported by wind from the lake floor.

Polygonal desiccation cracks are common on the surface of the lake. Polygons range up to 1 m in diameter and individual cracks up to several centimetres in width. Hollow blisters several centimetres across have developed extensively in near shore areas and give the surface a rough uneven appearance. The probable mechanism for the blistering is recrystallization and expansion associated with desiccation. However, the presence of algal beds elsewhere in the lake suggests that they too may be important in the

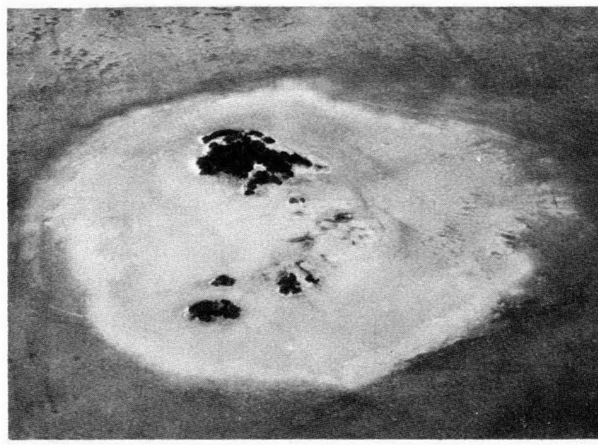

Figure 7. Aerial view of clastic sediment mound springs.

formation of these structures. Algal mats are present in the north-central areas of the lake. They are crumpled masses of algae and mud, probably derived from nearby bare patches. A rough northeast-southwest elongation of the mats suggests the influence of wind, although flowing water could also have been responsible.

Deflation depressions up to 1 m long and 30 cm wide are also elongated in a northeast-southwest direction. Tyre depressions act as loci of deflation.

Pieces of drift timber up to several metres in length litter the surface of the lake. Once buried this timber rots rapidly; this is best exemplified in the amount of decay of wooden pegs from the 1970 seismic survey (Austral United Geophysical, 1970).

Stratigraphy

The distribution of sediment on the surface of the lake is shown in Fig. 8. Sands are restricted to the western and eastern margins, and the southern areas around the islands; muds and clays occupy the centre of the lake. The shallow auger drilling, although providing no information below a depth of 4 m, does indicate the relationships of these clastic sediments. Three lithostratigraphic units can be distinguished and these can be demonstrated with reference to a cross-section in from the western margin of the lake (Fig. 9). At the lake margin a fine to medium-grained brown sand (Unit A) is underlain by a further sand that is commonly greenish in colour (Unit C). Both units grade eastwards—into the lake—to the muds of Unit B. All three units are commonly overlain by a salt crust, which constitutes a semi-permanent stratigraphic unit.

Lower sands (Unit C)

The lower sands are present at the margin of the lake at a depth of about one metre, and at progressively greater depths eastwards. The unit is composed largely of unconsolidated sand, muddy sand, and sandy mud. The bulk of the unit consists of very fine-grained, well sorted sand with subangular to rounded grains of quartz, feldspar, mica and mica schist.

The sands contain freshwater ostracods, marine foraminifera and oogonia of *chara*, a freshwater alga. The foraminifera present include *Ammonia becarii* (D. Belford, pers. com.). As Lake Frome at present lies 260 km northeast of marine waters, the presence of marine microfossils is difficult to explain. In similar cases elsewhere the presence of foraminifera in supposed freshwater sediments has been attributed to transport by birds (Ludbrook, 1953, 1955), and in this case the cemented and weathered nature of the

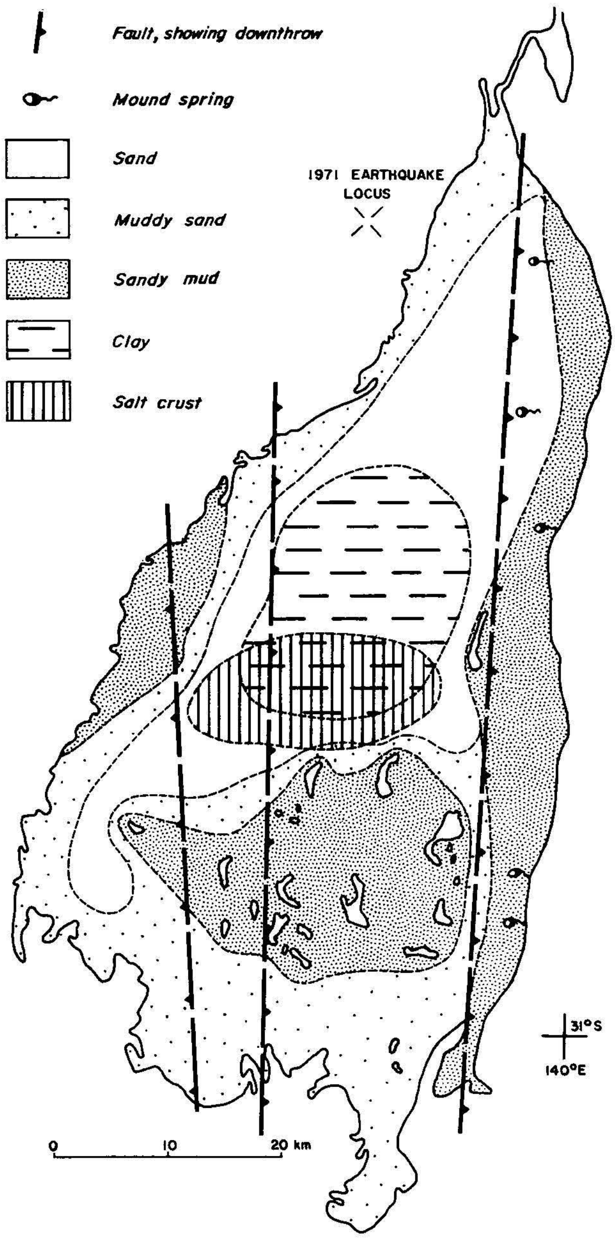

Figure 8. Sediment distribution and structural features, Lake Frome.

tests suggests reworking. Fossils present are of little stratigraphic value, ranging in age from Miocene to Recent. A single C^{14} determination of 14870 ± 370y B.P. (Table 1) measured on carbonaceous peaty material is supported by dates from contiguous parts of Unit B.

Muds (Unit B)

The muds are confined to the inner part of the lake. They lie at the surface in the central area and wedge out towards the margins (Fig. 9).

The unit consists of dark blue to blue-green or green laminated clays and muds, commonly smelling of hydrogen sulphide, which are pyritic in places. The clay is composed of kaolinite, montmorillonite and illite. Radiography of the clay in core samples reveals that the lamination is wispy and discontinuous, indicating the action of weak currents. Crystals of diagenetic gypsum disrupt the laminae in places.

The unit is at least two metres thick in the centre of the lake but the maximum thickness is unknown.

Few fossils were found. These were restricted to rare oogonia of *Chara;* and ostracods. In places the ostracods are concentrated along bedding planes; some are reworked, but in others some of the soft parts are intact. Five samples were dated from auger hole 60. (Table 1). The ages decrease from 16670 ± 680y B.P. at the base to 13340 ± 380y B.P. at the top.

A further four dates were obtained from cores taken in polycarbonate tubing from different locations. These samples, from nearer the surface show an increase from 4180 ± 590y B.P. just below the salt crust to 9300 ± 600y B.P. at one metre.

TABLE 1: RADIOMETRIC AGE DETERMINATIONS, LAKE FROME

Laboratory	*Sample No. BMR Prefix 73010*	*Unit*	*Locality*	*Depth*	*Age yBP*
S.U.R.L.	153	B	60	1.65	13340 ± 380
S.U.R.L.	154	B	60	1.95	14150 ± 610
S.U.R.L.	150	B	60	2.25	13460 ± *350*
S.U.R.L.	151	B	60	2.55	15310 ± 440
S.U.R.L.	152	B	60	2.85	16670 ± 680
S.U.R.L.	155	C	62	2.55	14870 ± 370
N.S.W.	160*	B	49	8-12 cm	4180 ± 590
N.S.W.	161*	B	49	39-46 cm	4370 ± 230
N.S.W.	162*	B	49	95-100 cm	9300 ± 600
N.S.W.	163*	B	53	76-91 cm	5540 ± 250

Sample 155 was peaty material in sand. All others consist of very finely disseminated carbonaceous material in silty clay. Analysts: Sydney University Radiocarbon Laboratory (S.U.R.L.); University of New South Wales, Department of Nuclear and Radiation Chemistry (N.S.W.).
* Samples obtained from cores.

The age was calculated using the Libby half-life of 5568y, with 0.95 NBS Oxalic Acid reference standard and expressed as Before Present (BP) with respect to AD 1950. The quoted uncertainty is one standard deviation based on samples, background and standard measurements only.

The radiocarbon dates were determined on the organic carbon content of the clays (except for sample 155 where peaty material was used): the carbonate having been removed by reaction with boiling phosphoric acid. Algal debris and transported plant remains form the bulk of the organic matter. Possible sources of contamination are reworked carbon, humic acids and the sampling technique (hand augering and coring).

Upper sands (Unit A)

The upper sands are distributed over much of the surface of Lake Frome. They consist of sand, muddy sand and sandy mud. Fine to medium-grained, well sorted, subangular to subrounded quartz with subordinate feldspar and rock fragments forms the bulk of the sediments. Mica is a common constituent, as is detrital carbonate in the upper sand unit. This carbonate consists of either irregularly shaped concretions, or platy white to greenish white grains which appear to be reworked calcrete-like material derived from calcrete deposits known to exist in the areas surrounding the lake (Callen, 1974).

The maximum thickness is unknown; at least 2 m of sediments exists on the western side of the lake.

Rare oogonia of *Chara,* foraminifera, ostracods and gastropods are present and are identical with those in Unit C. The unit is younger than the lower sands and is probably still forming today.

Quartz sand at the surface of the lake around the islands has been tentatively placed in the upper sands although it could be regarded as a separate unit. It has been presumably derived by erosion of the islands and is not related to the fan-deltas at the margins of the lake.

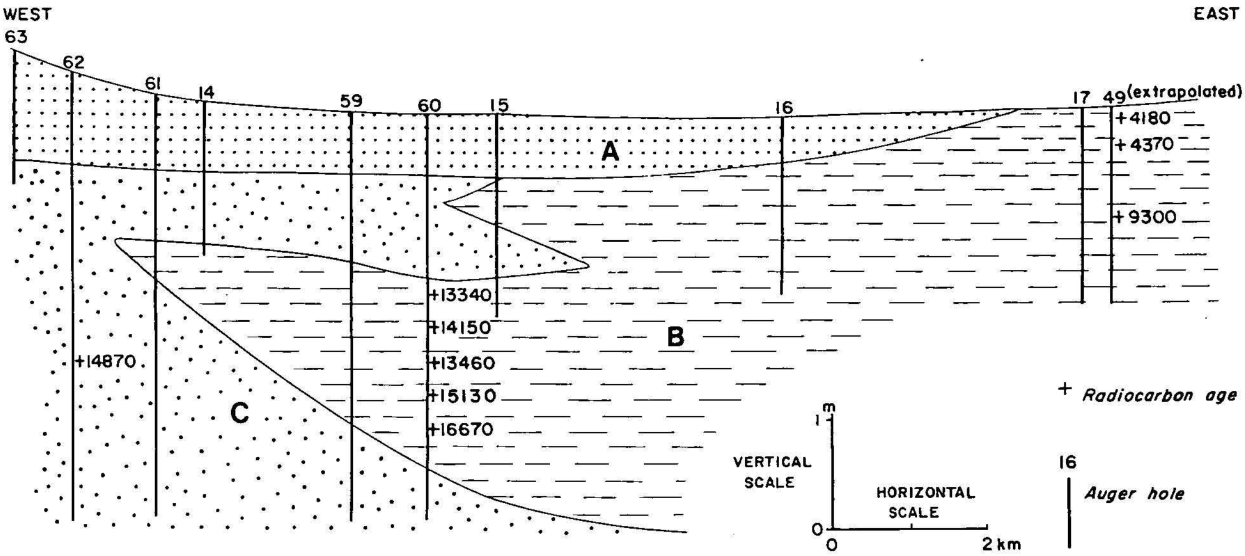

Figure 9. Diagrammatic cross-section from western side of Lake Frome, showing distribution of stratigraphic units A, B, and C, and radiocarbon ages.

Salt crust

A very thin veneer of evaporite minerals, mainly halite, covers most of the lake, but a solid crust is present only in the centre (Fig. 4) where it reaches a maximum thickness of 20 cm. The crust is mainly composed of halite with minor gypsum. Rafts of halite were forming actively on the surface of the water at the time of the survey, and then sinking to cover the bottom. Later recrystallization results in the formation of small cubic crystals.

Geochemistry

Chemical sediments

Halite crust

It has already been noted that a salt crust covers much of the lake surface. Seven analyses, not presented here, were carried out on the crust. Primarily it is composed of sodium chloride, with minor amounts of sulphate—generally less than 2 percent. Of the minor elements analysed none showed consistent concentration.

There are significant differences between the brines and the crusts. Calcium is enriched relative to sodium in the halite crust, and magnesium is enriched in the residual brine. The Ca/Mg ratios indicate that calcium is proportionately more abundant in the halite crust and magnesium is enriched in the residual brines. Values of the SO_4/Cl and CO_3-HCO_3/SO_4 ratios show that the chloride and the bicarbonate are enriched in the halite crusts, the sulphate being enriched in the brines.

The Cl/Br ratio is 1473 in the brine, and 16 600 to 23 320 in the halite crusts. This increase is to be expected as chloride is preferentially precipitated in halite, and bromide concentrates in the brine (Holser, 1970). The values for the crust are higher than those given by Holser for halite derived from a primary marine source.

Diagenetic gypsum

Well-formed platy, and in some cases prismatic, gypsum crystals up to several centimetres in size have formed within the sediments underlying the lake. Radiography of sediment cores showed that the gypsum crystals disrupt the laminations in the clay and that these crystals are loosely packed and randomly oriented. This is consistent with a diagenetic origin.

Gypsum can form by two processes in this type of environment. Oxidation of pyrite present within the sediment would result in the formation of sulphuric acid which in turn reacts with any carbonate present to form gypsum. This mode of formation is unlikely because: (a) the overall amount of carbonate present is very minor, (b) the detrital carbonate present shows no sign of acid solution, (c) the amount of pyrite present is very small, and (d) much of the gypsum is present within organic-rich clays containing pyrite with a fresh unoxidized appearance and some which has formed on the surface of the gypsum crystals.

A more likely explanation is that the gypsum is precipitated when saturation with respect to gypsum is reached by evaporation. The generally small crystal size (averaging approximately 1 mm) indicates reasonably rapid evaporation. The gypsum occurs in bands of variable thickness, but appears to become more common with depth. It is postulated that the gypsum precipitates at the top of the water table and that separate bands of gypsum indicate different water table levels. Many of the larger crystals show more than one phase of crystal growth, indicated by inclusions outlining crystal shapes. Generally two or three phases are discernible, but in at least one instance five or six phases can be recognized.

Pyrite

Pyrite is present in trace quantities and in all cases where it is observed gypsum is present. The sediment containing pyrite is not particularly organic-rich, with less than 2 percent organic carbon, although hydrogen sulphide was observed at some localities.

There are four basic types of occurrence: (a) discrete aggregate grains, generally of very fine sand size or smaller; (b) coatings on clay flakes and quartz and carbonate grains; (c) elongated blebs on the surface of gypsum crystals, the elongation being in the 010 direction; and (d) thin films on the 010 parting plane of gypsum crystals. In occurrence (d) the film appears to be black but when the crystal is split the film has a distinct brassy tinge. On some crystals the films have spread over the surface of the crystal and are definitely composed of pyrite. Some of the films could be FeS similar to that observed in gypsum from Lake Eyre by Baas Becking and Kaplan (1956).

Pyrite forms under reducing conditions produced by the presence of hydrogen sulphide derived from the anaerobic decay of organic matter. However, the consistent association of gypsum and pyrite and the close physical association between pyrite and gypsum would seem to indicate that much of the sulphur in the pyrite is derived from the gypsum. Sulphur can be released from gypsum in two ways: (a) gypsum would become slightly unstable under mild reducing conditions and return sulphate to solution, where it could be converted to H_2S along with free sulphate by reaction with free hydrogen formed by bacterial action or organic matter; or (b) direct reduction of sulphate to sulphide by halophilic bacterial attack on the gypsum crystals. Baas Becking and Kaplan (1956) propose the following equation for the formation of FeS under method (b) above:

$$CaSO_4 2H_2O + 8H + CO_2 + Fe(OH)_2 \rightleftharpoons FeS + CaCO_3 + 7H_2O$$

The iron monosulphide (FeS) is converted to pyrite (FeS_2) by reaction with free hydrogen sulphide. Presence of discrete grains and films suggests that both processes have occurred.

Precipitated carbonate

X-ray diffractograms indicate that very minor amounts of dolomite and calcite are associated with the gypsum. Detrital carbonate is known to be present, but diagenetic carbonate could be present as a result of two processes: precipitation from saturated brines or the formation of carbonate as a by-product of pyrite formation. Very fine sand sized fluffy irregular carbonate is present. It is thought to be diagenetic and probably consists of both calcite and dolomite.

Dolomite has been observed in a similar environment in Great Salt Lake, Utah (Bissell and Chillingar, 1962). Sonnenfeld (1964) claims that the formation of primary dolomite requires the presence of living or decaying vegetation. Much of the organic matter in Lake Frome is of undoubted vegetative origin. It is possible therefore that the dolomite could be primary, but dolomitization could be favoured in a situation where magnesium is enriched in brines in contact with the sediment.

Subsurface brines

Apart from the surface waters encountered around the islands at the time of the survey, at the mouths of some creeks on the western shoreline, and in the mound springs, the water table lay at depths ranging from 10 cm to several metres below the surface. A correlation matrix for the analyses, and student's t test of the correlation coefficients, are presented in Tables 2 (a) and (b) and the 25 brine analyses (for localities see Fig. 4) are presented in Tables 3 and 4. The analyses show that the surface and groundwaters of the lake are extremely saline. The salinity, expressed as Total Dissolved Solids (T.D.S.) (180°C) ranges from 24 to 34 percent, with a mean of 31 percent. Determinations of pH were attempted, but discontinued for technical reasons.

Major elements

Sodium and chloride are the major ions, and sulphate is far in excess of bicarbonate. Fig. 10 shows triangular plots of Na + K, Ca and Mg, and Cl, SO_4 and HCO_3. Chloride, sulphate and bicarbonate are all concentrated as the brine itself concentrates, but with increasing salinity sulphate is enriched relative to chloride. The correlation matrix indicates a highly significant correlation (99.9 percent confidence level) between T.D.S. and bicarbonate.

The Na(K)-Mg-Ca plot demonstrates that the brines tend to become magnesium-enriched relative to sodium. This and the fact that chloride is being depleted relative to sulphate suggest that sodium chloride was being precipitated from the groundwater at the time of the survey. This is supported by experimental observations which have shown that sodium chloride precipitates when seawater is concentrated about tenfold, i.e. to a salinity of about 35 percent (Braitsch, 1971; Herrmann & Knake, 1973).

The correlation matrix indicates highly significant correlations between T.D.S. and sodium, potassium and

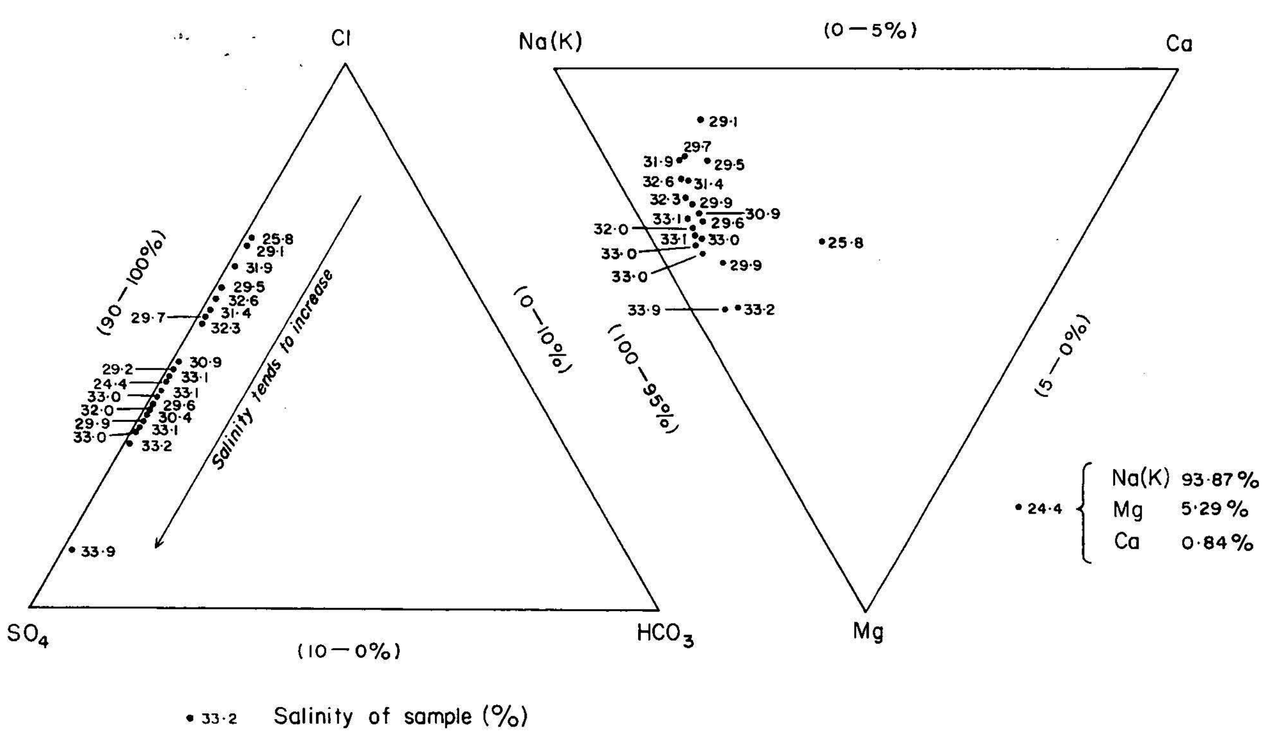

Figure 10. Triangular plot (mg/l)—showing the relationship between Cl-SO_4-HCO_3, and Na + K-Mg-Ca in Lake Frome brines

TABLE 2(a). CORRELATION MATRIX FOR SUBSURFACE BRINES

	Ca	*Mg*	*Na*	*K*	*HCO₃*	*SO₄*	*Br*	*Cl*	*TDS*	*SiO₂*	*B*	*Fe*	*Mn*	*Li*	*Sr*	*F*
Ca	1.00															
Mg	−.31	1.00														
Na	−.72	−.30	1.00													
K	−.68	.27	.67	1.00												
HCO₃	−.48	.13	.49	.56	1.00											
SO₄	−.89	.42	.60	.74	.41	1.00										
Br	−.84	.24	.70	.83	.43	.91	1.00									
Cl	−.65	−.30	.98	.64	.50	.51	.59	1.00								
TDS	−.76	−.17	.98	.76	.53	.67	.75	.97	1.00							
SiO₂	.02	.01	−.07	−.07	.37	−.08	−.04	−.14	−.10	1.00						
B	−.64	.27	.59	.88	.71	.69	.71	.59	.68	−.09	1.00					
Fe	−.40	−.16	.67	.66	.47	.37	.49	.72	.72	−.12	.65	1.00				
Mn	−.28	−.19	.23	−.02	.53	.12	.10	.23	.21	.19	.23	−.01	1.00			
Li	−.71	.48	.52	.88	.39	.82	.88	.47	.63	−.06	.77	.54	−.12	1.00		
Sr	.47	.20	−.44	.11	−.26	−.15	−.17	−.39	−.36	−.29	.12	−.05	−.39	.10	1.00	
F	.04	.30	−.28	−.25	−.20	−.12	−.03	−.31	−.29	.07	−.25	−.26	−.31	.08	−.15	1.00

No. of Samples = 21
p = o

(b): STUDENTS T TEST, SUBSURFACE BRINES

	Ca	*Mg*	*Na*	*K*	*HCO₃*	*SO₄*	*Br*	*Cl*	*TDS*	*SiO₂*	*B*	*Fe*	*Mn*	*Li*	*Sr*	*F*
Ca	0.00															
Mg	−1.42	0.00														
Na	−4.46	−1.39	0.00													
K	−4.02	1.22	3.90	0.00												
HCO₃	−2.39	.57	2.45	2.92	0.00											
SO₄	−8.39	2.05	3.24	4.76	1.95	0.00										
Br	−6.73	1.06	4.25	6.42	2.05	9.61	0.00									
Cl	−3.72	−1.40	19.60	3.67	2.53	2.55	3.20	0.00								
TDS	−5.15	−.76	23.89	5.10	2.76	3.94	4.96	18.03	0.00							
SiO₂	.10	.02	−.30	−.29	1.75	−.35	−.16	−.61	−.45	0.00						
B	−3.64	1.22	3.19	7.98	4.45	4.12	4.40	3.22	4.06	−.39	0.00					
Fe	−1.91	−.70	3.96	3.78	2.31	1.73	2.45	4.48	4.46	−.54	3.72	0.00				
Mn	−1.28	−.86	1.02	−.07	2.73	.52	.42	1.05	.92	.84	1.05	−.03	0.00			
Li	−4.42	2.39	2.67	8.25	1.82	6.28	8.15	2.33	3.53	−.24	5.18	2.79	−.54	0.00		
Sr	2.30	.88	−2.16	.47	−1.19	−.67	−.73	−1.87	−1.70	−1.32	.51	−.24	−1.84	.43	0.00	
F	.16	1.36	−1.26	−1.10	−.89	−.51	−.12	−1.44	−1.32	.30	−1.12	−1.20	−1.43	.33	−.68	0.00

Degrees of Freedom = 19

calcium. The correlation between T.D.S. and calcium is negative, indicating a depletion of calcium with concentration of the brines. This depletion is also indicated by the triangular plot (Fig. 10), and more particularly by the calcium distribution map (Fig. 11), which shows a decrease of values towards the centre of the lake, whereas the T.D.S. distribution map (Fig. 11) shows an increase towards the centre. This loss of calcium would be a result of carbonate or gypsum precipitation. Gypsum is the more likely precipitate in Lake Frome because of the high sulphate and very low bicarbonate content. Gypsum precipitation would have little effect on the overall behaviour of SO_4 because of the large differences in concentration between calcium and SO_4. Magnesium shows a negative non-significant correlation with T.D.S. This behaviour of magnesium is difficult to explain as a strong positive correlation was anticipated. Adsorption by clays or dolomitization of carbonates are two possible explanations.

Minor elements

Silica. Absolute silica values are very low and range from 1.1 mg/l to 5.2 mg/l with a mean value of 2.9 mg/l. By comparison, the value for average sea water is 6.5 ppm (Goldberg, 1963) and for average stream water, 13.1 ppm (Livingstone, 1963). Silica tends to decrease towards the centre of the lake (Fig. 11), but as the correlation coefficient of −0.10 for SiO_2/T.D.S. does not verify this, the decrease is not a function of evaporative concentration. In addition there is an area of high silica values in the centre.

The concentration of silica in alkaline brines is controlled by pH. The solubility remains constant below pH 9 (Krauskopf, 1967) and above that figure rises rapidly, due to the polymerization of silica acid (Jones *et al.*, 1967). The few pH measurements taken suggest a pH of between 6 and 7 for Lake Frome brines, and reference to Krauskopf's solubility graphs indicates that Lake Frome brines are considerably undersaturated with respect to silica and quartz. Decrease in values lakewards may be due to precipitation as silica, a silicate such as sepiolite ($Mg_2Si_3O_6\,(OH)_4$) (Garrels & Mackenzie, 1967), or formation of Mg-montmorillonite at the expense of kaolinite (Hardie & Eugster, 1970).

Boron. The distribution of boron (Fig. 11) is similar to that of T.D.S., indicating that the boron is concentrating in the brine. This is confirmed by a highly significant correlation coefficient of 0.68 for B/T.D.S. The reason for this concentration is that the boron in the Lake Frome brines presumably forms, as in seawater, relatively soluble polyborate complexes. The ratio of B/Cl in seawater is 242×10^{-6} whereas the same ratio in Lake Frome ranges from 2.07×10^{-6} to 15.57×10^{-6}; precipitation is therefore unlikely. If there is any loss of boron it could be by adsorption on clay minerals such as illite.

Iron. Absolute values of iron range from 3.0 to 5.3 mg/l with a mean value of 4.4 mg/1. This is considerably higher

TABLE 3. RESULTS OF ANALYSES OF SUBSURFACE AND MISCELLANEOUS BRINES.

Locality	Sample No. Prefix 73010	Ca	Mg	Na	K	HCO_3	SO_4	Br	Cl	NO_3	T.D.S.	SiO_2	B	Fe	Mn	Li	Sr	F	U	Cl/Br	B/Cl($\times 10^{-4}$)	Na/Li	Sr/Ca	HCO_3/SO_4
02(a)	002	365	193	7 760	47	82	534	6	12 449	<1	21 880	0.1	0.19	0.38	0.08	2.0	6.0	0.10	<5	2075	15.3	3 880	0.016	0.15
06	009	1175	900	9 660	68	44	6 831	70	148 720	8	258 400	3.0	0.45	3.9	0.74	8.6	23.6	0.15	<5	2125	2.82	11 233	0.020	0.006
13	016	780	560	112 500	165	69	10 045	115	169 156	<1	294 800	1.6	0.94	4.92	1.80	9.3	12.2	0.05	—	1471	5.56	12 097	0.016	0.007
14	018	675	525	113 000	107	71	11 060	100	168 964	7	196 900	3.0	0.78	4.80	0.88	7.4	9.8	0.15	<5	1690	4.62	15 270	0.015	0.006
15	023	525	930	117 000	287	124	13 705	150	174 701	1	309 250	1.7	1.25	3.76	1.50	10.0	10.0	0.20	<5	1165	7.16	11 700	0.019	0.009
16	026	412	1225	123 000	445	148	17 653	170	184 424	<1	331 200	2.1	1.50	4.96	1.56	14.4	8.1	0.05	<5	1085	8.13	8 542	0.020	0.008
17	031	435	1105	123 000	520	316	15 137	165	186 611	<1	330 800	4.0	2.85	5.26	3.06	15.6	8.4	0.20	<5	1131	15.27	7 885	0.019	0.008
19	038	425	990	122 500	753	96	16 110	185	185 807	<1	330 800	1.1	2.55	5.30	1.24	18.0	19.0	0.05	<5	1004	13.72	6 806	0.045	0.006
20	041	320	1570	125 000	813	124	24 083	240	183 002	<1	338 700	1.7	2.85	4.86	0.92	23.0	18.0	0.05	<5	762	15.57	5 435	0.056	0.005
21	044	455	1012	120 500	252	55	16 359	170	179 062	3	319 900	3.4	0.48	4.38	0.90	14.3	8.6	0.25	<5	1053	2.68	8 427	0.019	0.003
22	048	685	580	121 000	247	96	9 695	90	183 069	<1	318 900	3.8	1.20	4.30	1.24	9.8	10.0	0.05	5	2034	6.55	12 347	0.015	0.010
34	051	500	900	112 000	202	96	14 919	150	165 367	<1	295 700	4.7	0.92	4.08	2.48	11.8	9.7	0.05	5	1102	5.56	9 492	0.019	0.006
36(b)	057	175	151	11 800	52	175	1 471	19	17 351	<1	32 279	12.2	1.55	0.38	0.06	11.6	4.0	0.90	<5	913	89.33	1 017	0.023	0.187
38	064	500	825	114 000	196	96	15 612	160	165 561	<1	299 300	3.2	0.79	3.00	2.62	9.0	8.6	0.05	5	1035	4.7	12 667	0.017	0.006
43	073	490	1200	116 000	226	55	15 892	190	169 123	4	304 400	2.8	0.93	4.18	0.80	17.5	9.1	0.45	<5	890	5.50	6 629	0.019	0.004
44	077	700	2670	89 500	106	55	11 553	70	138 592	11	244 300	3.0	0.67	3.10	0.68	11.4	14.8	0.30	5	1980	4.83	7 851	0.021	0.005
45	080	945	328	112 000	150	55	7 903	75	168 776	<1	290 800	3.0	0.35	3.92	0.80	6.6	13.0	0.10	<5	2250	2.07	16 970	0.014	0.007
46(c)	081	570	735	122 500	414	55	11 271	125	184 087	<1	325 750	5.0	1.60	4.20	0.82	13.0	14.6	0.20	<5	1473	8.69	9 423	0.026	0.005
47(d)	085	83	123	5 750	34	1017	829	13	8 208	<1	15 600	16.1	1.80	0.24	0.04	12.2	18.2	2.10	<5	631	219.30	471	0.219	1.227
48	097	537	850	122 500	347	69	12 320	145	185 229	<1	332 950	2.0	1.00	4.20	1.66	13.0	8.9	0.25	<5	1277	5.40	9 423	0.017	0.006
49	101	455	1125	124 500	713	234	158 843	190	182 233	<1	329 550	5.2	1.80	4.96	1.12	16.8	9.9	0.10	5	959	9.88	7 411	0.022	0.015
50	105	637	905	112 000	360	82	13 147	170	162 063	<1	292 550	3.7	1.45	4.18	0.98	13.6	11.7	0.30	<5	953	8.95	8 235	0.018	0.006
51	108	600	705	118 000	336	55	11 458	130	176 581	1	314 500	2.2	0.82	4.86	0.94	12.8	9.5	0.20	<5	1358	4.64	9 219	0.016	0.005
53	113	412	1190	124 500	508	124	17 849	200	185 006	<1	330 050	2.8	1.70	5.08	1.12	15.6	7.3	0.10	<5	925	9.19	7 981	0.018	0.007
55	119	400	1475	121 500	905	137	18 164	245	179 572	<1	332 400	3.3	2.25	5.08	0.92	24.0	13.2	0.15	<5	732	12.53	5 063	0.033	0.007

(a) Sample from waterhole — Munyallina Creek.
(b) Northern mound spring.
(c) Surface water.
(d) Southern mound spring.
(All values in mg/l except U-ug/l).

TABLE 4. SUMMARY OF ANALYSES—SUBSURFACE BRINES

	Mean	*Variance*	*Standard Deviation*	*Skewness*	*Kurtosis*
Ca	574.1429	41 185.1286	202.9412	1.37	1.48
Mg	1 027.1429	234 942.8296	484.7090	1.67	3.75
Na	116 219.0476	81 967 619.0477	9 053.5970	−1.52	1.84
K	366.9524	61 562.1476	248.1172	.79	−.68
HCO_3	104.8095	4 296.9619	65.5512	1.81	2.99
SO_4	14 063.7143	15 814 107.0143	3 976.6955	.29	.01
Br	151.4286	2 585.3571	50.8464	−.05	−.90
Cl	173 410.4286	161 142 878.1572	12 694.2065	−1.13	.67
TDS	308 864.2857	608 410 285.7145	24 665.9743	−1.02	.40
SiO_2	2.9190	1.0746	1.0366	.28	−.55
B	1.3110	.5854	.7651	.77	−.67
Fe	4.4324	.4361	.6604	−.60	−.64
Mn	1.3314	.4413	.6643	1.26	.45
Li	13.4524	21.9286	4.6828	.62	−.36
Sr	11.5905	17.3319	4.1632	1.43	1.20
F	.1519	.0126	.1124	.85	.03
HCO_3/SO_4	.0068	.0000	.0025	1.63	3.46
Cl/Br	1 284.8095	213 660.8619	462.2346	.85	−.71

N = 21

than average river water which has an iron content of 0.67 ppm Fe (Livingstone, 1963) and seawater which has a content of 0.01 ppm Fe (Goldberg, 1963). The areal distribution pattern (Fig. 11) is similar to that of T.D.S., indicating that iron is concentrating in the brine, and this is verified by a highly significant correlation coefficient of 0.72 for Fe/T.D.S.

Braitsch (1971) used the Bocke Equation to examine the behaviour of iron during brine evolution using seawater as the initial solution. A value of 0.002 ppm increases to 0.005 ppm at the beginning of gypsum formation and to 0.017 ppm at the start of halite precipitation.

Manganese. Absolute values of manganese range from 0.68-3.68 mg/l with a mean of 1.33 mg/l. By comparison seawater has a manganese content of 0.002 ppm (Goldberg, 1963). The areal distribution (Fig. 11) is very different from the distribution of other elements. The only meaningful correlation coefficient obtained is a significant value of 0.53 for Mn/HCO_3. This could explain the concentration of values around the northern mound springs, the waters of which are more bicarbonate-rich than the brines of the lake. No concentration is apparent around the southern mound springs, but this may be related to sample distribution. The reaction of manganese with bicarbonate-rich waters in the east could have disrupted a normal concentration pattern.

Lithium. Absolute values of lithium range from 6.6 to 24 mg/l, with a mean value of 13.45 mg/l; by comparison, seawater has a value of 0.17 ppm (Goldberg, 1963). The distribution pattern (Fig. 11) is basically similar to that of T.D.S. and it would appear that lithium is concentrating in the brine; this relationship is significant with a correlation coefficient of 0.63.

The value of Na/Li ratios ranges from 5063 to 16 970. The same ratio in seawater is 61 765 and the crustal average is 1200. In Lake Frome the ratio decreases towards the centre of the lake (Fig. 11) indicating that lithium is enriched relative to sodium. There are two possible causes for this: (a) leaching of lithium from micas, or (b) precipitation of sodium salts. It has already been shown that NaCl was precipitating at the time of the survey and hence explanation (b) is more likely. Furthermore there is little mica towards the centre of the lake.

Strontium. Absolute values of strontium range from 7.3 to 23.6 mg/l (mean 11.6) compared with 8 ppm for seawater (Goldberg, 1963). The areal distribution pattern (Fig. 11) shows a distribution unrelated to T.D.S. or any other pattern. The only meaningful coefficient obtained is a significant value of 0.47 for Sr/Ca.

Braitsch (1971) calculated that for seawater the value of the Sr/Ca ratio increases from 0.020 to 0.022 at the commencement of gypsum precipitation and 0.044 at the beginning of halite precipitation. Sr/Ca ratios in Lake Frome brines range from 0.014 to 0.056. Borchert and Muir (1964) support the idea that strontium concentrates in a brine. On the other hand, Strakhov (1967) and Krauskopf (1967) maintain that strontium is removed from solution during calcium sulphate precipitation. The distribution of Sr/Ca ratios (Fig. 11) shows that the brines are becoming enriched in strontium relative to calcium. Nevertheless there may be some substitution of calcium by strontium in the gypsum.

Uranium. The brines contain a maximum of only 5 μg/l of uranium. The 5 μg/l values are around the edge of the lake and the lower values towards the centre. This distribution is almost identical with that of uranium in the subsurface sediments, and it strengthens the hypothesis that the uranium is precipitated from groundwater at the margins of the organic rich Unit B.

The low uranium values are in sharp contrast to the high values found in the waters of the Mount Painter Block. Figures supplied by Oilmin N.L. for waters in the vicinity of Paralana Hot Springs show a range of 180 to 6800 ppb of U_3O_8. Analyses carried out for Central Pacific N.L. (Spark, 1970) in an area between the Mount Painter Block and the northern end of Lake Frome show a range of values from 80 to 330 to less than 10 ppb U from the west to east. The Beverley prospect, a wavefront or blanket type deposit, is located in the Paralana area. Callen (1974) states that the clayey fine sands of the Namba Formation and coarser sandy facies of the Eyre Formation are the most suitable horizons for prospecting. Both are of Tertiary age. Uranium is in disequilibrium in the basin, but most is being precipitated close to the range, so that it is difficult to test whether uranium could concentrate in an evaporative environment.

Fluoride. Absolute values for fluoride range from less than 0.05 mg/l (0.05 being the analytical limit of detection) to 0.30 mg/l. The areal distribution (Fig. 11) in no way resembles that of T.D.S. and the correlation coefficient for F/T.D.S. is not statistically significant. The fluoride is not therefore being concentrated in the brines.

The highest values are present in the southeast corner, except for a high value in the sample closest to the Mount

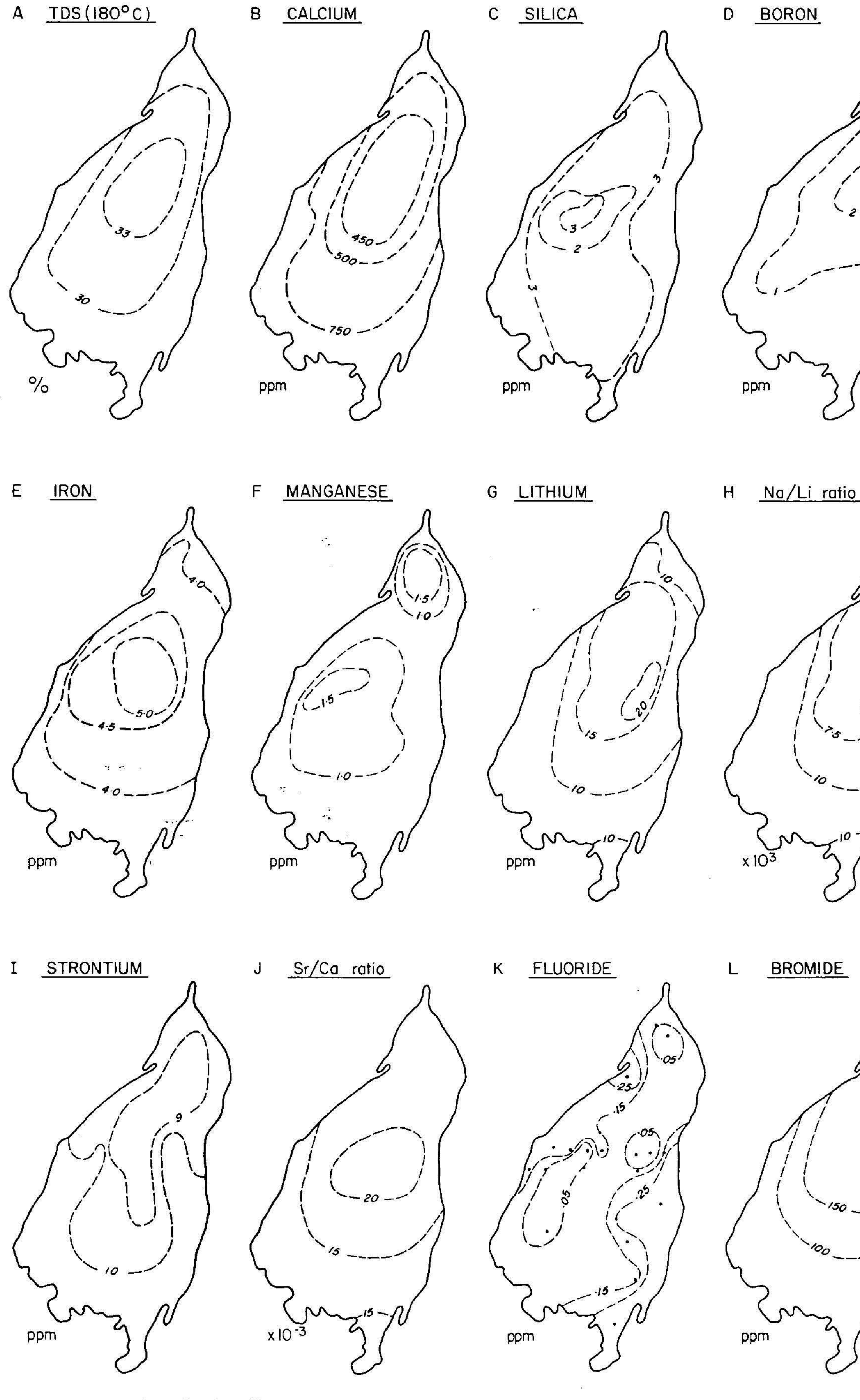

Figure 11. Element distribution in brines.

Painter Block. Sediment in the southeastern corner has a considerable mica content which is derived from either the Olary Ranges or southern North Flinders Ranges, and fluoride could be leached from this. Fluorine can replace (OH) groups in muscovite and phlogopite (Deer, Howie and Zussman, 1966) and be released as the micas are degraded. The sample closest to the Mount Painter Block is associated with mica-rich sediment. Low fluoride values might also result from precipitation of fluoride or apatite, although neither of these minerals has been detected in the sediments. Fluoride could be absorbed by clay minerals in which it replaces the (OH) groups, Koritnig (1951) found that fluoride values are higher in fine clay layers and salt clay in associated evaporite minerals.

Comparison of brine composition and sediment geochemistry indicates a close association between fluoride in the brine with organic carbon and, therefore, with clay content of the sediment. This suggests that sorption by clays is the major operative process.

Nitrate. Concentrations of nitrate are extremely low, being generally less than 1 mg/l. The only values above this are near the edge of the lake and near major stream inlets, the highest value found being in the sediment fan of the Siccus-Passmore River system. The low nitrate values in the centre could be due to conversion to nitrogen by denitrifying bacteria.

Bromide. Absolute values of bromide range from 70 to 245 mg/l with a mean of 151.4 mg/l as compared with 65 ppm for seawater (Goldberg, 1963). The distribution pattern (Fig. 11) indicates that bromide is concentrating with the brine and this is verified by the highly significant correlation coefficient of 0.75 for Br/T.D.S.

The ratio of chloride to bromide (Cl/Br) varies from 732 to 2250 (seawater, 292), part of the wide variations being due to chloride precipitation as outlined earlier. The ratios also show that the brines are bromide-poor compared with seawater. Bromide normally concentrates in the residual fluid (Braitsch, 1971) when seawater is evaporated. Cl/Br ratios for various rock types (using average values of Turekian and Wederpohl, 1961) range from 10 to 154. Lake Frome brines are therefore enriched in chloride relative to bromide compared with seawater and rocks.

Waters from mound springs

The salinity of the water from the mound springs ranges from 1.5 to 3.2 percent. These waters are characterized by enrichment of carbonate, whereas the subsurface brines are relatively deficient in bicarbonate. These differences are best expressed in terms of the HCO_3/SO_4 ratio which for brines ranges from 0.004 to 0.015 and for the mound spring waters from 0.187 to 1.227.

Minor element values reflect the significant differences between the spring waters and the brines, the spring waters being relatively enriched in silica and fluoride and depleted in iron and manganese. Little difference exists between the amounts of boron, lithium and strontium in the spring-waters and the brine.

Northern and southern mound spring waters differ significantly. The southern spring water is less saline, has a higher absolute bicarbonate value and HCO_3/SO_4 ratio, and is richer in silica and fluoride. In the northern water, the Ca ratio is 1.16 whilst in the southern water, the ratio is 0.67, and in the northern carbonate rock the ratio is 17.9 as compared to 13.5 and 5 in the southern carbonate rocks.

The ratios of Sr/Ca in northern and southern waters are 0.023 and 0.219 respectively. However, the ratios in the carbonate rocks are 0.011 in the north and 0.016 (Sample 89) and 0.0026 (Sample 90) in the south. The most aragonite-rich rock (Sample 89) has the highest ratio while sample 90 with a ratio of 0.0026 contains only a trace of aragonite. It is however, composed of dolomite and calcite in which the substitution of strontium for calcium is considerably less than in aragonite.

Minor element values are low and of no real significance. High Mn, Fe and P values in the northern sample probably reflect the presence of high Mn (4271 ppm), Fe (4.22 percent) and P (0.072 percent) in the organic-rich mud forming the interior of the mound. High fluoride values could indicate the presence of fluorite (CaF_2) in the rocks although none has been detected.

Clastic sediments

Ninety-four clastic sediments were analysed for the following—Cu, Pb, Zn, Mn, V, Fe, SO_4, V and organic carbon (Tables 6 and 7) and analyses were carried out on 10 of the samples for major ions: Si, Al, K, Ca, CO_2, and Na (Table 5). Details of analytical methods are available. The sediment samples were not washed free of saline water but were dried prior to analyses and, where necessary, the

TABLE 6. SUMMARY OF MINOR ELEMENT ANALYSES. CLASTIC SEDIMENTS

	Mean	*Variance*	*Standard Deviation*	*Skewness*	*Kurtosis*
Cu	27.8298 ppm	126.7664	11.2591	1.24	5.43
Pb	12.2872 ppm	48.2284	6.9447	0.70	0.46
Zn	73.1170 ppm	783.6743	27.9942	−0.12	−0.49
Mn	552.0426 ppm	101949.3960	319.2952	1.12	1.15
V	150.0851 ppm	2387.1540	48.8585	0.22	0.87
Fe	3.3399 %	0.9912	0.9956	−0.67	−0.35
P	0.0596 %	0.0004	0.0207	−0.43	−0.81
SO_4	5.5953 %	53.9465	7.3448	2.71	10.66
Org C	0.2851 %	0.0812	0.2850	1.32	0.70
Lightness	5.2128	0.7499	0.8660	0.57	−0.25

N=94.

TABLE 5. CLASTIC SEDIMENTS — MAJOR ELEMENT ANALYSES (CORRECTED TO ZERO WATER SOLUBLE NaCl)

Sample No. Prefix 73010	*Locality*	SiO_2	Al_2O_3	*Total Fe* Fe_2O_3	*CaO*	*MgO*	K_2O	CO_2	SO_3	*LOI*	H_2O^+	H_2O^-
017 (b)	14	72.0	8.7	3.1	2.4	2.6	1.7	2.2	0.43	8.4	3.03	1.88
029	17	33.9	13.8	4.3	10.0	3.0	2.7	4.1	10.05	23.4	6.71	4.16
030	17	37.4	14.3	5.1	6.6	3.8	2.3	4.7	3.77	24.6	7.20	4.19
033	18	38.4	16.7	5.6	4.7	3.0	2.5	2.6	4.8	22.6	6.52	6.64
037	19	40.1	18.1	5.8	2.7	2.8	2.5	1.5	3.65	24.0	7.13	8.01
072 (b)	43	74.5	8.1	3.6	0.38	2.14	1.9	0.2	0.85	6.2	2.90	1.28
084 (a)	46	43.9	7.2	2.1	15.6	0.99	1.3	1.7	23.4	10.9	5.16	2.78
110	53	48.7	15.8	5.8	3.9	4.0	2.4	2.6	2.51	19.3	5.86	4.74
114	54	43.0	13.3	4.7	3.9	3.9	2.2	2.6	3.12	21.1	5.95	4.67
138	57	37.2	13.0	4.5	14.5	2.0	1.9	5.7	2.65	17.1	5.40	4.11

(a) Sand containing detrital gypsum. (b) Quartz sands. Remainder are clayey sediments.

TABLE 7. CLASTIC SEDIMENTS—MINOR ELEMENT ANALYSES (CORRECTED TO ZERO WATER SOLUBLE NaCl)

Sample No. Prefix 73010	*Locality*	*Depth (m)*	*Cu ppm*	*Pb ppm*	*Zn ppm*	*Mn ppm*	*V ppm*	*Fe %*	*P %*	*U ppm*	*SO_4 %*	*OrgC %*
001	02	0	51	23	135	1058	216	5.3	0.092	<3	0.53	0.87
004	02	0.20	36	19	92	552	188	4.2	0.064	<3	1.48	1.15
006	06	0	9	6	23	174	53	1.38	0.019	<3	0.28	0.08
007	06	0.80	20	10	42	301	120	4.38	0.070	<3	0.65	0.13
008	06	1.00	25	13	73	674	155	3.53	0.048	3	0.65	0.15
010	13	0	26	13	79	725	154	3.57	0.068	<3	0.67	0.16
011	13	1.40	20	10	53	339	119	2.54	0.051	<3	18.8	0.15
012	13	1.50	36	14	67	707	123	3.20	0.058	<3	0.72	0.09
014	13	1.60	41	24	78	331	171	3.2	0.053	<3	8.2	0.26
017	14	0	85	13	48	538	97	2.4	0.036	<3	0.43	0.14
019	14	0.75	26	7	82	522	125	3.4	0.072	<3	0.79	0.11
020	14	1.50	29	4	81	573	172	4.01	0.070	<3	6.11	0.88
021	15	0	33	14	113	931	153	4.27	0.067	<3	1.79	0.29
022	15	1.50	34	8	105	622	209	4.39	0.091	<3	4.0	0.74
024	16	0	37	14	107	1377	180	4.49	0.081	5	1.97	0.56
025	16	1.50	32	4	88	511	186	4.28	0.080	<3	8.05	0.58
027	17	0	37	12	90	1059	174	4.46	0.084	<3	3.29	0.59
028	17	1.05	28	7	88	358	144	3.40	0.065	<3	17.3	0.41
029	17	AM	29	8	102	1952	134	3.58	0.102	<3	10.0	0.93
030	17	cc	33	30	86	1355	143	4.14	0.083	<3	3.77	1.72
032	18	0	38	12	89	523	163	4.3	0.072	5	3.20	0.57
033	18	1.20	33	9	83	649	188	4.37	0.072	<3	4.8	0.69
036	19	0	35	21	84	394	190	4.08	0.067	<3	6.66	0.58
037	19	1.50	33	9	97	457	179	4.71	0.071	<3	3.65	0.63
039	20	0	34	20	78	287	163	3.46	0.056	4	7.6	0.74
040	20	1.50	24	4	83	333	180	4.93	0.085	4	3.1	0.12
042	21	0	14	3	24	181	66	1.40	0.022	<3	0.57	0.07
043	21	1.20	24	7	58	235	118	2.7	0.066	<3	8.6	0.05
046	22	1.20	30	4	72	526	230	3.42	0.061	4	11.9	0.90
047	22	0	35	21	113	680	176	4.40	0.078	<3	0.77	0.23
049	34	0	24	17	60	457	97	2.91	0.049	<3	1.13	0.14
050	34	1.60	23	7	74	383	120	4.19	0.080	<3	1.33	0.08
052	35	cc	21	25	51	343	118	2.7	0.045	<3	1.77	0.34
053	35	0	20	10	43	307	97	2.4	0.040	<3	0.98	0.14
054	35	1.40	14	7	33	246	66	1.89	0.041	3	0.73	0.01
058	36	M/S	26	57	115	4271	156	4.22	0.072	<3	0.60	0.30
059	36	M/S	31	9	72	673	140	3.47	0.069	10	0.92	0.36
060	37	0	29	25	73	541	159	3.59	0.064	3.5	1.16	0.15
061	37	1.50	42	17	81	732	203	4.06	0.074	3.5	1.07	0.05
062	38	0	26	14	57	488	145	3.02	0.048	<3	1.02	0.16
063	38	1.50	40	28	127	570	240	4.4	0.088	<5	3.1	0.41
066	39	0	30	7	125	593	178	3.97	0.077	<3	1.16	0.19
067	39	1.50	34	4	91	517	228	4.61	0.068	<3	7.42	0.05
068	40	0	32	11	90	679	208	4.11	0.079	<3	1.20	0.20
069	41	0	30	11	82	586	205	4.04	0.068	3.5	1.49	0.32
070	42	0	34	18	91	841	170	4.03	0.073	<3	1.65	0.29
071	43	0	17	10	28	135	76	1.68	0.036	4	7.51	0.02
072	43	2.00	15	10	35	340	110	2.4	0.030	3	0.85	0.03
074	43	0.50	37	10	37	194	118	2.85	0.027	5	0.94	0.01
075	44	0	20	10	46	335	119	2.86	0.033	3	0.63	0:11
076	44	1.50	37	7	60	361	137	3.12	0.039	<3	0.58	0.05
078	44	2.00	23	38	51	240	163	3.00	0.029	5.5	0.55	0.01
079	45	0	29	14	80	597	161	3.82	0.055	<3	0.83	0.21
083	46	0	11	10	24	188	77	1.29	0.017	<3	3.88	0.08
084	46	1.20	10	3	34	151	110	1.87	0.026	<3	23.4	0.03
091	47	0	15	3	28	274	82	1.59	0.022	<3	0.48	0.05
092	47	0.60	43	23	103	362	328	4.52	0.077	3	0.81	0.03
093	47	0.80	15	21	33	285	77	1.73	0.033	5.5	0.58	0.11
094	48	0	8	3	16	85	51	0.79	0.015	<3	15.3	0.06
096	48	1.50	8	7	22	93	66	1.27	0.019	<3	3.6	0.13
099	49	0	31	5	88	362	146	3.43	0.062	5	11.4	1.08
100	49	0.30	27	15	72	358	158	2.81	0.050	8	19.7	1.07
102	49	1.20	33	17	99	507	232	3.91	0.084	<3	10.94	0.82
103	50	0	19	16	51	280	133	2.64	0.043	<3	2.45	0.10
104	50	1.40	12	3	25	165	66	1.27	0.024	<3	13.9	0.03
106	52	0	10	3	24	149	40	1.14	0.022	<3	3.9	0.40
107	52	1.20	16	3	50	320	114	2.35	0.048	3.5	3.83	0.10
109	53	AM	60	18	100	4013	172	4.42	0.104	<3	2.69	1.21
110	53	0	38	20	104	1064	184	4.47	0.082	<3	2.51	0.72
114	54	cc	29	8	81	1458	146	3.82	0.093	<3	3.12	1.46
115	54	0	34	13	107	945	176	4.23	0.080	4	3.5	0.80
116	54	1.50	25	7	91	373	211	3.97	0.079	<3	7.3	0.46
118	55	0	17	5	47	267	133	2.06	0.038	<3	48.1	0.47
122	57	0.17	29	21	82	1083	135	3.52	0.076	<3	0.37	0.14
123	57	0.34	41	20	113	1002	135	3.61	0.081	<3	0.44	0.12
124	57	0.51	58	22	95	1307	153	4.0	0.096	3	0.36	0.17
125	57	0.68	33	18	106	1206	154	3.8	0.087	<3	0.38	0.18
126	57	0.85	32	21	75	696	138	3.4	0.080	<3	0.47	0.30
127	57	1.02	33	17	78	1356	136	3.42	0.074	3	0.55	0.04
128	57	1.19	26	10	74	661	119	3.14	0.066	4	0.39	0.04
129	57	1.36	33	17	89	974	153	4.05	0.082	<3	0.46	0.05
130	57	1.53	33	18	102	1181	174	4.22	0.082	<3	0.67	0.15
131	57	1.70	35	14	87	1697	181	4.16	0.096	<3	1.31	0.20
132	57	1.87	51	22	77	870	870	3.82	0.076	<3	8.1	0.24
133	57	2.04	30	7	72	405	405	4.11	0.077	5	13.6	0.33
134	57	2.21	29	19	89	661	661	3.7	0.073	<3	3.5	0.87
135	57	2.38	42	10	91	495	495	3.40	0.063	4.5	5.5	0.47
136	57	2.55	27	3	66	500	500	3.06	0.060	<3	12.1	0.20
137	57	2.72	24	7	75	418	418	3.4	0.057	3.5	7.86	0.23
138	57	2.89	20	10	70	497	497	3.33	0.060	3.5	2.65	0.21
139	57	3.06	28	18	97	571	196	4.3	0.065	<3	10.8	0.16
140	57	3.23	19	7	65	565	138	2.82	0.055	3	16.8	0.11
141	57	3.40	25	18	96	562	180	3.77	0.060	<3	8.03	0.16
142	57	3.57	25	18	81	758	170	3.5	0.059	<3	6.39	0.10
143	57	3.74	21	18	71	683	151	3.55	0.050	3.5	12.1	0.10
144	57	3.91	22	10	142	772	153	3.81	0.058	3.5	8.91	0.09
145	57	4.08	21	10	76	558	157	3.8	0.062	<3	7.9	0.15
146	57	4.25	19	10	65	449	140	3.03	0.045	5.5	21.1	0.10
147	58	0	18	7	51	350	90	2.54	0.040	<3	1.50	0.16
148	58	1.70	20	3	52	405	127	2.43	0.046	<3	25.6	0.54
149	52	1.00	9	3	29	223	100	1.80	0.037	<3	10.65	0.10

M/S—Mound Spring, AM — Algal mat, cc—Carbonate clay

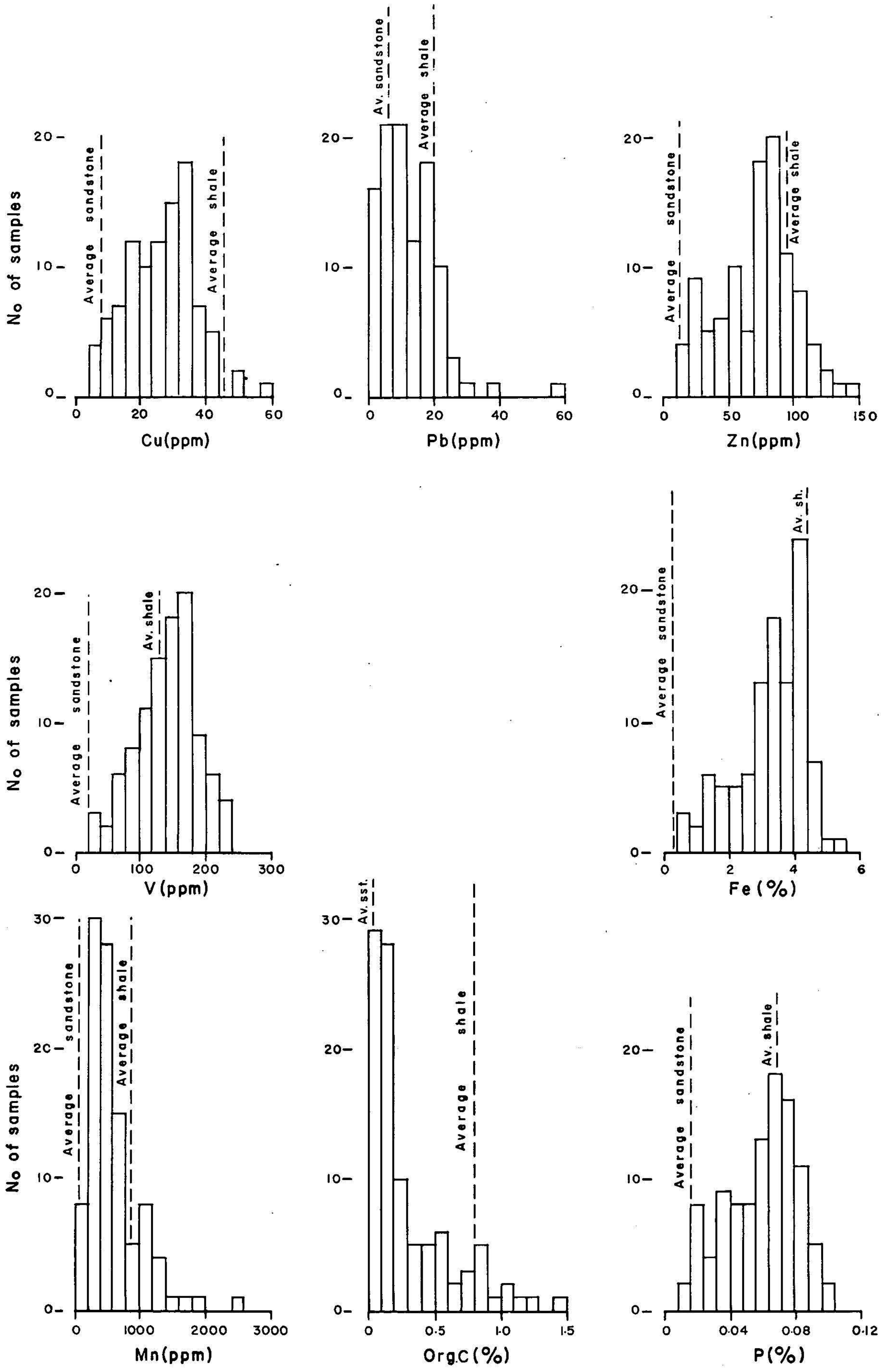

Figure 12. Histograms of minor elements, clastic sediments (average values from Turekian & Wedepohl).

TABLE 8. CORRELATION MATRIX AND STUDENT T TEST, MINOR ELEMENT ANALYSES, CLASTIC SEDIMENTS

Correlation Matrix

	Cu	Pb	Zn	Mn	V	Fe	P	SO_4	Org C
Cu	1.00								
Pb	.45	1.00							
Zn	.60	.42	1.00						
Mn	.51	.42	.66	1.00					
V	.58	.41	.77	.42	1.00				
Fe	.62	.39	.87	.61	.83	1.00			
P	.58	.35	.87	.73	.74	.88	1.00		
SO_4	−.27	−.33	−.17	−.30	−.03	−.25	−.22	1.00	
Org C	.30	.05	.40	.14	.41	.38	.36	.18	1.00

No. of samples = 94
$p = o$

Student t Test

	Cu	Pb	Zn	Mn	V	Fe	P	SO_4	Org C
Cu	0.00								
Pb	4.87	0.00							
Zn	7.18	4.42	0.00						
Mn	5.75	4.41	8.48	0.00					
V	6.89	4.32	11.49	4.42	0.00				
Fe	7.51	4.05	17.28	7.35	14.15	0.00			
P	6.86	3.60	16.55	10.29	10.60	17.84	0.00		
SO_4	−2.67	−3.40	−1.65	−3.01	−.31	−2.48	−2.12	0.00	
Org C	3.03	.48	4.25	1.38	4.34	3.93	3.72	1.80	0.00

Degrees of Freedom = 92

results adjusted for sodium chloride content. A correlation matrix for minor elements was prepared and is given in Table 8. No transforms were used in constructing this correlation matrix.

Major elements

Samples of clastic sediments analysed contained sodium chloride and gypsum. In all samples analysed the gypsum is of diagenetic origin with the exception of sample 084 in which it is mostly detrital. Silica and alumina are volumetrically important. The SiO_2/Al_2O_3 ratios reflect the grain size and mineralogy of the sediments. The sandy quartz-rich sediments (017, 072) have high ratios (8), the sandy gypsum sand (084) has a ratio of 6, and clayey sediments (remaining samples) have ratios of less than 3.5. Less important elements include iron, calcium (important in 084 and 038), magnesium, potassium and carbon as carbonate. The calcium and magnesium are present as carbonate, both detrital and diagenetic. The high calcium value in sample 73010138 can be related to the large detrital carbonate content. Non-carbonate magnesium and potassium are probably associated with clay minerals and mica. Iron is discussed under minor elements.

Minor elements

Copper values range from 8 to 85 ppm Cu, with a mean of 27.8 ppm; lead values range from 3 to 25 ppm Pb with a mean of 12.3 ppm; and zinc values range from 16 to 142 ppm Zn with a mean of 73.1 ppm. Histograms of these elements are shown in Fig. 12. The majority of values range between those for shale and average sandstone values.

The triangular plot of copper-lead-zinc (Fig. 13) shows the generally consistent proportions of these elements. This indicates that there is no major preferential concentration of one element in favour of another.

Minor differences do exist in the behaviour of these elements with respect to one another. The surface distribution patterns (Fig. 14) are similar, but whereas a similar pattern is found in subsurface for copper and zinc

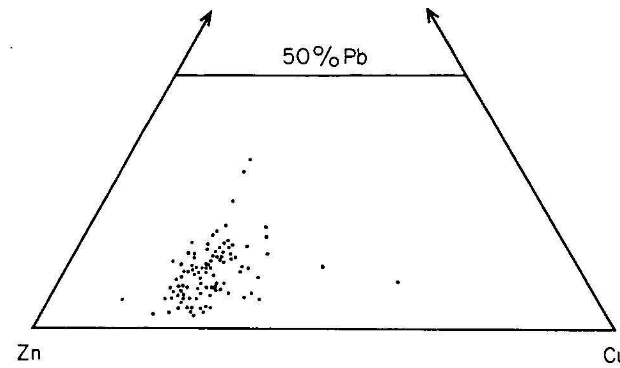

Figure 13. Pb-Zn-Cu triad in the clastic sediments (values summed to 100).

the pattern for lead is different. This difference is apparent in the correlation coefficients between these elements. For Cu/Zn the value is 0.60 but for Pb/Cu and Pb/Zn the values are 0.45 and 0.42 respectively. Lead appears to be relatively depleted in the subsurface, suggesting preferential desorption of lead by the chloride-rich subsurface brines.

Correlation coefficients were also determined between minor elements in the sediments, and the ions in the brines in contact with sediments. Nineteen subsurface brine samples were used along with the deepest sediment from the corresponding locality. The T.D.S. value was used as an evaporation factor, correlation being listed at the 95 percent level. Lead proved to be the only element in the sediments showing a significant correlation, negatively, with T.D.S. This supports the above suggestion that lead is being leached from the sediments by the brines in the form of highly soluble chloride complexes.

Values of manganese range from 85 to 1697 ppm with a mean of 552 ppm. Anomalous values of 1952 and 4013 ppm Mn were obtained in algal mat material from the surface of the lake. Manganese can be concentrated by bacterial activity (Trudinger, 1971) and algal decay may favour the presence of suitable bacteria. Manganese does not show a significant correlation with organic carbon. This is surprising in view of an apparent association with algae, and suggests that most of the organic matter is not an algal decay product but is transported matter.

Analyses for two algal mat samples, and the means and standard deviations for all clastic samples are shown below in Table 9.

TABLE 9: ALGAL MAT GEOCHEMISTRY

Element	Sample 1	Sample 2	Mean for all clastic sediments	St. dev. for all clastic sediments
Cu (ppm)	29	60	27.8	± 11.3
Zn (ppm)	102	100	73.1	± 28.0
Mn (ppm)	1952	4013	552	± 319
Fe (%)	3.58	4.42	3.34	± 0.99
Org C (%)	0.93	1.21	0.29	± 0.29

Of the elements in the table, all show values above the mean, but only manganese, zinc and organic carbon vary by more than one standard deviation. Manganese and organic carbon show the most significant enrichment relative to values in the clastic sediments. The higher organic carbon is only to be expected in algal-rich sediment.

Concentration by algae may have occurred in Lake Frome but the volume of algal material present is not sufficient to allow the volumetrically large concentrations of elements.

Values for vanadium range from 55 to 274 ppm V with a mean of 150 ppm. The areal distribution pattern (Fig. 15) shows a definite concentration towards the north of the lake, suggesting that the Mount Painter Block is the major contributor of vanadium to the sediment. Vanadium shows a highly significant correlation with organic carbon, an association that is well documented from elsewhere (Manskaya & Drozdova, 1968).

Values in iron range from 0.79 to 4.93 percent Fe with a mean value of 3.34 percent. The areal distribution pattern (Fig. 15) shows a concentration towards the north. A highly significant positive correlation exists between iron and organic carbon. This correlation probably relates to precipitation of pyrite under reducing conditions, there being an obvious association between organic carbon and such conditions.

Values of phosphorus range from 0.015 to 0.096 percent P with a mean value of 0.060 percent. The distribution pattern (Fig. 15) is similar at the surface and in the subsurface. Ronov & Korzina (1960) suggest that in arid zone sediments there is correlation between phosphorus and organic carbon, whilst in humid zone sediments there is correlation between phosphorus and iron. For Lake Frome sediments a significant correlation (0.36) exists between phosphorus and organic carbon but a more significant correlation (0.88) exists between phosphorus and iron. Ronov & Korzina assumed that the oxidized nature of iron in arid areas prevented a correlation. The presence of pyrite in Lake Frome shows that oxidizing conditions do not exist below the surface despite the arid climate.

Although the values of 0.01 to 1.19 percent C, mean 0.24, are low, organic carbon (Fig. 15) appears to have some role in the distribution of elements in the sediments. Highly significant correlations exist between organic carbon and zinc, vanadium, iron and phosphorus; a significant correlation exists with copper. Zinc, vanadium and copper are known to be concentrated by organic matter (Manskaya and Drozdova, 1968).

Concentrations of sulphate represent the diagenetic evaporative part of the sediment and any strong positive correlations between sulphate and another element could reflect some precipitation of that element by evaporative processes. There are some significant correlations, but in all cases the correlation is negative. Probably this is a result of increasing amounts of gypsum lowering the relative amount of that element in the sample.

The correlation matrix (Table 8) shows significant intercorrelation between Fe, P, Zn, Cu, Pb, Mn, V and organic carbon. This high degree of intercorrelation suggests that the manner of deposition of all these elements is similar, and that post-depositional changes were minimal. It follows that the distribution of the elements is controlled directly by the distribution of clastic sediments and that no major concentrations or depletions of any element have occurred. The relationship between these elements is, however, complex. It seems likely that co-precipitation of certain of them with iron and manganese hydroxides, adsorption by clays and organic matter, pyrite precipitation and substitution in various minerals, have all played a part in the present distribution.

In addition to the determination of the correlation matrix of elements in the sediments as a whole, correlation matrices were determined for the distribution of the elements within each unit and then compared. Differing degrees of freedom are involved, but it is possible to compare the correlation at roughly equivalent levels of significance. A P-Fe-Zn-V-Mn interrelationship was obtained into which Cu and Pb correlates at different levels and order for each unit.

Consideration of arithmetic means (Table 10) shows that Unit B contains significantly more organic carbon than either Unit A or C, and that the range is less in the muds than the sands. Relative to Unit C, Unit B is enriched in V, Fe and to a lesser extent Zn and P. Units A and C appear similar.

A multivariate comparison using means and discriminant analysis, was also made. Multivariate analysis takes into account the joint distribution of the elements. The results of the discriminant analyses are summarized in Table 11. Units A and C appear similar. Unit B is enriched in V, organic carbon, and Zn relative to Unit A. Relative enrichment of Zn, organic carbon, Fe and V help distinguish Unit B from Unit C which is relative enriched in Pb.

The similarity between the upper and lower sands is shown on a triangular Q-mode plot (Fig. 16), prepared after a factor analysis had been carried out on all minor element values from the clastic sediments. Unit B is strongly affected by factor 2 which relates mainly to the distribution of organic carbon. Factor 1 relates mainly to Fe-P-Zn, factor 3 to the distribution of lead.

TABLE 10: ARITHMETIC MEANS AND STANDARD DEVIATIONS OF MINOR ELEMENTS IN CLASTIC SEDIMENTS

	Upper sands		*Lower sands*		*Muds*	
	Mean	*Std. Dev.*	*Mean*	*Std. Dev.*	*Mean*	*Std. Dev.*
Cu (ppm)	25.8	± 14.4	28.4	± 10.3	28.6	± 7.0
Pb (ppm)	12.2	± 6.4	14.0	± 8.7	10.9	± 5.9
Zn (ppm)	63.4	± 32.7	70.4	± 25.9	83.4	± 18.2
Mn (ppm)	537.4	± 359.5	634.4	± 407.9	529.9	± 199.7
V (ppm)	124.5	± 45.3	147.2	± 51.1	170.9	± 28.9
Fe (%)	2.94	± 1.13	3.33	± 0.93	3.58	± 0.70
P (%)	0.052	± 0.023	0.065	± 0.024	0.064	± 0.013
Org C (%)	0.16	± 0.11	0.20	± 0.25	0.44	± 0.31

TABLE 11: RESULTS OF DISCRIMINANT FUNCTION ANALYSIS

Unit A —	*Unit C —*
F(8.45) = 1.31875	NOT SIGNIFICANT (AT 95% CONFIDENCE LEVEL)
Unit A —	*Unit B*
F(8.58) = 6.68748	SIGNIFICANT (AT 95% CONFIDENCE LEVEL)
Elements contributing most to difference: V, Org, C, Zn (enriched in Unit B).	
Unit C —	*Unit B —*
F(8.46) = 5.03392	SIGNIFICANT (AT 95% CONFIDENCE LEVEL)
Elements contributing most to difference: Zn, Org C, Fe, V (enriched in Unit B) : Pb (enriched in Unit C).	

Discussion

Stratigraphic framework

It is clear from the distribution of recent sediment on the lake surface that sand and muddy sand is deposited in delta fans on the western, southern and northern margins of the lake, and that progressively finer sediment is deposited away from the fans towards the centre of the lake.

From stratigraphic evidence, this pattern of deposition has existed for at least 17,000 years. Units A and C represent deposits of delta fans on the western shore of the lake, and Unit B is the result of the coeval accumulation of lacustrine muds. The progradation of the muds of Unit B over the sands of Unit C indicates a westerly movement of the shoreline and a probable rise in lake levels from about 17 000 years BP to 13 000-14 000 years BP. Since that time there has been an overall fall in lake levels, presumably in response to increasing aridity, and the progradation of the delta fan facies eastwards.

The history of the lowering of lake levels is further complicated by a tilting of the lake floor to the south over the last 4000 years. At the present time the lowest areas on the lake floor are adjacent to the islands, in the southern part of the lake; but the islands, because they were

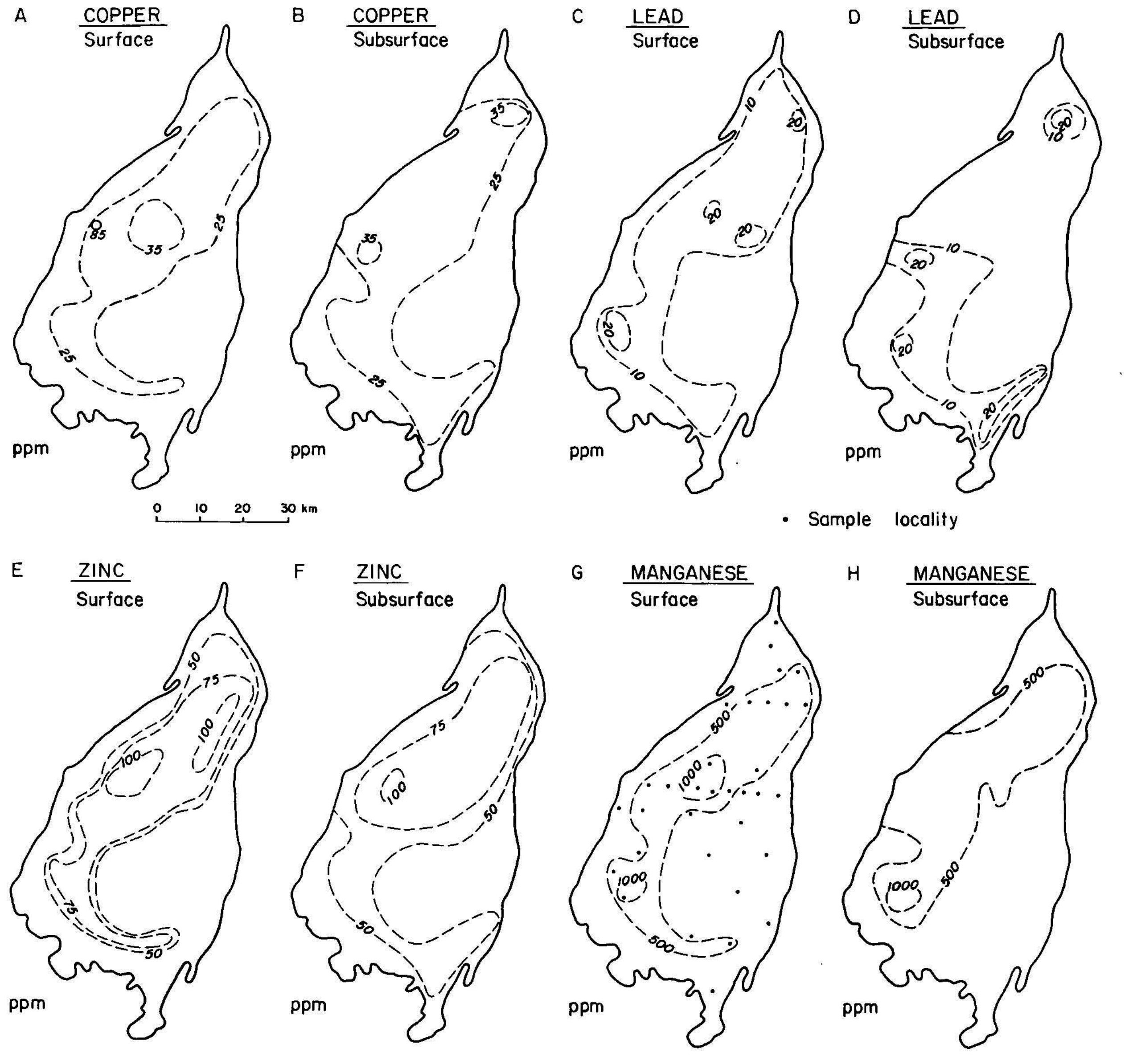

Figure 14. Element distribution—clastic sediments.

originally dunes, must have formed on relatively high ground. Furthermore, the thickest salt crust, which one would expect in the deepest part of the lake, lies well north of the islands in a relatively higher position. Thus, features formed in high areas are now found in the deep areas, and those formed in the deeper parts are now in shallower areas. At least some of this tilting must have taken place over the last 4000 years, which is the minimum age of the salt crust. A sample of carbonaceous material from mud a few centimetres below the crust (location 49) was dated at 4180 ± 590 years BP.

Origin of the salt crust and brines

The origin of the salt crust and the brines of Lake Frome remains an unsolved problem. The salts within brines of internal drainage basins can be derived from: (a) seawater, either through atmospheric circulation (cyclic salts) or release of water trapped in marine sediments at the time of deposition (connate water); (b) groundwater derived from outside the basin; (c) the weathering of rocks or sediments within the drainage basin; or (d) combinations of the various sources.

Cyclic salts were considered to be the major source of ions in the waters of Lake Eyre by Johns & Ludbrook (1963), and of Lake Torrens and Gairdner (Johns, 1968). This conclusion was based on the fact that although the geology of the drainage area varies from lake to lake, there is a degree of similarity of the various brine compositions. Support for this view comes from earlier finding by Dickinson (1942), who found that although rocks cropping out in the Lake Gairdner area are potassium-rich, the brines are no richer in potassium than those from potassium-poor areas. On the other hand, Wopfner & Twidale (1967), and Williams (1972) consider that the salts in these lakes have been derived by erosion of outcropping rocks such as those of the marine Cretaceous.

The general role of cyclic salts has been discussed by a number of authors such as Langbein (1961), and Gorham (1961). One of the most useful aspects studied however, has been the Cl/Br ratio, which is relatively constant in seawater and which it would be expected should be about the same value in cyclic salts. This is confirmed by Duce *et al.* (1963), who found that the Cl/Br ratio in aerosols and rainfall around Hawaii is similar to that of seawater. In the case of the brines of Lake Frome bromide is deficient relative to

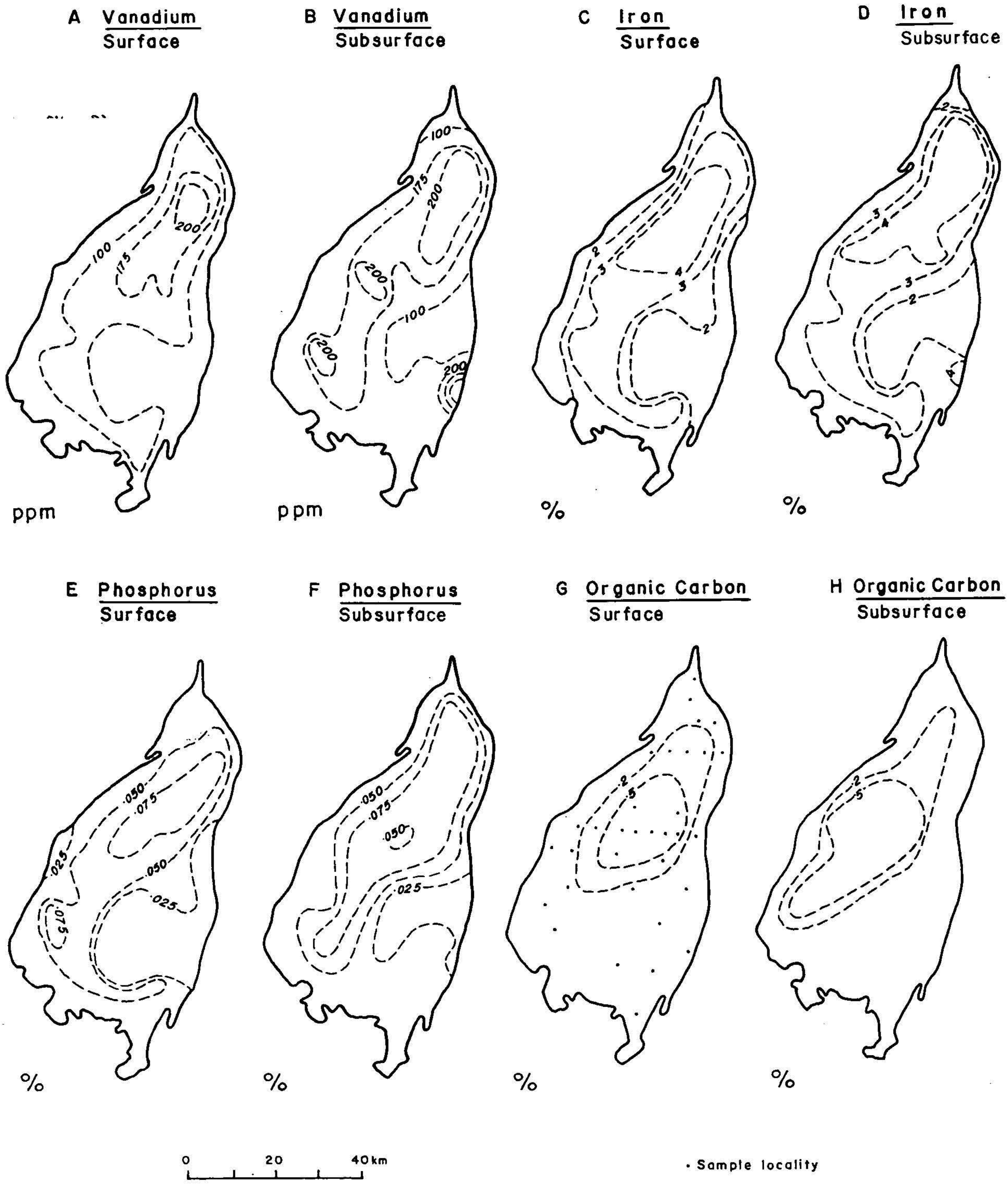

Figure 15. Element distribution—clastic sediments.

chloride when compared with seawater, and it is therefore considered unlikely that cyclic salts have been a major source of ions. The same is true of the Cl/Br ratios of Lakes Eyre, Torrens and Gairdner (Johns & Ludbrook, 1963; Johns, 1968), but this suggests a common source for the salts. Thus cyclic salts could play some role in the composition of the brines.

It is considered unlikely that the Lake Frome brines were largely derived from connate waters. The Cl/Br ratio of connate waters would be expected to be similar to that of seawater (292), but Holser (1970) has found that the ratio in connate waters is often 200, the enrichment in bromide being attributed to the action of organic matter in adsorbing and then releasing it. As stated previously, the Lake Frome brines are deficient in bromide. The Cl/Br ratios in Lake Frome are however, similar in value to those of second cycle marine brines (Holser, 1966) which are higher than those of primary brines such as connate water.

Groundwater from the Great Artesian Basin enters the lake via the mound springs. At present the amount of water contributed by the springs is insignificant. However, this water may have been more important in the past. There has been a reduction in flow of 25-50 percent observed in artesian bores to the east of the Lake Frome during the past 30 to 40 years (Callen, 1974). In addition, tilting which has occurred in the area would have modified the artesian flow.

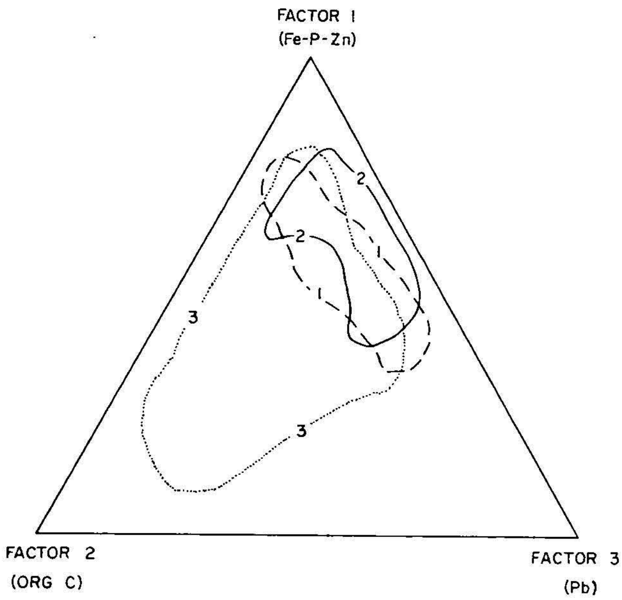

Figure 16. Q mode plot for clastic sediment minor elements (contours enclose densest concentrations of values).

Concentration of the mound-spring waters however, would not produce a brine similar to the subsurface brines. Major ions could be concentrated and precipitated to give a similar brine, but the fact that boron, a late stage precipitate, would attain a value ten times that in the subsurface brine tends to rule out such a situation. Fluoride, lithium and strontium values would also be excessively high. It is therefore highly unlikely that the mound spring waters and the brines have a common origin.

Bicarbonate-rich waters have been reported by Ker (1966) in Great Artesian Basin aquifers within the Frome Embayment. It is considered that the mound spring waters are a mixture of these bicarbonate-rich waters and saline brines. From Table 12 it can be seen that a mixture of 90 percent artesian water and 10 percent brine, and a mixture of 95 percent artesian water and 5 percent brine will give waters similar in chemical character to those actually determined for the northern and southern springs respectively. Such a model is feasible, as the artesian water must travel under pressure through the brine before reaching the surface. Fluoride values in the artesian water tend to be high (2 ppm) and this would explain the fluoride values obtained from the mound springs. It is felt that the model offers a feasible explanation for the chemical composition of the mound spring waters and the differences between the north and south, but the lack of minor element analyses prevents further testing of it.

The percentages given above assume an even mixing, with no precipitation or solution during or subsequent to mixing—a situation which does not occur. Nevertheless, it is felt that the assumptions made are approximate to the actual situation.

It seems clear then that the salts in the lake have not been mainly derived from groundwaters originating outside the basin, so one has to consider the possibility of groundwater and surface water within the local closed-basin.

In their study of evolution of closed-basin brines, Hardie and Eugster (1970) pointed out that the composition of such brines is determined by weathering reactions. Weathering, and therefore the products of weathering, are of course dependent on parent material, climate, relief, and time. With regard to parent material in the case of Lake Frome, because of the high Cl/Br ratio, it appears likely that the rocks contained some evaporites or marine sediments with

TABLE 12: MOUND SPRING ANALYSES COMPARED TO ARTESIAN WATER WITH BRINE ADMIXTURE.

Average artesian water analysis is calculated with (a) nearest brine sampled, (b) average Lake Frome brine.

	Na	*Ca*	*Mg*	*K*	*Cl*	SO_4	HCO_3	HCO_3/SO_4	*Salinity*
Northern mound spring									
Spring water	11800	175	151	52	17351	1471	275	0.187	32270
90/10 artesian-brine									
(a) nearest	12020	56	86	20	16835	1565	578	0.370	31160
(b) average	12466	65	110	38	17982	1432	583	0.407	32676
Southern mound spring									
Spring water	5750	83	123	34	8208	829	1017	1.227	15600
(a) nearest	6691	65	36	8	9469	397	629	1.584	17295
(b) average	6634	38	60	19	9254	719	609	1.328	17333

an above average content of saline material. There are, however, no known evaporite deposits in the area. Wopfner & Twidale (1967) have suggested marine rocks of Cretaceous age as possible source rocks but the hydrological setting of Lake Frome suggests that the brines sampled have moved mainly through Tertiary-Quaternary aquifers. Another possible source is the evaporitic rocks outcropping in the Flinders Ranges. The Lower and Upper Callana Beds and the Burra Group of Willouran-Torrensian age contain halite casts and mudcracks (Coats *et al.*, 1973). Webb (1961) found anomalously high contents of sodium chloride, calcium sulphate, magnesium chloride and magnesium sulphate in the Callana Beds in areas of diapirism. These rocks crop out on the eastern side of the Mount Painter Block overlooking the Lake Frome Plain. These same units crop out in the vicinity of Lakes Torrens and Eyre and are also present in the subsurface in these areas.

The source of the salts in Lake Frome is therefore considered to have been a combination of the sources discussed above, with weathering of saline rocks, deposition of cyclic salts and weathering of normal rocks the most important, in that order, and connate waters and artesian water of less importance.

Distribution of minor elements

The spatial distribution of the minor elements is predominantly a function of sediment type, but is modified by a number of factors. This gross relationship with lithology is indicated by the high degree of intercorrelation between the various elements, which indicates that the manner of deposition of all these elements is similar and that post-depositional changes have been minimal. On the spatial distribution maps (Figs. 4, 5), it can be seen that values generally increase towards the central areas of the lake and since there is no apparent correlation of the elements with evaporation this must indicate some enrichment in the finer sediments. Factor analyses show that the muds of Unit B are characterized by higher organic carbon values. The relationship between organic carbon and fine-grained sediments is well established. All elements except manganese show significant correlation with organic carbon. Enrichment of organic carbon, iron, zinc and vanadium in the muddy sediments is indicated by the results of the discriminant analysis. It is clear therefore that lithology and associated organic carbon exert considerable influence on the spatial distribution of the elements.

In detail, the distribution of the elements is modified by various factors. Leaching of lead and enrichment of manganese have already been discussed. The direct influence of provenance is shown by the occurrence of higher vanadium values in the northern areas of the lake, where the Mount Painter Block would contribute to the sediment. The distribution of the elements is also affected by the complex inter-element relationship brought about by the differing modes of formation and occurrence of the elements, which have already been discussed.

Lithology also controls the distribution of the major elements. This is shown by the variations in the SiO_2/Al_2O_3 ratio from 8 in quartzose sands to less than 3.5 in the muds.

Conclusions

Sands and muds have been accumulating in Lake Frome for at least the last 17 000 years. Sands on all but the eastern margin were deposited in delta fans at the mouths of large streams. The muds interfinger with the sands and represent the distal portion of the fans. There is stratigraphic evidence of a rise in lake level from about 17 000 to 13-14 000 years B.P. Since that time there has been an overall fall of lake level.

The spatial distribution of minor elements in the sediments of the lake is strongly influenced by the distribution of sediment type and organic carbon; this pattern is modified by provenance, physico-chemical factors, and biological activity.

There is no anomalous concentration of copper, lead or zinc, or of uranium in the sediments of Lake Frome. Lead appears to be relatively depleted with depth, suggesting preferential desorption by chloride-rich subsurface brines. Manganese is concentrated in algal mats on the surface of the lake.

Sodium and chloride are the principal components of the lake brines and consequently of the salt crust. The origin of the salts of the lake is uncertain, but it appears likely that a major source has been the weathering of rocks containing marine evaporites.

The water in the mound springs is a mixture of bicarbonate-rich artesian water with minor lacustrine brine.

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Gravity evidence for a major crustal fracture in eastern Antarctica

P. Wellman and R. J. Tingey

Gravity data are presented for 220 sites covering 180 000 square kilometres in the Prince Charles Mountains area of eastern Antartica. Bouguer anomalies range from +60 m Gal over the Amery Ice Shelf (near sea level) to −120 m Gal at altitudes above 2000 m on the Antarctic ice cap. Bouguer anomalies correlate with the mass per unit area above sea level in the relation expected for a region in isostatic equilibrium.

Smoothed free air anomalies range from +60 to −60 mGal. North-south trending anomalies over the Lambert Glacier and Amery Ice Shelf are thought to be due to a major fault along the Lambert Glacier, and a rift structure under the Amery Ice Shelf. To the west of these structures the free air anomalies trend mainly east-west.

Previous gravity observations on the Antarctic continent have been made mainly along glaciological traverses and on the coastal strip (Grushinsky *et al.*, 1972). There is extensive areal coverage only in the Transantarctic Mountains and the Antarctic Peninsula. This paper interprets a regional coverage of gravity observations in the Prince Charles Mountains of eastern Antarctica.

The Prince Charles Mountains (Fig. 1) fringe the Amery Ice Shelf and Lambert Glacier system and extend 600 km inland from the Antarctic coast (Fig. 2); the area is one of the few where the geology of the eastern Antarctic Shield can be investigated inland. Early geological mapping in the area is summarized by Tingey (1974). Following field work between 1969 and 1974 the Bureau of Mineral Resources has issued thirteen 1:250 000 scale preliminary edition geological maps of the mountains and a Bureau of Mineral Resources Bulletin describing the geology is in preparation. This paper interprets the results of gravity surveys carried out in conjunction with the geological mapping; outcrop areas on the east side of the Amery Ice Shelf are included for this purpose.

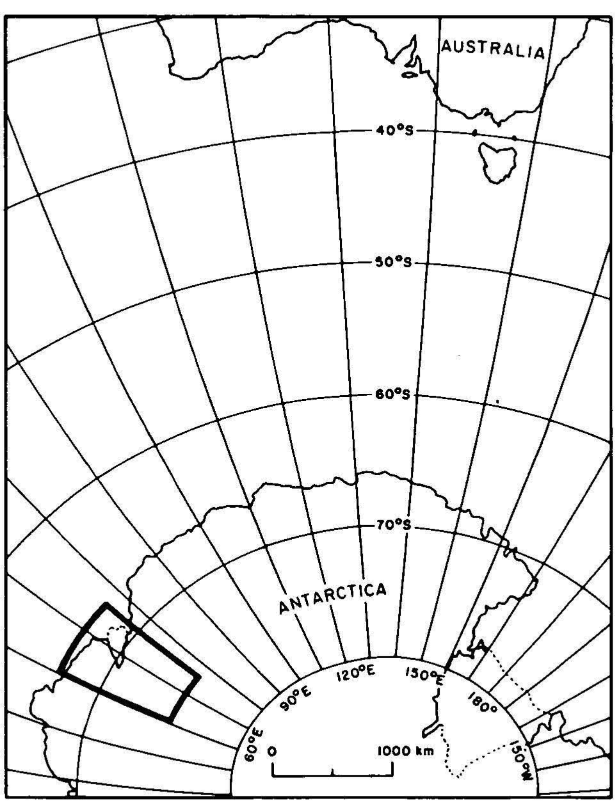

Figure 1. Locality map.

The area is underlain by a basement complex of granulite or amphibolite facies metamorphic rocks, mostly of middle to late Proterozoic age. Locally they have been retrogressively metamorphosed to lower amphibolite or greenschist facies grade. Archaean rocks are confined to the southern Prince Charles Mountains and comprise granitic basement, lower amphibolite facies metasediments, and possibly the banded ironstone formations at Mount Ruker (A; letters in brackets refer to Fig. 2). Metamorphosed basic dykes that intersect these older rock units are common in this part of the area but are not seen elsewhere. An elongate northwest-trending belt of late Proterozoic lower amphibolite facies or greenschist facies metasediments in the southern Prince Charles Mountains postdates the basic dykes and was affected by a major late Precambrian folding episode.

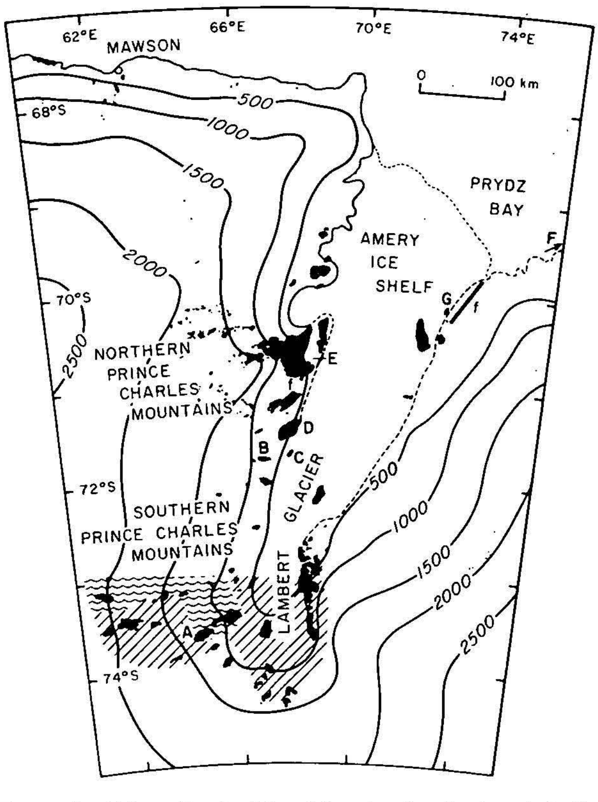

Figure 2. Prince Charles Mountains showing the trough in the ice surface (contours in metres). Outcrops are shown in black. Rocks are granulite or upper amphibolite metamorphic facies except for the area of greenschist facies (wave pattern), lower and middle amphibolite facies (diagonal shading), and an area of unmetamorphosed rocks at E. Lettered features are named in the text. The two middle to late Phanerozoic faults are marked 'f'.

The metamorphic complex is intruded by Cambro-Ordovician granites and pegmatites, and is unconformably overlain at Beaver Lake by unmetamorphosed coal-bearing Permian sediments. The Beaver Lake sediments were originally deposited against a fault scarp, and have subsequently been faulted, broadly folded, and intruded by minor alnoite sills of Cretaceous age. An Eocene olivine leucitite flow occurs nearby. Moraine boulders suggest that Permian sediments occur beneath the major glaciers in the Southern Prince Charles Mountains.

The Prince Charles Mountains are exposed because the Lambert Glacier—Amery Ice Shelf ice drainage system has formed a trough in the continental ice cap of eastern Antarctica (Fig. 2). In this trough ice surface elevations of less than 200 m are found 500 km inland, but around it the ice cap rises to more than 2000 m above sea level. The Lambert Glacier-Amery Ice Shelf system is believed to drain at least 12 percent of the Antarctic continental ice sheet. Along the trough Soviet workers have inferred a major linear structure cutting the Antarctic Continent (Grikurov, Ravich & Soloviev, 1972). In this paper we deduce information on the geological structure of the Prince Charles Mountains and adjacent areas from the gravity anomaly patterns, and attempt to relate these patterns to the geology of the area as revealed by field mapping.

Preparation of gravity maps

This paper is based almost entirely on land gravity observations made by Australian Antarctic expeditions (see Fig. 3). Between 1955 and 1963 eleven coastal stations were observed using ship transport (Langron, 1966), and gravity values and ice thicknesses were observed at 39 stations on the ice surface south of Mawson (Fowler, 1971). Between 1969 and 1974 about 170 gravity stations were observed during combined geological, glaciological and topographic surveys in the Prince Charles Mountains and in the coastal area near Mawson (Cooke, 1970, 1975; unpublished). The only other gravity data known from the area are early Soviet marine observations at a few places over the continental shelf in 1956-1959 (Grushinsky *et al.*, 1972) and a Soviet survey of the Amery Ice Shelf and Lambert Glacier made between 1971-1974—these latter data are not yet available.

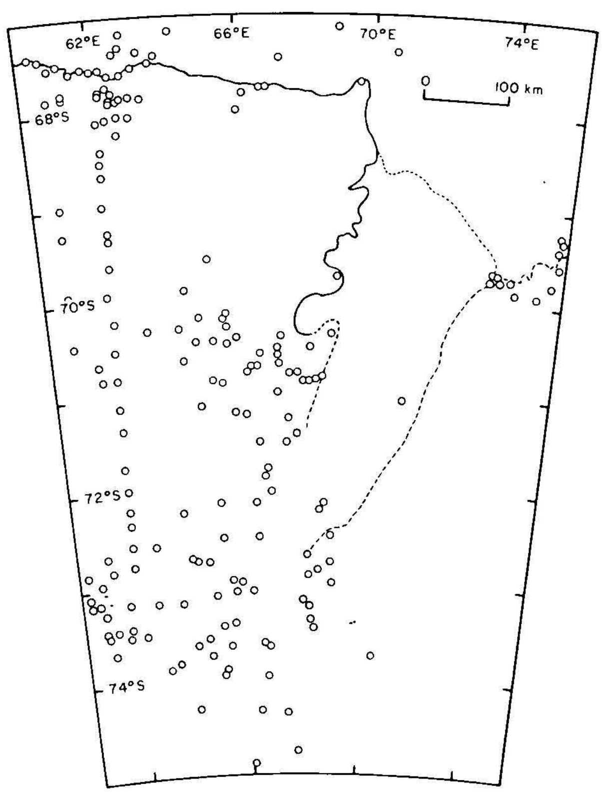

Figure 3. Gravity station distribution.

The observed gravity values have been calculated on the Potsdam system using the Mawson pendulum station gravity value of 982 481.8 mGal (Woollard & Rose, 1963). Bouguer anomalies have been calculated from conventional free air anomalies using standard densities of 2.67 t m^{-3} for rock, and 0.917 t m^{-3} for ice. Stations on rock have been corrected for the attraction of an infinite plate of rock between sea level and the station, and roughly for terrain effects above the ice surface. Stations on ice have been corrected for the attraction of the underlying ice and rock above sea level, and corrected for the difference in attraction between ice and rock for any ice below sea level. A rough terrain correction for the ice/rock interface has also been made. The resulting Bouguer anomalies (Fig. 4) are equivalent to Bouguer anomalies over areas of land.

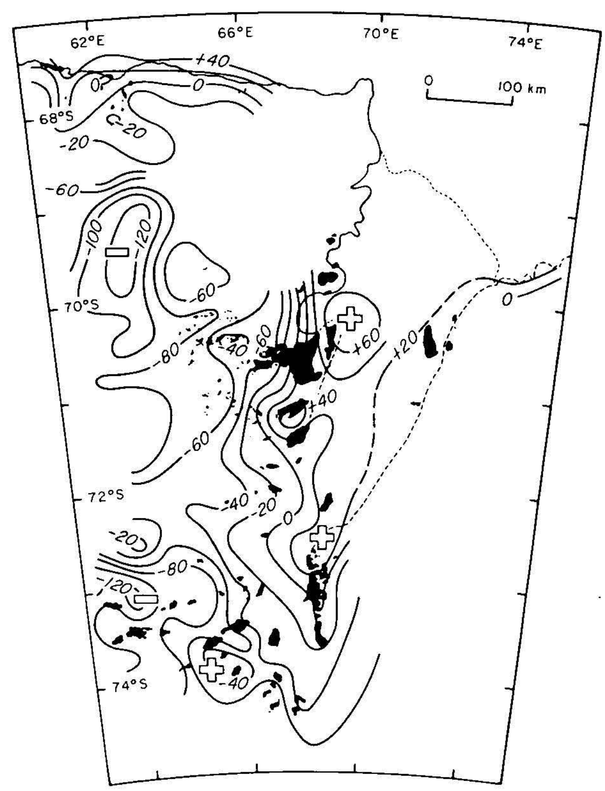

Figure 4. Bouguer anomaly map. Contour interval 20 mGal.

The Bouguer anomaly accuracy is better than ± 5 mGal near the coast, about ± 8 mGal on glaciological traverses (Fowler, 1971), between ±2 and ±20 mGal at trigonometric stations depending on the terrain correction, about ±10 mGal at the 1972-74 glaciology stations on ice, and ±10 mGal for stations on rock where the altitudes were determined from trisection or barometric levelling. The larger errors are due to uncertainties in the estimates of altitude, terrain corrections or ice thickness.

Bouguer anomalies

If the crust is in isostatic equilibrium the mass per unit area of the crustal load above sea level should be equal to the deficiency in mass per unit area of the compensating crustal root. The mean load above sea level has been estimated for 100 km sq. areas using altitudes of the ice and rock surfaces (Morgan & Budd, 1975). The mean load is expressed as the gravity attraction of this load, i.e. the Bouguer correction of 0.1118 mGal per metre of rock or 0.0384 mGal per metre of ice. The deficiency of mass of the compensating root is reflected in the Bouguer anomalies at individual gravity stations. If the crust is in isostatic equilibrium the Bouguer anomaly (BA) will on average be about 75 percent of the Bouguer correction (BC) (Woollard, 1970) because of earth curvature and because the gravity observation points are closer to the crustal load than to the compensating root. The expected relation is therefore BA =0.75BC + k, where k is the Bouguer anomaly at sea level.

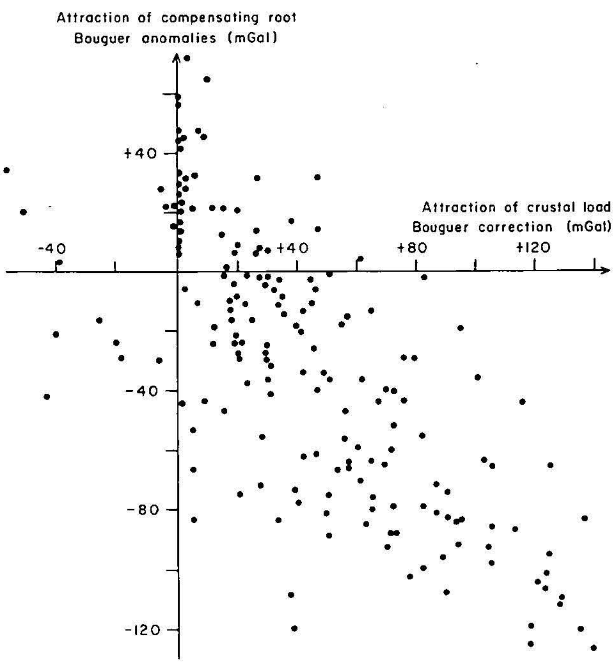

Figure 5. Relation between attraction of crustal load (Bouguer correction), and attraction of the compensating root (Bouguer anomaly).

Fig. 5 shows the relation between Bouguer anomaly and Bouguer correction in the area. The least squares relation is BA = −(0.84 ± .05)BC + (6 ± 2) mGal, the mean deviation from the regression line being 32 mGal. The observed relation between crustal load and compensating root therefore agrees, to within experimental error, with the expected relation for isostatic equilibrium; and so both the mountain ranges of the Prince Charles Mountains and the continental ice cap must be largely compensated isostatically by crustal roots. Variations in the rock and ice load in the area are equivalent to a 2 km thickness of rock. This is equivalent to variations of between 10 km and 15 km in the depth from sea level to the base of the crust; assuming the density increase at the base of the crust is between 0.55 t m^{-3} (Sazhina & Grushinsky, 1971) and 0.4 t m^{-3} (Woollard, 1970).

Free air anomalies

To obtain a correlation between gravity anomalies and geology it is desirable that the gravity anomalies are calculated in a form that mainly reflects horizontal density variations in the crust, and is largely independent of the crustal load and compensating root. In this study modified free air anomalies were used. These were calculated at each station by adding to the observed Bouguer anomalies the mean Bouguer correction for the surrounding one degree area. This technique supresses the short wavelength topographic effects.

The free air anomaly map (Fig. 6) shows anomalies ranging from +60 to−60 mGal in amplitude, and 50 to 200 km in wavelength. It is thought that the steep gradients are caused by horizontal density variations in the crust, and that the long wavelength gravity features originate from the base of the crust or deeper.

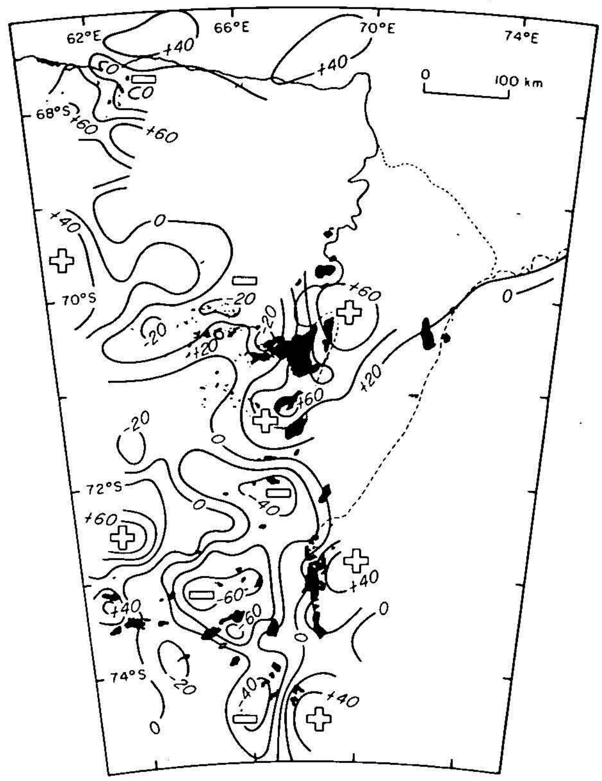

Figure 6. Free air anomaly map. Contour interval 20 mGal.

The trends and maximum amplitudes of the anomalies are generally adequately defined, but their exact shape and extent are not known in many cases. The main features of the map are a north-south trending high and low over the Lambert Glacier and western margin of the Amery Ice Shelf, and a set of anomalies to the west of these that trend mainly east-west. The north-south trending anomalies truncate the east-west trending anomalies so they are thought to reflect younger features.

A gradient extends along the Lambert Glacier and the western margin of the Amery Ice Shelf separating the prominent high and low. It is close to the 68°E meridian except where it is displaced to the west between latitude 71° to 72°S. East of the gradient the free air anomalies range from + 20 to + 60 mGal, and to the west they are between 0 and −60 mGal. The gradient varies from 80 mGal in 30 km at 74.5°S, to 80 mGal in 60 km at 70.5°S.

South of 72° S the gradient is interpreted as due to a fault with denser rocks to the east. Metamorphic grade is generally lower west of the postulated fault, and low grade calcareous metasediments are found only on its western side. The westerly displaced portion of the gravity high between 71° and 72°S partly corresponds to an area of mafic rocks at Mount Willing (B), Nilsson Rocks (C) and Fisher Massif (D).

North of 71° S along the western margin of the Amery Ice Shelf, the gradient seems to be caused by subsurface horizontal density variations, because exposed rocks on the two sides of the gradient near Beaver Lake (E) are granulite facies metamorphic rocks of similar density. A similar but poorly defined gravity gradient trends parallel to the eastern margin of the Amery Ice Shelf. Both gradients are inferred to be between a relative gravity high over the Amery Ice Shelf and surrounding gravity lows. The gravity observations suggest that the Amery Ice Shelf is underlain by a relatively dense upper crust that is isostatically compensated at depth. A Soviet deep seismic sounding profile from Beaver Lake (E) to Vestfold Hills (F) (Lopatin, 1973) suggests that the crust under the rift structure is reported to be 22 km thick and the adjacent crust 35 km thick. The two gravity gradients are consistent with the seismic structure beneath the Amery Ice Shelf. The only other evidence for this crustal rift structure is the existence of the topographic depression occupied by the Amery Ice Shelf, and two faults, one just west of Beaver Lake (E) and the other northeast from Jennings Promontory (G). These lie along sections of the two sides of the structure, and have moved in the middle to late Phanerozoic, the movements being down towards the Amery Ice Shelf.

In the western half of the mapped area gravity anomalies form a somewhat irregular pattern, but with a predominant east-west trend. In the southern Prince Charles Mountains a strong east-west-trending gradient occurs at 73°S with a negative anomaly to the south. This gradient correlates with the boundary between comparatively young metamorphic rocks of greenschist and lower amphibolite facies on the southern side, and older rocks of middle amphibolite facies to the north. A negative anomaly trending northwest towards Mawson correlates with a zone of porphyroblastic charnockites within granulite facies rocks. The density contrasts causing the other gravity anomalies on the western half of the mapped area are not known.

Acknowledgements

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Early Tertiary pollen from Napperby, central Australia

Elizabeth M. Kemp

Carbonaceous clays in a stratigraphic borehole near Napperby homestead, in the southern part of the Northern Territory, have yielded a microfloral assemblage comprising over thirty form-species of pollen. The assemblage can be referred to the middle Eocene *Proteacidites confragosus* Zonule on the basis of the presence of the nominate species, and is the most inland of any Australian Tertiary flora described. The Napperby sediments may be correlated, on a palynological basis, with the upper part of the Eyre Formation of northeastern South Australia; they are older than the vertebrate-bearing Waite Formation of the adjoining Alcoota Sheet area. A high frequency of pollen from aquatic and marsh-loving angiosperms and the presence of dinoflagellate cysts indicates deposition under lacustrine conditions. The presence of *Nothofagus* and podocarpaceous pollen types in significant amounts suggests that a humid climate prevailed, although seasonal aridity cannot be ruled out.

Tertiary sediments in the Napperby 1:250 000 Sheet area in the Northern Territory overlie folded Adelaidean and Palaeozoic sedimentary rocks (Evans, 1972). The sediments occupy depressions in the pre-Tertiary land surface and locally reach thicknesses of around 250 m (Evans & Glikson, 1967). Shallow stratigraphic drilling in the area has shown the Tertiary sequences to consist for the most part of reddish-brown, yellow and white sands and sandy clays (Evans & Nicholas, 1970). Silcrete and ferricrete beds occur in several of the drilled sections, and as cappings on exposures of older rocks; the relationship between these beds in outcrop and in the subsurface is presently unknown. Subdivision and formal naming of the units present have yet to be attempted.

The age of the Tertiary sequence in the region is difficult to determine as it generally lacks fossils. Palynology appears to offer the best scope for setting up a chronology because of the probable continental origin of the sediment, but even this tool is hampered by deep weathering and by the sandy nature of many sediments. Attempts were made in this investigation to recover pollens from core samples from nine shallow stratigraphic holes on Napperby and the

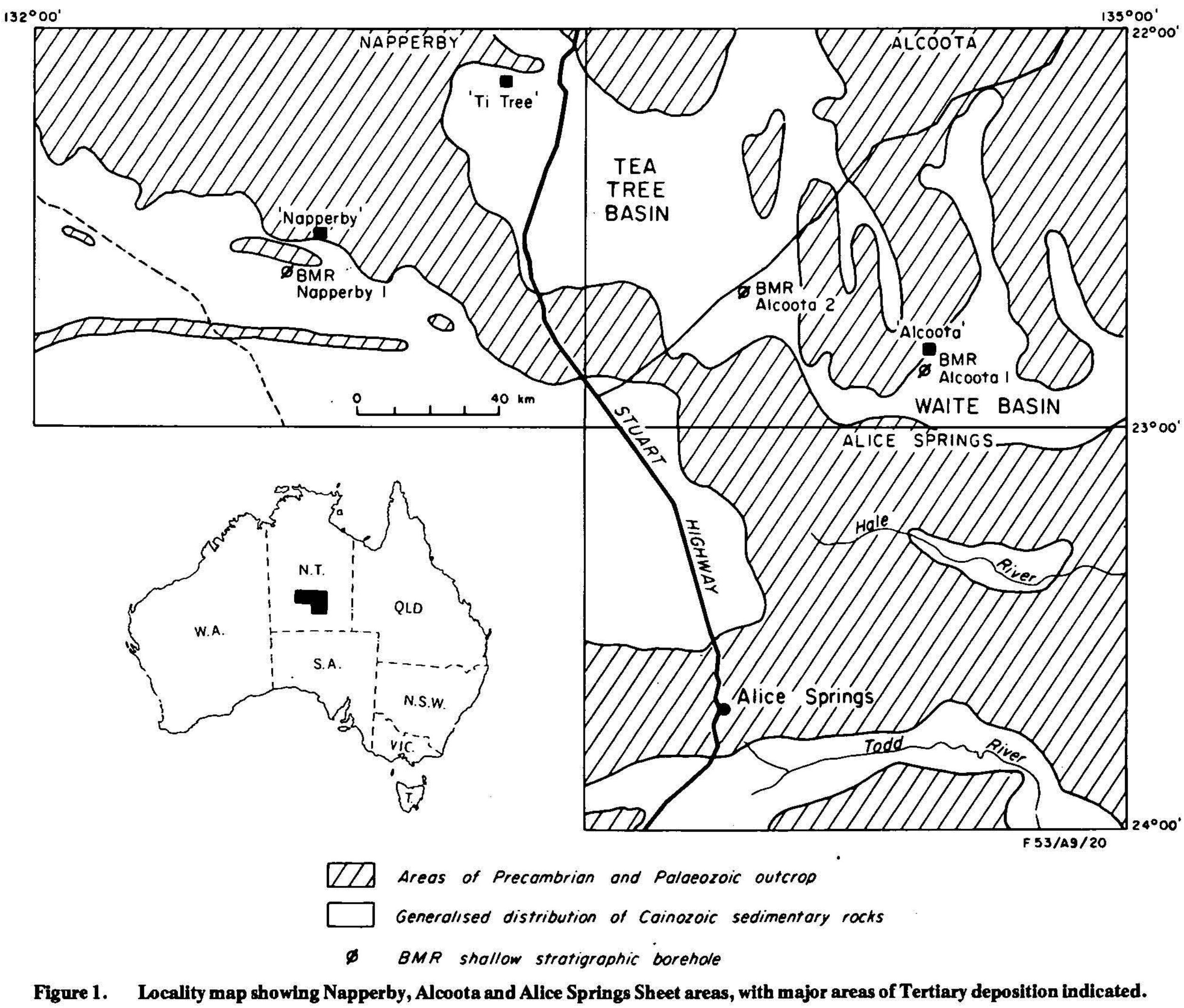


Figure 1. Locality map showing Napperby, Alcoota and Alice Springs Sheet areas, with major areas of Tertiary deposition indicated.

adjoining Mount Doreen and Alcoota Sheet areas, but only one locality, BMR Napperby 1 borehole, was productive. Lignitic clays at the base of the drilled sequence at this site were examined in a preliminary way by D. Burger, who suggested a 'post-Eocene—pre-Pliocene' age for them (quoted in Evans, 1972). In the present study this material has been re-processed and re-examined, and the age revised in the light of refinements which have been made in Australian Tertiary stratigraphic palynology during the last five years. The revised, more precise dating permits interpretation, although still in broad terms, of the relationship of this part of the Napperby sequence to Tertiary sequences in northeastern South Australia, which have recently been dated by palynological means (Wopfner *et al.*, 1974). and to sequences on the Alcoota Sheet which are dated by vertebrate fossils (Woodburne, 1967). Additionally, the Napperby microflora, which is the most inland of any Australian Tertiary pollen assemblage described, permits some broad inferences to be made regarding Early Tertiary climates in the region, and throws new light on the past distribution of some plant taxa.

Sample details

The BMR Napperby 1 borehole is situated some 13.5 km southwest of Napperby Homestead (Grid reference 587.5, 179.8 and Figure 1), at latitude 22°36'4"S and longitude 132°40'1"E. The sequence penetrated at the site is illustrated in Figure 2. Only Core 2, cut in the interval 135.94-138.99 m was suitable for the recovery of palynomorphs. Four samples from within this interval were macerated, from depths of 138.07 m, 138.25 m, 138.68 m and 138.83 m. The upper three samples, designated by the BMR palynological collection numbers MFP 4964, 6621 and 6622, were taken from a brownish-grey puggy clay; the fourth, MFP 6623, was cut in grey clay containing an abundance of black lignitic material.

Composition of the microflora

Plant microfossils were recovered from all four samples of core 2. They are excellently preserved, and over 30 form-species of pollen and spores were identified. These are listed in Table 1, and forms of particular stratigraphic or ecological interest are illustrated in Figure 4. Additionally, some five species of dinoflagellate cysts and acritarchs were isolated; these are grouped together in Table 1. It seems probable that these are fresh water types as they occur in sediments of lignitic character, but their identification could only be made to broad categories. The four closely spaced samples examined in this study differ from each other in the proportions of the major palynomorphs in each, probably as a result of rapid, minor fluctuations in local depositional environments.

In their general aspect, the microfloral assemblages have much in common with Palaeogene microfloras known from southern Australia. Pollen of *Nothofagus* Bl. (as *Nothofagidites* spp.) is present in proportions ranging from 5 to 50 percent; only grains of the *brassi* species group were observed. Casuarinaceae is well represented, as the form-species *Haloragacidites harrisii* (Couper) Harris, which occurs in relative frequencies of from 6 to 48 percent. Proteaceous pollen occurs in some diversity, with at least nine form-species recognizable. Pollen of Myrtacae, which is usually common in southern Australian assemblages, is, however, rare, reaching maxima of less than one percent in two samples. Fern spores are another rare element.

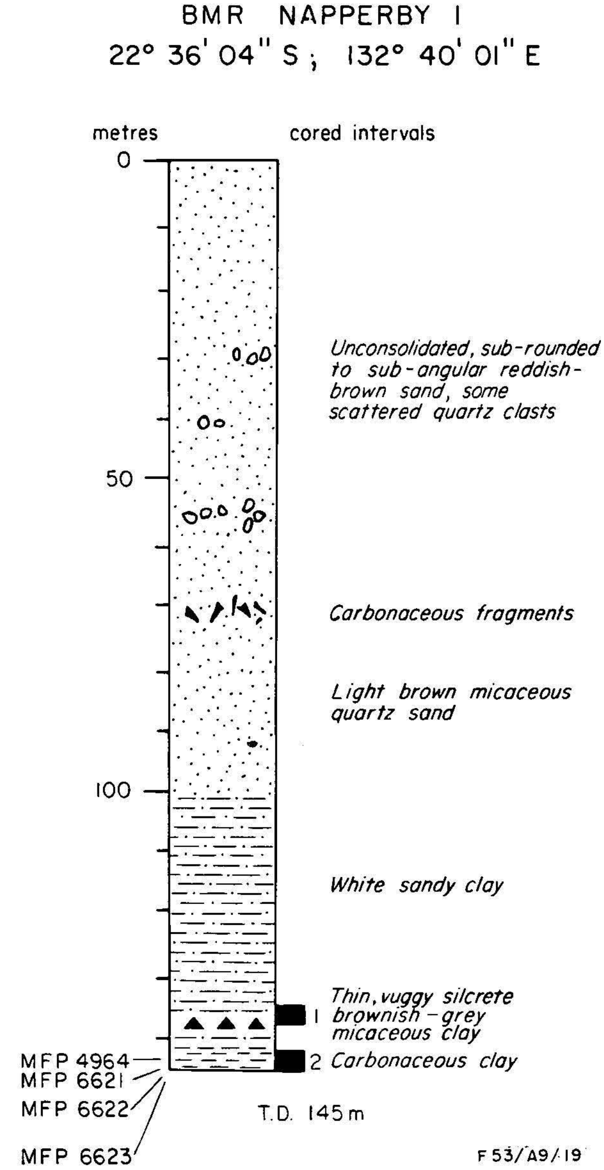


Figure 2. **Lithological sequence in BMR Napperby 1 borehole. Palynological sample horizons are indicated by, MFP numbers on left of column.**

Conifer pollens are dominated by those of podocarpaceous parentage: included here are representatives of the form-genera *Microcachryidites* Cookson, *Podocarpidites* Cookson, *Lygistepollenites* Stover & Evans, and a form herein informally referred to as *'Phyllocladus'* (Figure 4, f-h), which displays the small sacs characteristic of the extant genus, but for which there is presently no appropriate form-genus. The somewhat nondescript pollen of the Cupressaceae (Figure 4, d) is locally abundant.

Pollen of aquatic and marsh-loving angiosperms is represented in highest numbers in the deepest, lignitic core sample. In this interval the form-species *Aglaoreidia qualumus* Partridge (Figure 4, i, j,), which probably derives from the burr reed family Sparganiaceae, occurs with a frequency of 17 percent. Pollen of Restionaceae, or bog rushes, as *Milfordia* cf. *M. hypolaenoides* Erdtman (Figure 4, k-m), and of sedges (Cyperaceae; Figure 4, a, b) also reach their highest frequencies in this sample; pollen of the latter family has hitherto only been described from Plio-Pleistocene deposits in Australia (Martin, 1973a). The Liliaceae is represented by *Liliacidites bainii* Stover (Figure 4, q, r) and by an undescribed form-species. *Helciporites astrus* Partridge (Figure 4, e), an angiosperm pollen of unknown affinity but some stratigraphic utility, occurs rarely in one of the higher clay samples.

Of particular botanical interest is the presence in two samples of tricolporate pollens (Figure 4, u-w) comparable to those produced by members of the extant genus *Diplopeltis* Endl. (Sapindaceae), which has not previously been identified in fossil form. The dispersed forms in the Napperby samples are morphologically closest to the pollen of the extant *D. heugelii* Endl.; presently, the genus is represented in the area by *D. stuartii* F. Muell (see distribution maps in George & Erdtman, 1969).

Dinoflagellates and acritarchs make up approximately 40 percent of the total palynomorph suite in Sample MFP 6623. Most are thin-walled and fragmented. The most common dinoflagellate is referable to the genus *Saeptodinium* Harris, and is probably a new species. The acritarchs include smooth-walled *Leiosphaeridia* and spinose forms tentatively referred to *Baltisphaeridium* Eisenack emend. Downie & Sarjeant.

TABLE 1. DISTRIBUTION OF POLLEN AND SPORE FORM-SPECIES IN BMR NAPPERBY 1 SAMPLES.
Sample positions are indicated in Figure 2.

	MPF 4964	6621	6622	6623
Angiosperms				
Aglaoreidia qualumus Partridge				0
Banksieaeidites elongatus Cookson	0			
Cyperaceae pollen	0	0		0
Erecipites scabratus Harris		0	0	0
Haloragacidites harrisii (Couper) Harris	0	0	0	0
Helciporites astrus Partridge		0		
Liliacidites bainii Stover				0
Liliacidites sp				0
'*Micrantheum*' cf. *spinyspora* Martin	0	0		
Milfordia cf. *hypolaenoides* Erdtman		0	0	0
Myrtaceidites sp	0	0		
Nothofagidites emarcida Cookson	0	0	0	0
N. falcata Cookson			0	0
Polycolpites sp.		0		
Proteacidites annularis Cookson	0	0	0	0
P. confragosus Harris	0	0		0
P. crassus Cookson	0	0		0
P. cf. *parvus* Cookson	0	0	0	0
P. cf. *truncatus* Cookson	0	0		
P. spp. indet.	0	0		0
Sapotaceaepollenites rotundus Harris		0		
Tetracolporites sp.	0			
Tricolpites spp.	0	0		0
Tricolporites sp. (aff. *Diplopeltis*)		0		0
Conifers				
Araucariacites australis Cookson	0	0		
Lygistepollenites florinii (Cookson & Pike)	0	0	0	0
Microcachryidites antarcticus Cookson	0	0		0
'*Phyllocladidites*' sp.	0	0		
Podocarpidites ellipticus Cookson	0	0		0
Cupressaceae pollen	0	0	0	
Fern spores				
Cyathidites minor Cookson	0	0		
Gleicheniidites sp.	0	0		
Dinoflagellates and acritarchs				0
Botryococcus sp.				0

Age of the assemblage

Biostratigraphic schemes based on spore and pollen distribution in the Australian Tertiary have been erected by Harris (1971), Stover & Evans (1973), Stover and Partridge (1973) and Hekel (1972). All of these schemes, with the exception of the relatively broad one of Hekel, have been derived from studies of coastal basins in the southeast, where the age of the zonal units has been provisionally established through their relationship with planktonic foraminiferal zones, although debate about the precise correlation of zonal boundaries continues. Recognition of the same palynological assemblage zones in more northerly, inland sediments involves the assumption that regional differences in the Tertiary vegetation were not pronounced, and that migration of species from one area to another did not involve geologically significant intervals of time. That these palynological assemblage zones can be recognized away from the coast has recently been demonstrated by Harris (in Wopfner et al., 1974) who identified, in north-eastern South Australia, Palaeogene zonules which were originally set up in coastal sequences of the Otway Basin. For the present, it is assumed that the zonal units are not time transgressive; in the absence of independent age control on the inland sediments this is impossible to ascertain. If the coastal and inland pollen assemblages are indeed contemporaneous, this suggests that the geographic zonation of the Australian vegetation was much less pronounced than it is today, which probably reflects a less rigorous delineation of climatic belts.

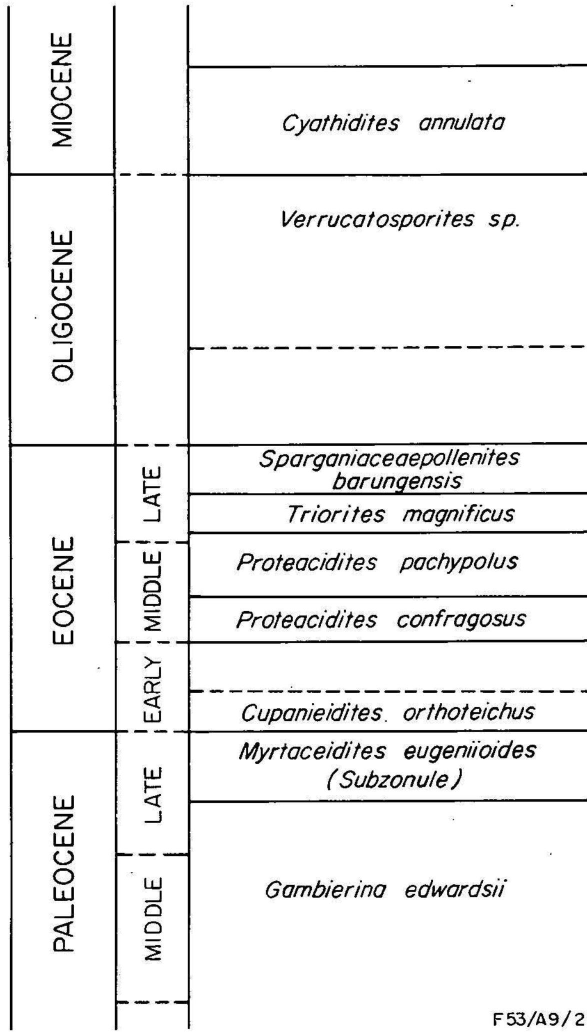


Figure 3. Palynological zonation in Tertiary sequences of the Otway Basin (after Harris, 1971).

Eleven units ('Zonules') were erected by Harris (1971) in Palaeocene to Pliocene sediments of the Otway Basin of southeastern South Australia and western Victoria (see Fig. 3); ten units have been isolated in the Late Cretaceous to Miocene sequences in the Gippsland Basin of coastal eastern Victoria (Stover & Evans, 1973; Stover & Partridge, 1973). These are based primarily on the restricted ranges of selected form-species, and are reinforced by variations in the relative abundances of long-ranging taxa. Those which have been identified inland, in the Eyre Formation of northeastern South Australia, are the *Gambierina edwardsi* Zonule, of late Palaeocene age, the *Proteacidites confragosus* Zonule, of probable middle Eocene age, and the *P. pachypolus* Zonule, which ranges from late middle to perhaps late Eocene.

The palyniferous sediments in Napperby 1 are considered to belong to Harris' *Proteacidites confragosus* Zonule, and hence to be approximately middle Eocene in age. The main justification for such an assignment rests on the presence of the nominate species in all samples. Other species which accord with the Eocene age attribution include *Helciporites astrus*, which is described as ranging from early to late Eocene in the Gippsland Basin (Stover & Partridge, 1973), and which has also been reported from the Eyre Formation, and *Liliacidites bainii*, which has a similar known range. Additionally, a high content of Casuarinaceae pollen is typical of sediments of this zone in northern South Australia, and this feature is shared by the Napperby sediments, The species *Aglaoreidia qualumus* is another species common at Napperby with a published restricted range, given as late Eocene to early Oligocene (Stover & Partridge, loc. cit.), but which Partridge (1975, pers. comm.) now regards as extending through a longer time interval.

The only fossil form which appears to be at odds with an Eocene age determination is that referred to *Proteacidites* cf. *P. truncatus* Cookson (Figure 4, y). The species *P. truncatus* was originally described from the Yallourn Open Cut (Cookson, 1950), and is unknown in southeastern Australia before the Miocene. The central Australian form is not, however, strictly conspecific with *P. truncatus*, differing from it in the structure of the exine adjacent to the pores.

Suggested regional correlation

The narrow sampling interval in BMR Napperby 1 means that it is not possible to determine just how much of the penetrated section is of Eocene age. The reference of the palyniferous sediments to the *P. confragosus* Zonule establishes the correlation of these with the younger parts of the Eyre Formation, which is widespread in northeastern South Australia. Much of this formation is Palaeocene, but a later depositional phase, commencing in the middle Eocene and extending perhaps into the late Eocene, has been identified in the southern part of its depositional area (Wopfner *et al.*, 1974). Silcretes occur in the upper parts of the Eyre Formation, and are believed to have formed in the late Eocene and Oligocene, a time interval which is bracketed by the presence of overlying fossiliferous Miocene beds. It is tempting to equate these silcretes with those that occur immediately above the carbonaceous clays in Napperby 1, and to suggest a parallel depositional history for that area, with silcrete formation following an early depositional phase that extended into the middle Eocene. However, the silcrete in Napperby 1 is thin and discontinuous, and in the absence of evidence concerning the time of its formation such a correlation is purely speculative.

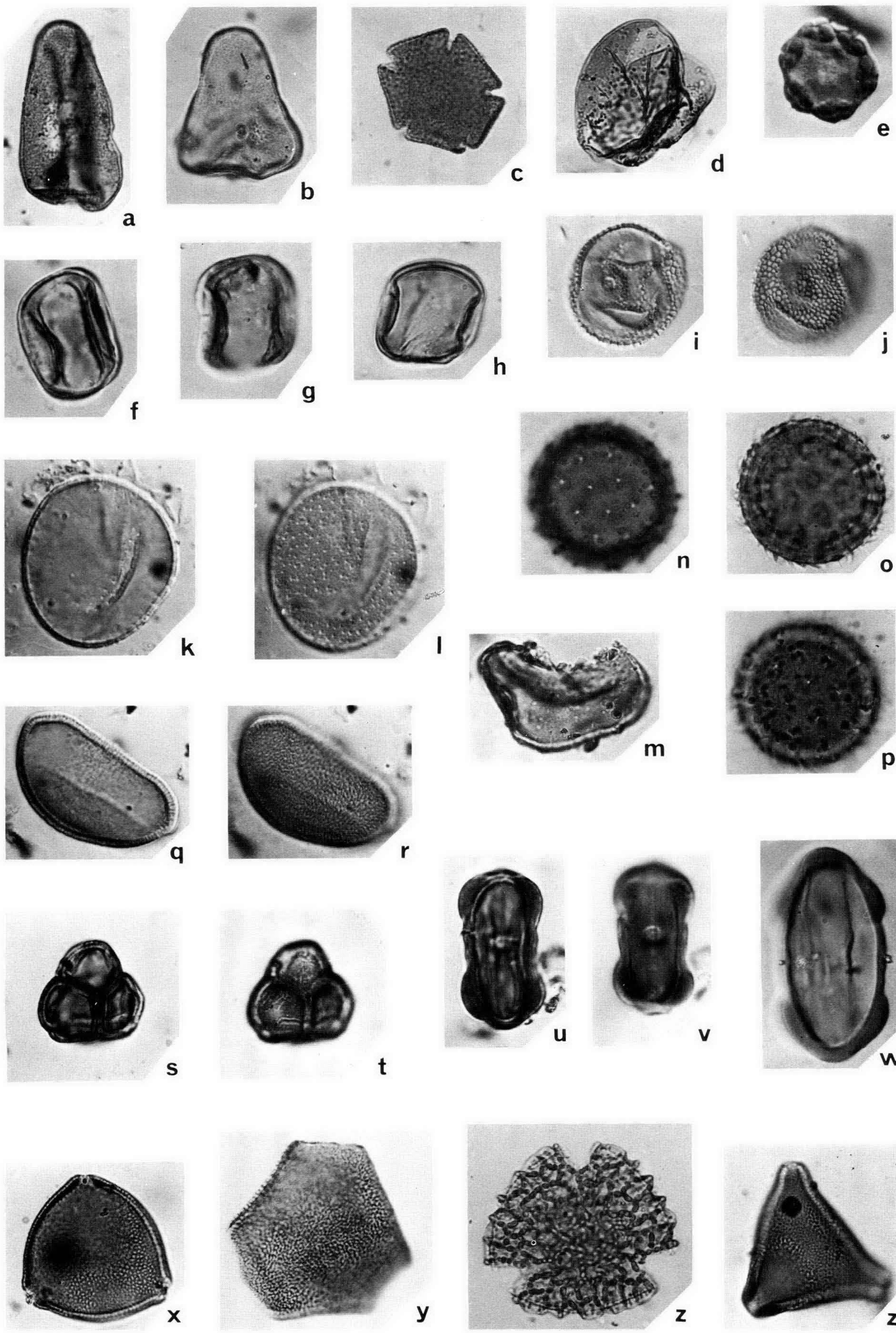
Correlation with Tertiary sequences in the adjacent Alcoota Sheet area is difficult because of the scarcity of fossils in that sequence. The Cainozoic sequence on Alcoota has been subdivided into a number of mostly unnamed depositional and weathering units (Senior, 1972; Shaw & Warren, 1975), but includes the Waite Formation of Woodburne (1967), which is tentatively dated as late Miocene-Pliocene on the vertebrate fossils. The Waite Formation in outcrop rests on lateritized Precambrian metamorphics; in BMR drillholes (Senior, 1972), it overlies a lacustrine mudstone and siltstone sequence of unknown age. Whether or not this latter sequence (designated Unit Ta by Senior) is as old as the Napperby sediments is presently unknown; attempts made in the course of this study to recover palynomorphs from greenish-grey mudstones cored in BMR Alcoota bores 1 and 2 proved unsuccessful.

Pollen-bearing sediments of Tertiary age are also known from near Alice Springs (P. R. Evans, quoted in Lloyd, 1968). Residues from cuttings from Alice Springs Farm Bore WRB/2G were re-examined in this investigation, but although they contain abundant pollen, the flora lacks diversity, consisting mainly of Casuarinaceae and Podocarpaceae types which are long-ranging, and indicate nothing more precise than a Palaeocene to perhaps Pliocene age.

Palaeoecological and palaeoclimatic considerations

The presence of abundant freshwater dinoflagellates indicates a lacustrine depositional environment for the Napperby microfloras; the high relative frequencies of pollen of aquatic and marsh-loving taxa accords with this. Variation in the pollen spectrum between samples of differing lithology probably reflects variations in the location of the depositional site with respect to the pollen source. The highly carbonaceous sediments at the base of the core, with their high count of aquatics and their dino-flagellate suite, probably represent a flora of extremely local origin, deriving from the lake waters themselves and from the immediate lake margin vegetation. Clays higher in the core have a higher content of tree pollen, notably of Casuarinaceae and Cupressaceae, and may represent inwash from a wider area of the surrounding drainage basin.

Figure 4. Selected form-species of pollen from BMR Napperby 1. All magnifications X 750. CPC numbers are those of the Commonwealth Palaeontological Collection in the BMR, where all figured specimens are housed. a, b, Cyperaceae gen. and sp. indet. Basal and lateral apertures are clearly visible in a. Sample MFP4964, CPC16501, CPC16502. c, *Nothofagidites emarcida* Cookson, MFP4964, CPC16503. d, Cupressaceae gen. and sp. indet., MFP4964, CPC16504. e, *Helciporites astrus* Partridge, MFP6621, CPC16505, f-h, '*Phyllocladus*' sp., MFP4964, CPC16506, CPC16507, CPC16508, i. j, *Aglaoreidia qualumus* Partridge, i, focus on pore, j, deep focus on sexine reticulum. MFP6621, CPC16509. k-m, *Milfordia* cf. *M. hypolaenoides* Erdtman. k, sectional focus on wall, 1, focus on sexine surface, MFP6623, CPC16510. m, laterally compressed grain showing sulcoid aperture, MFP6623, CPC16511. n-p, '*Micrantheum*' *spinyspora* Martin, n, high focus showing clusters of spines about pores. o, p, median and deep foci. MFP6621, CPC16512. q, r, *Liliacidites bainii* Stover, q, sectional focus on wall, r, deep focus on sexine surface. MFP6623, CPC16513. s, t, *Erecipites scabratus* Harris, sectional and surface foci, MFP6621, CPC16514. u-w, *Tricolporites* sp. aff. *Diplopeltis*. u, v, sectional and surface foci, MFF6621, CPC1615. w. sectional focus, corroded grain, MFP6623, CPC16516, x. *Proteacidites* sp. indet. MFP6621, CPC16517. y, *Proteacidites* cf. *P. truncatus* Cookson, MFP6621, CPC16518. z, *Proteacidites confragosus* Harris, MFP6621, CPC16519. zl, *Proteacidites* sp. indet., MFP6621, CPC16520.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The spore and pollen data bearing on the Eocene climate of this part of central Australia are ambiguous. The genus *Nothofagus* is represented only by pollen of the *brassi* species group, which is presently confined to New Guinea and New Caledonia and flourishes under precipitation regimes of 150-180 cm per year (Martin, 1973b). Additionally, the podocarpaceous genera, which occur in the pollen spectrum in frequencies up to 10 percent, are also presently members of rain-forest communities. The existence of climatic conditions necessary to support such rain-forests at the continental centre is difficult to visualize, especially in the Eocene when a significantly narrower Southern Ocean would have made effective continentality greater. This continental configuration may, however, have drawn moisture-bearing winds of monsoonal character inland from warm northern seas.

The question also arises as to whether the *Nothofagus* pollen in the sediments was derived from forests which grew in the immediate area, or whether it was transported to the depositional site from forests growing in wetter regions to the east and south. Dominance of *Nothofagidites* pollen in the Eyre Formation has been accepted as evidence of wet conditions in inland South Australia in the Eocene (Wopfner *et al.*, 1974). In only one of the Napperby samples, however, was *Nothofagidites* dominant; in the others it occurred in abundances ranging from 5 to 10 percent; these figures are perhaps low enough for a long-distance origin to be a possibility in an abundant pollen producer, especially if pollen sources were closer to the continental centre than they are now.

Other aspects of the Napperby microflora contrast with known coastal assemblages of the same age, and may reflect conditions of relative aridity. The first of these is the near-absence of a fern component — fern spores occur in frequencies of less than 1 percent — a scarcity which does not seem in accord with a high rainfall regime. The second is the abundance of Cupressaceae pollen in some samples; similar pollen is produced in Australia today by species of *Callitris*, which occur most commonly in dry sclerophyll forest associations. In sample MFP4964 this pollen type exceeds 70 percent, an abundance greatly in excess of that recorded previously in Tertiary microfloras from western New South Wales (Martin, 1973b), and which may indicate a climate with at least seasonal aridity.

Summarizing the climatic data, there are elements of the microflora which suggest the proximity of rain-forests, viz., the presence of *Nothofagus* type pollen, and of some podocarpaceous conifers; percentages of these are, however, generally low in relation to contemporary coastal microfloras. Other aspects, notably the scarcity of ferns and the abundance of Cupressaceae, can possibly be equated with a degree of dryness greater than that suggested by east and south coastal assemblages — seasonal aridity might perhaps be represented.

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Tectonic evolution and crustal setting of the middle Proterozoic Leichhardt River fault trough, Mount Isa region, northwestern Queensland

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The tectonic evolution of the fault-bounded volcanic-sedimentary Leichhardt River fault trough is reinterpreted in the light of detailed mapping of a part of this structure. Two major unconformities are indicated, the first above the Kalkadoon-Leichhardt acid igneous complex, and the second at the base of the ore-bearing Mount Isa Group and its equivalents — the Mingera and Surprise Creek Beds. A complex succession of movements is indicated, involving (1) early faulting of the Kalkadoon-Leichhardt acid igneous complex; (2) long-acting penecontemporaneous faulting; (3) folding and uplift accompanying or post-dating emplacement of Sybella Granite, and (4) a younger major faulting phase. During phase (2) syndepositional block movements resulted in differential accumulation of volcanic flows and of sediments, reflected by abrupt thickness changes across faults. In other instances the observed thickness variations can be explained by strike faulting of lenticular sedimentary units. Basic dyke swarms which intrude the volcanic-sedimentary sequence of the Leichhardt River fault trough have postdated the folding and predated the major faulting event defined as phase (4).

The Sybella Granite, thought by some workers to be younger than the Mount Isa Group on the basis of structure and lead isotope ratios, is considered by us to be older than this unit. The ore lead in the Mount Isa deposit could be related to erosion or leaching of lead from older rocks such as the Kalkadoon-Leichhardt basement complex and the Eastern Creek Volcanics. An age of between 1500-1600 m.y. is indicated for the syngenetic lead deposit at Mount Isa. The Eastern Creek Volcanics show very high Pb relative to average basalt, and high Cu, Zn and Pb levels relative to other basic volcanic rocks in this region, and may have a genetic relation to the Mount Isa Cu and Ag-Pb-Zn ore deposits.

Geochemical features of basalts of the Eastern Creek Volcanics are consistent with those of continental flood tholeiites, showing high FeO, FeO/MgO ratios, TiO_2, K_2O, P_2O_5, Ba and Rb and low Al_2O_3. Structural, sedimentological and geochemical changes between the Mount Isa area and the Cloncurry area to the east — where ocean floor type tholeiites occur — can be interpreted in terms of a transition into a continental margin environment in this direction.

The Precambrian terrain of northwestern Queensland (Fig. 1) consists of strongly deformed meridional belts of mostly low-grade metamorphosed basic and acid volcanic rocks, epicontinental-type arenaceous, pelitic, and carbonate sediments, granitic to granodioritic intrusions, and basic dyke swarms. It was systematically mapped and described by Carter *et al.* (1961). The Leichhardt River fault trough is a north-trending downfaulted zone within the "Western geosyncline" of this terrain (Carter et al. 1961). It is characterized by abundant basic volcanic rocks (Eastern Creek Volcanics), arenites (Mount Guide Quartzite, Lena Quartzite Member, Myally Beds, Warrina Park Quartzite), and pelitic sediments (Mount Isa Group and equivalents). Since the work of Carter *et al.* (1961) aspects of the structural and igneous evolution of the Mount Isa region have been reinterpreted by Cordwell *et al.* (1963), Smith (1967), Robinson (1968), Smith (1969), Farquharson & Wilson (1971), and Wilson (1973a, b). A recent detailed mapping survey by BMR and GSQ in the Mount Isa/Cloncurry region (Glikson & Derrick, 1970; Derrick *et al.*, 1971; Derrick *et al.*, 1974; Glikson, 1972; Derrick, 1974; Plumb & Derrick, 1975) has provided new field and geochemical data, warranting reappraisal of aspects of stratigraphy and structure of the Mount Isa terrain, of the sequence of events which led to its development, and of the geotectonic setting of the Leichhardt River fault trough.

Leichhardt River fault trough: definition and stratigraphy

The Leichhardt River fault trough, as defined here, refers to the north-trending structurally complex area bounded to the east by the Gorge Creek-Quilalar Fault Zone (the Quilalar fault occurs north of the area under consideration) and the Kalkadoon-Leichhardt acid igneous complex and to the west by the Mount Isa and Mount Gordon Fault Zone (Figs. 1, 2, 3, 4, 5-12). It contains a downfaulted stratigraphic succession about 10 000 m thick, comprising (from the base) the Haslingden Group (including the Mount Guide Quartzite, Eastern Creek Volcanics, and Myally Beds), the Surprise Creek Beds, and Mount Isa Group. Stratigraphically, the eastern limit of lateral distribution of the above units coincides with the eastern boundary of the fault trough; the western limit, however, lies beyond the Mount Isa-Mount Gordon fault zone. Thus, the Mount Guide Quartzite and the equivalent May Downs Gneiss, the Eastern Creek Volcanics, and Myally Beds or the equivalent Judenan Beds extend west to the Sybella Granite (Wilson, 1972); equivalents of the Mount Guide Quartzite and Eastern Creek Volcanics could occur at depth west of the Mount Gordon fault, and equivalents of the Mount Isa Group (i.e. Mingera Beds) extend to areas just west of the Sybella Granite.

Within the Leichhardt River fault trough, the metamorphic grade corresponds to the lower to middle greenschist facies. West of the fault trough near the Sybella Granite contact, low pressure amphibolite facies is reached. As shown below, the sequence uncomformably overlies the Kalkadoon-Leichhardt acid igneous and volcanic basement. The recent BMR-GSQ survey has confirmed the general stratigraphic subdivision of Carter *et al.* (1961), and has led to further subdivision of the Mount Guide Quartzite, Eastern Creek Volcanics (established earlier by Robinson, 1968), Myally Beds, and Mount Isa Group (Table 1; Fig. 13). The principal features of the revised stratigraphic column are summarized in Table 1.

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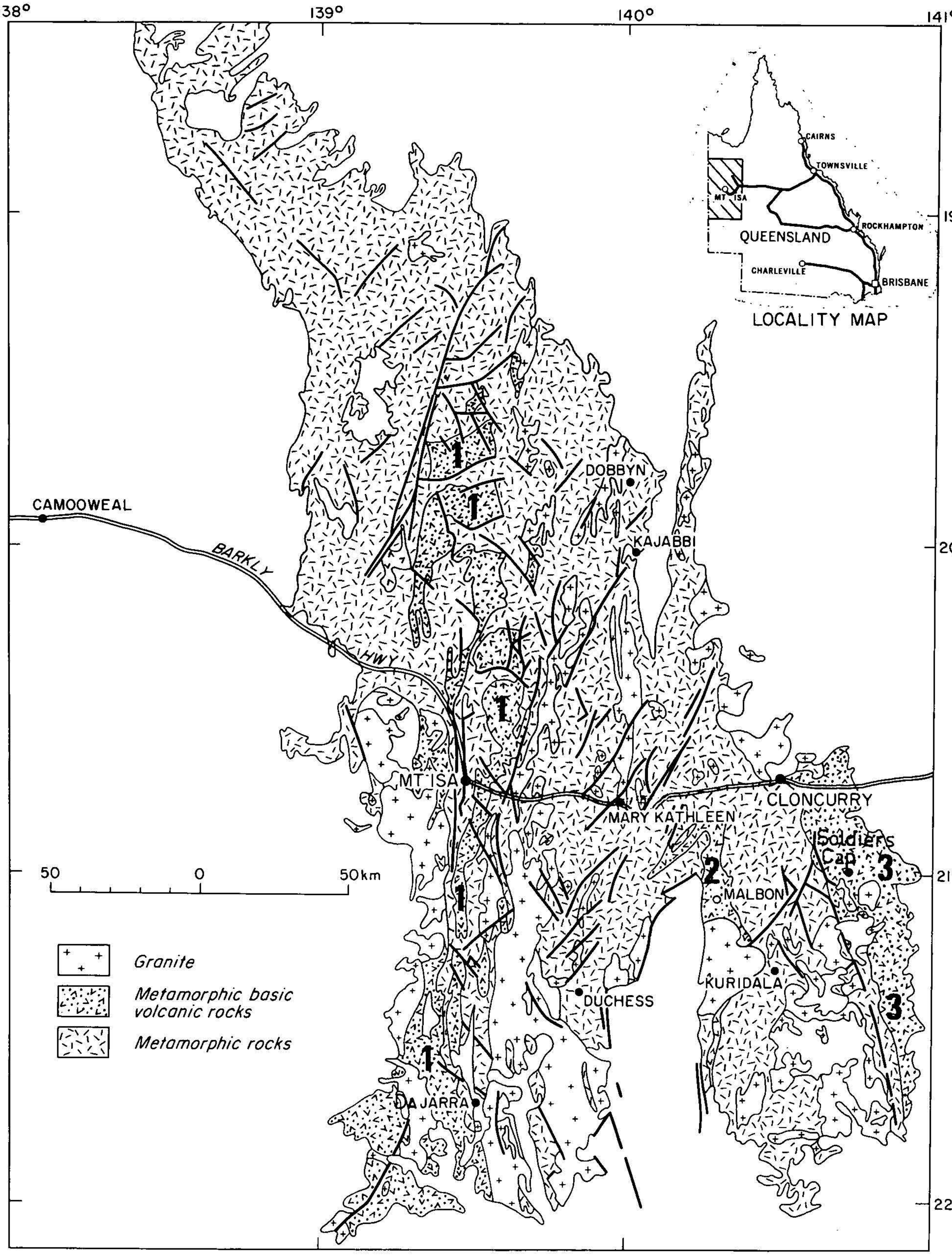

Figure 1. **A generalized geological map of the Precambrian terrain of northwestern Queensland, showing the distribution of the granites, metamorphic rocks (including mainly metasediments and acid volcanic rocks), and metamorphosed basic volcanic belts. The latter include the Eastern Creek Volcanics (1), Marraba Volcanics (2), and the Soldiers Cap Group (3).**

A lithologically-based correlation between the principal stratigraphic units of the Leichhardt River fault trough and other formations in the northwest Queensland and Carpentaria regions is given in Figure 14 (after Plumb & Derrick, 1975).

Unconformities

In this section evidence is presented and reviewed for the existence of two major unconformities within the Leichhardt River fault trough. The oldest unconformity occurs between the Haslingden Group and Kalkadoon-

Leichhardt basement rocks. East of Mount Isa the basal beds of the Mount Guide Quartzite include arkose and conglomerate containing clasts of acid porphyry resembling the Leichhardt Metamorphics of the Kalkadoon-Leichhardt basement. Similarly, near Rifle Creek to the south of Mount Isa, greywacke and conglomerates defining the base of the Mount Guide Quartzite contain volcanic clasts probably derived from both the Leichhardt Metamorphics and Argylla Formation, and also clasts of granite derived from the Kalkadoon Granite. North of the area discussed here the Mount Guide Quartzite was not deposited, so that the younger Eastern Creek Volcanics directly overlie the Ewen Granite unconformably (Carter *et al.*, 1961). Both the Ewen and Kalkadoon Granites are considered to be older than the Haslingden Group in all areas mapped by us to date. The evidence for this unconformity has been summarized by Smith (1972, 1973).

A second major unconformity defines the base of the ore-bearing Mount Isa Group, and the partly equivalent Surprise Creek and Mingera Beds. The presence of a lenticular arenite sequence at the base of the predominantly shaly Mount Isa Group is critical to recognition of this unconformity, since contacts between older Haslingden group arenites and younger shales are a focus for later faulting, folding and shearing which locally obscure stratigraphic relationships.

The basal arenite unit of the Mount Isa Group, the Warrina Park Quartzite (Derrick, 1974; Plumb & Derrick, 1975) has been variously regarded as part of the Mount Isa Group or part of the underlying Myally beds. Carter *et al.* (1961) included it in the Mount Isa Shale, and Bennett (1965), and Wilson (1972) assigned it to the Myally Beds, where it was known as the "quartzite marker". It was reinstated to the base of the Mount Isa Group by Smith (1969) and Bennett (1970), and was fully described by Derrick (1974). The Warrina Park Quartzite rests with angular unconformity on Myally Beds and Eastern Creek Volcanics (Carter *et al.*, 1961; Derrick, 1974) in an area 50 km north-northeast of Mount Isa, but is considered to be mainly disconformable in the Counter block northeast of Mount Isa (Fig. 2), where it overlies a nearly complete sequence of Myally Beds. Bennett (1970) described the relationship as conformable. However, east of Mount Isa, in the Mount Isa block (Fig. 2) the Warrina Park Quartzite is represented by a thin conglomerate which rests disconformably on the Lena Quartzite Member of the Eastern Creek Volcanics, thus implying erosion or non-deposition of all the Myally Beds and the upper part of the Eastern Creek Volcanics. To the south of Mount Isa in the Mount McArthur block (Fig. 2) the upper part of the Eastern Creek Volcanics and the Myally Beds gradually reappear from beneath the Mount Isa Group, thus indicating the presence of a low-angle unconformity. These relationships indicate that the Warrina Park Quartzite was deposited on an irregular surface developed on different units of the Haslingden Group, and that the Mount Isa block was probably structurally higher than the Counter block in pre-Mount Isa Group time.

The equivalents of the basal Mount Isa Group, the Surprise Creek Beds and Mingera Beds (Carter *et al.*, 1961; Derrick, 1974; Plumb & Derrick, 1975) have similar relationships to older rocks. For instance, the Surprise Creek Beds rest unconformably on Eastern Creek Volcanics southeast of Mount Isa, in the Rifle Creek granite dome (Fig. 2); at Sunday Gully, 56 km northeast of Mount Isa, they are clearly unconformable on the Kalkadoon Granite (Carter *et al.*, 1961; Derrick, 1974). Northwest of Mount Isa the basal Mingera Beds, which are considered equivalents of part of the Mount Isa Group, consist of conglomerate containing some granite and quartz-tourmaline pebbles derived from the adjacent Sybella Granite (Plumb & Derrick, 1975). Since the Sybella Granite intrudes the Judenan Beds (considered as western equivalents of the Myally Beds), a major time break is indicated between the Judenan and Mingera Beds.

Age limits on the unconformities described above are provided by isotopic ages of the Kalkadoon-Leichhardt basement complex and the Sybella Granite complex. The maximum age of the Haslingden Group is thought to be set by the minimum age of the basement, i.e. about 1700 m.y. The maximum age of the Mount Isa Group is set by the age of the underlying Sybella Granite, i.e., in the range 1656-1570 m.y. (Plumb & Derrick, 1975).

Structural patterns

Boundary zones of the fault trough

The eastern boundary of the Leichhardt River fault trough is defined in part by the **Gorge Creek-Quilalar Fault Zone**, which consists of narrow north-trending downfaulted blocks of sandstone, argillite, and carbonates of the Surprise Creek Beds, alternating with upfaulted blocks of Kalkadoon-Leichhardt basement rocks (Fig. 2). The sediments are strongly sheared parallel to the major boundary faults, and are tightly folded along north-plunging fold axes. East-trending faults causing movements in the sense of north-block-up result in repetition of the sequence. The width of the Gorge Creek-Quilalar Fault Zone ranges from about 3 to 8 km, and becomes generally wider north of the map area. The number of faults of which it consists are variable. The throw along some faults within the zone could be as much as 7000 metres, e.g., where Surprise Creek Beds and basement rocks are juxtaposed, 16 km east-northeast of Mount Isa.

Along the western boundary of the fault trough, the Mount Isa Fault Zone consists of a set of north-trending reverse faults of which the Mount Isa Fault is the principal one (Fig. 2). The faults are sub-parallel to the bedding and cleavage of the near-vertical to slightly overturned Judenan Beds west of Mount Isa and to the eastern intrusive contact of the Sybella Granite (see Wilson, 1972, 1973). The **Mount Gordon Fault Zone** is a complex zone of brittle failure (Dunnet, 1973), in which large strike slip and vertical movements have occurred (see Carter *et al.*, 1961).

Central zone of the trough

Within the area considered here the central zone of the Leichhardt River fault trough is dominated by several structural features which either occur in separate areas or are superposed on one another. The features are

(1) Fault blocks with north-striking strata, which constitute the eastern limb of a faulted syncline, the axis of which broadly coincides with the Mount Isa fault, e.g., Mount Isa block, Mount McArthur block (Figs. 2, 15).
(2) Fault blocks with mainly northeast to east-trending strata folded on steep to moderate north-plunging axes, e.g. Counter and Moondarra blocks (Figs. 2, 15), and similar blocks to the north.
(3) Major west to northwest-trending arcuate or spoon faults (Dunnet, 1973) with downthrow to the south, and which separate the above types of fault blocks from one another, e.g., Spillway Fault and similar faults to the north.
(4) Sets of west, northwest and north-trending faults oriented at high angles to bedding within the various fault blocks, and which are particularly closely spaced in the Counter block (Figs. 2, 15). In the latter block

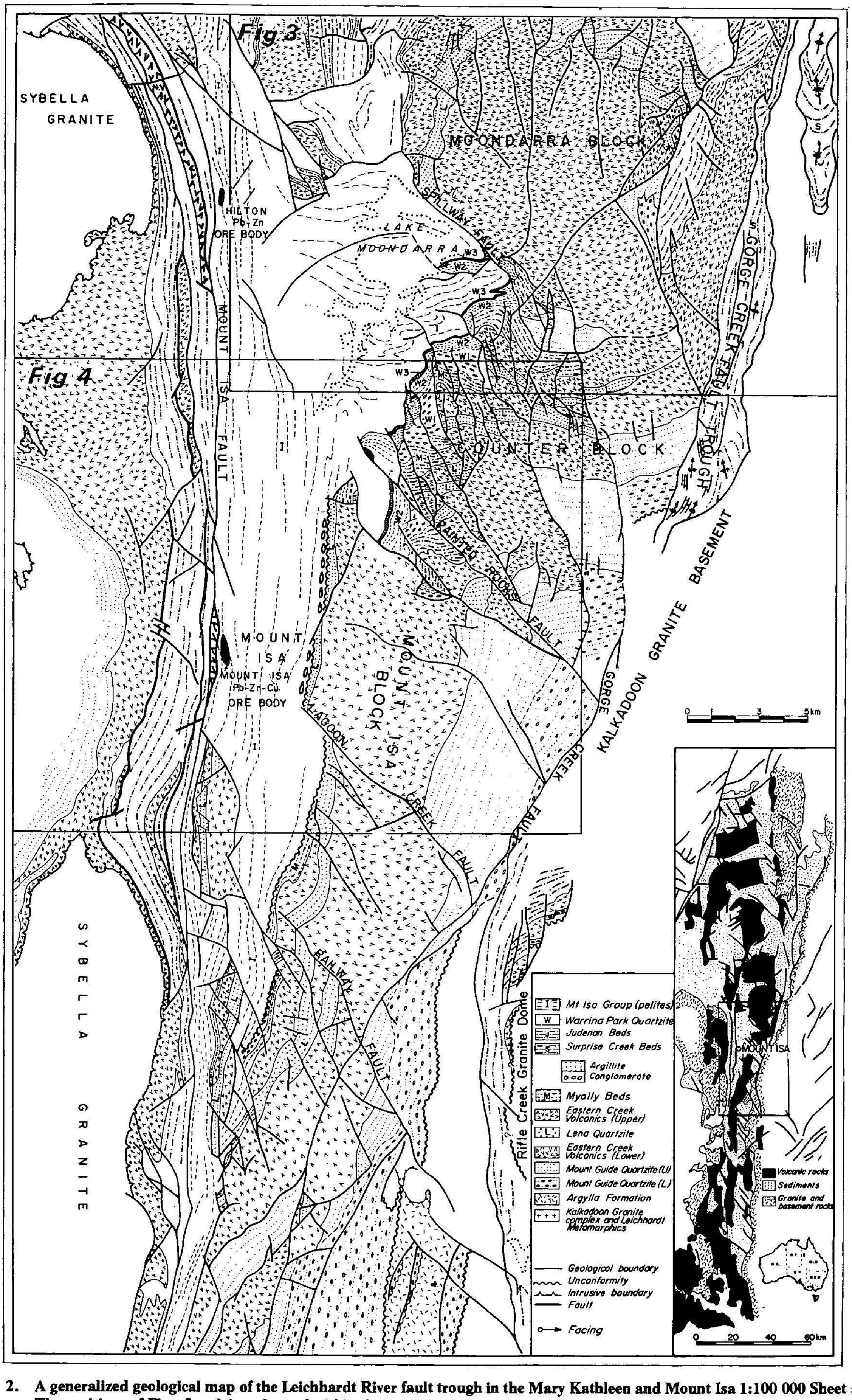

Figure 2. A generalized geological map of the Leichhardt River fault trough in the Mary Kathleen and Mount Isa 1:100 000 Sheet areas. The positions of Figs. 3 and 4 are framed within the map.

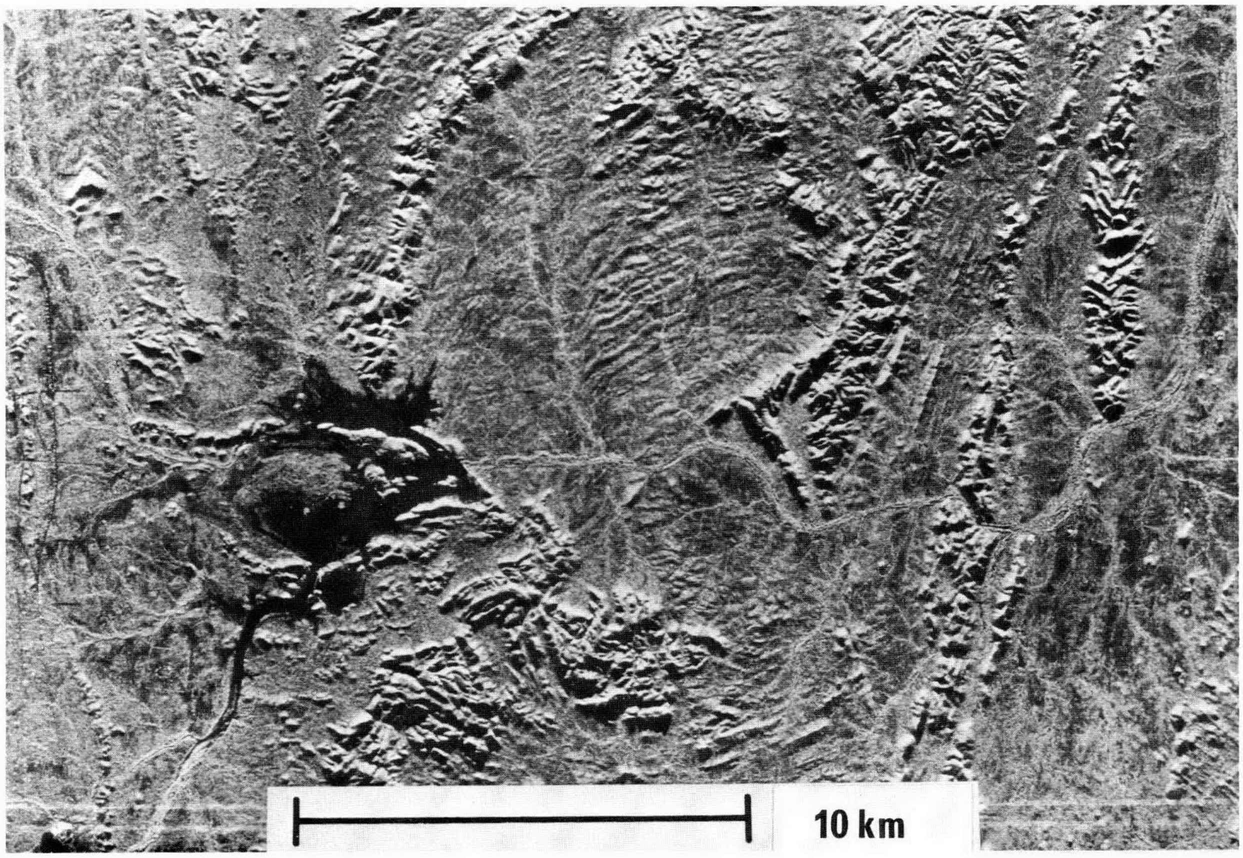

Figure 3. Airborne radar imagery of a part of the Leichhardt River fault trough; for corresponding delineation of the geology refer to Fig. 2.

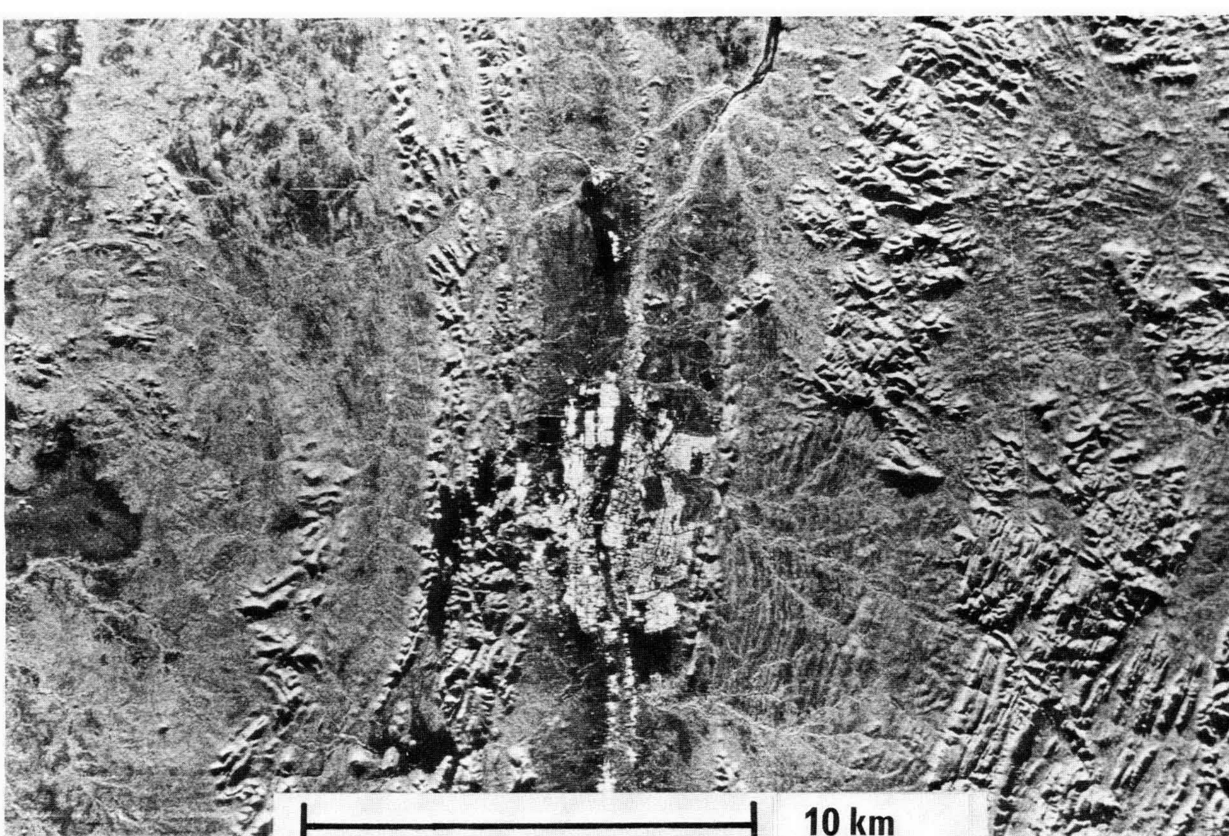

Figure 4. Airborne radar imagery of a part of the Leichhardt River fault trough; for corresponding delineation of the geology refer to Fig. 2.

most of these faults show strong strike-slip sinistral displacement. The faults form the most prominent part of a conjugate fault set, and together with minor northeast-trending dextral faults dissect the major blocks internally into small-scale fault wedges.

The large-scale flexures developed in both the Counter and Moondarra blocks (Figs. 2, 3, 4), and also to the north of the area, are interpreted as parts of an originally north-trending anticline whose eastern limb has been displaced by the Gorge Creek-Quilalar fault system, and which has been dissected by cross faults, such as the Spillway fault. This and other cross or spoon faults to the north are essentially curved normal faults, the south block being downthrown by up to 3000 m. The faults are thought to flatten in depth by Dunnet (1973). Rotation of the blocks about east-west axes associated with the normal faulting has resulted in the moderate to steep northerly plunges of the flexures.

Structural significance of basic dyke swarms

It is notable that the majority of the basic dykes intruded into the sedimentary-volcanic sequence of the Leichhardt River fault trough maintain a consistent northerly trend, and are not affected by the folding defined by the flexures in the Counter and Moondarra blocks. Thus, the dykes are parallel to the regional northerly bedding strike in the Mount Isa block, but cut across the easterly bedding strike within the folded Counter and Moondarra blocks. However, most of the dykes are displaced by faults, and it is therefore apparent that the folding and major faulting were separated from one another by a period of dyke intrusion. We therefore consider the dykes constitute a useful structural and time datum.

Significantly, the dykes progressively decrease in abundance upwards through the Mount Guide Quartzite, the lower Eastern Creek Volcanics, and the Lena Quartzite Member, in this stratigraphic order, and the Myally Beds and Mount Isa Group are only rarely intruded by dykes (Fig. 15). These relations could give the impression that most of the dykes were feeders for lavas of the Eastern Creek Volcanics, but we consider this interpretation unlikely as the dykes clearly postdate the folding of this formation. A more likely interpretation is that dykes were intruded along axial plane fractures of the pre-existing north-trending anticline postulated above prior to its dissection by faults, and the scarcity of dykes in the Myally Beds is the result of a lesser development of fractures in this unit. We attribute the difference in abundance of dykes in the different structural domains to control of dyke emplacement by the fracture patterns, namely, by the conjugate joint sets in the rigid Kalkadoon-Leichhardt basement blocks and by axial plane foliation and concordant fractures within the folded sedimentary-volcanic sequence of the Leichhardt River fault trough. The joint set orientations can be interpreted in terms of east-west compression (Anderson, 1942), to which the conjugate fracturing and faulting in the basement, north-south folding within the fault trough, and the reverse faulting along the Mount Isa Fault Zone can also be attributed.

Early and penecontemporaneous faults

The development of the Leichhardt River fault trough was preceded by that of an intrusive-extrusive acid igneous complex, formed through the successive intrusion of a granodiorite and adamellite (Kalkadoon Granite) into acid volcanics (Leichhardt Metamorphics). This was followed, in places, by further acid volcanic activity (Argylla Formation).

Figures 5-12. Oblique aerial views of parts of the Leichhardt River fault trough. K—Kalkadoon-Leichhardt basement complex; G—Mount Guide Quartzite; V—Eastern Creek Volcanics; L—Lena Quartzite Member; M—Myally Beds; I—Mount Isa group; J—Judenan Beds; S—Surprise Creek Beds; Sc—carbonates in Surprise Creek Beds; f—fault.

Figure 5. The Gorge Creek fault along Gorge Creek, looking north from a point about 20 km ENE of Mount Isa.

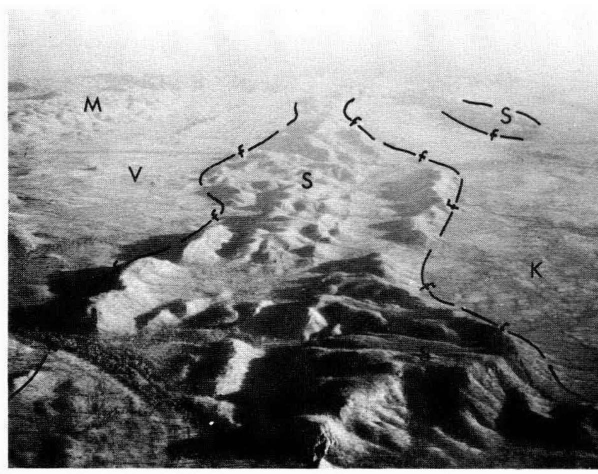

Figure 6. A view of downfaulted segments of the Surprise Creek Beds in the Gorge Creek fault zone, looking north from a point about 20 km ENE of Mount Isa.

During basal Mount Guide Quartzite time, coarse conglomerate containing plutonic, volcanic, quartzitic and quartz clasts was derived from and deposited adjacent to the basement complex. This strongly suggests the basement was uplifted, possibly along a hinge line now superposed by the Gorge Creek-Quilalar fault zone. This postulated ancient hinge line was also described by Carter *et al.* (1961, p. 188) as an "archetype Gorge Creek-Quilalar fault system", and early movements along it appear to have affected the distribution of the Mount Guide Quartzite and Eastern Creek Volcanics. For example, in the Rifle Creek dam area (Fig. 2), very thin sequences of basal conglomerate and basalt east of the Gorge Creek-Quilalar fault zone contrast with the much thicker sequences west of the zone (Fig. 13), which suggests that the eastern boundary of the Leichhardt River fault trough was already demarcated in Mount Guide Quartzite and Eastern Creek Volcanic times.

Apparent thickness variations in the same units in the Counter block (Fig. 13) indicate the early existence of a fault

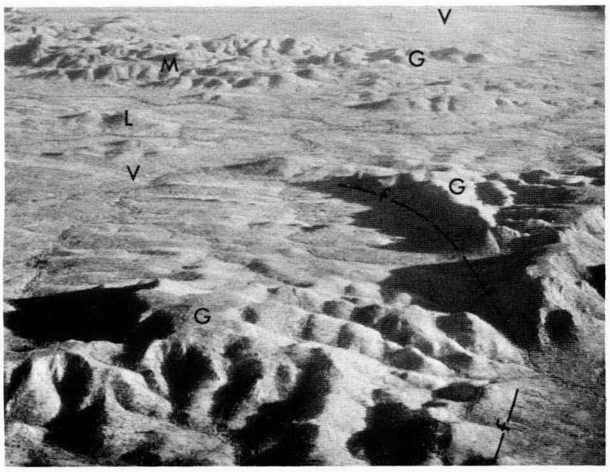

Figure 7. Faulted blocks of the Mount Guide Quartzite in the Counter block, looking NW from a point about 20 km ENE of Mount Isa.

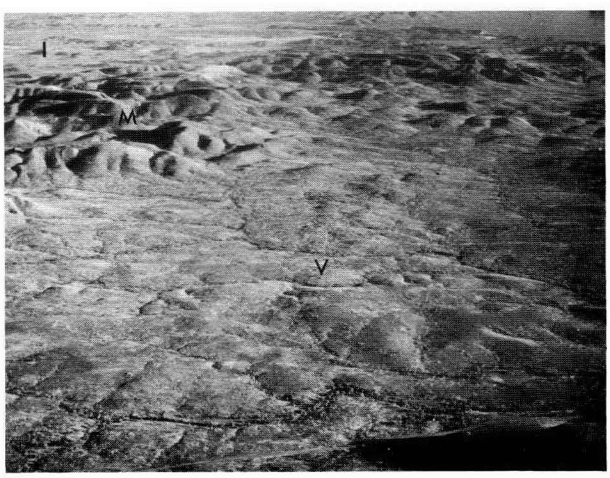

Figure 8. The Eastern Creek Volcanics (lower part) in the core of the Counter block, looking NW from a point about 11 km ENE of Mount Isa. Lake Moondarra is seen in the distance.

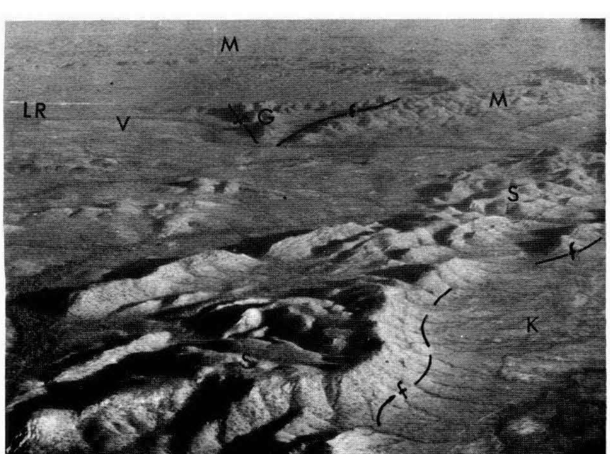

Figure 9. Looking NW from a point about 25 km ENE of Mount Isa; in the distance the flexure of the Moondarra block is expressed as an amphitheatre consisting of quartzite ridges (Lena Quartzite Member) surrounding a low terrain underlain by the Eastern Creek Volcanics. LR — Leichhardt River.

Figure 10. Looking south of Lagoon Creek, SE of Mount Isa; the contact between the Lena Quartzite Member and the Mount Isa Group (siltstones) is considered to be a probable unconformity.

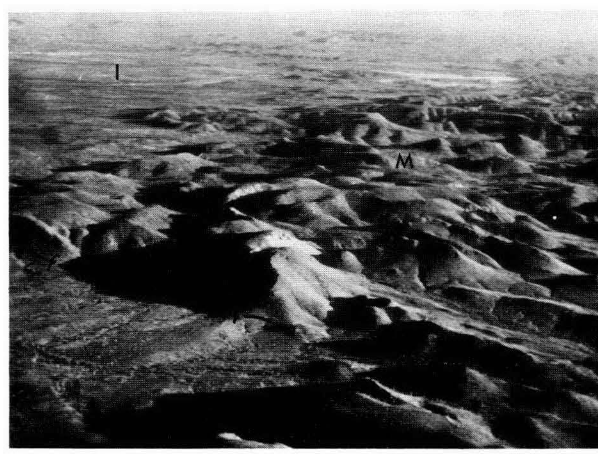

Figure 11. The Myally Beds NE of Mount Isa; looking NNW from a point 5 km east of Mount Isa.

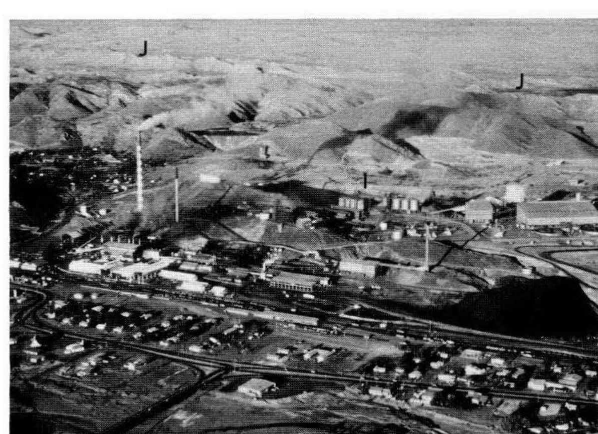

Figure 12. A view of the Mount Isa Ag-Pb-Zn and Cu mines, looking west. The contact between the Judenan Beds and the Mount Isa Group coincides with the Mount Isa thrust fault.

branch of the Gorge Creek-Quilalar fault zone. This area was discussed by Smith (1969), who described several faults as penecontemporaneous, mainly on the basis of thickness variations across faults, progressively smaller fault displacements in younger rocks, and the presence of blind and folded faults. He suggested that the evolution of the Leichhardt River fault trough was characterized by differential sedimentation and volcanism controlled by early block faulting. Some of the effects of these faults on the sedimentation of the Mount Isa Group and Surprise Creek Beds were described by Derrick (1974). Mathias *et al.* (1973) ascribed thickness changes and a local unconformity in the Mount Isa Group at Hilton mine to a penecontemporaneous transverse fault, the Transmitter Fault (Fig. 8).

In view of the different interpretations that can be placed on thickness variations in the Mount Isa area, the concept of penecontemporaneous faulting requires re-examination. Firstly recent field mapping shows that patterns of strike-slip faulting, particularly in the Moondarra and Counter blocks, are exceedingly complex (Figs. 2, 15) and true thicknesses of units are difficult to estimate. Also, faults in the Eastern Creek Volcanics are difficult to recognise in certain areas, where large apparent thicknesses ensue by repetition of thinner units, e.g. in an area south of the Railway Fault (Fig. 2). Secondly, the contacts between shale and quartzite at the base of the Mount Isa Group are a focus for post-depositional faulting; parts of the Mount Isa and Mount McArthur blocks display faulted contacts with Mount Isa Group shale, and most of the Myally Beds and the upper Eastern Creek Volcanics have been removed from the section. Thirdly, lenticular sedimentation not related to faulting is present in some areas, e.g., Lena Quartzite between the Armstrong and Police Creek Faults (Fig. 15). We therefore suggest that, before any fault be classified as penecontemporaneous, on the basis of thickness variations across it, etc., a careful assessment of the sedimentological and post-depositional structural patterns is required.

Nevertheless, the abrupt thickness variations between the Counter block and the apparently unfaulted northwestern part of the Mount Isa block, amounting to over 3000 m (Fig. 13), are difficult to interpret in terms of original lensing or subsequent faulting. We consider that the Mount Isa block and possibly the Mount McArthur block have been high relative to the Counter block during sedimentation and/or erosion, and that the Moondarra Fault is therefore superposed on an ancient hinge line. However no conglomerate or breccia deposition is recorded adjacent to and along the Moondarra Fault, which was therefore possibly much less active than the marginal, north-trending Gorge Creek-Quilalar hinge line. Similar relationships may well apply to the Moondarra block and the Spillway Fault in the area immediately north of Lake Moondarra (Fig. 2).

Sequence of events

Our prefered interpretation of the sequence of events is given in Table 2. As noted earlier, initiation of the Leichhardt River fault trough was preceded by development

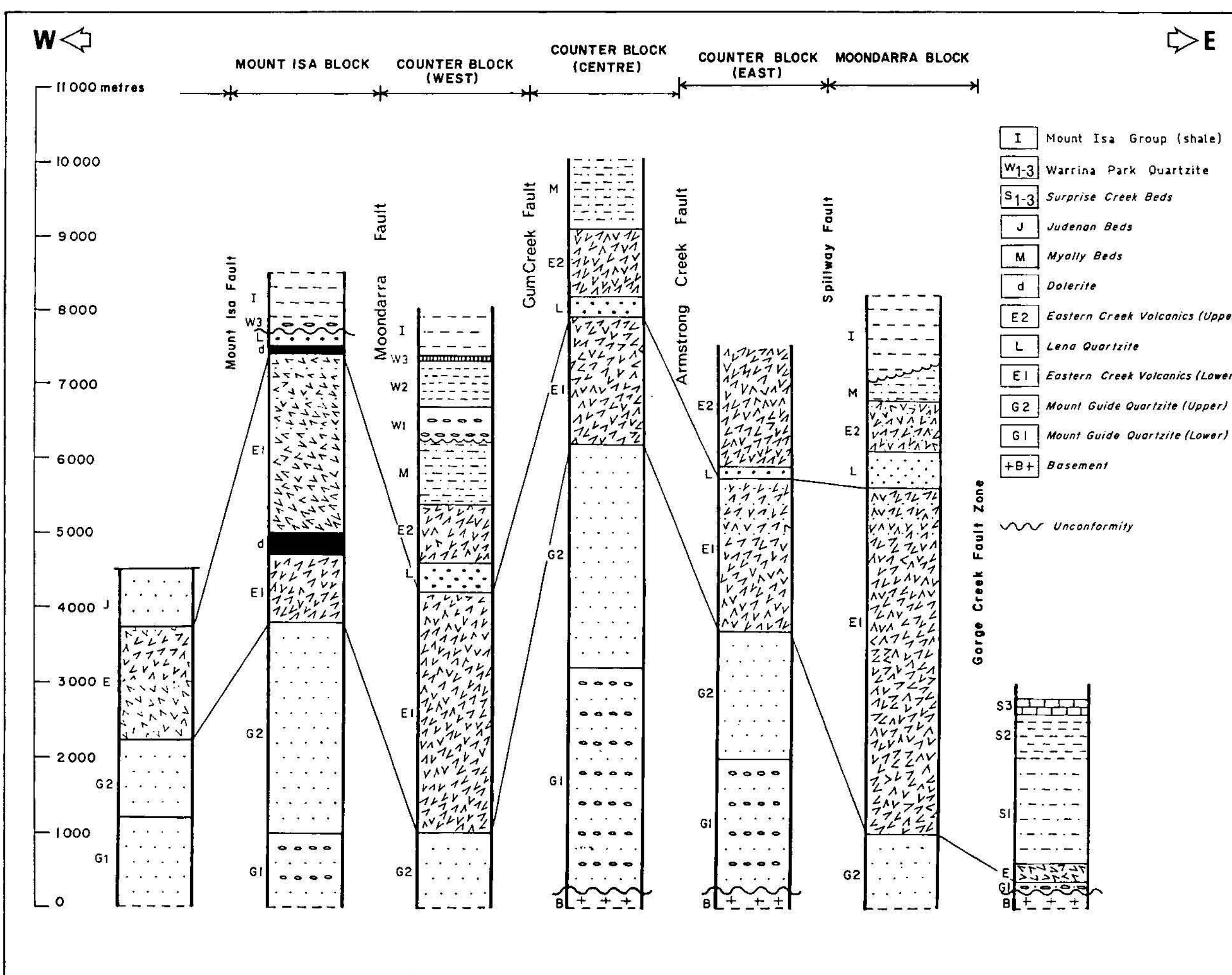

Figure 13. Columnar stratigraphic sections within the Leichhardt River fault trough.

of the plutonic-acid volcanic Kalkadoon-Leichhardt complex. The absolute age of this complex is not known, but a minimum age of near 1700 m.y. is indicated (Page & Derrick, 1973; Plumb & Derrick, 1975), which could also be the maximum age of the onset of Mount Guide Quartzite deposition.

Conglomerate and sand deposition of the Mount Guide Quartzite was followed by the first period of basic volcanic activity within the trough (Cromwell Metabasalt Member), which is characterized by a progressive increase in the frequency and thickness of sedimentary intercalations culminating in the Lena Quartzite Member. The latter was followed by renewed volcanic activity (Pickwick Metabasalt Member). The termination of volcanicity was succeeded by accumulation of basement-derived quartzo-feldspathic sand (Myally Beds) in a shelf or platform environment marked by some topographic variation between older fault blocks. Uplift and possibly faulting of the Myally Beds and older units was accompanied by intrusion of the Sybella Granite to the west, and by development of subsidiary troughs and marginal platforms in which subsequently the broadly equivalent Surprise Creek Beds, Mingera Beds and Mount Isa Group were deposited (Derrick, 1974).

The Mount Isa and Haslingden Groups (and their stratigraphic equivalents) were co-folded during a major deformation; this event could be related to the emplacement of the Sybella Granite, as the major fold axes within the trough are parallel to the boundary of the latter. Had this been the case, the Mount Isa Group would have been older than the Sybella Granite. However, the Mingera Beds, which are correlated with the lower part of the Mount Isa Group northwest of Mount Isa, have at their base a conglomerate containing pebbles almost certainly derived from the northern part of the Sybella Granite. Hence, the Mount Isa Group is considered to postdate the exposure of at least some, if not all, of the phases of the Sybella Granite, but antedate the major deformation which affected the Leichhardt River fault trough. If this interpretation is correct, it follows that the major folding deformation, and possibly also the development of the Mount Isa Fault Zone, postdated *both* the emplacement of the Sybella Granite (ca. 1645-1570 m.y., Page & Derrick, 1973) and the deposition of the Mount Isa Group (at about 1600-1500 m.y., ages after Richards *et al.*, 1963; Ostic *et al.*, 1967; Cooper *et al.*, 1969). We suggest that this deformation ensued from east-west compression of the Haslingden and Mount Isa Groups between the rigid blocks of the Kalkadoon-Leichhardt complex and Sybella Granite. This could also have been the stage at which the Surprise Creek Beds were downfaulted and deformed through reactivation of the Gorge Creek-Quilalar Fault Zone. It is likely that the isotopic K-Ar ages of 1500-1400 m.y. determined over much of the Mount Isa-Cloncurry region (Richards *et al.*, 1963) reflect cooling and cessation of Ar diffusion upon the waning of regional metamorphism associated with this major deformation stage.

To summarize, we consider that the folds with north-south trending axes within the Leichhardt River fault trough can be interpreted in terms of one major tectonic

TABLE 1. SUMMARY OF STRATIGRAPHY AND CORRELATIONS WITHIN THE LEICHHARDT RIVER FAULT TROUGH, NEAR MOUNT ISA.

	Unit	*Thickness*	*Lithology*	*Correlations*	*Notes*
Mount Isa Group (MG)	Magazine Shale, Spear & Kennedy Siltstone, Urquhart Shale, Native Bee Siltstone, Breakaway Shale, Moondarra Siltstone	about 5000 m	Shale, siltstone, dolomitic siltstone, acid tuff; the group is divided into several formations (Cordwell et al., 1963; Bennett, 1965, 1970)	Moondarra Siltstone and Warrina Park Quartzite equivalent to most or all of Surprise Creek Beds and Mingera Beds.	Urquhart Shale contains the Mount Isa Ag-Pb-Zn and Cu ore deposits; it thins to ca. 2000 m at Hilton.
Mount Isa Group (MG)	Warrina Park Quartzite (WPQ)	670-1320 m	(a) Ortho quartzite, conglomerate (40-70 m) (b) Ferruginous argillite member (330-610 m) (c) Quartzite-conglomerate member (300-580 m)		Very thin in the Mount Isa and Moondarra blocks.
	Unconformity in places				
Haslingden Group (HG)	Myally Beds (MB)*	about 800 m	Feldspathic quartzite, orthoquartzite, minor siltstone and conglomerate. In the Counter block divisible into three units (from top to base) Feldspathic sandstone member (380-580 m) Clayey sandstone, siltstone (220 m) Orthoquartzite (200 m)	Judenan Beds	The stratigraphic sub-divisions in the Counter Block are not recognised in the Mount Isa and Moondarra blocks, but are repeated in the Prospector Sheet area to the north.
Haslingden Group (HG)	Eastern Creek Volcanics (ECV)	2600-6700 m	Metabasalt, amydaloidal metabasalt, flow-top breccias, quartzite and epidote quartzite intercalations, minor pelitic beds. Subdivided as follows (from top to base) (a) Pickwick Metabasalt Member (700-1500 m) (b) Lena Quartzite Member (170-500 m) (c) Cromwell Metabasalt Member (1750-4700 m)	Correlated with the 'western greenstones', west of the Mount Isa fault, and greenstone fault slices adjacent to the Mount Isa fault.	Thickness changes are shown in Figs. 2 & 3.
Haslingden Group (HG)	Mount Guide Quartzite	3500-6200 m	Feldspathic sandstone, quartzite, greywacke and greywacke-conglomerate. Subdivided as follows (from top to base) (a) Sandstone Member (cross-bedded) (1750-3170 m) (b) Greywacke-conglomerate (1720-3030 m) arkose member	Correlated with May Downs Gneiss west of the Mount Isa fault, and with a thin arenite-conglomerate unit overlying the Rifle Creek granite dome.	
	Unconformity				
	Kalkadoon-Leichhardt acid igneous complex		Granite, gneiss, granodiorite, aplite, pegmatite; intruded into acid volcanics and porphyries.		Within the southern part of the Leichhardt River trough the Mount Guide Quartzite rests disconformably on acid volcanics correlated with the Argylla Formation.

*** The term is currently being updated to 'Myally Subgroup'.**

TABLE 2. INTERPRETED STRUCTURAL TIMETABLE FOR THE LEICHHARDT RIVER FAULT TROUGH

Age Datum (approx.)		Event
1400 m.y.		Stabilization; some dyke intrusion; cooling (cessation of Ar diffusion).
	post-depositional	Major period of conjugate fault system, with sinistral NW faults and dextral NE faults. Max stress E-W, int. stress vertical, min. stress N-S.
		Cross-faulting and some northwards tilting of blocks about E-W axes (sense of movement N-block up) max. stress E-W, int. stress N-S, min. stress vertical.
		Basic dyke intrusion along axial plane fractures of NS folds.
		Broad regional folding about N-S axes; north-trending reverse faulting with some strike-slip: some older meridional faults reactivated. Greenschist facies regional metamorphism.
	syndepositional	Deposition of the Mount Isa Group.
1656 m.y.		Intrusion of Sybella Granite and associated uplift and deformation.
		Sand deposition (Myally Beds); development of topography by reactivation of older E-W and N-S faults.
		Faulting on EW trends.
		Erosion of basement (MGQ), fissure eruption of the ECV over irregular fault controlled terrain.
pre-depositional *1700 m.y.*		Uplift of Kalkadoon-Leichhardt basement areas along eastern margin of the trough.

event, during which the Haslingden and Mount Isa Groups were co-folded between the Leichhardt and Sybella granitic blocks. This event was preceded by early and penecontemporaneous faulting and uplift and tilting of Haslingden Group rocks, and was postdated by strong faulting which dissected and tilted northward the north-trending folds. A major basic dyking phase occurred between the folding and the late faulting phases. We are unable to correlate directly the above fold episode with the several folding phases suggested on the basis of a study of a small area west of Mount Isa by Farquharson & Wilson (1971). It remains to be demonstrated whether the three coaxial fold types described from this area indicate temporally distinct events or have evolved continuously during the principal tectonic episode which affected the Leichhardt River fault trough.

Implications for mineralization

Richards *et al.* (1963) and Ostic *et al.* (1967) deduced a single-stage model lead age of 1600 m.y. for the syngenetic Ag-Pb-Zn Mount Isa deposits, whereas Cooper *et al.* (1969) recalculated the age to near 1500 m.y. Farquharson & Wilson (1971) considered the ores to be as old as 1800-1930 m.y., as a corollary of their view that the Kalkadoon Granite is younger than the Mount Isa Group. As is shown above, however, the Kalkadoon Granite is older than the succession in the Leichhardt River fault trough. Moreover, since the deposition of the Mount Isa Group almost certainly postdates at least the main phase of the Sybella Granite (Plumb & Derrick, 1975), a probable maximum limit ca. 1650 m.y. (the age of the main Sybella Granite) can be placed on the age of the Mount Isa ore deposits. The model lead ages of the ore are thus in broad agreement with both the field and isotopic Rb-Sr data. The present model

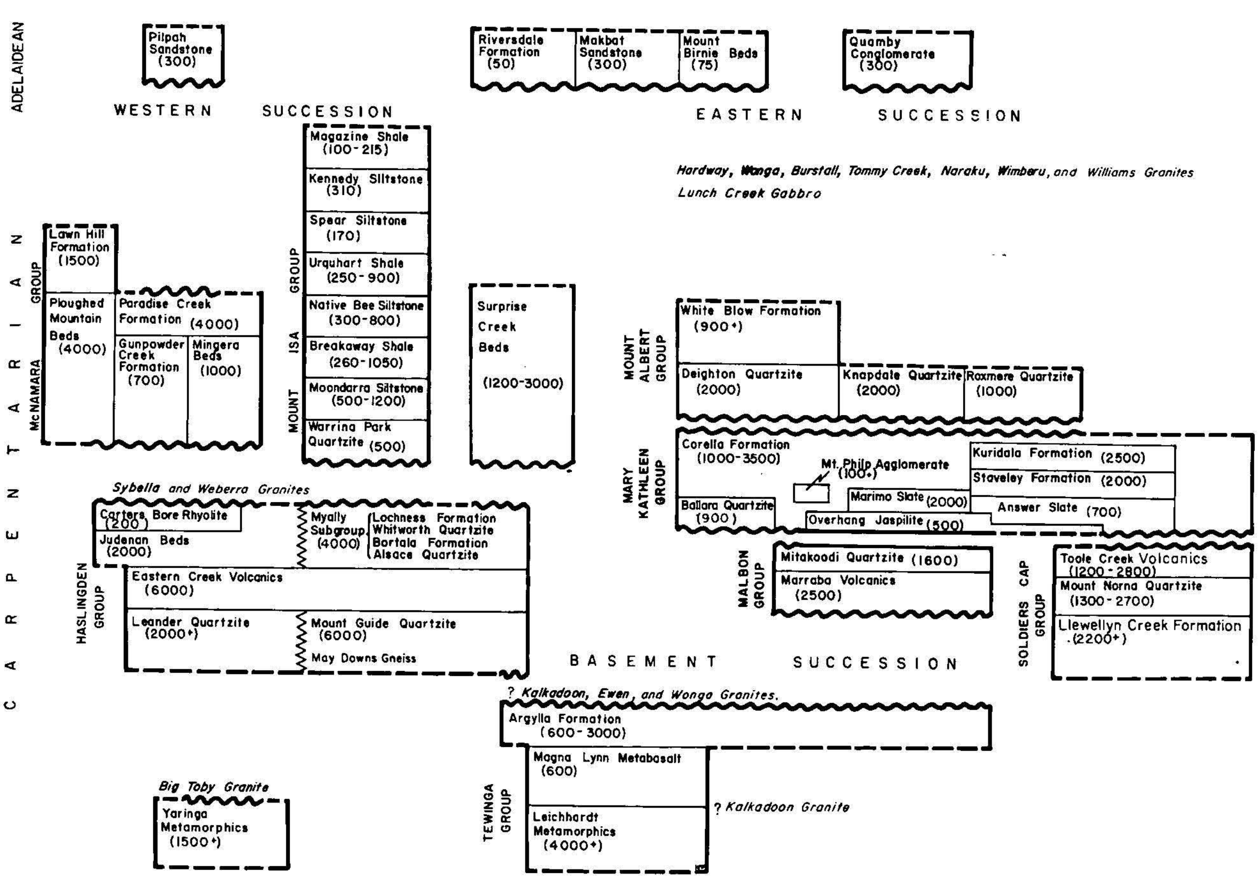

Figure 14. A stratigraphic correlation chart for the Mount Isa-Cloncurry area (after Plumb and Derrick, 1975).

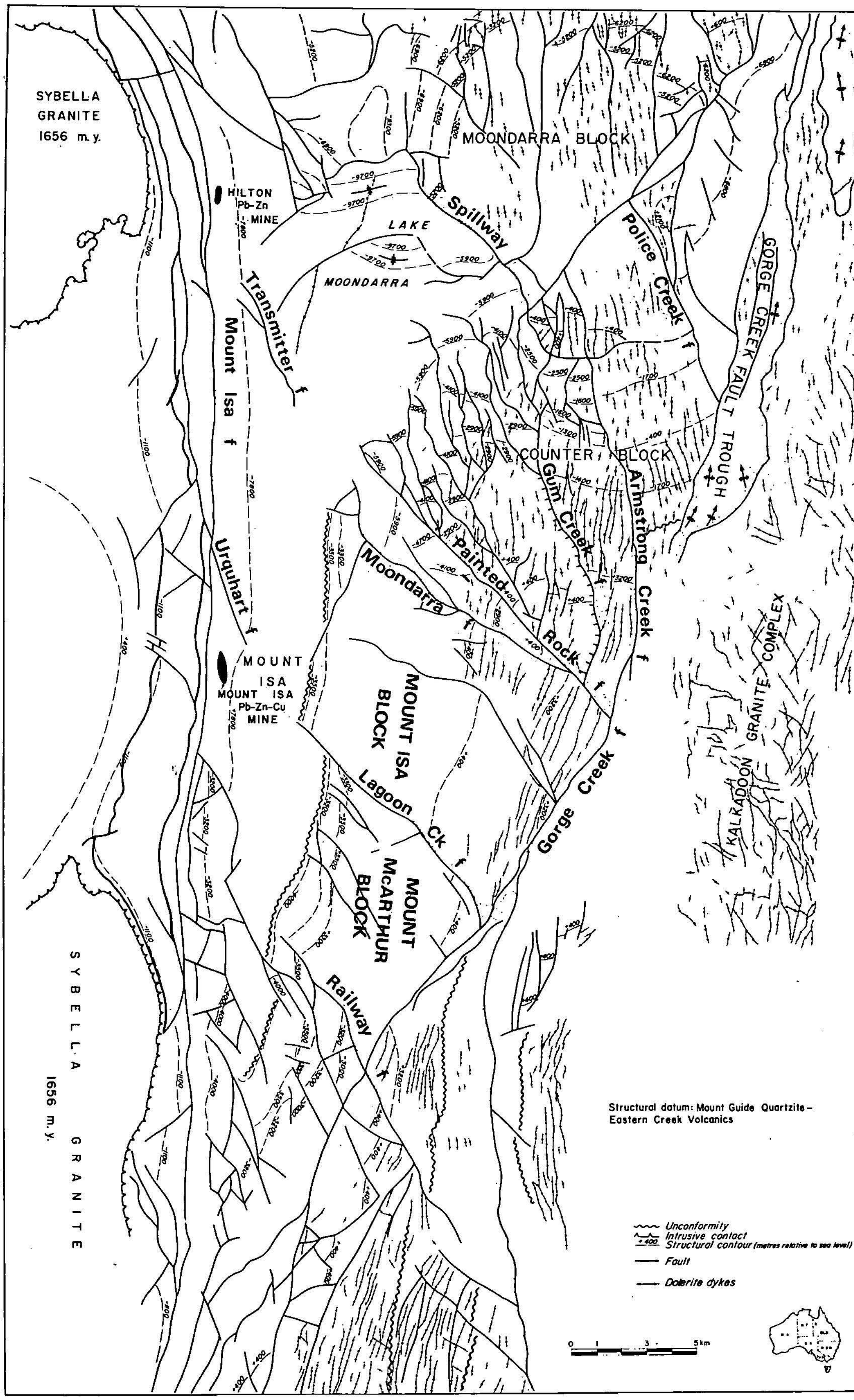

Figure 15. Structural units, major faults, and basic dykes within the Leichhardt River fault trough. Structural contours are shown for the Mount Guide Quartzite — Eastern Creek Volcanics boundary; depths of the contours are estimated from surface information only, and are regarded as decreasingly reliable with depth.

of evolution is also consistent with the similarity of Pb isotope ratios in the Eastern Creek Volcanics, Kalkadoon Granite, and the Mount Isa Ag-Pb-Zn ore reported by Farquharson & Richards (1974), since erosion of the Kalkadoon-Leichhardt complex and the Eastern Creek Volcanics may have contributed lead to the Mount Isa ore bodies.

Cu, Pb, and Zn levels are generally higher in basalts of the Eastern Creek Volcanics than in average basalts (Table 3), and these rocks may have been the source of the Ag-Pb-Zn ores, which are considered to be syngenetic (cf. Croxford, 1965), and of the Cu ores, which may be epigenetic (Smith & Walker, 1971). Sedimentary derivation of base metals from the volcanic rocks suggest exposure and denudation of the Eastern Creek Volcanics in the Mount Isa block, but is not in accord with the absence of basic debris in the overlying Myally Beds and Warrina Park Quartzite. It is possibly significant that the Mount Isa and Hilton Ag-Pb-Zn deposits overlie the upfaulted Mount Isa and Moondarra blocks respectively, but that no mineralization is known to occur in the Mount Isa Group above the Counter block, where a full sequence of Haslingden Group and Warrina Park Quartzite is developed. This feature could perhaps be explained if upfaulted blocks of Eastern Creek Volcanics constituted sources of Cu-rich solutions responsible for epigenetic ores in the Mount Isa Group. Accordingly, further prospecting in those parts of the Mount Isa Group that unconformably overlie upfaulted blocks of Eastern Creek Volcanics may be warranted.

Crustal setting of the the Leichhardt River fault trough

In order to gain an insight into the crustal setting of the Leichhardt River fault trough we examine in this section the tectonic implications of the geochemistry of basalts within the trough, i.e. the Eastern Creek Volcanics, as compared to those of broadly time equivalent basalts in other parts of the region, such as the Soldiers Cap Group and Marraba Volcanics, and also to those of modern basalts.

Some pertinent results of a comparative geochemical investigation of basic volcanic belts in northwestern Queensland are summarized as averages presented in Table 3, and are briefly listed below. The full results will be discussed in more detail elsewhere (Glikson & Derrick, in prep.).

(1) Metabasalts of the Eastern Creek Volcanics, like those of the Soldiers Cap Group and Marraba Volcanics (Figs. 1, 14), have a high total FeO (total Fe as FeO), high FeO/MgO ratios, low Al_2O_3, low MgO, low Sr and Sr/Ca, low Ni and Ni/Mg, and low Cr and Cr/Fe in comparison to the average basalts of Turekian and Wedepohl (1961) and Taylor (1964).

(2) Metabasalts of the Eastern Creek Volcanics commonly show high Pb and low S in comparison to average basalts. They also show high TiO_2, K_2O, Rb, P_2O_5, Pb, Cu, Zn, and Ni in comparison to metabasalts of the Soldiers Cap Group.

TABLE 3: AVERAGE MOUNT ISA—CLONCURRY METABASALTS COMPARED WITH AVERAGE BASALTS.

	Northwest Queensland Proterozoic metabasalts								*Average basalts*					
	SCF	*Average Deviation*	*% Average Deviation*	*ECV*	*Average Deviation*	*% Average Deviation*	*MV*	*BD*	*(1)*	*(2)*	*(3)*	*(4)*	*(5)*	*(6)*
SiO_2	48.93	1.67	3.41	48.68	1.92	3.94	50.63	50.80	49.3	49.2	51.57	50.59	50.56	50.1
TiO_2	1.61	0.49	30.43	2.07	0.67	32.37	1.60	1.50	2.3	1.39	0.80	1.05	2.78	2.17
Al_2O_3	14.04	1.32	9.40	13.57	0.89	6.56	14.45	14.07	14.7	15.8	15.91	16.29	12.79	14.0
Fe_2O_3	4.41	1.50	34.01	5.25	2.21	42.09	4.69	2.07		2.2	2.74	3.66	3.23	13.5t
FeO	9.68	2.64	27.27	8.37	1.00	11.95	7.94	9.72		7.2	7.04	5.08	11.28	
MnO	0.23	0.06	26.09	0.20	0.03	15.00	0.27	0.19	0.2	0.16	0.17	0.17	0.22	0.18
MgO	5.39	1.20	22.26	5.94	1.13	19.02	5.33	6.19	7.6	8.5	6.73	8.96	5.40	6.46
CaO	10.21	2.25	22.04	7.97	1.64	20.58	8.66	8.22	10.6	11.1	11.74	9.50	10.29	9.82
Na_2O	2.57	1.07	41.63	2.92	0.74	25.34	1.89	3.20	2.4	2.7	2.41	2.89	2.55	2.54
K_2O	0.82	0.49	59.76	1.05	0.40	38.09	1.67	1.01	1.0	0.26	0.44	1.07	0.59	0.80
$H_2O_{(t)}$	0.71	0.27	38.03	2.77	0.97	35.02	0.17	1.77		—	0.45	0.81	—	
CO_2	0.33	0.32	96.97	0.73	0.71	97.26	0.53	0.27		—	—	—	—	
P_2O_5	0.16	0.05	31.25	0.34	0.20	58.82	0.22	0.19	0.25	0.15	0.11	0.21	0.31	
Total	99.09			99.86			98.05	99.20	99.45	98.66	100.11	100.28	100.00	99.55
Total Fe as FeO	13.64	2.49	18.25	13.09	2.39	18.26	12.16	11.58	11.1	9.18	9.51	8.37	14.19	12.15
Ba ppm	247	133	53.85	253	111	43.87	791	221	330	12	75	115		352
Pb	8	4	50.00	40	8	20.00	12	33	6					
Rb	22	18	81.82	25	15	60.00	35	46	30	1	5	10		36
Sr	172	87	50.58	185	51	26.98	152	197	465	.123	200	330		428
Zr	121	28	23.14	239	76	31.80	147	149	140	100	70	100		224
La	64	5	7.81				76		15		1.1	9.6		
Y	33	6	18.18	49	12	24.49	34	36	21	43				
Zn	29	17	58.62	111	47	42.34	75	65	105	122				
Cu	61	42	68.85	123	66	53.66	56	143	87	87				
Co	47	12	25.53				45		48					
Ni	56	22	39.29	79	25	31.65	71	85	130	123	30	25		124
Sc	40	5	12.50	38	2.5	6.58	33	38	30					36
V	372	132	35.48	277	60	21.66	237	262	250	289	270	255		
Cr	85	59	69.41	90	52	57.78	114	135	170	296	50	40		
S	426	203	47.65	52	4	7.69	925	67	300					

Key for Table 3.

SCF — Average of 25 metabasites of the Soldiers Cap Formation.
ECV — Average of 20 metabasites of the Eastern Creek Volcanics.
MV — Average of 6 metabasites of the Marraba Volcanics.
BD — Average of 6 basic dykes from the Mount Isa area.

(1) — Average basalt (Turekian and Wedepohl, 1961).
(2) — Average oceanic tholeiite (Melson and Thompson, 1971).
(3) — Average island-arc tholeiite (Jakes and White, 1971).
(4) — Average calc-alkaline basalt (Jakes and White, 1971).
(5) — Average Deccan Plateau basalt (Sukheswala and Poldervaart, 1958).
(6) — Average continental tholeiite (Condie *et al.*, 1969).

(3) As shown by Ol'-Ne'-Q' ratios and by the FMA diagram metabasalts of the Eastern Creek Volcanics correspond to the subalkaline field and display an iron enrichment trend typical of tholeiitic basalts.
(4) A relatively high abundance of large-radius lithophile elements, and of TiO_2, in the Eastern Creek Volcanics preclude a correlation with ocean-floor tholeiites.
(5) The relatively high TiO_2, Ni, Cr, Co, and Sc levels in the Eastern Creek Volcanics preclude a correlation with island-arc tholeiites, and the alumina abundances are lower than those of circum-Pacific calc-alkaline basalts (Kuno, 1960; Taylor *et al.*, 1969; Gill, 1970; Jakes & White, 1971).

In attempting a tectonic classification of the Eastern Creek basalts, it is borne in mind that open-system metamorphism must have been widespread in places, involving introduction of H_2O and CO_2, and the redistribution of mobile elements such as K, Rb and Ca. Criteria derived from abundances of alkali and alkaline earth elements must therefore at best lead to highly tentative conclusions. On the other hand, criteria based on the distribution of ferromagnesian elements and transition metals may be more acceptable in this regard. Pearce and Cann (1971; 1973) have shown that $Ti.10^{-2}$:Zr:Y.3 ratios of basalts are diagnostic with respect to their tectonic environment, and that due to their low mobility these elements are relatively little effected by metamorphic redistribution processes. Plots of data for the basaltic rocks of the Mount Isa-Cloncurry area (Fig. 16) show that 12 out 15 samples of the Eastern Creek Volcanics plot within the field of calc-alkaline basalts, whereas 18 out of 25 samples of the Soldiers Cap Group plot within the field of ocean floor tholeiites. Neither group plots in the field of 'within-plate basalts', which includes continental and ocean-island basalts.

A further discrimination between non-oceanic and ocean-floor basalts is afforded by the TiO_2-K_2O-P_2O_5, diagram (Pearce *et al.*, 1974) — subject to the qualification arising from the mobility of potassium during metamorphism. 13 out of 18 samples of the Eastern Creek Volcanics plot within the field of non-oceanic basalts, whereas 16 out of 25 samples of the Soldiers Cap Group plot within the oceanic field (Fig. 17).

From the above criteria, the metabasalts of the Eastern Creek Volcanics correspond to either calc-alkaline or 'non-oceanic' basalts. However, as indicated above on the basis of their high TiO_2, Ni, Cr, Co, and Sc contents, these rocks are unlikely to be of calc-alkaline lineage. The high TiO_2 and P_2O_5, which reside in the relatively stable minerals ilmenite and apatite, respectively, suggest a correlation with continental flood tholeiites (Table 3). This correlation is corroborated by the high FeO/MgO ratios and the low Al_2O_3 levels of the metabasalts of the Eastern Creek Volcanics. Bearing in mind the preceding qualifications regarding alkali and alkaline earth elements as indicators of primary composition in metamorphic rocks, plots of K against K/Rb, K/Ba, Ca/Sr, and K/Sr (Condie *et al.*, 1969) furnish supporting evidence for the correlation between the Eastern Creek Volcanics and continental tholeiites (Glikson & Derrick, in prep.). Thus, whereas due to secondary alteration, possible crustal contamination, and original mantle heterogeneity none of the above parameters can *in itself* be considered a sufficient basis for tectonic classification of the basalts, taken *together* these criteria argue for a correlation between the Eastern Creek Volcanics and continental flood tholeiites.

The geochemical correlation is consistent with considerations based on the structural and stratigraphic disposition of the Eastern Creek Volcanics, as follows:

(1) Calc-alkaline and island-arc volcanic sequences generally comprise mafic to acid cycles (Gill, 1970; Jakes & White, 1971). In contrast, in the Liechhardt River fault trough basic volcanic activity was in places preceded by acid volcanic activity represented by the Argylla Formation.

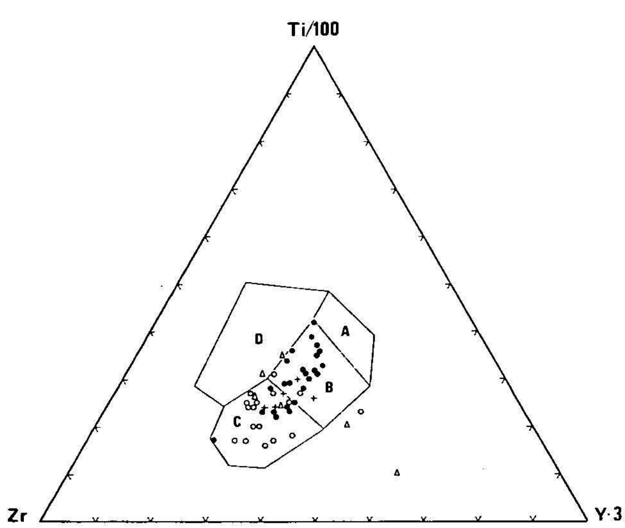

Figure 16. $T.10^{-1}$–Zr-Y.3 ternary diagram, showing plots of chemical data of metabasalts of the Eastern Creek Volcanics (open circles) and basic igneous rocks of the Soldiers Cap Group (solid circles). Also included are plots of the Marraba Volcanics (triangles) and basic dykes intruded into the Eastern Creek Volcanics and the Kalkadoon-Leichhardt basement complex (crosses). A—low-K tholeiite field; B—ocean-floor tholeiites field; C—calc-alkaline basalt field; D—within-plate basalts field (including ocean-island basalts and continental basalts) (after Pearce and Cann, 1973).

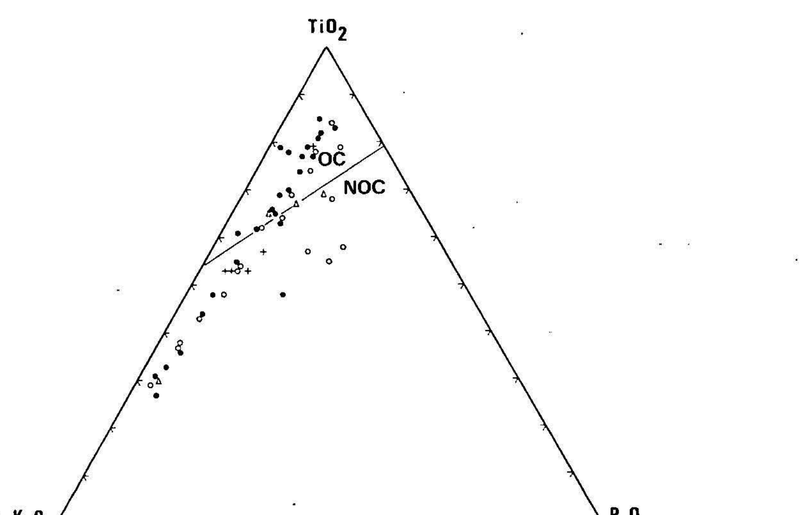

Figure 17. K_2O-TiO_2-P_2O_5 ternary diagram, showing plots of chemical data of metabasalts of the Eastern Creek Volcanics and basic igneous rocks of the Soldiers Cap Group (symbols as for Fig. 10). Also included are plots of the Marraba Volcanics and basic dykes intruded into the Eastern Creek Volcanics and the Kalkadoon-Leichhardt basement complex. OC—field of oceanic basalts; NOC—field of nonoceanic basalts (after Pearce et al., 1974).

(2) The development of the Eastern Creek Volcanics adjacent to and probably above sunken blocks of the Kalkadoon-Leichhardt basement precludes its correlation with the mostly ensimatic volcanic successions of island arcs.

Thus, the classification of the Eastern Creek Volcanics as mainly continental flood tholeiites, and of basalts of the Soldiers Cap Group as mainly ocean-floor tholeiites, suggests a transition from an ensialic environment in the west to a continental margin domain in the east. This possibility is also supported by the following observations:

(1) An abundance of graded, turbidity current-type greywackes in the lower part of the Soldiers Cap Group — these are unique in the Cloncurry-Mount Isa region, and may imply more open marine conditions (Kuenen, 1964) in the east, in contrast to an epicontinental environment in the west;
(2) Middle amphibolite facies metamorphic rocks are exposed in the anticlines in the Soldiers Cap Group south of Cloncurry. In the Leichhardt River fault trough and adjacent areas, lower to middle greenschist facies predominate, and higher grade rocks are confined to thermal aureoles around granites. If a reciprocal relation between crustal thickness and geothermal gradient is assumed, the above variations could reflect a thinning of the crust eastwards;
(3) a predominance of faulting in the west (which includes the Leichhardt River fault trough) and of folding in the east (Fig. 1). These differences may be related to increasing ductility associated with eastward crustal thinning.

Certain elements of the geology of the Leichhardt River fault trough can be compared with those of rift valleys; these include (1) the indications of an early existence of the Gorge Creek-Quilalar Fault Zone, discussed above; (2) the possible occurrence of early faults within the trough; (3) the continental nature of sedimentation and volcanism within the trough; and (4) the general analogy between the stratiform syngenetic Mount Isa and Hilton Ag-Pb-Zn ores and the Red Sea sulphide deposits. On the other hand, alkaline volcanism, typical of the Syrian-African rift system, has not been recognized to date in the Mount Isa-Cloncurry terrain, nor has regional doming, which is associated with parts of the east African rift valleys, been detected. It must be borne in mind, however, that Precambrian ensialic rift valleys could have differed from their modern counterparts, and that Proterozoic aulacogens (Hoffman, 1973) may have been characterized by different types of volcanic activity compared to younger structures. It is pertinent to note here the general scarcity of alkaline volcanics in the Precambrian, possibly due to generally shallower levels of partial melting and basalt generation during this era (cf. Glikson, 1970).

Conclusions

(1) The Leichhardt River fault trough is a distinct structural domain deformed between older granitic terrains. The suggestion by Carter *et al.* (1961) that early pre-depositional faulting took place along the eastern border of this trough is supported by further evidence. It is not clear whether early phases of the Mount Isa and Mount Gordon fault zones along the western border of the trough existed during sedimentation and volcanism in the trough.
(2) Two major unconformities are present within the Leichhardt River fault trough; the first occurs above the Kalkadoon-Leichhardt acid igneous complex. The second occurs at the base of the Mount Isa Group in certain fault blocks, but is not evident in other areas. The younger unconformity indicates that uplift, erosion and some deformation occurred in pre-Mount Isa Group times. Reactivation of old fault lines is a common feature, in agreement with Smith's (1969) concept of penecontemporaneous faulting. However, thickness changes across some of these faults may be due to complex, post-depositional faulting of lenticular units.
(3) The major deformation and metamorphism within the Leichhardt River fault trough can be related to an east-west compression which resulted in the formation of north-trending folds and possibly also the Mount Isa fault zone. The peak of this phase probably postdates both the emplacement of the Sybella Granite (ca. 1650 m.y.) and the deposition of the Mount Isa Group. It was accompanied by regional metamorphism which was followed by dyke intrusion and younger major faulting.
(4) Geochemical data suggest the Eastern Creek Volcanics may be related to continental flood basalts. High Cu, Pb, and Zn levels are characteristic of these rocks. The Ag-Pb-Zn ores at Mount Isa and Hilton could be related to erosion of basement and volcanic rocks, and the Cu ores of Mount Isa to epigenetic deposition from Cu-rich solutions derived from upfaulted blocks of Eastern Creek Volcanics which underlie the Mount Isa Group (Smith & Walker, 1971).
(5) The Leichhardt River fault trough formed within an ensialic environment transitional eastwards into a continental margin domain. Although the trough has certain features in common with modern rift valleys, the absence of alkaline volcanics is inconsistent with such a correlation. A classification as an ensialic rifted zone, possibly analogous to an aulacogen (Salop & Scheinmann, 1969; Hoffman, 1973) may be applicable.

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The Karumba Basin, northeastern Australia and southern New Guinea

H. F. Doutch

The Karumba Basin in its present form coincides areally with the Gulf of Carpentaria and the river systems draining into it.

The Basin is mainly of Cainozoic age, epi-cratonic, and superimposed on the Mesozoic Carpentaria Basin of the Trans-Australian Platform Cover. The development of the Karumba Basin related to the separation of Australia from Antarctica, and to subsequent plate margin events in New Guinea, in contrast to the evolution of the Carpentaria Basin which probably correlated with plate convergence to the east.

The structural basin contains four main sets of deposits, each primarily resulting from an uplift episode. The oldest set, the Bulimba Formation, is probably of late Cretaceous-Paleocene age; the next, the Wyaaba Beds and equivalents, is Miocene to early Pliocene; the third, the Yam Creek Beds and equivalents, is of Pliocene age; the youngest began accumulating in the late Pliocene and is still being deposited. The total thickness of the four sets is about 400 m; they occupy a relatively small part of the present Karumba structural Basin.

This paper proposes and describes the mainly Cainozoic Karumba Basin, accenting it as a tectonic entity. The Karumba Basin is named after Karumba township at the head of the Gulf of Carpentaria; the Basin as it is now coincides with the Gulf of Carpentaria and the river systems draining into it. In the past the rocks and sediments of the Basin have been regarded as being part of the Carpentaria Basin, or as surficial deposits.

Differentiation of the Karumba Basin from the Carpentaria Basin could be based on the regional unconformity between them, and on lithological differences. However, basins cannot be completely defined by their structures and stratigraphies, and ultimately need to be specified according to their origins. Thus recognition of separate Karumba and Carpentaria Basins will be more acceptable if the unconformity and lithologies can be related to distinctive stages of crustal history. The author considers that the evidence given in this paper suggests that the Karumba Basin was consequent on the separation of Australia from Antarctica, an event which ended the development of the Carpentaria Basin.

The history of development of the Karumba Basin thus differentiated provides a uniformitarian and actualistic model with which the evolution of older basins can be compared. However, the Gulf of Carpentaria, which covers most of the Basin, provides an expensive obstacle to investigation, and nearly all the facts about the Basin's rocks come from onshore; between the Gulf and the Arafura Sea the only information about the basin's margins is bathymetry, and a little geophysical evidence which suggests that thin Cainozoic deposits may occur there (cf. Jongsma, 1974).

In what follows the term sedimentary basin will broadly mean the structural entity in which the sedimentary fill is platform cover, and in which most provenance areas to the fill occur.

Late Cretaceous-Early Tertiary: inception of the Basin

The most direct evidence for distinguishing the Karumba Basin from the underlying Carpentaria Basin comes from the Bulimba Formation and the stratigraphic relations it displays (Smart *et al.*, 1972). The Bulimba Formation is present in Cape York Peninsula, and extends under the adjacent part of the Gulf of Carpentaria (Fig. 1; Zwigulis, 1971; Smart, in prep.a).

The continental clayey quartzose sandstone and sandy claystone of the Bulimba Formation rest unconformably mainly on early Cretaceous marine mudstone and labile sandstone of the Rolling Downs Group of the Carpentaria Basin, and to a lesser extent on older rocks of the Basin and of the Georgetown, Yambo and Coen Inliers (Smart, ibid; Smart & Bain, in prep.). The greatest known thickness of the Bulimba Formation is approximately 139 m in BMR Holroyd 1 (Gibson *et al.*, 1974).

That the unit is more than just an alluvial depositional wedge consequent solely on an eustatic regression of the sea from the Carpentaria Basin is shown by 'piano-key' block faulting and associated broad folding along the northern flanks of the Georgetown Inlier. These tectonic movements occurred after Jurassic and early Cretaceous rocks consolidated and before deposition of the Bulimba Formation (Smart & Bain, ibid). The tectonic origin of the unconformity separating the Bulimba Formation from the various early Cretaceous units it overlies is a prime reason for differentiating the Karumba Basin from the Carpentaria Basin; lithological differences and the depositional hiatus are almost as important, but not critical.

Tectonism probably affected most of the eastern margin of the Karumba Basin at this time. Uplift seems necessary before a granitic provenance for the Bulimba Formation could be exhumed from below Carpentaria Basin rocks to provide what was originally arkosic detritus for the unit (Smart, in prep. a), which, apparently also as a result of uplift, in part consists of valley-fill deposits on the flanks of the present Great Dividing Range and Georgetown Inlier.

There is no evidence that the formation accumulated in a downwarp, although some sagging occurred just north of the Euroka Arch (Fig. 1) after early Cretaceous deposition ceased.

The unfossiliferous Bulimba Formation was deposited between early Cretaceous and Miocene times (see discussion on Wyaaba Beds below). The lateritized Aurukun Surface on the formation appears to correlate with an unnamed surface to the south in the Eromanga Basin which was lateritized in Paleocene times (B. R. Senior, pers. comm.; Table 1). The Bulimba Formation is therefore probably of late Cretaceous-early Paleocene age. As corroborative evidence, the uplift with which the formation was associated can be correlated with emergence of adjacent areas to the north in New Guinea between Cenomanian and Miocene times (Dow, in prep.; APC, 1961).

Cessation of deposition of the Bulimba Formation may have occurred more or less simultaneously with, and as a re-

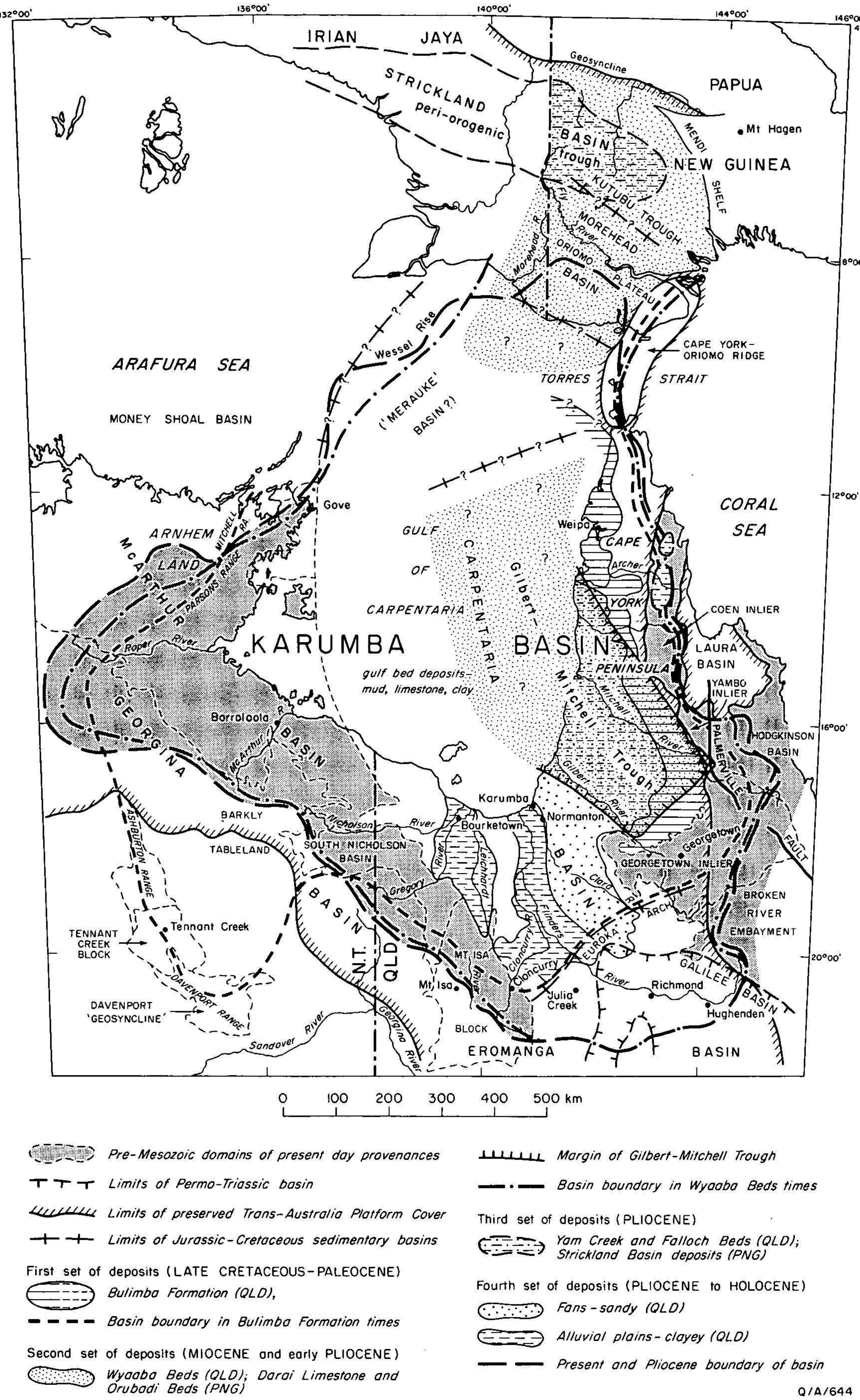

Figure 1. Simplified geology of the Karumba Basin.

sult of, lowering of relief and altitude in provenance areas. Such a terminal state would favour lateritization. This appears to have been the situation in northern Cape York Peninsula, where laterite associated with the Aurukun Surface, preserved as mesa-top peneplain remnants (author, work in progress), occurs on both the Bulimba Formation and the immediately adjacent rocks of Jurassic-Cretaceous age from which it was derived, but not on younger rocks.

The Aurukun Surface is equivalent to Hays' (1967) Tennant Creek Surface (author, work in progress), which was present in southwestern provenance areas of the Bulimba Formation. The bauxite at Gove in eastern Arnhem Land is also an indicator of a contemporaneous surface. In due course parts of these surfaces became provenance areas within the Karumba Basin and were eroded, providing detritus for subsequent basin units.

The late Cretaceous-early Tertiary emerged area in New Guinea is taken to be the northern structural margin of the Karumba Basin at that time. An ancestral Great Dividing Range formed the eastern structural margin. West and south of the present Gulf of Carpentaria equivalents of the Bulimba Formation have not been preserved, and much of this area was probably a provenance for, and in part within, the Basin; the margins of the sedimentary basin there at that time would have been watersheds in the vicinity of the present Parsons and Mitchell Ranges further west of Arnhem Land, the Davenport Range-Tennant Creek-Ashburton Range area in the southwest, and the Mount Isa Block and Euroka Arch in the south (Fig. 1).

Overall, it is proposed that inception of the Karumba Basin occurred in late Cretaceous times as a result of uplifts in New Guinea and Cape York Peninsula. This tectonism is thought to broadly reflect the breaking apart of Australia and Antarctica (Table 1; Falvey, 1971; Boeuf & Doust, 1975). Consequent sedimentation making up the first set of Basin deposits terminated when uplift relief was reduced by erosion. Lateritization completed the initial history of the Karumba Basin.

Late Tertiary: Development of the Basin

Faulting and warping disrupted the lateritized Aurukun Surface (Table 1; Doutch *et al.*, 1973), setting the scene for accumulation of the second set of Karumba Basin deposits, the Wyaaba Beds and their equivalents (Smart *et al.*, 1972; Powell *et al.*, in press), which consist mainly of clayey quartzose sand and sandstone; they are not unlike the Bulimba Formation.

In particular the Gilbert-Mitchell Trough came into existence as the eastern part of the basin (Fig. 1). The downwarping of this trough probably complemented renewed uplifts of the basin margin, which gave rise to a new version of the ancestral Great Dividing Range to the east — especially in the vicinity of the Palmerville Fault (cf. de Keyser & Lucas, 1965, and Willmott *et al.*, 1973 on extent and movements of the fault). The uplifted areas became a new provenance supplying Basin deposits.

The Bulimba Formation, topped by remnants of the Aurukun Surface, forms the basement of the Trough. The contents of the trough may account for the greater part of the 300 m of Cainozoic sediments beneath the Gulf of Carpentaria (Pinchin, 1973); onshore in the southwest of Cape York Peninsula they are represented mainly by the Wyaaba Beds. Again, as in the case of the Bulimba Formation, there is the possibility that slowing down and then the cessation of deposition went hand in hand with a lowering of relief in the provenance areas — and in this instance demonstrably with a reduction in the actual area of provenance. Similarly the culminating event was widespread deep weathering. This time it resulted in the development of patchy silcrete and silicification of the terminal, combined erosional-depositional, Strathgordon Surface, the pediplain part of which resulted from the destruction of the Aurukun Surface by scarp retreat (Grimes & Doutch, in prep.; cf. Doutch *et al.*, 1973). The Aurukun Surface was reduced to a dissected plateau and mesa-top remnants.

The Wyaaba Beds are partly marine, containing fossils with a Pliocene age range (Palmieri, 1973); the pediplain part of the Strathgordon Surface in basalt areas west of Townsville appears to be of early Pliocene age (Grimes & Doutch, ibid). As a result the onshore Wyaaba Beds are considered likely to be of an early Pliocene age, if not older.

In parts of the Gilbert-Mitchell Trough presently under the Gulf of Carpentaria older strata of the Basin's second set of deposits may well occur. This possibility is enhanced by the occurrence, conformably under late Miocene to early Pliocene Orubadi Beds (Bain & Mackenzie, 1974; Dow, in prep.), of 1000 m or more of Darai Limestone that accumulated on the Australian Platform in southern New Guinea during nearly all of Miocene times (Table 1; of APC, 1961, and Willmott, 1972). Both New Guinea units appear to continue southwards into the Karumba Basin, and possibly reflect a northern extension of the Gilbert-Mitchell Trough, representing a northern facies equivalent of the Wyaaba Beds.

These postulated relationships raise the possibility that the marine deposition marked the beginnings of the Gulf of Carpentaria, and thus of the consequent base level regime controlling erosion and deposition in the Karumba Basin ever since. Marine conditions may in part have resulted from transgression following the glacial-eustatic sea level low of early and mid Oligocene times postulated by Kennett *et al.* (1972).

Thus uplift of the ancestral Great Dividing Range, sinking of the Gilbert-Mitchell Trough and the New Guinea part of the Australian Platform, and dislocation of the Aurukun Surface seem on the available stratigraphic evidence to have begun in Eocene to early Miocene times; this tectonism can be associated with the Oligocene orogenic event in New Guinea reported by Dow (in prep.). Downwarping continued during the Miocene deposition of the Darai Limestone, Orubadi Beds and Wyaaba Beds. The early Pliocene silicification (Table 1) suggests that deposition had ceased by then; tectonism may have died down somewhat earlier.

In the north it is impossible to localize the Karumba Basin boundary of the times. But in the east, the sedimentary and structural margin of the Basin was the contemporary version of the Great Dividing Range. The margin of the sedimentary basin was probably pushed westwards and southwards (Fig. 1) by pediplanation concurrent with that which produced the Strathgordon Surface.

The southwestern margin was in the lateritized Cretaceous rocks of the Tennant Creek Surface. This surface has been cut into by pediplanation which advanced simultaneously from the northeast and southwest, and shaped the first watershed between the Karumba Basin and the Barkly Tableland. There is no evidence of tectonism disturbing this area during this event or since (author, work in progress). The maximum elevation of the Cretaceous rocks of this watershed is presently about 300 m, and uplift of these rocks seems more likely than that eustatic regression of the sea stranded sediments at this altitude. Such an uplift, the Pine Creek Upwarp postulated by Hays (1967), would have had to occur before pediplanation produced the watershed and the Wave Hill Surface below it (Hays, ibid); thus uplift could well have taken place at the same time as the Aurukun Surface was dislocated further

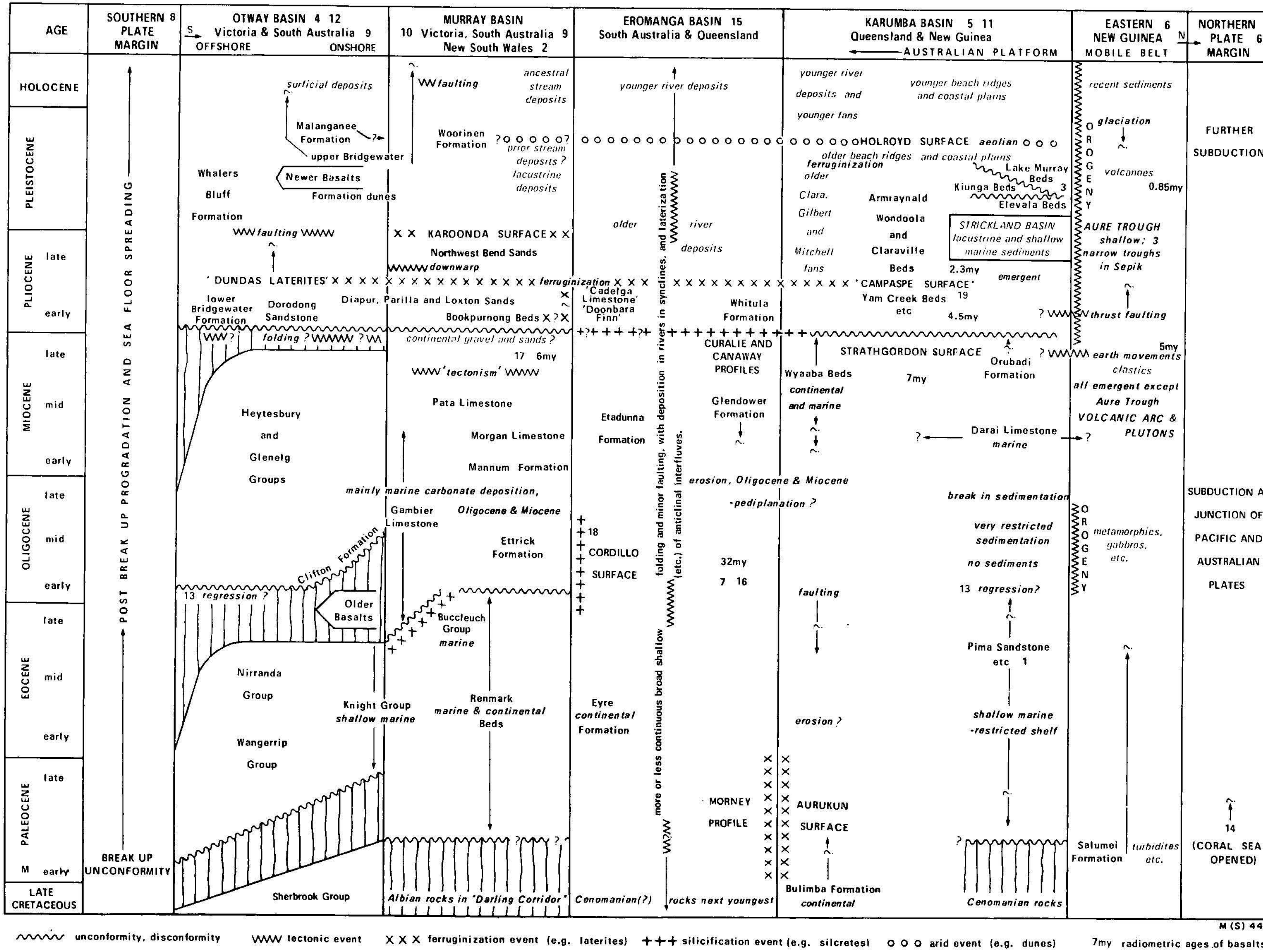

Table 1.
Possible Cainozoic correlations 1. Bain & MacKenzie, 1974; 2. Bembrick, 1974; 3. Blake, 1971; 4. Boeuf & Doust, 1975; 5. Work in progress by the author; 6. Dow, in prep.; 7. Exon et al., 1970; 8. Falvey, 1974; 9. Firman, 1973; 10. Gill, 1973; 11. Grimes & Doutch, in prep.; 12. Kenley, 1971; 13. Kennett *et al.*, 1972; 14. Mutter, 1975; 15. B. R. Senior, pers. comm.; 16. Webb & McDougall, 1967; 17. P. Wellman, pers. comm.; 18. Wopfner *et al.*, 1974; 19. Wyatt & Webb, 1970.

east, i.e. Oligocene, and for the same reason: namely the collision of the Australian and Pacific plates, which resulted in the Oligocene orogeny in New Guinea (Table 1; Dow, in prep.). Furthermore, the Wave Hill surface pediplanation which cut into the upwarped Tennant Creek Surface can be looked on as an event closely related to the destruction of the Aurukun Surface by the developing Strathgordon Surface. As an important side issue here, the Barkly Tableland thus had its inception by isolation from the Karumba Basin by the upwarp; The Davenport Range-Tennant Creek-Ashburton Range source area for the Bulimba Formation became a Tableland provenance thereafter. So the Pine Creek Upwarp is proposed to have been the structural margin of the Karumba Basin in the southwest during deposition of the Wyaaba Beds, and was in much the same place as the present Gulf of Carpentaria watershed.

In summary, late Tertiary development of the Karumba Basin began with uplift along the eastern and southwestern margins and a downwarp in the east. These movements were probably related to the Oligocene orogeny in New Guinea, attributed to a collision of the Australian and Pacific Plates. In a repetition of the Basin's initial history, the second set of deposits was consequent on these uplifts, and similarly, deposition and erosion gave way to deep weathering after relief could be reduced no more. This phase of Karumba Basin history ended with patchy silicification of the Strathgordon Surface.

Pliocene: Modern Basin beginnings

During Pliocene times the two continuing and probably related events that dominated development of the Karumba Basin were the beginning of orogeny in New Guinea and uplifts and associated volcanism in the ancestral Great Dividing Range.

Basalt 7 million years old in the McBride Basalt Province west of Townsville (Griffin & McDougall, 1975) probably indicates the beginning of the end for the Strathgordon and Wave Hill Surfaces. Basalt 4.5 million years old in the Nulla Basalt Province (Wyatt & Webb, 1970) just southeast of the McBride province, occurs in valleys of, or eroded into, the Strathgordon and Aurukun Surfaces (author, work in progress); basalts, apparently also about 4 million years old, of the Chudleigh Park Basalt Province west of the Nulla province, were erupted after an uplift (Doutch *et al.*, 1970) which dislocated the Strathgordon Surface.

Subsequently the Strathgordon and Wave Hill Surfaces were removed from most of the Karumba Basin by pediplanation mainly during Pliocene times; associated with the erosion was deposition of the Basin's third set of deposits, for example the clayey sandstone and conglomerate of the Yam Creek Beds, Falloch Beds and others in Cape York Peninsula. Powell *et al.* (in press) suggested that these units might correlate with the Wyaaba Beds, but this is not supported by the denudation chronologies of each locality. South of the Gulf of Carpentaria the similar Floraville Formation beneath the Doomadgee Plain (Grimes, 1974) was probably deposited during this interval. In the Nulla province the Campaspe Beds are equivalent (Wyatt, 1968; Wyatt & Webb, ibid). What happened in these times in the Gulf of Carpentaria is unclear.

Patchy lateritization and ferruginization followed termination of development of the erosional-depositional surface. In the Nulla province ferricrete formed on the Campaspe Beds in late Pliocene times (Wyatt, ibid). The terminal surface is tentatively named the Campaspe Surface. It is an early phase of Hays' (1967) Koolpinyah Surface, which occurs around the southern and western coasts of the Gulf of Carpentaria, the Campaspe 'phase' in this area being represented by the lateritized 'coastal plain' of Dunn (1963), Plumb & Paine (1964), and others.

In the island of New Guinea orogeny has been raising the central highlands during Pliocene times and since (Visser & Hermes, 1962; Dow, in prep.). South of the rising highlands there was a complementary sinking in the Pliocene of a 'peri-orogenic' trough (Visser & Hermes, ibid.) of which the 'Strickland Basin' (APC, 1961; Fig. 1) is the eastern part (GSA, 1971). This 'basin' is a 3000 metre downwarp of the margin of the Australian Platform and is separated from the Karumba Basin by an east-west upwarp south of the Fly River (Blake, 1971). This upwarp closed the Karumba Basin structurally.

At the end of the third phase of development of the Karumba Basin its margin had altered substantially only in the north, the uplifts in the east hardly affecting the Great Dividing Range watershed; elsewhere Campaspe Surface erosion left a selvedge of Wave Hill and Strathgordon Surfaces piedmont to the remnants of the Tennant Creek and Aurukun Surfaces. The Basin's third set of sediments are the least of the four by volume and area, and are restricted to the south and east of it.

Pliocene-Holocene: latest Basin history

From Pliocene times onwards the northern and southeastern parts of the Karumba Basin continued to be sporadically subject to tectonic disturbance. However, there is little or no evidence of tectonism elsewhere in the basin, and in general the basin margins are watersheds inherited from the Campaspe Surface which have since been modified by headward erosion.

To the southeast, in the eastern part of the Georgetown Inlier, the basaltic volcanism initially associated with uplift in the Chudleigh Park area continued until about 50 000 years ago (Wyatt & Webb, 1970; Griffin & McDougall, 1975; Grimes & Doutch, in prep.). Complementary to this uplift there was dislocation of the Campaspe Surface around the margins of the Gilbert-Mitchell Trough (Grimes & Doutch, op. cit) which could be interpreted to indicate a further slight sinking of the Trough. However, onshore in the Trough, Pliocene to Holocene sandy and clayey delta-like fan deposits of the Gilbert, Mitchell and smaller rivers are probably only of the order of 50 m thick (Powell *et al.*, in press), and uplift of the Campaspe Surface and later prograding of the fans are as likely as sinking of the Trough.

The fan units, together with the sediments below the alluvial plains of the Flinders, Cloncurry and Leichhardt Rivers, make up most of the fourth set of Karumba Basin deposits seen onshore.

There have been five main episodes of fan growth (Grimes & Doutch, op. cit) controlled by changes in climate and sea level. The same controls on landscape evolution can be interpreted from a variety of depositional and erosional features throughout most of the Basin — e.g. terraces, nick points, valley fills — though less easily than in the Gilbert-Mitchell Trough.

The first three episodes seem to be reactions to eustacy for the most part (Grimes & Doutch, op. cit) although minor faulting occurred during the period. The event which separates them from the final two was climatic: sand dunes and dune-like forms, sand plains with clay pans, deflation features and choked drainage are claimed by the author to indicate a desiccation event at that time. Similar features in similar geomorphological sequences are preserved throughout much of Queensland and the Northern Territory, and the event also appears to have occurred in southeastern Australia (Table 1). The features claimed to identify the event make up the Holroyd Surface, a surface the author will define more fully in due course. The event affected older inner beach ridges which are probably between 100 000 to 120 000 years old, but not younger, outer, ridges containing shells giving C^{14} dates of 6440 yrs. BP and less (Smart, in prep. b; Rhodes, pers. comm.; Australian National University, Sydney University and University of N.S.W. laboratory datings). This event may well correlate with the last glacial maximum and corresponding sea level minimum circa 20 000 years ago (cf. Mabbutt, 1967, on the 'great Australian Arid Period'), at which time the Gulf of Carpentaria was dry (Smart, in prep. b).

Increased rainfall after the desiccation event rejuvenated drainage, initiating the last two episodes of erosion and deposition — although some valleys choked during this event have not yet been incised. The increase probably occurred about 11 000 years ago (Kershaw, 1975). The first of the depositional episodes probably began when rainfall increased and terminated when sea level reached a probable maximum 7000 years ago (Smart, in prep. b); the second corresponds with sea level fall since.

South of the Gilbert-Mitchell Trough the fan of the Clara River, which shared the history just outlined, interfingers with the deposits below the 'black soil' plains of the Flinders and Cloncurry Rivers. Grimes (pers. comm.) and the author find it difficult to correlate fan episodes with the history of these two rivers and their deposits, or to the history of the Leichhardt River deposits further west.

Elsewhere in the Karumba Basin, except in New Guinea, erosion predominated in Pliocene to Holocene times. The Holroyd Surface is conspicuous as sand sheets in most areas and as dunes south of the Gulf, and is ubiquitously represented by choked drainage that is now being rejuvenated (author, work in progress).

The little that is known of the offshore equivalents of fan deposits was first outlined by Smart (in prep. a). The sediments consist of thin Pleistocene marine calcareous clay and limestone and late Pleistocene and Holocene sandy shelly muds; the two units overlie the Wyaaba Beds (and/or contemporary sediments) and equivalents of the older fans below the Gulf of Carpentaria.

Phipps (1970) reported C^{14} dates and environmental interpretations from samples collected from the bed of the Gulf by piston coring. His oldest deposits he considered to be of non-marine origin, and they are more than 19 600 years old. Smart (in prep. a) correlated them with his calcareous clay unit. Phipps recognized another non-marine interval which began about 16 600 years ago, and a youngest one which occurred between about 10 000 and 6 500 years B.P.; he considered that these alternations were the result of uplift of the Gulf bed keeping pace with rising sea level. There are no features on shore which support these interpretations.

Smart (in prep. b) has re-examined Phipp's information together with that of Bates *et al.* (1970), Zwigulis (1971) and Gunn (1972). He considered that the older unit was calcreted during an arid period between 35 000 and 11 000 years ago, when the sea had departed from the area of the Gulf. The younger unit was deposited during the subsequent transgression, which reached the Gulf about 11 000 years ago. It is probably more than a coincidence that this is about the time when rainfall began to increase.

In southern Papua New Guinea, Karumba Basin beds correlating with fan deposits are difficult to recognize. Blake (1971) describes Pliocene(?) to Holocene deposits whose stratigraphic inter-relationships are not fully worked out, but which probably belong to the Karumba Basin; Table 1 follows Blake (ibid). Most of them were affected by uplift, one physiographic expression of which is the Oriomo Plateau between the Fly River and the south coast. The Oriomo Plateau is the present northern structural and provenance margin of the Karumba Basin.

Thus the latest phase of the development of the Karumba Basin is related to tectono-magmatic events modifying the Georgetown Inlier which correlate with orogeny in New Guinea. The Basin's fourth, Pliocene-Holocene, deposits are restricted to the Gilbert-Mitchell Trough and to the alluvial plains country in Queensland south of the Gulf of Carpentaria.

Correlation

Table 1 proposes tentative correlations for Cainozoic epicratonic events in eastern Australia. It is no more than a working hypothesis to be tested by more dating. It was constructed by considering events in sequence rather than in isolation, which should enhance the probability that the correlations proposed are sound: e.g., overall the fabrics of Cainozoic tectonism and climatic changes in the Karumba and Eromanga Basins appear similar, and many events are therefore postulated to be penecontemporaneous (of course, the consequences of these events in each basin may differ morphologically). Thus the downwarping that initiated the Gulf of Carpentaria after Aurukun Surface lateritization and before Strathgordon Surface silicification is correlated witht the broad shallow folding that occurred between lateritization and silicification in the Eromanga Basin; this framework then provides a basis for correlating consequent erosion and deposition — e.g., for 'correlating' the Wyaaba Beds with the Glendower Formation — and for a better understanding of crustal evolution.

The overall simplicity and broad uniformity of the Cainozoic evolution of eastern Australia suggested by Table 1 indicates the degree of stability the craton has acquired since Tasman Geosyncline mobility ceased, and the quality of the craton's resistance to plate collision in New Guinea.

Somewhat surprising, considering the Australian continent's dimensions and its northwards drift during the Cainozoic, is the uniformity of the response of the eastern half of it to changes in climate. Ferruginization, including lateritization, in both early Tertiary and Pliocene times was widespread (Table 1), and so, it is beginning to be shown, were the results of the silicification event in early Pliocene times. A general similarity and contemporaneity of response to both climate and tectonism is shown by the histories of the Clara, Gilbert and Mitchell Fans of the Karumba Basin and the Riverine Plains of the Murray Basin (author, work in progress). The arid Holroyd Surface occurs not only in most of eastern Australia but also in a large part of the rest of it: the author has made spot checks of maps, air photographs, Landsat 1 imagery, and from the air. Thus, the climatic history of the Karumba Basin was not unique to it.

Resources

Cainozoic erosion of provenance areas within the structural basin during its development exposed much of the mineral resources of the Cloncurry-Mount Isa areas (Fig. 1; Plumb & Derrick, in press) and parts of the Coen, Yambo and Georgetown Inliers (Fig. 1; Oversby *et al.*, in press), and led to concurrent deposition of alluvials such as gold and tin at Croydon (Doutch, in prep.), the gold deposits of the Palmer River, and gold at Wenlock (Whitaker & Gibson, in prep.). More detrital concentrations probably remain to be discovered.

Pliocene deep weathering of Paleocene (?) laterites of Aurukun Surface plateau and mesa tops culminated in bauxites at Gove (Dunn, 1965; Grubb, 1970) and Weipa (Evans, 1959; Plumb & Gostin, 1973, Smart, in prep. a).

The sediments of the Karumba Basin are not known to contain currently useful mineral reserves at the moment. The known gold and tin alluvials are worked out or uneconomic. Sub-economic heavy mineral beach sands occur south of Weipa (Miller, 1957). Salt could be produced in some coastal areas. Hydrocarbon accumulation in the basin deposits is highly unlikely (Doutch, in press).

Groundwater, some of it highly saline, occurs in discontinuous aquifers in all three sets of Karumba Basin deposits (see e.g. Warner, 1968; Grimes, 1972; Pettifer *et al.*, in prep.). Potable water for the inhabitants of Weipa and Aurukun is obtained from the Bulimba Formation, and for Edward River from the Wyaaba Beds, these settlements being on tidal inlets. Some Bulimba Formation water is used for processing bauxite at Weipa. Pastoralists use some groundwater for stock during the dry season.

Synthesis, discussion and conclusions

Structurally the Karumba Basin is seen as one element of the response of the eastern half of the wholly cratonic continent of Australia to separation from Antarctica and collision with the Pacific Plate during Cainozoic times. The basin developed its present form more from uplift of its margins than from downwarping of its interior, although the Gilbert-Mitchell Trough is an important feature (Fig. 1). Tectonism occurred much more frequently and strongly in the eastern than the western half, and practically all the sediments are also in the east. This suggests relative stability of older cratonic basement blocks in the west with respect to younger ones in the east (cf. GSA, 1971).

The continental clayey sands, sandstones and silts of the Karumba Basin contrast with the underlying marine mudstones and labile sandstones of the Carpentaria Basin, and the sediments of the two basins are separated by an unconformity reflecting a hiatus in late Cretaceous deposition. Sedimentation episodes in the Karumba Basin were initiated by the tectonism responsible for its structure, but arid climates dominate most of the histories of the deposits. Areas between the limits of deposition in the Karumba Basin and the structural margins of the basin were practically the only provenance sources for its deposits.

Erosion in the source areas exposed the mineral resources of the Mount Isa-Cloncurry and McArthur River areas and parts of the Coen, Yambo and Georgetown Inliers, while deep weathering culminated in bauxites at Gove and Weipa. The Basin contains negligible mineral and energy resources of current value.

Tectonically, the Karumba Basin could be regarded as being the youngest part of the Trans-Australian Platform Cover in the sense of the Tectonic Map of Australia and New Guinea, 1971 (GSA, 1971). In the legend of this map the Cover is tied conceptually to the cratonization of the Tasman Geosyncline. More realistically, the three elements of this cover in eastern Australia — the Permo-Triassic, Jurassic-Cretaceous and essentially Cainozoic basins — can be said to reflect three different events in Australia's crustal history. This is an aspect of the Cover which is basic to recognition of the Karumba Basin, and of similar features elsewhere, as a specific and distinctive tectonic entity rather than merely as a collection of surficial deposits.

In the Trans-Australian Platform Cover the Permo-Triassic Cooper and Galilee Basins and equivalents (GSA, op. cit) were hinterland epi-cratonic responses to the Hunter-Bowen tectonic event (cf. Scheibner, 1974). The overlying Jurassic—early Cretaceous Eromanga and Carpentaria Basins were probably the result of mild crustal warping possibly associated with further plate convergence to the east (Veevers & Evans, 1973); this occurred before late Cretaceous rifting which presaged the separation of Australia from Antarctica (Falvey. 1974). The Karumba Basin began forming over the Carpentaria Basin at the time of this split, and developed further during a period of plate margin events in New Guinea. It is probably better not to include the Karumba Basin in the Trans-Australian Platform Cover because of this history; somewhat similar reasoning is inherent in the depiction on the Tectonic map of Australia and New Guinea of the Trans-Australian Platform Cover overlapping older platform covers (GSA, op. cit).

A change in the environment of the Australian Craton between Mesozoic and Cainozoic times seems also to be reflected in the change from submergent to something like emergent-oscillatory epeirogenic conditions in the sense of Sloss & Speed (1974). In Australia both regimes were less energetic than the North American prototypes, while the types of consequent deposits these authors' definitions require are not present in the Carpentaria and Karumba Basins. However, what the deposits in these basins should be according to Sloss & Speed is not as important as that they should differ, which is the case.

Sloss & Speed (op. cit) inferred from their evidence that vertical movements of continental lithospheres relate to the behaviour of oceanic lithospheres. Their conclusion that submergent conditions on the craton correlate with active orogeny or plate convergence raises the question of what the plate margins around Australia were in Carpentaria Basin times — late Jurassic and early Cretaceous — and what their manifestations were. Relatively minor early Cretaceous plutonism and north-trending folding, of late Hunter-Bowen Orogeny affinities perhaps, represent the most vigorous tectonism on the periphery of the Australian continent, or within it for that matter, during those times (GSA, 1971; cf. Dickins & Malone, 1973). The area affected lies east of the Eromanga Basin, the southern and adjacent analogue of the Carpentaria Basin, suggesting a plate margin still further to the east; the relatively minor, if widespread, Jurassic-Cretaceous downwarping and submergence of these two basins was of much the same order of magnitude as the contemporaneous 'orogeny'.

Sloss and Speed's correlation of oscillatory cratonic behaviour with convergence of oceanic and continental plates at distances relatively remote from cratonic margins does not give quite the same picture as that which the Karumba Basin gives of an epicratonic hinterland adjacent to craton margin collision areas in New Guinea. Therefore it may be better to consider the Karumba Basin as being the result of sporadic rather than oscillatory emergence; sporadic emergence could be defined by generalizing the history of movements and kinds of sedimentation marking the development of the Karumba Basin (albeit the Basin is probably still developing). As already shown, these details differ from those of the preceding Carpentaria Basin.

Johnson (1971) demonstrated that orogeny, epeirogeny and eustacy worked in concert in the Phanerozoic in North America — his 'Antler Effect' — in which orogeny and the maximum spread of epeirogenic seas coincide. This idea once again raises the question of a linked orogeny during the Aptian maximum of marine transgression in the Carpentaria and Eromanga Basins, and the answer is the one already given above; the idea also embraces the relationship between the Gulf of Carpentaria and the Pliocene—Holocene orogeny in New Guinea. These two transgressions, then, represented two separate occurrences of the Antler Effect.

Both Sloss and Speed, and Johnson, used the term Sequence: the former correlated a Sequence with each emergent or submergent state of the craton, while the latter described Sequences as major onlap-offlap cycles. The Carpentaria and Karumba Basin successions would seem to be two such Sequences, Aptian-Albian and Miocene-Holocene times being periods of transgression and onlap.

The author neither accepts nor rejects the use of the term Sequence in this context, and is awaiting the outcome of the debate on unconformity-bounded stratigraphic units which began in Circulars 45 and 46 of the International Subcommission of Stratigraphic Classification of the IUGS Commission on Stratigraphy.

Sequences can represent the Tectonic Stages of Doutch (1974) and Schiebner (1974). Their Stages depend on regional unconformities as domain boundaries to more or less conformable successions each with its own structural style. Stages, however, can consist of successions of the order of Sequences on the one hand, or sets (as in the Karumba Basin) on the other, depending in part on assessment of deformation relations between them and with crustal movements elsewhere. Whether the Karumba Basin consists of one or three tectonic Stages is not clear yet, but that the Carpentaria Basin stands on its own as a distinct Tectonic Stage seems undeniable.

The term 'Synthem' has been discussed in the ISSC Circulars mentioned above, and has been proposed formally and used by Chang (1975, a, b, c) for Korean unconformity-bounded successions very like Tectonic Stages. It appears that the Carpentaria Basin constitutes such a Synthem, and the Karumba Basin another, its sets being Chang's 'Interthems'.

These various approaches to the analysis of epeirogeny when taken together emphasize the contrasts between the Carpentaria and Karumba Basins and provide the most fundamental criteria so far available for recognizing and differentiating between sedimentary basins and also between platform covers. They are sufficient for differentiating the Eromanga Basin from the underlying Galilee and Cooper Basins, for example. Recognition of the Karumba Basin also makes the terms Cainozoic and Mesozoic more meaningful for the Australian continent and plate.

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Some aspects of Carboniferous biostratigraphy in eastern Australia: a review[1]

P. J. Jones and J. Roberts[2]

Progress in detailed mapping and biostratigraphical work in New South Wales has resulted in a revision of the current correlations of the Carboniferous rocks in eastern Australia (Jones *et al.*, 1973). Revision of the brachiopod zonation (Roberts, 1975) indicates the widespread distribution of the *Tulcumbella tenuistriata. Schellwienella* cf. *burlingtonensis. Delepinea aspinosa, Rhipidomella fortimuscula. Marginirugus barringtonensis* and *Levipustula levis* Zones; the absence of the *Spirifer sol* and *Orthotetes australis* Zones in Queensland; and the restriction of the latter Zone to the Hunter Valley region of New South Wales. The brachiopods faunas are largely endemic, and where ammonoids, conodonts, and foraminifera are available, attempts have been made to date them in terms of the standard European series.

The lower three brachiopod zones as dated from the goniatite evidence are mainly Tournaisian in age (*tenuistriata* Zone = TnIb or cuI; *sol* Zone = Tn2; cf. *burlingtonensis* Zone = Tn3a to VIa or CuIIγ). Although these ages are broadly consistent with those of the conodont evidence, in detail, there is an apparent discrepancy between the ages of the sequence of gnathodid faunas in the *Schellwienella* cf. *burlingtonensis* Zone at Carellan and Rouchel. A conflict between the late Visean—early Namurian (V3a-EI) ages suggested by the goniatites for the younger brachiopod zones (*australis, aspinosa, fortimuscula* and *barringtonensis* Zones), and the early Visean (VIa) age suggested by the conodonts (Jenkins, 1974), has been partly resolved by Crane (1975, unpubl.), who has shown that the conodonts associated with the *barringtonensis* Zone are no older than cuIIIα (V3b) and probably no younger than early Namurian (EI). However, there still remains the problem that the upper limit of the upper part of the *australis* Zone, as based on the Trevallyn ammonoids (Brown *et al.*, 1965), is the same age as or younger (cuIIδ/cuIIIα = V3b α/β) than the upper limit of the upper subzone (*Gigantoproductus tenuirugosus* Subzone) of the younger *aspinosa* Zone, as based on foraminifera (Mamet's zones 13 to 15; V2b-V3b).

Goniatite (Campbell, 1962) and conodont evidence (Crane, 1975, unpubl.) suggest that the base of the *Levipustula levis* Zone on the correlation chart of Jones *et al.* (1973) should be lowered to almost meet the *barringtonensis* Zone in the earliest Namurian (EI). Apart from brachiopod evidence there is no reliable information available to date the top of the *L. levis* Zone, and at present it is accepted that it extends into the Westphalian (Roberts, 1976).

More biostratigraphical studies of brachiopods, ammonoids, conodonts, foraminifera, and other fossil groups from the Carboniferous of eastern Australia are needed, and an integration of the results of such studies is necessary in order to resolve many of the problems of correlation.

Two charts showing correlations of Carboniferous rocks in Australia have appeared in the past eight years. The first was published for the 1st Gondwana Symposium in Argentina in 1967 (Campbell *et al.*, 1969). The second chart, published by the Bureau of Mineral Resources (Jones *et al.*, 1973), contained a bibliography of the literature dealing with the Carboniferous of Australia between the years 1952 and 1973. References to the literature before 1952 may be found in "Symposium sur les Series dė Gondwana", published in 1952 for the 19th International Geological Congress at Alger. In both charts attempts were made to correlate the Australian sequences with the standard European stages on the basis of ammonoid evidence, supplemented to a lesser extent by brachiopods and conodonts.

In the eastern part of the continent, local correlations were based primarily on the sequence of brachiopod zones, with non-marine portions being correlated rather imprecisely by plants (Fig. 1). Previously published correlation charts and zonal schemes of the Carboniferous of eastern Australia (Roberts, 1965; Campbell & Roberts, 1969; Campbell & McKellar, 1969; Campbell *et al.*, 1969; and Jones *et al.*, 1973) have been based on the results of geological mapping of a reconnaissance nature, and a limited number of fossil localities (Campbell & Roberts, 1969, p. 261). The status of the stratigraphic mapping of the Carboniferous rocks in New South Wales is now beyond that of reconnaissance, and has reached a stage where a detailed stratigraphy is known in many areas (Rouchel 1:50 000 map, Roberts &Oversby, 1974; Paterson-Gresford district 1:126 720 map, Hamilton *et al.*, 1974). Some of the correlations shown in the chart prepared by Jones *et al.* (1973) must now be revised as a result of work either published, in press, or in progress during the past two years.

This paper, based essentially on a Chairman's Address to the New South Wales Division of the Geological Society of Australia by Roberts, aims to review some of these developments, which include revisions to the brachiopod zonation (Roberts, 1975), advances in the biostratigraphy of the conodonts (Jenkins, 1974; Crane, 1975 unpubl.), and rugose corals (Jull, 1974 a, b), and the taxonomic reassessment of some of the ammonoids (Jenkins, 1974; Roberts, 1975). It attempts to analyse, but not solve, some of the conflicting biostratigraphic evidence provided by these fossil groups. Many other fossil groups being studied include polyzoans (B. A. Engel, University of Newcastle), trilobites (B. A. Engel and Noreen Morris, University of Newcastle), plants (J. Rigby, Geological Survey of Queensland; Noreen Morris, Mary E. White, Sydney), and spores (G. Playford, University of Queensland, P. R. Evans, University of New South Wales, and R. Helby, Sydney), but these are not discussed here.

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Wales), Dr T. B. H. Jenkins (Department of Geology & Geophysics, University of Sydney), and Dr K. S. W. Campbell (Department of Geology, Australian National University, Canberra), who provided information relevant to this review. We are indebted to Drs K. S. W. Campbell, T. B. H. Jenkins, B. S. Oversby, E. C. Druce and R. S. Nicoll for valuable discussion and criticism of previous drafts; the opinions expressed herein, however, are entirely our own.

Brachiopods

A sequence of nine brachiopod zones (Fig. 2) is recognized throughout eastern Australia (Campbell & McKellar, 1969; Jones *et al.*, 1973; Roberts, 1975). Roberts (1975) has recently selected reference sections for each of the zones between and including the *Tulcumbella tenuistriata* and the *Rhipidomella fortimuscula* Zones. Because the sections were chosen in areas in which the stratigraphy is well documented, and where there are sequences of diverse brachiopod faunas, they provide an improved definition of the faunal content within each zone, and the stratigraphical relationships between the zones.

In New South Wales, the Swains Gully section (Carey, 1937) in the Werrie Syncline provides a reference for the *Tulcumbella tenuistriata* Zone, the *Spirifer sol* Zone, and part of the *Schellwienella* cf. *burlingtonensis* Zone. The upper portion of the cf. *burlingtonensis* Zone, the *Pustula gracilis* Subzone, the *Orthotetes australis* Zone and the lower part of the *Delepinea aspinosa* Zone have reference sections in the Rouchel area. Richly fossiliferous sections from Salisbury and Brownmore provide a basis for the subdivision of the *aspinosa* Zone into the *Inflatia elegans* and *Gigantoproductus tenuirugosus* Subzones, and references for the *Rhipidomella fortimuscula* Zone. The remaining three zones have yet to be referred to specific sections. The *Marginirugus barringtonensis* and *Levipustula levis* Zones are well known in both New South Wales and Queensland, but the *Syringothyris bifida* Zone is recognized from only one locality near Booral, and may not constitute a valid zone. Engel (1975) has discontinued the use of the *bifida* Zone but has recognized the *Cancrinella levis* Zone as the latest Carboniferous zone in Eastern Australia. *Cancrinella levis* Maxwell is now the type species of *Auriculispina* Waterhouse (1975), and hence the name of Engel's zone becomes the *Auriculispina levis* Zone. The zone is not present in New South Wales, but in Queensland it is recognized in the basal part of the Burnett Formation at Yarrol (Maxwell, 1964) and in the uppermost beds of the Neerkol Formation at Stanwell near Rockhampton (Fleming, 1967). Waterhouse (1975) considers that the *Auriculispina levis* Zone belongs to the Asselian Stage of the Early Permian; Engel (pers. comm.), on the other hand, considers the polyzoans in the *A. levis* Zone to be of Late Carboniferous aspect.

Three major faunal subdivisions are recognizable in the sequence of Carboniferous brachiopod zones (Fig. 2); the first subdivision — the Werrian — corresponds to the *tenuistriata*, *sol* and cf. *burlingtonensis* Zones; the second — the Gresfordian — corresponds to the *australis*, *aspinosa* and *fortimuscula* Zones; and the third — the Barringtonian — corresponds to the *barringtonensis*, and *L. levis* Zones. The lower boundaries of the Werrian, Gresfordian and Barringtonian faunal subdivisions coincide with the respective lower boundaries of the *Tulcumbella tenuistriata*, *Orthotetes australis*, and *Marginirugus barringtonensis* Zones as defined by Roberts (1975), for each of their reference sections. There are major faunal changes between these subdivisions. At present, no reason for the change between

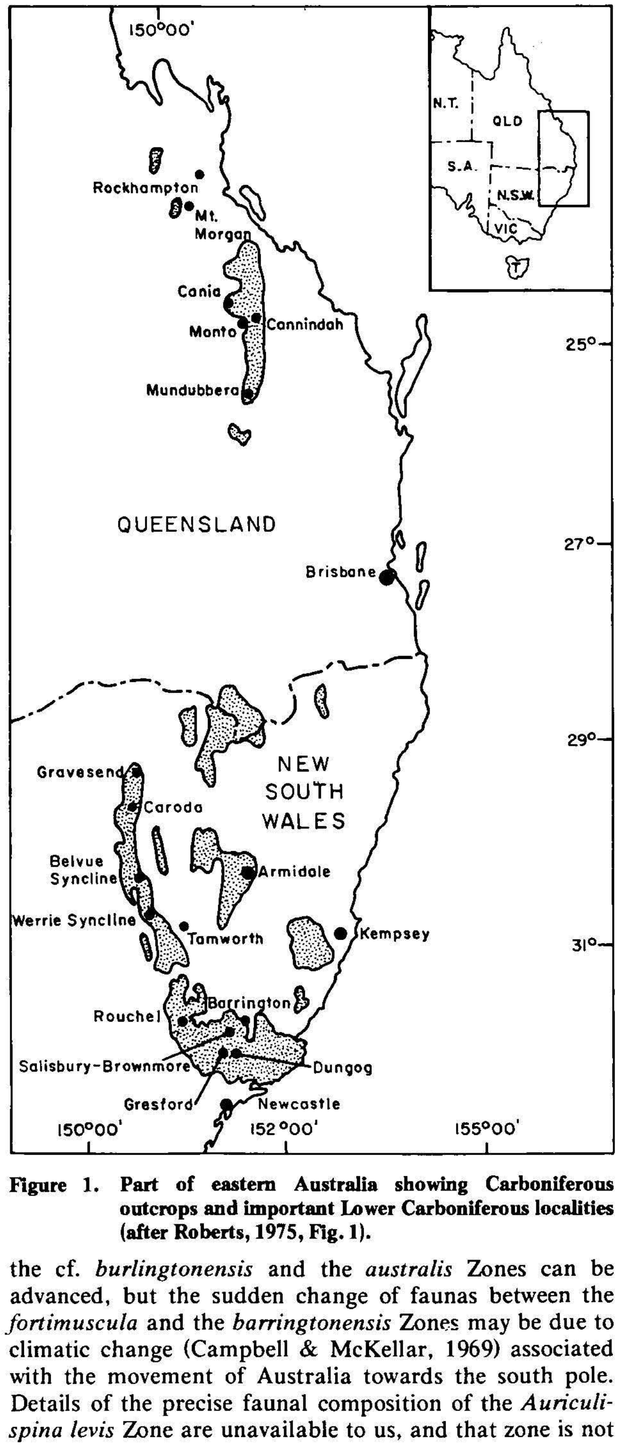

Figure 1. Part of eastern Australia showing Carboniferous outcrops and important Lower Carboniferous localities (after Roberts, 1975, Fig. 1).

the cf. *burlingtonensis* and the *australis* Zones can be advanced, but the sudden change of faunas between the *fortimuscula* and the *barringtonensis* Zones may be due to climatic change (Campbell & McKellar, 1969) associated with the movement of Australia towards the south pole. Details of the precise faunal composition of the *Auriculispina levis* Zone are unavailable to us, and that zone is not dealt with further.

Roberts (1975) has reinterpreted the zones from new information on the ranges of the brachiopod species and on detailed stratigraphy; this has resulted in changes in the identification of certain zones, particularly the *sol* Zone, and alterations to stratigraphic correlations within both New South Wales (Fig. 3) and Queensland (Fig. 4). Five zones, the *tenuistriata*, cf. *burlingtonensis*, *fortimuscula*, *barringtonensis*, and *L. levis* Zones are widespread throughout eastern Australia. The *sol* Zone, considered by Campbell & McKellar (1969) and Jones *et al.* (1973) to be equally widespread, is now recognizable in the strict sense only in the Werrie and Belvue Synclines in northeastern New South Wales. Faunas in Queensland (Yarrol Trough), probably similar in age to the *sol* Zone, and previously assigned to the zone, are now referred to local assemblage zones: the *Schizophoria* Zone of Maxwell (1954), and Fauna A of McKellar (1967).

The *Orthotetes australis* Zone can be definitely recognized only in the Hunter Valley region of New South Wales: it cannot be recognized in the Werrie, Belvue and Rocky Creek Synclines of northeastern New South Wales because non-marine sedimentation followed deposition of the Namoi Formation (Roberts, 1975). The *australis* Zone, as defined by its brachiopod fauna, has yet to be recognized in Queensland. Jull (1974 a, b), however, identified the zone in the Yarrol Trough, on the basis of corals, but as Campbell & McKellar (1969) pointed out, the zonal position of many coralline limestones in eastern Australia is difficult to determine because they lack the fossils upon which the zones are based.

The *Delepinea aspinosa* Zone, which is well developed in the Hunter Valley, is represented by the *tenuirugosus* Subzone in the Werrie and Rocky Creek Synclines, and possibly in two units in Queensland: at the top of the Splinter Creek Formation in the Cannindah Creek area, and in the basal part of the O'Bil Bil Road Conglomerate in the Mundubbera district. The Lion Creek Limestone, near Rockhampton, was originally correlated by Jull (1969, addendum) with the upper part of the Cannindah Limestone in the Monto district on the basis of corals, which he considered to be late Visean in age. Jull (1974a) now regards this coral fauna as equivalent to the *Delepinea aspinosa* Zone, but again we should heed the cautionary words of Campbell & McKellar (1969) with regard to the identification of brachiopod zones on the basis of coral assemblages.

Therefore, allowing for the absence in Queensland of the *sol* Zone, and possibly the *australis* Zone, the brachiopod zones occur in the same order throughout eastern Australia, and are considered to be valid biostratigraphic units. They are used to correlate the marine parts of the Lower Carboniferous (Dinantian) sequences, and the non-marine portions can be fitted into this zonal sequence because of marine intercalations in areas such as Rouchel and Carrow Brooks (Roberts & Oversby, 1974). The non-marine sequences frequently contain mappable ignimbrite members, and hence the internal correlations of these units are well controlled. Correlation of the Upper Carboniferous (Silesian) non-marine and glacial sequences in New South Wales, however, is more tenuous, but the recent work of Morris (1975) and Rigby (1973) on plants may provide a basis for more reliable correlation.

For intercontinental correlation, few of the brachiopods can be used to indicate ages in terms of the fine subdivisions of European or North American series because of the endemic nature of the faunas. Therefore, the ages of the brachiopod zones, in terms of the standard European series, have been based mainly on the sparse ammonoid faunas accompanying the brachiopod assemblages.

Ammonoids

Ammonoids are relatively rare in the Carboniferous of eastern Australia, but where present provide useful indices in terms of world-wide correlation. In Queensland, the lowermost fauna with *Protocanites planorbiformis* (Etheridge) and *Pseudarietites ammonitiformis* (Etheridge) was first recorded from an unknown locality in the Rockhampton district (Etheridge, 1892; Whitehouse, 1930), which was later shown (Fleming, 1967; McKellar, 1967) to be from the mudstone overlying the Gudman Oolite in the base of the Malchi Formation. D. Weyer (pers. comm., 1975) suggests that the association of *Protocanites* with *Pseudarietites* in European terms, indicates a middle

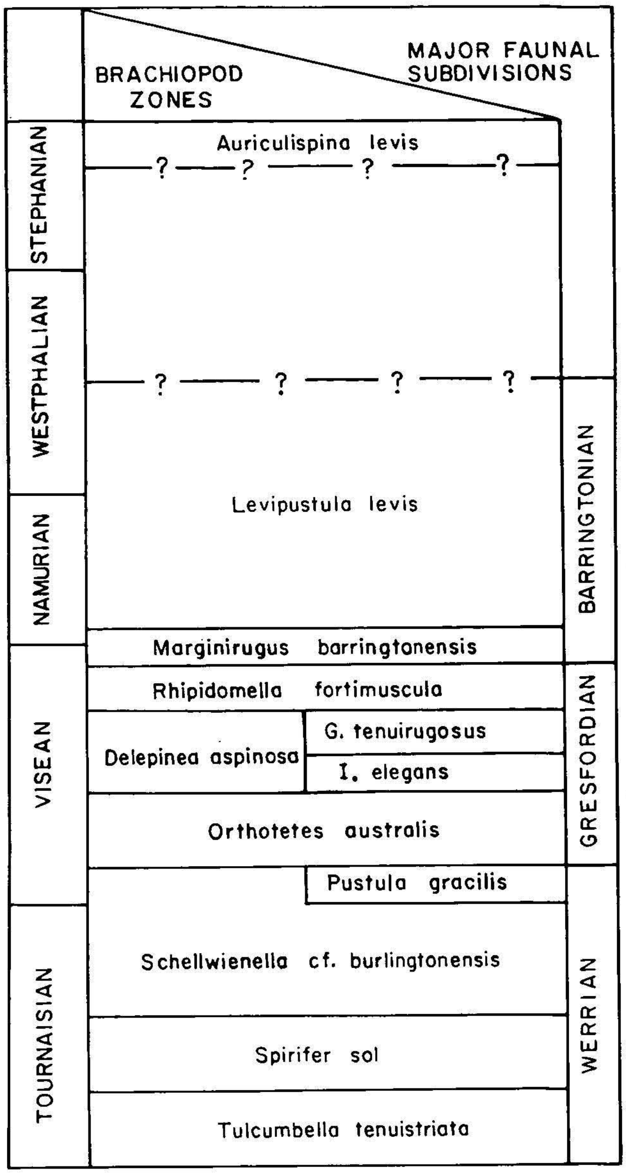

Figure 2. Eastern Australian brachiopod zones and major faunal subdivisions.

Tournaisian age, which agrees with the conclusion reached by Crane for the age of the conodonts in the Gudman Oolite. The ammonoids are associated with brachiopods which indicate an age equivalent to that of the *Schizophoria* Zone at Mount Morgan (McKellar, 1967).

Most of the ammonoid specimens in New South Wales are recorded from the western limb of the Werrie-Belvue Synclines (Campbell & Engel, 1963). They were collected from a siltstone at Swains Gully (L22 UNE), Carellan (= 'one mile north-west of Croydon Homestead . . .' *in* Campbell & Engel, 1963, p. 59, fig. 1), and a bioclastic limestone in the Rangari area (L76, L77, UNE). The association of *Protocanites (Protocanites) lyoni* (Meek & Worthen), *P. (Eocanites) australis* (Delépine), and *Prionoceras (Imitoceras)* sp. in the upper part of the *Spirifer sol* Zone in the Tulcumba Sandstone (L76) at Rangari, and the basal Namoi Formation (L22) at Swains Gully, suggests that the lowest limestone of the conodont sequence established in the basal Namoi Formation near Carellan (Jenkins, 1974, fig. 1) is also from the top part of the *sol* Zone. Both this ammonoid fauna and the one from the Rockhampton area correspond to the earliest goniatite fauna *(Protocanites* without *Muensteroceras)* of Hodson & Ramsbottom (1973), which in European terms ranges from Early to earliest Late Tournaisian (i.e., Tnl to Tn3a) in age.

The addition of *Muensteroceras* cf. *oweni* (Hall) to the presence of *Protocanites (Protocanites) lyoni* (Meek & Worthen), and *P. (Eocanites) australis* (Delépine) in the basal Namoi Formation (L77 UNE) near Rangari indicates a slightly younger age. Indeed, the meagre brachiopod fauna from locality L77 (*Spirifer sol* Campbell and *Brachythyris solida* Campbell) may belong to the basal *Schellwienella* cf. *burlingtonensis* Zone, and not to the *sol* Zone as previously believed (Roberts, 1975). The presence of *Prionoceras (Imitoceras) werriense* Campbell & Engel, however, suggests that the ammonoids from the L77 locality are slightly older than those from the Carellan locality of Jenkins which Campbell & Engel (1963) have described viz., *Protocanites (Protocanites) lyoni* (Meek & Worthen), *P. (Eocanites) australis* (Delépine), and *Muensteroceras* cf. *oweni* (Hall).

The occurrence of *Protocanites lyoni* (Meek & Worthen), *Ammonellipsites* sp. and *Muensteroceras* in the *Schellwienella* cf. *burlingtonensis* Zone, high in the Namoi Formation in the Belvue and northern Werrie synclines indicates a cuII*α* (early Tn3c) age. Both these ammonoids and those of the Carellan and Rangari (L77 UNE; not L76) sequences belong to the second Carboniferous goniatite fauna (*Protocanites* with *Muensteroceras*) of Hodson & Ramsbottom (1973), which in Europe is referred to the Late Tournaisian (Calcaire de Vaulx — Tn3b; Calcaire de Calonne — Tn3c). The New South Wales fauna has long been known to be closely related to that from the Chouteau and Rockford Limestones (late Kinderhookian-early Osagean) of the USA (Campbell & Engel, 1963), and from conodont evidence, the younger of these ages is preferred (Jenkins, 1974; Jones *et al.*, 1973).

The first indication of a Viséan age is the incoming of *Merocanites (Erdbachites)* cf. *houghtoni* (Winchell) high in

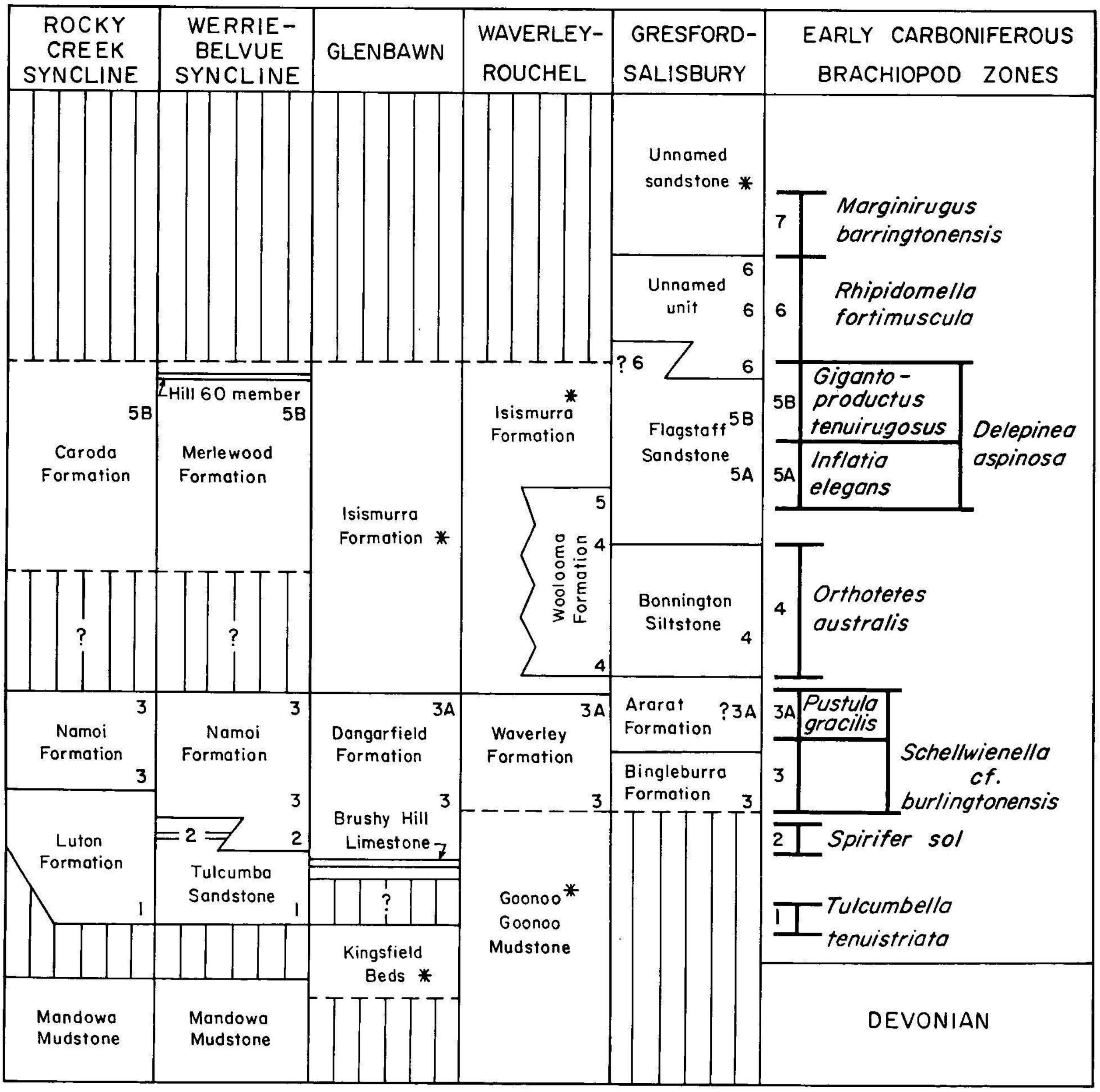

Figure 3. Modifications to correlations between some of the Lower Carboniferous formations of N.S.W. (after Roberts, 1975, Fig. 11). Units marked by an asterisk have no internal palaeontological evidence of age.

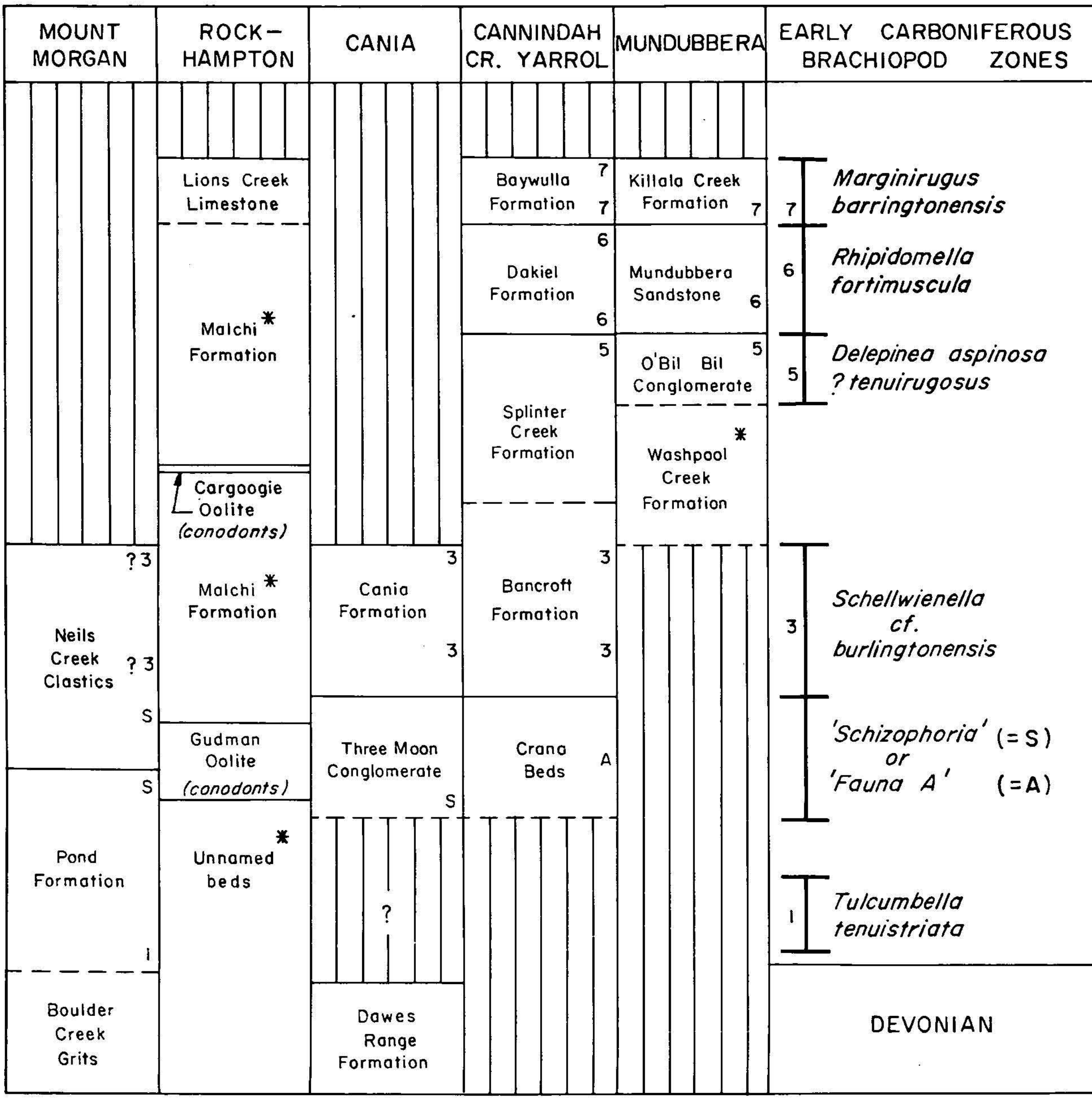

Figure 4. Modifications to correlations between some of the Lower Carboniferous formations of Queensland (modified from Roberts, 1975, Fig. 12). Units marked by an asterisk have no internal paleontological evidence of age.

the *Schellwienella* cf. *burlingtonensis* Zone on the eastern limb of the Werrie Syncline in the Goonoo Goonoo Mudstone (Campbell & Bein, 1971). In Europe, *Merocanites (Erdbachites)* is not known to range below cuIIγ of Germany, and its main occurrences are in the cuIIγ and cuIIδ. This New South Wales occurrence of *Merocanites (Erdbachites)* is probably equivalent to the third mondial goniatite fauna (the *Merocanites/Muensteroceras* association) of Hodson & Ramsbottom (1973).

The next main marker is within the *Orthotetes australis* Zone where *Beyrichoceras trevellynense* is associated with *Prolecanites* sp. in the Bonnington Siltstone at Trevallyn (Jones *et al.*, 1973). Brown *et al.* (1965) contended that this association indicated an age equivalent to late cuIIδ or early cuIIIα. On the other hand, Jenkins (1974) considered that the sutures of *Beyrichoceras trevallynense* were intermediate between *Muensteroceras* and *Beyrichoceras*, and inferred that the form from Trevallyn could be as old as the *kochi-nasutus* Interregum, the gap between cuIIγ and cuIIδ of Weyer (1972). Despite Jenkins's objection to the identification of *Prolecanites* sp., on the grounds of preservation, it is clear that the specimen in question has four pointed lateral lobes, thus placing it in the *Prolecanites-Cantabricanites* group, which, from the work of Weyer (1972), first appears at the base of the *Goniatites crenistra* Zone, i.e., cuIIIα.

The authors of *Beyrichoceras trevallynense* do not see any valid reason for changing the generic assignment of the species (Jones *et al.*, 1973; Roberts, 1976). They still consider it closest to *B. submicronotum* Bisat, and, where it is associated with *Prolecanites* sp., to indicate an equivalence with Subzones 3 (*Beyrichoceras castletonense* Subzone) and 4 (*Goniatites maximus* Subzone) of the *Beyrichoceras* Zone (Bisat, 1934; 1952). Hodson & Ramsbottom (1973) suggest that this NSW record of *Beyrichoceras* corresponds to their fauna iv, but it is probably younger than this because their fifth fauna contains *Goniatites hudsoni* Bisat (index fossil for Bisat's

Subzone 2), and its base is defined by the replacement of *Merocanites* by *Prolecanites*.

A rich ammonoid fauna of late Viséan aspect is present in the *Rhipidomella fortimuscula* Zone in both New South Wales and Queensland. In the lower part of the Copeland Road Formation in the Barrington area, NSW, it includes *Girtyoceras* sp. Campbell & McKelvey (1972), a species with affinities with the *G. platyforme-G. cowdalense* group from the Pla and Plb subzones of England (Moore, 1946). In the Yarrol Basin of Queensland, the discovery in the *R. fortimuscula* Zone of *Beyrichoceras* cf. *obtusum* (Phillips) and *Sudeticeras* sp. suggests that this zone should be mainly correlated with cuIIIβ, though it may extend a little above or below the German Zone (Jones *et al.*, 1973). These and additional ammonoids from the *R. fortimuscula* Zone in Queensland are currently being studied by Dr K. S. W. Campbell and Professor D. A. Brown at the Australian National University, Canberra.

Jones *et al.* (1973) suggest that the *Marginirugus barringtonensis* Zone spans the interval cuIIIγ to early Namurian. In the area south of Forster, NSW, in rocks mapped as the Wootton Beds, a beyrichoceratoid found about 30 m above a thin layer of this zone is latest Viséan (cuIIIγ) in aspect. The presence of the brachiopod *Lissochonetes* in the upper part of the zone in the Gloucester-Myall region of NSW suggests that the *M. barringtonensis* Zone extends into the early Namurian.

At Kempsey, NSW, *Cravenoceras kullatinensis* Campbell, the youngest known Carboniferous ammonoid recorded from Australia (Campbell, 1962), indicates a Namurian, probably El, age for beds which lie within the *Levipustula levis* Zone. Lindsay's (1969) initial report of *L. levis* from below *Cravenoceras kullatinensis* has now been confirmed (Roberts, 1976). The Namurian age for the base of the zone is supported by field evidence from Yagon Gibber, near Forster, NSW, where in a conformable sequence exposed along the coastline the *L. levis* Zone first appears only about 50 metres above the *Marginirugus barringtonensis* Zone. The *Levipustula levis* Zone was considered by most workers (Campbell, 1961; McKellar, 1965; and Jones *et al.*, 1973) to be Westphalian in age because of the close morphological relationship between *Levipustula levis* Maxwell and *L. piscariae* (Waterlot) and *L. rimberti* (Waterlot); in West Germany the combined range of the latter species is from Westphalian A to the Westphalian B/C boundary. *L. piscariae* (Waterlot) first appears at the Namurian/Westphalian boundary (Böger & Fiebig, 1963). However, because of the ammonoid evidence, the base of the *L. levis* Zone on the correlation chart of Jones *et al.* (1973) should be lowered to almost meet the *Marginirugus barringtonensis* Zone in the earliest Namurian (El). Apart from brachiopod evidence there is no reliable information available to date the top of the *levis* Zone, which is currently accepted as extending into the Westphalian (Roberts, 1976).

Conodonts

In Queensland, conodonts have been described from limestones in the Lower Carboniferous sequence in the Rockhampton area of the Yarrol Basin (Druce, 1970), and the Upper Carboniferous in the Murgon area (Yarraman Block) 160 km northwest of Brisbane (Palmieri, 1969).

Recently Jenkins (1974) recognized seven successive conodont faunas from New South Wales (Fig. 5). The lowest fauna, (a), characterized by *Siphonodella* spp., is found in one locality only in the Brushy Hill Limestone Member of the Dangarfield Formation at Glenbawn Dam (Roberts & Oversby, 1974). Because the stratigraphical limits of the fauna are controlled by lithology, it was not given zonal status. The siphonodellids were too few to permit identification, but Jenkins suggested that some resemble late Kinderhookian forms. This age assignment has been confirmed by Crane (1975, unpubl.), who has since recognized three zones based on *Siphonodella* in an unnamed limestone within the Wootton Beds, east of Gloucester. The zones (Fig. 5) are, in ascending order:— (i) the *Siphonodella cooperi* — *S. quadruplicata* Zone, (ii) the *Siphonodella crenulata* Zone, and (iii) the *Siphonodella isosticha* Zone. The two lower zones are correlated with the *Gnathodus delicatus-Siphonodella cooperi cooperi* Zone of southwestern Missouri (Thompson & Fellows, 1970), which in Belgian terms is equivalent to part of the middle Tournaisian (Tn 2). Crane regards the *Siphonodella* spp. fauna of Jenkins (1974) as the equivalent of the lower part of his *S. crenulata* Zone. Thus, it appears that the earliest known Carboniferous conodont fauna in New South Wales may be younger than that in Queensland, from the Gudman Oolite, in the Rockhampton district. Druce (1970) described a sparse and poorly preserved fauna from this unit, which he regarded as early Tournaisian in age. D. Crane (pers. comm. 10 Dec. 1975) subsequently reports that the Gudman Oolite contains *Siphonodella crenulata* and *S. cooperi*, which suggests a correlation with his *S. crenulata* Zone or below (viz., *S. cooperi-S. quadruplicata* Zone). This implies a middle Tournaisian age for the Gudman Oolite, and the overlying *Pseudarietites* and *Protocanites* association.

Jenkins (1974) regarded his successive conodont faunas (b) to (g) as indicating informal biostratigraphic zones. His faunas (b) to (d) are found in the Carellan section of the Belvue Syncline, and are characterized by the following species—(b) *Gnathodus punctatus* (Cooper); (c) *Gnathodus semiglaber* Bischoff; and (d) *Gnathodus* sp. A. Jenkins, 1974. Crane has recently found the *Gnathodus punctatus* Zone in the Wootton Beds of the Gloucester district, above the *Siphonodella isosticha* Zone, and he correlates both zones with the *Gnathodus punctatus-Siphonodella cooperi hassi* Zone of the Thompson & Fellows (1970) conodont scale in southwestern Missouri. The *Gnathodus semiglaber* Zone, which Jenkins (1974) correlates with the *G. semiglaber-Polygnathus communis carina* Zone of Thompson & Fellows (1970), is apparently represented by an unfossiliferous interval in the Wootton Beds (Crane, 1975, unpubl.). In terms of the Belgian scale, it is mainly Tn3a in age (Groessens, 1971).

Jenkins (1974) noted that the ammonoid horizon in the base of the Namoi Formation at Carellan lies in the lower half of the *Gnathodus* sp. A Zone, a zone which he correlated with "either Tn3a or, more probably, Tn3b" of the Belgian stratotypes, and in terms of the Mississippi Valley sequence, with the pre-*pinnatus* part of the Burlington Limestone. Therefore, the conodont and ammonoid evidence suggests that the Carellan sequence is early Tn3b in age and belongs to the upper part of the cuIIα gap of Matthews (1970), and is equivalent to the early Osagean of North America.

Although the *Scaliognathus anchoralis* Zone (= Jenkins's fauna e) is relatively widespread, and known from five localities between Gresford and the coast at Taree, the field relations did not permit Jenkins (1974) to establish the vertical continuity of the zone from an underlying conodont horizon. Crane (1975, unpubl.), however, has recently recognized in the Wootton Beds, east of Gloucester, a conodont zone (named by Crane — *Gnathodus delicatus* — *Pseudopolygnathus triangula* subsp. B Zone), which lies below one of Jenkins's *anchoralis* Zone localities, and is broadly correlated with Jenkins's *Gnathodus* sp. A Zone. At present, the *anchoralis* Zone is overlain by a higher

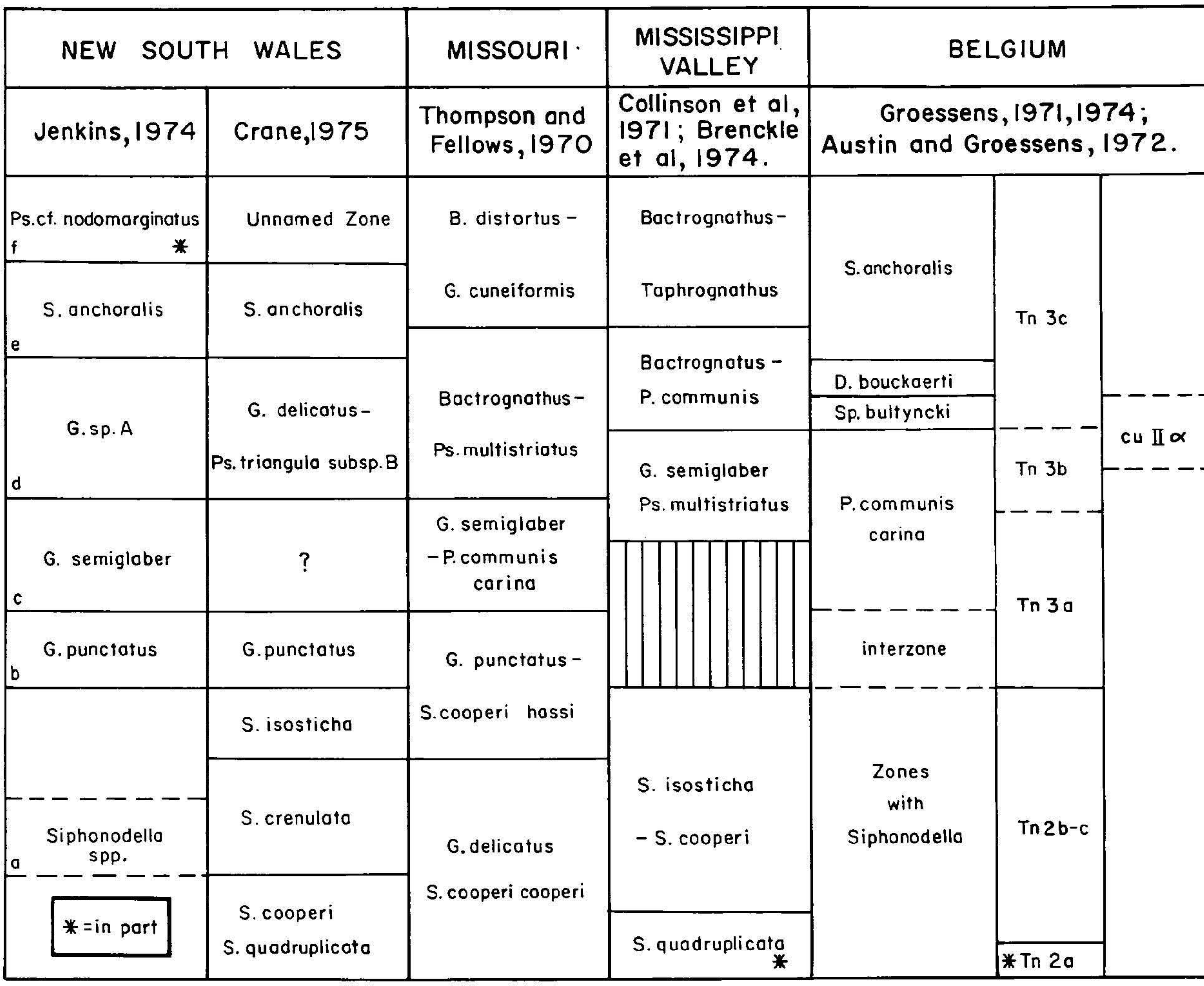

Figure 5. **Comparison and correlation of conodont zones for the middle and upper parts of the Tournaisian Series in New South Wales, U.S.A., and Belgium. The letters a to f on the left side of the left column indicate the faunas of Jenkins, 1974. Generic names are abbreviates as follows—*B.*=*Bactrognathus*; *D.* = *Dollymae*; *G.* = *Gnathodus*; *P.* = *Polygnathus*; *Ps.* = *Pseudopolygnathus*; *S.* = *Siphonodella*; and *Sp.* = *Spathognathodus*.**

conodont horizon at only one known locality, in the Lewinsbrook Syncline. The *anchoralis* Zone is present in limestone near the faulted base of the Bingleburra Formation, and is overlain by mudstone containing brachiopods of the *Schellwienella* cf. *burlingtonensis* Zone. Jenkins's succeeding *Pseudopolygnathus* cf. *nodomarginatus* Zone (Jenkins's fauna f) is present in the overlying Ararat Formation along with brachiopods which probably belong to the *gracilis* Subzone.

Outside New South Wales, two other Australian localities may eventually be proved to belong to the *anchoralis* Zone; one in Queensland (Druce, 1970; 1974) and the other in the Bonaparte Gulf Basin (Druce, 1969; Jenkins, 1974). A late Tournaisian fauna described by Druce (1970) from an unnamed limestone bed in the Malchi Formation in the Rockhampton district includes *Gnathodus delicatus* (Branson & Mehl), *Pseudopolygnathus nodomarginatus* (E. R. Branson), *P. triangulus* Voges, and a staurognathid-like form (= *Staurognathus cruciformis, sensu* Druce, 1970). This suggests a probable equivalence with the upper part of the *Gnathodus* sp. A Zone or the lower part of the *anchoralis* Zone, as recognized in New South Wales (Jenkins, 1974); in Belgian terms it probably correlates with the *Dollymae bouckaerti* Assemblage Zone or possibly the *Doliognathus latus* Subzone of the *anchoralis* Zone of Groessens (1971).

Jenkins (1974) reported *Pseudopolygnathus* cf. *nodomarginatus* in the *Scaliognathus anchoralis* Zone and succeeding *Pseudopolygnathus* cf. *nodomarginatus* Zone of New South Wales and pointed out that some part of this New South Wales range 'probably includes the *Ps. nodomarginatus* Assemblage Zone of Druce and this raises the possibility that the *S. anchoralis* Zone may be represented in the Bonaparte Gulf Basin by sandstones above or within the upper part of the Septimus Limestone.' This agrees well with the late Tournaisian or early Viséan age which Thomas (1971) assigned to his *Spirifer spiritus* brachiopod assemblage in the upper part of the Septimus Limestone.

Jenkins (1974) compared the nominate-species of his *Pseudopolygnathus* cf. *nodomarginatus* Zone with *Polygnathus mehli* Thompson, a species present in the Missouri *Bactrognathus distortus-Gnathodus cuneiformis* Zone — above the *Doliognathus latus* Subzone—and which is now known in the upper part of the Burlington Limestone in both Iowa and the Mississippi Valley in association with *Eotaphrus burlingtonensis* Pierce & Langenheim (= *Pelekysgnathus*-like new genus of Collinson *et al.*, 1971, p. 379). Brenckle *et al.* (1974) have provided evidence based on the conodonts and foraminifera of the Keokuk Limestone, and the distribution of *Eotaphrus burlingtonensis* in the Tn3c stratotype and in rocks of equivalent age in North America and Britain, to show that 'the Tournaisian-Viséan boundary should fall at or near the boundary between the Burlington and Keokuk Limestone in the type area of these formations'. This raises the possibility that the *Pseudopolygnathus* cf. *nodomarginatus* Zone in New South Wales is latest Tournaisian in age, and that the combination of this zone with the *anchoralis* Zone of Jenkins (1974) may be equivalent to the *anchoralis* Zone of the Belgian Tn3c stratotype. The *Pseudopolygnathus* cf. *nodomarginatus* Zone is found in limestone lenses in the Ararat Sandstone about 8 km northeast of Gresford, and in the Raglan Limestone 8 km west of Booral (Jenkins, 1974) in association with brachiopods of the *Schellwienella* cf. *burlingtonensis* Zone (probably *Pustula gracilis* Subzone; Roberts, 1975).

The *Patrognathus?* cf. *capricornis* Zone, the youngest (fauna g) of Jenkins's succession of faunas in New South Wales, is based on conodonts found in limestone bands in the upper part of the Flagstaff Sandstone (*Gigantoproductus tenuirugosus* Subzone of the *Delepinea aspinosa* Zone), 4 km south of section 85 of Roberts (1975, figs. 7, 10) at Brownmore. The stratigraphic column shown by Jenkins (1974, fig. 1) under the title Brownmore and Lewinsbrook is misleading in that it combines two different sections of approximately the same age, in a continuous sequence. The lower section (section 72 of Roberts, unpubl.) in the Lewinsbrook Syncline, extends from the Bingleburra Formation, through the Ararat Sandstone and Bonnington Siltstone into the lower 115 m of the Flagstaff Sandstone. The upper section (section 85 of Roberts, 1975, figs. 7, 10) in the Brownmore fault block, begins with 350 m of Ararat Sandstone (shown by Jenkins as Flagstaff Formation, *sic*, 850-1200 m above the top of the Bonnington Siltstone), 350 m of Bonnington Siltstone (shown by Jenkins as shale and mudstone 1200 m above the Bonnington Siltstone), and 1800 m of Flagstaff Sandstone (shown by Jenkins as Flagstaff Formation?). The unnamed formation of Roberts (1975, fig. 7), above the Flagstaff Sandstone is included within the top of the Flagstaff Formation? of Jenkins. Because there is no conodont fauna which succeeds the *Pseudopolygnathus* cf. *nodomarginatus* Zone in the Lewinsbrook section, and neither is there one which precedes the *Patrognathus?* cf. *capricornis* Zone in the Brownmore section, the relationship between these two conodont zones has yet to be proved within a single section. However, because the *Pseudopolygnathus* cf. *nodomarginatus* Zone occurs no higher than Roberts's *Schellwienella* cf. *burlingtonensis* Zone, and the *Patrognathus?* cf. *capricornis* Zone occurs no lower than the *Delepinea aspinosa* Zone, there is little doubt that the latter conodont zone is the youngest in the sequence of Jenkins's faunas (a to g).

The *Patrognathus?* cf. *capricornis* Zone has also been reported (Jenkins, 1974) from the Verulam Limestone (=Verulam Oolite Member of the Wootton Beds; Campbell & McKelvey, 1972), near Gloucester. At Barrington, near Gloucester, the Verulam Oolite Member occurs below the *fortimuscula* Zone, and contains a fauna (*Delepinea gloucesterensis* Assemblage Zone of Campbell & McKelvey), which should be correlated with the upper subzone of the *D. aspinosa* Zone (Roberts, 1975).

According to Jenkins, the unfigured index species of his *Patrognathus?* cf. *capricornis* Zone is close to the element described by Druce (1970) as *Taphrognathus capricornis* from the Cargoogie Oolite Member of the Malchi Formation in the Rockhampton district of Queensland. Jenkins (1974) favoured an early Viséan age for the *Patrognathus?* cf. *capricornis* Zone, because its *Gnathodus bulbosus-Taphrognathus varians* fauna in North America is younger than *Scaliognathus anchoralis*, and in Belgium this zonal species is confined within Tn3c. He noted that *Gnathodus texanus pseudosemiglaber*, the second member of the phylogenetic lineage (*Gnathodus bulbosus-G. texanus pseudosemiglaber-G. texanus texanus*) postulated by Thompson & Fellows (1970), occurs in the Baywulla Formation (*marginirugus barringtonensis* Zone) of Queensland. Crane (1975, unpubl.), however, rejected this hypothesis, and regarded *Gnathodus texanus pseudosemiglaber* as the mature form of *G. texanus* ss.

Crane (1975, unpubl.) has provided new conodont evidence on which to date the boundary between the *Marginirugus barringtonensis* Zone and the succeeding *Levipustula levis* Zone in the Forster area, New South Wales. From O'Sullivans Gap he has described *Gnathodus girtyi simplex* within the *barringtonensis* Zone, which suggests that the upper limit of the zone may be as young as the topmost Mississippian (upper Hl). However, because *G. girtyi girtyi* is associated with *Levipustula levis* at Seal Rocks and *G. girtyi simplex* is present beneath a similar brachiopod horizon at O'Sullivans Gap, Crane suggested that the lower age limit of the *levis* Zone in this area was no older than E2 and no younger than H1. Therefore, the conodont evidence suggests that the *barringtonensis/levis* boundary in the Forster area can be approximately correlated with the E1/E2 boundary.

The Lower Pennsylvanian conodonts described by Palmieri (1969) from the Murgon area, Queensland have been discussed by Jones *et al.* (1973), Druce (1974), and Lane & Straka (1974). These faunas may be as old as late Namurian (R2) and at least as young as basal Westphalian (G2) in age: at least as young as the *Idiognathodus sinuosis* Zone of the Arkansas conodont-scale (Lane & Straka, 1974). They represent the youngest known conodont faunas in the Carboniferous of Australia.

Discussion

Several points of conflict emerge when the brachiopod zonation is dated in terms of ammonoids, conodonts and foraminifera (Fig. 6). In general, the conodonts identified from the Tournaisian limestones of NSW by Jenkins (1974) suggest ages which agree with those determined from ammonoid evidence (Jones *et al.*, 1973). There is, however, an apparent discrepancy between the conodont and brachiopod zonations, because the three successive gnathodid zones of Jenkins — *punctatus, semiglaber* and sp. A, which are recognized in the Carellan sequence, apparently in the basal *Schellwienella* cf. *burlingtonensis* Zone, are also identified in the Rouchel district in the *gracilis* subzone, the uppermost portion of the cf. *burlingtonensis* Zone.

Furthermore, the presence of *anchoralis* below the *gracilis* subzone at Gresford, infers that in NSW the *anchoralis* Zone lies below the *punctatus* Zone, the lowest of Jenkin's gnathodid zones. This inference is incompatible with the known succession of conodont faunas in North America and Europe. Further studies are necessary in order to resolve this problem.

A major discrepancy arises in the ages of the younger brachiopod zones (*australis* and *aspinosa* Zones) mainly because Jenkins (1974) referred the conodonts from the upper part of the Flagstaff Sandstone at Brownmore (*Gigantoproductus tenuirugosus* subzone of the *Delepinea aspinosa* Zone) to the early Viséan. The discrepancy between the ages of the brachiopods and the conodonts is widened by the fact that Jenkins argued, on phylogenetic grounds, that the presence of *Gnathodus texanus pseudosemiglaber* in the Baywulla Formation of Queensland (=*Marginirugus barringtonensis* zone) tends to suggest an early Viséan age rather than late Viséan. Crane (1975,

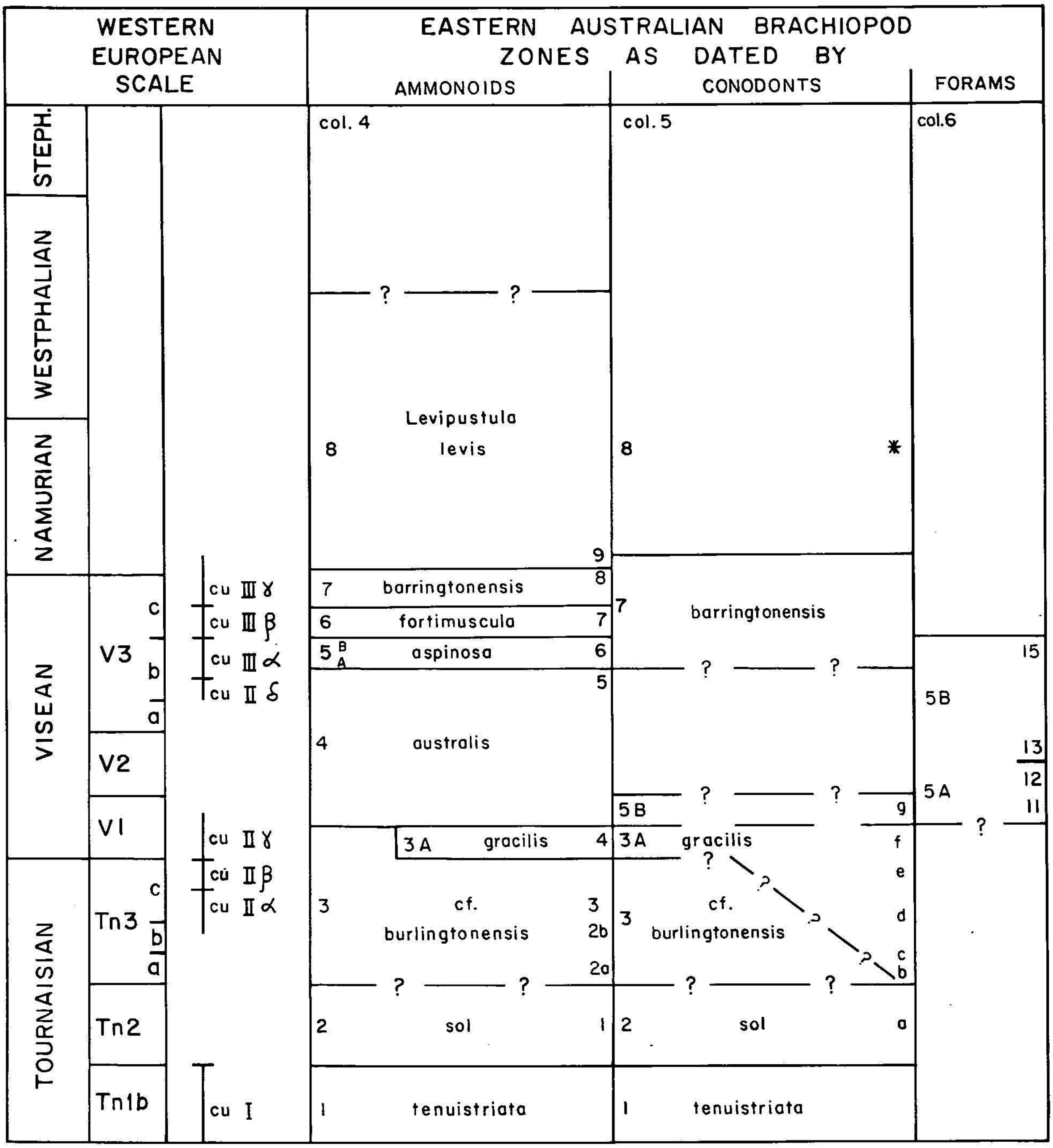

Figure 6. **Comparison of ages of eastern Australian brachiopod zones, in terms of the western European scale, as dated by ammonoids, conodonts and foraminifera.**
Brachiopods—**the numbers on the left side of columns 4, 5, and 6 refer to the brachiopod zones and subzones (Jones et al., 1973; Roberts, 1975).**
Ammonoids—**the numbers on the right side of column 4 indicate ten ammonoid horizons: 1. (Whitehouse, 1930); 2a (*Protocanites* without *Muensteroceras*), 2b (*Protocanites* with *Muensteroceras*) (Campbell & Engel, 1963; Jones et al., 1973; Jenkins, 1974); 3. (Campbell & McKellar, 1969); 4. (Campbell & Bein, 1971); 5. (Brown et al., 1965); 6. (Roberts & Oversby), 1974; this paper); 7. (Campbell & McKellar), 1969; Jones et al., 1973); 8. (Jones et al., 1973); 9. (Campbell, 1962; Roberts, 1976).**
Conodonts—**the letters on the right side of column 5 indicate the seven conodont faunas of Jenkins (1974), and the asterisk refers to the lower Pennsylvanian conodonts of Palmieri (1969).**
Foraminifera—**the numbers on the right side of column 6 refer to Mamet's Zones (*in* Roberts, 1975).**

unpubl.), however, has shown that the *barringtonensis* Zone in NSW is no older than cuIIIα, and probably ranges into Namurian (E1), and Roberts (1975) pointed out that the evidence from the ammonoids and foraminifera indicate late Viséan ages for the uppermost parts of the *aspinosa*, and the *fortimuscula* and *barringtonensis* Zones.

There is also a problem regarding the ages assigned to the upper part of the *aspinosa* Zone (*Gigantoproductus tenuirugosus* Subzone) on the basis of foraminifera, and those assigned to the upper part of the *australis* Zone, on the basis of the ammonoids *Beyrichoceras trevallynense* and *Prolecanites* sp. These ammonoids indicate an equivalence with the upper *Beyrichoceras* Zone (B2) of Bisat (1934, 1952), which Weyer (1972) correlates with the cuIIδ/cuIIIα (the lower part of V3b in Belgium). The foraminifera identified by Mamet (*in* Roberts, 1975) from the same limestones at Brownmore sampled by Jenkins (*Gigantiproductus tenuirugosus* Subzone) are from Mamet's zones 13 to 15 (V2b-V3b). Therefore, the upper limit of the upper part of the *australis* Zone, as based on Trevallyn ammonoids, is the same age as the upper limit of the upper subzone of the supposedly younger *aspinosa* Zone, as indicated by the foraminifera. Although this evidence suggests that the *australis* and the *aspinosa* Zones may be at least partly equivalent in geological time the two Zones, where present in the one stratigraphic section, are always found in correct superposition. As Roberts (1975) pointed out, the *australis* Zone is only present in the Hunter Valley region, and cannot be recognized in Queensland, or in the Rocky Creek, Werrie and Belvue Synclines of northeastern New South Wales.

These problems cannot be resolved until more biostratigraphic studies of brachiopods, ammonoids, conodonts, foraminifera and other fossil groups are undertaken in eastern Australia. It is equally important that attempts should be made to co-ordinate the results of these studies. Until this is done the more doubtful of the correlations expressed in this paper will remain in the realms of speculation.

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Stream-sediment geochemistry as an exploration technique in the Westmoreland area, northern Australia

Allan G. Rossiter

Orientation geochemical studies indicate that stream-sediment sampling is a potentially powerful exploration technique in the Westmoreland region of Northern Australia. Uranium, copper, tin, and lead mineralization can all be detected by the use of a combination of sieved samples and heavy-mineral concentrates.

Vein-type uranium deposits occur in a variety of rock units in the area. The secondary dispersion of uranium from these deposits appears to be dominantly chemical, and sieved samples are very effective in prospecting; heavy-mineral concentrates rarely contain detrital uranium minerals and consequently are less efficient. Arsenic is a useful pathfinder element for uranium mineralization in some instances.

Copper deposits are encountered in both the granites and the basic igneous rocks of the area. Heavy-mineral concentrates are particularly sensitive in tracing copper mineralization. At several localities no anomalous copper was detected chemically in sieved samples, whereas malachite was conspicuous among the heavy minerals.

Tin deposits occur in pneumatolytically altered zones within high-level granites and acid volcanic rocks. The chemical analysis of sieved samples and the optical examination of heavy-mineral concentrates for cassiterite are equally effective in prospecting for tin. If sieved samples are preferred, lithium and tungsten are useful pathfinder elements.

Lead mineralization of syngenetic origin is associated with the dolomitic rocks of the region. The analysis of heavy-mineral concentrates appears to have great potential in exploration for this type of deposit, but the technique has yet to be fully evaluated. Near mineralization sieved samples contain anomalous lead and zinc; minor enrichment of copper also occurs. Scavenging by secondary manganese compounds leads in places to false zinc anomalies, so great care is required in the interpretation of 'anomalous' zinc values.

During 1972 and 1973 orientation geochemical studies were carried out by the Bureau of Mineral Resources in the Westmoreland area to provide the basic framework for a regional stream-sediment program. The aim of the orientation work was to appraise the types of geochemical anomalies that would be encountered during regional sampling, and to developing criteria for distinguishing anomalous from background values. Consequently, samples were collected in both mineralized and unmineralized environments. The regional survey commenced during 1975, but no results are available at this stage.

The study area comprises adjoining parts of the Calvert Hills and Westmoreland 1:250 000 Sheet areas. It occupies a band about 50 km wide straddling the Queensland-Northern Territory border and extending from the Nicholson River in the south to the Redbank mines in the north (Fig. 1).

The average annual rainfall is about 700 mm. Rain is almost entirely confined to the period November to April, and consequently most streams are dry during the winter. Average maximum daily temperature throughout the year is about 32°C.

The region is covered by savannah woodland; small eucalypts dominate and large trees are generally found only near stream channels.

The elevation of the area ranges from about 60 m to some 300 m above sea level. The physiography is controlled largely by the differential rates of erosion of the various rock types. The most prominent feature is the China Wall which consists of a series of strike ridges of resistant Precambrian conglomerate. The 'wall' extends from the headwaters of the Nicholson River for over 100 km in an east-northeasterly direction to near Westmoreland homestead. It varies from 3 to 10 km in width and in most parts is bounded to the south by a near-vertical escarpment about 130 m high. Flat-lying sandstone remnants of both Precambrian and Mesozoic age also form positive features. The topography is more subdued in areas underlain by Precambrian volcanic units, although rugged hills occur locally. Precambrian granite and pelitic and calcareous sedimentary/metamorphic rocks generally form lowlands. Towards the east the Cainozoic-Recent plains slope gently to the sea.

Drainage is well developed on all rock types. It is generally dendritic, although in some areas pronounced trends parallel the regional east-northeast strike of the country rocks. In the higher areas streams are youthful, and gorges and waterfalls are common; on the lowlands drainage is more mature.

Geology

The geological features of the Westmoreland region have been discussed by Carter (1959), Carter *et al.* (1961), and Roberts *et al.* (1963). The results of more recent geological mapping are described by Sweet & Slater (in press), Mitchell (in preparation), and Gardner (in preparation).

The Precambrian rocks of the area form part of the Australian Shield. Four major tectonic units are represented—the Murphy Tectonic Ridge, the McArthur Basin, the Lawn Hill Platform, and the South Nicholson Basin (Fig. 2).

The Murphy Tectonic Ridge is a narrow east-northeast-trending belt of Lower Proterozoic and Carpentarian igneous and metamorphic rocks. The oldest outcrops are schist and gneiss of the Murphy Metamorphics. Unconformably overlying these are the Cliffdale Volcanics, consisting of rhyolitic to dacitic lavas and tuffs, some of which have ignimbritic textures. The earlier workers in the area distinguished the Nicholson Granite, which appears older than the Cliffdale Volcanics, from the Norris Granite —which is younger. The two granites are very similar chemically, and isotopic dating shows that their age difference is rather small. Consequently Gardner (in preparation) has abandoned the term Norris Granite and described all granites as phases of the 'Nicholson Granite Complex' (tentative name).

The Murphy Tectonic Ridge is flanked to the north by the McArthur Basin which contains rocks of the Carpentarian

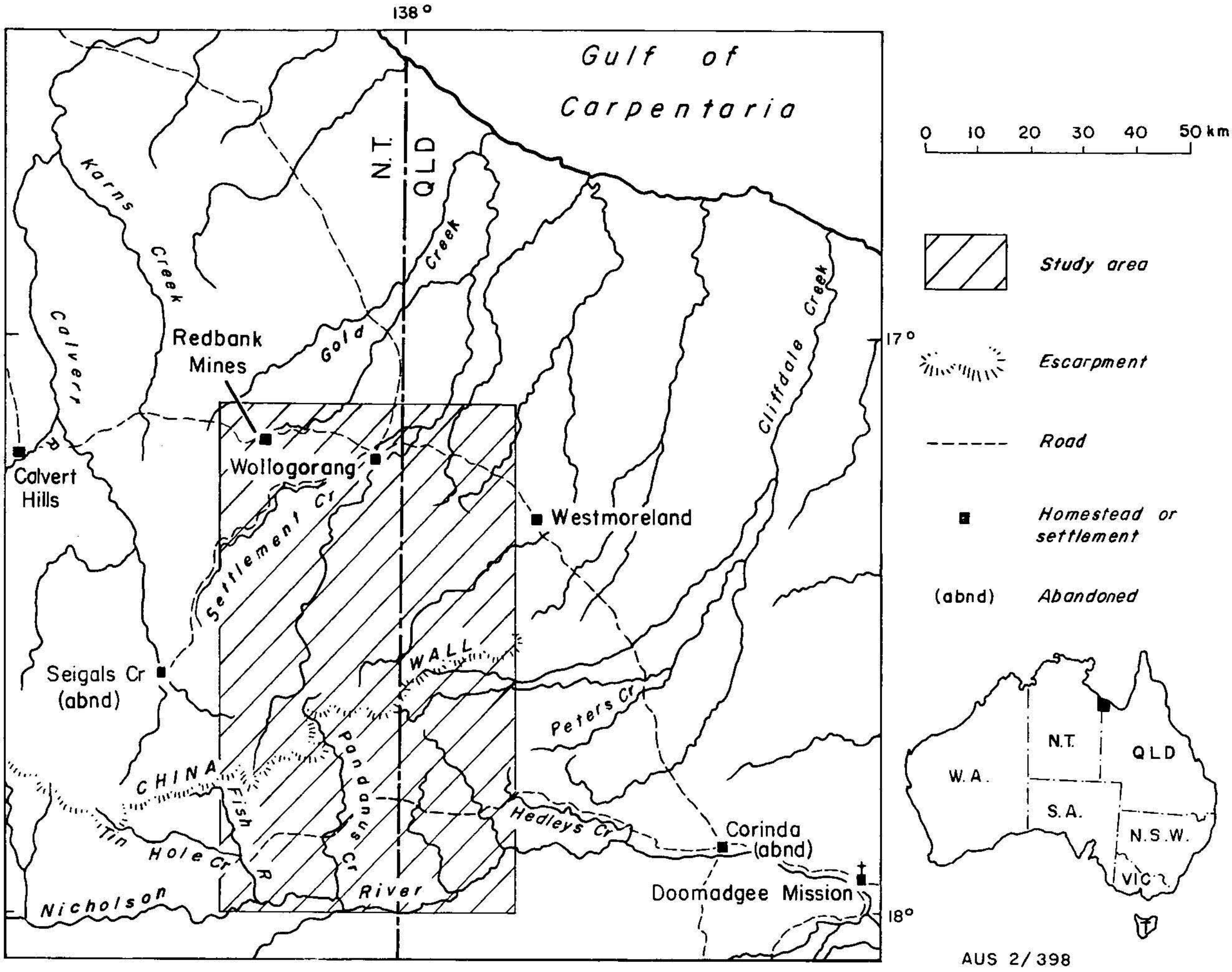

Figure 1 **Locality map**

Tawallah Group. The sequence begins with the Westmoreland Conglomerate resting unconformably on the older rocks. The conglomerate passes up into basic volcanics (Seigal Volcanics) which are in turn overlain by a number of dominantly sedimentary formations (McDermott Formation, Sly Creek Sandstone, Aquarium Formation, Settlement Creek Volcanics, Wollogorang Formation, and Masterton Formation).

To the south of the Murphy Tectonic Ridge on the Lawn Hill Platform the sequence is similar, although volcanics are more abundant relative to sedimentary units. Correlations have been made by Sweet & Slater (in press) between the Wire Creek Sandstone and the Westmoreland Conglomerate and between the Peters Creek Volcanics and the remainder of the Tawallah Group. The Peters Creek Volcanics are overlain unconformably by sandstone of the Fish River Formation. This in turn passes up into the dolomitic Fickling Group.

In the south of the study area the rocks of the South Nicholson Basin unconformably overlie those of the Lawn Hill Platform. The South Nicholson Group consists mainly of sandstone and siltstone; the most important unit is the Constance Sandstone.

Mineralization is widespread throughout the region. Uranium deposits occur within fractures in three lithological units—Westmoreland Conglomerate, Seigal Volcanics, and Cliffdale Volcanics. Copper, tin, and minor tungsten are found in the Cliffdale Volcanics, and the high-level phase of the Nicholson Granite Complex that was previously known as Norris Granite. Copper is also associated with basic lavas of the Seigal and Peters Creek Volcanics and the Masterton Formation. Lead mineralization occurs in the dolomitic rocks of the Fickling Group. Small amounts of alluvial gold are reported from the Tin Hole Creek and Gold Creek areas (Roberts *et al.*, 1963), and gold is associated with some uranium deposits. During 1975 the only mining activity in the region was a small-scale alluvial tin operation at Crystal Hill.

Nearly all exploration work has been aimed at locating uranium mineralization. A number of companies have carried out airborne and ground radiometric surveys, but geochemical methods have been used only rarely in the search for this metal. On the other hand, geochemical sampling has played a relatively important role in base-metal exploration programs, but only a small number of these have been carried out.

Sampling and analytical procedures

The sampling and analytical procedures used during this survey have been discussed in detail by Rossiter *et al.* (1974) and only a brief account is given here.

Sieved stream-sediment samples

Stream-sediment samples were sieved on site using plastic sieves fitted with nylon bolting cloth. It was ascertained during the initial stages of the program that the optimum sieve size was 180μm (85 mesh BSS). Generally 20-

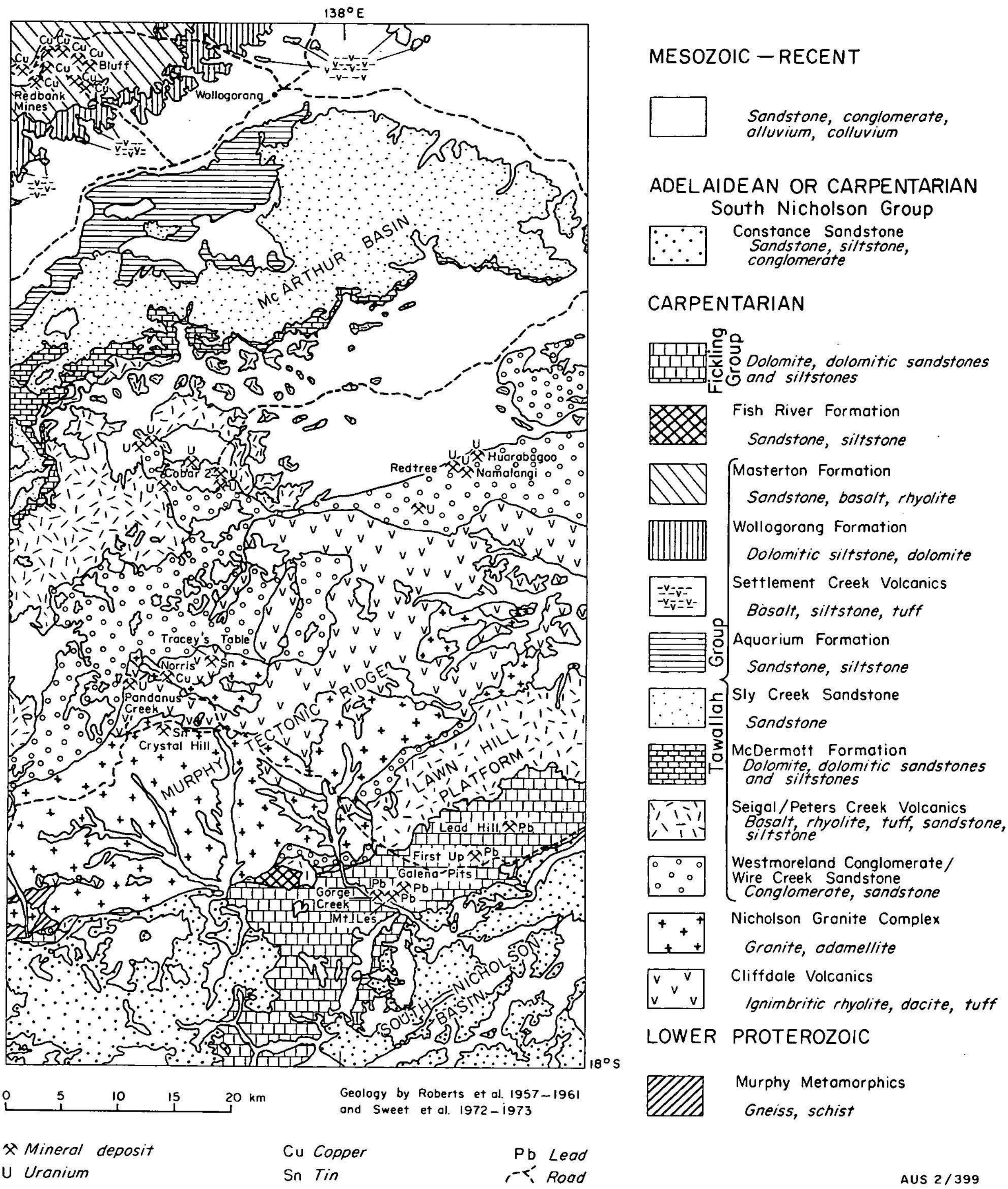

Figure 2 **Geological map of the Westmoreland region showing the more important mineral deposits**

50 g of sieved material were collected. All samples were analyzed in the BMR laboratories for beryllium, cadmium, cobalt, chromium, copper, lead, lithium, manganese, nickel, silver, and zinc by atomic absorption spectrophotometry, and about 40 percent of them for arsenic, barium, cerium, rubidium, sulphur, thorium, tin, tungsten, and uranium by X-ray fluorescence spectrometry. Of these elements barium, cadium, cerium, chromium, cobalt, nickel, rubidium, sulphur and thorium appear to be of limited use for future exploration, as they either show a lack of anomalous values near mineralization or their geochemical behaviour closely parallels that of more easily determined elements.

Heavy-mineral concentrate samples

At many localities where a sieved stream-sediment sample was taken, a bulk sample weighing about 5 kg was collected for the extraction of heavy minerals. In the field a rough concentrate was obtained by panning. Back in the laboratory the panned material was passed through bromoform to remove the remaining quartz and feldspar and treated with a hand magnet to remove magnetite. The concentrates were then examined under a binocular microscope and analyzed for bismuth, cerium, chromium, cobalt, copper, lanthanum, lead, molybdenum, nickel, niobium, silver, tantalum, tin, tungsten, yttrium, zinc, and zirconium by optical emission spectrography. Chemical tests and X-ray diffraction patterns were sometimes needed to aid mineral identification.

Soil samples

Soil samples were collected from a depth of about 20 cm using a miner's pick. Many samples contained fairly large pebbles which were removed by sieving through 500μm (30 mesh BSS) sieves. As the soils contained predominantly very fine material the choice of mesh size was not critical. Soil samples were analyzed for the same elements and by the same methods as stream sediments.

Errors

The sampling and analytical errors associated with the above procedures have been investigated in the Georgetown region 600 km to the east of the present study area (Rossiter, in press, a). Errors were found to be very small for all elements except manganese, which showed sampling fluctuations possibly attributable to organic activity. This does not appear to be a problem at Westmoreland, however, and to date in this area no difficulties have been experienced in interpreting manganese data for stream-sediment samples.

Discussion of results

Optimum stream-sediment size fraction

Bulk stream-sediment samples weighing about 10 kg were collected from 9 sites scattered throughout the Westmoreland region and sieved into various grainsize fractions. The distribution of zinc in the different size fractions of 4 of these samples is shown in Figure 3. The general increase in concentration in the finer grainsizes illustrated by the diagram occurs for a wide range of elements. Since the geochemical contrast (the difference between anomalous and background samples) is greater in the finer size fractions it follows that, for the purpose of delineating anomalies, the finer the material sampled the better. However, as some samples contained as little as 0.2 percent of minus 180 μm material, it was found that sieving time was excessive if a sieve finer than 180 μm was used. It was decided, therefore, that for all subsequent sampling 180 μm sieves would be employed.

Sampling in areas remote from mineralization

It is important during geochemical surveys to establish the normal background variation for those elements considered significant in the detection of economic mineral deposits. After the geochemical background has been investigated it becomes possible to recognize anomalous values and thereby delineate exploration targets.

Several catchments draining single rock units were sampled in order to assess the variations in trace-metal contents of sediments derived from each of the different rock types. Attention was focussed on those units

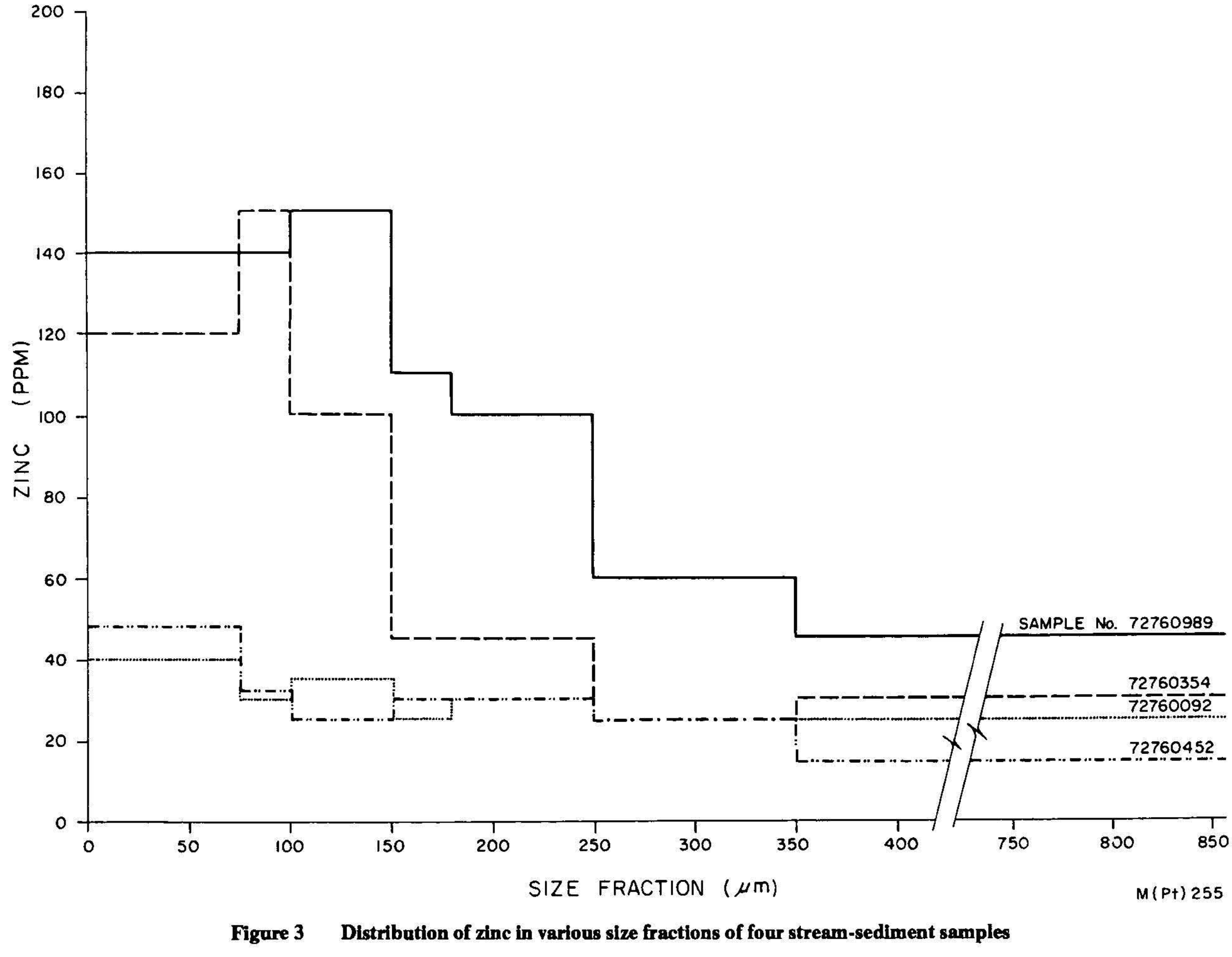

Figure 3 **Distribution of zinc in various size fractions of four stream-sediment samples**

considered to have the greatest mineral potential. Results for the elements of economic interest are summarized in Table 1. Lead is fairly homogeneously distributed among sediments related to different lithologies and this appears to be so for uranium as well, although there are no data for the high-level phase of the Nicholson Granite Complex or the Fickling Group. Copper shows a pronounced enrichment near the basic lavas of the Siegal and lower Peters Creek Volcanics, while tin values are considerably higher on Cliffdale Volcanics than on any of the other rock units for which data are available. It is likely that higher background tin levels also occur on the high-level granitic rocks of the Nicholson Granite Complex, as these are genetically related to the Cliffdale Volcanics. The similarity in geochemistry of the two rock units is evidenced by the copper and lead data of Table 1.

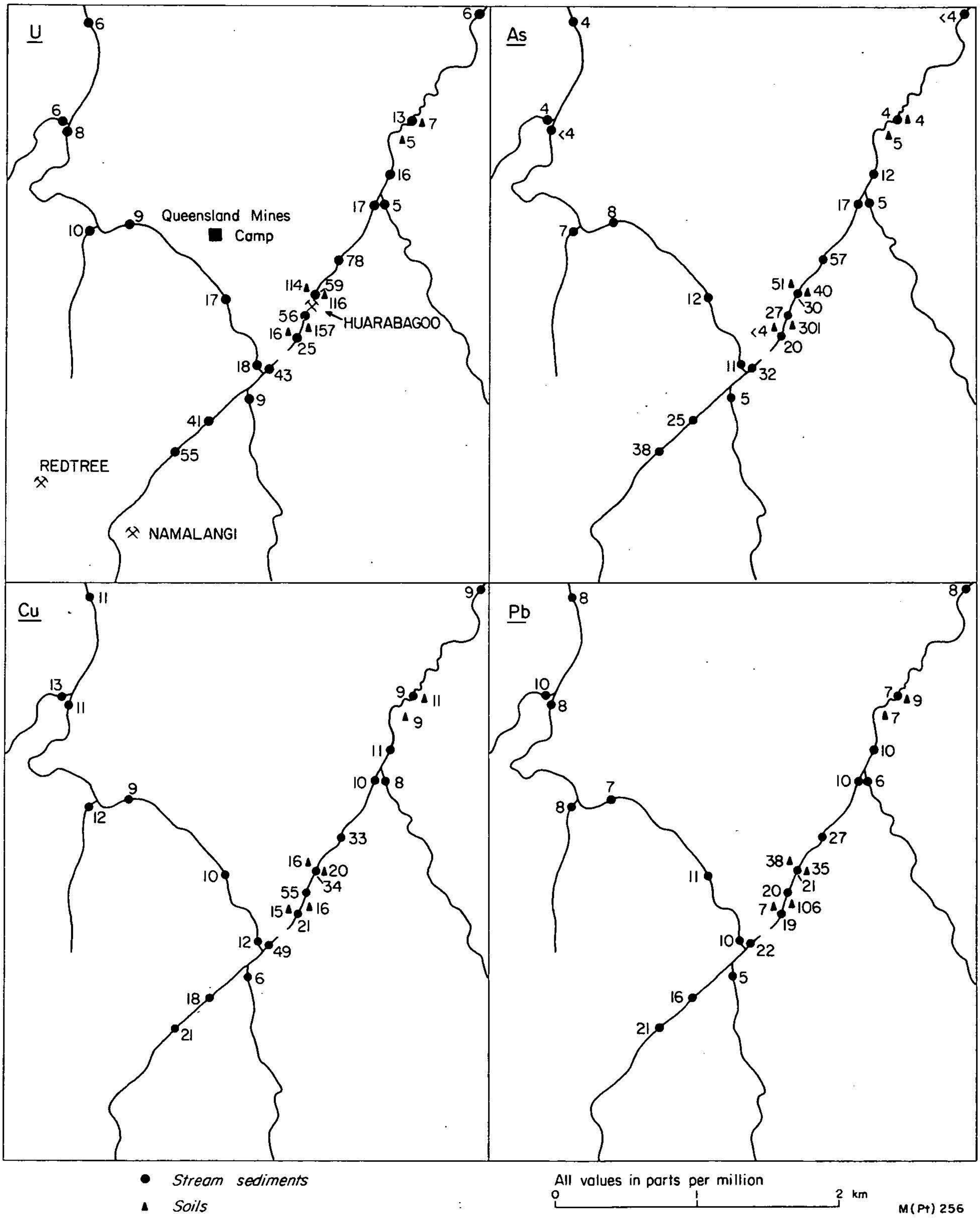

Figure 4 **Results of geochemical sampling near the Westmoreland uranium deposits**

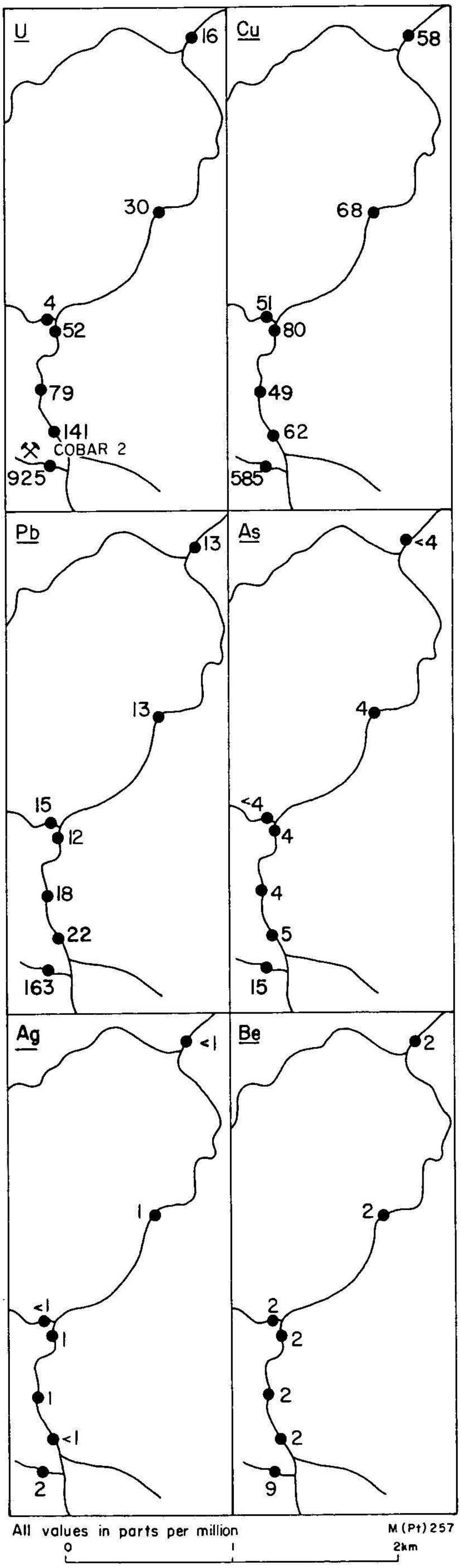

Figure 5 **Results of stream-sediment sampling near the Cobar 2 uranium deposit**

When metal contents vary considerably between stream sediments associated with different rock types threshold values should be defined very carefully. For example, a copper value of 100 ppm on basic volcanics is probably not significant, but in a granitic terrain this level would be anomalously high. The problem is not a major one when the highest background values occur on the rock types most likely to contain mineralization. This is the case for tin.

TABLE 1: GEOCHEMICAL VARIATION IN STREAM-SEDIMENT SAMPLES COLLECTED FROM CATCHMENTS DRAINING DIFFERENT ROCK UNITS.

Rock unit	*No. of samples*	*Cu*	*Pb*	*Sn*	*U*
Cliffdale Volcanics	25	26 15-40	23 11-40	8 3-24	5 4-7
High-level phase of Nicholson Granite Complex	6	24 13-35	26 18-40		
Westmoreland Conglomerate/ Wire Creek Sandstone	10	12 8-25	10 7-12	— < 2-4	3 2-5
Seigal Volcanics/lower Peters Creek Volcanics	60	72 43-122	17 9-79		
”	9			— < 2-2	— < 2-4
Fickling Group	13	16 11-21	30 11-39		

All values are in ppm. Arithmetic means and the actual (not statistical) ranges of values are presented. Where no mean is given the element was not detected in all samples.

Sampling in areas of known mineralization

To evaluate the geochemical expression of each type of deposit, sieved stream-sediment, heavy-mineral concentrate, and some soil samples were collected from around uranium, copper, tin, and lead mineralization.

Uranium

Structurally-controlled uranium mineralization occurs in a number of rock units. The Pandanus Creek deposit is located within Cliffdale Volcanics, the Cobar 2 and related smaller occurrences in Seigal Volcanics, and the Westmoreland group of deposits in Westmoreland Conglomerate (Fig. 2). The ore minerals are mainly secondary, and pitchblende is relatively rare; minor chalcopyrite, galena, and gold are sometimes present.

The Westmoreland (Namalangi-Huarabagoo-Redtree) deposits discussed by Brooks (1972) are among the largest known in Queensland. Queensland Mines' annual report for 1972 announced probable reserves of 1.7 million tonnes of ore averaging 0.25 percent U_3O_8, but no figures are available for Mount Isa Mines' Redtree leases. The only production in the area has been from the Pandanus Creek and Cobar 2 mines. At Pandanus Creek 311 tonnes of ore containing 8.37 percent U_3O_8 were mined between 1960 and 1962 (Morgan, 1965). From Cobar 2, 73 tonnes of hand-picked ore averaging 10.52 percent U_3O_8 were trucked to Rum Jungle for processing (Stewart, 1965).

Extensive anomalies occur downstream from the three areas of uranium mineralization sampled. Presumably uranium has first passed into solution in ionic form and then has been adsorbed by clays, hydrated oxides, and organic matter in the stream sediments. A detailed appraisal of the secondary dispersion of uranium (and the other elements determined during this survey), under climatic conditions similar to those prevailing in the Westmoreland region, has been given by Rossiter (in press, a).

Anomalous levels of arsenic (Fig. 4), copper and lead (Fig. 5), and lithium, tin, and tungsten (Fig. 6) also occur near uranium deposits. Minor enrichment of beryllium and silver is sometimes observed. The extremely strong correlation between uranium and lead values in samples collected near uranium mineralization (Table 2) suggests that much if not all of the lead is being produced by radioactive decay and is not primary. The high lithium, tin, and tungsten levels associated with the Pandanus Creek deposit may be coincidental as it is possible, although unlikely, that the stanniferous greisen occurring here (Fig. 6) is unrelated to the uranium orebody. It should be remembered that exploration and mining activity has probably exaggerated the anomalies in the three mineralized areas, but it is encouraging from an exploration viewpoint that uranium dispersion trains persist for greater distances downstream than do those of the associated elements.

The distribution of uranium in the stream sediments and soils of the Westmoreland area is shown in histogram and probability cumulative frequency form in Figure 7. The

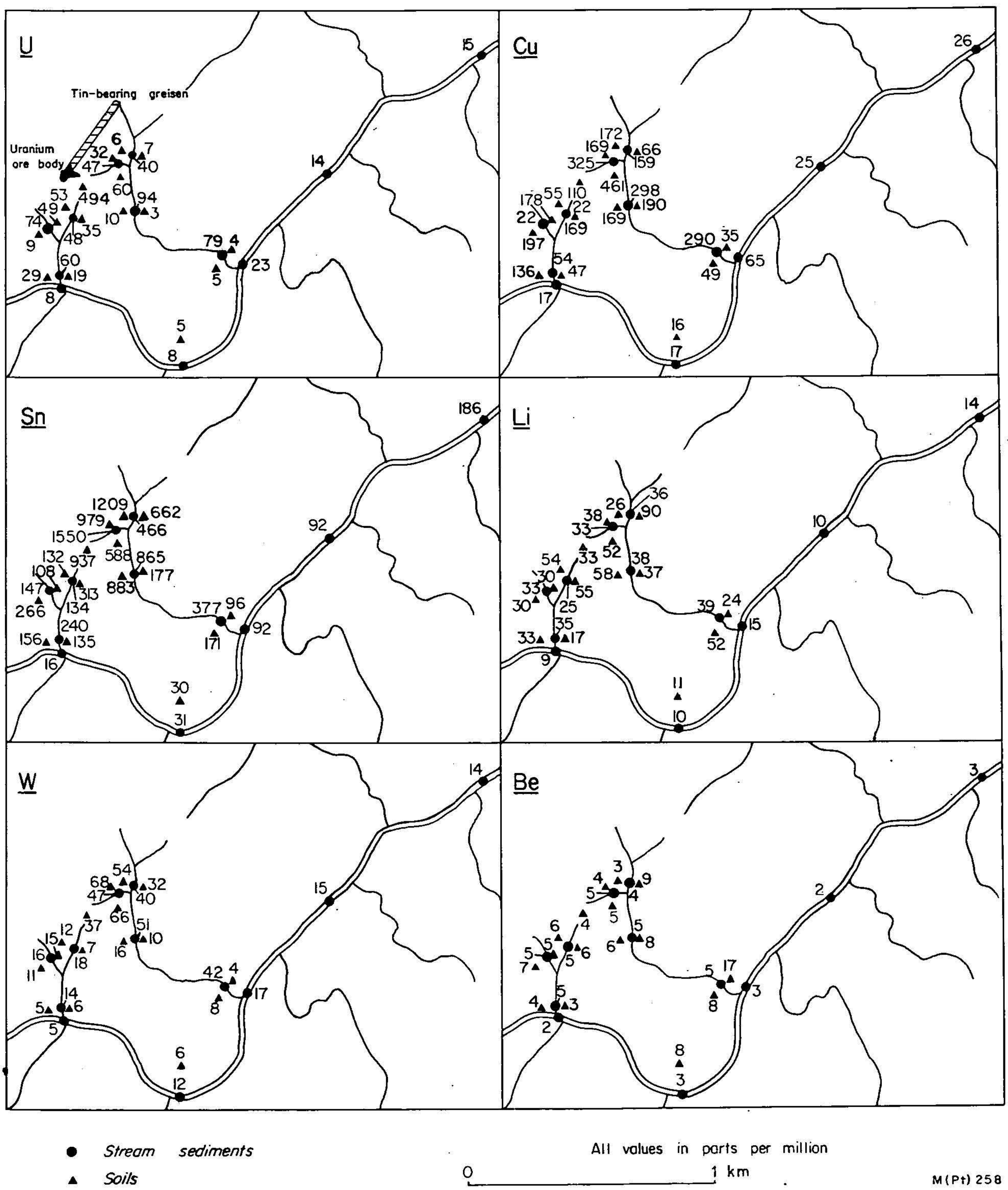

Figure 6 **Results of geochemical sampling near the Pandanus Creek uranium deposit**

positive skew of the histograms for both media suggests that the distributions may have lognormal affinities. The linearity of the logarithmic cumulative frequency diagrams for low uranium values confirms that the background populations can be reasonably approximated by the ideal lognormal distribution. Above values of 8 ppm for stream sediments and 12 ppm for soils there are abrupt changes in the slopes of the logarithmic plots, implying deviations from typical background values. In each case a second, anomalous, population is beginning to make a significant contribution to the total uranium distribution. Values of 8 ppm in stream sediments and 12 ppm in soils can be used, therefore, to distinguish anomalous from background samples. Sinclair (1974) and Parslow (1974) have proposed elaborate graphical partitioning techniques for deducing geochemical threshold values from cumulative frequency diagrams, but the results usually compare closely with those obtained using the much simpler 'break in slope' method. Arsenic levels of 15 ppm in stream sediments and 12 ppm in soils should also be regarded as significant during uranium exploration programs in the area (Rossiter, in press, b).

Heavy-mineral sampling appears to be of little use in detecting uranium deposits. Sometimes detrital gold is present in concentrates near mineralization but secondary uranium minerals are rare owing to their softness and solubility. Monazite has not been observed in significant quantities in the region and is unlikely to interfere with the interpretation of stream-sediment surveys for uranium, as it does in the Georgetown area (Rossiter, in press, a).

Copper

There are two varieties of copper mineralization in the region. Deposits of the first type occur in basic volcanic rocks. The best examples are the Redbank mines, which are

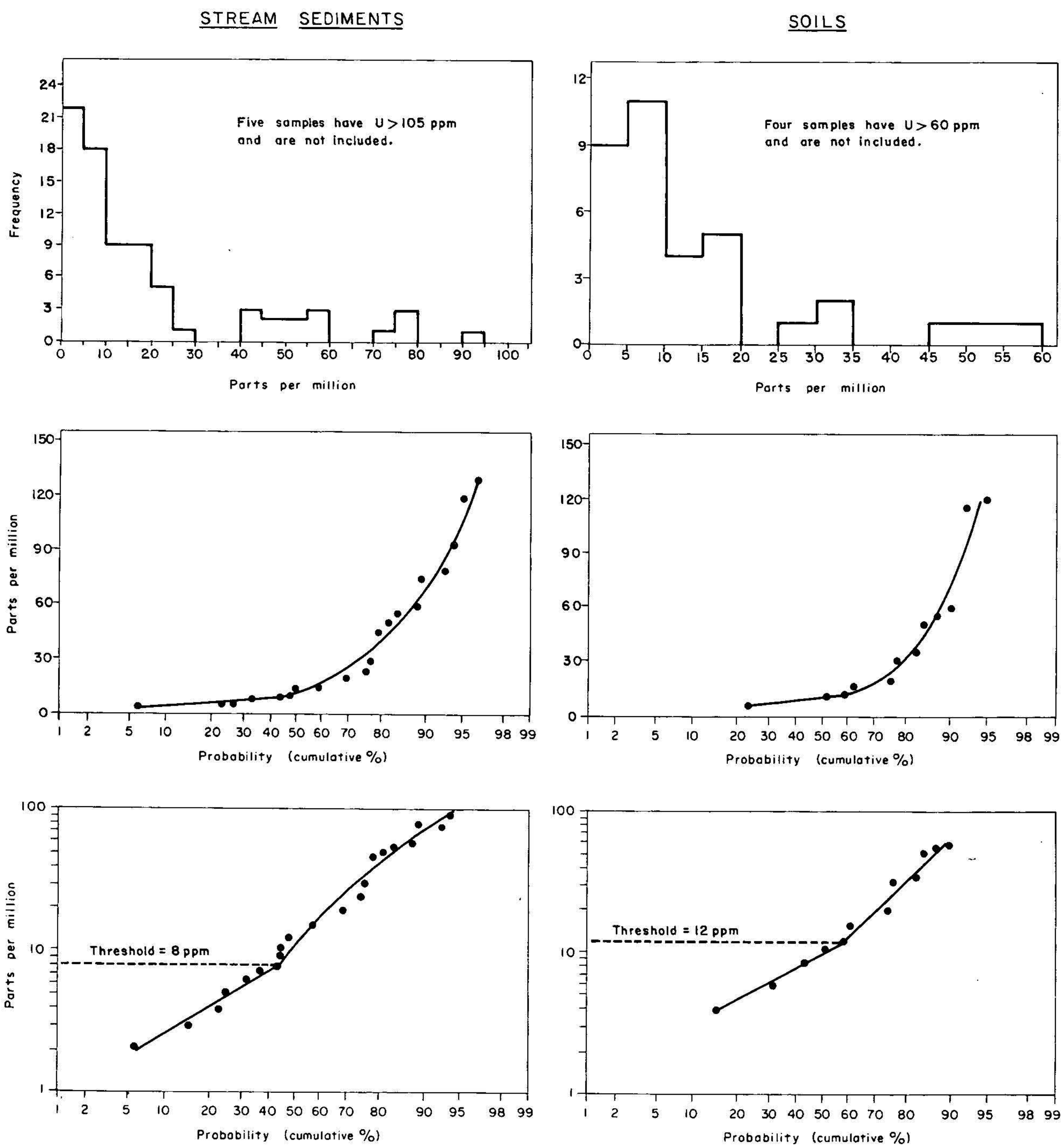

Figure 7 Uranium distributions in histogram and cumulative frequency form

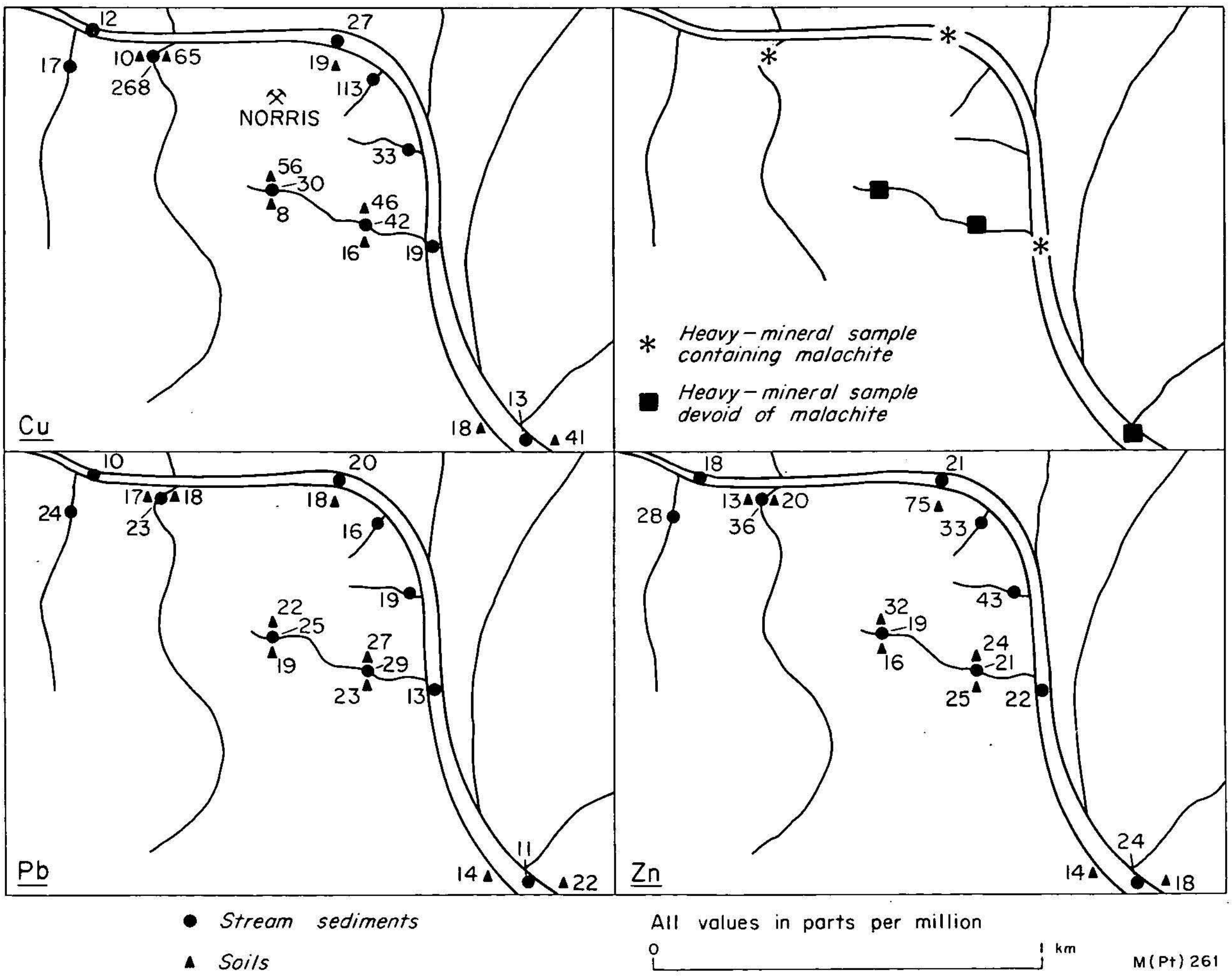

Figure 8 Results of geochemical sampling near the Norris copper deposit

located within a volcanic member of the Masterton Formation (Fig. 2). The ore occurs in breccia pipes and, in the old workings, consists entirely of secondary minerals with malachite, chrysocolla, azurite and chalcocite being the most abundant. Drilling in recent years, however, indicates chalcopyrite at depth. Total production from the Redbank field was about 1000 tonnes of ore, ranging in grade from 25 to 52 percent copper (Roberts *et al.*, 1963). No other deposits in basic volcanics have been exploited commercially.

Copper deposits of the second type occupy faults and shears in the Cliffdale Volcanics and the high-level phase of the Nicholson Granite Complex. Of these the Norris mine (Fig. 2) has been the only significant producer. The orebody is associated with a small quartz-filled fracture related to the Calvert Fault, a major structure. Chalcopyrite, altered in places to digenite, constitutes the primary ore; malachite occurs in the oxidized zone. Minor uranium mineralization occurs nearby. The records of the Queensland Mines Department show that during 1968, when mining was most active, 310 tonnes of ore containing 19 percent copper were trucked to Mount Isa. Total production has probably not exceeded twice this amount.

Copper dispersion trains in stream sediments are relatively short (Figs. 8 & 9) and a very close sample spacing would be needed to reliably detect mineralization using sieved samples. Heavy-mineral sampling appears to promise more as a reconnaissance exploration method. As detrital malachite grains are so conspicuous under the microscope, a few small fragments in an original bulk sample of 5 kg can be readily detected. Hence, although most of the copper is probably in adsorbed form in the fine-grained fraction of the stream sediments (maximum copper value encountered in heavy-mineral concentrates is 100 ppm), the optical heavy-mineral technique is more sensitive than the chemical analysis of sieved material. It is probably only with the use of a mechanical concentrating device such as a Wilfley table that the full potential of the heavy-mineral method will be realized.

The definition of threshold copper values for stream sediments (and soils) is difficult because background levels differ greatly between areas of basic igneous rocks and other rock types (Table 1). To overcome this problem the data for samples from catchments draining only basic rocks and those from areas of differing rock type have been plotted separately (Fig. 10). The two copper distributions show lognormal tendencies and threshold values deduced from the logarithmic cumulative frequency diagrams are 120 ppm for basic rocks and 80 ppm for other rock types. Thresholds for soils are 150 ppm and 80 ppm respectively (Fig. 11). No metal other than copper is significantly enriched in sediments or soils around the Norris and Bluff mines (Figs. 8 & 9) and there appear to be no pathfinder elements very useful in the search for copper deposits.

Tin

Tin occurs at several localities within the Cliffdale Volcanics and the high-level phase of the Nicholson Granite Complex (Fig. 2). The largest deposit is at Crystal Hill where a greisenized vein contains cassiterite, wolframite,

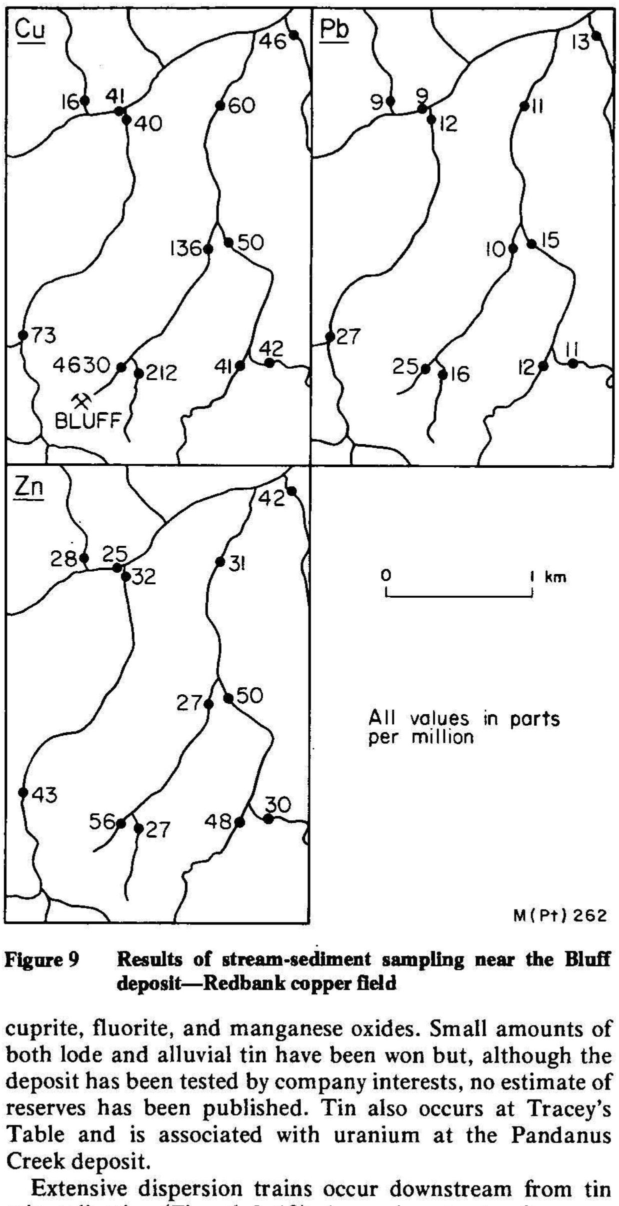

Figure 9 **Results of stream-sediment sampling near the Bluff deposit—Redbank copper field**

cuprite, fluorite, and manganese oxides. Small amounts of both lode and alluvial tin have been won but, although the deposit has been tested by company interests, no estimate of reserves has been published. Tin also occurs at Tracey's Table and is associated with uranium at the Pandanus Creek deposit.

Extensive dispersion trains occur downstream from tin mineralization (Figs. 6 & 12). Anomalous levels of copper, lithium, tungsten, and uranium also occur, together with minor enrichment of beryllium. The dispersion of tin in the secondary environment is dominated by mechanical processes because of the chemical stability of cassiterite. Consequently heavy-mineral concentrate samples collected downstream from tin mineralization are extremely rich in detrital cassiterite. In addition, high tungsten (> 2000 ppm) and tantalum (to 200 ppm) in heavy-mineral samples suggest the present of wolframite and tantalite, although these minerals were not identified optically. Topaz is also abundant.

The distribution of tin in the stream sediments and soils of the area is shown in Figure 13. The dispersed cassiterite is fine enough for substantial amounts ot occur in some minus 180 μm samples. Threshold tin values of 50 ppm for stream sediments and 40 ppm for soils are obtained from the arithmetic cumulative frequency plots. Lithium values of greater than 20 ppm in both stream sediments and soils should be regarded as significant during exploration for tin, as should tungsten levels exceeding 20 ppm in either medium (Rossiter, in press, b). The analysis of sieved samples and the optical examination of heavy-mineral concentrates are equally effective for the detection of tin deposits.

Lead

Syngenetic galena occurs in silicified dolomitic rocks of the Fickling Group at several localities in the southeast of the study area (Fig. 2). The primary mineralization contains some pyrite, sphalerite, and minor chalcopyrite, while cerussite, pyromorphite, and some malachite are present in the near-surface parts of the deposits. The most significant occurrences are the Lead Hill, Mount Les, Gorge Creek, Galena Pits, and First Up prospects. Lead Hill is the only one with an economic grade, but the deposit is very small. The largest is Mount Les where Carpentaria Exploration has outlined 1.5 million tonnes of 0.1 percent lead (Taylor, 1970).

Substantial lead, zinc, and very weak copper anomalies occur in stream sediments associated with deposits of this type (Fig. 14). Rossiter (in press, a) has shown that in the climatically and physiographically similar Georgetown area, lead is dispersed by mechanical processes as anglesite ($PbSO_4$) and cerussite ($PbCO_3$) and there is no reason to suspect that the manner of dispersion differs in the Westmoreland region. No heavy-mineral concentrate data are available for the Westmoreland lead deposits, but it is likely that heavy-mineral studies will prove a useful exploration tool for this type of mineralization in the area—this possibility will be investigated by further sampling. As anglesite and cerussite are difficult to identify optically, chemical analysis of the heavy-mineral samples will probably be needed to establish the presence of these minerals. The occurrence of the lead sulphate leads to anomalous sulphur values in sieved samples at Georgetown, and this may also be the case here.

The distribution of lead in the stream sediments and soils of the area is shown in Figure 15. Both distributions are complex with neither normal nor lognormal models fitting the data very well. Nevertheless well-defined breaks in the cumulative frequency diagrams indicate that a threshold value of 120 ppm is appropriate in both media. Both zinc distributions are adequately described by combinations of lognormal populations—thresholds of 140 ppm in stream sediments and 100 ppm in soils are obtained from logarithmic cumulative frequency plots (Rossiter, in press, b). The zinc threshold value for stream sediments (and possibly also soils) must be used with care, however, as there is evidence that this element is more susceptible than other metals to co-precipitation with and adsorption by manganese compounds such as $Mn(OH)_4$ and MnO_2.

An example of apparent manganese scavenging of zinc is shown in Figure 16. Several stream-sediment samples in catchments draining basic volcanics contain anomalous zinc but normal amounts of copper and lead; these samples also have manganese contents which exceed 1000 ppm and are anomalous (Rossiter, in press, b). If these high zinc and manganese levels were due to increased amounts of a rock-forming ferromagnesian mineral in the stream sediments, correspondingly high chromium and nickel values would be expected. As these do not occur, the alternative explanation that zinc and manganese are associated in secondary oxidate compounds, is more likely. Some enrichment of silver also appears to take place.

No rock type is associated with consistently high manganese values, rather very high levels are observed sporadically in areas of differing lithology. To date they are known to occur where Peters Creek Volcanics or Fickling Group rocks crop out and are probably the result of precipitation. Conditions conducive to manganese precipitation are not commonly encountered in areas of seasonal rainfall (Horsnail, *et al.*, 1969; Rossiter, in press, a) and manganese scavenging is not likely to occur on a wide scale in the Westmoreland region, however occasional false zinc anomalies can result. The problem of deciding just how significant is a high zinc value can be overcome by examining the abundances of other elements, especially copper, lead, and manganese. Factor analysis is an elaborate way of doing this.

Multivariate data evaluation

As indicated in the preceding discussion the distributions of the various elements in the stream sediments of the Westmoreland region combine both normal and lognormal characteristics. Consequently statistical parameters are calculated below for both raw and logarithmically transformed data.

Correlation coefficients

The interrelation between two or more elements determined during a geochemical survey may be quantified by the use of Pearson correlation coefficients. When these are calculated for the Westmoreland stream-sediment data most of the significant inter-element relations already noted on an empirical basis reappear in mathematical terms (Table 2). A correlation is not considered meaningful unless it is statistically significant for both raw and logarithmically transformed values.

There is strong correlation between uranium values and silver, beryllium, copper, and lead levels in sediments near uranium mineralization; arsenic correlation may be high in the case of a specific deposit (Fig. 4) but its association with uranium is not sufficiently widespread to produce a significant total data correlation between these two elements.

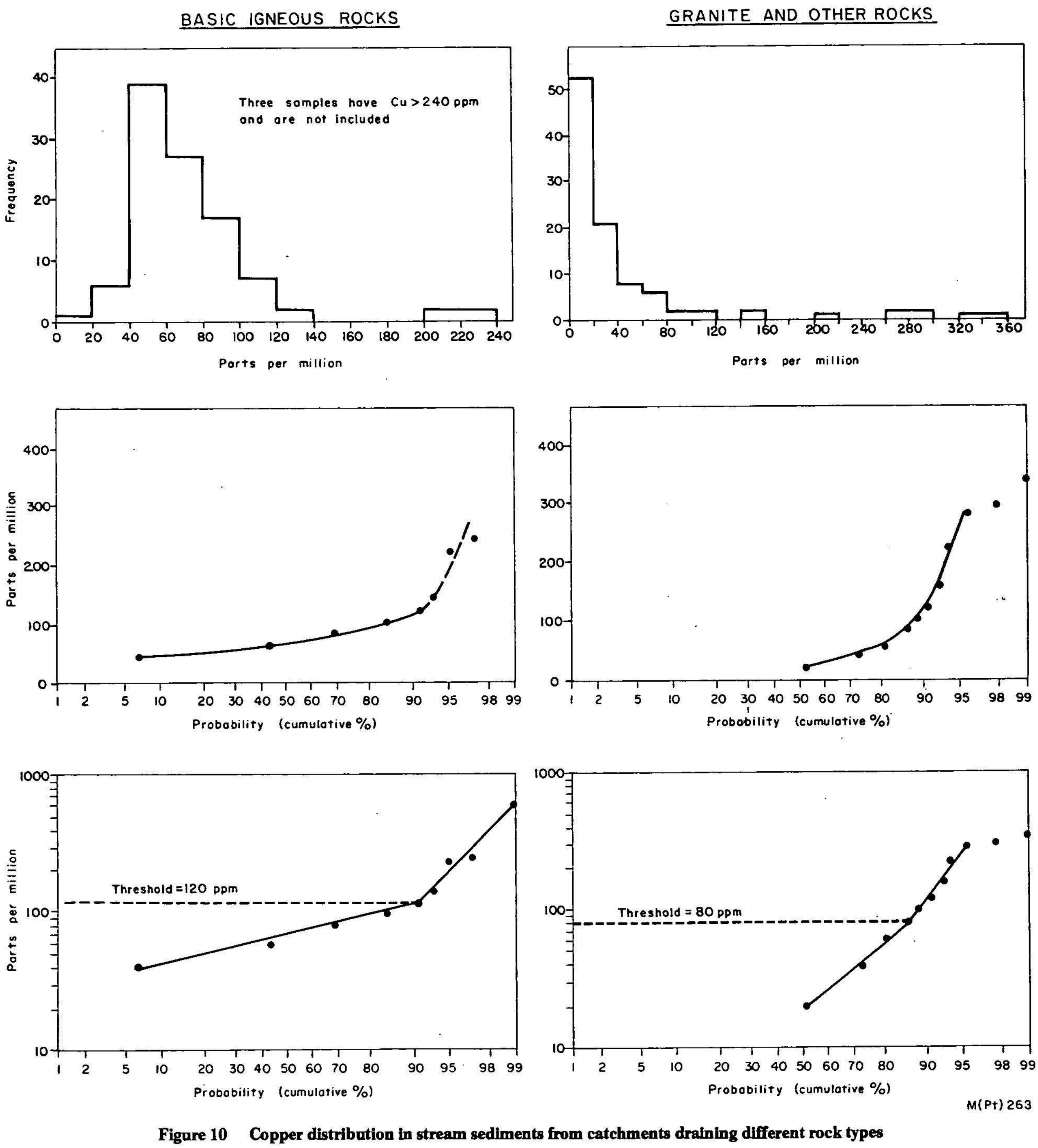

Figure 10 Copper distribution in stream sediments from catchments draining different rock types

TABLE 2: PEARSON CORRELATION COEFFICIENTS FOR STREAM SEDIMENTS

Raw Data

	Ag	*Be*	*Cu*	*Li*	*Mn*	*Pb*	*Zn*	*As*	*Sn*	*U*	*W*
Ag		0.30*	0.27*	0.09	0.46*	0.09	0.52*	–0.04	0.13	0.47*	0.02
Be	0.30*		0.25*	0.38*	0.09	0.06	0.02	–0.01	0.37*	0.65*	0.18
Cu	0.44*	0.62*		0.09	0.08	0.03	0.04	0.06	0.49*	0.77*	0.27
Li	0.18	0.54*	0.58		–0.01	–0.08	0.05	–0.11	0.54*	0.03	0.54*
Mn	0.34*	0.36	0.53	0.29		0.14	0.55*	–0.27	0.01	0.17	–0.01
Pb	0.08	0.19	0.28	–0.01	0.30		0.38*	0.22	0.08	0.98*	0.01
Zn	0.42*	0.31	0.52	0.40	0.70*	0.41*		–0.12	–0.08	0.15	–0.02
As	0.20	–0.03	0.06	–0.09	–0.35	0.33	–0.20		–0.09	0.22	–0.04
Sn	–0.07	0.63*	0.37*	0.60*	0.11	0.27	–0.01	–0.08		0.05	0.46*
U	0.50*	0.49*	0.51*	0.28	–0.10	0.75*	0.03	0.54	0.31		–0.02
W	0.08	0.52	0.47	0.60*	0.17	0.38	0.13	0.14	0.68*	0.34	

Logarithmically Transformed Data

Coefficients above and to the left of the dashed line were calculated for 214 samples, the remainder were calculated for 84 samples. Asterisks indicate positive correlations that are significant at the 99% confidence level for both raw and logarithmically transformed values.

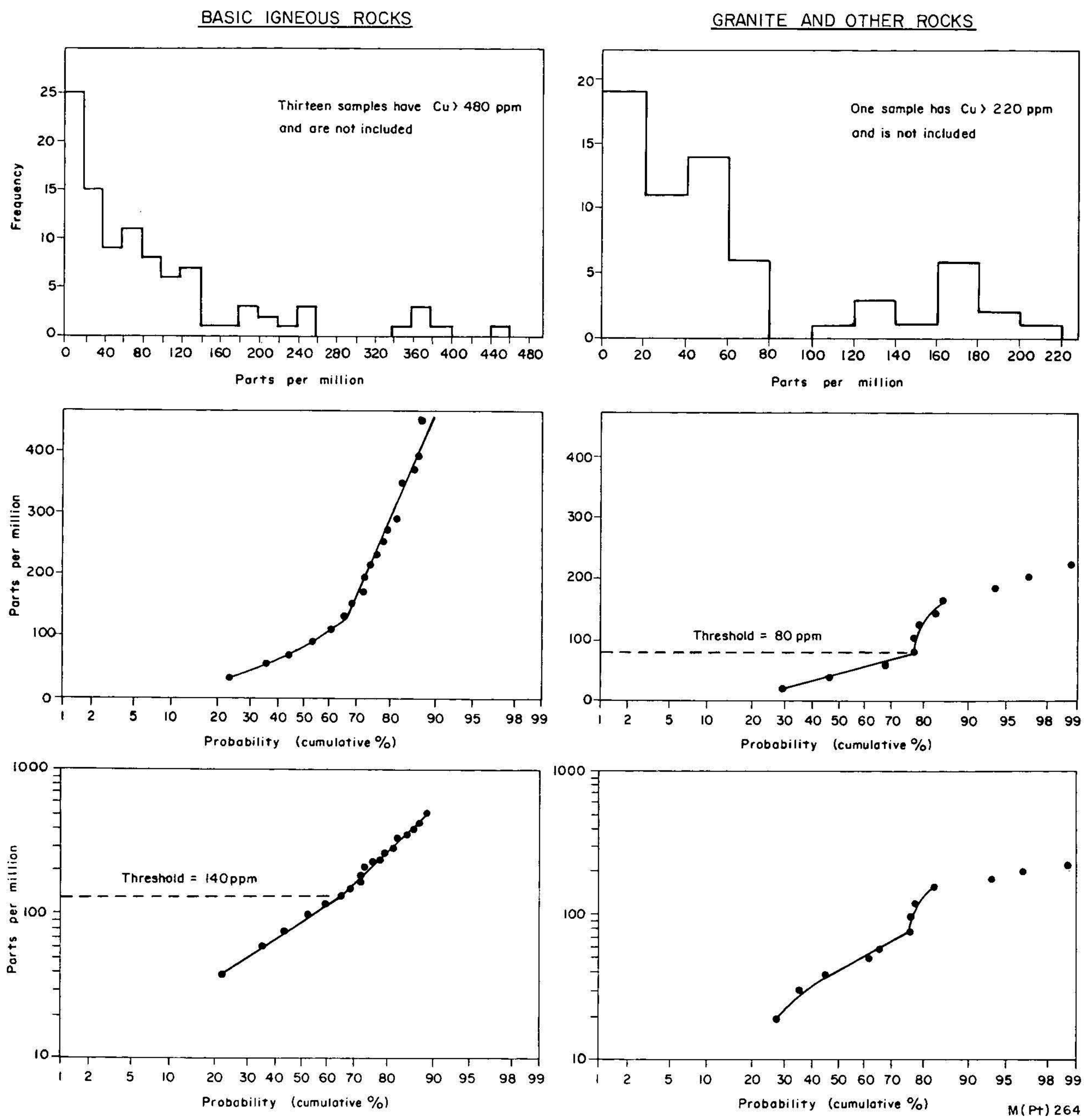

Figure 11 Copper distribution in soils overlying different rock types

Copper shows covariation with silver, beryllium, tin, and uranium. It should be pointed out, however, that the existing tin and uranium data apply only to copper mineralization in granitic rocks. No tin and uranium values for the deposits in basic volcanics are available for inclusion in the correlation coefficient calculations, and these two elements are not necessarily associated with copper in a basic environment.

Near tin mineralization concentrations of beryllium, copper, lithium, and tungsten are to be expected.

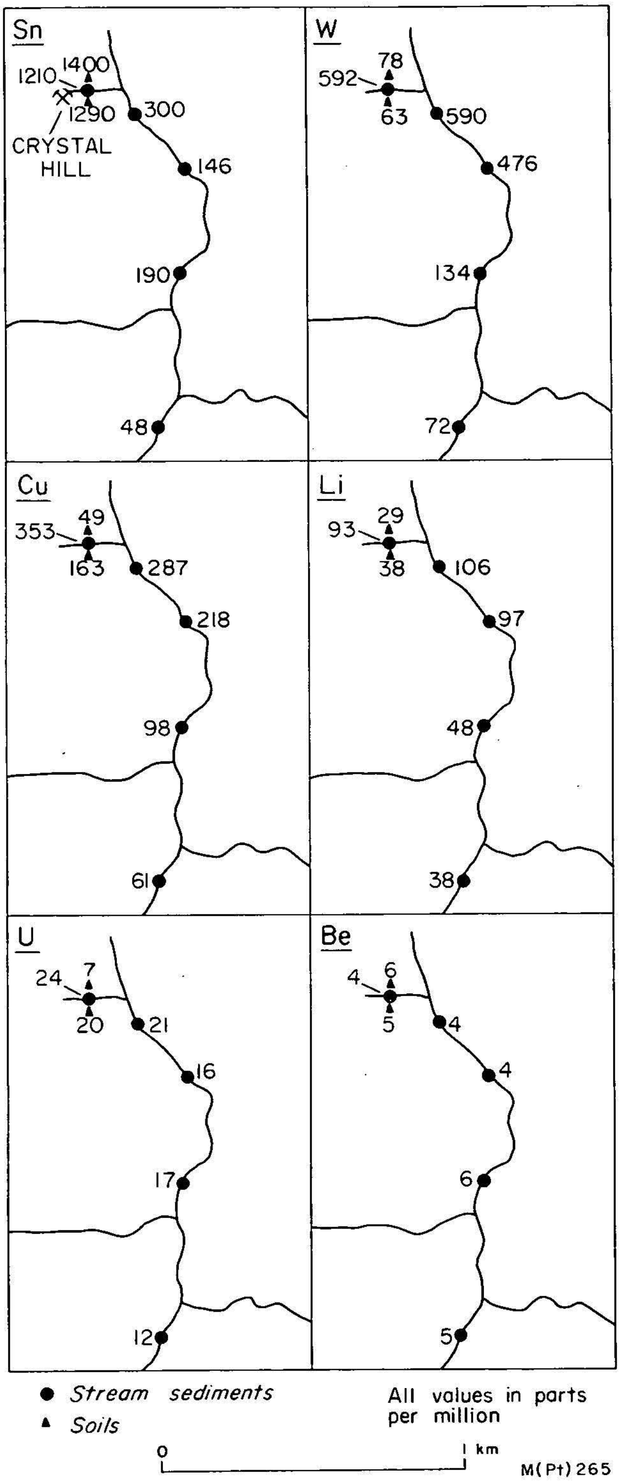

Figure 12 Results of geochemical sampling near the Crystal Hill tin deposit

Lead is correlated with zinc and with uranium. It should be noted that the correlation coefficient between lead and uranium is calculated for a limited number of samples, all collected near uranium mineralization. There are no data for uranium in the vicinity of lead deposits. Consequently the high correlation between lead and uranium indicated in Table 2 does not necessarily imply that high uranium values are to be expected near lead mineralization.

R-mode factor analysis

The interrelation of the elements can be studied in additional depth by means of R-mode factor analysis. This technique generates a set of new variables (or factors), a few of which are usually sufficient to describe most of the variance in the original data. Generally any elements showing covariation, either sympathetic or antipathetic, are combined in the one factor. In this way a large array of data can be reduced to a small number of highly significant variables.

The mathematics involved in the extraction of R-mode factors are extremely complex and will not be gone into in detail here. However, the general outline is as follows.

Initially the Pearson correlation coefficients are calculated and expressed as vectors in multi-dimensional space. The factors are actually a framework of co-ordinate axes superimposed on this vector array. The factor axes are rotated both orthogonally (Varimax rotation) and obliquely (Promax rotation) so that the correlation vectors have the simplest possible factor constitution (or factor loadings). All samples can be represented in terms of the factor model by numeric values known as factor scores.

The choice of the number of factors to be extracted is arbitrary, and consequently the interpretation of the results of factor analysis is rather subjective. Although alternative procedures have been suggested, it has become established practice in geochemical survey work 'to employ as many factors as are necessary to simplify the data to a pre-determined degree of geochemical simplicity, or alternately use as many factors as one can confidently interpret in terms of the local geochemistry' (Garrett & Nichol, 1969).

A large number of factor analyses have been carried out for the Westmoreland stream-sediment data. Both raw and logarithmically transformed values have been used and the number of factors extracted has been varied many times. Only the two most easily interpreted factor matrices are described here. The first (Table 3) is a four-factor raw data model constructed from 214 samples analyzed for silver, beryllium, copper, lithium, manganese, lead, and zinc.

The matrix is accounted for as follows:—

Factor 1 high negative loadings of silver, manganese, and zinc. This factor is probably a manifestation of the process of scavenging of zinc and silver by hydrated manganese oxides.

Factor 2: high negative loadings of beryllium and lithium. This factor reflects fractionated or pneumatolytically altered acid igneous rocks—these are often associated with mineralization.

Factor 3: high positive loadings of lead and zinc. This is a lead mineralization factor.

Factor 4: high negative loadings of silver and copper. This factor reflects copper mineralization.

The four factors describe 80.1 percent of the total variance in the data set.

This model provides a solution to the problem noted earlier of deciding whether a high zinc value is significant from an exploration viewpoint. Factor scores have been calculated for all samples containing anomalous (> 140 ppm zinc). High Factor 3 scores very successfully distinguish samples related to mineralization from those in which manganese scavenging has presumably occurred (Table 4). Factor 1 scores are also useful, but to a lesser degree. It could be argued that simple inspection of the abundances of elements other than zinc would suffice and although this is often true, in borderline cases mathematical quantification is desirable or even necessary.

TABLE 3: FOUR-FACTOR RAW DATA MATRIX FOR STREAM SEDIMENTS

Factor No.	*1*	*2*	*3*	*4*
Ag	—0.80	—0.09	—0.11	—0.29
Be	0.21	—0.64	0.06	—0.21
Cu	—0.06	0.03	0.05	—0.94
Li	—0.13	—0.91	—0.04	0.18
Mn	—0.86	0.08	0.11	0.05
Pb	0.02	0.00	0.99	—0.05
Zn	—0.78	0.00	0.28	0.13
Eigenvalues (cumulative %)	32.3	53.5	67.0	80.1
Principal loadings	—Ag —Mn —Zn	—Be —Li	Pb Zn	—Ag —Cu

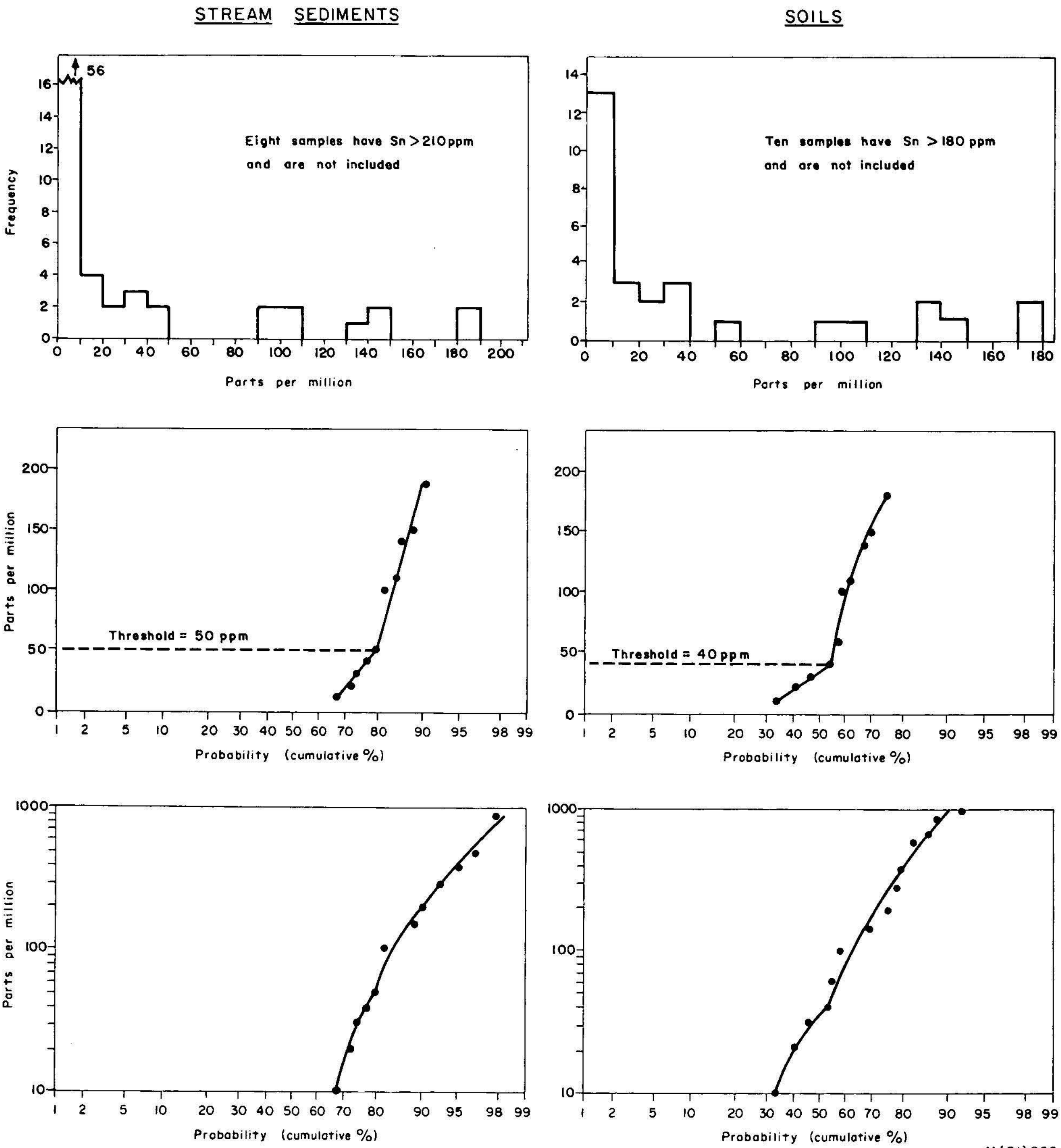

Figure 13 Tin distribution in histogram and cumulative frequency form

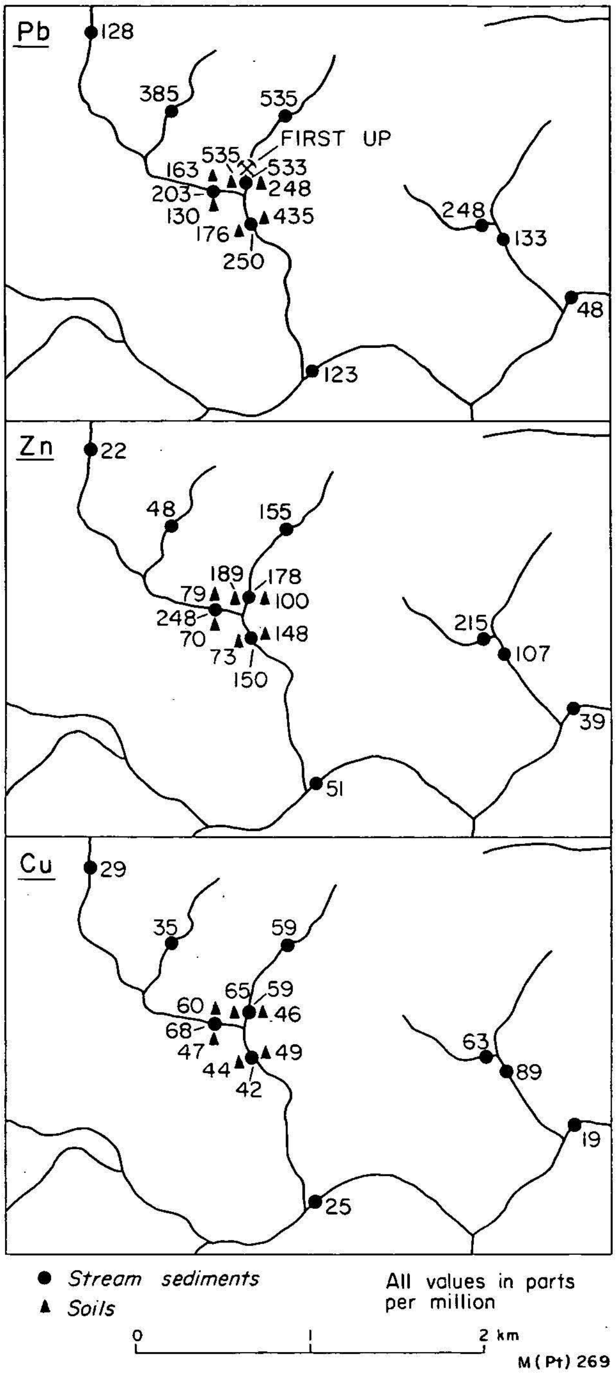

Figure 14 Results of geochemical sampling near the First Up lead deposit

The second factor model (Table 5) is a five-factor raw data matrix constructed from 84 samples analyzed for silver, beryllium, copper, lithium, manganese, lead, zinc, arsenic, tin, uranium, and tungsten.

The five-factor model is interpreted as follows:

Factor 1: high positive loadings of copper, lead, and uranium. This is a mineralization factor; high positive factor scores are found near uranium deposits.

Factor 2: high negative loadings of copper, lithium, and tin. This is also a mineralization factor; high negative scores occur near copper and tin deposits.

TABLE 4: FACTOR SCORES (FOUR-FACTOR RAW DATA MODEL) FOR ALL STREAM-SEDIMENT SAMPLES ANOMALOUS IN ZINC

	Factor 1 (Manganese scavenging)	*Factor 3 (Mineralization)*
Samples from near mineralization	—3.6	8.4
	—3.9	4.0
	—2.0	4.0
	—2.3	8.3
	—3.6	4.5
	—7.0	3.0
Samples remote from mineralization in which high zinc values are probably due to manganese scavening	—2.9	0.6
	—2.4	0.6
	—12.9	2.1
	—4.2	0.9
	—4.6	1.0
	—2.8	0.6
	—2.9	0.5
	—5.0	1.7
	—3.6	0.5

All samples associated with mineralization have a Factor 3 score of 3.0 or greater, those in which manganese scavenging has presumably occured have scores of 2.1 or less. There is also some tendency for greater negative Factor 1 scores in the latter group of samples.

TABLE 5: FIVE-FACTOR RAW DATA MATRIX FOR STREAM SEDIMENTS.

Factor No.	*1*	*2*	*3*	*4*	*5*
Ag	0.26	—0.25	0.58	0.08	0.23
Be	0.14	—0.07	—0.28	—0.14	0.04
Cu	0.74	—0.39	0.01	—0.03	—0.06
Li	—0.07	—0.66	0.15	0.01	—0.33
Mn	—0.01	0.01	0.90	—0.15	0.03
Pb	1.05	0.14	—0.05	0.01	—0.02
Zn	—0.07	0.19	0.99	0.05	—0.10
As	0.02	—0.01	0.04	1.00	0.00
Sn	—0.11	—1.02	—0.22	0.01	0.08
U	1.05	0.18	—0.08	0.01	—0.02
W	0.06	—0.06	0.01	0.00	—0.94
Eigenvalues (cumulative %)	39.0	57.6	74.7	82.3	87.3
Principal loadings	Cu Pb U	—Cu —Li —Sn	Ag Mn Zn	As	—Li —W

Factor 3: high positive loadings of silver, manganese, and zinc. This may be described as a manganese scavenging factor, and the process should be suspected in any sample with a high positive factor score.

Factor 4: high positive loading of arsenic. This is a mineralization factor, high positive scores are encountered near some uranium deposits.

Factor 5: high negative loadings of lithium and tungsten. Again this is a mineralization factor; high negative factor scores are found near tin-tungsten lodes.

These five factors describe 87.3 percent of the total variance in the data. The most striking feature of the matrix is the confirmation of the very strong uranium-copper (Factor 1) and tin-copper (Factor 2) associations noted in previous sections. Beryllium practically disappears from the factor model, and perhaps this element has less to offer than the others during future geochemical surveys in the region.

Conclusions

The results of the orientation survey are summarized in Table 6. Stream-sediment sampling is a potentially powerful exploration technique in the Westmoreland region and can detect each of the four main mineralization types occurring here. A combination of sieved samples (minus 180 μm) and heavy-mineral concentrates is the best approach.

Uranium deposits are associated with extensive uranium, and in some instances arsenic, copper, lead, lithium, tin, and tungsten anomalies in sieved samples. Minor enrichment of beryllium and silver also occurs. Uranium appears to be dispersed mainly by chemical processes, and heavy-mineral concentrates show little evidence of nearby mineralization—they contain only rare grains of gold and secondary yellow uranium minerals.

The best indicator of copper deposits is the presence of malachite in heavy-mineral samples. In sieved sediments copper anomalies normally do not persist for long distances downstream from the source. A study of geochemical backgrounds on different rock units shows that copper is the only element for which it is necessary to consider rock type when defining threshold values. Background copper levels are higher on basic volcanics than they are in areas where other rock types crop out.

Tin is dispersed mechanically, and near mineralization heavy-mineral concentrates are very rich in detrital cassiterite. Wolframite and tantalite are probably also present. The dispersed cassiterite is fine enough for

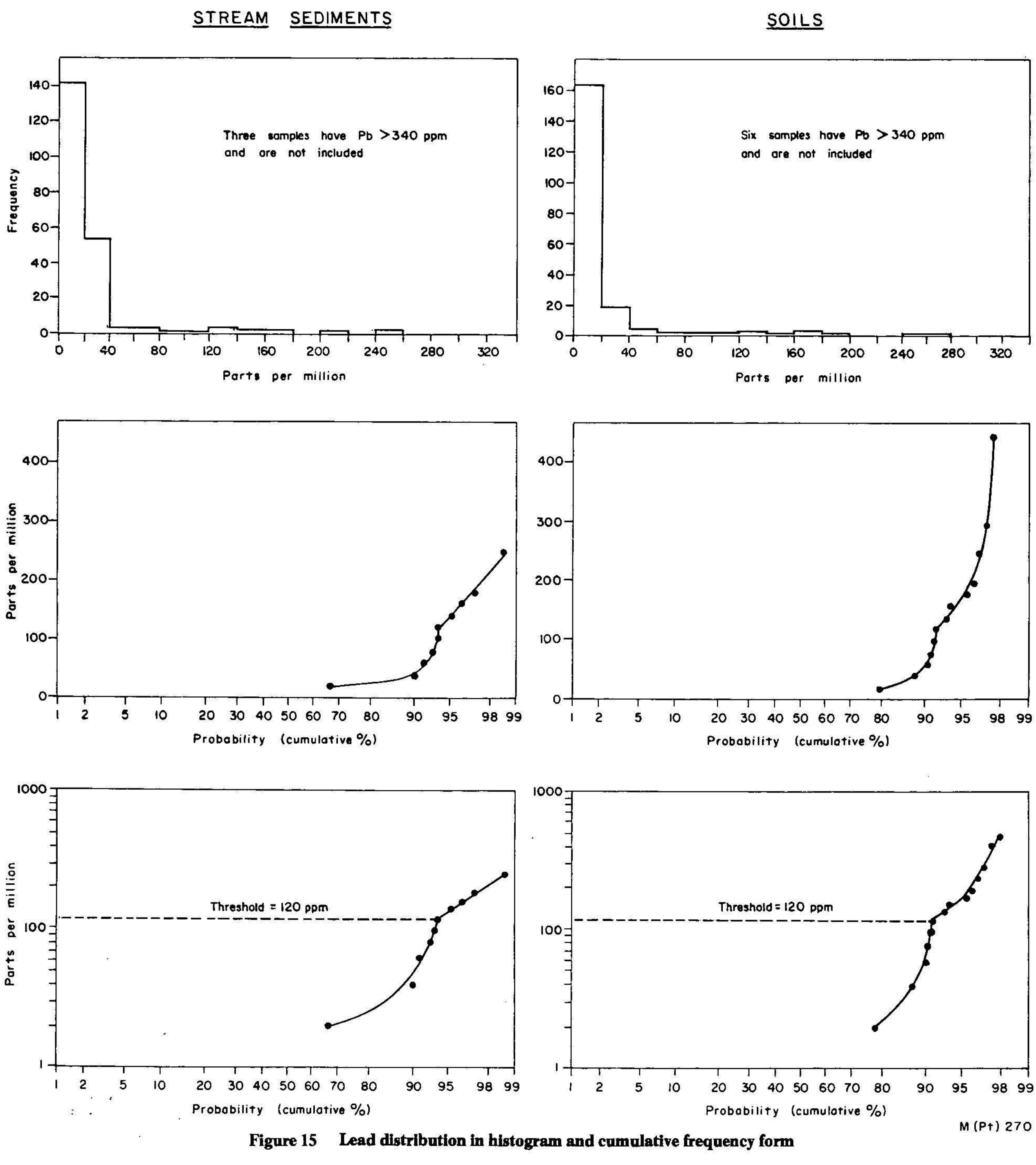

Figure 15 Lead distribution in histogram and cumulative frequency form

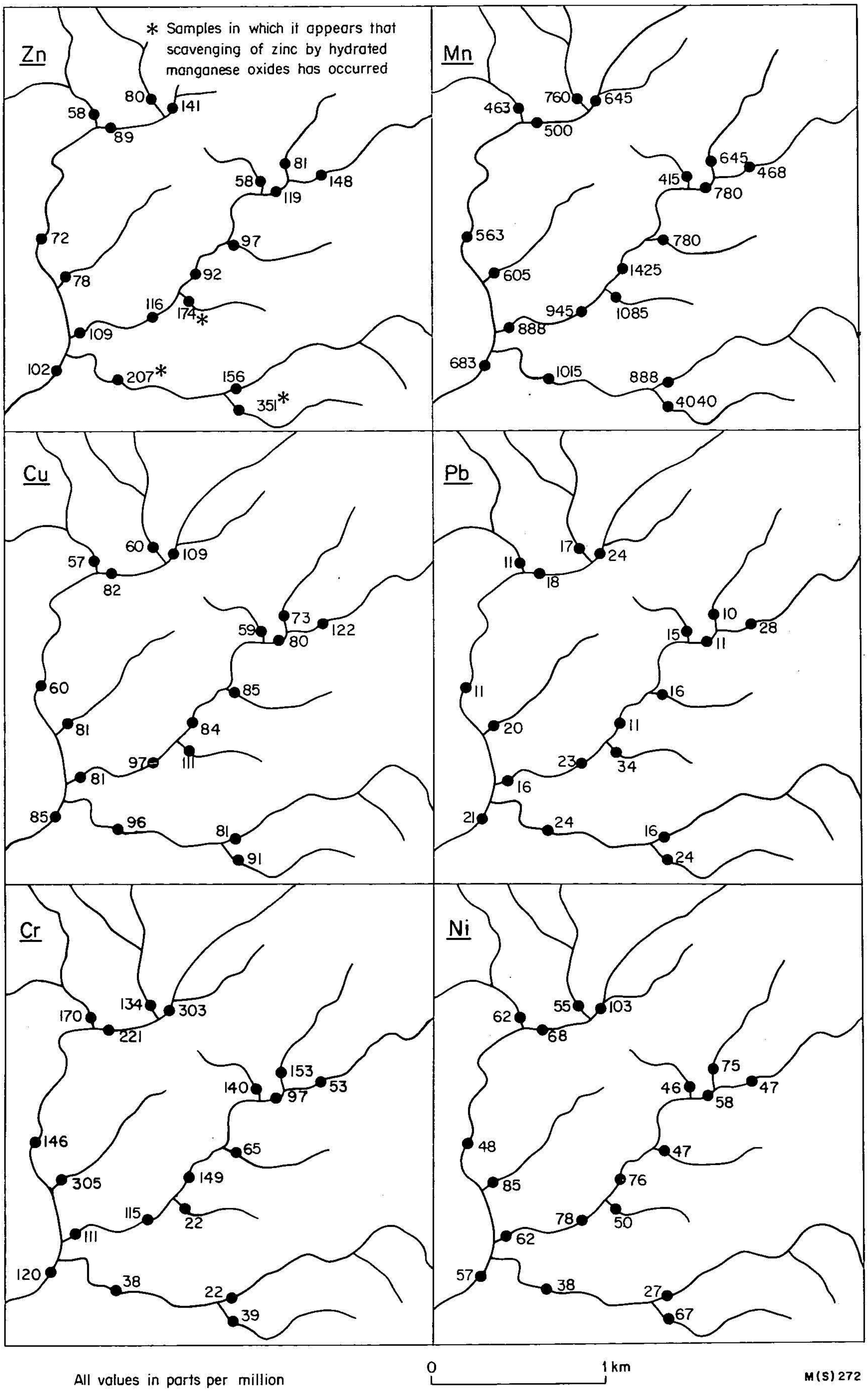

Figure 16 An example of apparent manganese scavenging of zinc in stream sediments

substantial amounts to occur in minus 180 μm stream sediment, and consequently sieved samples are just as effective as heavy minerals in detecting tin deposits. Copper, lithium, tungsten, uranium, and to a lesser degree, beryllium are enriched in sediments near tin mineralization.

TABLE 6: STREAM-SEDIMENT SURVEYS IN PROSPECTING FOR THE MAJOR MINERALIZATION TYPES OF THE WESTMORELAND REGION

Element sought	*Threshold (ppm) in minus 180 μm sediment*	*Useful pathfinder elements*	*Applicability of the heavy-mineral technique*
Uranium	8	Arsenic (threshold 15 ppm) copper, lithium (threshold 20 ppm), lead, tin, tungsten (threshold 20 ppm)	—
Copper	Basic rocks 120 Other Lithologies 80	—	Optical examination of heavy-mineral samples for malachite
Tin	50	Copper, lithium, uranium, tungsten	Optical examination of heavy-mineral samples for cassiterite
Lead	120	Copper, zinc (threshold 140 ppm)	Chemical analysis of heavy-mineral samples?

The thresholds shown are relevant only for surveys using identical analytical techniques to those followed here, otherwise the values should be taken as a guide only.

Lead deposits are associated with lead, zinc, and weaker copper anomalies in sieved stream sediments. If zinc values are used during exploration, the possibility of false anomalies caused by manganese scavenging should be borne in mind. It is likely that lead is dispersed mechanically as anglesite and cerussite and the chemical analysis of heavy-mineral samples will probably prove a useful prospecting tool.

Multivariate statistical analysis provides useful insights into the metallogenesis of the area. For example, the very high uranium-lead correlation coefficient calculated for samples collected near uranium deposits, strongly suggests that the lead is the product of radioactive decay. A further example is the use of R-mode factor analysis in assessing whether high zinc values reflect proximity to mineralization or have been caused by manganese scavenging—the technique is successful because the associated element suite is characteristic in each case.

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The Bullara Limestone, a new rock-stratigraphic unit from the Carnarvon Basin, Western Australia

George C. H. Chaproniere

A new rock unit, the Bullara Limestone, is proposed for a Late Oligocene bioclastic limestone, which is probably restricted to the subsurface of Rough Range. The Bullara Limestone is a lateral equivalent of the lower part of the Mandu Calcarenite, and contains a Tertiary lower *e* stage larger foraminiferal fauna and a Zone N.3 planktic fauna.

Condon *et al.* (1955, 1956) formalized the rock-stratigraphic nomenclature that had been previously used informally by Clapp (1925), Raggatt (1936), Singleton (1941) and Condon (1954), for the North West Cape part of the Carnarvon Basin, and created several new units. McWhae *et al.* (1958), Condon (1968) and Quilty (1974) have presented summaries of the rock stratigraphy for this part of the Carnarvon Basin, based on the earlier published work. The scheme of Condon *et al.* (1955), as modified by Condon (1968), has been retained for this note. However, because of additional subsurface information resulting from a number of petroleum exploration wells drilled by West Australian Petroleum Pty Ltd. (WAPET), an additional name is required for a bioclastic limestone in the subsurface of Rough Range. The purpose of this note is to formally define this unit. Figure 1 gives the relevant locality information, and Figure 2 illustrates the stratigraphic relationships for the area discussed.

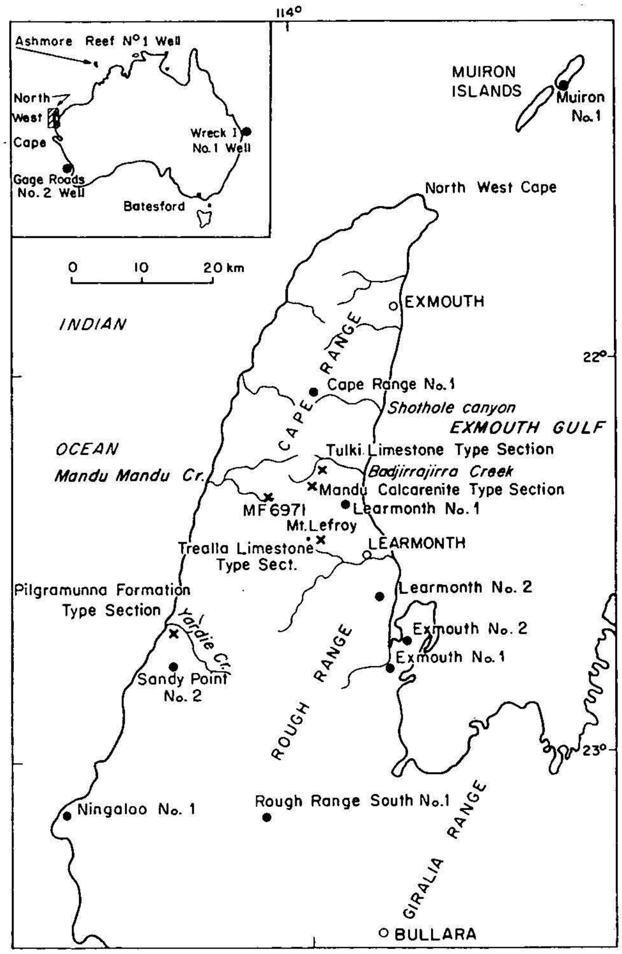

Figure 1 **Locality Map**

Bullara Limestone (new name)

The name Bullara Limestone is proposed for a massive, brown to grey, poorly to well cemented, often recrystallized bioclastic calcarenite that unconformably underlies the Trealla Limestone and disconformably overlies the Giralia Calcarenite lateral equivalent, in the Rough Range area. It differs from the Mandu Calcarenite (Condon *et al.*, 1955) in being coarser grained, containing less mud and a different fauna, and by being brownish.

The type section is designated as the interval between 220 and 306 m in Rough Range South No. 1 Well (lat. 22°37'-17.5"S, long. 113°57'37.6"E) (Fig. 1). The type thickness is 86 m. Figure 3 gives the geophysical logs and other information for the type section. Representative samples from cores 4 and 7 to 11 have been placed in the collections of the Department of Geology, University of Western Australia (registered numbers UWA53673, to UWA53678, and UWA70600). The name is taken from the 'Bullara Homestead', 12 km southeast of the type section (Fig. 1). Approval for this new name has been given by the Stratigraphic Nomenclature Committee of the Geological Society of Australia.

The top of the Bullara Limestone is nearly wholly recrystallized, but the rocks become progressively less altered down the sequence. The interval about 274 m is made up of lithologies containing poorly sorted, coarse-grained, bioclastic material (algal nodules, larger foraminiferids and rare molluscan fragments) in a matrix containing very little or no mud (see Chaproniere, 1975, fig. 8F-H). Below 274 m the lithologies are generally finer grained and the larger foraminiferids and algal nodules are absent.

The Bullara Limestone is probably restricted to the subsurface of Rough Range: its only surface exposure may be a recrystallized limestone exposed in a valley on the east side of Rough Range, referred to the Tulki Limestone by Condon *et al.* (1955), and to the Mandu Calcarenite by Condon (1968). The unit has been recognized in three wells north of the type section: the thinnest sequence is seen between 119 and 156 m in Exmouth No. 1 Well (37 m) and the thickest is 134 m in Learmonth No. 2 Well (between 215 and 349 m); in Exmouth No. 2 Well it is 83 m thick (between 167 and 250 m).

On the basis of the fauna, the limestone can be subdivided into two parts. The larger foraminiferal fauna from the upper part comprises *Lepidocyclina* (*Eulepidina*) *ephippioides*, *L.* (*Nephrolepidina*) *sumatrensis*, *Heterostegina borneensis*, *Operculina complanata* and *Gypsina howchini*, a fauna which forms the *Lepidocyclina* (*Eulepidina*) *ephippioides*—*Heterostegina borneensis* (= LF.2 in Fig. 3) association of Chaproniere (1975); smaller benthic foraminiferids are common, but subordinate to the

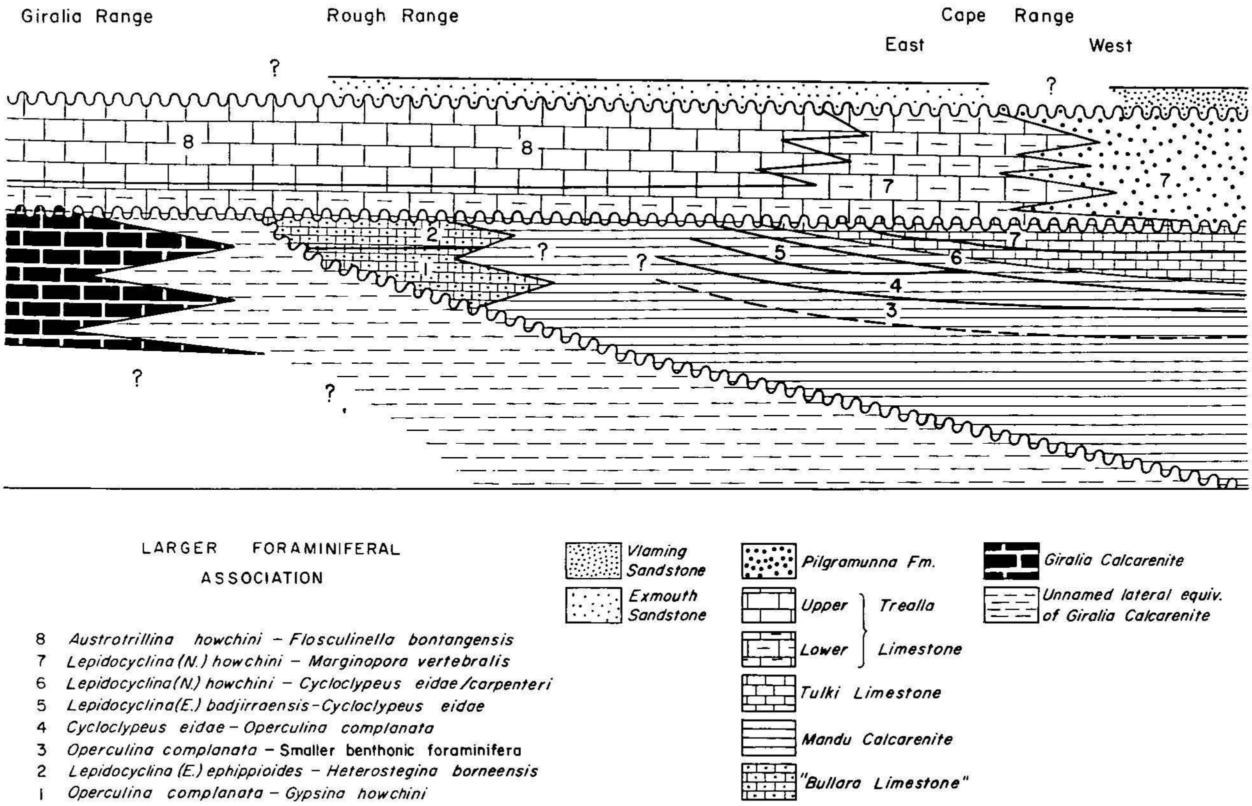

Figure 2 **Diagrammatic east-west cross-section of the North West Cape area, showing the stratigraphic relationships between the Oligo-Miocene units (after Chaproniere, 1975).**

larger forms, and planktic forms are extremely rare. *Gypsina howchini*, *Operculina complanata* and very rare *Lacazinella* sp. cf. *L. wichmanni* are the only larger foraminiferids found in the lower part; this assemblage forms the *Operculina complanata* — *Gypsina howchini* (= LF.1 in Fig. 3) association of Chaproniere (1975); smaller benthic forms dominate the faunas from this part, and planktics have not been encountered. Fragments of articulated coralline algae are important constitutents at all levels.

The presence of *Globorotalia (Turborotalia) kugleri*, without *Globigerinoides quadrilobatus primordius* (in only one sample), is indicative of Zone N.3 of Blow (1969). The presence of *Heterostegina borneensis*, which becomes extinct within Zone N.3 (Clarke & Blow, 1969, fig. 1), permits correlation with the Tertiary lower *e* stage (Late Oligocene). This correlation is supported by the low mean values for parameter A ($\bar{A}$ = 39.31 ± 3.18 percent) for *Lepidocyclina (Nephrolepidina) sumatrensis*, that are similar to those obtained by van der Vlerk & Postuma (1967) for populations of *Lepidocyclina (Nephrolepidina)* associated with a Zone N.3 planktic fauna from Indonesia. The presence of *Lacazinella* sp. cf. *L. wichmanni* in the lower part of the Bullara Limestone suggests a correlation with either the Tertiary *b* or *c* stages (Adams, 1970). There is no good evidence, however, for a large stratigraphic break within the Bullara Limestone, nor is there any major change in the smaller benthic foraminiferal fauna. Moreover, the absence of typical Eocene forms within the limestone, other than probably reworked forms together with the evidence presented above, suggests that the lower part of the Bullara Limestone is of similar age to the upper part; that is Tertiary lower *e*. The presence of *Lacazinella* sp. cf. *L. wichmanni* can be explained either by reworking from the underlying Eocene rocks, which is the preferred explanation, or by its ranging to higher stratigraphic levels than previously recorded. The age of the Bullara Limestone is latest Oligocene.

The Bullara Limestone correlates with the lower part of the Mandu Calcarenite in the subsurface of Cape Range, and is its shallow-water lateral equivalent.

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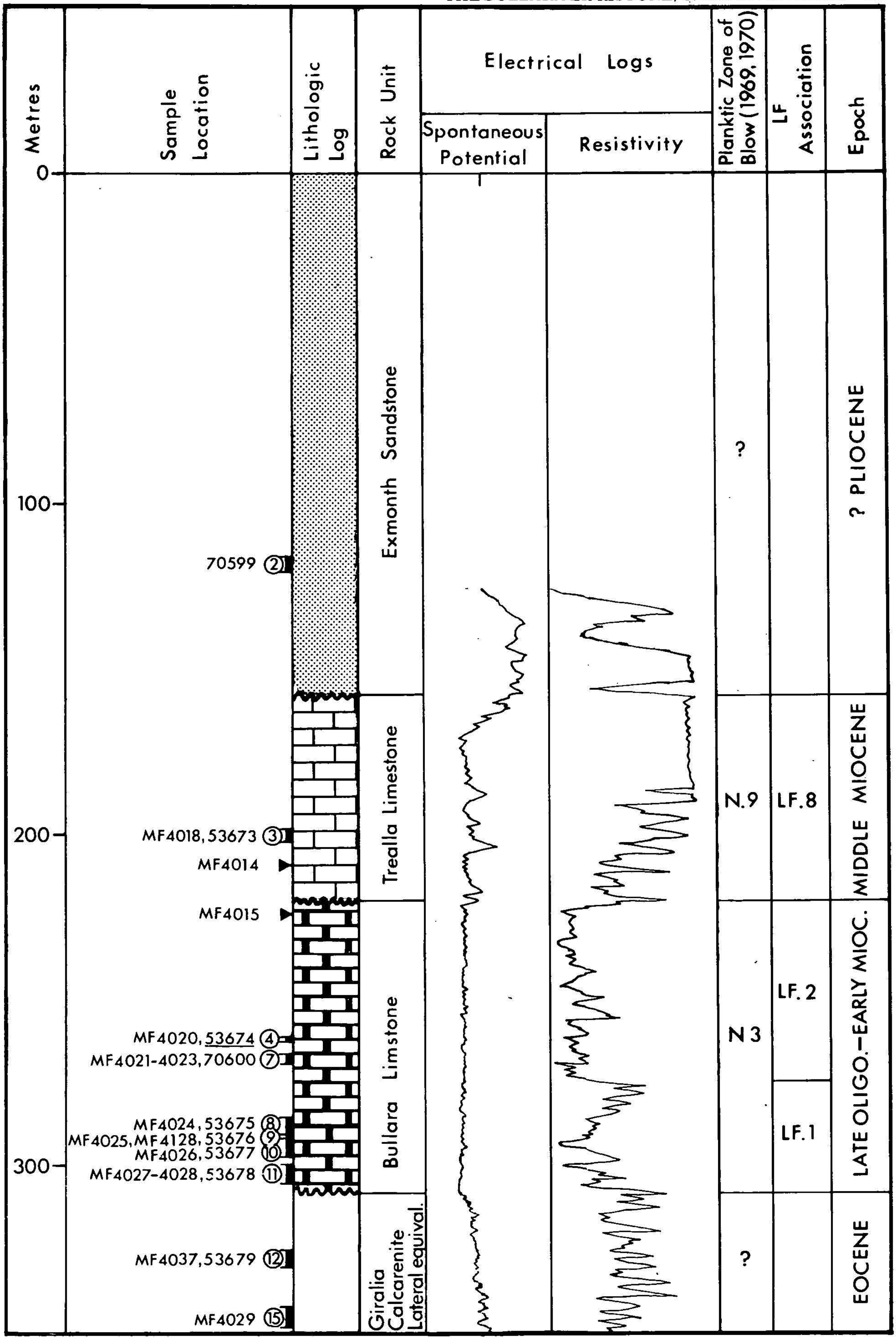

Figure 3 Sample location, rock stratigraphy and biostratigraphy of the type section for the Bullara Limestone in Rough Range South No. 1 Well.

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