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Front cover:
Dibolisporites distinctus (Clayton) Playford, 1976; a plant microfossil characteristic of Lower Carboniferous strata in Australia. Scanning electron micrograph (X3400). This number contains a review of Carboniferous and Permian palynostratigraphy in Australia and Antarctica.

Photograph: John Hardy, Electron Microscope Centre, University of Queensland.

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Field tests of a new electromagnetic depth-sounding technique

*K. Duckworth**

A program of field tests of a new electromagnetic sounding technique was conducted in the Northern Territory. The tests were conducted to evaluate the operational features of the technique, and to determine its ability to provide useful depth information over localised conductive structures. The results are compared with earlier work which used an alternative electromagnetic sounding technique, and with drilling results.

The tests demonstrated the operational and interpretive flexibility of the new technique. In particular they showed that the technique can be applied with normal, unmodified, electromagnetic prospecting equipment. The depth information which the new technique provided was in good agreement with control information.

Introduction

Electromagnetic depth sounding is not normally applied to localised conductive structures. This is because of the lack of theoretical interpretation procedures related to such work, and to the specialised nature of the equipment which is normally necessary for such work. The source-orientation method of depth sounding is a new electromagnetic technique which was developed to provide a procedure which can be applied to localised structures and which can use unmodified electromagnetic prospecting equipment. Details of the technique were provided by Duckworth (1975).

The first field tests of this new technique were conducted in August 1975 in association with the Bureau of Mineral Resources of the Department of National Resources of Australia. BMR was responsible for earlier tests of an alternative electromagnetic depth-sounding technique, so that advantage was taken of the opportunity for comparative tests. These earlier tests were reported by Duckworth (1970), and involved a geometric sounding technique—this being the descriptive classification of the technique which was provided by Ryu *et al* (1972).

The geometric technique achieves soundings by variation of the separation between a source and a receiver. This variation does not require complicated instrumentation and it was found that the technique could be applied to normal electromagnetic prospecting equipment. The technique was shown to be capable of providing useful depth information over localised conductive structures but it did prove to have some operational features which were troublesome. Among these features were the need for extended, undisturbed sounding sites and a prolonged calibration procedure. In addition, it was necessary to modify the equipment to permit geometric soundings to be taken.

The source-orientation technique was developed to avoid these problems. Its operational features are described later.

The tests were conducted at two sites in the Northern Territory, close to the Rum Jungle Mine. The first site which was used lies nineteen kilometres south of the mine at Mount Minza. The second site lies approximately sixteen kilometres to the east of the mine at the Woodcutters prospect, which is close to the Stuart Highway. These are the sites which were used in the earlier tests of the geometric technique.

The Mount Minza site provides a tabular conductor of variable dip and very high conductivity. The conductor is a graphitic shale, as shown by the metallic lustre of drill cores. It is situated in a sequence of low conductivity sediments which show no response to electromagnetic prospecting systems. In contrast, the response of the target shale is close to that of a perfect conductor. Laboratory tests of core samples from this conductor were reported by Spies (1972). They show that its conductivity exceeds 0.1 siemens/metre. Depth information at this site was available from the log of a diamond-drill hole and from the earlier depth-sounding tests. This information indicated that the top of the unweathered shale lies at a depth of approximately 15 metres.

The Woodcutters site offers the opportunity to sound to a conductor of large lateral extent, which, in the earlier tests, exhibited a pronounced conductivity anisotropy. This site has been extensively drilled following the discovery of massive lead-zinc mineralisation. However, the mineralisation is not the conductor which is of interest. The target conductor is graphitic shale of the Golden Dyke Formation, which is host to the mineralisation. Diamond-drill hole logs indicate that the conductivity of this shale is equal to or slightly greater in that of the mineralisation. The upper surface of the weathered shale lies at a depth in excess of 40 metres.

The tests which are described here were conducted on survey grids which were established in imperial units. Consequently, all dimensions are quoted in imperial and metric units.

The equipment which was used in these tests was the ABEM EM Gun (frequencies 3520 Hz and 880 Hz) and the Geonics TX27 source and EM16 receiver (frequency 16.55 kHz). A special source coil was constructed for use with the Geonics TX27 as it is not normally used with this type of source. The ABEM equipment was tripod-mounted to facilitate operation (Figure 1 (a) and (b)). The Geonics equipment is shown in Figure 1 (c) and (d). A specially designed, easily readable inclinometer was used on both receivers even though both are equipped with inclinometres in standard form.

The source-orientation sounding technique

The procedure which is followed in making a sounding with the source-orientation technique may best be illustrated by referring to Figure 2. The source and receiver coils are placed at a fixed spacing and are constrained to rotate about parallel axes which are contained by the plane of each coil and which are oriented perpendicular to the line joining the coils. The direction of the line joining the coils is referred to as the azimuth of the system while the plane defined by the axes is termed the reference plane. The orientation of the source coil with respect to the reference

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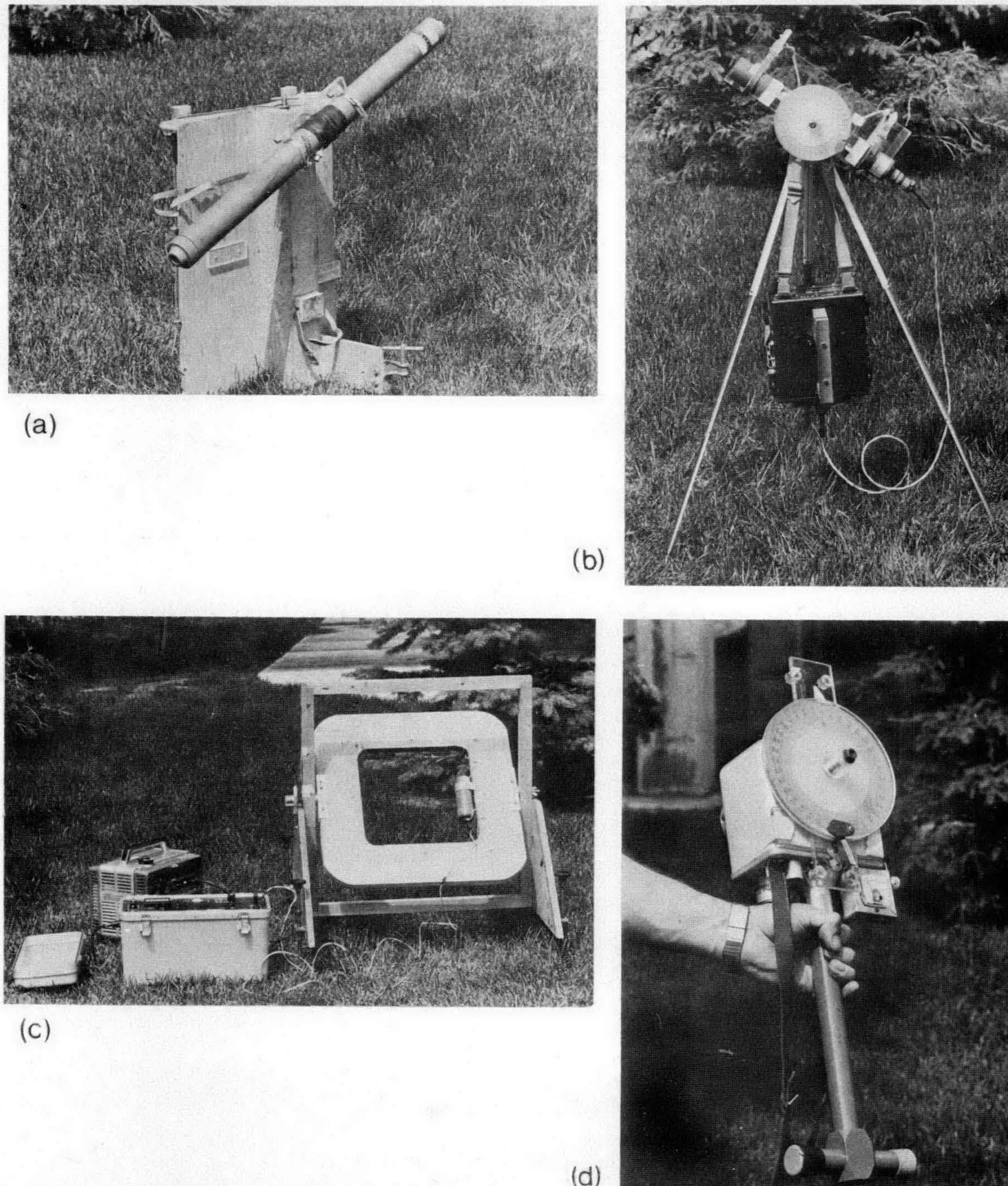

Figure 1. (a) The ABEM EM Gun source coil mounted on a backpack.
(b) The Em Gun receiver mounted on a tripod.
(c) The Geonics TX27 oscillator with motor generator and experimental source coil.
(d) The Geonics EM16 with a lockable inclinometer added.

plane is described by the angle Θ and the orientation of the receiver coil, by the angle δ. Typical plots of δ versus Θ, for soundings performed with the reference plane parallel to a perfect conductor, are also shown in Figure 2. The angle δ is the tilt of the major axis of the polarisation ellipse for any given value of Θ. In practice, δ is determined by the orientation of the receiver coil which gives a minimum received signal. The same frequency is used throughout the sounding.

At the beginning of a sounding, the source coil is oriented with its plane perpendicular to the reference plane ($\Theta = 0°$). Rotation of the top of the source coil away from the receiver provides positive increments of Θ, rotation towards the receiver provides negative increments. The increments of Θ may be any desired value.

Curve C in Figure 2 is the theoretical free space response of the system, while curves A and B are the responses for depth-to-coil spacing ratios (n) of 0.1 and 0.5 respectively. Increasing this ratio causes the responses to approach the free space response but it is necessary to go to $n = 10$ before the response becomes indistinguishable from the free space response. However, practical use of the technique is limited to n values no greater than 1.0.

Theoretical depth-sounding curves may be computed for any orientation of the sounding system with respect to a planar conductor of infinite extent. This is most easily

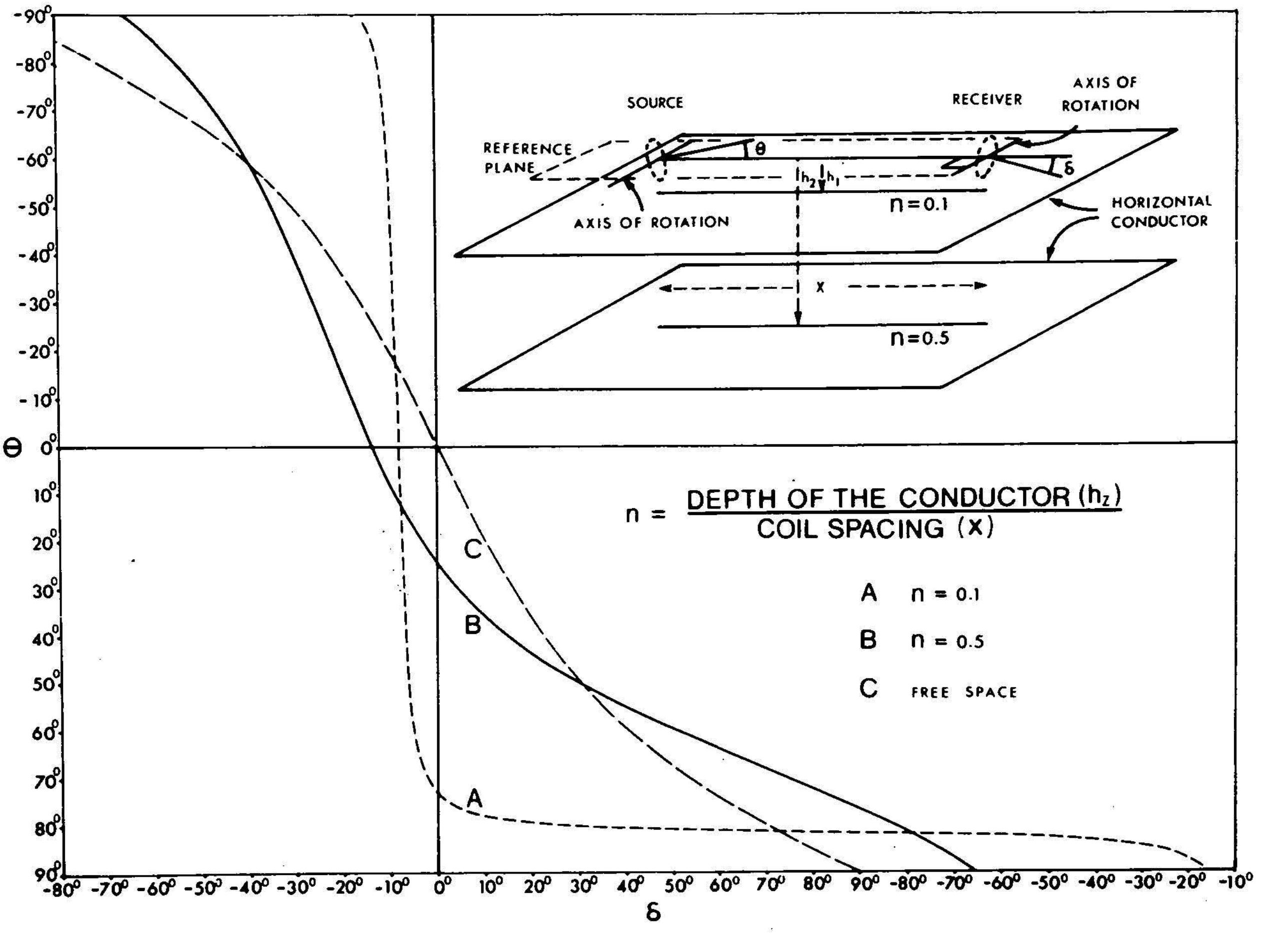

Figure 2. Examples of sounding curves for a perfect conductor with its plane parallel to the reference plane.

accomplished if the conductor can be regarded as having perfect conductivity, as described by Duckworth (1975). However, it is possible to treat cases involving finite conductivity by using the methods described by Frischknecht (1967). Neither the perfect conductor theory nor the finite conductor theory can treat structural complexity, so that interpretation of structurally complex situations can only be achieved by scale model simulation. Interpretation of observed sounding curves involves a matching of the observed curves with curves derived from theory or scale models. This process is greatly aided by use of suites of master curves such as those provided by Duckworth (1975).

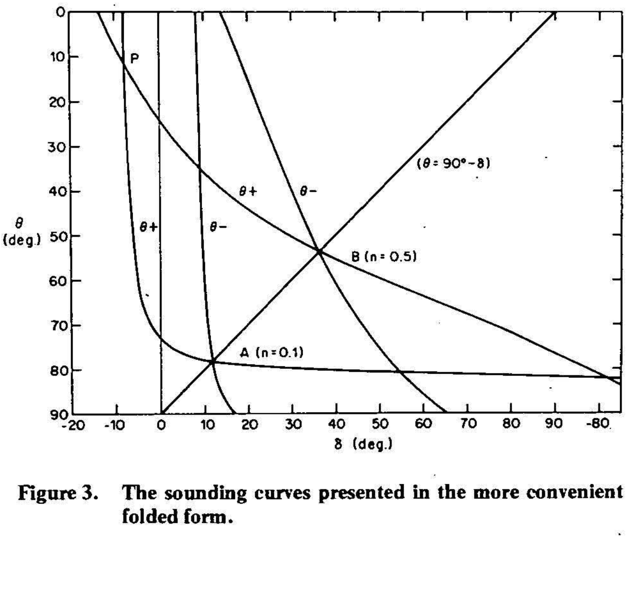

Figure 3. The sounding curves presented in the more convenient folded form.

The sounding curves are more convenient if presented in the form shown in Figure 3. In this form, the curve for Θ negative is folded about the vertical and horizontal axes. This provides a more compact presentation and it causes the curves for Θ positive and negative to cross. The behaviour of this crossover point can be used as an aid to interpretation. For instance, when the reference plane and the plane of a good conductor are parallel, the crossover point lies symmetrically on the line $\Theta = 90° - \delta$. However if the conductor dips at an angle Δ with respect to the reference plane and the system azimuth makes an angle S with the strike of the conductor, then the crossover point is displaced off the symmetry line. This effect was discussed in detail by Duckworth (1975), and an example of the effect is discussed in the test results presented later. If the target being investigated is not a good conductor it is probable that the crossover point will be displaced—even if both S and Δ are zero. In such cases the diagnostic value of the behaviour of the crossover is reduced.

Calibration of the system requires only that a properly graduated inclinometer be provided for the transmitting and receiving units.

Sounding sites of limited lateral extent may be used because the coil spacing remains fixed throughout a sounding.

The theoretical facility to treat any general orientation of the sounding system with respect to the conductive target means that interpretations of the responses from dipping targets are readily achieved, provided that the target does not introduce edge effects. In practice, this has been found to work well over tabular bodies with dips as great as 30°, as described later.

A feature of the response of the source-orientation sounding system is that for n values greater than 0.5 the sounding curves are remarkably insensitive to the dip of the conductor. Depending on the circumstances this can either prove to be beneficial or a hinderance. An example of this effect is discussed later.

In cases where soundings are known to be strongly influenced by edge effects it may be necessary to resort to scale modelling to achieve an interpretation. Such modelling is most conveniently applied to cases involving good conductors situated in free space but as the work of Gupta Sarma & Maru (1971) and Gaur *et al* (1972) shows, modelling also offers the possibility of treating much more generalised conductivity distributions. An example of the use of scale model interpretation as applied to the current test is given later.

The physical principle of the technique

Any single reading of the coupling between the source and receiver is a measure of the distance to any nearby conducting body but any interpretation of such a single reading is indeterminate. This is illustrated by point P in Figure 3, for which the Θ and δ values satisfy two distinct cases with n values of 0.1 and 0.5. It is only when we move Θ away from 11.0° that we recognise that two cases exist. Thus, by variation of the source-orientation angle Θ over a full 360°, the indeterminacy of the interpretation is brought to a manageable level but not eliminated. A serious indeterminacy will remain if we cannot be sure that we are dealing with a single interface of very high conductivity contrast. An effective test for this is illustrated later.

Conventional electromagnetic sounding techniques of the parametric or geometric types, as classified by Ryu *et al* (1972), operate by probing deeper and deeper into an assumed layered structure as the sounding variable changes. The source-orientation mode of sounding can be seen to differ fundamentally from those techniques, for it makes no attempt to achieve a variation of the depth of signal penetration, this being precluded by the fixing of both frequency and spacing. Soundings to a single interface of high conductivity contrast may be accomplished equally well by the source-orientation technique or the conventional techniques. However, the operational simplicity and flexibility of the new technique do perhaps justify its use. The source-orientation technique is not suited to sounding to successive interfaces in a layered sequence.

It appears that the source-orientation technique must be viewed as being best suited to providing depth information over very good conductors which are situated in low conductivity host rocks—this situation being one where only a single interface is of importance. The instrumental simplicity allows the technique to be viewed as an additional interpretation aid in the treatment of structures which are discovered by electromagnetic profiling. Thus, rather than obtaining only a conductivity-thickness product and generalised depth and dip figures from the profile data, one may, by some extra use of already available equipment, obtain a good deal more detail concerning the target. The tests described below suggest that the source-orientation depth-sounding technique can fulfil such a role.

Field test results

Mount Minza

At this site the target conductor is a tabular body which strikes north-south and dips to the west. The dip varies from a minimum of 20° to a maximum of 70° along the 2000 metres of strike length. The soundings were expected to detect the upper surface of this body. This surface is the interface between the conductor and an overlying shale, but at the outcrop it is the top of the unweathered conductor. Depth of weathering at this location is approximately fifteen metres, and the transition from weathered to fresh rock is abrupt.

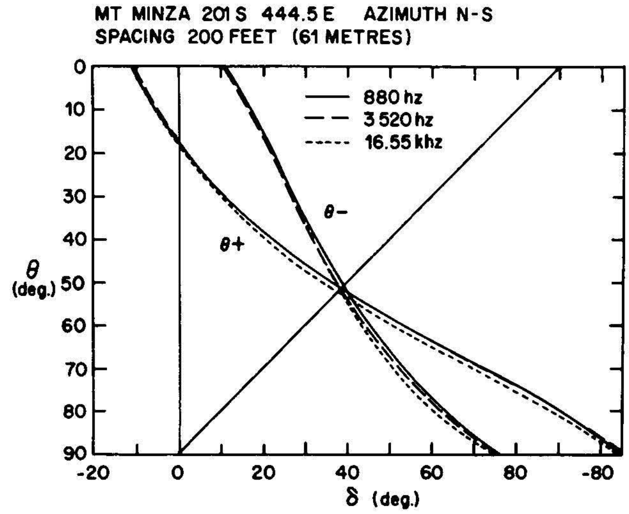

Figure 4. Example of a sounding performed at a single site using three frequencies to check that the target was behaving as a perfect conductor situated in free space.

The assumptions that this target could be treated as a perfect conductor and that the surrounding rocks could be treated as free space, were tested by performing three soundings at a single site, using three different source frequencies. The results of this test are shown in Figure 4. The fact that the three sounding curves for 800 Hz, 3520 Hz and 16.55 kHz, are remarkably similar can only be explained in terms of the conditions stipulated above.

The initial test at the Mount Minza site was conducted on line 207S of the survey grid described by Shatwell & Duckworth (1966). A group of seven sounding sites was selected. The system parameters employed at each of the seven sites were: source frequency 3520 Hz; coil separation 200 feet (61 metres); system azimuth north-south. The results of this test are shown in Figure 5. With the azimuth of the system and the strike of the conductor being parallel (S = 0°), it was expected that, in all cases, the crossover point would fall on the symmetry line. This expectation was fulfilled except at 442E, 447E, and 448E.

At 447E and 448E, the response was dominated by edge effects and no depth determination was attempted for these locations. The reversal of the relationship between the Θ positive and Θ negative curves which was observed at 448E was caused by the location of the site, which was off the edge of the conductor. This effect was anticipated as it also occurred in model studies of the technique described by Duckworth (1975). In the case of 442E, the displacement of the crossover may have been due to a change in the strike of the conductor with depth. There was evidence of this, in that 400 feet (122 metres) to the north, the conductor appeared to dip at 30° rather than at the overall mean of 20° shown at this site. However, in the case of 442E the displacement was treated as an alignment error and a correction was applied to the curves. After correction, a good fit was found between the observed curve and a perfect conductor curve. The perfect conductor curve indicated a depth of 140 feet (n = 0.7) (43 metres) with Δ = 0° and S = 0°. This prediction of zero dip provides an example of the insensitivity to dip which the sounding curves display when n exceeds 0.5. It was evident that the conductor had an overall dip of about 20° as shown by the other soundings, therefore, the depth value for 442E was moved to a position displaced 20° from the vertical. Details of the interpretation by curve matching, in the cases of 444E and 445E, are shown in Figure 6. At 444E, a good match was achieved by a theoretical curve for n = 0.42 (84 feet) (26 metres) $\Delta = 0°$ $S = 0°$, while at 445E, the response revealed a shallower conductor and some dip was required, and the result was n = 0.28 (56 feet) (17 metres) $\Delta = 20°$ $S = 0°$. In the case of 444E a scale model interpretation was tried and it gave essentially the same curve using the same depth figure. The interpretation for 446E was carried out assuming no edge effect, even though the edge probably lay not much more than half the coil spacing away from the site. The depth figure which was obtained seems compatible with the trend of depths indicated by the results for 444E and 445E. Thus it appears that effective results can be obtained by the use of extended conductor theory, even when an edge lies at 0.5 coil spacings from the system. The surface of the conductor which was defined by the earlier geometric soundings is compared with that defined by the source-orientation soundings in Figure 5. The agreement between the two sets of results can be described as good. The minor disagreement between the two surfaces appears to be caused by the fluctuation of the surface which was defined by the geometric method. This fluctuation might be explained by the fact that the geometric method sampled a much larger area of the conductor than did the source-orientation method. The geometric method used a range of spacings from 75 to 400 feet (23 to 122 metres). However, it is evident that the surface defined by the source-orientation technique is not in agreement with the dip figures provided by some of the individual soundings. This lack of agreement indicates that additional intermediate sounding sites might have provided more detail of the surface. Fluctuations of the surface probably do exist and are responsible for the dip figures at 445E and 446E. However, it did not appear appropriate to attempt to accommodate these dips in drawing the surface. No drilling control was available for this site.

The next test was conducted on line 201S, where a diamond-drill hole provided some control. The earlier geometric sounding tests had indicated that the conductor dips more steeply at this location, the mean dip being 30°. The conductor surface which was indicated by the earlier tests is shown in Figure 7 (a). This model suggests that the body has two distinct top edges. With this in mind, it was felt that all responses obtained over this body would contain edge effects. Consequently this body appeared to be a good location for testing the use of scale model interpretation. The opportunity was also taken to test the ability of the system to provide useful interpretation regardless of the azimuth that is used. Accordingly, an array of soundings was performed by rotating the system azimuth in 45° increments about a single source position. This source position coincided with the original drill collar. The observed sounding curves for the array are given in Figure 7 (b) to (f), with best fitting model curves. The source frequency was 16.55 kHz, and the spacing was 200 feet (61 metres). The observed curves provide a good example of the influence of Δ and S on the crossover point, in that the crossover point migrates from above to below the symmetry line as the azimuth is rotated. This effect was observed in the model tests which were described by Duckworth (1975). In the case where $S = 0°$, which was case C, the curve shows good

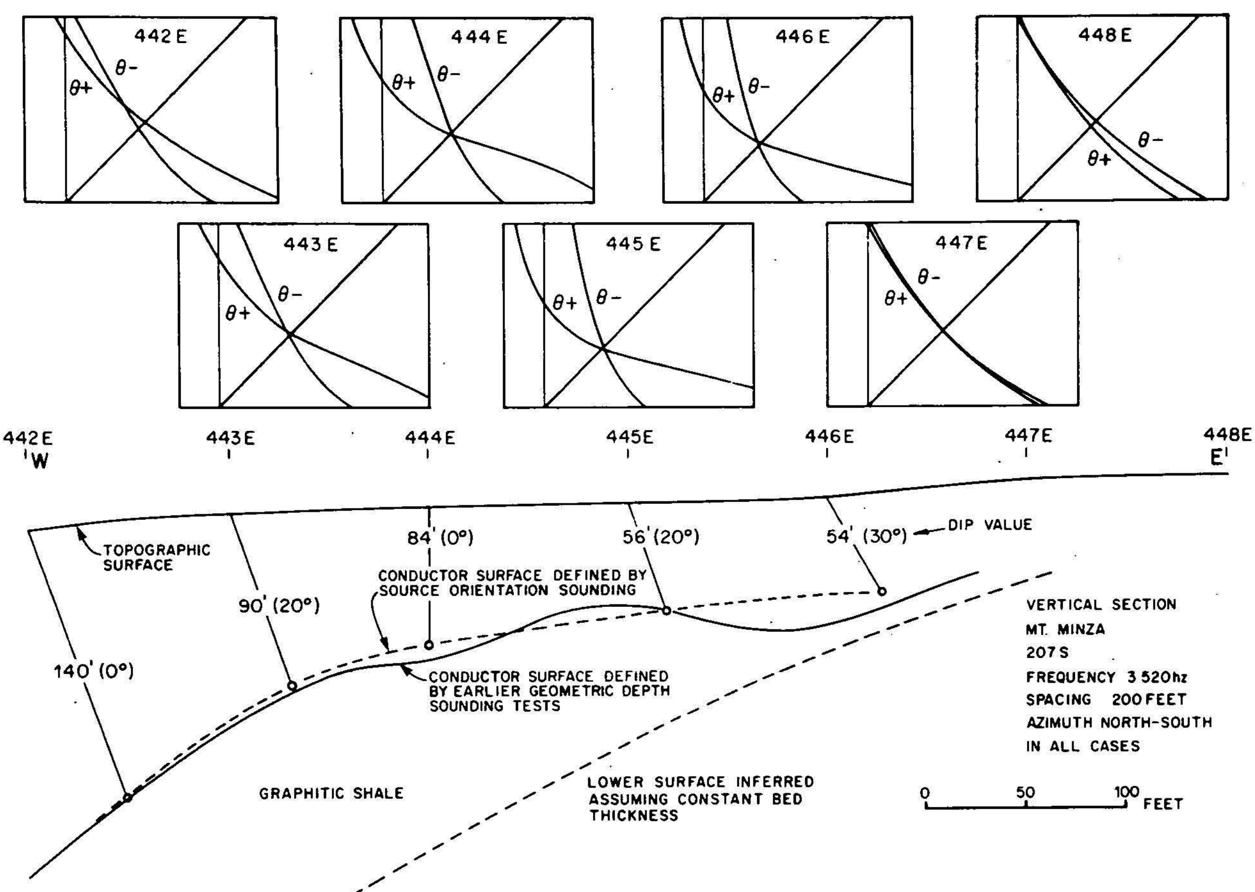

Figure 5. Sounding results for the Mount Minza 207S site. The conductor surfaces as defined by the source-orientation and geometric methods are compared.

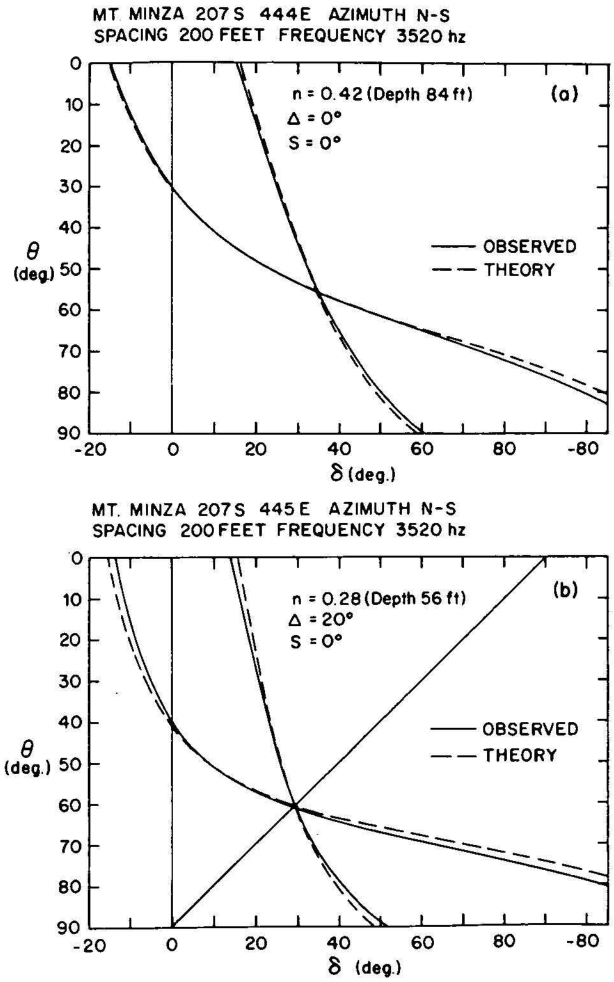

Figure 6. Examples of interpretation of the soundings on 207S by matching to theoretical curves.

symmetry, as expected. The scale modelling was performed at a frequency of 20 kHz using a coil spacing of 20 cm over a sheet of aluminium foil of 0.06 mm thickness dipping at 30°. This sheet was folded to simulate the weathered top of the body. The model curves in cases A and B were derived with the metal sheet set at a simulated vertical depth of 130 feet (40 metres) below the source coil and it was found that they did not contain any edge effect. In case C, both the source and receiver were set at a vertical distance of 128 feet (39 metres) from the sheet. This gave a slope distance of 111 feet (34 metres), which corresponds to the depth down the drill hole at which the conductor was cut. In fact, the hole cut the conductor at 126.5 feet (38.5 metres). A check was made to see if this low value for the depth estimate was due to edge effects. This test consisted of applying the extended conductor theory to interpretation of case C. This gave a vertical depth of 127 feet (39 metres) and a slope depth of 110 feet (34 metres). The good agreement between the scale model and the theory indicated that edge effects were not involved. The earlier geometrical tests conducted at 1760 Hz gave a slope depth of 125 feet for this site. The disagreement between the earlier tests and the current tests at this site is hard to explain. Frequency differences can not explain the effect because this is the site which gave essentially the same results for three frequencies as shown in Figure 4. Additional work with both methods at this site would be needed to resolve this problem. The model interpretation for curve D certainly did involve edge effects and yet the scale model was able to provide a reasonably good match. This confirmed the vertical depth below the source to be 128 feet (39 metres) and placed the receiver 80 feet (24 metres) above the conductor in a location 67 feet (20 metres) down dip from the western edge of the top of the body. The picture presented in Figure 7 (a) would place the receiver directly over that edge at a vertical separation of 65 feet (20 metres). Again, additional work would be needed to explain this discrepancy. In case E it proved impossible to obtain a match despite changes in the dip and in the width of the top of the body; perhaps an undetected alignment error or an unsuspected structural complexity was responsible for this problem. The overall result for site 201S must be viewed as a mixed success, but it does suggest that the extended conductor theory can be used over quite steeply dipping structures. Edge effects appear to be unimportant for sounding sites which are located more than half a coil spacing away from an edge.

The results from Mount Minza site do show that the source-orientation technique can provide effective information over dipping bodies, and that interpretation can be achieved even when the system azimuth is set at any arbitrary angle with respect to the strike of the conductor.

Woodcutters Prospect

In the earlier geometric sounding tests conducted at this site, a strong conductivity anisotropy was detected. This was revealed by a systematic change of depth estimates which occurred in response to changes in the azimuth of the geometric sounding system. It was found that the smallest depth values came from east-west azimuths and the greatest from the north-south azimuths. This indicated better conductivity in the north-south trend, which suggests that

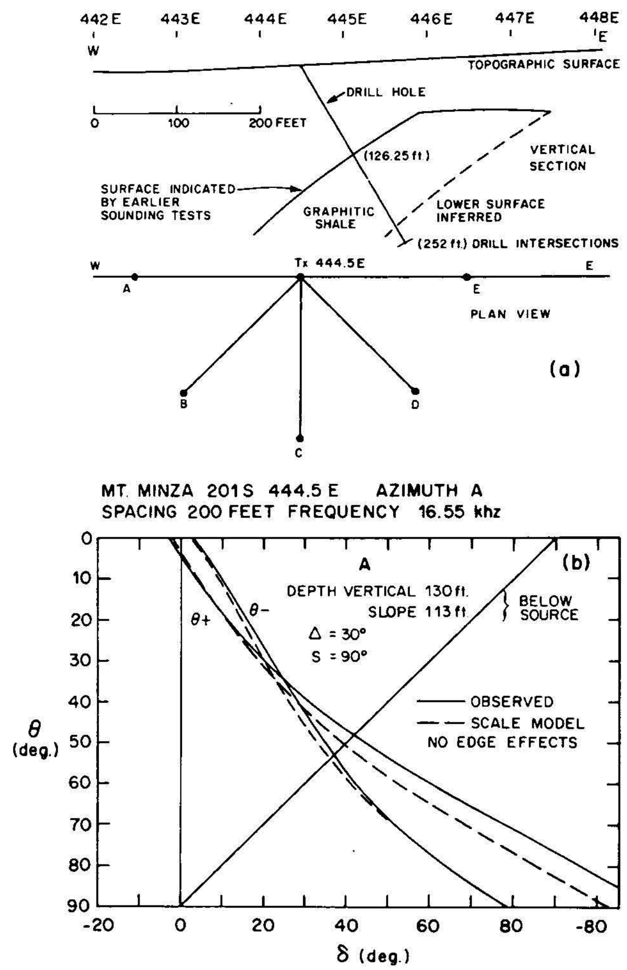

Figure 7 (a, b); caption, see p. 7.

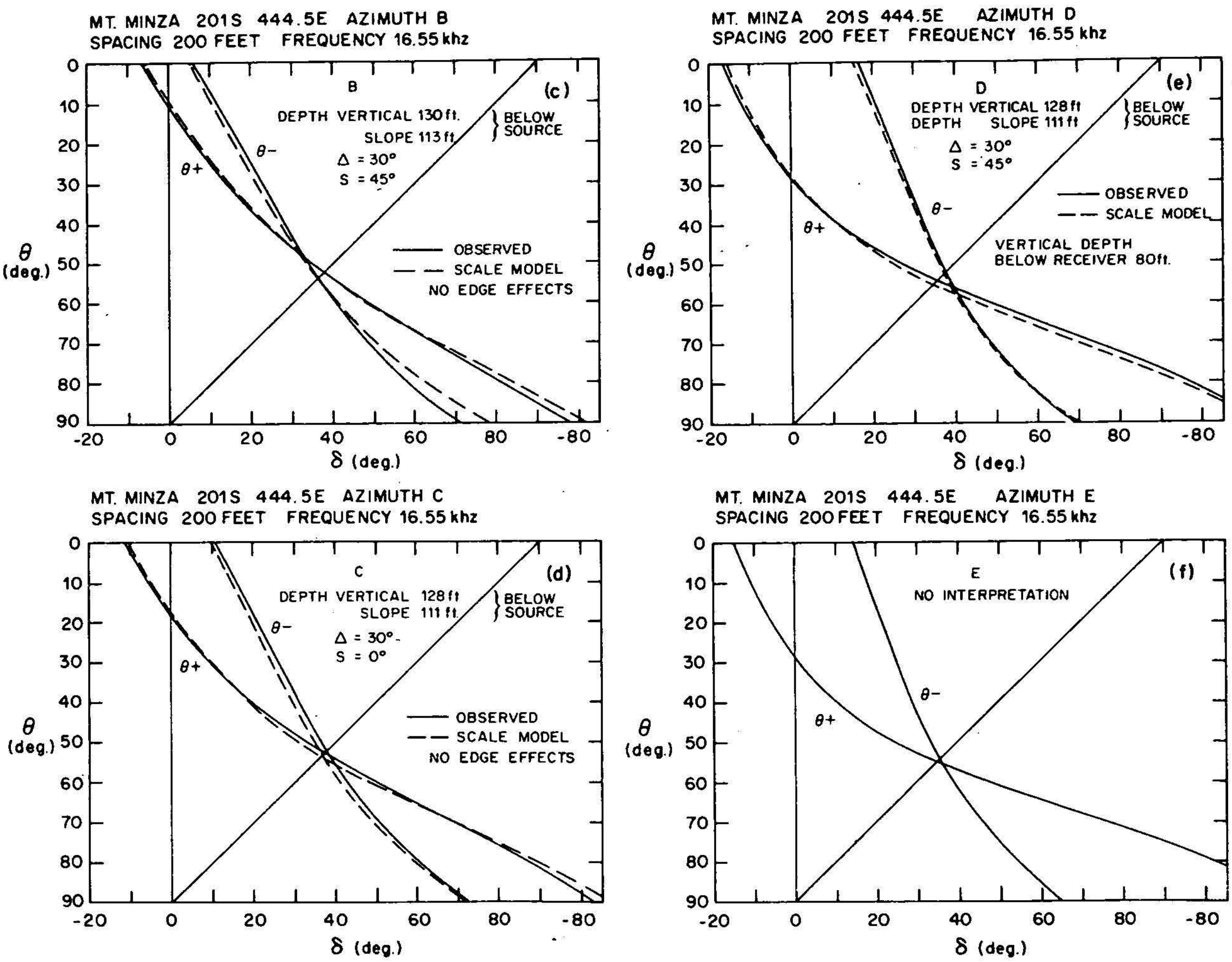

Figure 7. (a) Vertical structure section of Mount Minza 201S as indicated by earlier depth-sounding tests. Also shown are drilling results and the array of orientation-sounding azimuths used at this site.
(b) to (f) Observed and matching sounding curves for Mount Minza 201S, the azimuths being indicated in Figure 7 (a). The matching curves were derived by scale modelling.

this effect was a cleavage controlled anisotropy because the cleavage trend of the graphitic shales is also north-south.

A test of the source-orientation technique was conducted at this site to determine if its response was also sensitive to the anisotropy. Three soundings were performed using a common source point at 36E on line 220S of the BMR grid. The receiver was located to the south, southwest and west of the source. The spacing employed was 300 feet (91 metres) and the three soundings were performed at 3520 Hz and 16.55 kHz. The results for 3520 Hz appear in Figure 8, and for 16.55 kHz in Figure 9. The curves shown in Figure 8 (a) are the observed sounding at 3520 Hz using an east-west azimuth and the best matching horizontal perfect conductor curve. This fit seems reasonably good and it gives a depth value of 174 feet (53 metres). The observed curves for the south and southwest azimuths are shown in Figure 8 (b). These do indicate a change of conductivity with change of azimuth, by the migration of the crossover point away from the symmetry line and away from the origin ($\Theta = \pm 90°$ $\delta = 0°$). This displacement of the crossover point could be misinterpreted as being caused by dip on the conductor surface, but the conductor surface is known to be horizontal at this location. The east-west azimuth curve at 16.55 kHz is shown in Figure 9 (a) along with the best matching, horizontal, perfect conductor curve. The poor match in this case is known to be caused by a defect in the source coil, which was an experimental prototype. The problem appeared to be that this coil generated a distorted field, which was not a perfect dipolar field as was assumed. Despite the fact that this distortion reduces the value of the interpretation it is still useful to compare the results for 3520 Hz and 16.55 kHz. The depth figure given by the 16.55 kHz sounding was 126 feet (38.4 metres). The curves for the other azimuths were again indicative of lower conductivity, although not so clearly as in the case of the 3520 Hz soundings.

The difference between the depth figures of 126 feet (38.4 metres) and 174 feet (53 metres) provided by high and low frequencies respectively, is probably due to a transition zone in the weathering of the shales. Such a transition zone was logged in a hole which was drilled 400 feet (121 metres) to the east of the sounding site. The top of this zone occurred at a depth of 147 feet (45 metres). The topographic slope rises to the east so that a depth of 126 feet to the top of the transition zone at the sounding site seems reasonable. The bottom of the zone was logged as being quite variable over a lateral distance of 800 feet (242 metres) in the east-west direction but at 400 feet (121 metres) to the east of the sounding site it was at 180 feet (55 metres) which appears to agree with the low frequency depth estimate. This then illustrates that choice of frequency can be employed to permit the system to emphasise the response of different interfaces in a layered sequence. The earlier geometric soundings indicated a depth of 141 feet (43 metres) for this same site. As these earlier tests were performed at 1760 Hz we might have expected a greater depth estimate from these results, in view of the 174 feet (53 metres) derived at 3520 Hz

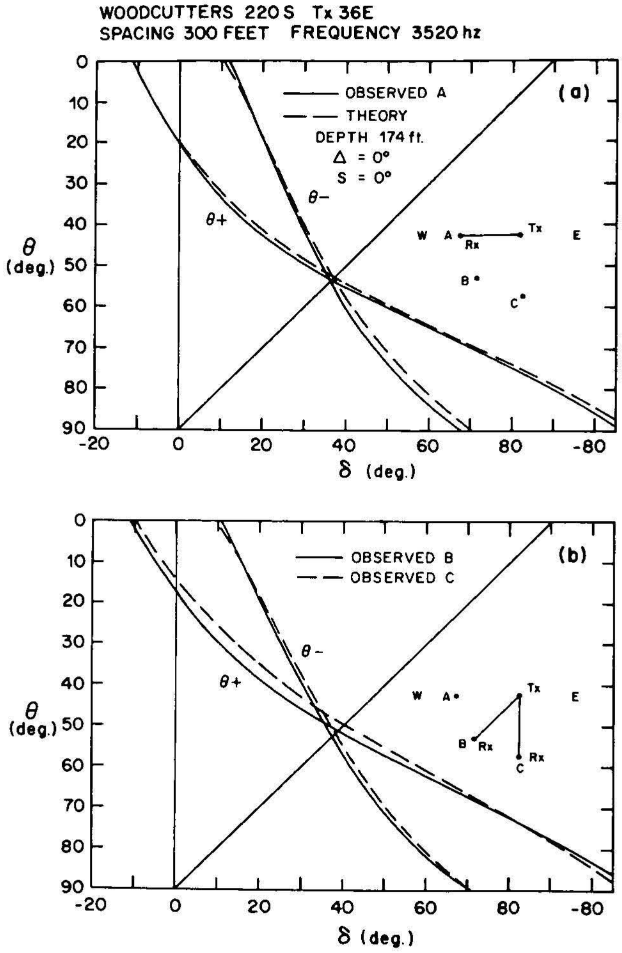

Figure 8. **Soundings for Woodcutters 220S showing anisotropy in the conductivity of the target as the system azimuth is rotated (Frequency 3520Hz).**

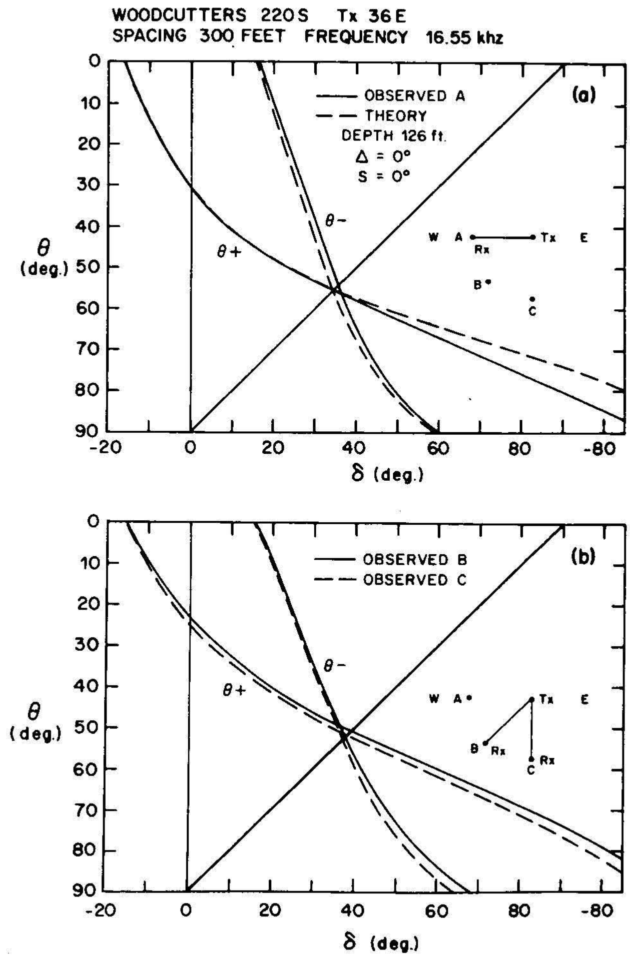

Figure 9. **High-frequency soundings at the same site as shown in Figure 8. The change in depth value as compared with Figure 8 indicates that this response comes from the top of a transition zone in the weathering (Frequency 16.55 kHz).**

with the new technique. However as the coil spread in the earlier tests extended over known disturbances to the east and west of 36E, then perhaps the geometric results are suspect. Drilling results for the immediate location of this site do indicate the weathering base as 150 feet (46 metres) but this was a cased hole and no mention of a transition zone was made, yet the later drilling to the east clearly showed such a zone.

Conclusions

These tests indicate that the source-orientation technique of electromagnetic depth sounding can provide useful depth information over localised good conductors and that the quality of this information is comparable to that derived by geometric sounding. Both techniques can be applied with conventional prospecting equipment but some modification of that equipment is normally needed in order to perform geometric soundings. In contrast, the source-orientation technique can be applied without modification to the electronic components of the equipment. In terms of flexibility the source-orientation technique offers advantages in operation and interpretation.

The application to which this technique is best suited is as an immediate means of acquiring depth information on a conductive target. A crew running a normal profiling electromagnetic survey could apply the technique over any newly discovered target using the equipment employed in profiling. The additional cost would be moderate and the quality of depth data should be considerably greater than that which can be derived from the profile data alone.

Acknowledgements

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Geochemistry of the Cullen Granite, Northern Territory

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A geochemical study of the Cullen Granite in the Northern Territory, involving major elements and 25 trace elements (Li, Be, F, S, V, Co, Ni, Cu, Zn, Ga, As, Rb, Sr, Y, Zr, Nb, Mo, Sn, Ba, La, Ce, W, Pb, Th, U) has been carried out. The results support field observations in that they indicate that one of the five phases of granite identified is younger and more highly fractionated than the rest.

The existence of a relationship between the geochemistry of the Cullen Granite and mineralisation contained within the granite and surrounding sediments is suggested by only a few of the trace elements determined. High U concentrations within the granite near Edith River can be correlated with known mineralisation in the granite, although no U mineralisation has been reported from a region southwest of Frances Creek where the U content of the granite is also high. Anomalously high concentrations of Cu and W in the granite may be related to mineralisation in nearby sediments.

The well documented tendency for the Sn content of intrusive rocks associated with Sn deposits to be higher than in those rocks without deposits is not supported by the Cullen Granite data. Although numerous Sn deposits occur in and around the granite, its Sn content is near or below the limit of detection.

Introduction

In 1975, the Bureau of Mineral Resources and the Northern Territory Geological Survey initiated a joint project to study the geochemistry of the Cullen Granite in the Northern Territory. This investigation followed from a pilot study undertaken by Willis (1974).

Although the Cullen Granite is a large batholith occupying a prominent position within the Pine Creek Geosyncline, its geology and geochemistry have received little attention in the past, and consequently have been poorly understood. There appears to be little doubt that the granite is in some way genetically related to extensive mineralisation in the adjacent sediments, but the nature of this relationship is unclear.

The aims of this project were to provide:

(i) information on the geochemistry of the Cullen Granite, including the relationships between the various phases.

(ii) clues as to the relationship between the geochemistry of the granite and mineralisation contained within the granite and surrounding sedimentary rocks.

A field program was devised involving the collection of 100 to 150 samples distributed as evenly as possible over the exposed portions of the granite, taking into consideration the different phases recognised within the granite.

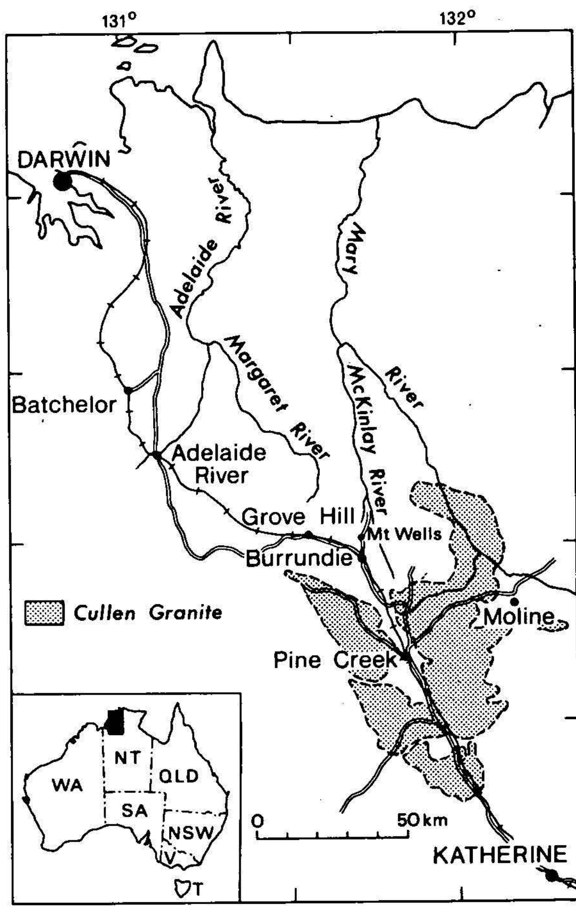

Figure 1. Locality map

Geology

The geology of the Pine Creek Geosyncline has been described by Walpole and others (1968). The geosyncline is a composite structure containing Lower Proterozoic rocks. These rocks are intruded by a number of Middle Proterozoic granites, of which the Cullen Granite is by far the largest.

The Cullen Granite forms a discordant, roughly V-shaped batholith in the south-central part of the geosyncline about 200 km southeast of Darwin (Fig. 1), and is exposed over about 2800 km². Small isolated granites to the east of the main batholith, the most notable being in the Mount Diamond area (Fig. 2), are considered to be cupolas of the Cullen Granite (Walpole and others, 1968). The granite was named after the Cullen River (Noakes, 1949), a tributary of the Fergusson River.

Erosion of the granite in central areas of the batholith has produced low-lying, undulating country in which exposures are generally poor. Outcrop consists of expanses of bare rock, boulders, and occasional rocky rounded hills separated by an extensive drainage pattern of converging alluvial flats. In the northeastern lobe, the granite forms rugged hills with almost continuous outcrop along the margins of the granite. Vegetation is poorly developed, and is mainly a scrubby, mixed open forest community with tall annual sorghum grass.

There has been little systematic study of the granite. In the course of mapping the Mount Todd and Lewin Springs 1-mile sheets, Rattigan & Clarke (1955) identified three types of granite from the southernmost part of the batholith in the Edith River area. Walpole and others (1968) subsequently extended this to five phases, recognising three

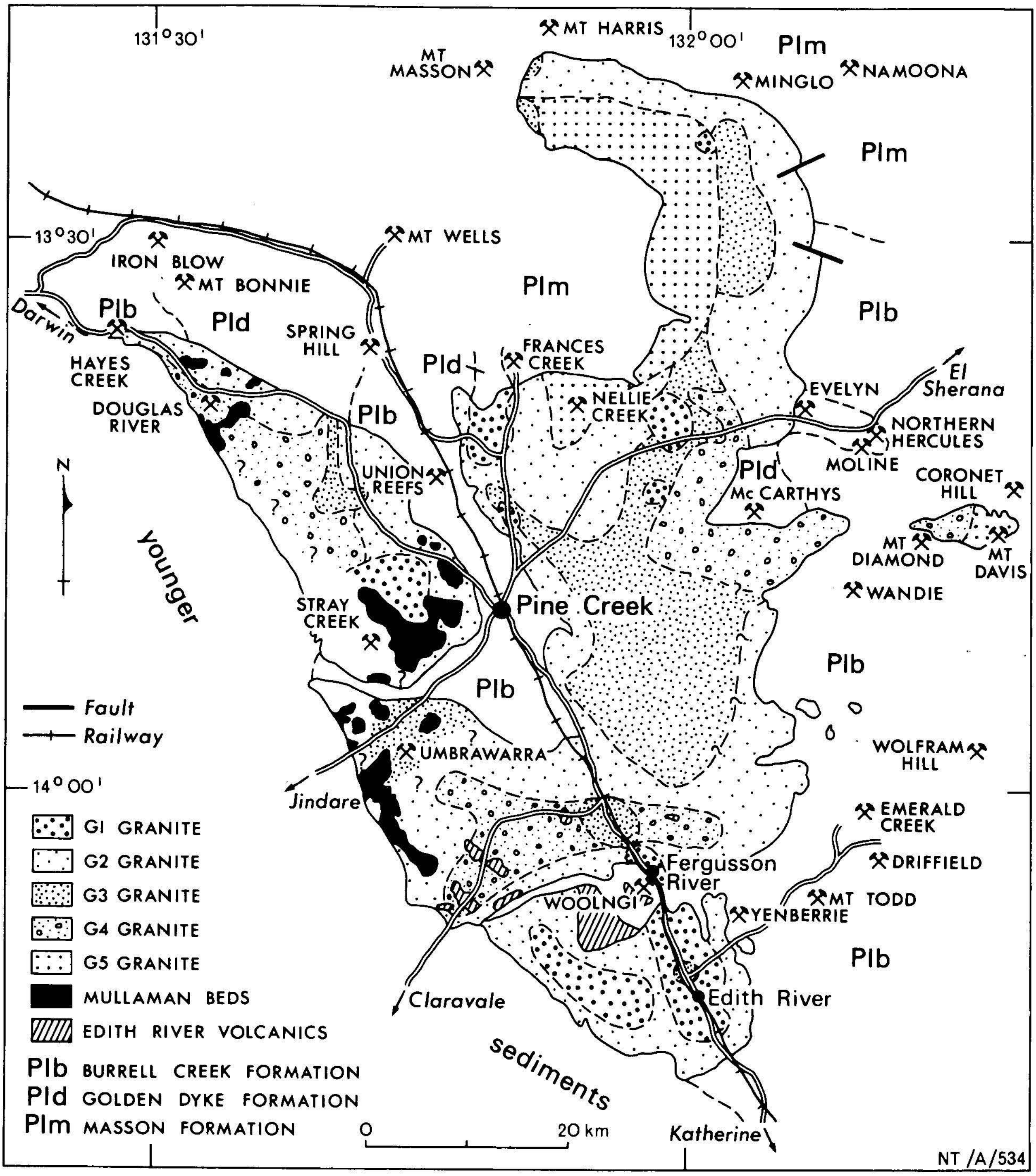

Figure 2. Geological map of the Cullen Granite and surrounds showing approximate distribution of main granite types and the main mineral prospects (crossed hammers)

varieties of granite and two varieties of adamellite. In the present study, samples have been classified following the recommendations of the IUGS for the nomenclature of plutonic rocks (IUGS Subcommission on the Systematics of Igneous Rocks, 1973); they are all considered to be granites, although the more felsic samples may be referred to as leucogranites (colour index 0-5) and the more mafic ones as melagranites (colour index > 20). There has been no attempt to map the granite in detail, and the exact distribution of the five phases is not known. However, on the basis of limited field observations and an examination of samples collected during this study, a map outlining the broad distribution of these granite types has been prepared (Fig. 2).

The pink coarse porphyritic granite phase (G1) is exposed mainly in the Edith River, Fergusson River, and Frances Creek areas though other outcrops are known. The rock is a massive porphyritic granite with phenocrysts of pink potassium feldspar up to 5 cm in diameter, and an average grain size of 3 mm. In the Fergusson River area, the rock has been sheared and veined by chlorite and epidote, and typically consists of quartz, microcline, microperthite, albite-oligoclase which has been largely sericitised, red iron oxides, biotite which has partly altered to chlorite, minor hornblende, some secondary muscovite, and accessory minerals such as sphene, zircon, apatite, and fluorite.

The pink and green coarse porphyritic granite (G2) is a major phase of the Cullen Granite with widespread outcrop, particularly around the margins of the batholith. It is a massive, very coarse-grained variety with large phenocrysts of pink microcline and microperthite up to 6 cm in diameter and smaller grains of pale green plagioclase. Twelve kilometres to the north of Fergusson River the granite has been sheared, and is veined with chlorite and epidote. It has the same mineralogy as the G1 phase, but differs in three respects—the plagioclase is more calcium-rich (i.e., oligoclase-andesine), hornblende is more abundant, and the iron oxides are black and opaque.

The grey coarse porphyritic granite (G3) crops out mainly in the central region of the northeastern lobe of the Cullen Granite, although it is also present in the western and southern areas of the batholith. The rock is massive and coarse-grained with grey phenocrysts of microline and microperthite up to 3 cm long in a groundmass of quartz, partly sericitised albite-oligoclase, microcline, microperthite, biotite, hornblende, black iron oxides, sphene, zircon, fluorite, minor secondary muscovite, and traces of epidote and allanite.

Exposures of the grey fine porphyritic granite (G4) were noted in three main areas—along the eastern margin of the batholith to the southwest of Moline, in the Claravale Road area, and along the western margin of the granite southwest of Hayes Creek. This phase is fine to medium-grained, with phenocrysts of microcline and microperthite up to 2 cm in diameter. The mafic mineral content varies between samples, but is consistently higher in the Claravale Road area. Minerals present are quartz, microcline, microperthite, biotite, hornblende, partly sericitised oligoclase, black iron oxides, accessory apatite and zircon, and traces of epidote.

The fifth variety is a grey fine even-grained granite (G5), which is confined mainly to the western side of the northeastern lobe of the batholith. It consists of quartz, microcline, microperthite, sericitised albite-oligoclase, biotite partly altered to chlorite, minor hornblende, iron oxides, and accessory zircon, apatite and fluorite. This phase also contains some secondary muscovite, epidote, and traces of allanite.

Hurley and others (1961) have dated two samples of biotite from the Cullen Granite at 1695 m.y. using the K-Ar method. One sample came from the Edith River area, and the other came from an area about 5 km north of Pine Creek (Fig. 2). They found that further dating of the Edith River sample by the Rb-Sr method indicated an age (which has since been confirmed by P. J. Leggo and quoted in Walpole and others, 1968) of 1765 ± 90 m.y. With the possible exception of the Grace Creek Granite and granites in the Rum Jungle complex, Rb-Sr dating of most of the granites in the Pine Creek Geosyncline (e.g., Cullen Granite, Burnside Granite, Malone Creek Granite) has shown that they plot on a 1760 m.y. isochron (P. J. Leggo *in* Walpole and others, 1968).

The age relations between the five Cullen Granite phases are difficult to ascertain as good exposures along contacts are rare. Fisher (1952) concluded from field observations that, in the Edith River area, the pink coarse porphyritic granite is intrusive into the pink and green coarse porphyritic granite. In places the contacts were found to be sharp and well defined, whereas in others a transition zone existed in which the granite was of a hybrid character apparently due to partial digestion of the earlier phase by the later phase. It is apparent from the present study that transitional zones between the various granite phases are quite common.

Dolerite dykes are intruded into shear zones within the Cullen Granite; they occur mainly in the Edith River area, and an area about 15 km north of Pine Creek. Quartz veins and aplite dykes are also common in these areas. Associated with the granite are greisens which consist of quartz, micaceous minerals (predominantly muscovite and sericite), and in some places tourmaline (Rattigan & Clarke, 1955). Some of these greisens have formed through the alteration of granite along shear zones. In the Fergusson River area, Edith River Volcanics appear to have pierced the Cullen Granite and been extruded over it (Fig. 2). The volcanics in this locality have been referred to as toscanites by Carter (1952). They attain a maximum thickness of about 100 metres, commonly show a flow alignment of feldspars, and in some places contain xenoliths of granitic material.

Mesas, buttes and tablelands of flat-lying Mesozoic sandstone, siltstone and conglomerate (the Mullaman Beds) occur as relics of an old peneplain formed before the present erosion cycle, and overlie areas of the western lobe of the granite. The Cullen Granite may extend beyond its exposed western margin, where it is overlapped by Upper Proterozoic, Palaeozoic, and Mesozoic sediments.

The Cullen Granite was intruded into Lower Proterozoic sediments of the Finniss River Group and Goodparla Group. Rocks of the Burrell Creek Formation are the only unit of the Finniss River Group which are in contact with the granite. They consist predominantly of medium to fine-grained greywacke, siltstone, and quartz greywacke, and occur as a major re-entrant within the batholith in the Union Reefs-Pine Creek area, and along the eastern margin of the granite (Fig. 2). Those sediments of the Goodparla Group which are in contact with the granite are the Masson Formation and Golden Dyke Formation. The Masson Formation consists mainly of lenses of quartz greywacke intertonguing with different types of siltstone, and is exposed around the northern part of the northeastern lobe of the granite. The Golden Dyke Formation adjoins the Cullen Granite in the Evelyn-Moline area, the Frances Creek area, and to the west of Hayes Creek, and comprises mainly dolomitic and carbonaceous siltstone, quartz siltstone, chert and dolomite.

Intrusive contacts between the lower Proterozoic sediments and the granite are generally sharp where they are exposed. At the granite contact, there appears to be no marked reduction in grain size, little evidence of chilled margins, and only minor assimilation of sedimentary material. However, a contact-metamorphic aureole of varying width is evident, and gives rise to high topographic relief where the sediments have been converted to hornfels. On the eastern side of the batholith this aureole is four or five kilometres wide. Walpole and others (1968) have cited this fact and the presence of numerous quartz-porphyry dykes and granite cupolas within the aureole as evidence that the main contact of the granite dips at a low angle to the east. In the Mount Harris area, Hays (1960) has observed that the metamorphic aureole is only about 100 metres wide and discontinuous, whereas in the Union Reefs area it has been reported as up to 1000 metres wide (White and others, 1965).

The Lower Proterozoic rocks around the Cullen Granite have been closely folded; the fold axes generally trend northwest, approximately parallel to the main axis of the geosyncline. Faults trending in the same direction are also common. In the Pine Creek area, this faulting is exemplified by bedding-plane shears, quartz-filled shears, and intense shearing of the Burrell Creek Formation where it forms an embayment in the granite. The margins of the embayment are parallel to the direction of shearing, and are probably controlled by faults.

Mineralisation

The Lower Proterozoic sedimentary rocks of the Pine Creek Geosyncline are host rocks for most of the mineralisation within the area, especially where they are close to major granitic intrusions.

With the exception of iron ore deposits in the Frances Creek area, which are considered by Walpole and others (1968) to be the product of supergene enrichment of ferruginous beds in the Masson Formation, most of the mines and prospects in the vicinity of the Cullen Granite are of hydrothermal origin. These deposits (Fig. 2) include the Hayes Creek, Mount Masson, and Mount Harris tin fields; the complex gold-copper-lead-zinc lodes at Iron Blow and Mount Bonnie; the lead prospects at Minglo and Namoona; the Mount Wells tin-copper mine; the silver-lead-zinc lodes of the Evelyn and McCarthy's mine; the Northern Hercules gold mine and the copper and copper-gold-arsenic lodes of Coronet Hill, Mount Davis and Mount Diamond. There are also the tin and tungsten lodes, some of which have copper and lead associated with them, at Emerald Creek, Mount Todd, and Yenberrie, and the gold deposits of Wandie, Driffield, Mount Todd, and Woolngi. In the Spring Hill-Union Reefs-Pine Creek area, where sediments of the Burrell Creek Formation crop out in an embayment into the Cullen Granite, gold, tin, copper, and silver-lead deposits have been worked.

Commonly the deposits are associated with faults and shear zones, and occur as quartz veins, fissure lodes, greisens, and pegmatites. This is particularly evident in the Spring Hill-Union Reefs-Pine Creek area, where gold-bearing quartz lodes, and silver-lead and tin deposits are localised along a major fault or shear zone trending north-northwest.

However, there are also examples of stratigraphic and lithological control. The Golden Dyke Formation hosts massive sulphide deposits such as Iron Blow and the silver-lead lodes at Evelyn, and most of the quartz-gangue gold and tin deposits are associated with the Burrell Creek and Masson Formations (Walpole and others, 1968). The Golden Dyke Formation contains dolomitic and carbonaceous siltstone (which in some places is pyritic), quartz siltstone, chert and dolomite, whereas the other two formations are composed essentially of greywacke and siltstone.

Mineralisation within the Cullen Granite is only minor, and is confined to alluvial tin deposits and some patchy uranium mineralisation. Of the tin deposits, the Umbrawarra field (which is about 18 kilometres southwest of Pine Creek) has been the most productive. Since 1909, about 245 tonnes of tin concentrate have been recovered, and at Stray Creek (15 kilometres west-southwest of Pine Creek) 16 tonnes of tin concentrate have been mined. The recovery of small tonnages of alluvial tin concentrates have also been reported from Nellie Creek (25 km northeast of Pine Creek) and in the vicinity of the Douglas River about 30 km northwest of Pine Creek. According to Walpole and others (1968), the primary deposits appear to have been mainly small zones of disseminated cassiterite in chloritised granite.

In 1950 uranium mineralisation, mainly torbernite and autunite, was discovered in association with copper and cobalt in a narrow vein within a sheared zone of the Cullen Granite near Fergusson River (Rattigan & Clarke, 1955). Subsequent investigation revealed that this prospect was of no economic importance. Several years later, further discoveries were made in the Edith River area (YMCA and Tennyson's prospects) and were reported on by Fisher (1952). In both of these deposits the uranium occurs as meta-autunite associated with hematite (and at the YMCA prospect with apatite) in narrow siliceous reef formations which have been partly brecciated and mylonitised. However, once again these deposits proved to be low-grade and uneconomic.

Sampling

The sampling of the Cullen Granite was carried out along random traverses across the main batholith, and the cupola near Mount Diamond. In all, 143 samples were collected—124 from outcrops and 19 from drillcore.

The surface material included 108 samples of Cullen Granite, and 16 samples of sediments, volcanics, basic dyke material, aplite and greisen associated with the granite. Composite samples of 5 to 10 kilograms were taken from each sampling site, and only where fresh material was available. Road cuttings were frequently productive because of recent blasting. At each sampling site, the outcrop was surveyed for up to two kilometres to ensure that the sample was representative. Some areas of the granite could not be sampled owing either to lack of outcrop, extreme weathering, poor access, or coverage of the granite by younger rocks—in particular by the Mullaman Beds.

Core samples were selected from the Northern Territory Geological Survey and BMR core sheds at Winnellie in Darwin. This material came from a number of prospects close to the Cullen Granite: Pine Creek, Union Reefs, Mary River (about 8 kilometres west of Minglo), Evelyn, Mount Diamond, Lakeside (near Mount Diamond), and Mount Todd. Most samples were mineralised and unmineralised carbonaceous shale, greywacke, slate, and hornfels.

Core samples obtained from Evelyn were limestone, and one sample selected from the Lakeside prospect was from a drillhole which intersected relatively unaltered granite.

Methods

Analysis

After retaining a hand specimen of each sample, the remainder was crushed and then ground in a chrome-steel Siebtechnik mill. Si, Ti, Al, total Fe (as Fe_2O_3), Mn, Mg, Ca, Na, K, P, Pb, Sn, Mo, As, V, W, U, Th, Rb, Sr, Ba, Zr, Ga, Y, Nb, Ce, and La were determined with a Philips PW 1210 automatic X-ray flurorescence spectrometer. Analyses for the major elements (with the exception of Na) were made on fusion discs using the method outlined by Norrish & Hutton (1969). USGS rock standards and BMR secondary rock standards were used for calibration, and for assessing the accuracy of the analyses. The trace elements (and Na) were determined on powder pellets by direct measurement of the mass absorption coefficients on each sample (Norrish & Chappell, 1967). Synthetically prepared standards were used throughout, and were checked against USGS rock standards.

Interfering element corrections were made where necessary, and by taking the ratio of each measurement on an unknown to measurements on a reference standard, the effects of all but very short-term drift in machine conditions were virtually eliminated. Each determination was made in duplicate (on the same sample), and in those cases where the duplicate analyses differed significantly, the analyses were repeated.

Be, Co, Cu, Li, Ni, and Zn were determined using a Varian AA-6DA spectrophotometer interfaced with a

Hewlett-Packard 2100A computer system. Before analysis, each sample (1.000 ± 0.003 gm) was digested in a mixture of perchloric acid (5 ml; 1 : 1) and hydrofluoric acid (10 ml; 48%), taken to dryness, dissolved in hydrochloric acid (5 ml; 1 : 1), and transferred to a 25 ml volumetric flask.

Loss on ignition values were determined by heating the powdered sample to 1000°C, and maintaining temperature for 2 hours. Analyses for CO_2 (only on sediments collected) and F were carried out by the Australian Mineral Development Laboratories, Adelaide.

A computer print-out of all chemical data on the Cullen Granite, including the IUGS nomenclature for each sample is available on request.

Statistics

Basic statistics (means and variance), a Spearman's rank correlation coefficient matrix, and cluster analysis were computed for the 108 granite samples (Mayo & Long, 1976). The conclusions drawn from the correlation matrix are summarised in the next section.

Cluster analysis was undertaken to see if it was possible to distinguish between the five granite phases on the basis of their chemistry. Both R-mode analysis (which determines inter-relations between elements) and Q-mode analysis (which determines inter-relations between samples) were carried out. However, the results were inconclusive, and bore little relationship to the phases which had been classified according to texture and colour.

CIPW norms were obtained by processing analytical results on a Hewlett-Packard 9820A calculator.

Results and discussion

General geochemistry

Table 1 summarises the analytical data for the 108 samples of Cullen Granite, and provides a comparison with analyses available for other granites. The SiO_2 content ranges from 62.81 to 76.52 percent, although the majority of the samples contain between 68 and 76 percent SiO_2. When the alkalinity ratio of Wright (1969) is plotted against the SiO_2 content, the Cullen Granite shows a typically calc-alkaline affinity, becoming more alkaline with increasing SiO_2 content (Fig. 3). Upper Palaeozoic granites from northeast Queensland have a similar distribution (Sheraton & Labonne, in press).

Comparisons between analyses for the average granite of Taylor (1968) and the Cullen Granite indicate that the latter is more highly fractionated. The Cullen Granite averages less TiO_2, Al_2O_3, total Fe (as Fe_2O_3), CaO, Na_2O, P_2O_5, S,

%	Mean	S.D.	Max.	Min.	R.S.D.	1	2
SiO_2	71.66	3.35	76.52	62.81	0.05	71.2	73.4
TiO_2	0.27	0.17	0.97	0.03	0.63	0.40	0.24
Al_2O_3	13.53	0.97	16.31	11.52	0.07	14.7	13.42
Fe_2O_3*	2.96	1.18	7.38	1.12	0.40	3.60	2.31
MnO	0.04	0.03	0.20	0.01	0.75	0.05	0.05
MgO	0.59	0.42	1.77	0.05	0.71	0.55	0.56
CaO	1.52	0.78	3.42	0.41	0.51	2.00	1.66
Na_2O	3.17	0.31	4.20	2.23	0.10	3.54	3.47
K_2O	5.02	0.50	6.34	3.70	0.10	4.18	4.22
P_2O_5	0.09	0.05	0.30	0.01	0.56	0.16	0.06
LOI	0.78	0.27	1.60	0.30	0.35	—	—
TOTAL	99.63	—	—	—	—	—	—
ppm							
Li	26	14	82	5	0.54	30	34
Be	4	1	8	2	0.25	5	4
F	1260	610	2900	250	0.48	850	n.d.
S	148	78	550	45	0.53	270	n.d.
V	36	24	136	< 3	0.67	40	n.d.
Co	7	3	15	< 2	0.43	2	5
Ni	5	3	18	< 2	0.60	4	3
Cu	5	3	85	2	0.60	10	6
Zn	28	14	120	6	0.50	40	37
Ga	17	2	26	12	0.12	20	17
As	< 1	—	10	< 2	—	1.5	n.d.
Rb	224	67	389	6	0.30	145	301
Sr	151	98	445	13	0.65	285	88
Y	28	10	64	6	0.36	40	57
Zr	171	76	401	26	0.44	180	134
Nb	11	4	37	2	0.36	n.d.	n.d.
Mo	7	5	86	< 3	0.71	2	n.d.
Sn	2	2	7	< 2	1.00	3	5
Ba	549	332	1433	11	0.60	600	311
La	67	32	169	12	0.48	55	38
Ce	127	53	302	37	0.42	57	67
W	3	3	14	< 2	1.00	2	n.d.
Pb	29	7	59	10	0.24	30	26
Th	41	12	87	< 2	0.29	17	30
U	9	5	30	2	0.56	4.8	7
No. of Samples	108					—	246

1. Average granite (Taylor, 1968; Be, F, S, Zn, W, from Taylor, 1964)
2. Average of 246 Upper Palaeozoic granites from northeast Queensland (Sheraton & Labonne, in press)

n.d. = not determined

* total iron as Fe_2O_3

When calculating means and standard deviations, three exceptionally high values were omitted: 85 ppm Cu; 120 ppm Zn and 86 ppm Mo.

Table 1: Average composition of the Cullen Granite in relation to other granites.

Cu, Sr, Zn, and Y, and is significantly higher in K_2O, F, Rb, Ce, Th, and U. In comparison with the Upper Palaeozoic granites of northeast Queensland, the Cullen Granite analyses show less systematic variation, although they do suggest that the Cullen Granite is less fractionated.

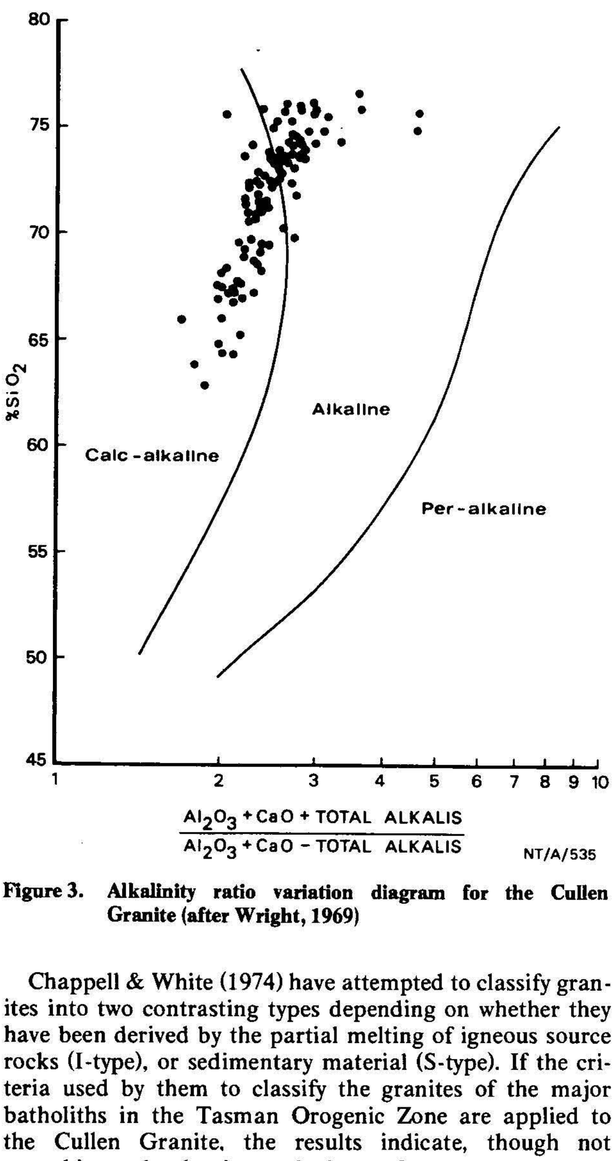

Figure 3. Alkalinity ratio variation diagram for the Cullen Granite (after Wright, 1969)

Chappell & White (1974) have attempted to classify granites into two contrasting types depending on whether they have been derived by the partial melting of igneous source rocks (I-type), or sedimentary material (S-type). If the criteria used by them to classify the granites of the major batholiths in the Tasman Orogenic Zone are applied to the Cullen Granite, the results indicate, though not unambiguously, that it may be best referred to as an I-type granite. The Cullen Granite consists of a broad spectrum of compositions from felsic to mafic types, generally has CIPW normative diopside or less than 1 percent normative corundum, and shows fairly regular inter-element variations with linear or near-linear trends on variation diagrams. In keeping with most I-type granites, the Cullen Granite also commonly contains hornblende in both the more mafic and the felsic samples, and includes sphene as an accessory mineral. In contrast, S-type granites may contain accessory monazite, and in the more felsic varieties muscovite is common and hornblende is absent. Chappell & White (1974) have suggested that I-type and S-type granites may also be distinguished by their characteristic Sr^{87}/Sr^{86} ratios. However, the data on which this distinction can be made is not available for the Cullen Granite or the other Middle Proterozoic granites in the Pine Creek Geosyncline.

Correlation coefficients for the major and minor elements indicate that three main groups exist. Al_2O_3, CaO, Fe_2O_3, MgO, MnO, TiO_2, P_2O_5, Zr, Ce, La, Ba, Sr, Zn, Co, V, Cu, and Ni all have strong positive correlations in one group, whereas Rb, Y, F, Be, Li, Pb and U form a second group. Ga, Nb, and Th tend to show some affinity with elements in each of these groups. SiO_2 exhibits a strong negative correlation with most elements, though weak positive correlations do exist with U, Rb, and Pb. No conclusive correlations can be drawn for Mo, As, Sn, W, K_2O and Na_2O.

The results of this investigation confirm the conclusions of Walpole and others (1968) that the Cullen Granite consists of five phases. In this and earlier studies (Fisher, 1952, Rattigan & Clarke, 1955; Walpole and others, 1968), the various granite types have been distinguished mainly on the basis of texture and colour. The mineralogy of each phase is essentially the same except for the pink coarse porphyritic granite (G1), which contains red rather than black opaque iron oxides. This phase also tends to be more leucocratic than the other phases, and contains only minor hornblende. The grey fine, even-grained granite (G5) is characterised by its grainsize, and like G1 contains very little hornblende. The other three phases commonly contain hornblende, and differ only in colour and texture.

Both Fisher (1952), and Rattigan & Clarke (1955), have noted that transition zones rather than sharp contacts generally exist between the phases. Of the 108 samples of granite collected in this study, 80 could be classified in hand specimen as being from one phase or another, and 28 samples, with the characteristics of two or more phases, were from transition zones.

Comparisons between the chemical features of the five phases can be drawn from Table 2. The most striking feature is that G1 (the pink coarse porphyritic granite) appears to be more highly fractionated than any of the other phases. G1 is appreciably lower in TiO_2, Al_2O_3, total Fe (expressed here as Fe_2O_3), MgO, CaO, P_2O_5, V, Sr, Zr, Ba, La, and Ce; and is significantly higher in SiO_2 than any of the other varieties.

The distinction between the G1 granite and the other phases is further reinforced if the differentiation index (which has been defined by Thornton & Tuttle (1960) as the sum of normative quartz, orthoclase, albite, leucite, nepheline, and kaliophilite) is plotted against the concentration of a selection of elements which tend to show fractionation trends (Fig. 4). The G1 granites cluster at high values for the differentiation index, and are typically more depleted in Sr, Ba, Zr, and Ce than the other phases. Rb shows some increase as the differentiation index increases, whereas Li concentrations become more erratic, and show no systematic variation.

Binary element variation diagrams such as those in Figure 5 again indicate that the G1 granite is relatively more depleted in Sr and Ca than the other phases. However, the variation of Rb with K does not follow normal trends. The range in K concentrations is small (generally 3.5 to 4.5%), and Rb is enriched relative to K, though this feature is not restricted to any particular phase of the Cullen Granite. Such enrichment is a well known feature in the crystallisation products of late-stage residual melts such as aplites and pegmatites (Ahrens and others, 1952; Nockolds & Allen, 1953; Ahrens, 1953), but it is unusual in normal igneous rocks. Taylor and others (1956) have observed a similar enrichment in Rb relative to K in the St Austell (Cornwall) and Mourne (County Down) granites, and have suggested that these rocks crystallised from a magma which had already undergone considerable differentiation.

El Bouseily & El Sokkary (1975) have attempted to use the ternary relation between the elements Rb, Ba, and Sr to trace differentiation trends in salic suites. Using 139 published analyses for Rb, Ba and Sr from different, well documented igneous assemblages, they delimited fields for

	G1		G2		G3		G4		G5	
%	*Mean*	*S.D.*	*Mean*	*S.D.*	*Mean*	*S.D.*	*Mean*	*S.D.*	*Mean*	*S.D.*
SiO_2	75.00	1.22	71.01	3.54	72.55	2.65	70.59	4.07	72.43	1.38
TiO_2	0.10	0.06	0.30	0.16	0.24	0.10	0.34	0.24	0.26	0.12
Al_2O_3	12.57	0.53	13.79	1.16	13.28	0.90	13.69	0.94	13.61	0.34
Fe_2O_3*	1.87	0.52	3.23	1.23	2.58	0.74	3.40	1.51	2.33	0.54
MnO	0.03	0.01	0.04	0.03	0.03	0.01	0.04	0.02	0.05	0.06
MgO	0.27	0.17	0.62	0.34	0.44	0.25	0.90	0.58	0.37	0.14
CaO	0.69	0.20	1.64	0.67	1.26	0.43	2.03	0.89	1.29	0.34
Na_2O	3.27	0.54	3.19	0.30	3.11	0.22	3.11	0.25	3.20	0.16
K_2O	5.11	0.48	5.04	0.41	5.31	0.45	4.61	0.22	5.24	0.33
P_2O_5	0.04	0.03	0.10	0.06	0.08	0.04	0.11	0.08	0.09	0.04
LOI	0.78	0.35	0.71	0.20	0.65	0.09	0.88	0.42	0.69	0.16
TOTAL	99.73		99.67		99.53		99.70		99.56	
ppm										
Li	19	14	25	12	32	20	25	9	27	13
Be	5	2	4	2	4	1	4	1	4	1
F	1390	920	1280	520	1330	540	1010	460	860	540
S	142	65	137	56	121	46	166	111	153	153
V	11	8	37	20	29	17	50	30	34	20
Co	4	2	7	3	6	2	9	4	6	1
Ni	3	1	5	2	4	2	8	5	4	2
Cu	6	4	4	2	4	1	7	3	5	1
Zn	20	9	29	13	25	7	29	20	19	7
Ga	17	3	17	3	17	2	16	3	17	1
As	1	2	<1	—	1	2	<1	—	<1	—
Rb	266	75	209	49	255	57	199	37	257	45
Sr	52	45	186	104	122	70	178	92	107	43
Y	36	16	28	8	32	9	21	5	26	5
Zr	108	36	190	77	159	69	157	69	188	87
Nb	12	8	12	4	11	3	10	3	13	3
Mo	7	6	8	6	7	5	7	5	5	5
Sn	3	2	2	2	3	2	2	2	2	2
Ba	187	152	641	358	489	326	608	358	520	207
La	35	26	81	32	73	41	54	19	65	19
Ce	78	44	149	53	138	66	105	33	127	38
W	4	4	2	2	3	3	3	3	1	2
Pb	30	11	27	5	31	6	26	3	36	7
Th	39	13	43	12	41	10	35	9	49	10
U	14	8	9	4	9	4	8	3	8	4
No. of Samples	16		33		13		9		9	

* total iron as Fe_2O_3.

Table 2 Average compositions of the Cullen Granite phases

each of the different rock types from diorite to strongly differentiated granite. In Figure 6 the Cullen Granite data have been plotted on the Rb-Ba-Sr ternary diagram, and the fields determined by El Bouseily & El Sokkary and the direction of differentiation superimposed. Under the term normal granites, they have included those types similar to the low-Ca granites of Turekian & Wedepohl (1961). The rather ill-defined group of anomalous granites is taken by El Bouseily & El Sokkary to include 'metasomatised, granitised and rapakivi granites; magmatic granites subjected to metasomatism and granites that have suffered chemical changes or were not formed by a simple mechanism'. Although the Cullen Granite data do not invariably fall within the nominated fields, and their interpretation in terms of the rock types outlined is open to conjecture, the samples do plot along the differentiation trend line, and show extreme differentiation in the case of the pink coarse porphyritic granite (G1).

FMA and K_2O-Na_2O-CaO ternary diagrams (Fig. 7) further illustrate the relationships between the Cullen Granite phases. The G1 granite is relatively depleted in Mg, total Fe, and Ca. Yet, from these diagrams and the preceding figures, there is little to distinguish the other four phases (i.e., G2, G3, G4, G5). Samples of the fine even-grained granite (G5) plot in each diagram within a restricted field which is fairly central to the field of compositions for all the Cullen Granite samples. However, the significance of this observation is not clear. With reference to Table 2, it also appears that, on average, the grey fine porphyritic phase (G4) is the least differentiated phase of the Cullen Granite. However, as the standard deviations indicate, there is a wide range of compositions within this phase, and considerable overlap with the other granites.

The conclusion that the pink coarse porphyritic granite is a highly fractionated late phase of the Cullen Granite supports earlier field observations. In the Edith River area, W. B. Dallwitz (*in* Fisher, 1952) has noted that the pink and green coarse porphyritic phase (G2) has been intruded, probably at a late stage of cooling, by the pink coarse porphyritic granite (G1). He considered that this later phase was most likely derived from either the deeper portions of the batholith or residual liquids present in the granite at a late stage in its crystallisation, and that its emplacement was probably related to the shearing commonly seen in the area. Rattigan & Clarke (1955) observed the same intrusive relationship, and noted that the late G1 phase in places forms sheet-like intrusions over the roof of the G2 granite.

Ternary diagrams based on the normative mineralogy (i.e., Q-Ab-Or, An-Ab-Or, Q-Pl-Or) were plotted, and the experimentally derived phase diagrams for the system Q-Ab-Or-H_2O were considered in this study. However, no further trends were apparent, and no generalisations about their significance in terms of the petrogenesis of the Cullen Granite were possible.

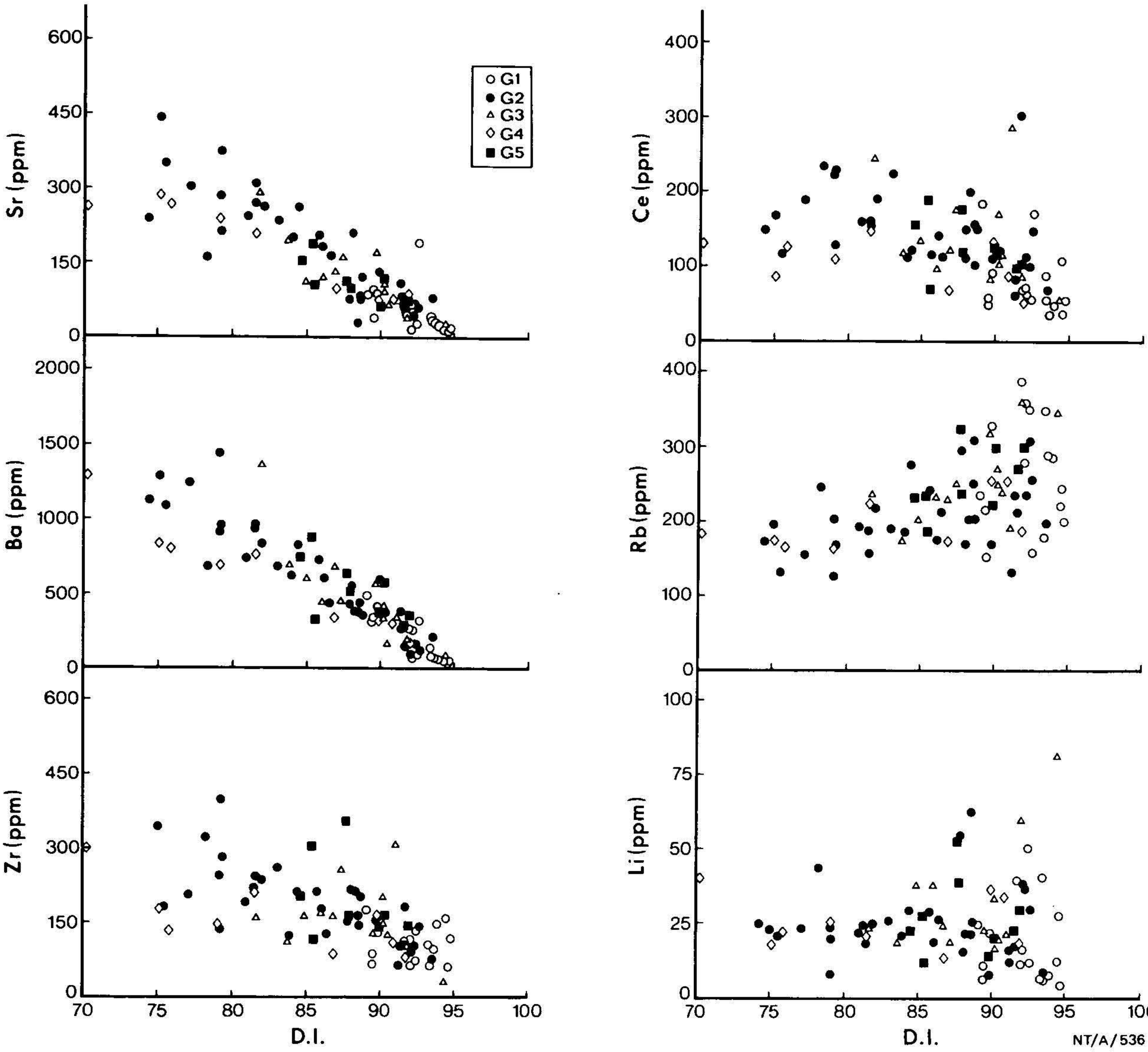

Figure 4. Variation of Sr, Ba, Zr, Ce, Rb and Li with the differentiation index.

Relationship between granite geochemistry and mineralisation

The existence of a relationship between the geochemistry of the Cullen Granite and mineralisation in the granite and in surrounding sediments is suggested by only a few of the trace elements considered in this study.

In Figure 8, the distribution of U throughout the granite has been plotted together with the known uranium mines, fields, and prospects in the area (taken from Walpole and others, 1968). The average concentration of U in the Cullen Granite is 9 ppm—almost double the value given by Taylor (1968) for average granite. In the Edith River area, this concentration is even higher, and can be correlated with the U mineralisation reported by Fisher (1952). Uranium concentrations within the granite are also consistently high in an area about 5 km southwest of Frances Creek. Although no U mineralisation has been reported from this area, it is interesting to note that exposures of the pink coarse porphyritic granite phase are common both there and around Edith River. A genetic relationship may exist between this phase and the U mineralisation within the granite, as U values are high in most exposures.

For Cu and W, some anomalous areas in the granite appear to be related to known mineralisation in the sediments. Several samples from the granite cupola near Mount Diamond contain above average Cu concentrations, and lie close to Cu mineralisation (Fig. 8). However, as only two samples from this area were analysed, this association may be more apparent than real. One sample from the eastern side of the Cullen Granite (about 20 km northeast of Fergusson River) was found to contain 85 ppm Cu and traces of chalcopyrite in hand specimen, but no known Cu mineralisation occurs within a 15 km radius. In the Edith River area, W values were above average (Fig. 8), and may be related to W mineralisation in the adjacent sediments.

The remaining elements (Pb, Zn, Co, Ni, Sn, As, F, V, Mo, S, Th), which are either found in economic quantities in the sediments or may be used as geochemical indicators of mineralisation, suggest that no correlation exists between the granite geochemistry and mineralisation in and around the Cullen Granite.

The existence of a correlation between the Sn content of rocks and the occurrence of Sn deposits has received considerable attention in the literature. Ivanova (1963), Rattigan (1964), and Štemprok (1965), have claimed that a relationship does exist, whereas others (Chauris, 1965; Hosking, 1967) have questioned such a correlation. The explanation for these differing opinions may lie in the realisation that whether Sn mineralisation occurs depends

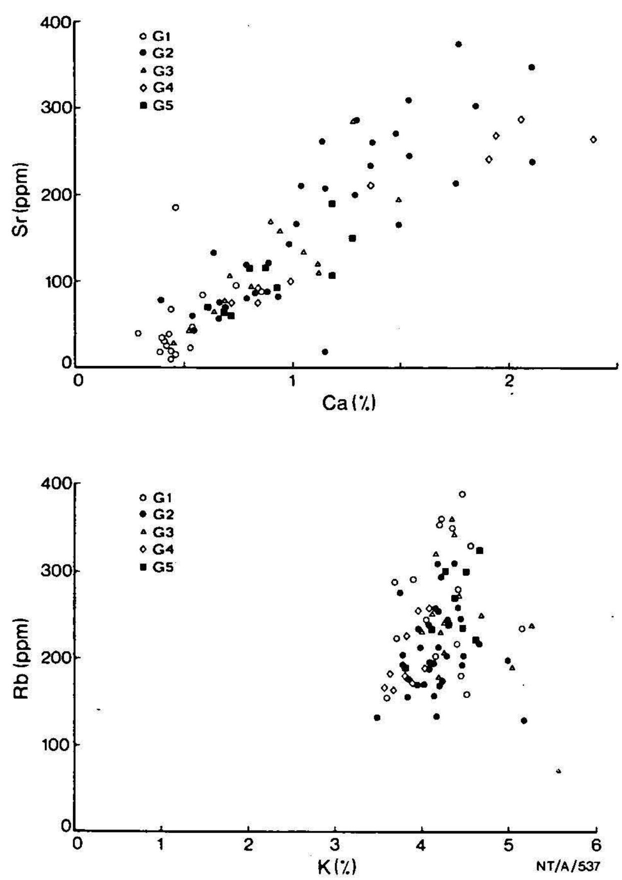

Figure 5. Variation of Sr with Ca and Rb with K.

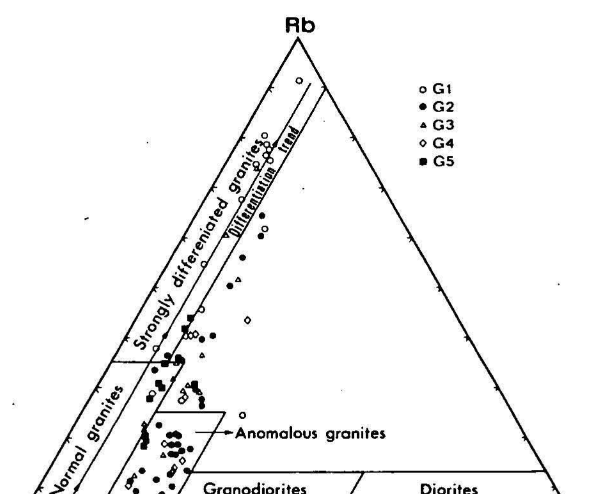

Figure 6. Rb—Ba—Sr variation diagram (after El Bouseily & El Sokkary, 1975).

primarily on the physico-chemical conditions (e.g., temperature, pressure, pH, Eh) and geological environment (e.g., type of wallrock, occurrence of fracture zones) at the site of deposition, rather than on the absolute concentration of Sn.

Nevertheless, there is evidence to suggest that the mean Sn content of rocks associated with deposits is higher than that observed for those without deposits, and that within a

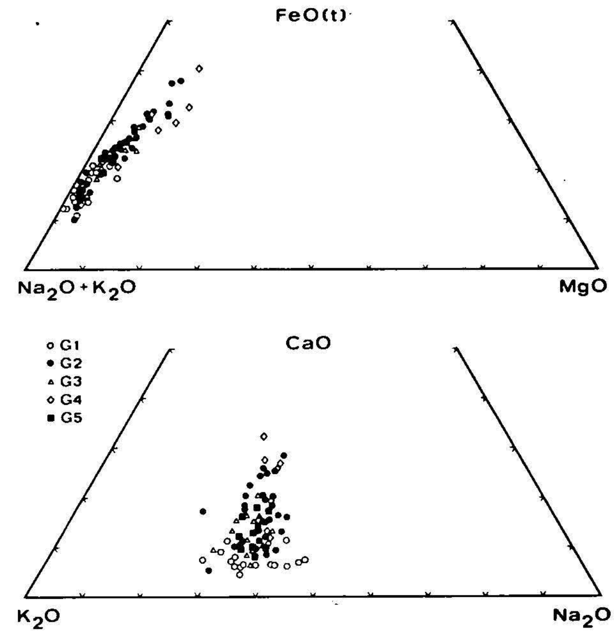

Figure 7. FMA and K_2O—Na_2O—CaO variation diagrams.

single intrusion, the Sn content may be higher in the roof zone (Tauson and others, 1968). Hesp & Rigby (1974) noted that for all rocks in the Tasman Geosyncline the ratio of the mean Sn content in mineralised and unmineralised rocks was around 7 : 1. According to Ivanova (*in* Wedepohl, 1969), Rattigan (1963), and Barsukov (1967), Sn-bearing granitic rocks often contain 15-30 ppm Sn, whereas the average Sn content of granites is about 3 ppm. However, Sheraton and Labonne (in press) found that granitic rocks with related Sn deposits in northeast Queensland average 7 ppm Sn, and similar values have been reported by Tauson and others (1966) for the stanniferous granitic rocks of eastern Transbaikaliya. In the light of these conclusions it is surprising to find that the average Sn content for the Cullen Granite (about 2 ppm) should be so low despite the extensive Sn mineralisation in and around the granite (Fig. 8). In the Mount Harris area, in particular, the Sn content of the granite is near or below the limit of detection (2 ppm), even though numerous Sn deposits occur in close proximity.

Above average concentrations of Co, Ni, and V in the granite southeast of Hayes Creek, and in the Claravale Road area cannot be correlated with known mineralisation. These anomalous concentrations are a reflection of the higher mafic mineral content of samples from these areas.

Thorium concentrations within the Cullen Granite are high when compared with those of other granites (Table 1), but bear no relationship to mineralisation. They do, however, exhibit an interesting feature for which there is no apparent explanation. The Th content of those samples collected from the northeastern lobe (to the north of latitude 13°40′) averages 48 ppm whereas those for the western and southern areas of the batholith average less than 35 ppm. The results of a recent radiometric survey (Horsfall & Wilkes, 1975) covering the Mount Evelyn 1:250 000 Sheet area and taking in a small part of the northeastern lobe of the Cullen Granite, indicate that all the granites covered (and the Cullen Granite in particular) are anomalously radioactive, and that K and Th are the major sources. Heier & Rhodes (1966) carried out gamma-ray analyses of 3 samples from the Cullen Granite, and reported U, Th, and K concentrations up to 12 ppm, 47 ppm and 4.7 percent, respectively, which is in good agreement with the data from this study.

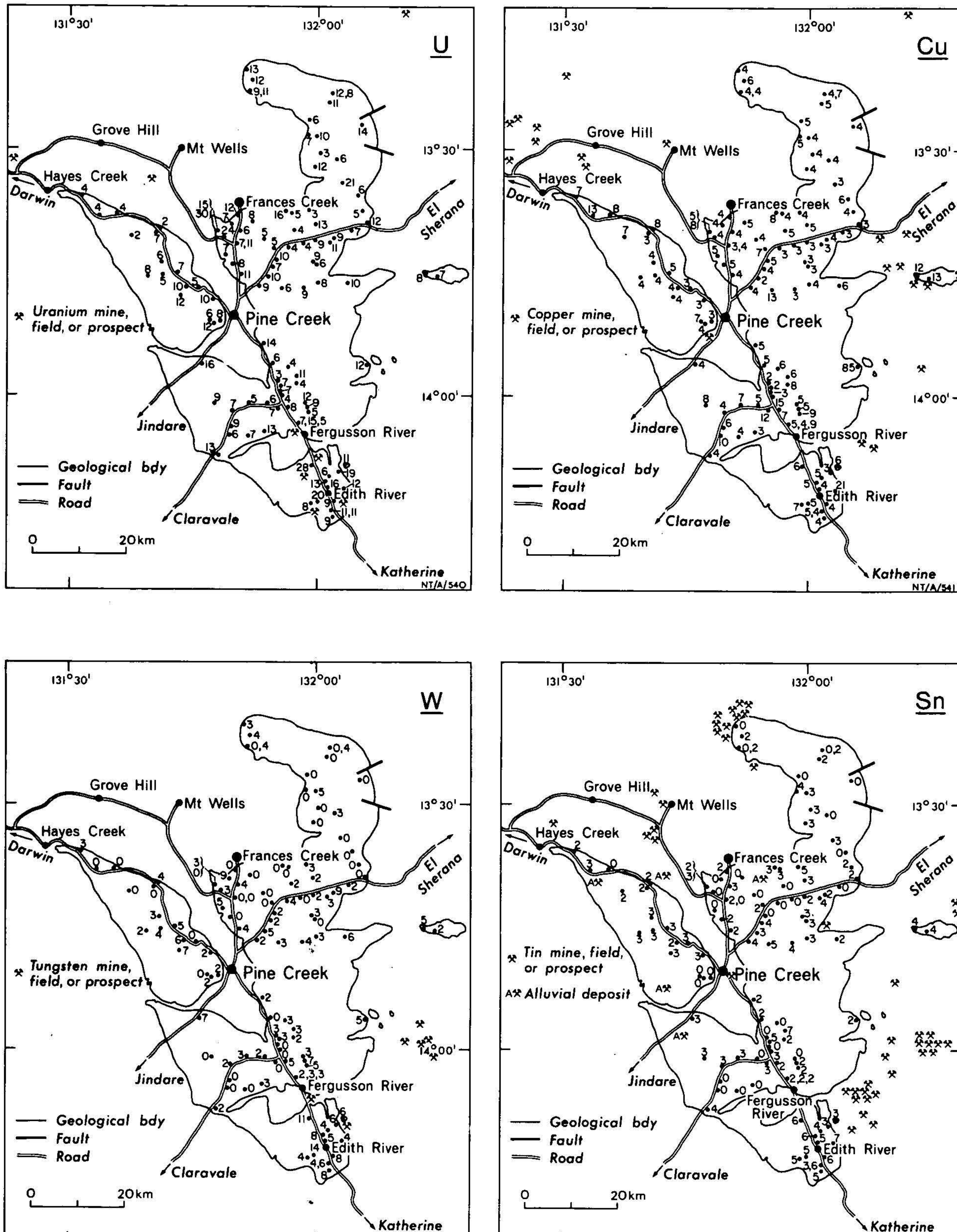

Figure 8. Contents of U, Cu, W and Sn (in ppm) in the Cullen Granite in relation to known mineralisation.

Source of ore metals and genesis of the mineralisation

The identification of source rocks from which metals have been derived and concentrated into an ore deposit has seldom proved easy. Krauskopf (1967, 1971) has speculated on the source, and outlined the difficulties in relating the concentration of ore metals in acid intrusives to the occurrence of economic deposits. Abundance levels higher and lower than those considered as background or normal have been cited as evidence in support of metals being derived from granites. For all metals (with the possible exception of Sn), the evidence is conflicting, and Krauskopf (1967, p. 13) quotes examples that illustrate the confusion.

Although the concentrations of ore metals are small in most rocks, the sizes of igneous intrusions are such that only a slight depletion in their metal content would be required to account for a significant ore deposit. Krauskopf (1967) gives the following example. 'To concentrate a million tons of metal in an ore body—which would constitute a sizeable deposit for such metals as copper, lead and zinc—requires only that the amount of metal in 100 km^3 of granite be diminished by about 3 ppm. A volume of 100 km^3 would represent a small stock, and a decrease of 3 ppm is hardly significant out of the average 10-70 ppm of the trace metals which normal granites contain.' A 10000 ton deposit of Mo or W would involve a 0.03 ppm decrease in the metal content of a stock of the same size—which is negligible in relation to the 1-2 ppm of these metals in normal granites. In view of the large size of the Cullen Granite batholith (the area of outcrop is about 2800 km^2) and the small size of the ore deposits discovered adjacent to the granite, it is impossible to decide whether or not the granite was the source of the ore metals.

It is equally difficult to determine whether the Lower Proterozoic sediments, which constitute an even larger volume of rock, were the source material. Analytical data was obtained for sediments sampled by drillcore from localities around the margins of the granite. The trace element contents for these sediments are likely to be anomalously high as drilling was carried out only in areas of known or suspected mineralisation. However, in those sediments which did not appear to be mineralised, the trace element concentrations were more than adequate for them to act as source rocks.

Although there may be conjecture over the source of the metals, there is little doubt that the granite has played an important role in the genesis of the mineralisation. The Middle Proterozoic granites of the Pine Creek Geosyncline and the Cullen Granite in particular are almost invariably associated with numerous small hydrothermal deposits in nearby sediments. One of these deposits is the Cu-Pb-Zn lode at Mount Bonnie, which is situated about 5 km from the Cullen Granite (Fig. 2). In a recent study of the carbon, oxygen, and sulphur isotopes at the Mount Bonnie deposit, Donnelly & Roberts (in preparation) have suggested that the deposit formed at temperatures around 200°C from connate water which incorporated magmatic sulphur from nearby basic sills. Carbonates in the ore lenses were produced during a skarn reaction which precipitated the sulphides. They considered that the conformable ore-body was hydrothermally emplaced as there is extensive wall-rock alteration around the deposit. The age of the mineralisation and the source of the metals are not known, and Donnelly & Roberts do not speculate on the heat source for the ore solutions. However, we consider that the Cullen Granite, at the time of its intrusion, may have acted as a heat engine—providing both heat to the ore solutions and a geothermal gradient through which these fluids were driven. In this way, the intrusion of the Cullen Granite may have initiated the sequence of events which have produced the mineralisation at Mount Bonnie and other places around the granite.

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Carboniferous and Permian palynostratigraphy in Australia and Antarctica: a review

E. M. Kemp, B. E. Balme[1], R. J. Helby[2], R. A. Kyle[3], G. Playford[4], and P. L. Price[5].

Continued research in late Palaeozoic palynological biostratigraphy in Australia since about 1970 permits the delineation of a series of informally defined palynostratigraphic units in both Western and eastern Australia. The units include both informal assemblage zones and taxon-range-zones. In the older, pre-glacial (and periglacial) part of the Carboniferous, two palynofloras, designated the *Granulatisporites frustulentus* and the *Secarisporites* Microfloras are recognised. The *Granulatisporites frustulentus* Microflora is subdivided into the *Grandispora spiculifera* Assemblage, of Tournaisian age, and the *Anapiculatisporites largus* Assemblage, which spans the early to late Viséan interval. The succeeding *Secarisporites* Microflora, the contents of which are incompletely described, is subdivided into three: the *Grandispora maculosa*, *Anabaculites yberti*, and *Potonieisporites* Assemblages. The *Secarisporites* Microflora characterises strata ranging in age from late Viséan to perhaps Missourian. The preglacial palynofloras are best known from the Canning and Bonaparte Gulf Basins in Western Australia, but are known in eastern Australia from scattered localities in the Drummond Basin and the New England Block.

For the later Carboniferous and Permian, palynostratigraphic schemes have developed independently in Western and eastern Australia. In Western Australia, the Canning Basin interval commencing with the glacials of the Grant Formation at the base, and extending to the top of the Liveringa Formation, has provided the stratigraphic standard for the definition of eight informal palynological assemblages, designated Units I to VIII. These span a time interval approximately equivalent to the Missourian to late Guadalupian.

In eastern Australia, the palynostratigraphic schemes currently in use represent modifications of the palynological 'Stages' synthesised by Evans (1969). Subdivisions within these stages are based in most cases on the first appearances of individual form-species; two subdivisions have been described within both Stages 2 and 3, three within Stage 4, and four within Stage 5. Correlation of these new units with the assemblage units described from Western Australia is tentative at present. The subdivisions of Evans' scheme have been identified within, *inter alia*, the Bowen, Cooper, Galilee, Sydney, and Tasmania Basins.

Recent studies in Antarctica have compared palynological assemblages from the central Transantarctic Mountains and south Victoria Land with eastern Australian palynofloras: Stages 2, 4, and 5 have been identified from these areas. Assemblages from the Prince Charles Mountains have been referred to Stage 5.

Introduction

The history of Carboniferous and Permian palynology in Australia is closely linked with the development of economic, particularly energy resources. The early acquisition of knowledge was closely related to coalfield development; later, the impetus for palynological research came from rapid expansion in petroleum exploration. These phases mirrored comparable developments that occurred on a world-wide scale.

The economic associations of palynological research in Australia were manifest at an early date—indeed in one of the first palynological papers ever published. This was the description of the algal fossil *Tasmanites punctatus* by Newton in 1875, from the 'combustible schists' or oil shales which were mined and distilled on the banks of the Mersey River in northern Tasmania in the second half of the nineteenth century (Twelvetrees, 1911).

After this somewhat precocious beginning, interest in the study of acid-insoluble microfossils waned until the late nineteen forties and the fifties. At that time there appeared a number of articles describing plant microfossils from the Permian coal seams of New South Wales, Queensland, Tasmania, and Western Australia (Dulhunty, 1945, 1946; de Jersey, 1946; Dulhunty & Dulhunty, 1949; Balme, 1952). The intention of these papers was to provide a descriptive base for eventual coal seam correlation using dispersed spores; the nomenclature employed was one of a system of numbered types, with spores being allocated to some 40 groups on the basis of their gross morphology and sculpture. The aim of coal seam correlation was never realised, but descriptive work associated with the palynology of Palaeozoic coals continued through the nineteen fifties. This resulted in the publication of a series of systematic papers in which binomial nomenclature was applied to the dispersed fossil forms (Balme & Hennelly, 1955, 1956, 1956a; Hennelly, 1959). These profusely illustrated papers remain, at the time of writing, standard reference works for the taxonomy of Australian Permian spores and pollen.

The next phase of development recognisable in research into the palynology of the late Palaeozoic coincided with the acceleration of oil exploration activity in Australia in the early nineteen sixties. Pressure to provide a tool for correlation of strata both within and between sedimentary basins led to more emphasis on determining the stratigraphic distribution of dispersed microfossils, and less on their formal description. Biostratigraphic schemes encompassing the Late Carboniferous and Permian were established independently in Western and eastern Australia.

In Western Australia, palynological subdivision of the late Palaeozoic was first made by Balme (1964) into 'Lycosporoid' and *'Striatites'* microfloras, of Early Carboniferous and Permian ages respectively. A threefold subdivision of

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the *Striatites* Microflora was proposed as follows: at the base, the '*Nuskoisporites* Assemblage' was considered to have an approximate time-span of Sakmarian to early Artinskian; the '*Vittatina* Assemblage' encompassed the late Early Permian; and the '*Dulhuntyispora* Assemblage' the Late Permian. In 1968 Balme prepared a report with restricted circulation that proposed a more refined, but still generalised biostratigraphic subdivision of the uppermost Palaeozoic sequence in the Canning Basin. A modified version of that scheme is presented in this review.

In the northern part of the Perth Basin, Segroves (1970) delineated five palynostratigraphic units in what is generally regarded as a wholly Permian sequence, and which consists of both marine and continental sediments. The palynological units, from the oldest to the youngest, he termed the '*Microbaculispora*', '*Quadrisporites*', '*Acanthotriletes*', '*Haplocystia*' and '*Dulhuntyispora*' assemblages. Recognition of these was based on the quantitative and qualitative distribution of spores, pollen grains, and non-spinose acritarchs.

Unpublished investigations carried out in Western Australia since Balme's (1964) account include those of the Irwin River Coal Measures by B. S. Ingram, the Collie and Wilga Coal Measures by Miryam Glikson, and the Early Permian of the southern Carnarvon Basin by M. McLeod. Some of the results obtained by these workers are summarised in this account.

Some elements of the Early Carboniferous 'Lycosporoid' Microflora were illustrated and briefly described by Balme in 1960. As a generalisation, however, the development of a Carboniferous palynostratigraphic framework has been one of the lower priority objectives of Australian palynologists. This has resulted partly from the low hydrocarbon potential of many Carboniferous sediments and partly because in many areas they are fairly strongly metamorphosed. However, over the past decade it has become clear that a reasonably representative Carboniferous sequence occurs in the Canning and Bonaparte Gulf Basins of north-western Australia. This awareness, together with the development of several faunal zonations in the Bonaparte Gulf Basin, has facilitated the recognition and interpretation of the major features of the palynological sequence through the Carboniferous in that basin. A descriptive base for the Early Carboniferous has been provided by the major taxonomic papers of Playford (1971, 1976); a biostratigraphic scheme based on Playford's work and on hitherto largely unpublished work by Helby has been assembled and is presented in this review.

In eastern Australia, P. R. Evans, working initially in intercalated marine and non-marine sequences in the southern Bowen Basin of Queensland, established a series of 11 biostratigraphic units for the Late Carboniferous and Permian, using the ranges of both spores and acritarchs. The development of this scheme is traceable in unpublished company reports (Evans, in Mines Administration Pty Ltd, 1962), and in the Record series of the Bureau of Mineral Resources (Evans, 1964c, 1966 a, b, c). Its extension into totally non-marine sequences in other basins necessitated reorganisation of Evans's zonal units because acritarchs were no longer present. The original scheme was synthesised by Evans (1967, 1969) into five broad divisions based entirely on spore and pollen distributions; these he designated informally as 'Stages' 1 to 5. The geographic distribution of these units in eastern Australia (as understood to 1967), together with a broad account of the stratigraphic limits of the spore and pollen species which defined them, were outlined by Evans in 1969.

The stratigraphic range of Evans's scheme was extended by Helby (1969b), who recognised, in the Hunter Valley, a unit which he designated the '*Grandispora*' microflora. This was based on an assemblage described from the Italia Road Formation (Playford & Helby, 1968), and occurs in strata stratigraphically below Evans's Stage 1. Helby called the Stage 1 assemblage the '*Potonieisporites*' microflora. Both this original '*Grandispora*' microflora, in modified form, and the '*Potonieisporites*' microflora are redefined herein and form part of a now better understood Carboniferous palynofloral sequence. At the other end of the scale, Helby (1970, 1973) described a plant microfossil assemblage which succeeds the Stage 5 assemblage at a level above the highest coal measures in the Sydney Basin. This association, which he designated the '*Protohaploxypinus reticulatus*' Assemblage, is considered to be of Late Permian age.

Modifications of the scheme erected by Evans (1969) have been introduced in eastern Australia by Paten (1969), and Price (in Gatehouse, 1972, and Battersby, 1976) working in the Cooper Basin, and by Norvick (1971, 1974), working in the Galilee Basin of Queensland. The subdivisions of Evans's scheme which Price has introduced have also been applied in the Bowen Basin (Price, 1976); their palynological basis, and their distribution in lithostratigraphic units in a number of eastern Australian basins, are outlined in this review.

Palynological research on Antarctic sedimentary rocks has understandably lagged behind that of Australia, mainly because of that continent's inaccessibility, and because of the poor preservation of many Antarctic Permian assemblages. The account given in this review of progress in late Palaeozoic palynological studies outlines the recognition of units comparable to those defined in eastern Australia.

The present review is an attempt to summarise the major advances that have occurred in the study of the palynology of the Carboniferous and Permian in both Australia and Antarctica since about 1970, and to make some new proposals concerning the palynostratigraphic subdivision. Because the Carboniferous/Permian boundary is difficult to identify, the account of the palynostratigraphy has been divided into two sections; the older, preglacial Carboniferous, and the latest Carboniferous and Permian. These sections reflect natural lithostratigraphic entities and the history of biostratigraphic research has followed the same pattern. There is, however, overlap between the two sections in that interval which reflects the late Palaeozoic glaciation—both sections include accounts of palynological assemblages from the glacial rocks. The geographic coverage is of necessity uneven. The brief accounts of research in some sedimentary basins does not necessarily reflect lack of research there. A great deal of unpublished information has been accumulated by exploration companies, but much of this remains inaccessible. Also, it is likely that the palynologically-based biostratigraphic units discussed herein will be modified in the light of future detailed work; this paper is certainly to be regarded as no more than an 'interim statement' reflecting the state of current knowledge.

The location of the major sedimentary basins with accumulations of Carboniferous and Permian rocks, and of drillsites and other localities mentioned in the text, are shown in Figure 1. Authorship of the review is as follows: Pre-glacial Carboniferous palynofloras—G. Playford and R. J. Helby; Canning Basin, Perth, Carnarvon, and Collie-Wilga Basins—B. E. Balme; Officer Basin—E. M. Kemp; eastern Australian biostratigraphic units—P. L. Price and E. M. Kemp; Bowen and Cooper Basins—P. L. Price; Galilee Basin—E. M. Kemp and P. L. Price; Sydney Basin—E. M. Kemp and R. J. Helby; Tasmania Basin and minor basins—E. M. Kemp; Antarctica—R. A. Kyle; introductory and concluding remarks—E. M. Kemp.

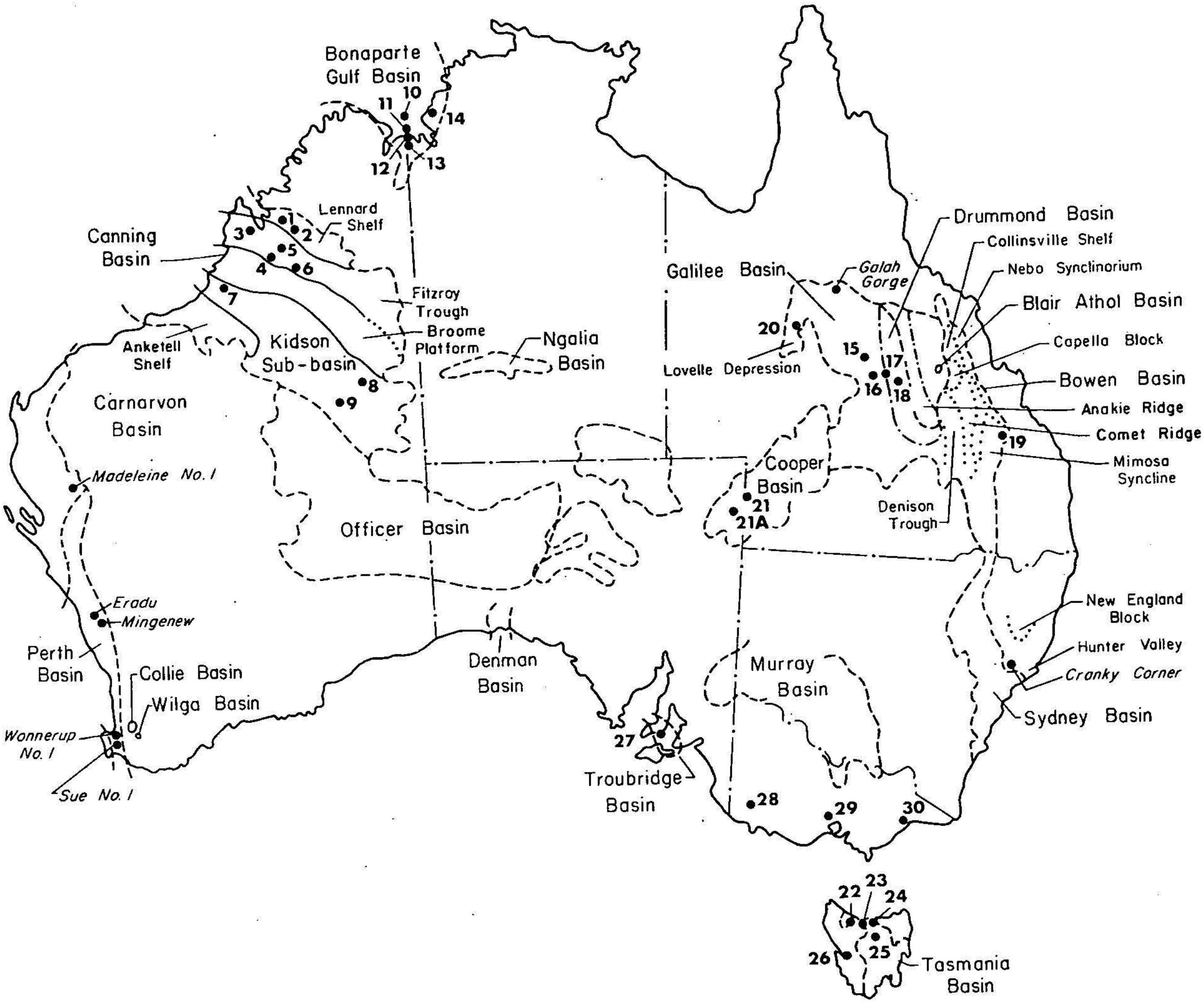


Figure 1. Sedimentary basins in Australia from which Carboniferous and Permian palynological data are available. Borehole and other localities discussed in the text of this review are numbered as follows: **1,** WAPET Meda No. 1. **2,** WAPET Blackstone No. 1. **3,** WAPET Fraser River No. 1. **4,** WAPET Frome Rocks No. 2. **5,** WAPET Grant Range No. 1. **6,** A.F.O. Nerrima No. 1. **7,** WAPET Willara No. 1. **8,** A.A.P. Point Moody No. 1. **9,** WAPET Kidson No. 1. **10,** ARCO Lacrosse No. 1. **11,** ARCO Pelican Island No. 1. **12, 13,** A.O.D. Bonaparte Nos. 1 & 2. **14,** A.A.P. Kulshill No. 1. **15,** Amerada Thunderbolt No. 1. **16,** GSQ Galilee NS 5. **17,** GSQ Aramac No. 1. **18,** GSQ Hexham No. 1. **19,** Theodore area. **20,** H.P.P. Weston No. 1. **21,** Delhi-Frome-Santos Innamincka No. 1. **21A,** Frome-Santos Gidgealpa No. 2. **22,** Hellyer Gorge. **23,** Mersey Coal Basin. **24,** Beaconsfield. **25,** Golden Valley. **26,** Strahan. **27,** Waterloo Bay. **28,** Coleraine. **29,** Bacchus Marsh. **30,** ARCO-Woodside Duck Bay No. 1.

Pre-glacial Carboniferous palynofloral sequence

The palynological contents of Australian Carboniferous pre-glacial (and periglacial) sediments, i.e. those deposited prior to the establishment of the *Glossopteris* flora in latest Carboniferous to earliest Permian time, are known in considerably less detail than are those of later Palaeozoic, dominantly Permian age. On the basis of published and unpublished work in Western Australia (Balme, 1960, 1964; Playford, 1971, 1972, 1976; Helby, unpubl.; Playford, unpubl.) and in eastern Australia (Playford & Helby, 1968; Helby, 1969, 1969b; Playford, 1977), the following sequence of palynofloras can be assembled in descending stratigraphic order.

Secarisporites Microflora
- *Potonieisporites* Assemblage
- *Anabaculites yberti* Assemblage
- *Grandispora maculosa* Assemblage

Granulatisporites frustulentus Microflora
- *Anapiculatisporites largus* Assemblage
- *Grandispora spiculifera* Assemblage

Granulatisporites frustulentus Microflora

Balme (1964) used the term 'Lycosporoid Microflora' to embrace the then-known Carboniferous assemblages of the Canning Basin and Bonaparte Gulf Basin in northwestern Australia. The appellation 'Lycosporoid' signified that the palynofloras are almost invariably characterised by a profusion of the morphologically variable miospore species *Granulatisporites frustulentus* Balme & Hassell emend. Playford, 1971, many representatives of which are 'lycospore-like', i.e. are in close morphological accord with the genus *Lycospora*, so characteristic of northern hemisphere Carboniferous palynofloras. In this paper, it is appropriate to rename the 'Lycosporoid Microflora' as the *Granulatisporites frustulentus* Microflora and to recognise within it two stratigraphically successive units, discussed below. In addition to its conspicuous content of *G. frustulentus*, the microflora as a whole includes a wide variety of forms attributable to such genera as *Grandispora*, *Convolutispora*, *Punctatisporites*, and *Knoxisporites*. The following species are particularly characteristic: *Verrucosisporites nitidus* (Naumova) Playford, 1964, *Dibolisporites distinctus* (Clayton) Playford, 1976, *Cristatisporites colliculus* Playford, 1971, *Auroraspora macra* Sullivan, 1968, *Endosporites micromanifestus* Hacquebard, 1957, *Grandispora uncata* (Hacquebard) Playford, 1971, *Velamisporites lacertosus* Playford, 1971, *V.* sp. cf. *V. rugosus* Bharadwaj & Venkatachala, 1962, and *Hymenospora* sp. cf. *H. caperata* Felix & Burbridge, 1967.

As discussed below, the *G. frustulentus* Microflora occurs in sediments that range in age from earliest Carboniferous (Tournaisian, Tnlb) to late Viséan, i.e. is confined to the Early Carboniferous. This corresponds broadly with the known stratigraphic distribution of the *Lepidodendron* Flora of Morris (in Jones *et al.*, 1973) in eastern Australia; and it is entirely reasonable to suggest that the *G. frustulentus* Microflora is the palynofloral analogue of Morris's *Lepidodendron* Flora.

Grandispora spiculifera Assemblage. This, the older subdivision of the *Granulatisporites frustulentus* Microflora, occurs in Early Carboniferous (Tournaisian) sediments that conformably succeed those containing the *Retispora lepidophyta* Assemblage (see Playford, 1976) of latest Devonian age, i.e. latest Famennian, Fa2d, to earliest Tournaisian, Tnla or early Tnlb. The characteristics of the latter assemblage, as it occurs in the lower Fairfield Formation (*sensu* Playford & Lowry, 1966) of the Canning Basin, have been detailed by Balme & Hassell (1962) and Playford (1976).

Palynological components of the *Grandispora spiculifera* Assemblage that serve to distinguish it from the *R. lepidophyta* Assemblage (stratigraphically below) include the following trilete miospores: *Grandispora spiculifera* Playford, 1976, *Dibolisporites distinctus*, *Cristatisporites colliculus*, *Hymenospora* sp. cf. *H. caperata*, *Hymenozonotriletes explanatus* (Luber) Kedo, 1963, and *Velamisporites lacertosus*. In a negative sense, the *G. spiculifera* Assemblage is readily distinguishable from the *R. lepidophyta* Assemblage by its lack of such species as *R. lepidophyta*, *Brochotriletes textilis* (Balme & Hassell) Playford, 1976, *Hystricosporites porrectus* (Balme & Hassell) Allen, 1965, and *Grandispora clandestina* Playford, 1976. The wealth of data that has accumulated, especially in the northern hemisphere, on the stratigraphic range of *R. lepidophyta* indicates that its incoming coincides approximately with the base of the youngest Fammennian subdivision (Fa2d) and its outgoing with the Devonian-Carboniferous boundary. Thus it follows that the lower limit of the suceeding *G. spiculifera* Assemblage is basal Carboniferous,·i.e. Tournaisian, lower Tnlb, approximately. From other palynofloral and associated faunal evidence (see Playford, 1976) it appears that the *G. spiculifera* Assemblage of the Canning Basin continues upwards into late Tournaisian (Tn3) sediments.

Anapiculatisporites largus Assemblage. The *Anapiculatisporites largus* Assemblage is here proposed as the younger suite attributable to the *Granulatisporites frustulentus* Microflora. The following miospore species comprise, *inter alia*, a distinctive association permitting clear discrimination from that of the *Grandispora spiculifera* Assemblage: *Anapiculatisporites largus*. *A. semisentus*, *Punctatisporites subvaricosus*, *Convolutispora balmei*, *Foveospirites appositus*, *Crassispora scrupulosa*, *C. invicta*, *Camptozonotriletes robertsi*, *Exallospora coronata*, *Raistrickia pinguis* (all instituted by Playford, 1971), and *Knoxisporites* sp. cf. *K. ruhlandi* Doubinger & Rauscher, 1966.

The *Anapiculatisporites largus* Assemblage is typified by the palynoflora described by Playford (1971) from the upper Bonaparte Beds and overlying Tanmurra Formation, and their equivalents in part, of the Bonaparte Gulf Basin, Western Australia and Northern Territory. These host strata of the assemblage have been dated independently from faunal evidence, cited by Playford (1971) and Jones *et al.* (1973) as being early to late Viséan. A fourfold subdivision of the sequence containing the *A. largus* Assemblage was tentatively suggested by Playford (1971, pp. 55-6) on the basis of stratigraphic occurrences of certain species in Bonaparte Nos 1 and 2 Wells. Further data are needed before such subdivision can formally be proposed.

The two subdivisions of the *G. frustulentus* Microflora have yet to be observed in a single continuous stratigraphic sequence. Thus it is not yet possible to delineate a precise stratigraphic boundary between them. Presumably, it corresponds fairly closely to the Tournaisian-Visean boundary.

Secarisporites Microflora.

The palynofloral suite here term the *Secarisporites* Microflora includes the *Grandispora* Microflora which Helby (1969b) originally recognised in the 'Kuttung' succession in the Sydney Basin, New South Wales. As now used (i.e., in a broader sense than '*Grandispora* Microflora'), the *Secarisporites* Microflora is believed to encompass three major floral successions, each of which is represented by distinct plant microfossil associations. These latter form the basis for a provisional subdivision of the *Secarisporites* Microflora into three assemblages, which from oldest to youngest are; *Grandispora Maculosa*, *Anabaculites yberti*, and *Potonieisporties* Assemblages. An analogous threefold subdivision of the megafloral record in eastern Australia has been proposed by Retallack (in press), who subdivided Morris's (1975), *Rhacopteris* flora into the *Otopteris argentinica*, *Sphenopteridium*, and *Botrychiopsis* floras.

The advent of the *Secarisporites* Microflora is marked by a drastic decline and ultimate disappearance of *Granulatisporites frustulentus*. The genera *Grandispora*, *Kraeuselisporites*, *Raistrickia*, *Dibolisporites*, *Punctatisporites*, and *Verrucosisporites* are abundant and diverse in the microflora, and many of their constituent species are distinct from those of the *Granulatisporites frustulentus* Microflora. By comparison with the latter, *Convolutispora* is quantitatively and qualitatively insignificant. Much taxonomic work remains to be completed, but the following are common elements of the *Secarisporites* Microflora: *Anabaculites yberti* Marques-Toigo, 1970, *Grandispora maculosa* Playford & Helby, 1968, *Raistrickia accincta* Playford & Helby, 1968, and *Secarisporites* spp.

Grandispora maculosa Assemblage. This is the older subdivision of the *Secarisporites* Microflora and is represented in the Bonaparte Gulf Basin in Pelican Island No. 1, Lacrosse No. 1, Kulshill No. 1, and Bonaparte No. 1 Wells. In Pelican Island No. 1, the assemblage occurs within the interval 1164-1264 feet* (Helby, 1972). Some 76 miospore species were recorded from the unit in this well, including *Grandispora maculosa*, *Auroraspora macra*, *A. solisortus* Hoffmeister, Staplin & Malloy, 1955, *Anabaculites yberti*, *Raistrickia accincta*, and *Kraeuselisporites kuttungensis* Playford & Helby, 1968.

The lower stratigraphic limit of the *G. maculosa* Assemblage is datable (in the Bonaparte Gulf Basin) from its association with the *Anthracospirifer milliganensis* brachiopod zone of Roberts (1971) in Kulshill No. 1 Well (Core 27, see Figure 3), although it should be noted that the *A. milliganensis* Zone is also associated with the upper

* Depth intervals are quoted in feet in this review when they were so given in the original well completion report.

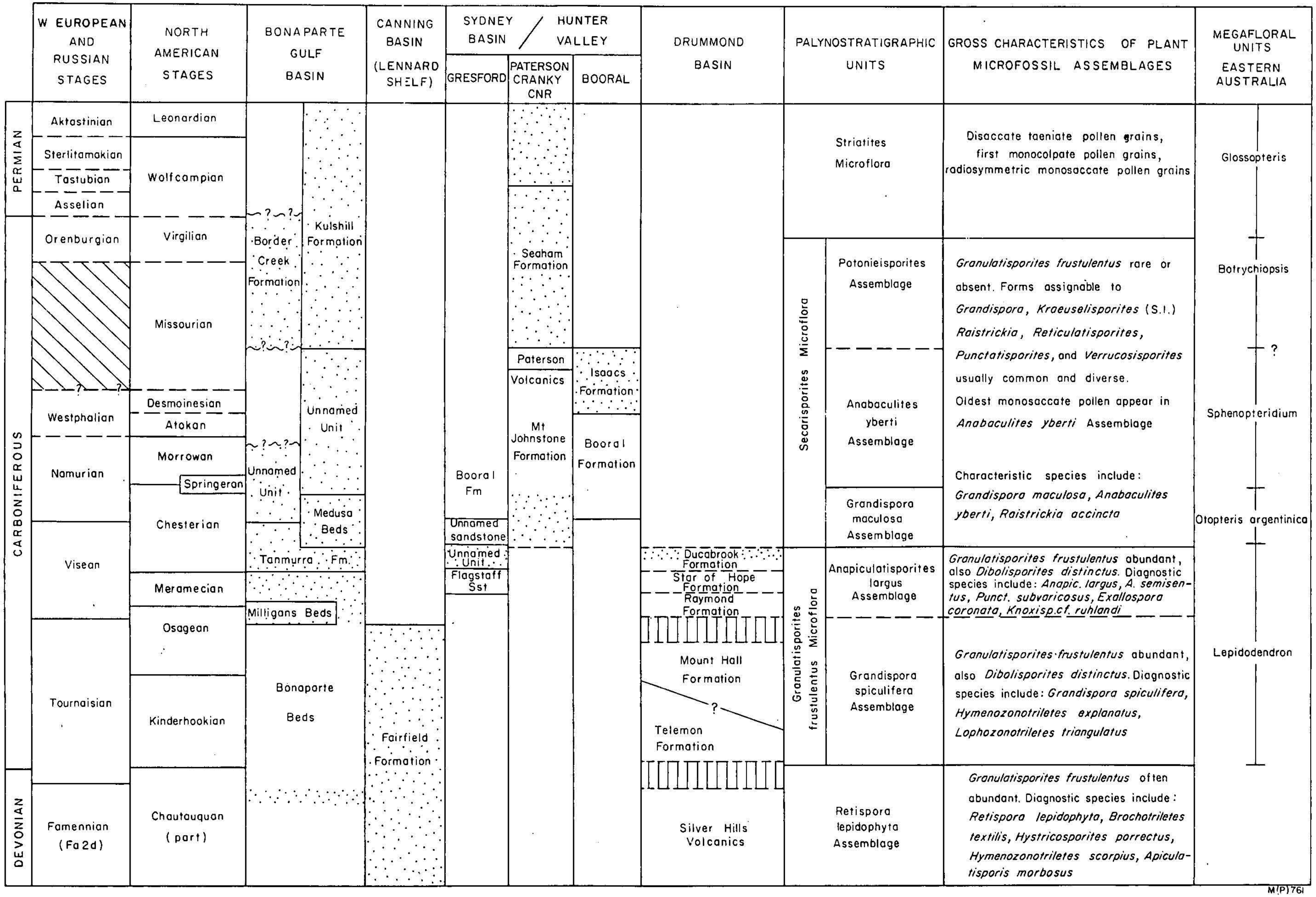


Figure 2. **International correlation, stratigraphic occurrence, and principal features of Australian Carboniferous palynofloras.** Dotted symbol denotes lithostratigraphic units (or parts thereof) from which palynological data have been obtained. Correlations between the Stephanian Stage of Europe and the North American stages, based on palynological data, are at variance with older correlations (e.g. Moore, 1944, Wanless, 1969). To avoid confusion, the *Potonieisporites* Microflora and the *Striatites* Microflora (at its lower range) are compared to the North American stages only.

portion of the *Anapiculatisporites largus* Assemblage in Bonaparte No. 1 Well (Roberts, 1971). From this it would appear that the base of the *G. maculosa* Assemblage lies within the range of the *Anthracospirifer milliganensis* Zone. This zone correlates with the late Viséan units CuIII β-γ, according to data of Jones *et al.* (1973). Foraminiferal evidence supports this (Mamet & Belford, 1968), although conodont evidence from the Canning Basin suggests that the upper limit of the *Anapiculatisporities largus* Assemblage might possibly range into the earliest Namurian (Bischoff, in Jones *et al.*, 1973).

Anabaculites yberti Assemblage. The base of strata characterised by this association is marked by the first appearance of bilaterally and radially symmetrical, monosaccate pollen grains. These represent the oldest undoubtedly gymnospermous pollen in the Australian palynological record and are referable to such genera as *Potonieisporites* and *Parasaccites* (or possibly *Cordaitina*). In Pelican Island No. 1 Well the assemblage was identified from cuttings within the interval 560-1130 feet.

The lower stratigraphic limit of the *A. yberti* Assemblage appears to be early Namurian in age, from associated conodont and ostracode evidence in Kulshill No. 1 Well: see Jones *et al.*, (1973). However, the similarly associated brachiopods, the *Echinochonchus gradatus* Fauna of Roberts (1971) were considered by the latter author to be latest Viséan to early Namurian. The presence of *Potonieisporites* lends some support to a Namurian dating, as the genus first appears at about the Viséan-Namurian boundary in Great Britain, and, as a rarity, in the Chesterian Goddard Formation of Oklahoma (Sullivan & Mishell, 1971). The age of the upper limit of the *A. yberti* Assemblage is speculative, for no independent palaeontological data are available. The diversity of the palynoflora strongly implies a parent flora that is pre-glacial. Helby (1969, 1969b) has argued that the onset of glaciation in Gondwanaland coincided with the cessation of widespread, lower delta-plain, coal measure sedimentation in the northern hemisphere. If so, the upper stratigraphic limit of the *A. yberti* Assemblage is perhaps Missourian and may correlate with a horizon within the European upper Stephanian C.

Potonieisporites Assemblage. In contrast to the two older assemblage constituents of the *Secarisporites* Microflora, the *Potonieisporites* Assemblage is poorly diversified. In Pelican Island No. 1 Well (Bonaparte Gulf Basin), the extent of the assemblage is uncertain, but it probably extends from the surface to at least 200 feet (Helby, 1972). Few species extend upwards from strata containing the *Anabaculites yberti* Assemblage into those containing the *Potonieisporites* Assemblage. The species include largely undescribed representatives of *Densoisporites, Endosporites, Punctatisporites* and *Verrucosisporites.* The assemblage is characterised by large monosaccate pollen grains and cavate spores and its paucity may reflect a genuine periglacial flora, in sharp contrast to the luxuriant *Sphenopteridium* flora.

Radiosymmetrical trilete monosaccate pollen of the *Parasaccites-Cordaitina* type are common in Late Pennsylvanian (Desmoinesian-Virgilian) strata in the North American midcontinent (Kirkland & Frederiksen, 1970). They have also been frequently reported from the Upper Carboniferous (C_3) of Russia (e.g. Oshurkova, 1973). In the absence of independent palaeontological control, the incoming of the *Potonieisporites* Assemblage is placed very tentatively within the Missourian.

At present nothing definitive can be said concerning the upper limit of the *Potonieisporites* Assemblage. It is certainly not younger than Asselian and probably correlates with a horizon within the Virgilian.

Occurrence of the pre-glacial palynofloras

The present, admittedly sparse knowledge of the areal and stratigraphic distribution of the Carboniferous palynofloras discussed above is given below in summary form. The distribution of the assemblages, their stratigraphic occurrence and their principal features, are summarised in Figure 2. Some of the stratigraphically significant miospores are illustrated in Figure 4.

Canning Basin. On the Lennard shelf, northern Canning Basin, the *Grandispora spiculifera* Assemblage is well typified, as discussed above, by its occurrence through the upper part of the Fairfield Formation (= Laurel Formation; Thomas, 1959). These sediments conformably succeed those (lower Fairfield) containing the latest Devonian *Retispora lepidophyta* Assemblage (Playford, 1976). In the Fitzroy Trough, a deep fault-bounded depression immediately south of the Lennard Shelf, preliminary and mostly unpublished work indicates the presence of all the pre-glacial Carboniferous assemblages in several subsurface sections.

Bonaparte Gulf Basin. Knowledge of the Carboniferous palynology of the Bonaparte Gulf Basin rests on published (Playford, 1971) and unpublished (Helby, 1972) work on subsurface material from several oil-exploration wells. Palynostratigraphic synthesis of these studies is portrayed by Figure 3. From this it is evident that all the pre-glacial microfloral suites described herein are represented, with the exception of the *Grandispora spiculifera* Assemblage. Apparent absence of the latter probably reflects inimical preservation. The palynoflora of the upper part of the Bonaparte Beds together with the overlying Tanmurra Formation typifies the profuse *Anapiculatisporites largus* Assemblage, as described above. Within the range of this unit in the Bonaparte 1 and 2 sections, Playford (1971) tentatively suggested a fourfold subdivision; this seems to be applicable to other subsurface sections in the basin (Helby, 1972).

The sections in Pelican Island No. 1 and Kulshill No. 1 Wells in particular form the basis for the characterisation and dating of the *Secarisporites* Microflora and its three constituent assemblages. Problems remain concerning the relation between palynofloral assemblages and lithological units in parts of this basin; for instance, the palynological data illustrated on Figure 3 suggests that the Tanmurra Formation in Kulshill No. 1 Well is considerably younger than in Bonaparte No. 1 Well, and may have been misidentified.

Below the documented *A. largus* Assemblage (i.e., below depths of 1326 m and 1502 m in Bonaparte 1 and 2 respectively) plant microfossil preservation is poor or non-existent due to a relatively high degree of carbonisation. However, Playford (1971) reported specimens of the nominate taxon of the *Retispora lepidophyta* Assemblage at considerable depths in Bonaparte 1.

Sydney Basin. The *Granulatisporites frustulentus* Microflora (undifferentiated) has been identified in the upper part of the Flagstaff Sandstone on the southern edge of the New England Block. These palynofloras are associated with the mid to late Viséan *Delepinia aspinosa* (brachiopod) Zone and the *Lepidodendron* Flora (Jones *et al.*, 1973). Diversity of the associations is limited, with *Granulatisporites frustulentus* dominating all samples. *Dibolisporites distinctus* was recognised in several samples.

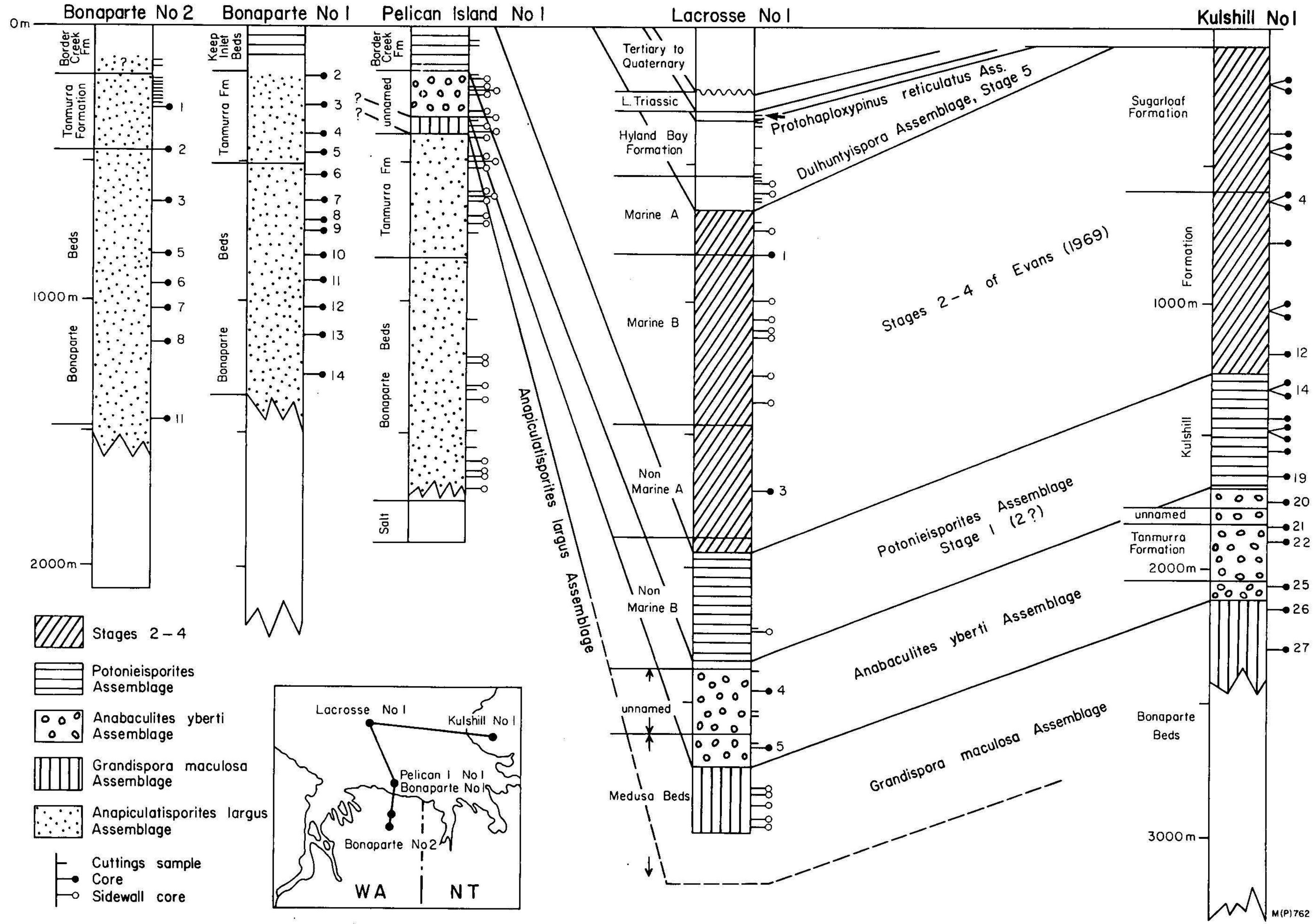
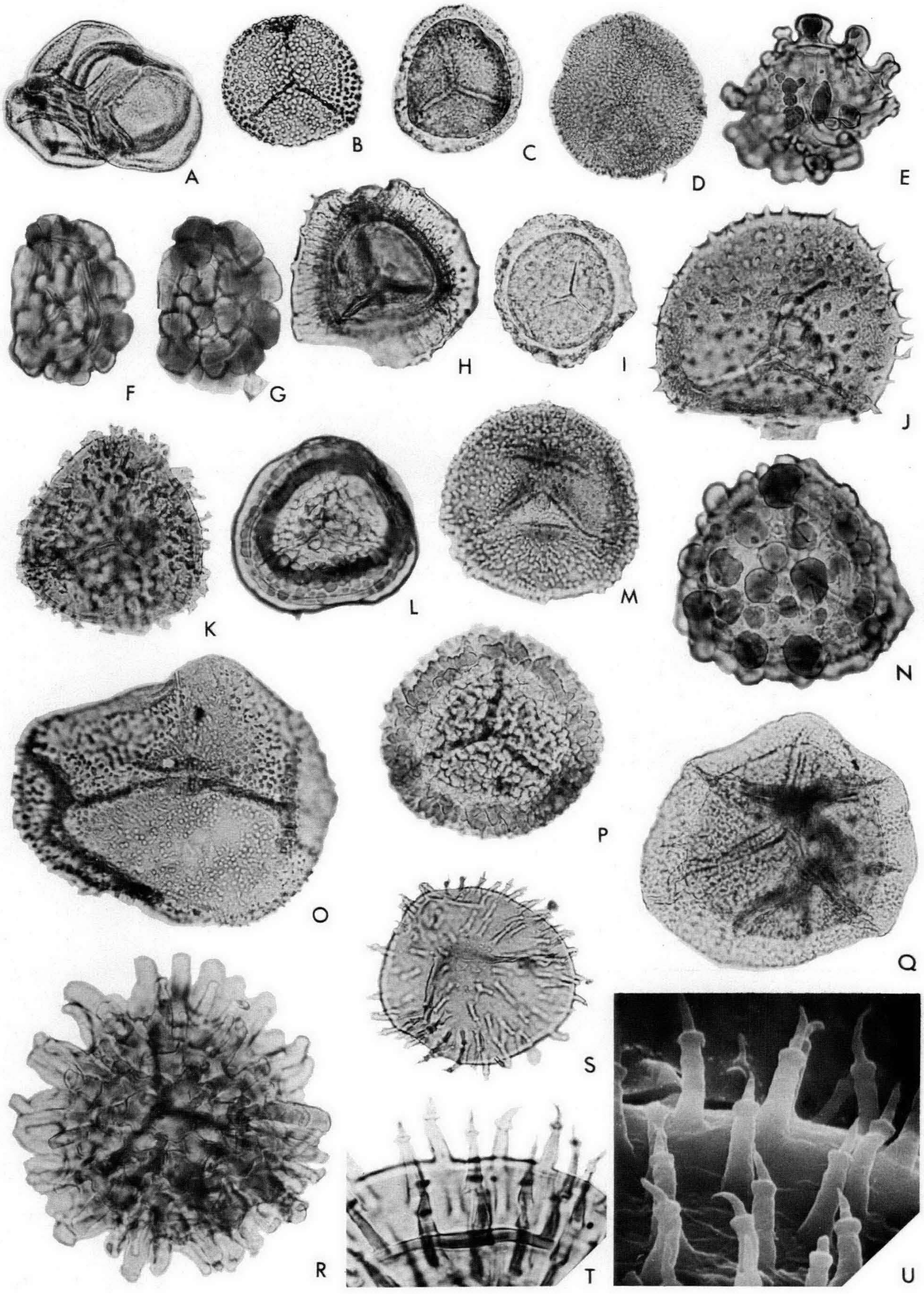


Figure 3. Distribution of palynological assemblages in selected boreholes in the Bonaparte Gulf Basin, Western Australia and Northern Territory.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The *Grandispora maculosa* Assemblage has been recorded from the upper part of the Wallaringa Formation, the Italia Road Formation, and the Mount Johnstone Formation on the southern edge of the New England Block (Playford & Helby, 1968; Helby, 1970). The palynofloras are associated with the *Otopteris argentinica* Flora (Retallack, in press), and display less diversity than their Western Australian counterparts. Characteristic western species of *Secarisporites* and *Dibolisporites* were not encountered.

The *Anabaculites yberti* Assemblage has been recognised only in the McInnes and Isaacs Formations on the southern edge of the New England Block (Helby, 1969b and unpubl. data; Roberts *et al.*, 1976), where it is associated with the *Sphenopteridium* Flora (Retallack, in press). The assemblages are more restricted than their Western Australian counterparts and the nominate zone species has not been recorded to date. It should be noted that the lower limit of the *Anabaculites yberti* Assemblage in eastern Australia does not appear to correspond to the same position in Western Australia, in terms of a European time-scale. Faunal correlations across the continent suggest that the boundary between the *Grandispora maculosa* and the *A. yberti* Assemblage in eastern Australia should approximate to the Viséan-Namurian boundary: the sparse data available suggests, however, that it might be as young as Westphalian (see Roberts *et al.*, 1976, fig. 7, p. 209). It should be noted, however, that no sequences are known wherein both assemblages occur. The *Potonieisporites* Assemblage is encountered throughout the lower and middle portions of the Seaham Formation on the southern edge of the New England Block and the adjacent Sydney Basin (Evans, 1969; Helby, 1969b), where it is associated with the *Botrychiopsis* Flora of Gould (1975).

Drummond Basin. The dominantly non-marine, Late Devonian-Early Carboniferous sequence of the Drummond Basin is currently being investigated palynologically by one of us (G.P.), and a preliminary report on the miospore flora of the Early Carboniferous Ducabrook Formation appeared recently (Playford, 1977). In this unit, the presence of the *Granulatisporites frustulentus* Microflora is manifest by the preponderance of the nominate species. A clear affinity exists between the Ducabrook palynoflora and that described (Playford, 1971) from the Viséan of the Bonaparte Gulf Basin, thus indicating that the younger (Viséan) portion of the *G. frustulentus* suite, i.e., the *Anapiculatisporites largus* Assemblage, is represented. The following are some of the taxa shared by these eastern and Western Australian sequences: *Anapiculatisporites largus, Raistrickia inprofusa* Playford, 1971, *Convolutispora balmei, Knoxisporites* sp. cf. *K. ruhlandi, Crassispora invicta, C. scrupulosa*, and *Velamisporites* spp. Of especial interest is the presence in the Ducabrook sediments of several forms that had not previously been reported from southern hemisphere sediments, or indeed from outside the British Carboniferous, viz. *Acanthotriletes acritarchus* Neville, 1973, *Raistrickia nigra* Love, 1960, and *Stenozonotriletes? mirabilis* Neville, 1973. As discussed by Playford (1977), these provide corroborative evidence of a Viséan age determination for the Ducabrook's *G. frustulentus* Microflora. Further work will undoubtedly illuminate the palynostratigraphic and phytogeographic relationships of the Drummond Basin Carboniferous.

Ngalia Basin. Almost as this account was going to press, well-preserved palynofloras were recovered by one of us (E.M.K.) from siltstones within the Mount Eclipse Sandstone. A very preliminary examination of these suggests that the *Anapiculatisporites largus* Assemblage may be represented; this would indicate a Viséan age for the formation. Previous age assessments were based on poorly preserved plant megafossils which suggested a possible Late Carboniferous age (Jones *et al.*, 1973, p. 28).

Latest Carboniferous and Permian palynofloral sequence

As outlined in the introduction, separate palynostratigraphic systems have developed in Western and eastern Australia for the subdivision of sedimentary rocks deposited during the latest Carboniferous and Permian. These rocks constitute the lower part of the Gondwana System which commences with lithological units bearing the imprint of glaciation in varying degree. In Western Australia, the Canning Basin sequence, which is relatively undeformed, and hence characterised by good miospore preservation, has provided the standard for palynostratigraphic subdivisions, defined by Balme (1964, 1968, and herein). In eastern Australia, the palynological 'stages' of Evans (1969) have provided a basis for further subdivision. The precise relationship between palynostratigraphic units established in the eastern and western parts of the continent remains uncertain in detail; broad correlations between the schemes are possible, however, and are shown in Figures 7 and 12. Stratigraphically significant miospores from the latest Carboniferous to Permian interval in both eastern and Western Australia are illustrated in Figures 9 and 10.

There is a probable overlap of the oldest units defined in this section with the youngest assemblage described in the preceding section. The *Potonieisporites* Assemblage, described above from the Bonaparte Gulf Basin, is almost certainly equivalent to Unit I of the Canning Basin sequence, and to Stage 1 of eastern Australia. Description of all three units is retained here for completeness, and because they have been recognised independently by different authors working in widely separated basins.

Western Australia

Canning Basin

Most palynological data from the uppermost Palaeozoic of Western Australia come from the Canning Basin, in which the succession consists of a thick glacial unit, the Grant Formation, at its base, overlain by a paralic

Figure 4. Selected form-species from Australian pre-glacial Carboniferous palynofloras, with their known ranges expressed in terms of palynofloral units. Magnifications X500 unless otherwise specified. A, B. *Granulatisporites frustulentus* Balme & Hassell emend. Playford, 1971; *Retispora lepidophyta* Assemblage through *Granulatisporites frustulentus* Microflora. A, tetrad, X500. B, single spore, X750. C, *Grandispora maculosa* Playford & Helby, 1968; *Secarisporites* Microflora. D, *Grandispora spiculifera* Playford, 1976; *Grandispora spiculifera* Assemblage. E, *Raistrickia accincta* Playford & Helby, 1968; *Secarisporites* Microflora. F, G, *Secarisporites* sp. nov., proximal and distal views; *Secarisporites* Microflora. H, *Hymenozonotriletes explanatus* (Luber) Kedo, 1963; *Grandispora spiculifera* Assemblage. I, *Auroraspora macra* Sullivan, 1968; *Retispora lepidophyta* Assemblage through *Anabaculites yberti* Assemblage. J, *Crassispora drucei* Playford, 1976; *Retispora lepidophyta* through *Grandispora spiculifera* Assemblages. K, *Dibolisporites* sp. nov.; *Grandispora maculosa* through *Anabaculites yberti* Assemblages. L, *Exallospora coronata* Playford, 1971; *Anapiculatisporites largus* Assemblage. M, *Anapiculatisporites largus* Playford, 1971; *Anapiculatisporites largus* Assemblage. N, *Secarisporites* sp. nov.; *Secarisporites* Microflora. O, *Anabaculites yberti* Marques-Toigo, 1970; *Grandispora maculosa* through *Anabaculites yberti* Assemblages. P, *Cristatisporites colliculus* Playford, 1971; *Granulatisporites frustulentus* Microflora. Q, *Velamisporites lacertosus* Playford, 1971; *Granulatisporites frustulentus* Microflora. R, *Raistrickia strumosa* Playford, 1976; *Retispora lepidophyta* through *Grandispora spiculifera* Assemblages. S-U, *Dibolisporites distinctus* (Clayton) Playford, 1976; *Granulatisporites frustulentus* Microflora; T, detail, light microscopy, X1000, U, detail, SEM, X1700.

succession consisting mainly of clastic sediments. Plant microfossils are common throughout, and enable the sequence to be divided into eight biostratigraphic units. Two oil exploration wells drilled by West Australian Petroleum Pty Ltd (WAPET) on the Lennard Shelf, Meda No. 1 and Blackstone No. 1, provided the principal reference sections on which the palynological succession here is based. In these the successions are relatively condensed, but all the palynological subdivisions are recognisable—apart from Unit I which has been found only in the deeper parts of the basin.

Figure 5 summarises the principal characteristics of the eight palynostratigraphic units now recognised in the uppermost Palaeozoic of the Canning Basin. Further details of the composition of the units are given in Table 1. This scheme remains deficient in many ways in terms of standard stratigraphic practice, and the units are not in any sense formally proposed. It is hoped to present a properly codified biostratigraphic standard when studies of the glacial succession, at present being carried out by G. Powis at the University of Western Australia, have been completed. The semi-quantitative information included in Figure 5 is based on examination of samples from Blackstone No. 1 Well, apart from that for Unit I. Depth intervals in which units are currently recognised are given below; it should be stressed that further examination may change these boundaries. Details of the stratigraphic relationships and age of the units follow.

Unit I. This unit occurs in the basal part of the Grant Formation, but not in the so-called 'Lower Grant', that below about 4700 feet in Blackstone No. 1, for instance, which contains the *Anabaculites yberti* Assemblage (rather than a correlative of the *G. maculosa* Assemblage, as suggested by Balme in Jones *et al.*, 1973). Distribution of Unit I is not well-known; it has been recognised only from four deep wells in the Fitzroy Trough and the Gibson Sub-basin, including Fraser River No. 1, (3300-3409 feet), Grant Range No. 1 and Point Moody No. 1 Wells. Unit I cannot be directly dated on palaeontological evidence. It probably correlates with Stage 1 of Evans (1969) and from the increase in abundance of monosaccate pollen resembles the Missourian. No palynological evidence suggests that it is younger than Carboniferous.

Unit II. Unit II characterises the middle section of the Grant Formation in widely distributed wells in the Canning Basin. In Blackstone No. 1 Well it was identified between 2752-3864 feet. The maximum thickness so far determined for Unit II is about 600 m in Willara No. 1 Well in the Kidson Sub-basin. The unit correlates in broad terms with Stage 2 of Evans (1969). Its age is uncertain relative to Carboniferous and Permian stratotype sections in the northern hemisphere. Australian palynologists (e.g. Evans, 1969) have, in the past, referred Stage 2 to the Permian, but it is possible that it correlates with strata referred by American stratigraphers to the Late Pennsylvanian. The chronostratigraphic relationship of these to the European Stephanian is still not entirely resolved. Certainly the plant microfossil assemblages of Stage 2 do not contain the diversity of disaccate, taeniate pollen that characterises Wolfcampian (or even Virgilian) equivalents in the mid-continental United States. Whether this difference is explicable in temporal, geographic, or climatic terms is uncertain.

Unit III. This palynostratigraphic unit occurs in the upper, shalier part of the Grant Formation and in the Nura Nura Member of the Poole Sandstone; in Blackstone No. 1 Well it was identified from sidewall cores in the interval 2663-2715 feet. The maximum thickness so far recognised is about 200 m in Kidson No. 1 Well. Spinose acritarchs in some assemblages from the unit indicate that it is partly marine in certain areas of the Canning Basin. Diversification of plant microfossil assemblages coincides with the initiation of low energy sedimentation and the disappearance of tillites and other lithologies of glacial aspect. It seems reasonable, therefore, to assume that amelioration of the climate provided many new ecological niches that were rapidly colonised.

The age of the upper part of Unit III is suggested as Sterlitamakian by the presence of ammonoids, including *Propopanoceras* and *Metalegoceras* in the Nura Nura Member (Glenister & Furnish, 1961). Arenaceous foraminifera occur throughout Unit III in some sections but no other invertebrate fossils are known from below the base of the Nura Nura Member. It is likely that Unit III correlates with all or part of the Holmwood Shale in the Perth Basin, the middle (Beckett) member of which, on ammonoid evidence, is Tastubian (Glenister & Furnish, 1961). The age range of Unit III, therefore, is Tastubian, possibly extending to the Sterlitamakian and/or Asselian.

Unit IV. This unit occurs in the upper part of the Poole Sandstone and the lower Noonkanbah Formation; it was originally identified from sidewall cores between 2408-2540 feet in Blackstone No. 1 Well. Unit IV has been identified in oil exploration wells sunk on the Lennard Shelf, in the Fitzroy Trough, Broome Platform, Kidson Sub-basin and Gregory Sub-basin. The maximum thickness so far encountered is about 250 m in Nerrima No. 1 Well.

The age of Unit IV is probably early Artinskian (Aktastinian), in the sense in which this stage was used by Furnish (1973). The lower limits of Unit IV may extend downwards to the Sterlitamakian, and it may range upwards into the Baigendzhinian (Leonardian). Assemblages sharing common characteristics with those from Unit IV occur in the lower part of the Barakar Group in peninsular India (Bharadwaj, 1975; Tiwari, 1974).

Unit V. Unit V occurs in the middle section of the Noonkanbah Formation and has been recognised in wells from all the main onshore structural subdivisions of the Canning Basin except the Anketell Shelf. In Blackstone No. 1 Well it was identified between 2126-2380 feet. Its maximum known thickness is about 150 m in Frome Rocks No. 2 Well.

The unit is equivalent in age to part of the Artinskian Series and is probably not younger than early Baigendzhinian. This also implies a correlation with part of the Leonardian Stage.

Unit VI. This unit, which occurs in sidewall cores in the interval 1676-1921 feet in Blackstone No. 1, is distinguished from Unit V by its high relative frequency of the trilete spore *Granulatisporites trisinus* Balme & Hennelly, 1956. It occurs in the upper part of the Noonkanbah Formation but probably does not extend to the top of that formation. Despite what may seem an insecure basis for its definition, Unit VI is extraordinarily persistent. It has not only been recognised in widely separated wells in the Canning Basin but is identifiable in the Byro Group in the Carnarvon Basin and the upper part of the Carynginia Formation in the Perth Basin. Its maximum known thickness in the Canning Basin is about 120 m in Meda No. 1 Well.

Stratigraphic relationships between Unit VI and the base of the Liveringa Group are not clear. Sub-surface evidence suggests that Unit VI is all older than the marine Lightjack Formation which contains ammonoids that Furnish (1973) believes indicate a Roadian age. Unit VI is therefore Leonardian to early Roadian.

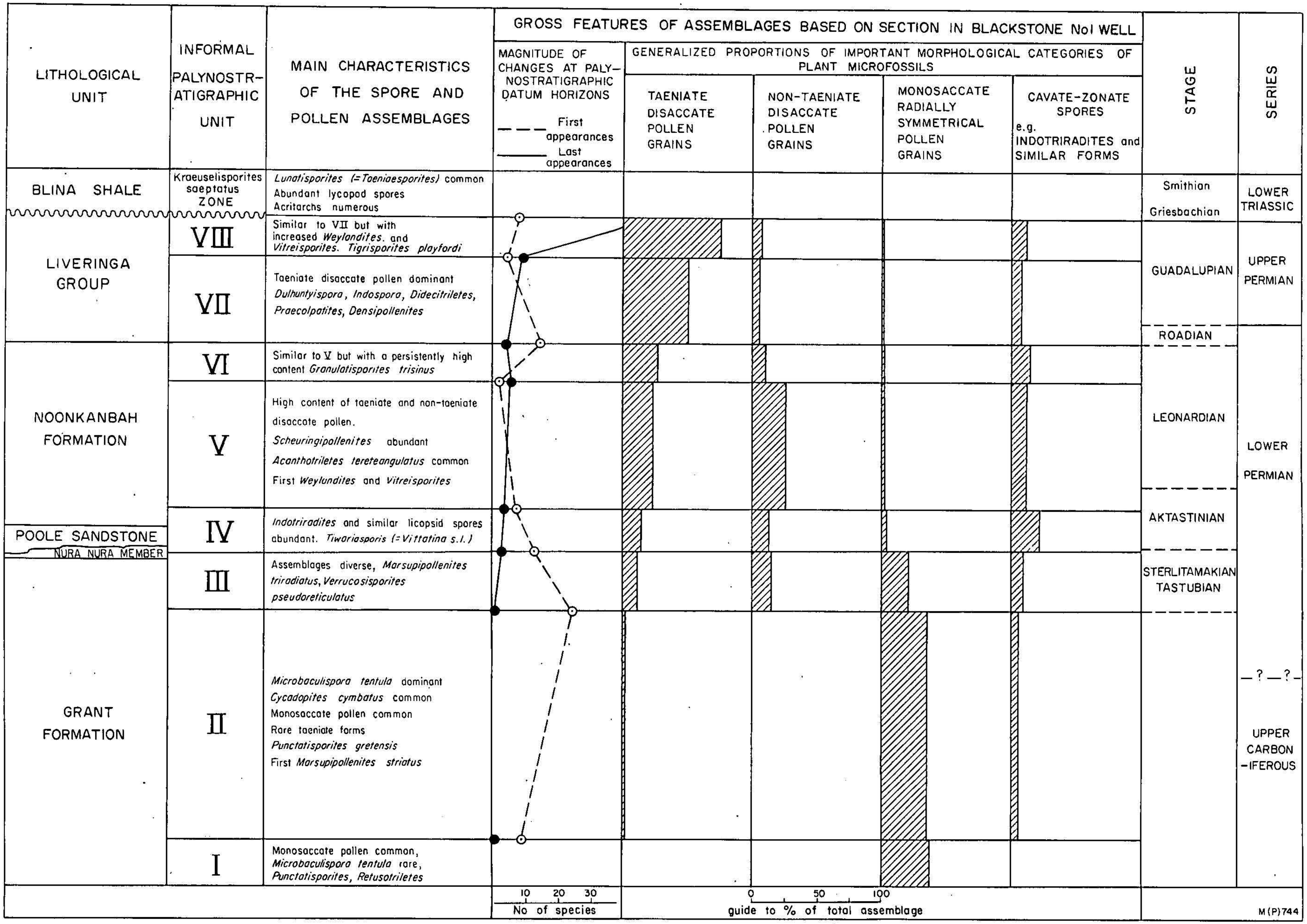


Figure 5. Characteristics of Late Carboniferous and Permian spore and pollen assemblages in the Canning Basin, Western Australia, based on the section in Blackstone No. 1 Well. Note: R. J. Helby recognizes the *Protohaploxypinus reticulatus* Zone in the upper part of the Liveringa Group in bores drilled in a synclinal area near Paradise Station.

Palynostratigraphic unit	Diversity	Composition
VIII	*High.*	Several forms that occur rarely or sporadically in lower units become constant and common components of assemblages at this interval. Some rare species, such as *Tigrisporites playfordi* de Jersey & Hamilton are confined to it in the Canning Basin. Species that increase in abundance include *Weylandites lucifer* (Bharadwaj & Salujha), *Vitreisporites pallidus* (Reissinger), non-taeniate pollens such as *Falcisporites* and trilete types resembling *Lophotriletes novicus* Singh. *Kraeuselisporites rallus* Balme; an undescribed form of *Polypodiidites* and a small form with rigid sacci, resembling *Protohaploxypinus rugatus* Segroves are other typical components.
VII	*High. 51 species in Blackstone No. 1.*	Taeniate, disaccate pollen grains, including haploxylonoid and diploxylonoid forms, dominant. Other distinctive spore and pollen species include *Indospora clara* Bharadwaj, *Dulhuntyispora dulhuntyi* Potonié, *D. parvithola* (Balme & Hennelly), *Didecitriletes ericianus* (Balme & Henn.), *Microbaculispora villosa* (Balme & Henn.), *Microreticulatisporites bitriangularis* Balme & Henn., *Praecolpatites sinuosus* (Balme & Henn.), *Densipollenites* spp., and *Bascanisporites undosus* Balme & Henn. Some of these occur in older strata but their constant occurrence in association allows the identification of Unit VII.
VI	*Similar to V*	Similar to Unit V except for a sharp increase in the relative abundance of *Granulatisporites trisinus* Balme & Henn.; its highest recorded frequency was 16% and its lowest 5%. *Microbaculispora tentula* Tiwari, *Scheuringipollenites maximus* (Hart), *Acanthotriletes tereteangulatus* Balme & Henn., *Verrucosisporites pseudoreticulatus* Balme & Henn., and *V. naumovae* Hart are less common than in Unit V.
V	*Moderate*	Disaccate pollen abundant, especially haploxylonoid, taeniate forms and *Scheuringipollenites maximus* (Hart) and *S. ovatus* (Balme & Henn.). *Marsupipollenites triradiatus* common. *Microbaculispora tentula* Tiwari abundant but less than in older units. *Acanthotriletes tereteangulatus* Balme & Henn., *Laevigatosporites colliensis* Balme & Henn., *Leiotriletes directus* Balme & Henn., *Granulatisporites trisinus* Balme & Henn., *Granulatisporites micronodosus* Balme & Henn., *Verrucosisporites pseudoreticulatus* Balme & Henn., and *colliensis* Balme & Henn., *Leiotriletes directus* Balme & Henn., *Granulatisporites trisinus* Balme & Henn., *Weylandites lucifer* (Bharadwaj & Salujha), *Indospora clara* Bharadwaj, *Praecolpatites sinuosus* (Balme & Henn.) and cf. *Punctatisporites priscus* Bharadwaj.
IV	*Moderate*	Sharp increase in relative proportions of species of *Indotriradites* and other spores of lycopsid aspect. *Microbaculispora tentula* Tiwari abundant. *Granulatisporites trisinus* Balme & Henn., *Laevigatosporites colliensis* Balme & Henn., *Platysaccus leschiki* Hart, *Acanthotriletes tereteangulatus* Balme & Henn., *Tiwariasporis* cf. *simplex* (Tiwari), *Verrucosisporites pseudoreticulatus* Balme & Henn. and *V. naumovae* Hart present in most assemblages. *Scheuringipollenites maximus* (Hart) and taeniate, disaccate pollen about equally common. Monosaccate pollen grains less frequent than in units I to III; other species characteristic of those units, e.g. *Punctatisporites gretensis* Balme & Henn., *Apiculatisporis cornutus* (Balme & Henn.), *Brevitriletes levis* (Balme & Henn.) and *Cycadopites cymbatus* (Balme & Henn.) rare or absent.
III	*More diverse than Unit II. 40 species in Blackstone No. 1.*	Taeniate, disaccate pollen consistently present in small numbers. Trilete spores represented by *Verrucosisporites pseudoreticulatus* Balme & Henn. *V. naumovae* Hart common in most assemblages. *Microbaculispora tentula* Tiwari dominates most assemblages. Prominent species persist from Unit II. Also present are representatives of genera such as *Diatomozonotriletes*, *Gondisporites*, *Indotriradites*, and *Scheuringipollenites*. *Marsupipollenites triradiatus* Balme & Henn. and *Granulatisporites* cf. *trisinus* Balme & Henn. occasionally present.
II	*More diverse than Unit I. 15 species in Blackstone No. 1.*	*Microbaculispora tentula* Tiwari usually most abundant species; *Cycadopites cymbatus* (Balme & Henn.) occasionally dominant; rare taeniate, disaccate pollen; radial monosaccate pollen dominant. Persistent components include *Punctatisporites gretensis* Balme & Henn., *Densosporites* cf. *rotundidentatus* Segroves, *Apiculatisporis cornutus* (Balme & Henn.), *Brevitriletes levis* (Balme & Henn.), *Neoraistrickia* spp., and *Dentatispora* spp. First occurrence of *Marsupipollenites striatus* (Balme & Henn.) and *Granulatisporites micronodosus* Balme & Henn.
I	*Low*	High frequency of radially symmetrical monosaccate pollen, occasional *Potonieisporites*, and disaccate, non-taeniate pollen. Taeniate disaccate pollen absent. Spores mainly simple trilete forms; *Punctatisporites*, *Leiotriletes*, *Retusotriletes*. Zonate forms resembling *Dentatisporites* sometimes common.

Table 1. Main characteristics of palynostratigraphic units defined in the Canning Basin of Western Australia.

Unit VII. In Blackstone No. 1, Unit VII assemblages have been identified in sidewall cores between 1350 and 1582 feet. In general, the base of Unit VII may coincide with that of the Liveringa Group, although the precise relationship of the palynostratigraphic and lithostratigraphic units is uncertain. The sharp palynological break between Units VII and VIII may reflect a sedimentary hiatus between the Noonkanbah Formation and the Lightjack Formation of the Liveringa Group, or within the Noonkanbah Formation itself.

Assemblages resembling that of Unit VII are identifiable in most of the large late Palaeozoic basins of Australia. They correspond with the *Dulhuntyispora* Assemblage of Balme (1964) and characterise Stage 5 of Evans (1969). Comparable plant microfossil assemblages occur in the Middle Beaufort Group of South Africa (J. Anderson, unpubl. data) and in the Radok Conglomerate and Bainmedart Coal Measures in eastern Antarctica (Balme & Playford, 1967; Kemp, 1973). Most of the forms that typify Unit VII, with the significant exception of *Dulhuntyispora*, have also been recorded from the Raniganj Coal Measures of India (cf. Bharadwaj, 1975).

Unit VIII. In Blackstone No. 1 and Meda No. 1 Wells, sunk on the Lennard Shelf about 40 km apart, assemblages from the uppermost part of the Liveringa Group differ in some ways from those that characterise Unit VII (see Table 1). In addition to the spore and pollen species, small spinose acritarchs also occur constantly in assemblages from all the samples so far examined from Unit VIII. The distribution of the unit is not clear in any comprehensive sense, as it has been recognised at only two sites. At both of these localities Unit VIII represents the uppermost 40 m or so of the Liveringa Group. The relative abundance of acritarchs in the unit suggests that it may represent strata that are lateral equivalents of the marine Hardman Formation.

No obviously comparable assemblages to those from Unit VIII have been recognised in other Western Australian basins. The most similar plant microfossil associations occur in the upper part of the Sue Coal Measures in the southern part of the Perth Basin (Balme, unpublished data). However these southern assemblages include distinctive species such as *Guttulapollenites hannonicus* Goubin, 1965, *Iraqispora labrata* Singh, 1964, *Playfordispora cancellosa* (Playford & Dettman) Maheshwari & Banerji, 1975, *Ephedripites* sp., and *Nevesisporites fossulatus* Balme, 1970, which clearly link them with Chhidruan assemblages of the Salt Range. They also resemble (apart from the presence of *Guttulapollenites hannonicus*) assemblages from the Late Permian *Protohaploxypinus reticulatus* Zone in the Sydney Basin, New South Wales (Helby, 1973).

If Thomas & Dickins (1954), and Dickins (1963), correctly correlate the Hardman Formation with the Upper 'Middle' to 'Upper Productus Limestone' of the Salt Range then it is equivalent to the Kalabargh Member of the Wargal Limestone or to the Chhidru Formation. Ammonoid and brachiopod workers disagree on the age of these Salt Range faunas. Furnish (1973) believes that they are equivalent to the mid-Dzulfian, whereas Grant (1970) and Waterhouse (1972) assign them to the Guadalupian.

Palynological evidence from Unit VIII is equivocal, but a reasonable assumption is that the assemblages are older than those from the upper part of the Chhidru Formation. This is based on the fact that most of the distinctive species described from the upper Chhidru Formation (Balme, 1970) have not been recorded from Unit VIII, although they are present in the uppermost Permian of the Sydney Basin and the southern Perth Basin.

Until the invertebrate palaeontologists resolve their differences Unit VIII cannot be precisely dated. For the present it is regarded as late Guadalupian.

Carnarvon, Perth, Collie-Wilga Basins

Although data are fewer and the stratigraphic spread of samples less satisfactory, a similar pattern is recognisable in the uppermost Palaeozoic succession in the Carnarvon, Perth, and Collie-Wilga Basins. Figure 6 represents a summary of the information available and indicates the general relationships between the Canning Basin palynostratigraphic units and the successions in these basins.

Officer Basin

Late Palaeozoic sedimentary rocks form a flat-lying cover over thick Proterozoic sequences in the Officer Basin. The Palaeozoic sequence, which is about 300 m thick, is essentially continuous with sequences in the southeastern part of the Canning Basin; it consists of fluvioglacial and lacustrine deposits that are referred to the Paterson Formation. Kemp (1976), in a recent summary of palynological information from stratigraphic and oil exploration drillsites, assigned microfloral assemblages from the Paterson Formation to Stage 2 of Evans's terminology, and suggested further that an equivalent of the late Stage 2 subdivision of Norvick (1974) was represented. The presence of *Microbaculispora tentula* Tiwari, 1965, in significant amounts, and the presence in the uppermost Paterson Formation samples of *Marsupipollenites triradiatus* Balme & Hennelly, 1955, suggests that the correlation is with late Stage 2, and with the upper part of Balme's Unit II. *Verrucosisporites pseudoreticulatus* Balme & Hennelly, 1956 was not observed.

Eastern Australia

The biostratigraphic scheme which was synthesised by Evans (1967, 1969) has been widely applied in sedimentary basins in eastern Australia; it has also been used in the Canning Basin in Western Australia (see Price, 1975). The scheme incorporated five broad palynological 'stages', spanning the interval from the late Palaeozoic glacial sequences upwards to the top of the youngest Permian coal measures. The biostratigraphic units were defined on quantitative aspects of the palynofloras, viz., on the abundance of selected morphological groups, and on the first appearances of particular species.

Present biostratigraphic practice retains much of the broad concept of the stages as they were defined by Evans; they have, however, been modified and subdivided by a number of subsequent authors (Paten, 1969; Norvick, 1971, 1974; Price, 1973, 1973a, 1976). Additional biostratigraphic units have been recognised at the top of the sequence, above the coal measures (Helby, 1973; Price, herein). Much of the later redefinition and subdivision of the original stages has been based on first appearances of selected species. Formalisation of the redefined stages and substages into taxon-range-zones, each bearing the name of a diagnostic form-species, awaits description of many of the nominate forms. For the present, a numbered system of stages is retained. The content of the biostratigraphic units, as they are understood at present, is detailed below. The stages, with their most recent subdivisions, and the palynological criteria on which they are based, are illustrated in the left-hand column of Figure 7.

Stage 1. This unit, which remains undivided, is distinguished by low species diversity. Monosaccate, radially symmetrical pollen are dominant, and represented by species of *Potonieisporites* and *Parasaccites*. Taeniate, disaccate pollen are absent. The trilete spore component was outlined by Evans (1967, 1969) and includes species of *Punctatisporites*, *Retusotriletes* and *Verrucosisporites*. Zonate, cavate forms may be locally abundant. Much descriptive work remains to be done on the constituent species of this unit. There seems little doubt that it corresponds to the *Potonieisporites* Assemblage of Helby (1969b) and outlined herein, and with Unit I of the Canning Basin sequence.

Stage 2. The base of Stage 2 is defined by the introduction of taeniate, disaccate pollen; most of the earliest forms of these are referable to the genus *Protohaploxypinus*. They occur in low frequencies throughout the unit, and monosaccate forms remain dominant. Trilete spores include *Microbaculispora tentula*, *Apiculatisporis cornutus* (Balme & Hennelly) Høeg & Bose, 1960, *Punctatisporites gretensis* Balme & Hennelly, 1956, and *Verrucosisporites* spp. Norvick (1971), working in the Galilee Basin of central Queensland, introduced a twofold subdivision of Stage 2. 'Lower Stage 2' he identified by the persistence of some trilete spores from Stage 1, including species of *Vallatisporites* and *Verrucosisporites*. The base of 'Upper Stage 2' is marked by the disappearance of these species and by the first appearance of *Microbaculispora tentula* and a monocolpate pollen similar to *Cycadopites cymbatus* (Balme & Hennelly) Hart, 1965. Additionally, *Granulatisporites micronodosus* Balme & Hennelly, 1956, *Acanthotriletes tereteangulatus* Balme & Hennelly, 1956, and *Marsupipollenites striatus* (Balme & Hennelly) Foster, 1975 appear late in Stage 2.

The oldest known elements of the *Glossopteris* flora in Australia occur in association with palynofloras referable to Stage 2. Leaf fragments with a glossopterid venation occur in the Boonderoo Beds of the northern Galilee Basin (White, 1964); the same beds have yielded Upper Stage 2 palynofloras (Norvick, 1974).

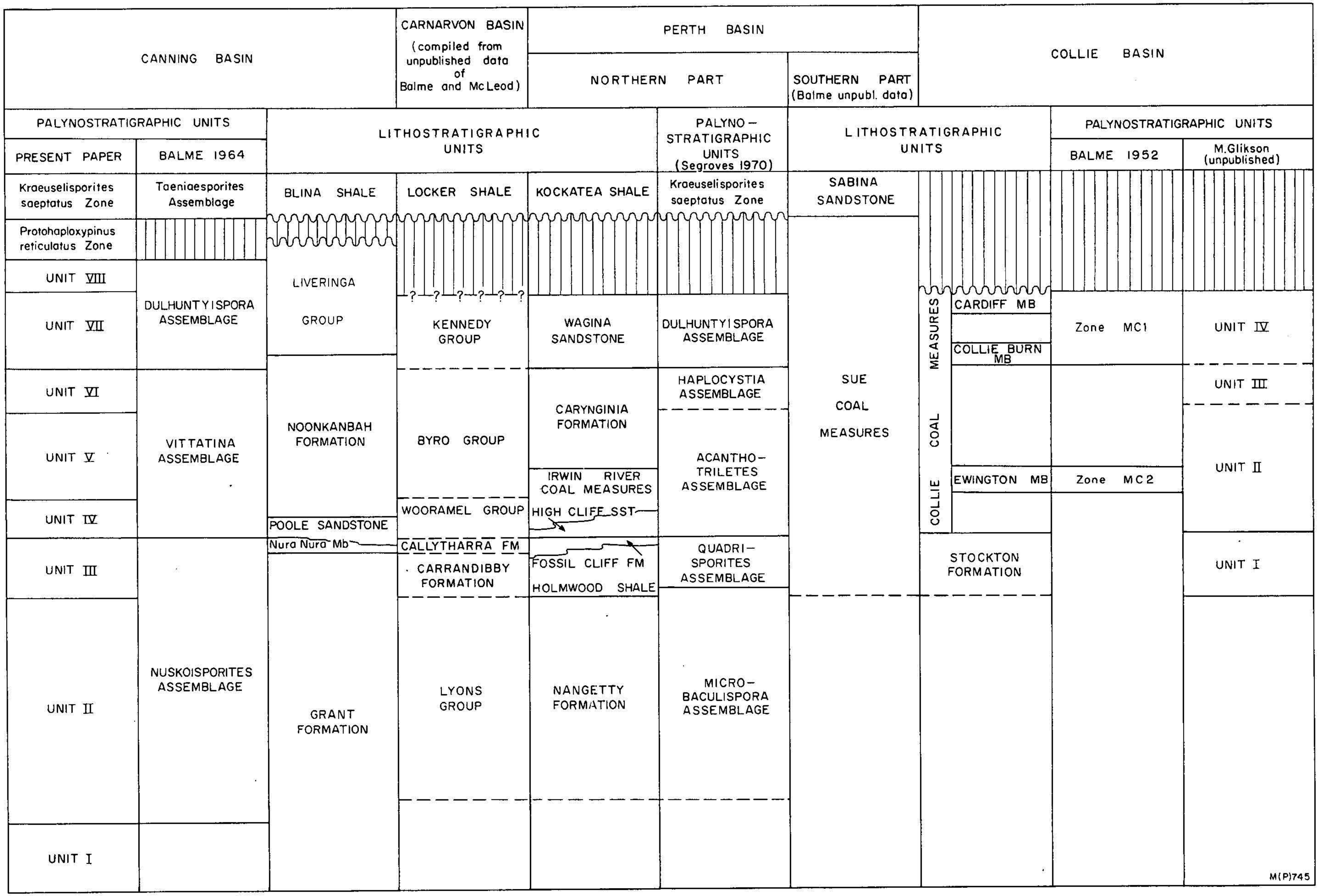


Figure 6. Distribution of Late Carboniferous and Permian palynological units in Western Australian sedimentary basins.

Stage 3. In this unit, the proportion of taeniate, disaccate pollen is generally higher than in Stage 2, and monosaccate forms show a corresponding decline in importance. The stage base is defined by the first appearance of *Verrucosisporites pseudoreticulatus*, in accordance with Paten's (1969) interpretation of the biostratigraphic units of Evans (1967, 1969).

The stage top is defined by the first appearance of *Polypodiidites cicatricosus* (Balme & Hennelly) Rigby & Hekel, 1977. Apiculate, trilete spores are common throughout the unit, and include *Horriditriletes ramosus* (Balme & Hennelly) Bharadwaj & Salujha, 1964, *Microbaculispora tentula*, *Granulatisporites micronodosus*, and a form close to *Diatomozonotriletes*. Non-taeniate, disaccate pollen with a proximal scar, such as *Limitisporites* and *Jugasporites*, are locally abundant. Price (1976) has recognised two substages within this unit. The oldest, designated Stage 3a, lacks *Granulatisporites trisinus* and is characterised by the persistence of some forms (such as '*Rugulatisporites* sp. 22' of Evans, 1964b) from older stages, and by a higher proportion of monosaccate pollen. The younger substage, 3b, is identified by the presence of *Granulatisporites trisinus*.

Stage 4. Stage 4 assemblages are similar in general character to those of Stage 3b, with most forms persisting from the older unit. The first appearance of *Polypodiidites cicatricosus* defines the unit base. There is an increase in quantity of taeniate, disaccate pollen and a continuing decline of monosaccate types. Species of *Marsupipollenites* are conspicuous, as are apiculate forms such as *Brevitriletes levis* (Balme & Hennelly) Bharadwaj & Srivastava, 1969, *Horriditriletes ramosus*, and *Acanthotriletes filiformis* (Balme & Hennelly) Tiwari, 1955. Towards the top of the stage *Granulatisporites trisinus* becomes abundant. Paten (1969), using Cooper Basin sections, introduced a twofold subdivision. The upper unit he identified by the introduction of *Praecolpatites sinuosus* (Balme & Hennelly) Bharadwaj & Srivastava, 1969. Within this upper division, *Bascanisporites undosus* Balme & Hennelly, 1956 and *Indospora clara* Bharadwaj, 1962 appear as rare elements. The upper part of Stage 4 was further subdivided by Price (1973, 1973a, 1976) into 'upper Stages 4a and 4b', the base of Stage 4b being marked by the appearance of *Microbaculispora villosa* (Balme & Hennelly) Bharadwaj, 1962. Within the youngest of these Stage 4 units there appear for the first time several new and distinctive trilete forms showing interradial sculptural modification. These may be the morphological precursors of a lineage which culminates in the *Dulhuntyispora* complex characteristic of Stage 5.

Stage 5. The base of this, the youngest of Evans's stages, is marked by the introduction of species of the morphologically distinctive genus *Dulhuntyispora*. The top has been defined by Price (1973, 1973a) as being immediately below the oldest occurrence of *Tigrisporites playfordi* de Jersey & Hamilton, 1967. A division into lower and upper units based on distribution of the two species of *Dulhuntyispora* then recognised was introduced by Paten (1969); the lower unit was characterised by the appearance of *Dulhuntyispora dulhuntyi* Potonié, 1956 *sensu lato*, and the upper by *Dulhuntyispora parvithola* (Balme & Hennelly) Potonie, 1960. Finer subdivisions were effected by Price (1973, 1973a, 1976). Some of these are based on the successive appearance of morphological variants of *Dulhuntyispora*, which are currently being described (Price, unpubl. data). The base of the oldest unit, 'lower Stage 5a', is defined by the appearance of '*Dulhuntyispora dulhuntyi forma* 296' of Price (see Fig. 10, O, P, R, this paper); the appearance of *Didecitriletes ericianus* (Balme & Hennelly) Venkatachala & Kar, 1965 marks the base of the succeeding 'lower Stage 5b'; and 'lower Stage 5c' is delineated by the introduction of '*Dulhuntyispora dulhuntyi forma* 297' of Price (Fig. 10, Q, U-W, this paper).

In the upper part of Stage 5, distinguished by the presence of *Dulhuntyispora parvithola*, the abundance and diversity of cryptogamic spores declines from the base upwards, so that near the top of the stage, disaccate, gymnospermous pollen are dominant. Subdivision of upper Stage 5 is possible on the basis of the introduction of undescribed species such as '*Dulhuntyispora dulhuntyi forma* 312' of Price (Fig. 10, T). Some of the distinctive species of earlier units, such as *Verrucosisporites pseudoreticulatus* and *Polypodiidites cicatricosus*, become extinct at a level low in upper Stage 5.

Weylandites Zone. The introduction of *Tigrisporites playfordi* presages the transition from upper Stage 5 assemblages to the Triassic *Falcisporites* microfloras of Helby (1973). The early part of the transition, defined by the appearance of *Tigrisporites playfordi*, and recognised in the Cooper Basin at the top of the Toolachee Formation, corresponds to the *Weylandites* Zone proposed here. In earlier Cooper Basin reports (Price, 1973a), this unit was referred to as the '*Paravittatina* Assemblage'. In addition to *Tigrisporites playfordi*, the interval is characterised by an increase in the proportion of *Weylandites lucifer* (Bharadwaj & Srivastava) Foster, 1975, *Indospora clara*, *Vitreisporites pallidus* (Reissinger) Nilsson, 1958, *Lophotriletes* sp., *Polypodiisporites mutabilis* Balme, 1970, and *Lundbladispora* sp. The appearance of *Densoisporites playfordi* (Balme) Playford, 1965, and *Nevesisporites fossulatus* Balme, 1970, defines the upper limit of the *Weylandites* Zone; this is considered, on the somewhat limited data presently available, to correspond to the base of the *Protohaploxypinus reticulatus* Assemblage. The base of this last assemblage was established initially at a disconformity, and consequently, there are problems in precisely defining its base outside the Sydney Basin, where it was first recognised.

The known distribution of the *Weylandites* Zone is limited, but it corresponds at least in part with Unit VIII of the Canning Basin, and is also known from the Bonaparte Gulf Basin, Bowen and Cooper Basins (Helby, de Jersey, Foster, Price, unpubl. data). In wells drilled earlier in the Cooper Basin (e.g. in Merrimelia No. 3, Core 10), the *Weylandites* Zone was referred to Trla of Evans (1966d). However, Trla is now interpreted in the more restricted sense as representing the palynoflora referred to by Helby (1973) as the *Protohaploxypinus reticulatus* Assemblage.

Protohaploxypinus reticulatus Assemblage. Helby (1970, 1973) designated as the *Protohaploxypinus reticulatus* Assemblage, that plant microfossil suite which replaces Stage 5, or the *Dulhuntyispora* assemblage, at a sharp disconformity above the coal measure sequence of the Sydney Basin. Similar assemblages were described by Hennelly (1959). The *P. reticulatus* Assemblage also appears to be the equivalent of Trla of Evans (1966d). Two assemblages, or 'zonules', have been recognised within it (Helby, 1972a, 1973). Within the lower zonule, representative species of Stage 5 are still common, and *Nevesisporites fossulatus*, *Playfordispora cancellosa*, *Triquitrites proratus* Balme, 1970, and *Densoisporites playfordi* make their first appearance. The upper zonule is distinguished by a lower frequency of Stage 5 types and by a dominance of *Falcisporites*. The establishment of *Lunatisporites pellucides* (Goubin) Helby, 1973 defines the top of this assemblage.

A number of forms that characterise the *P. reticulatus* Assemblage, such as *Playfordispora cancellosa, Nevesisporites fossulatus, Tigrisporites playfordi*, and *Triquitrites proratus* have been reported from the Chhidru Formation of the Salt Range, in the central Tethyan region (Balme, 1970). The palynological evidence, according to Balme & Helby (1973), strongly suggests that the *P. reticulatus* Assemblage is Late Permian. It is younger than Unit VIII of the Canning Basin sequence, and younger than the *Weylandites* Zone; it may indeed, on the basis of the gross composition of the assemblage, be younger than any part of the Chhidru Formation, and correspond in time to an interval represented by the paraconformity between the Permian and Triassic in the Salt Range sequence. This missing interval was referred to the Changsinghian Stage by Furnish & Glenister (1970), although the insecurity of this stage, as pointed out by Waterhouse (1976, p. 37), among others, is acknowledged.

In the Sydney Basin, the *P. reticulatus* Assemblage is succeeded, without apparent break, by equivalents of the *Kraeuselisporites saeptatus* Assemblage Zone, that was described from Western Australian basins by Dolby & Balme (1976). This latter assemblage is considered to Griesbachian to lower Smithian in age. The contention of Waterhouse (1976) that the Griesbachian is of latest Permian age is noted, but discussion of the arguments surrounding this attribution is outside the scope of this review. For the present, the *P. reticulatus* Assemblage is regarded as the uppermost palynological unit of the Permian sequence.

Occurrence of the palynological stages

Bowen Basin. The stratigraphic succession and structural setting of the Bowen Basin have been reviewed by Power (1967), Dickins & Malone (1973), Prouza & Park (1973), Hawthorne (1975), and Paten & McDonagh (1976). The first palynological investigation in the basin was that of de Jersey (1946), who examined coal samples from scattered localities. Further work followed the initiation of oil exploration in the late nineteen fifties. In 1962, Evans (in Mines Administration Pty Ltd) introduced his original biostratigraphic scheme based on sequences from the Denison Trough, and utilising spores, pollen and acritarchs. This scheme was modified (Evans, 1967, 1969) to form the palynological stages; many of the more recent modifications introduced by Price (1973, 1973a, 1976) are founded on Bowen Basin sequences.

The relationship of the presently applied units to the earlier units instituted by Evans (1962, 1966 a, b, c) was illustrated by Price (1976, p. 46). The relationship of the units currently in use to the Denison Trough sequence of the Bowen Basin is shown herein in Figure 7. This sequence is the most complete section within the Bowen Basin to have been examined palynologically. Many areas outside the Denison Trough, particularly those close to the folded zones of the eastern margin, have failed to produce identifiable palynofloras.

The oldest recognisable palynoflora in the Bowen Basin comes from the 'pre-Reids Dome Beds' Volcanics in A.F.O. Comet No. 1. The assemblage, although sparse and highly carbonised, probably represents Stage 2. No other assemblages older than Stage 3 have been identified in the basin.

From the Reids Dome Beds, the oldest identifiable assemblages are referable to Stage 3a; they have been recovered in the Capella district, north of the Denison Trough. Stage 3b is also known from this area. To the south, in the main part of the Denison Trough, the Reids Dome Beds attain their maximum thickness, and Stage 3b and possible Stage 3a assemblages have been recovered. They occur in the upper part of the Reids Dome Beds; the lower part of the unit is unknown palynologically as organic material within it is highly carbonised. Stage 3b assemblages also occur in the Reids Dome Beds of the Comet Ridge, east of the Denison Trough.

The upper part of the Reids Dome Beds in the Denison Trough and the Comet Ridge areas includes a significant number of coal seams, and has yielded the oldest lower Stage 4 assemblages in the basin. In the Denison Trough, the non-marine lower Stage 4 assemblages are succeeded by an association which includes spinose acritarchs (mainly *Michrystridium* spp.); this younger, marine part of lower Stage 4 represents 'P2' of Evans (1962, 1964c, 1966b), and corresponds to the lower part of the Cattle Creek Formation. The equivalent, marine-influenced assemblages extend on to the Comet Ridge and possibly to the Capella district.

In the Denison Trough, upper Stage 4a palynofloras have been recovered from the upper Cattle Creek Formation and the basal Aldebaran Sandstone. Assemblages from upper Stage 4b through to lower Stage 5c are confined to the latter unit. Spinose acritarchs are common in the Cattle Creek assemblages, and occur sporadically through the Aldebaran Sandstone, particularly in the southern part of the trough. Assemblages referable to the subunits of upper Stage 4 and lower Stage 5 are widely distributed over the Denison Trough, the Comet Ridge, and the southern end of the Collinsville Shelf. They have not been recovered from the northern Collinsville Shelf, the Nebo Synclinorium, the Eastern Fold Zone or the Taroom Trough. From the Blair Athol Coalfield, a small Permian basin to the west of the Bowen Basin, Foster (1975) has recently given a detailed account of assemblages from the coal measures, which he has equated with upper Stage 4a.

The remainder of the Denison Trough sequence, except for some isolated areas in the axial parts of the trough, falls within upper Stage 5. The lithological units assignable to this substage are shown in Figure 7. The upper Stage 5 assemblages from the Aldebaran Sandstone, Freitag Formation and Ingelara Formation are characterised by a similar diversity of cryptogam elements to that of lower Stage 5. Above this, disaccate pollen dominate the assemblages. The transition between the cryptogam-rich assemblages and the disaccate pollen assemblages is not abrupt, and may be time-transgressive.

Outside the Denison Trough and the Comet Ridge, the older part of upper Stage 5 has not been widely recognised. Isolated samples from the southern Collinsville Shelf have produced cryptogam-rich upper Stage 5 palynofloras. The younger, disaccate-rich upper Stage 5 assemblages are widely distributed throughout the basin, and are mainly associated with coal measure development; they are known from the northern Collinsville Shelf, the Nebo Synclinorium, the Denison Trough, Comet Ridge, and Taroom Trough. In the Denison Trough and equivalent sections on the Comet Ridge and Springsure Shelf, spinose acritarchs occur in upper Stage 5 assemblages below the Bandanna Formation. On the western margin of the basin, a swarm of acritarchs dominated by a single species of *Michrystridium* forms a persistent marker towards the base of the Black Alley Shale, or within the Mantuan Productus Bed at some localities on the Springsure Shelf.

In isolated parts of the basin, sedimentation appears to have persisted into the youngest parts of the Permian. From the Theodore area of the Taroom Trough, and from the Denison Trough, Foster (unpubl. data) and de Jersey (unpubl. data) have found palynofloras apparently referable to the *Weylandites* and *Protohaploxypinus reticulatus* Assemblages. The *P. reticulatus* Assemblage occurs in

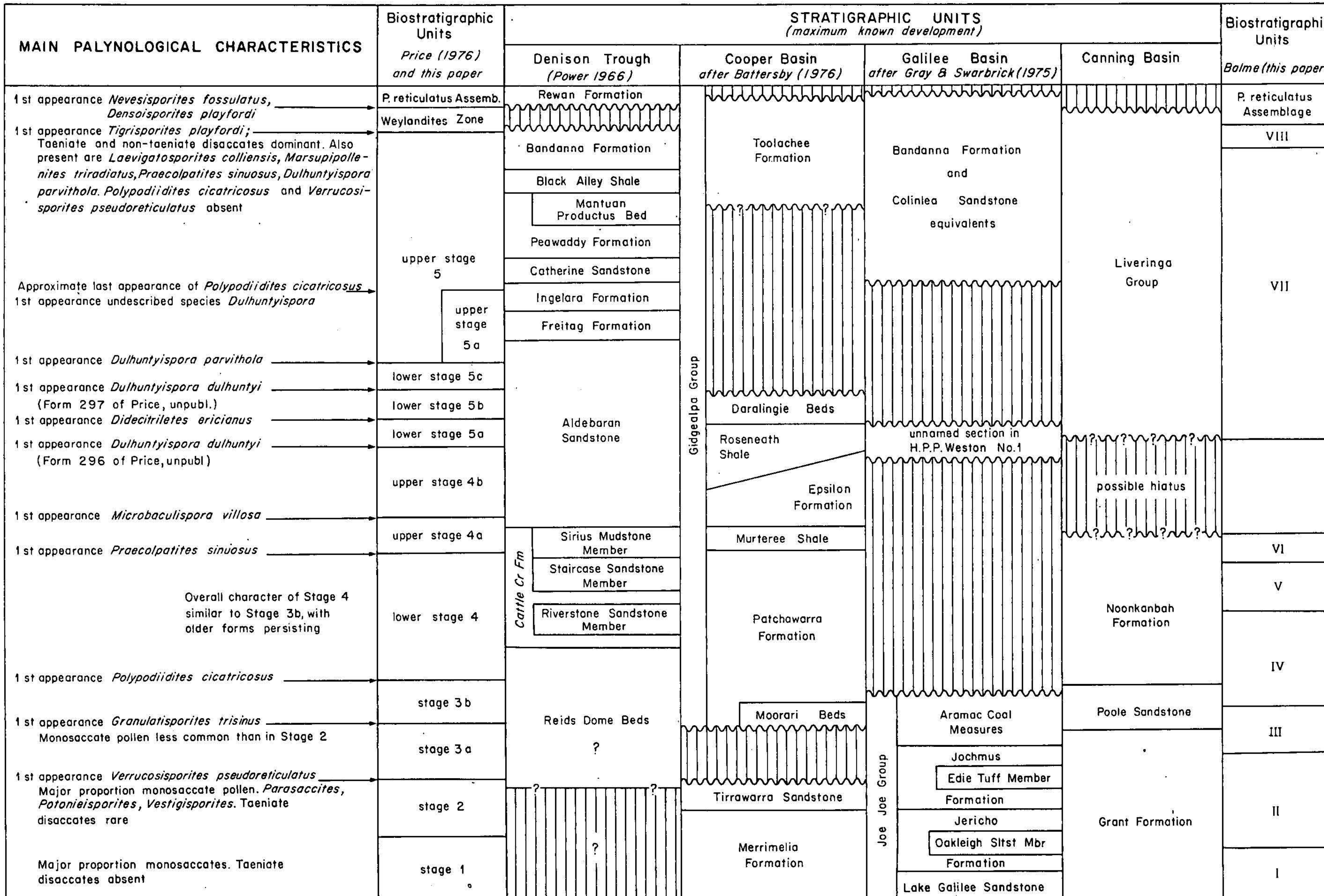


Figure 7. Characteristics of eastern Australian palynological stages (left hand column) and their distribution in lithostratigraphic units of the Bowen, Cooper, and Galilee Basins. A tentative correlation with the units identified by Balme (this paper) in the Canning Basin of Western Australia is shown in the right hand columns.

other parts of the Taroom Trough, in the Blackwater area of the Comet Ridge, and probably in the Nebo Synclinorium; these assemblages are generally regarded as representing the basal part of the Rewan Formation.

Cooper Basin. The Permian succession in the Cooper Basin provides both source and reservoir rocks for most of the hydrocarbons known to occur in the basin; commercial quantities of gas were first discovered in 1963 in Gidgealpa No. 2 Well. The stratigraphy and structural setting of the basin were first described by Kapel (1966); subsequent descriptive papers include those of Martin (1967), Kapel (1972), Gatehouse (1972) and Battersby (1976).

Balme, who in 1959 examined cuttings from Innamincka No. 1, was the first to recover palynomorphs from the Cooper Basin. Since then, palynological studies have been attempted on almost all the exploration wells drilled (in excess of 100). The early palynological work was summarised by Paten (1969), who introduced a modification of the units proposed by Evans (1967, 1969). Paten's zonation was modified again by Price (see Gatehouse, 1972, fig. 3; Price, 1973), who applied the zonation outlined herein, and shown in Figure 7.

Assemblages referable to Stage 2 have been recovered from the Merrimelia Formation, the basal lithological unit in the Cooper Basin. This formation generally gives low yields of acid-insoluble material. Impoverished microfloras have been recovered from it which lack taeniate disaccate pollen, but which are otherwise similar to those of Stage 2; no unequivocal Stage 1 assemblages have been found. However, the lower levels of the Merrimelia Formation have either failed to yield palynomorphs, or not been examined. Stage 2 palynofloras have also been recovered from the basal and middle units of the Tirrawarra Sandstone, although relatively few samples have been examined from this part of the sequence.

Assemblages from the upper part of the Tirrawarra Sandstone, which is probably equivalent to the Moorari Beds of Kapel (1972), and from the lower half of the Patchawarra Sandstone, can be referred to Stage 3. *Granulatisporites trisinus* is present throughout the section assigned to Stage 3 (with the possible exception of the extreme basal part of the Moorari Beds), indicating that Stage 3b is represented. The virtual absence of Stage 3a in the basin suggests that a depositional break is represented within the Tirrawarra Sandstone between its middle and upper units, or between the Tirrawarra Sandstone and the Moorari Beds, depending upon interpretation.

All three subunits of Stage 4 are represented in the Cooper Basin sequence. Lower Stage 4 is confined to the Patchawarra Formation; it has been identified in the upper half of that formation except for the top one hundred metres or so. Upper Stage 4a of Price (1973, 1973a) includes the uppermost Patchawarra Formation, the Murteree Shale, and the basal part of the Epsilon Formation. Assemblages referable to upper Stage 4b have been recovered from the upper Epsilon Formation, and, in some parts of the basin, from the basal Roseneath Shale. The boundary between the Epsilon Formation and the Roseneath Shale appears to be slightly diachronous in relation to the upper Stage 4b/lower Stage 5a boundary.

Where the Cooper Basin Permian sequence is complete, three of the four subunits recognised in Stage 5 have been identified. The oldest of these, lower Stage 5a, has been recovered from the upper part of the Epsilon Formation and from the Roseneath Shale. Lower Stage 5b is confined to the Daralingie Beds and to the extreme top of the Roseneath Shale. Lower Stage 5c has not been recognised in the Cooper Basin. The basal assemblages from the Toolachee Formation differ markedly from the lower Stage 5b assemblages from the Daralingie Beds. These Toolachee Formation palynofloras are dominated by taeniate, disaccate pollen and include few cryptogamic elements—this suggests that they represent a high level within Stage 5. Assemblages compare closely, both in the taxa present and in their relative abundance, with those from the Bandanna Formation of the Denison Trough; they contrast with assemblages from the uppermost Aldebaran Sandstone, Freitag Formation and Ingelara Formation. It thus seems likely that a significant hiatus is represented between the Daralingie Beds and the Toolachee Formation. In several parts of the basin the depositional break is erosional, as much of the Gidgealpa Group is truncated, with the Toolachee Formation resting on progressively older units (Battersby, 1976).

Towards the top of the Toolachee Formation, at or above the youngest Permian coal development, upper Stage 5 assemblages are sometimes succeeded by palynofloras of the *Weylandites* Zone. This unit occurs in isolated parts of the basin, and is confined to a thickness of 10 to 20 m. In a few of these areas, a younger assemblage, representing the *Protohaploxypinus reticulatus* Assemblage, has been observed. The transition between these assemblages is not abrupt. In earlier studies, both the *Weylandites* Zone and the *P. reticulatus* Assemblage have been referred to Trla of Evans (1966d), and, as they were above the top Permian coal, were considered to be from the Nappamerri Formation. However, Gatehouse (1972), in redefining the Toolachee Formation, assigned this youngest Permian section to the Toolachee Formation rather than to the Nappamerri Formation.

Galilee Basin. The downwarp of the Galilee Basin was filled by sediments of almost entirely non-marine origin during the Late Carboniferous to Triassic interval. General accounts of basin evolution include those of Vine (1976), and Allen (1974). In both, stratigraphic nomenclature of the late Palaeozoic sequence remains informal—only recently has a start been made on formal definition of rock units (Gray & Swarbrick, 1975).

Palynological investigations in the Galilee Basin were pioneered by Evans (1964c, 1966a). Earlier investigations were summarised in detail by Norvick (1974), who compiled data from some 42 petroleum exploration wells and two outcrop sections. Norvick's account, which was presented as a Bureau of Mineral Resources Record with a restricted distribution, summarised unpublished data gathered by a number of workers including N. J. de Jersey, P. R. Evans, G. Playford, and D. Burger.

Stage 1 assemblages occur in a restricted geographic area in the central, deep part of the basin; the assemblages have been recovered from thick, coarse, clastic sequences which are correlatives of part of the Joe Joe Group which crops out on the Springsure Shelf, to the southeast of the Galilee Basin. Stage 2 assemblages occur across a slightly wider area within the basin, in dominantly coarse clastics which bear only a minor glacial imprint. Using Thunderbolt No. 1 Well as a basis, Norvick (1971, 1974) subdivided Stage 2 as originally conceived by Evans (1969). The Boonderoo Beds at Galah Gorge in the northern part of the basin, which have yielded fragmentary remains of *Glossopteris* (White, 1964), Norvick referred to the upper part of Stage 2.

Stage 3 assemblages are distributed within a very restricted area in the west of the basin, in coal measure sequences overlying the coarse clastic interval. Palynological studies have permitted the identification of a basin-wide hiatus, involving the loss of all of Stage 4 and early Stage 5 sediments, before the deposition of further coal measure sequences across the entire area of the basin. Limited deposition, however, occurred in some areas, as Price (unpubl. data) has identified what he considers to be lower Stage 5 assemblages in an unnamed unit in Weston No. 1 Well, in the Lovelle Depression (see Fig. 7).

Recent drilling in the deep, central part of the Galilee Basin by the Geological Survey of Queensland has allowed the formal naming and definition of lithological units, and clarified the relationship of these to palynological units. At the base of the sequence, the probable correlatives of the Joe Joe Formation have been elevated to group status; from the base, named formations in the group include the Lake Galilee Sandstone, the Jericho and Jochmus Formations, and the Aramac Coal Measures (Gray & Swarbrick, 1975).

According to data recently presented by McKellar (in Swarbrick & Wallin, 1976) from GSQ drillholes Aramac No. 1 and Hexham No. 1, the Aramac Coal Measures contain a Stage 3 assemblage, identified by the presence of *Verrucosisporites pseudoreticulatus*. Early Stage 3 assemblages persist downward into the upper part of the Jochmus Formation; that part of the underlying Jericho Formation which was sampled in these drill sites yielded assemblages referable to Stage 2. A somewhat older part of the Joe Joe Group was penetrated in Lake Galilee No. 1; the oldest interval in this well is probably equivalent to the older part of the Jericho Formation, according to correlations shown by Swarbrick & Wallin (1976). Data presented by Norvick (1974) suggest that the Stage 1/Stage 2 transition occurs within this lower part of the Jericho Formation, perhaps within the Oakleigh Siltstone Member.

Above the unconformity at the top of the Aramac Coal Measures, lithological nomenclature remains informal. McKellar recorded Upper Stage 5 assemblages in the Aramac and Hexham boreholes from sequences of sandstone, siltstone, shale, and coal which are referred to as 'Colinlea' and 'Bandanna' Formation correlatives, the reference being to units which crop out in the region of the Springsure Shelf. The youngest Permian core from Aramac No. 1 yielded an assemblage identifiable with the *Protohaploxypinus reticulatus* Assemblage; reference to this assemblage, rather than to the older *Weylandites* Zone, is confirmed by the presence of *Nevesisporites fossulatus*.

Sydney Basin. The palynology of Permian and Late Carboniferous sequences in the Sydney Basin was described by Evans (1967a), and reviewed again briefly by that author (Evans, 1969) in terms of his palynological stage nomenclature. In the first review attention was drawn to the carbonisation of palynomorphs over much of the basin—especially to the south of the Hunter Valley—and to the constraints that this imposes on palynological biostratigraphy. The present brief discussion of palynological studies in the basin focusses on data which have become available since 1969. A decline in petroleum exploration since about 1970, caused by disappointing results from earlier exploration programmes, has meant that new data are sparse and geographically restricted. Most are available from the latest Permian, or from the older, Late Carboniferous to Early Permian part of the known sequence.

The palynology of the section above the upper coal measures has been described in detail by Helby (1970, 1973). The *Protohaploxypinus reticulatus* Assemblage occurs in the basal lithologic units of the Narrabeen Group, viz. the lower shaly portion of the Munmorah Conglomerate, the Coalcliff Sandstone and Wombarra Shale in the central basin area, and in much of the Caley Formation in the west (Helby, 1973; Balme & Helby, 1973; Mayne *et al.*, 1974). Studies undertaken by Grebe (1970) in the Lake Munmorah area showed the change from a *Dulhuntyispora* assemblage to the *Protohaploxypinus reticulatus* Assemblage to occur within the Munmorah Conglomerate; the underlying Vales Point Coal Member contains a *Dulhuntyispora* assemblage akin to that of the Wallarah Seam of the underlying Newcastle Coal Measures.

For the early part of the Permo-Carboniferous sequence in the Sydney Basin, new data have recently become available from the northern extremities of the basin. Drilling carried out by the New South Wales Department of Mines in the Cranky Corner Basin, a small synclinal area of Carboniferous and Permian rocks located to the north of the Hunter Thrust, penetrated a sequence which appears to have been continuously deposited through the latest Carboniferous to Early Permian interval. According to McClung *et al.* (1972), the Cranky Corner sequence represents in part a condensation of the Dalwood Group of the Hunter Valley. The sequence at Cranky Corner, and the distribution of drilled sections within it, is shown in Figure 8. With the exception of the Seaham Formation, the formation names lack formally published description at present, although they have been referred to in a number of papers (McClung *et al.*, 1972; Runnegar & McClung, 1975; McClung, 1975). The biostratigraphic importance of the sequence rests on its contained fauna; brachiopod assemblages have provided a basis on which Runnegar & McClung (1975) have delineated a sequence of zones based on brachiopod lineages—these are part of a wider biostratigraphic scheme which encompasses much of the marine Permian in eastern Australia. The distribution of zones in the Cranky Corner sequence is shown in Figure 8. The *elongata*, *konincki* and *branxtonensis* Zones are based on evolving species of the genus *Martiniopsis* Waagen; the *campbelli* Zone is an assemblage zone identified by the mutual occurrence of *Trigonotreta campbelli*, *Eurydesma cordatum* and *Megadesmus pristinus* (Runnegar & McClung, 1975).

Helby (unpubl. data) has examined the associated spore and pollen assemblages from Cranky Corner. The range of significant forms is illustrated here for that sequence (Fig. 8). While disaccate, taeniate pollen, such as those referable to *Protohaploxypinus*, are present throughout the sequence, thus establishing all of the section as equivalent to Stage 2 or younger, they are subordinate in number to monosaccate forms. The presence of the cryptogam spore *Verrucosisporites pseudoreticulatus* in strata identified as uppermost Seaham Formation establishes the base of Stage 3 within that formation. The new data means that the Seaham Formation ranges from Stage 1 in its lower parts (Helby, 1969b), through to Stage 3. Most of the overall sequence penetrated in the Cranky Corner drilling belongs to Stage 3a; the presence of *Granulatisporites trisinus* at the top of the Cranky Corner Sandstone, however, means that the upper part of that formation, and the overlying Billy Brook Formation, can be identified with Stage 3b.

The age of the palynological assemblages represented in the Cranky Corner sequence can be gauged using wide-ranging faunal correlations. The faunas from the upper part of the Cranky Corner Sandstone, according to McClung *et al.* (1972), correlate with the fauna from the Allandale Formation in the Hunter Valley. This was listed by Runnegar (1969), who related it to faunas of the Carandibby Formation and upper Lyons Group of the Carnarvon Basin, Western Australia, and suggested a late Asselian to early Sakmarian age for the Allandale fauna. This correlation suggests that the late Stage 3a to Stage 3b palynological interval may be of similar age. It has also been suggested that the base of the Permian may approximate to the base of the *campbelli* Zone (Runnegar & McClung, 1975); this represents a traditional position in Australia, corresponding to the first appearance of

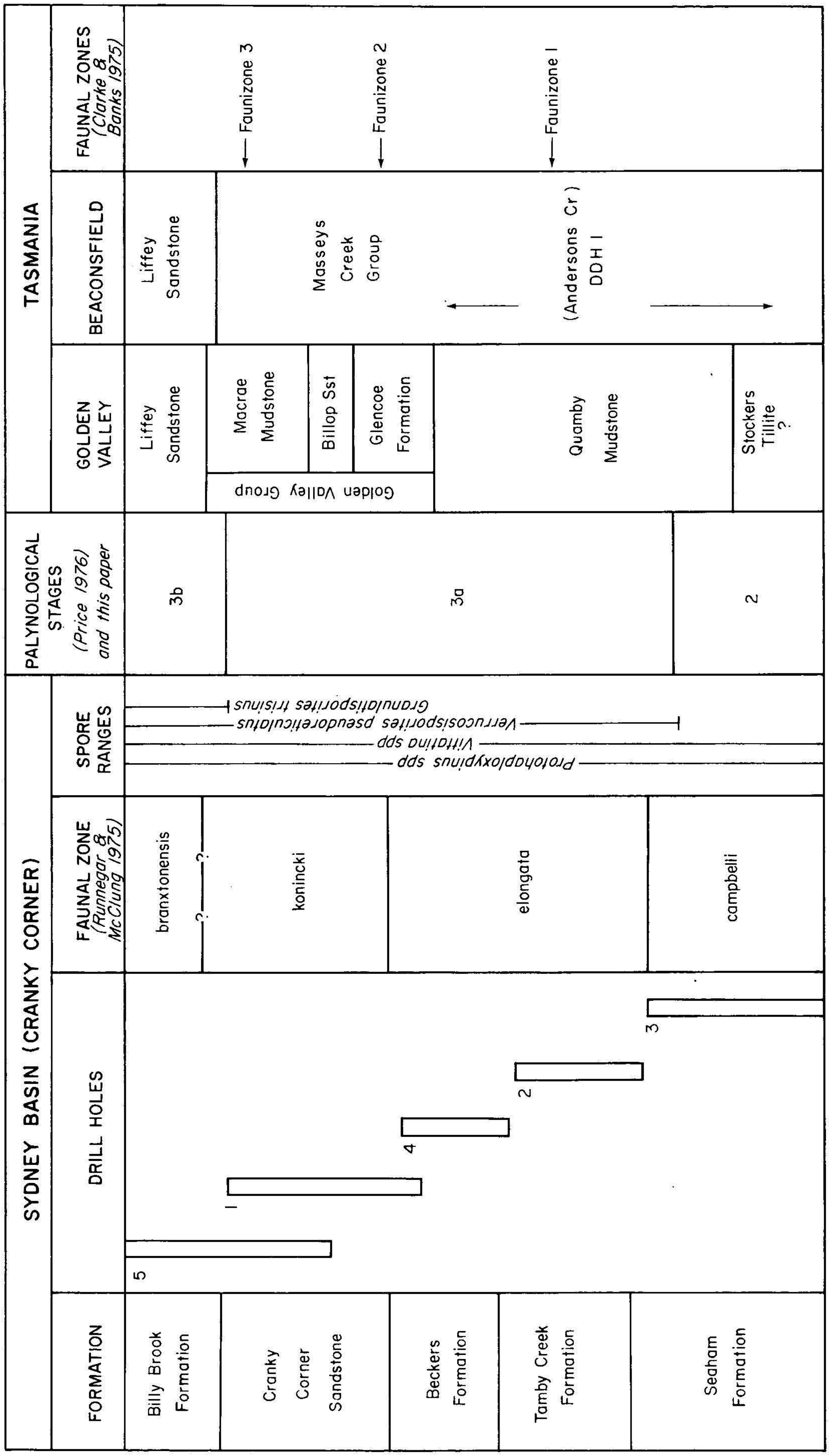


Figure 8. Distribution of palynological stages in lithostratigraphic units at Cranky Corner, New South Wales, and at Golden Valley and Beaconsfield in Tasmania. The distribution of the faunal zones of Runnegar & McClung (1975) and Clarke & Banks (1975) is also shown, as are the stratigraphic positions of boreholes drilled at Cranky Corner by the New South Wales Mines Department.

Eurydesma faunas, but it is by no means certain that it approximates to the base of the Permian in the Russian sense (see also Runnegar & Campbell, 1976). It is possible that the lower part of Stage 3 at Cranky Corner may be Asselian, and that the Stage 2/Stage 3 boundary corresponds approximately to the Carboniferous-Permian boundary.

Finally, mention should be made of palynological work at the southern margin of the Sydney Basin, where Helby & Herbert (1971) identified Stage 3 assemblages from the Clyde Coal Measures, in the Shoalhaven Group. One sample from the top of the sequence in Clyde Gorge is probably as young as Stage 4. This determination established the position of the Clyde Coal Measures at a stratigraphic level higher than that suggested by earlier work; it now seems likely that they lie at a higher level than the Pigeon House Creek Siltstone and the Yadboro Conglomerate. Both of these last units may have been deposited in a valley of possible glacial origin during the Late Carboniferous. Probable Stage 1 assemblages have been recovered from the Pigeon House Creek Siltstone.

Tasmania Basin. The late Palaeozoic sequence in Tasmania has been referred to the lower part of the Parmeener Super-Group (Banks, 1973; Clarke & Banks, 1975). The sequence is thinner than elsewhere in Australia, but can be shown on palaeontological evidence to be much condensed, and to be as complete as many of the sequences in other major eastern Australian basins. It commences with a glacial unit at its base, and passes upwards through an alternating series of marine and freshwater deposits, including coal measures at two distinct levels. Diverse brachiopod faunas throughout the marine parts of the sequence have allowed the delineation of 10 informal assemblage units (Clarke & Banks, 1975).

The palynological data that are available come from scattered localities within the basin. The available data, both published and unpublished, are at present being compiled into an interim report (E. M. Kemp, in prep.). At least two localities in the lower part of the sequence have presented ideal opportunities to relate the palynological assemblages to the faunas. At Golden Valley, near Poatina, in central Tasmania, a borehole drilled by the Tasmanian Department of Mines penetrated, from above, the Liffey Sandstone, the Golden Valley Group (Macrae Mudstone, Billop Sandstone, Glencoe Formation), and the Quamby Mudstone (Clarke, 1968). The sequence was sampled throughout, and the assemblages examined by Helby (1972b). They showed little variation throughout the sequence, and were assigned by Helby to Evans' Stage 2; those above the upper part of the Quamby Mudstone he referred to late Stage 2. Helby's data have been incorporated into Clarke & Farmer's (1976) review of late Palaeozoic biostratigraphy in Tasmania.

The identification of *V. pseudoreticulatus* down to a level low in the Quamby Mudstone, however, means that most of the sampled section should in fact be assigned to Stage 3 as this was defined by Paten (1969) and used by Price (1976). Most of the sampled sequence is referable to Stage 3a; the base of Stage 3b, defined by the first appearance of *Granulatisporites trisinus*, falls in the top of the Golden Valley Group just below the base of the Liffey Sandstone. The relationship of spore ranges, palynological units and lithological units in the Golden Valley Group is shown in Figure 8. Faunas from the group have been assigned by Clarke to his Faunizone 2 (Clarke & Banks, 1975)—this faunizone is considered equivalent to part of the Allandale fauna in the Sydney Basin, and a relationship of Faunizone 2 to part of the *konincki* Zone was suggested by Runnegar & McClung (1975). Tentative relationships of the Tasmanian and Sydney Basin (Cranky Corner) sequences are also shown in Figure 8.

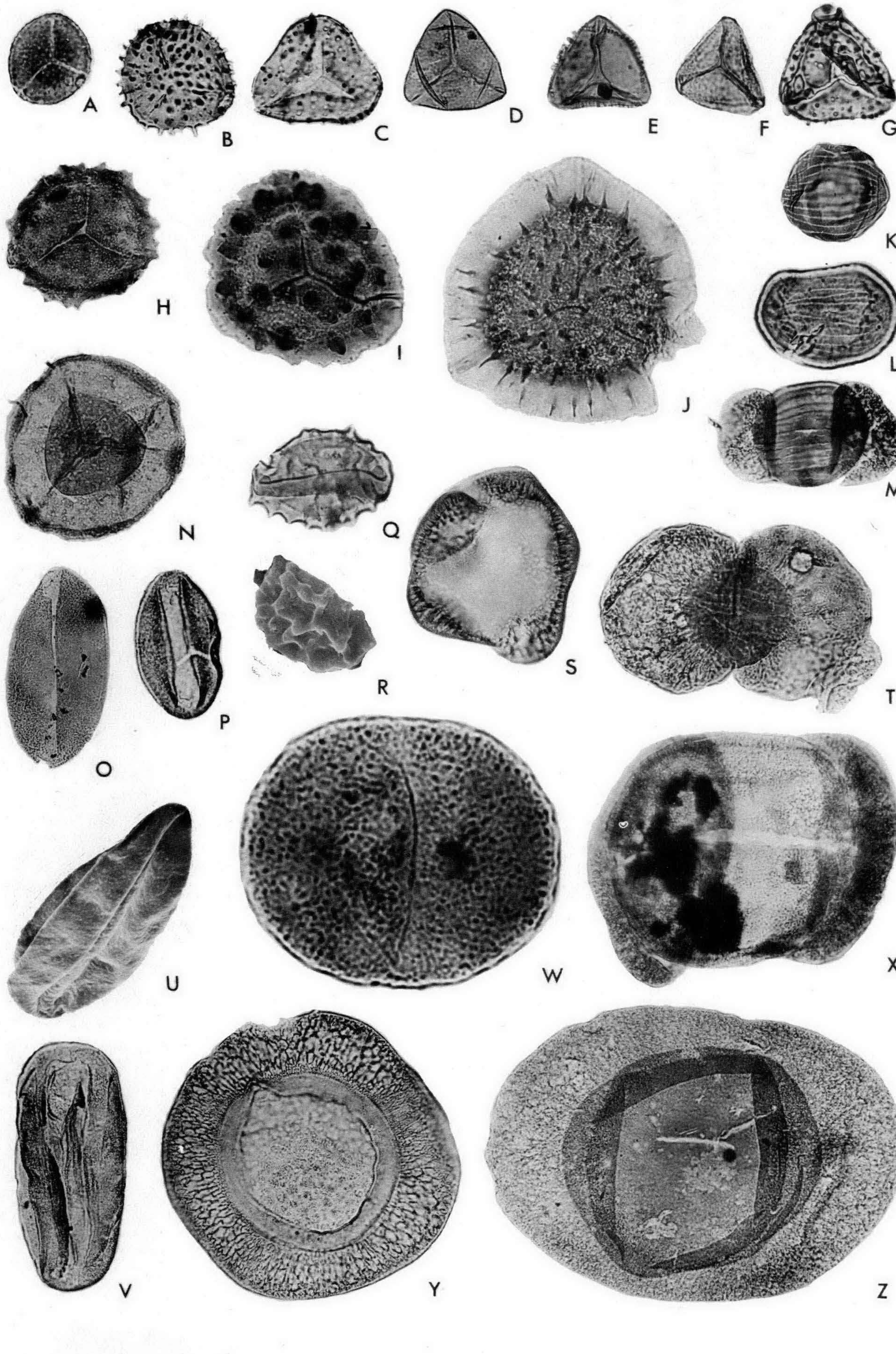
From the Andersons Creek borehole near Beaconsfield in northeastern Tasmania, Helby (unpubl. data), and Kemp (unpubl. data), have recovered assemblages that show marked resemblance to those from Golden Valley. The assemblages range through the lower part of the Masseys Creek Group, from which faunas probably referable to Faunizone 1 have been identified (Clarke, in Gee & Pike, 1974). The sampled section here apparently does not range up as high as Stage 3b; its lower part lacks *V. pseudoreticulatus*, and has been assigned to Stage 2 (Fig. 8). The part of the section assigned to Stage 2 incorporates a thin interval in which *Tasmanites punctatus* Newton is common, and which may thus be the correlative of the tasmanite shale at other localities.

Older assemblages, comparable to Stage 1, have been recovered in Tasmania from rhythmites interbedded with diamictites in Hellyer Gorge, in the northwest of the State (Evans, in Banks & Clarke, 1973); plant macrofossils associated at this locality include *Botrychiopsis plantiana* (Carruthers) and *Aphlebia* (Gould, 1975). Stage 1 assemblages have also been identified from glacial strata near Strahan, on the west coast (E. M. Kemp, unpubl. data). Stage 2 assemblages have been noted in tasmanite shale at the base of the Inglis Siltstone in the Hellyer Gorge sequence. Stage 3 occurs in the Inglis Siltstone at the same locality, and in the Mersey Coal Measures of the Mersey Coal Basin. Assemblages from this unit have been observed from sampled sections near Sassafras (E. M. Kemp, unpubl. data), and are referable to Stage 3b. This observation shows them to be older than the Greta Coal Measures of the Sydney Basin, which contain Stage 4 assemblages (Evans, 1969); earlier, Spry & Banks (1962) had suggested the time equivalence of these coal measures. From the Cygnet Coal Measures and the Jackey Formation, high in the lower Parmeener Super-Group, Balme (1969, and in Spry & Banks, 1962; Banks & Naqvi, 1967) recorded a *Dulhuntyispora* assemblage, equivalent probably to the upper part of Stage 5. Palynofloras from most of the intervening sequence, the interval which includes Faunizones 4 to 10 of Clarke & Banks (1975), remain undescribed.

Minor basins in Victoria and South Australia. Basins grouped within this category include those in which relatively thin glacial deposits, which have usually been referred to the Permian, are known to occur. In the basinal deposits at Bacchus Marsh in Victoria and Hallett Cove in South Australia evidence of glaciation is reinforced by the presence of striated pavements and by basement topography. Other localities included here are those from which Permian or Late Carboniferous deposits are known, but for which both geological and palaeontological data are sparse; e.g. the Gippsland Basin in Victoria and the Denman Basin in South Australia.

(a) Victoria. Deposits at Bacchus Marsh were among the earliest glacial deposits in Australia to be studied palynologically when they attracted the attention of Indian workers (Virkki, 1946; Pant, 1942, 1943, 1949, 1955; Pant & Mehra, 1963). According to Douglas (1969), who surveyed the palynology of a number of Victorian glacial deposits, the material examined by Virkki and by Pant probably came from Comadai Creek, although the precise locality is unknown.

In his review, Douglas mentioned material from Korkuperrimal Creek and Lederderg Gorge, in the same general area, which was too poorly preserved to assign to a biostratigraphic unit, but which contained common monosaccate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pollen grains. Material from diamictites in Lederderg Gorge, near Morven Bridge, was collected by E. M. Kemp in 1973, and yielded a sparse assemblage that includes some taeniate disaccate forms, and *Cycadopites cymbatus*, indicating an age at least as young as Stage 2. Recycled pollen grains described by Douglas (1969) from Old Nuggetty Gully include *Verrucosisporites pseudoreticulatus*, suggesting Stage 3. Sparse marine faunas occur low in the sequence at Comadai Creek (Bowen & Thomas, 1976), and include *Trigonotreta narsarhenis occidentalis* Thomas, which occurs in the upper Lyons Group and basal Callytharra Formation of the Carnarvon Basin, Western Australia, and is thus suggestive of a Sterlitamakian age. The stratigraphic relationship of the lens containing the fauna to the palynological sampling horizons, however, remains obscure.

Near Coleraine, in western Victoria, from an outcropping succession which Bowen & Thomas (1976) described as fluvioglacial sediments, Harris (1965) described a palynological assemblage which he considered to be Early Permian. The species list for this assemblage includes *V. pseudoreticulatus* and *Microbaculispora villosa*; the presence of the latter form would indicate Stage 4, suggesting that these deposits are younger than those from Bacchus Marsh, so that this determination remains anomalous. The occurrence of strata at least as young as Stage 3 in the basal sequence of the Gippsland Basin, sampled in the Duck Bay No. 1 Well (Evans & Hodgson, 1964), was also noted by Douglas (1969).

(b) South Australia. Glacial deposits in the Troubridge Basin of the Yorke and Fleurieu Peninsula areas of South Australia have been studied by Harris & McGowran (1971) and, in more detail, by Foster (1974). From clays and claystones cropping out at Waterloo Bay, Foster described an assemblage of some 46 species. He equated the assemblage with Evans' Stage 2, and with Segroves' (1970) *Microbaculispora* Assemblage, although noting that there were similarities to Segroves' younger *Acanthotriletes* Assemblage. *Granulatisporites trisinus* was, however, among the forms recorded, suggesting an age younger than Stage 2.

Foster equated the sampled section with the Cape Jervis Beds, and correlated them (1974, Fig. 4) with the Merrimelia Formation of the Cooper Basin, with Units 1 and 2 in Cootanoorina No. 1 Well in the Arckaringa Basin (McGowran & Harris, 1971) with the Crown Point Formation of the Pedirka Basin (Evans, 1964b), and with unnamed units in the Denman and Murray Basins. Correlation may probably also be effected with the glacial Lake Phillipson Beds of the Lake Phillipson bore; these were described initially by Balme (1957) and were subsequently referred by Evans (1969) to his Stage 1. McGowran & Harris (1971) however noted the presence of *Protohaploxypinus goraiensis* in these beds, and suggested that they should more correctly be assigned to Stage 2.

Antarctica

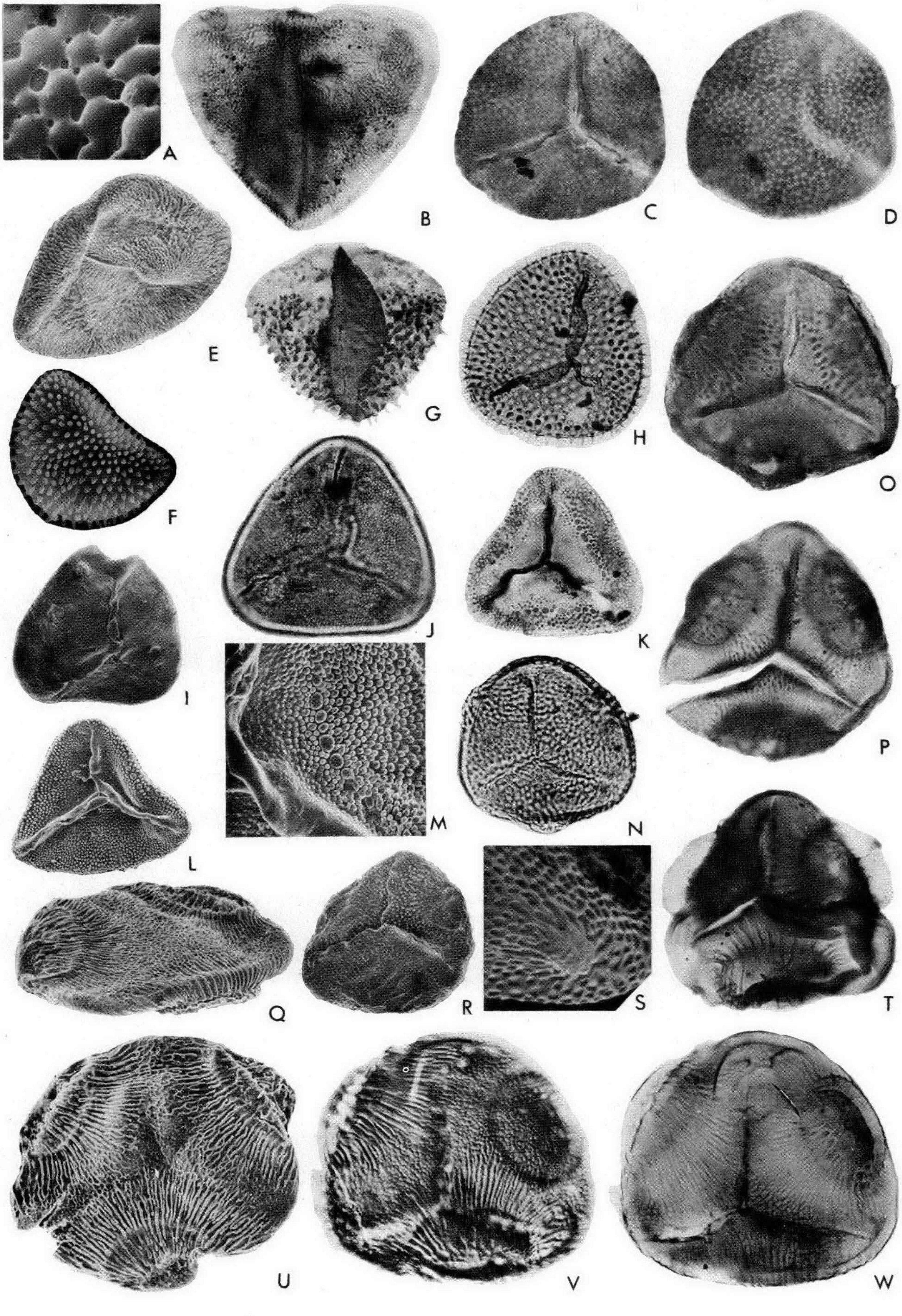
Palynological work in Antarctica is still very much in the preliminary stages. The scarcity of available data is due in part to the inaccessibility of the continent, but in the Transantarctic Mountains at least, it results from the great difficulty in extracting recognisable palynomorphs from sediments which have been thermally metamorphosed. In this area the uppermost Palaeozoic sedimentary succession is referable to the lower part of the Victoria Group of the Beacon Supergroup. It is broadly comparable to, though thinner than, the uppermost Palaeozoic sequence of eastern Australia, and consists of glacial beds overlain by continental, predominantly fluvial sediments, including coal measures. The upper Victoria Group consists of Triassic to early Jurassic fluvial sediments, with minor coal measures. Jurassic basalt extrusion and dolerite intrusion followed Beacon deposition and thermally metamorphosed the coal to semi-anthracite rank (Schopf & Long, 1966), reducing most of the spore and pollen exines to carbonised skeletons.

Early work on Antarctic Permian palynology includes a report of a Late Permian assemblage dominated by *Protohaploxypinus* from a coal from the Prince Charles Mountains (Balme, in Crohn, 1959), and a description of poorly preserved spores in the *Glossopteris*-bearing coal measures of the Ohio Range (Schopf, 1962). Similarly preserved spores and pollen of possible Permian or Triassic age were reported from coal measures at Horn Bluff (Pavlov, 1959), Mount Bastion (Balme, in Allen, 1962) and the Law Glacier (Norris, 1965).

During the last decade the few studies made indicate that the Antarctic palynological succession is similar to that in Australia, although Stage 1 or older Carboniferous palynofloras have not been recognised. The late Palaeozoic glacial beds disconformably overlie Devonian sediments and most of the Carboniferous is apparently not represented in the sedimentary record.

Stage 2 assemblages have been recovered from the glacial Buckeye Formation in the Ohio and Wisconsin Ranges (Kemp, 1975), the Darwin Tillite in the Darwin Mountains (Barrett & Kyle, 1975; Kyle, in press); and from the Roaring Formation, a carbonaceous shale unit overlying the glacial beds on the Nilsen Plateau (Kyle, unpubl. data). These assemblages, referred to the informal *Parasaccites* zone by Kyle (in press), are dominated by monosaccate pollen. Rare, non-taeniate, disaccate pollen were noted in the Wisconsin Range samples; the Nilsen Plateau samples contain up to 4 percent disaccate pollen, which is rarely taeniate; and the Darwin Mountains assemblage contains 5 percent disaccate pollen, most of which is taeniate. *Cycadopites cymbatus* is common. The trilete spore component includes

Figure 9. Selected form-species from Australian Late Carboniferous and Permian palynofloras, with their known ranges expressed in terms of palynofloral units of Western and eastern Australia. Magnifications are X500. A, *Brevitriletes levis* (Balme & Hennelly) Bharadwaj & Srivastava, 1969. Unit II-VII; Stages 2-5. B, *Apiculatisporis cornutus* (Balme & Hennelly) Hoeg & Bose, 1960. Unit II-IV; Stages 2-4. C, *Acanthotriletes tereteangulatus* Balme & Hennelly, 1956. Unit II-VIII; Stages 3-5. D, *Microbaculispora tentula* Tiwari, 1965. Unit II-VII (rare); Stages 2-5. E, *Diatomozonotriletes* sp. Unit III-VI; Stages 3-4. F, *Microreticulatisporites bitriangularis* Balme & Hennelly, 1956. Unit VII-VIII; Stage 5. G, *Indospora clara* Bharadwaj, 1962. Unit V, or upper Stage 4 to *Protohaploxypinus reticulatus* Assemblage. H, *Dentatispora* sp., Unit 1-(?) VIII; Stages 1-5. I, *Kraeuselisporites* cf. *K. splendens* (Balme & Hennelly) Segroves, 1970. Unit III-VII; Stages 3-5. J, *Kraeuselisporites* sp. cf. *Cirratriradites africanus* Hart, 1963. Unit III-VIII; Stages 3-5. K, *Weylandites lucifer* (Bharadwaj & Salujha) Foster, 1975. Unit V, or Stage 4a, to *Protohaploxypinus reticulatus* Assemblage. L, *Tiwariasporis* sp. cf. *Marsupipollenites scutatus* Balme & Hennelly, 1956. Unit III-VII; Stages 3-5. M, *Striatoabieites* sp., Unit II-VIII; Stages 2-5. N, *Gondisporites* sp. Unit II-VIII; Stages 2-5. O, *Cycadopites cymbatus* (Balme & Hennelly) Hart, 1965. Unit II-IV; Stages 2-4. P, *Marsupipollenites triradiatus* Balme & Hennelly, 1956. Unit III, or Stage 3a, to *Protohaploxypinus reticulatus* Assemblage. Q, R, *Polypodiidites cicatricosus* (Balme & Hennelly) Rigby & Hekel, 1977. Unit IV-VII; lower Stage 4-upper Stage 5a. R, SEM X500. S, *Bascanisporites undosus* Balme & Hennelly, 1956. Unit VII-VIII; upper Stage 4b-5. T, *Striatopodocarpites fusus* (Balme & Hennelly) Potonié, 1958. Unit III-VIII; Stages 3-5. U, V, *Praecolpatites sinuosus* (Balme & Hennelly) Bharadwaj & Srivastava, 1969. Unit V, or upper Stage 4a, to *Protohaploxypinus reticulatus* Assemblage. U, SEM X500. W, *Scheuringipollenites maximus* (Hart) Tiwari, 1973. Unit IV-VIII; Stages 4-5. X, *Corisaccites alutas* Venkatachala & Kar, 1966. Mainly Unit IV (rare); Stage 4. Y, *Plicatipollenites* sp. Unit I or Stage 1, to *Protohaploxypinus reticulatus* Assemblage. Z, *Potonieisporites* sp. Unit I-VII; Stages 1-5.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Microbaculispora tentula. Rare specimens of a form closely similar to *Granulatisporites micronodosus* occur in the Darwin Mountains sample. A correlation with upper Stage 2 as defined by Norvick (1974) is suggested.

In south Victoria Land the glacial beds are overlain by the Weller Coal Measures. No microfossils have been recovered from the lower member of this formation. The middle and upper members contain assemblages assigned to the informal *Protohaploxypinus* zone (Kyle, in press). They are characterised by abundant disaccate pollen (47-55 percent), of which more than half is taeniate (mainly *Protohaploxypinus*), and include rare monosaccates (1-3 percent). Their composition suggests correlation with Stage 4, although none of the index fossils used to define the base of that unit or its subdivisions has been recognised.

In the Nilsen Plateau, probable Stage 5 assemblages occur in coal measures (the Queen Maud Formation) overlying the Roaring Formation and a sandstone formation. Disaccate pollen, especially taeniate forms, predominate, and one sample contains *Praecolpatites sinuosus* and *Bascanisporites undosus* (Kyle, unpubl. data). The distinctive Australian index fossil *Dulhuntyispora* has not been found in Antarctica.

The best preserved Antarctic Permian assemblages are those referable to Stage 5 from the Prince Charles Mountains. Balme & Playford (1967) described assemblages from the Bainmedart Coal Measures of the upper Amery Group. They were considered comparable to Australian and Indian Late Permian assemblages, judged by the high proportion of taeniate disaccates, and by the presence of *Praecolpatites sinuosus, Microbaculispora villosa, Densipollenites indicus* Bharadwaj, 1962, and *Didecitriletes ericianus*. More recently, Kemp (1973) described additional assemblages from the Bainmedart Coal Measures and the underlying Radok Conglomerate; the Late Permian age was further confirmed by the identification of *Indospora clara* and *Guttulapollenites hannonicus*. Further compositional details of miospore assemblages from the same sequence have been given by Dibner (1975).

Summary and conclusions

At present some 13 palynostratigraphic units have been defined in Western Australia, spanning the interval from the Tournaisian to the latest Permian. In eastern Australia 16 units have been identified within the same interval. These schemes incorporate a variety of zonal concepts. The Western Australian units discussed in this paper by Balme, Playford, and Helby are assemblage zones, defined on the basis of associations or assemblages of microfossils, distinguished from each other by the presence or absence of particular forms, and by differences in the proportion of various morphological groups. Stages 1 to 5, applied in eastern Australia by Evans, were, as originally conceived, also assemblage zones. The modification of these units begun by Paten (1969) and elaborated herein, represents a redefinition of the original concept in terms of units akin to range zones. These depend largely for their definition, not on the total ranges of individual species, but on the first appearances of selected forms; they represent a modification of the 'taxon-range-zones' of the International Subcommission on Stratigraphic Classification (Hedberg, 1972). The application of these units bears some resemblance to the datum-plane concept employed by Cainozoic stratigraphers. The detailed subdivisions which are recognised in the lower part of Stage 5 in fact approach lineage zones, as they depend in part for their definition on morphological changes within the form-genus *Dulhuntyispora*.

Palynologically based assemblage zones and taxon-range-zones must both be used cautiously in regional stratigraphic syntheses. Local factors may influence the quantitative composition of plant microfossil assemblages and restrict their usefulness to relatively small areas or particular sedimentary basins. Phytogeographic controls, agents of sedimentation, even preservational differences may control the presence or absence of the index species of range zones in any given succession. Despite these obvious imponderables, many of the broad quantitative changes appear to be very widespread, and to reflect large-scale gross changes in the composition and distribution of late Palaeozoic vegetation. The change from dominance of large monosaccate pollen in the Stage 1/Unit I interval, to dominance of taeniate, disaccate forms by the Late Permian, is one which is recognised throughout Gondwanaland, and thus forms the basis of a useful two-fold biostratigraphic subdivision. It is quite uncertain whether a comparable change occurs in synchronous northern hemisphere floras and the Gondwanaland palynological sequence may be linked to broad-scale climatic events that affected only that region. It is notable that some apparently minor quantitative changes in palynological assemblages seem to have wide lateral persistence within Australia. The high relative abundance of *Granulatisporites trisinus* for instance, which has been used to define Unit VI in the Canning Basin in Western Australia, has been observed in strata occurring in a similar stratigraphic position in the Denison Trough, Queensland. This enables Unit VI of the Canning Basin to be correlated with Upper Stage 4a of the eastern Australian sequence.

Progress in achieving refined and stable palynological zonation of the Australian late Palaeozoic has been handicapped by a tendency to synthesise without an adequate systematic basis. This has resulted from the strongly applied tenor of most early investigations and, indeed, from the great success of palynology in providing a technique for elucidating the broad stratigraphy of Australian sedimentary basins with their great thicknesses of continental and paralic sediments. This situation is now being rectified, and systematic studies are being undertaken by Foster, Kemp, Playford, Powis, Price, and other workers. The palynological units at present in use remain informally

Figure 10. Selected form-species from Australian Permian palynofloras, with their known ranges expressed in terms of Western and eastern Australian palynofloral units. Magnifications are X500 unless specified otherwise. A, C, D, *Verrucosisporites pseudoreticulatus* Balme & Hennelly, 1956. Unit III-VI; Stages 3a-upper 5a. A, surface detail, SEM X3000. C, D, proximal and distal views. B, E, *Microbaculispora villosa* (Balme & Hennelly) Bharadwaj, 1962. Unit VII, or upper Stage 4b, to *Protohaploxypinus reticulatus* Assemblage. B, lateral view, proximal surface uppermost; E, inclined proximal surface, SEM X500. F-H, *Didecitriletes ericianus* (Balme & Hennelly) Venkatachala & Kar, 1965. Unit VII, or lower Stage 5b, to *Protohaploxypinus reticulatus* Assemblage. F, distal surface, SEM X500; G, lateral view, proximal surface uppermost; H, proximal surface. I, J, *Granulatisporites trisinus* Balme & Hennelly, 1956. Unit III, or Stage 3b, through *Protohaploxypinus reticulatus* Assemblage. I, sculptured proximal face, SEM X500; J, distal surface. K-M, '*Granulatisporites* sp. 204' (Price, unpubl. data). Unit III-VI; upper Stage 4-lower Stage 5. K, proximal surface; L, SEM X500; M, proximal surface, detail of sculpture, SEM X500. N, S, *Dulhuntyispora parvithola* (Balme & Hennelly) Hart, 1965. Unit VII, or upper Stage 5 through *Protohaploxypinus reticulatus* Assemblage. N, proximal view; S, detail of interradial sculpture, SEM X1500. O, P, R, *Dulhuntyispora dulhuntyi* Potonié, 1956. 'Forma 296' of Price (unpublished). Unit VII-VIII; lower Stage 5-upper Stage 5a. P, proximal view; R, proximal surface, SEM X500. T, *Dulhuntyispora* sp. nov. 'Forma 312' of Price (unpublished). Late upper Stage 5. Proximal view. Q, U-W, *Dulhuntyispora dulhuntyi* Potonié, 1956. 'Forma 297' of Price (unpublished). Lower Stage 5c-upper Stage 5. Q, U, distal surface, oblique and polar views, SEM X500; V, distal surface, interference contrast microscopy; W, distal surface.

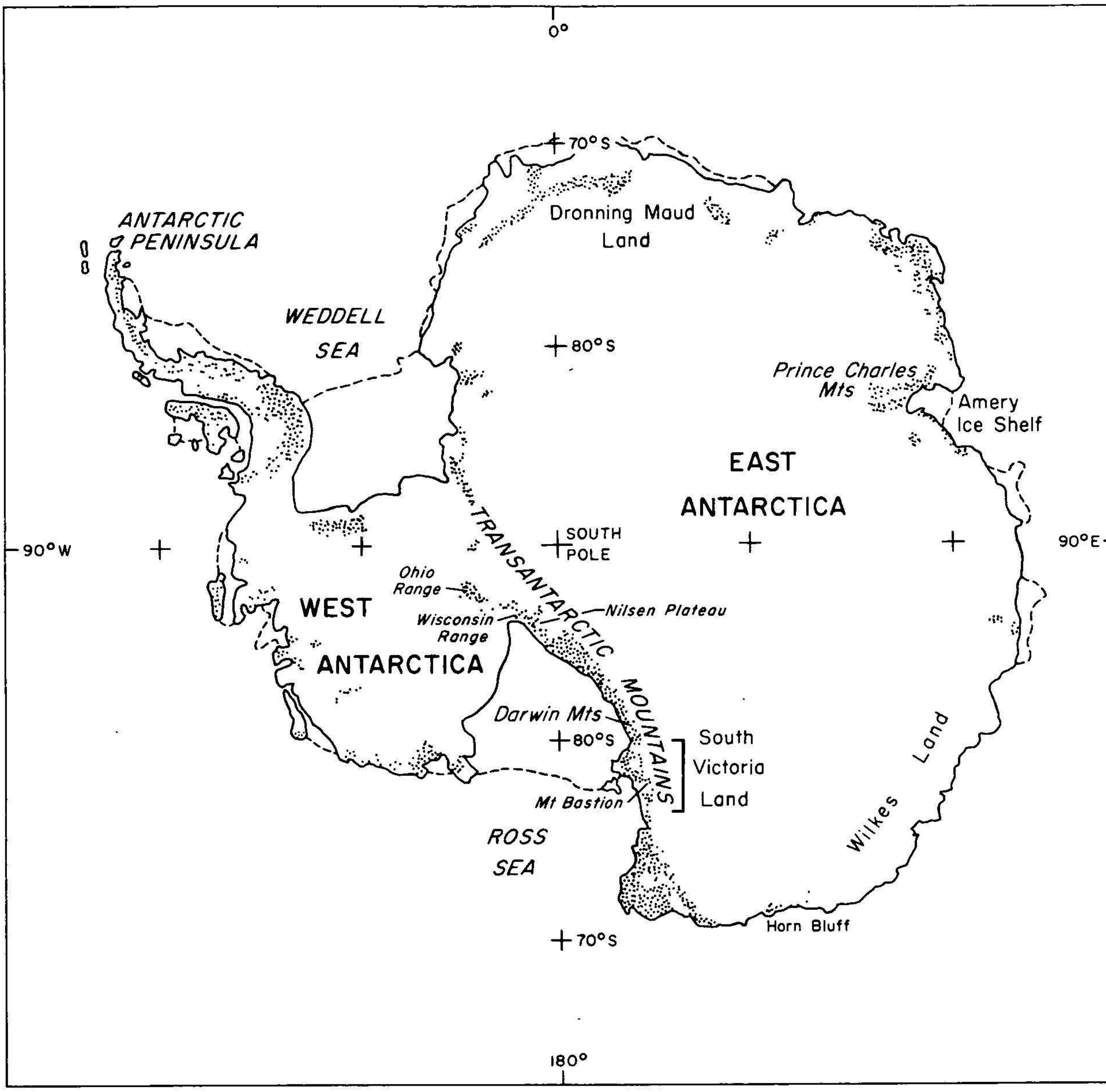

Figure 11. Antarctica, showing localities which have yielded Late Carboniferous and Permian palynofloras.

defined, and most lack designated stratotypes. The provision of these for the assemblage zones presents no great difficulty, and should follow further detailed taxonomy. For the range-zone units it is not possible to provide formal stratotypes, but the selection of representative reference sections should eventually clarify the concepts.

The establishment of the ages of the palynostratigraphic units in terms of an international time-scale is perhaps not of such high priority for future research as is the proper documentation of taxa and the provision of firmer and more complete definitions of palynostratigraphic units. Nevertheless, correlation with international stages of the Permian and Carboniferous has been suggested when inferences are warranted on the basis of the data available.

The suggested correlations for Australia are given in Figure 12. This figure summarises, in the left-hand columns, the ages of the palynostratigraphic units identified in the Canning, Bonaparte Gulf, and other Western Australian basins as evidenced by marine faunas in those basins. Correlation of the eastern Australian palynostratigraphic units with those in Western Australia is also indicated, although these are tentative—more so for some parts of the sequence than for others. The probable equivalence of Units I and II with Stage 1 and Stage 2 of the Evans scheme has been suggested by Balme (this paper); correlations within the Unit III to Unit VI interval are made with less confidence, although the probable equivalence of Unit VI with Upper Stage 4a has already been noted. The introduction of the *Dulhuntyispora* complex of spores at the base of Unit VII provides a clear link with the base of Stage 5, although probable precursors of this complex have been identified by Price (unpubl. data) high in Stage 4. The fine subdivisions of lower Stage 5 have not been identified by Balme in Western Australia, although Price (in Yeates *et al.*, 1975) has recognised them in the basal Liveringa Group.

The probable relationship of the eastern Australian palynostratigraphic units to faunal subdivisions is shown in columns 3-5 of Figure 12. The general relationship of the palynological units to the faunal units of Dickins (1964) is established from Bowen Basin sequences; the relationship to the modified version of these units described by Runnegar (1969) is reflected in Sydney Basin sequences.

PALYNOLOGICAL UNITS Western Australia (this paper)	INTERNATIONAL AGES from Western Australian sequences	PALYNOLOGICAL UNITS eastern Australia (this paper, & Evans 1969)	FAUNAL ZONES eastern Australia (Dickins (1964))	FAUNAL ZONES eastern Australia (Runnegar (1969))	BRACHIOPOD ZONES (Runnegar & McClung, 1975; Roberts, 1975)	INTERNATIONAL AGES (Runnegar & McClung, 1975; Roberts et al., 1976; Runnegar, 1969)
P. reticulatus	Changhsingian ?	P. reticulatus				
Unit VIII	late Guadalupian ?	Weylandites				
Unit VII	Guadalupian	Stage 5	Fauna IV	Fauna IV Fauna III	M. ovalis M. isbelli M. undulosa	
		Upper Stage 4 b	Fauna III	Ulladulla fauna	M. brevis	Baigendzhinian
Unit VI	Leonardian to early Roadian	Upper Stage 4 a			M. plana	
Unit V	Leonardian	Lower Stage 4	Fauna II Fauna I	Fauna II	M. ovata	Aktastinian
Unit IV	Aktastinian to Leonardian	Stage 3 b			M. branxtonensis	
Unit III	Tastubian to Sterlitamakian	Stage 3 a		Allandale fauna *2	M. konincki M. elongata	early Sakmarian – late Asselian
Unit II	No faunal evidence, possibly Virgilian on palynological grounds	Stage 2			T. campbelli	
Unit I	No faunal evidence. Probably at least as old as Missourian	Stage 1 or Potonieisporites				
Anabaculites yberti	early Namurian — ?	Anabaculites yberti			L. levis	Namurian – Westphalian
Grandispora maculosa	late Viséan-?early Namurian	Grandispora maculosa				
Anapiculatisporites largus	early to late Viséan	Granulatisporites* 1 frustulentus (undiff.) / A. largus			R. fortimuscula D. aspinosa	late Viséan
Grandispora spiculifera	Tournaisian (Tn Ib — Tn3)					
1	2	3	4	4	5	6

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Figure 12. Summary diagram showing international correlation of Western and eastern Australian palynostratigraphic units. The probable relationship to eastern Australian faunal assemblages and brachiopod zones is also shown. *1 An undifferentiated *Granulatisporites frustulentus* Microflora is known from the upper Flagstaff Sandstone, associated with faunas of the *D. aspinosa* Zone. *Anapiculatisporites largus* Assemblage floras occur in the Ducabrook Formation, Drummond Basin. *Grandispora spiculifera* Assemblage floras have not been definitely identified in eastern Australia. *2 Allandale Fauna is shown in the sense of Runnegar (1969), rather than in the extended sense of Runnegar & McClung (1975).

The correlation of palynozones to the brachiopod zones of Runnegar & McClung (1975) is again tentative, and draws in part on correlations suggested in the summary chart shown by these authors (Runnegar & McClung, 1975, fig. 31.4). A direct relationship between brachiopod zones and palynological zones, with both groups of organisms being recovered from the same rock sequence, has been established in few localities. The Cranky Corner sequence has enabled the relationship of Stage 2/Stage 3 to the *campbelli* to *branxtonensis* Zones to be established, and Price (unpubl. data) has described the preliminary identification of the *ovata, plana, undulosa, isbelli,* and *ovalis* Zones in Denison Trough sequences from which palynological data are also available. The relationship of faunizones established in Tasmania (Clarke & Banks, 1975) to the palynological Stages 2 and 3 has also been noted (Fig. 8). The *Auriculispina levis* Zone (Engel, 1975) is omitted from Figure 12, as no direct palynological correlation is available for it.

From Figure 12 it is evident that the poorest faunal control within the sequence of playnostratigraphic units is in the interval between the *Anabaculites yberti* Assemblage and Balme's Unit III. This interval incorporates the bulk of sedimentary rocks in which a glacial imprint is evident. The onset of glacial and periglacial climates probably explains the sharp drop in plant microfossil diversity immediately above the *Anabaculites yberti* Assemblage; the rarity of faunal remains in the interval probably relates to the same cause.

Evans (1969) indicated that the Carboniferous-Permian boundary lay at the base of Stage 2. He argued that taeniate, disaccate pollen first appear in Stage 2, and that these were probably associated with the advent of the *Glossopteris* flora; the traditionally held Australian view is that this flora is entirely of Permian age. In this regard it is interesting to note that the earliest macrofossil remains of the *Glossopteris* flora in Australia, those in the Boonderoo Beds in the north of the Galilee Basin (White, 1964) are associated with microfossil assemblages of *late* Stage 2 aspect (Norvick, 1974).

Helby (1969) pointed out that the top of the type Stephanian sequence in western Europe did not coincide with the base of the Permian type section in the Urals, and indicated that the most appropriate location of the top of the Carboniferous in Australia was at the base of the *Potonieisporites* Assemblage (or Stage 1). More recently he suggested that the base of the Permian approximates to an horizon within the lower part of Stage 3 (R. J. Helby, Chairman's Address to the Geological Society of Australia, N.S.W. Division, 1974). Support for such a conclusion comes chiefly from comparison of Australian palynological assemblages with those of North America. Assemblages from the Missourian of Kansas have elements in common with the *Potonieisporites* Assemblage, Virgilian strata in Kentucky show a diversity of taeniate, disaccate pollen reminiscent of Stage 3 in Australia. A similar comment has been made here in discussion of the Western Australian palynofloras; disaccate pollen in Unit II in the Canning Basin is not as diverse or plentiful as it is in Wolfcampian, even Virgilian, strata in the mid-continent United States. Whether this is to be interpreted to mean that the Unit II assemblages are older than say, Virgilian, is uncertain, especially in view of the clear climatic differences between the Gondwanaland continents and Laurasia at this time.

Although the precise position of the Carboniferous-Permian boundary in Australia remains obscure, there no longer seems any clear reason to regard Stage 2 of the eastern Australian sequences, nor its Western Australian correlatives, as Permian. The base of Stage 2 remains defined by the introduction of taeniate, disaccate pollens. The appearance of these in large numbers in Virgilian strata has been noted; the same circumstance, of abundant taeniate, disaccate pollen, also characterises the type Orenburgian strata in the USSR (Faddeeva, 1975). It seems, therefore, not unreasonable to suggest that Stage 2 is of Carboniferous age, and that the Carboniferous-Permian boundary approximates to the Stage 2/Stage 3 boundary.

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Seismic travel-times to east Papua from USSR nuclear explosions

D. M. Finlayson

Recordings of P seismic waves from a Novaya Zemlya nuclear explosion at 26 sites on the east Papuan peninsula show that there are significant apparent departures (residuals) from travel-times calculated using average earth models. The residual at Port Moresby (PMG) differs by between +0.3 and +0.5 seconds from previous attempts to assign a station effect there. Without precise times and locations of the Novaya Zemlya events it is not possible to determine the proportions of the residual due to source effects and velocity anomalies in the mantle. It is shown that complex crustal structure in the east Papuan region accounts for a significant proportion of the station residuals, which differ from the PMG residual by between −0.72 seconds and +1.41 seconds. There is a tendency towards more negative residuals on the northeast side of the Papuan peninsula.

Introduction

During the 1973 investigation of crustal structure in the east Papuan region (Finlayson and others, 1976) some 42 seismic stations were deployed to record 111 shots fired in the Solomon and Coral Seas from the L/V "Sir Allan". At 06h 59 min 57.37 ± 1.00s U.T. on 27 October 1973 (USGS, 1973), during that survey, the USSR detonated a nuclear device on Novaya Zemlya, and it was successfully recorded at 26 stations in east Papua (Fig. 1). These recordings have been used to determine seismic travel-time residuals, i.e. departures from the Herrin (1968) seismological travel-time tables, for P phases. The residuals were then analysed with respect to interpreted crustal models derived from the local explosion seismic and gravity observations (Finlayson and others, 1976, 1977).

Freedman (1967) has discussed the problems associated with trying to determine station residuals which apply to all azimuths and sources . She points out that small location errors and azimuth varying source residuals make the use of a world-wide distribution of sources essential for the determination of an average station residual. This was not possible with most of the east Papua stations because recording times were usually limited to those required for the local explosion seismic work, thus severely limiting the usable sources. Only at the permanent Papua New Guinea seismic stations are other source data available. The detonation of the 27 October 1973 USSR nuclear device

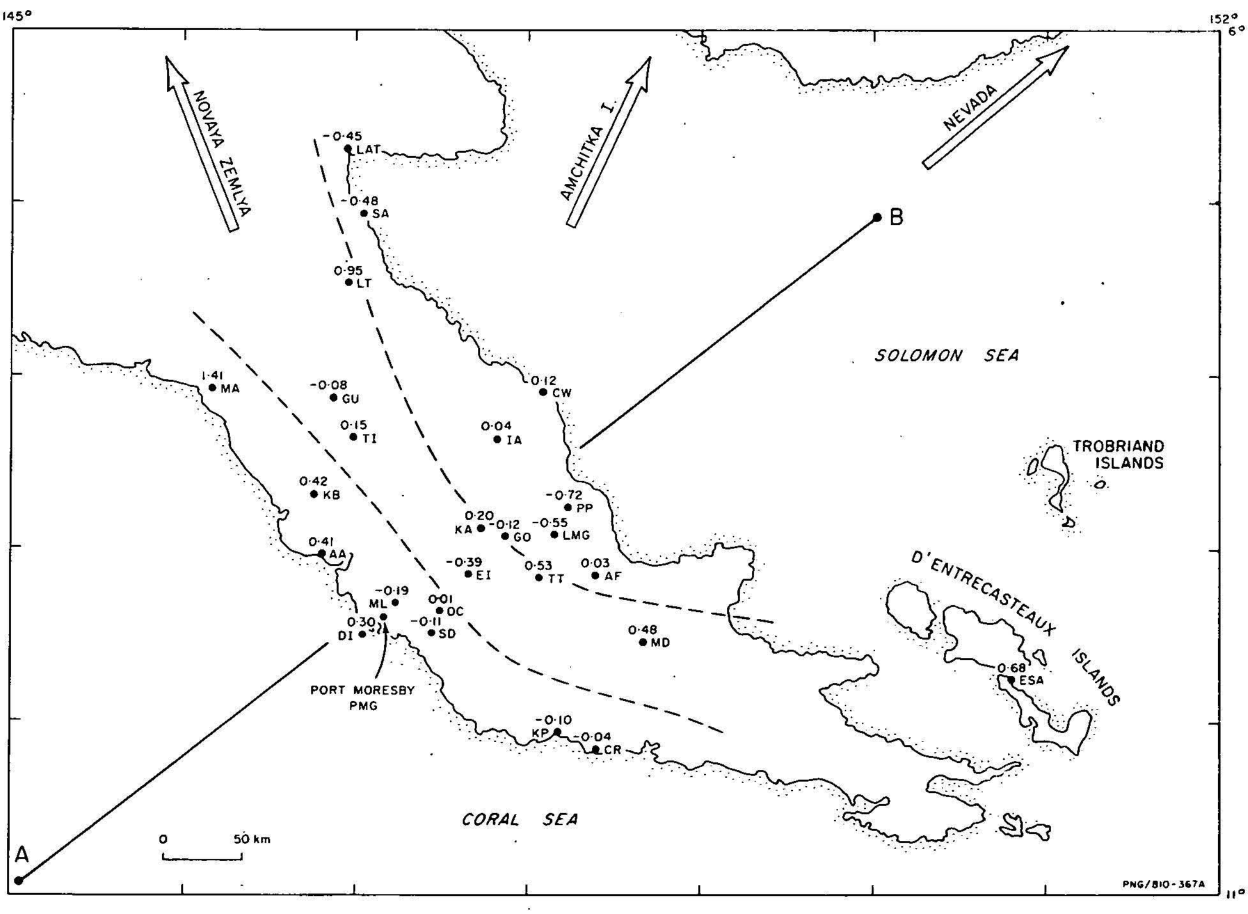

Figure 1. Location of seismic stations on the east Papuan peninsula and residual differences (in seconds) from Port Moresby. Three letter mnemonics indicate permanent stations; dashed lines indicate station groupings discussed in text; A-B indicates location of crustal profile shown in Figure 4; arrows indicate the azimuths of various nuclear explosion sites from Port Moresby.

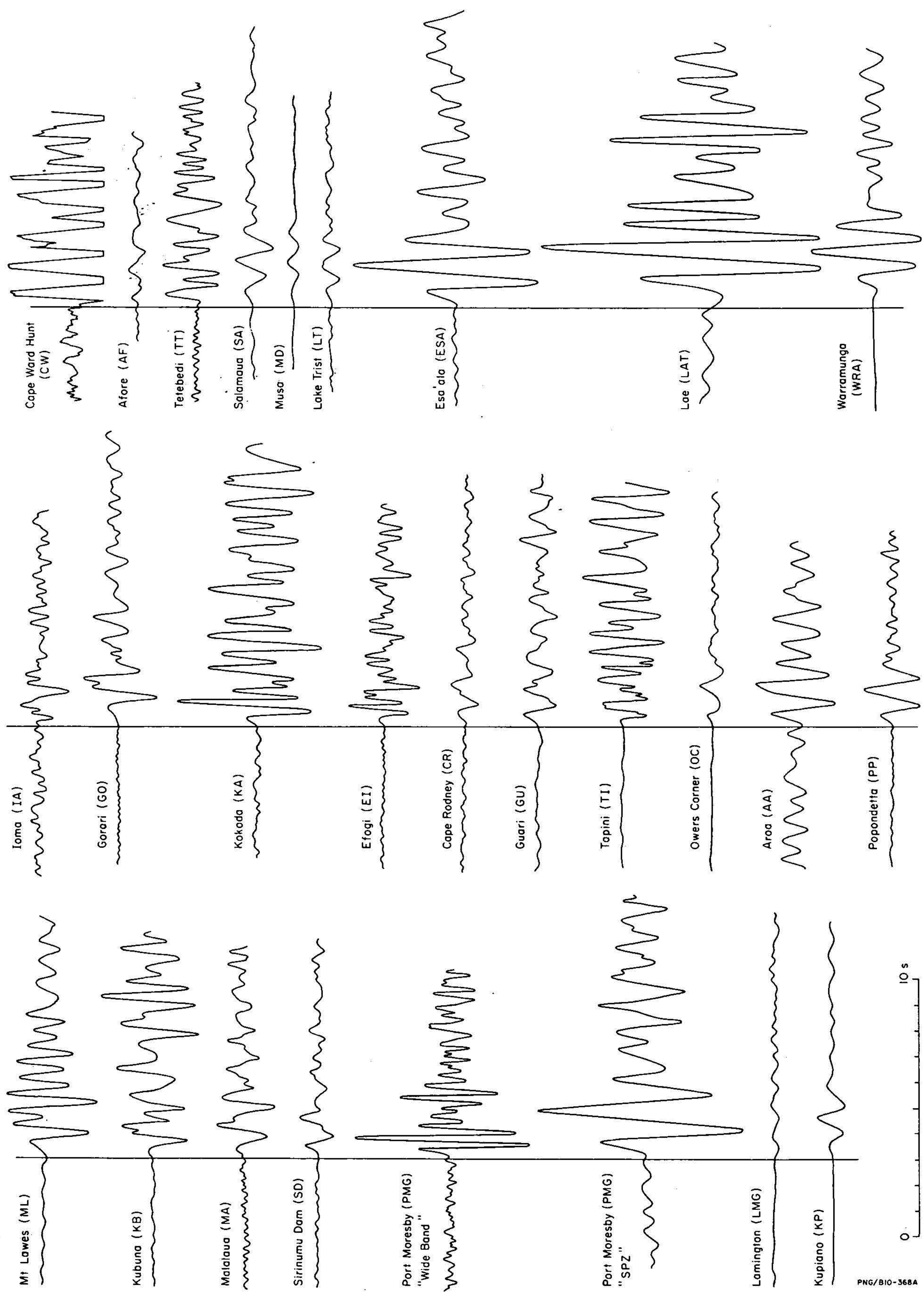

Figure 2. Recordings of the Novaya Zemlya nuclear explosion of 27 October 1973 at seismic stations on the east Papuan peninsula, and a processed record from the Novaya Zemlya nuclear explosion of 27 October 1966 recorded at Warramunga seismic array (Wright & Muirhead, 1969, fig. 2). The onset used to compute residuals is indicated on each record.

while many instruments were recording was purely fortuitous. Even with a single event, however, some comments can be made on the residuals within the survey area relative to a standard station, which, in this case, was taken as the World-Wide Standard Seismograph Network (WWSSN) station at Port Moresby (PMG).

Seismic recordings

Four of the stations (PMG, LAT, LMG and ESA) in Figure 1 that recorded the USSR explosion, were part of the Papua New Guinea permanent seismic observatory network, and the remaining sites were occupied temporarily by field recording equipment. A typical set of field equipment consisted of a Willmore Mk. 2 vertical seismometer, amplifier, long-endurance tape recorder, internal crystal clock, and radio time-signal receiver locked to the Australian standard frequency and time-signal tranmission VNG.

Reproductions of the recordings for the stations are contained in Figure 2. The replayed records have not been filtered and the reproductions of observatory records were made from photographic enlargements. Despite some differences in the recording characteristics of the equipment, the character of the first three seconds of the wave train could generally be recognised in most records. On some reproductions from tape recording systems, signal saturation is evident by folding of the high amplitude peaks. However, the basic form of the initial wave train is seen plainly in the reproductions from Port Morseby, Esa-ala, Kupiano, Popondetta and Salamaua.

Much has been written on the waveforms to be expected from underground nuclear explosions. Thirlaway (1966) has indicated that in general the first few seconds of wave forms from the same site are similar with minor variations resulting from variations in depth of burial. Carpenter and others (1967) have determined amplitude-distance curves from various nuclear explosions, and the initial wave forms of their examples of records from French and Russian explosions are strikingly similar to the 1973 recordings made in east Papua. For comparison purposes, Figure 2c also shows the initial wave form of a Novaya Zemlya nuclear explosion on 27 October 1966 as recorded at the Warramunga seismic array in northern Australia (Wright & Muirhead, 1969). This basic wave-form has been used to ensure that the onsent time is identified correctly on all east Papuan records.

The observed travel-times are listed in Table 1 together with other data, and an estimate has also been made of the observational uncertainty in the onset times which takes into account the instrumental factors connected with clock errors, parallax errors, etc. The components of possible error classified by Freedman (1966) as miscounts, misidentifications and instrumental errors are deemed to have been eliminated by independent examination of records by at least two geophysicists.

The positions of the seismic stations were determined, using a Decca trisponder system, to within the 0.1 minute of arc in latitude and longitude required for the local seismic survey. The location and time of the USSR explosion are taken from the US Geological Survey Earthquake Data Report 65-73 (USGS, 1973). The angular distances of the stations from the shot point, with ellipticity corrections, were in the range 97.17° to 101.32°. Using the Herrin (1968) model of the earth, the angle of emergence (angle from the vertical) of P waves at these distances is 14.5 ± 0.1° (Pho & Behe, 1972). The seismic rays can therefore be considered as emerging almost vertically through the upper mantle and crustal structure of east Papua.

The angular distances at which the east Papua records were made puts them at the outer limit of direct P wave observation. Figure 3 shows the Herrin (1968) P and PcP phases converging beyond 80°. Beyond 97.5° the travel-time curve is substantially straight with a gradient of 4.56 seconds per degree. Jeffreys & Bullen (1948) travel-times are between 1.7s and 1.8s greater than those of Herrin (1968) in the range between 95° and 100°. There are three Papuan stations that are between 100° and 101° and one station at 101.32° and it is possible that some diffraction at the core-mantle boundary may have occurred. However Wright & Muirhead (1969) consider the differences from the linear

1 *Station*	2 *Mnemonic*	3 *Angular distance degrees*	4 *Observed travel-time min.*	*s.*	5 *Elevation correction s.*	6 *Corrected travel-time min.*	*s.*	7 *Herrin (1968) travel-time min.*	*s.*	8 *Residual (R) s.*	9 *R-R* (PMG) s.*
Port Moresby	PMG	99.80	13	45.97 ± .10	−.01	13	45.96	13	45.64	0.32	—
Daugo Island	DI	99.86	13	46.63 ± .05	0	13	46.63	13	45.94	0.69	0.30
Aroa	AA	99.33	13	44.34 ± .03	0	13	44.34	13	43.54	0.80	0.41
Kubuna	KB	99.00	13	42.76 ± .01	−.01	13	42.75	13	41.94	0.81	0.42
Malalaua	MA	98.22	13	40.24 ± .02	0	13	40.24	13	38.44	1.80	1.41
Guari	GU	98.51	13	40.33 ± .03	−.38	13	39.95	13	39.64	0.31	−0.08
Efogi	EI	99.73	13	45.53 ± .05	−.19	13	45.34	13	45.34	0.0	−0.39
Tapini	TI	98.76	13	41.63 ± .01	−.15	13	41.48	13	40.94	0.54	0.15
Lamington	LMG	99.67	13	45.28 ± .10	−.20	13	45.08	13	45.04	0.04	−0.55*
Kupiano	KP	100.76	13	50.43 ± .05	0	13	50.43	13	50.14	0.29	−0.10
Cape Rodney	CR	100.93	13	51.29 ± .03	0	13	51.29	13	50.94	0.35	−0.04
Gorari	GO	99.58	13	44.99 ± .01	−.08	13	44.91	13	44.64	0.27	−0.12
Afore	AF	99.96	13	46.98 ± .10	−.12	13	46.86	13	46.44	0.42	0.03
Tetebedi	TT	99.87	13	47.13 ± .10	−.17	13	46.96	13	46.04	0.92	0.53
Kokoda	KA	99.50	13	44.90 ± .01	−.07	13	44.83	13	44.24	0.59	0.20
Popondetta	PP	99.56	13	44.23 ± .01	−.02	13	44.21	13	44.54	−0.33	−0.72
Owers Corner	OC	99.87	13	46.43 ± .01	−.09	13	46.34	13	45.94	0.40	0.01
Ioma	IA	99.04	13	42.48 ± .10	−.01	13	42.47	13	42.04	0.43	0.04
Mount Lawes	ML	99.76	13	45.80 ± .01	−.06	13	45.74	13	45.54	0.20	−0.19
Sirinumu Dam	SD	99.96	13	46.79 ± .01	−.07	13	46.72	13	46.44	0.28	−0.11
Salamaua	SL	97.56	13	35.43 ± .10	0	13	35.43	13	35.34	0.09	−0.48
Lae	LAT	97.17	13	34.03 ± .10	−.01	13	34.02	13	33.54	0.48	−0.45*
Esa'ala	ESA	101.32	13	53.73 ± .10	−.01	13	53.72	13	52.54	1.18	0.68*
Lake Trist	LT	97.93	13	38.73 ± .10	−.25	13	38.48	13	37.14	1.34	0.95
Musa	MD	100.43	13	49.48 ± .10	−.02	13	49.46	13	48.59	0.87	0.48
Cape Ward Hunt	CW	98.86	13	41.95 ± .10	0	13	41.95	13	41.44	0.51	0.12

*Date from Table 3, Residual A.

Table 1. Observed and calculated data from east Papuan seismic stations of the Novaya Zemlya nuclear explosion, 27 October 1973, 06h 59 min 57.37s U.T.

section of the travel-time curve to be negligible out as far as 106°, the distance at which they recorded the October 1966 Novaya Zemlya event at Warramunga. Herrin & Taggart (1968a) use data out to 105° in their investigations of regional variations in P travel-times.

Travel-time residuals

The travel-time residuals (observed travel-time minus travel-time derived from the Herrin (1968) tables for P phases) for the east Papuan stations are listed in Table 1, column 8. Station elevation corrections are applied according to the method of Engdahl & Gunst (1966), using a velocity of rock above sea level of 5.8 km/s. Although the explosion source is listed in the Earthquake Data Report 65-73 (USGS, 1973) as being at zero depth, this is unlikely. Robinson & Iyer (1976) used a source depth of 1 km for the same USSR event and this is the value used here. Herrin (1968) used an average crustal model consisting of 15 km with velocity 6.0 km/s, overlying 25 km with velocity 6.75 km/s, for correcting shallow focus travel-times. The correction to the Herrin travel-time for the depth of the shot is −0.16s, and has been applied to all data in Table 1 column 7. The validity of applying this correction to the data is discussed later in connection with the station residual for Port Moresby.

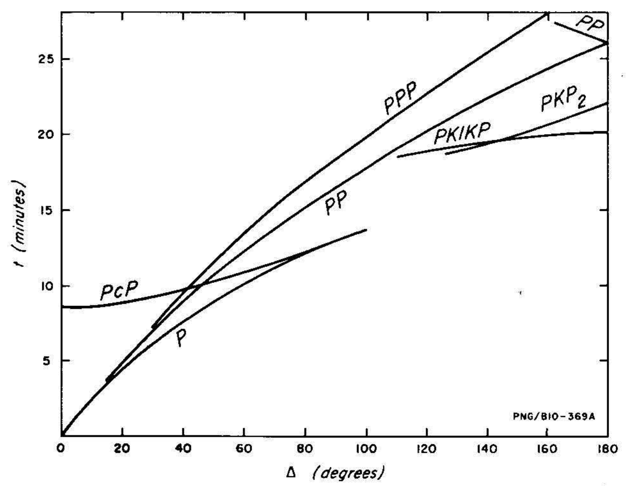

Figure 3. Travel-time curves (surface focus) from the 1968 Seismological Tables for P phases (Herrin 1968, fig. 1).

Permanent recording station residuals

Some comment can be made about the value of the travel-time residuals at the permanent seismic stations. As mentioned earlier, azimuth variations in the crust and upper mantle beneath the stations affect station residuals. Thus observations are required from many sources, in all azimuths, to determine a statistically significant value of the residual at any particular station.

The PMG station is the only one in east Papua for which such a study has been undertaken and has been included in a number of world-wide investigations of P wave travel-time analyses (Cleary & Hales, 1966; Cleary, 1967; Carder, Gordon & Jordon, 1966; Herrin & Taggart, 1968a; Lilwall & Douglas, 1970; Sengupta & Julian, 1976). Cleary (1967) derived a station residual of −0.84s for PMG based on 10 events relative to the Cleary & Hales (1966) revision of the Jeffreys & Bullen (1948) travel-time curve for P waves. This value was determined using data mostly from the azimuth of Japan and the Aleutian Islands, to the north and northeast of PMG.

Herrin & Taggart (1968a) determined azimuthally dependent station residuals relative to the Herrin (1968) travel-time curves for 321 world-wide seismic stations including PMG. Their data for PMG were determined using 122 arrivals and the residual (R) was given by the equation

$$R = -0.38 + 0.29 \sin (Z + 340) \text{ along azimuth } Z.$$

This gives PMG residual values of between approximately −0.2s and −0.5s for events to the north and northeast, and a value of −0.55s for events in the azimuth of the October 1973 Novaya Zemlya nuclear explosion (approx. 338°). A residual value for PMG of −0.28 ± 0.45s has been determined recently by Sengupta & Julian (1976). These authors have reduced the standard deviation of their value to about half that of previous authors by using deep-focus earthquakes, which eliminates source effects due to crustal and upper mantle structure, and by tight control of data quality. The value determined in this paper from the observation of the October 1973 USSR explosion (Table 1) is +0.32s; the difference between this and the Herrin & Taggart (1968a) or the Sengupta & Julian (1976) value is considerable, and, clearly, further comment is required on the possible sources of travel-time corrections.

The timing and positioning tolerance on the data from east Papua preclude any significant systematic error from instrumental sources at all 26 stations operating independently. Residual differences between PMG station and temporary stations in the vicinity, e.g. Mount Lawes (ML), Daugo Island (DI), Sirinumu Dam (SD), (Fig. 1), are consistent with the Port Moresby local geology, as will be shown later in this paper. Six other observations of Novaya Zemlya nuclear explosions on PMG records were also considered; the residuals for these are listed in Table 2. The average of these residuals is 0.43s, which substantially agrees with the value of 0.32s in Table 1, considering the reading error of the observatory WWSSN records of about ±0.1s. The difference between the Sengupta & Julian (1976) or the Herrin & Taggart (1968a) PMG residual value and the observed October 1973 value cannot therefore be explained in terms of observational inaccuracy.

Permanent recording station data consistency

The consistency of the PMG data with respect to other permanent stations in the region was also examined. The residuals at Lae (LAT), Lamington (LMG), Esa'ala (ESA), and Manton (MTN) near Darwin for a number of Novaya Zemlya events are listed in Table 2. These have been determined using the arrival times listed in U.S. Geological Survey Earthquake Data Reports, as were the PMG residuals listed in Table 2. The averages for LAT, LMG and ESA were +0.21s, −0.46s and +1.04s respectively, compared with the values in Table 1 of +0.48s, +0.04s and +1.18s respectively. The consistency of the LAT and LMG residuals can clearly be questioned.

The residual differences between MTN and the four Papua New Guinea stations were also determined. The MTN and PMG data were consistent within a standard deviation of ±0.10s. Those LAT and LMG residuals which were not consistent with either the MTN or PMG data within ±0.2s were rejected; these data are marked with an asterisk in Tables 1 and 2. Also, it was noted that those nuclear explosions with a magnitude (m_b) less than 6.5 were less reliably recorded, so the PMG residuals from three Novaya Zemlya explosions have been rejected (marked by asterisk in Table 2). The resultant mean residuals from

Station	Mnemonic	Event	Date	Origin Time U.T. h min s	Angular distance, degrees	Residual Observed—Herrin (1968) s	Magnitude m_b	Azimuth (approx)
Port Moresby	PMG	Novaya Zemlya	14 Oct '70	05 59 57.1	99.52	0.51	6.7	338°
Port Moresby	PMG	Novaya Zemlya	27 Sept '71	05 59 55.18	99.54	0.74*	6.4	338°
Port Moresby	PMG	Novaya Zemlya	28 Aug '72	05 59 56.51	99.54	0.59*	6.3	338°
Port Moresby	PMG	Novaya Zemlya	12 Sept '73	06 59 54.33	99.52	0.28	6.8	338°
Port Moresby	PMG	Novaya Zemlya	2 Nov '74	04 59 56.70	99.84	0.46	6.7	338°
Port Moresby	PMG	Novaya Zemlya	23 Aug '75	08 59 57.90	99.67	0.03*	6.4	338°
Port Moresby	PMG	Nevada	26 Mar '70	19 00 00.2	100.64	1.49*	6.4	50°
Port Moresby	PMG	Nevada	12 Feb '76	14 45 00.2	100.67	−1.14*	6.2	50°
Port Moresby	PMG	Amchitka Island	6 Nov '71	22 00 00.1	66.61	−0.15	6.8	25°
Lae	LAT	Novaya Zemlya	12 Sept '73	06 59 54.33	96.96	−0.18	6.8	338°
Lae	LAT	Novaya Zemlya	2 Nov '74	04 59 56.70	97.21	0.05	6.7	338°
Lae	LAT	Novaya Zemlya	23 Aug '75	08 59 57.90	97.01	0.75*	6.4	338°
Lae	LAT	Nevada	12 Feb '76	14 45 00.2	99.20	2.06*	6.2	338°
Lae	LAT	Amchitka Island	6 Nov '71	22 00 00.1	64.18	−0.22	6.8	25°
Lamington	LMG	Novaya Zemlya	12 Sept '73	06 59 54.33	99.39	−0.37	6.8	338°
Lamington	LMG	Novaya Zemlya	2 Nov '74	04 59 56.70	99.69	−0.54*	6.7	338°
Manton	MTN	Novaya Zemlya	12 Sept '73	06 59 54.33	98.29	−0.27	6.8	342°
Manton	MTN	Novaya Zemlya	27 Oct '73	06 59 57.37	97.87	−0.11	6.9	342°
Manton	MTN	Novaya Zemlya	2 Nov '74	04 59 56.70	97.84	0.16	6.7	342°
Manton	MTN	Novaya Zemlya	23 Aug '75	08 59 57.90	98.39	−0.24	6.4	342°
Esa 'ala	ESA	Novaya Zemlya	14 Oct '70	05 59 57.1	100.89	1.07	6.7	338°
Esa 'ala	ESA	Novaya Zemlya	27 Sept '71	05 59 55.18	100.96	1.27	6.4	338°
Esa 'ala	ESA	Novaya Zemlya	28 Aug '72	05 59 56.51	101.03	1.02	6.3	338°
Esa 'ala	ESA	Novaya Zemlya	12 Sept '73	06 59 54.33	100.94	0.81	6.8	338°
Esa 'ala	ESA	Amchitka Island	6 Nov. '71	22 00 00.1	65.68	−1.52	6.8	25°

* Rejected data

Table 2. Residuals at east Papua and Manton seismic stations using Novaya Zemlya, Nevada and Amchitka Island nuclear explosions.

reliably recorded Novaya Zemlya explosions for PMG, LAT, LMG, ESA and MTN, using the Herrin (1968) tables for P waves are listed in Table 3 (Residual A).

Source uncertainties.

USSR does not publish precise location and timing data for their nuclear explosions and therefore these data must be obtained by normal earthquake-inversion modelling. Robinson & Iyer (1976), in their analysis of temporal as well as spatial variations of travel-time residuals in the Californian region, clearly consider the origin time of the October 1973 event to be more precise than the USGS standard deviation of ±1.0s indicates. The data from that event are consistent with travel-times from 7 other nuclear explosions in the Novaya Zemlya region. Their average standard deviation of residuals from the means at 107 stations was ±0.06s using 8 Novaya Zemlya events. However the Robinson & Iyer average residual in the area of the Berkeley (BKS) WWSSN station is about +0.12s whereas the average value determined from four world-wide studies listed by Sengupta & Julian (1976) is +0.59s. Thus the seismic P phases from Novaya Zemlya explosions seem to arrive early in the California region (about 70° from the sources), whereas in east Papua they arrive late. Hence although the Robinson & Iyer data indicate that the USGS origin times are consistent, there may still be a systematic bias.

Subsequent recomputation of revised data by the International Seismological Centre, Edinburgh (ISC) indicates that the USGS origin time for the October 1973 event was 0.23s early. This trend is seen in other recomputed data (ISC, 1970-1974). Hence a correction of between −0.20s and −0.25s may be applied to the residuals listed in Table 3 to obtain better estimated values. This correction results in a PMG station residual of between +0.14s and +0.19s.

The validity of applying a source-depth correction of 0.16s may also be questioned, bearing in mind the statistical techniques applied in determining the origin time. It is probable that the convergence of the origin time is little affected by small variations in depth of about 1 km at the source and therefore the depth correction should not be applied. If no source depth correction is applied the PMG residual in Table 3 is further altered to between −0.02s and +0.03s. This is still significantly different from the Herrin & Taggart (1968), and the Sengupta & Julian (1976), values of −0.55s and −0.28s respectively.

Table 3 contains values of the residuals at the permanent east Papuan stations with an origin time correction of 0.23s applied and without a source-depth correction (Residual B).

Source bias at the Novaya Zemlya nuclear test site is clearly another factor to be considered in trying to account for travel-time variations from average earth models. Reported results, from World Wide Standard Seismograph Stations at Guam (GUA), Hong Kong (HKC), Manila (MAN) and Lembang (LEM), of the two 1973 Novaya Zemlya explosions were used to investigate whether there was any systematic lag in P arrivals in the general direction of Port Moresby. Unfortunately there was considerable scatter in the data and no clear bias was indicated.

Other indications of source bias are not available. There are few seismic observatories in USSR whose records are available for scrutiny and the precise origin times of USSR nuclear explosions are not published. Sengupta & Julian (1976) among others have evaluated the residuals in the northern Scandinavian shield area as being between 0s and

Station	Residual A	Residual B*	Difference from PMG
Port Moresby (PMG)	+0.39s	0.0s	
Lae (LAT)	−0.06s	−0.45s	−0.45s
Lamington (LMG)	−0.16s	−0.55s	−0.55s
Esa'ala (ESA)	1.07s	0.68s	+0.68s
Manton (MTN)	−0.12s	−0.51s	−0.51s

* Residual A with − 0.23s origin-time correction applied, and without source depth correction (see text).

Table 3. Residuals, using Herrin (1968) tables, for east Papuan permanent stations and Manton from Novaya Zemlya explosions.

−1.0s, but this is probably not representative of Novaya Zemlya, which is considered an extension of the Ural Mountain chain, a zone of inactive continental collision. For lack of other evidence there is assumed to be no source bias at Novaya Zemlya due to crustal and upper mantle structure.

Permanent station data from other sources

Some data from nuclear explosions along azimuths from PMG other than Novaya Zemlya were examined. Table 2 contains the residuals at PMG, LAT and ESA using nuclear explosions on Amchitka Island in the Aleutian Islands. ("Cannikin" explosion), and in Nevada. Unfortunately the Nevada explosions are not large enough for the onsets to be picked reliably and these data have therefore been rejected.

The Cannikin explosion gave residuals of −0.15s, −0.22s, and −1.52s at PMG, LAT and ESA respectively (azimuth approx. 25°). The magnitude of this explosion (m_b= 6.8), and the shorter distances, preclude rejecting these results. The difference between these residuals and those in Table 3 from Novaya Zemlya explosions illustrates the caution which must be exercised in the interpretation of residuals from different azimuths. In the case of the Cannikin nuclear explosion, it is probable that shot-point corrections differ considerably from the average because of major tectonic activity along the Aleutian Island chain (Herrin & Taggart, 1968b).

Residual differences

The uncertainties in the determination and interpretation of the residuals shown in the preceding sections do not preclude their use for the determination of residual differences which can be used to comment on crustal structure. Generally, the onset of the P arrivals at the temporary stations was more reliably and precisely determined than at the permanent stations. The spread of the stations over a small angular distance from the source (4.15°) encouraged the assumption made in this paper that all residual differences could be due to variations in crust and upper mantle structure beneath the east Papuan peninsula.

Hales and others (1968), in their studies of residuals in North America and Australia, concluded that the major part of regional residual variations could be attributed to small velocity variations in the mantle at depths of between 100 km and 600 km. However the results by Cleary and others (1972) of their recordings of the Cannikin explosion across eastern Australia clearly indicate that, as well as a regional effect, there is also a local component of station residuals which can be attributed to crustal and upper mantle structure. This component has been shown to be quite large (1-2 seconds) at recording stations in sedimentary basins (Everingham, 1969). In tectonically active areas this may even be the major component.

The values of the residual differences listed in Table 3 for LAT, ESA and LMG have been quoted in Table 1, column 9. The other east Papuan station residual differences from PMG, i.e. station residual minus PMG residual (Table 1, column 9), have been determined using a PMG residual value of +0.39s. The resultant residual differences ranged from +1.41s at Malalaua to −0.72s at Popondetta. Their spatial distribution is shown in Figure 1. The range of residual differences in east Papua, 2.13s, is greater than that found in California by Robinson & Iyer (1976), 1.48s; and that found across eastern Australia by Cleary and others (1972), 1.53s.

The angle of emergence of the seismic rays recorded at east Papuan stations is less than 15° from the vertical, using the Herrin (1968) earth model. In order to obtain the magnitude of the effects of crustal structure on the travel-times it has been assumed that rays are travelling vertically through the crust. Figure 4 shows the crustal structure along the line A-B shown in Fig. 1, interpreted by Finlayson and others (1977). The sedimentary structure has been derived from interpretations by Tallis (1975), and Brown and others (1975) for the southwestern coast, and by Davies & Smith (1971) for the northeast coast.

Coral Sea Coast

The residual differences along the southern and southwestern coasts are considered first. Three stations, Malalaua (MA), Kabuna (KB), and Aroa (AA), lie within the unstable eastern shelf area of Brown and others (1975); the stations from Port Moresby towards the southeast lie within their southeastern Papua Volcanic province.

In the unstable eastern shelf area, there is a sequence above seismic basement which is probably more than 10 km thick. It consists of clastic sediments of the Cainozoic Papuan Geosyncline unconformably overlying a sequence of deformed, faulted and metamorphosed Mesozoic to Lower Tertiary rocks. The three seismic stations were situated on surface alluvium.

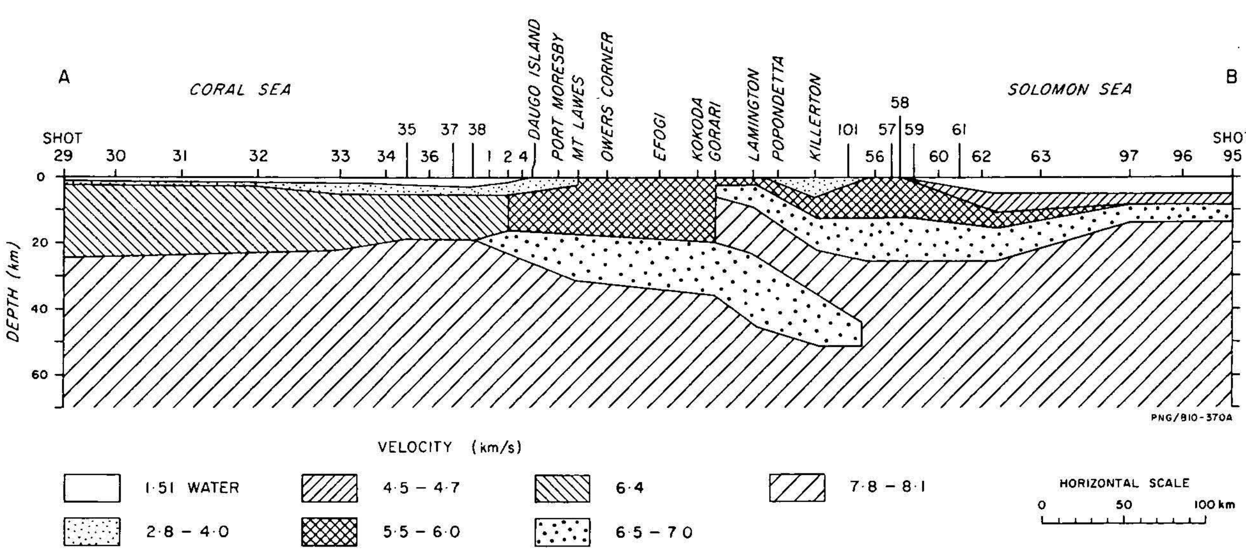

Figure 4. Crustal cross-section along line A-B indicated in Figure 1 (Finlayson and others, 1977).

Estimates of the interval velocities above seismic basement under MA, KB and AA can be made from various oil-drilling and exploration activities (Tallis, 1975). In this way it is possible to make estimates of travel-time differences due to the sedimentary sequence. For seismic rays arriving vertically the effects of variation in the depth of the Moho from Port Moresby of about 5 km are small (approx. 0.02 s/km) compared with the considerable delays introduced nearer the surface. Using velocities varying from 2.0 km/s to 5.0 km/s for the various sedimentary layers under MA, KB and AA, the residual differences can be adequately explained. Similarly the residual difference at Daugo Island of 0.30s can be reasonably explained using a low-velocity sequence about 0.8 km thick.

The residual differences at Mount Lawes (−0.19s), Sirinumu Dam (0.11s), Kupiano (−0.10s) and Cape Rodney (−0.04s) are all consistent with their location within the southeast Papua volcanic province of Brown and others (1975). Drummond and others (in prep.) interpret very little change in crustal structure between Port Moresby and Cape Rodney. The near-surface volcanic rocks are likely to have only a slightly higher seismic velocity than the Eocene marine clastic sedimentary rocks, cherts and limestone on which the PMG station is located.

Owers Corner (OC) is situated on pyroclastics, lavas and clastic sedimentary rocks which overlie Owen Stanley low-grade metamorphic rocks. The residual difference of +0.01s is slightly more positive than the values at ML (−0.19s) and SD (−0.11s). This can readily be accounted for by the near-surface geological differences; Finlayson and others (1977) do not interpret any significant difference in Moho depth under these three stations.

Central Papuan Peninsula

The second group of results are those residual differences at stations located along the centre of the Papuan peninsula (Fig. 3). The stations at Lake Trist (LT), Kokoda (KA), Tetebedi (TT) and Musa (MD) are located on or close to outcropping rocks of the Papuan Ultramafic Belt (Davies, 1971), but all have significant positive residual differences, +0.95s, +0.20s, +0.53s and +0.48s respectively. It is clear, therefore, that although these stations are associated with surface rocks with a high seismic velocity, the underlying rocks of the crust must have lower velocities compared with those under Port Moresby. Up to 0.3s could be accounted for by the morphology of the crust-mantle interface of Finlayson and others (1977). The balance at KA, TT and MD can reasonably be attributed to underlying metamorphic rocks with a velocity structure similar to that under Owers Corner (OC). The balance at Lake Trist (LT) requires a thickness of underlying low-velocity rocks of about 10 km if a velocity contrast from Port Moresby upper crustal rocks of about 1.5 km/s is assumed.

The residual difference at Guari (GU) and Tapini (TI) are not very large, +0.08s and +0.15s respectively. Because of the location of the stations, these values support the argument that the larger positive residual differences at MA, KB and AA are entirely due to near-surface geology. The residual difference at Efogi (EI), of −0.39s, is anomalous when viewed in terms of known surface geology, since positive values close to those at Owers Corner (OC), Kokoda (KA), and Tetebedi (TT) might be expected. It is therefore concluded that the surface geology must mask unrecognised deeper geological features which include high velocity rocks.

The station at Esa'ala (ESA) has a residual difference of +0.68s and may be considered within this group of stations because crustal rocks which make up the core of the Papuan peninsula, extend offshore (Davies & Smith, 1971). The high positive residual difference does not seem to indicate any great reduction in crustal thickness under Esa'ala compared with stations onshore. However the volcanic activity in the D'Entrecasteaux Islands probably has an effect on the seismic velocities in the area and thus may alter this inferred crustal structure.

Solomon Sea Coast

The third group of stations are those on or near the Solomon Sea coast. The stations at Ioma (IA) and Cape Ward Hunt (CW) have residual differences of +0.04s and +0.12s respectively. Davies & Smith (1971) report several thousand metres of basaltic pyroclastic shallow-marine sediments and limestone in the region of these stations. Substituting a higher velocity for the low velocity material at the surface will result in negative residual differences of −0.1s to −0.3s, which are close to residual differences at other stations on the Solomon Sea coast. The value at Afore (AF) of +0.03s is also positive only because of surface Quaternary lavas and pyroclastics.

The trend towards negative residual differences on the northeast side of the Papuan peninsula can be attributed to the lack of crustal rocks with velocities in the range 5.5-6.0 km/s in the crustal models (Fig. 4) interpreted by Finlayson and others (1977). The small negative residual difference at Gorari (GO) of −0.12s probably implies that a thin layer of high velocity surface rock of the Papuan Ultramafic Belt is underlain by lower velocity material.

The residual difference at Lae (LAT) of −0.45s is close to those for stations on the northeast Papuan peninsula coast. The crustal structure north-northwest of LAT is not likely to be the same as that towards the southeast but there is little other geophysical data to speculate on a crustal model.

Conclusions

The following conclusions can be drawn from the data presented:

The value of the residual at Port Moresby as determined from Novaya Zemlya explosions is apparently significantly different from previous evaluations, but the location of the velocity variation along the ray path leading to the travel-time difference cannot be determined without precise data on shot times and locations.

The residual differences from Port Moresby seismic station at other stations throughout the Papuan peninsula can reasonably be explained in terms of variations in crustal structures in this tectonically complex area.

A regional crustal effect which can be recognised is a tendency towards negative residual differences on the northeast side of the peninsula.

The determination of regional residual values from widely spaced observatories must take into consideration the sometimes considerable crustal effects. This would best be achieved by operating small seismic networks rather than single observatory sites.

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Conodont apparatuses in an Upper Devonian palaeoniscoid fish from the Canning Basin, Western Australia

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Conodont elements recovered from the gut region of a palaeoniscoid fish from the Gogo Formation, Upper Devonian (Frasnian), of the Canning Basin, Western Australia, are assigned to two multielement taxa. The complete apparatus of *Oulodus angulatus* (Hinde) has 15 elements, most of which have excellent preservation of the basal plate. An additional 13 elements are assigned to the *Icriodus brevis* apparatus which is not a complete apparatus.

The term 'crown' is introduced for the upper part of the conodont element. A conodont element, or element, is thus composed of two parts, the upper part or crown, and the lower part or basal plate. Four new terms—boss structure, prong, furrow and notch—are introduced to describe features of the basal plate.

Introduction

Examination of a limestone nodule collected by the author in 1972, from the Gogo Formation (Upper Devonian) of the Canning Basin (Fig. 1), Western Australia, has revealed the presence of conodont elements located in the gut region of a stegotrachelid palaeoniscoid fish. The fish has not yet been prepared or identified, but probably can be referred to one of three monotypic genera of palaeoniscoid fish that have been recovered from the Gogo Formation (Gardiner, 1973; Gardiner & Miles 1975), and are now being studied by Brain G. Gardiner of Queen Elizabeth College, University of London.*

The nodule, 115 mm long and 82 mm wide, was split along the axial plane of the fish with part of the fish adhering to each half of the nodule (Fig. 2). The fish is slightly more than 100 mm in length and has only the tip of the caudal fin missing. Preservation of the palaeoniscoid fish is excellent with intact scale layers and bone structure of the head region. Directly under the scale layer throughout much of the body region is a fibrous white layer (Fig. 3E, F) that may represent mineralisation of the muscle tissue of the fish. The gut region is delineated by the presence of sparite and silty looking material between the scale layers. There are also patches of dark organic material concentrated in the gut region of the fish.

Broken edges of conodont elements (Fig. 3A), subsequently identified as belonging to the multielement genus *Oulodus*, Sweet & Schonlaub (1975), were observed on the right half of the nodule. After initial photography a 10 percent solution of acetic acid was applied, drop by drop, to a small region surrounding the conodonts. The process was observed under the microscope and a series of photographs, Fig 3B-F, was taken at several stages. When the last of the conodont elements had been removed a cavity about 7 mm in diameter and 2 mm deep had been etched in the fish, and had extended slightly into the calcareous siltstone matrix of the nodule.

As the etching process progressed it became apparent that the elements represented a complete and intact apparatus with exceptional preservation of the basal plates. Some of the elements of the apparatus were broken when the nodule was originally split, but all elements within the right half of the nodule were unbroken. No elements were observed on the left half of the nodule and it is assumed that a thin sliver of material was lost when the nodule was split.

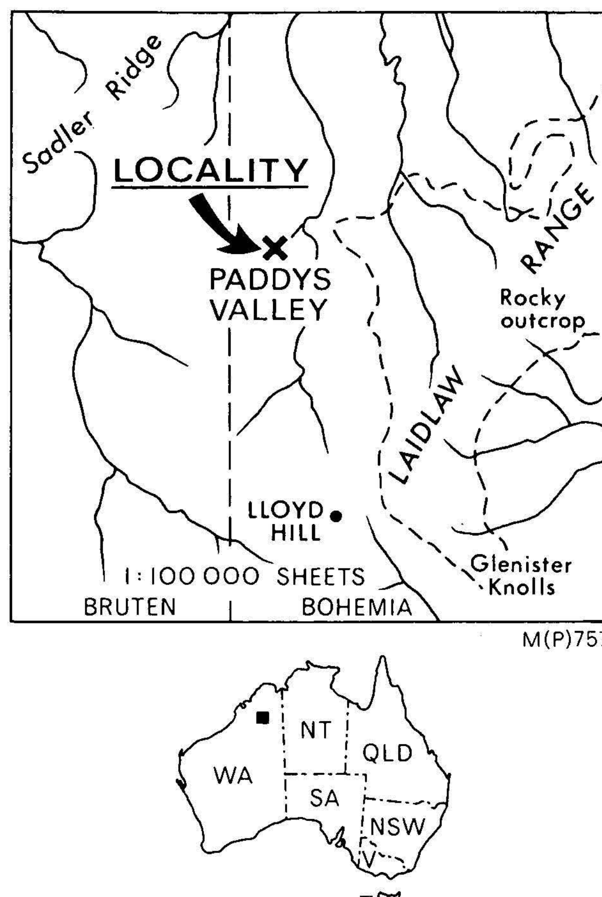

Figure 1. Locality map.

Study of the complete elements of the *Oulodus* apparatus has presented a problem of terminology. The majority of previous workers have applied the term conodont or conodont element to the laminated, denticulate structure which may or may not have had a basal plate attached to the 'lower' surface. Other workers, most recently Muller & Nogami (1971, 1972), have restricted the term conodont to the upper part of the element. The majority of present workers apply the terms conodont element or element to the entire structure of each individual part of an apparatus, that is the upper part and the basal plate. Because there is no unambiguous term for the upper part of the element it is suggested that the crown be applied to the upper part of the conodont element. Thus a conodont element would be

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* Since this paper went to press, two stegotrachelid palaeomisciform fish from the Gogo Formation have been described by Gardiner & Bartram (1977). These are *Mimia toombsi* and *Moythomasia durgaringa*. The specimen from this study probably belongs to one of these species, but until the fish is prepared, identification is not possible.

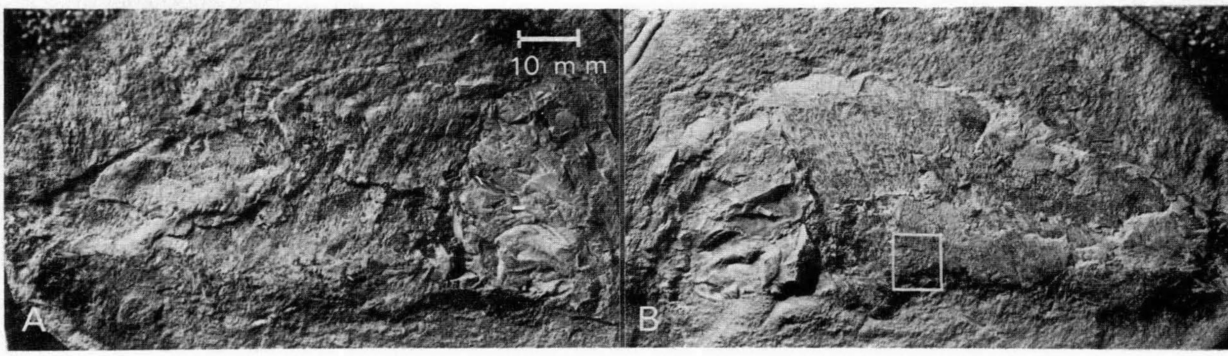


Figure 2. Left and right halves, respectively, of the limestone nodule containing the palaeoniscoid fish and conodont apparatuses. The square on Figure 2B outlines the area shown in Figure 3A-F.

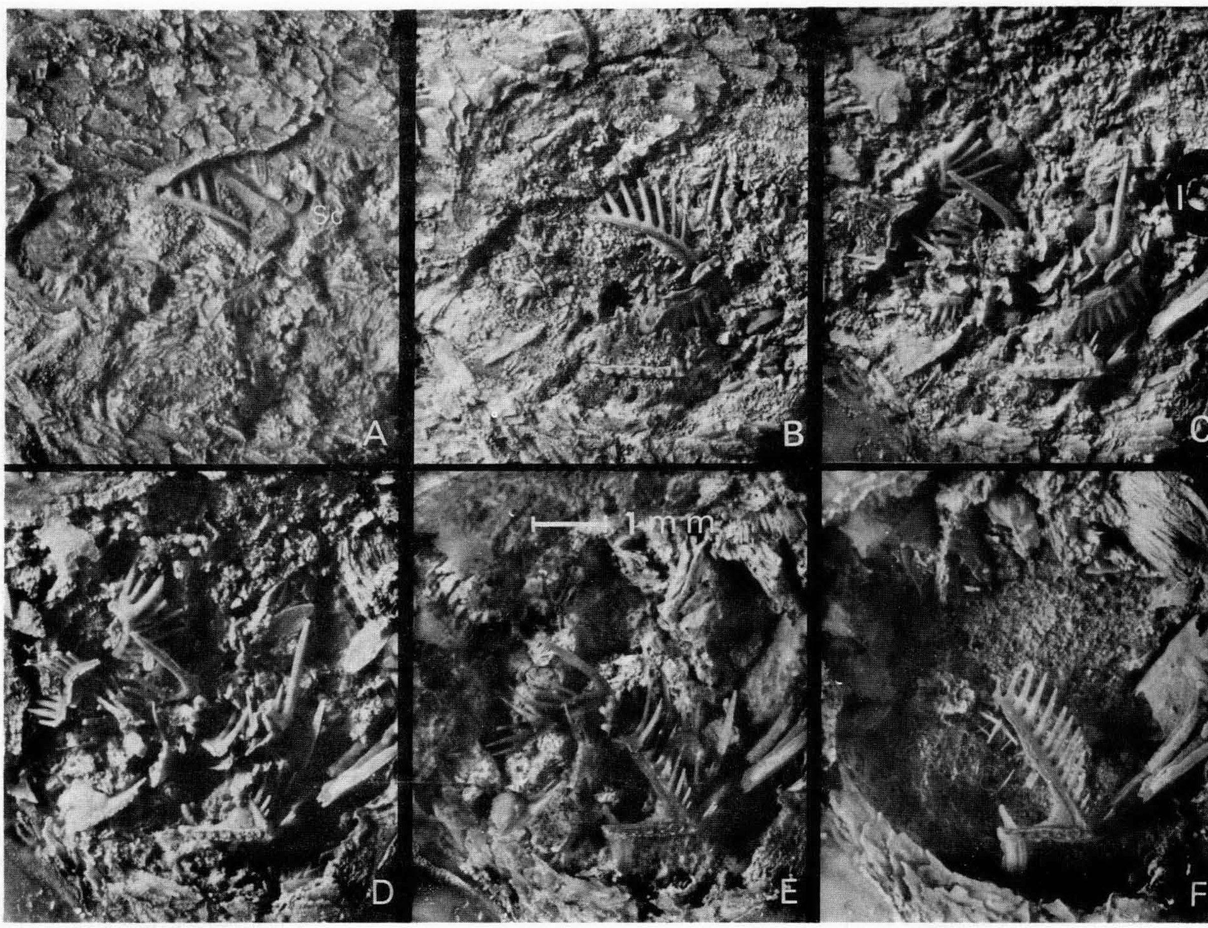


Figure 3. Sequence showing the area containing the conodont apparatuses at different stages of the acidization process. 3A-prior to etching, note impression of Sc element (CPC 17195). 3B-early etching stage. 3C-note I element of *Icriodus brevis* apparatus (circled). 3D, E-later stages of etching, note probable mineralized muscle fibres in upper right corner. 3F-Sa element with floor of cavity showing matrix and sponge spicules underlying fish.

composed of two parts, an upper part termed the crown and a lower part termed the basal plate.

Locality and specimen data

The limestone nodule containing the fish and the conodont elements was collected from an exposure of the Gogo Formation, Upper Devonian (Frasnian), in Paddys Valley, between the Laidlaw Range and Sadler Ridge, grid ref. 4160-840360, Bohemia 1:100 000 topographic map.

The material from this study has been assigned the following CPC numbers. Elements of the *Oulodus angulatus* apparatus—CPC 17192-17206. Elements of the *Icriodus brevis* apparatus—CPC 17202-17210. The faunal slide containing the discrete conodont elements enumerated in Table 1—CPC 17221. The two halves of the nodule containing the fish—CPC 17220. In addition one faunal slide that contains the insoluble residue from around the conodont elements within the fish—CPC 17222, and a faunal slide that contains fish fragments, sponge spicules and one fragment of crustacean exo-skeleton from the 297 g of dissolved nodule—CPC 17223.

Conodont elements recovered

In all, 15 elements representing a complete *Oulodus* apparatus and 13 elements of an *Icriodus* apparatus were recovered from the cavity dissolved in the gut region of the fish. All elements of the *Oulodus* apparatus were observed in situ (Fig. 4), and comments will be made on the nature and function of the apparatus. Only one I element (Fig. 7N-Q) of the *Icriodus* apparatus was observed in situ (Fig. 3C) and the rest of the elements of this apparatus were recovered from the insoluble residue of the cavity.

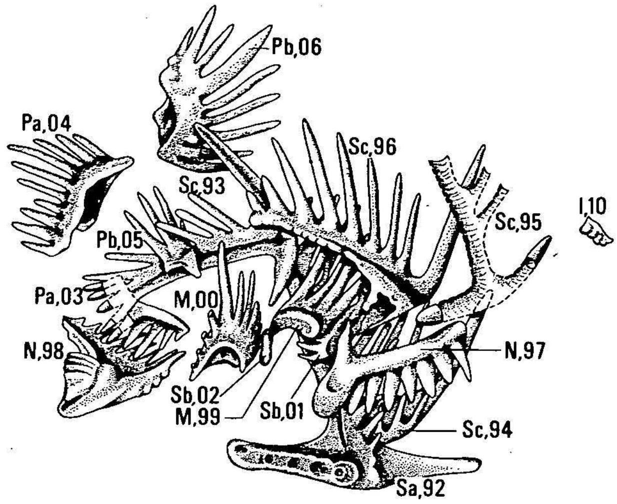


Figure 4. Drawing showing relative positions of the elements of the *Oulodus* apparatus and the single I element of the *Icriodus* apparatus prior to their removal from the nodule. The number is the last two digits of the CPC accession number. Symmetrical element: Sa-92. Left elements: Sc-93, 94; N-97; M-99; Sb-01; Pb-05; Pa-03. Right elements: Sc-95, 96, N-98; M-00; Sb-02; Pb-06; Pa-04.

An additional 37 discrete elements were recovered from a slab cut from the outer edge of the right half of the nodule (Table 1). The slab, was processed without crushing, and the residue collected by decanting. A number of elements belonging to the *Icriodus brevis* (14) and *Oulodus angulatus* (2) apparatuses were recovered along with 21 elements that were assigned only to form taxa or left in open nomenclature.

The number and types of discrete elements recovered from the slab suggest that the *Icriodus brevis* and *Oulodus angulatus* apparatuses recognised from the body cavity are not representative of the random distribution of elements in the associated matrix material.

Element type	Number of elements
Icriodus brevis	
I element	12
S_1 element	2
Oulodus angulatus	
M element	1
Pb element	1
Pa elements	
Polygnathus xylus	4
Spathognathodus brevis	1
Pb elements	
ozarkodinan	2
N elements	
neoprioniodontan	1
Sa (A_3,B_3) elements	
hibbardellan	1
Sb (A_2,B_2) elements	
angulodontan	2
lonchodinan 'a'	1
lonchodinan 'b'	1
Sc (A, B) elements	
hindeodellan 'a'	2
hindeodellan 'b'	3
hindeodellan 'c'	1
ligonodinan 'a'	1
ligonodinan 'b'	1
	37

Table 1 Disjunct elements recovered from nodule.

The composition and function of the *Oulodus* and *Icriodus* apparatuses discussed in the following sections is based only on the elements recovered from the gut region of the fish.

The *Oulodus* apparatus

Sweet & Schonlaub (1975) recognised the multielement genus *Oulodus* as an apparatus composed of six distinct morphologic types and placed in synonymy the multi-element taxa *Delotaxis* Klapper & Philip, and *Ligonodina* Bassler *sensus* Jeppsson that were thought to contain only five element types. In the present study the apparatus assigned to the multielement genus *Oulodus* has seven element types.

Sweet & Schonlaub (1975, p. 42) recognised the six components of their *Oulodus* apparatus on the basis of similar morphologic features of the elements. However it is now apparent that gross morphologic similarity of all types of elements within an apparatus is not necessarily a fact. In the *Oulodus* apparatus recovered in this study the denticles and general morphology of the N element are different from those of all other elements of the apparatus.

In the following section the letter designations of elements suggested by Sweet & Schonlaub (1975) are followed except that the neoprionioodontiform element, not recognised by Sweet & Schonlaub, is designated by the letter N.

Systematic description

Genus *Oulodus* Branson & Mehl, 1933

Type species: *Cordylodus serratus* Stauffer, 1930 (= senior subjective synonym of *Oulodus mediocris* Branson & Mehl, 1933, the originally designated type species).

Oulodus angulatus (Hinde, 1879)
(Figs. 5, 6)

Sa element

1879 *Prioniodus angulatus* Hinde, p. 360, pl. 15, fig. 17.
1933 *Hibbardella angulata* (Hinde), Branson & Mehl, p. 141, pl. 11, fig. 16.
1968 *Hibbardella angulata* (Hinde), Huddle, pl. 14, pl. 8, figs. 2, 7; pl. 9, fig. 3 (with synonymy).
1970 *Hibbardella* sp. cf. *H. angulata* (Hinde), Seddon, pl. 15, figs. 13, 16.

Sc element

1879 *Prioniodus panderi* Hinde, p. 361, pl. 16, fig. 4.
1926 *Ligonodina panderi* (Hinde), Ulrich & Bassler, p. 13, pl. 2, figs. 1, 2.
1968 *Ligonodina panderi* (Hinde), Huddle, p. 19, pl. 9, fig. 11, pl. 10, figs. 1-8, 11 (with synonymy).
1970 *Ligonodina panderi* (Hinde), Seddon, pl. 15, figs. 8, 10.

N element

1879 *Prioniodus? alatus* Hinde, p. 361, pl. 16, fig. 5.
1957 *Neoprioniodus alatus* (Hinde), Hass in Cloud, Barnes & Hass, p. 809, pl. 4, fig. 3.
1968 *Neoprioniodus alatus* (Hinde), Huddle, p. 25, pl. 6, figs. 1, 2 (with synonymy).
1970 *Neoprioniodus alatus* (Hinde), Seddon, pl. 15, figs. 12, 14.

Pa element

1970 *Prioniodina?* Seddon, pl. 15, fig. 9.

The above are the only elements that have been positively identified from the literature. The lonchodiniform elements (M, Sb and Pb) are highly variable and no attempt was made to develop synonymies for these elements.

Diagnosis:

An apparatus of 15 elements with 7 morphologic types represented as Pa (2), Pb (2), Sa (1), Sb (2), Sc (4), M (2) and N (2). The Pa element is prioniodiniform, Pb element is lonchodiniform, Sa element is hibbardelliform, Sb element is lonchodiniform, Sc element is ligonodiniform, M element is lonchodinoform, and the N element is neoprioniodontiform.

Description:

The 15 elements of the *Oulodus* apparatus form three groups based on the morphology of the crown and the basal plate. The first group has three element types (N, Sa, Sc), and 7 elements. The members of this group are characterised by long posterior processes and shorter downward directed anterior or anterior-lateral processes.

The second group contains 2 element types, Sb and M, and 4 elements. Members of this group have processes of similar length with a tendency for the anterior process to be the longest. The third group also contains 2 element types, Pa and Pb, and has 4 elements.

Four new terms are applied to features found on the basal plate: these are boss structure, prong, furrow and notch. Boss structures (Fig. 5X-CC) are small raised features distributed over part of the upper surface of the basal plate; most have an oblong outline and at high magnification (Fig. 5AA) have a rough surface texture. There is no preferred orientation of the long axis of the structure.

Prongs are projections on the margin of the basal plate. These are best developed on the N and M elements (Figs. 5F-H, 6J & K), but are also found on other elements. Furrows are grooves on the upper surface of the basal plate. The furrows may radiate from the vicinity of the contact between crown and basal plate to the margin of the plate, as in the N and M element (Figs. 5F & I, 6L), or show a complex of radiate and parallel pattern as in the Sc element (Fig. 5X). The notch is a deep identation of the margin of the basal plate. This feature is developed on the inner lateral margin of M and Sb elements (Fig. 6L, N, & V) and on the outer lateral margin of the Pa and Pb elements (Fig. 6T & BB). The notch is interpreted as an accommodation by the basal plate to a T or L-shaped ridge in the soft anatomy of the organism to which the element was attached. The Sc and Sa elements have an elongated posterior process that is attached to this ridge with short lateral processes that are transverse to the long ridge, and presumably follow the axis of a short transverse ridge. The elements of Groups 2 and 3, lacking posterior processes, are located on the short transverse ridge; the notch accommodates the long ridge which is not covered the element.

Group 1:

The Sa element is hibbardelliform with prominent downwardly directed lateral processes and a long, well-developed posterior process on which the denticle size increases posteriorly towards the end of the bar. The basal plate is developed as a web linking the posterior and lateral processes and narrows toward the tip of the posterior process.

The Sc element is ligonodiniform and the four elements represent two left-right pairs. The three elements that were recovered intact are morphologically similar but are not identical. It is impossible to conclusively pair the well-preserved left element with either of the right elements to establish a direct mirror image pair due to the minor morphologic variation that is expected between paired elements.

The N element has denticles that are laterally compressed, and the lower part of each denticle is fused to the adjacent one. The crown has a prominent anticusp and a large flange on the lower inner margin of the cusp denticle. The basal plate is largest under the cusp and narrows toward the anticusp and the end of the posterior process.

The N element is placed in group 1 because it has a long posterior process (conventional orientation), but this element type differs from all other elements in the cross-sectional profile of the denticles. All other element types have discrete denticles with a small ridge or flange on the margin of the denticle. Denticles of the N element lack this flange and are fused with adjacent denticles near the bar.

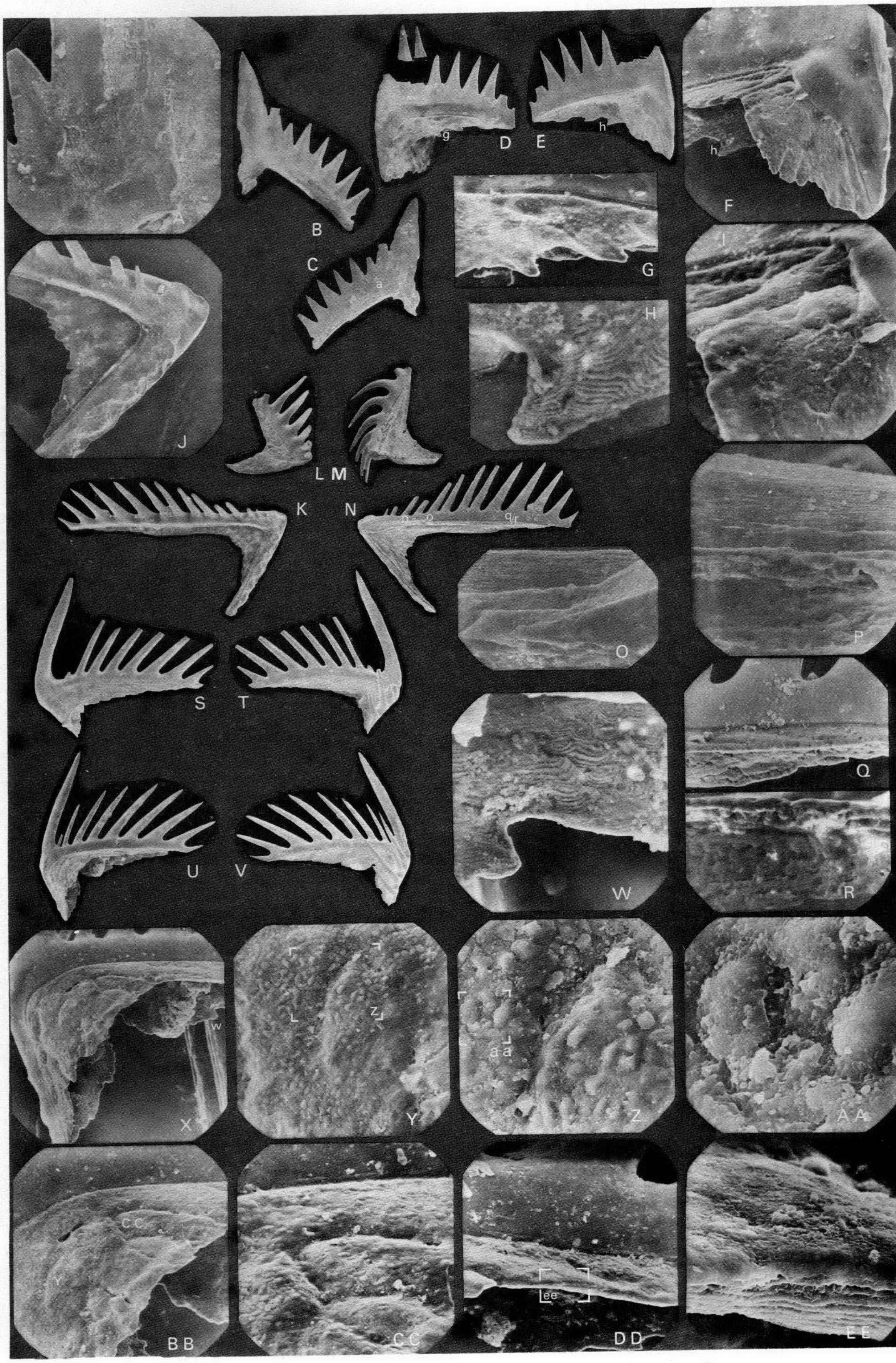
The inner surface of the basal plate of group 1 elements shows parallel ribs along the portion of the plate that extends along the posterior process. However under the cusp the ribs give way to a pattern of intersecting ridges (Fig. 6A, B). The ribs probably continue under the reticulate pattern.

Group 2:

The M and Sb elements of this group are characterised by similar lengths of the processes, with the anterior process slightly longer, and a large notch in the inner lip of the basal plate.

The M element is lonchodiniform. The anterior process has 5 to 7 denticles, the posterior process 4 to 5. The cusp is slightly offset to the inner side and all denticles are posteriorly directed. The two denticles just anterior to the cusp are joined slightly above the process. The inner lip of the basal plate is broader than the outer lip, but it has a large notch located below the cusp that is not found on the

Figure 5. ***Oulodus angulatus* apparatus. Small letters on photos indicate location of areas shown in enlargements. A-C, N element, CPC 17197.** A. enlargement of etched outer lateral surface (100X). B. inner lateral view (20X). C. outer lateral view (20X). **D-I, N element, CPC 17198.** D. outer lateral view (23X). E. inner lateral view (23X). F. view of basal plate below cusp showing deep furrow structures (100X). G. outer view of prongs developed on margin of basal plate (85X). H. inner view of the posterior of the two prongs in G (350X). I. view of the outer surface of the basal plate showing the contact of the basal plate and the crown, furrows, and boss structures (230X). **J-R, Sa element, CPC 17192.** J. anterior part of element showing basal plate web developed between the posterior and lateral processes (42X). K. oral view (16X). L. oral view of broken left lateral process (16X). M. aboral view of broken left lateral process (16X). N. aboral view (16X). O. aboral view of left margin of basal plate showing basal plate (broken margin) and ridged under lip of the crown (300X). P. aboral view of left margin of basal plate showing transect from ribbed under lip of crown, broken attachment area of basal plate to crown, and part of the aboral surface of the basal plate (300X). Q. aboral-lateral view of part of the posterior process showing ribbed pattern and irregular grooves (72X). R. aboral view of area shown in Q (X). **S-T, Sc element, CPC 17194.** S. outer lateral view (14X). T. inner lateral view (14X). **U-EE, Sc element, CPC 17193.** U. outer lateral view (13X). V. inner lateral view (13X). W. aboral view of basal plate showing contortion of ribs (280X). X.-AA. progressive enlargement of outer lateral basal plate surface to show detail of boss structures and furrows. X (40X), Y (150X), Z (370X), AA (1350X). BB. outer lateral surface of basal plate showing detail of furrows (80X). CC. enlargement of area of branching furrow structures (170X). DD. view showing the relationship of the crown surface, and the oral and aboral surfaces of the basal plate. Note that the boss structures are more prominent toward the crown-plate contact (100X). EE. enlargement of lower edge of the basal plate showing the transition from the ribbed aboral surface to the rough upper surface to the rough upper surface (500X).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outer lip. The edge of the basal plate around the notch is regular and there is no indication that the notch is the result of breakage.

The Sb element is also lonchodiniform. Only one of the two Sb elements is complete (Fig. 6V-Y)—the second is represent only by isolated denticles (Fig. 6P). The element has 5 posterior and 4 anterior denticles, but the tip of the anterior process is broken. The cusp is posteriorly directed and both processes are bent slightly posteriorly. As with the M element the outer lip of the basal plate is smaller but continuous, and the inner lip is larger, but interrupted by a large notch.

I have oriented both the M and Sb elements transverse to the long axis of the apparatus (Figs. 9,10). This is based on the orientation of the elements when found (Figs. 3E, 4), and the attitude of the denticles.

The basal plate of the M and Sb elements is not as well preserved as those in group 1. However they show similar furrows and boss structures on the upper surface. The lower surfaces have parallel ribs developed under the lateral processes and the over-coating of smooth or reticulate pattern under the cusp (Fig. 6J).

Group 3:

The Pa and Pb elements are the most posterior elements of the apparatus. I have shown them surrounding the mouth area in the reconstructed apparatus (Fig. 10).

The Pb element is lonchodiniform, with 5 denticles on the anterior process, and 3 denticles on the posterior process. The element is slightly bowed and arched with the denticles curved posteriorly and slightly inward. There is a prominent notch below the cusp on the outer lip of the basal plate. The inner lip of the basal plate is broken, and it is not clear if there was a notch on the inner side.

The Pa element is prioniodiniform with 6 anterior and 4 posterior denticles. Denticles of this element are erect, the element is bowed outward, and the posterior process is bent slightly down. There is a notch in the outer lip of the basal plate but, again, the inner lip is broken and no notch can be seen.

Unlike the elements of group 2, the elements of group 3 have a notch on the outer lip of the basal plate. This is taken to indicate a more normal orientation for these elements. The ridges of soft tissue of the group 3 element could have been roughly parallel to the tissue ridges of groups 1 and 2. Boss structures and shallow furrows are present on the outer surfaces of the basal plates.

The *Icriodus* apparatus

The *Icriodus* apparatus was shown by Klapper & Philip (1971) to consist of two element types, I and S_2. Later Klapper & Ziegler (1975, p. 67) suggested that the *Icriodus* apparatus might also contain a M_2 element. The present study confirms the presence of an M_2 element in the apparatus.

A total of 13 elements of an *Icriodus* apparatus were recovered from the body cavity of the fish. There were 4 I elements, 6 S_2 elements and 3 M_2 elements. Only one, an I element, was observed in situ (Fig. 3C) during the etching process and the rest were picked from the residue.

Systematic description

Genus *Icriodus* Branson and Mehl, 1938

Type species: *Icriodus expansus* Branson and Mehl, 1938;
Icriodus brevis Stauffer, 1940
Fig. 7

Synonymy:

I Element

1940 *Icriodus brevis* Stauffer, p. 424, pl. 60, figs. 36, 43, 44, 52.

1975 *Icriodus brevis* Stauffer, Klapper, p. 89, pl. 3, figs. 1-3 (with synonymy).

S_2 Element

Stauffer (1940) described several species of *Acodina* from Austin, Minnesota. Several of them appear from the illustrations to be within the range of variation of the S_2 elements recovered in this study. The species of *Acodina* include *A. velva*, *A. concava* and *A. cuspidata*. Without an examination of both original and topotypic material to establish its variability, it is impossible to assign the specimens from this study to a form species. It is probable that all three species of *Acodina* named above were associated with the *I. brevis* apparatus.

M_2 Element

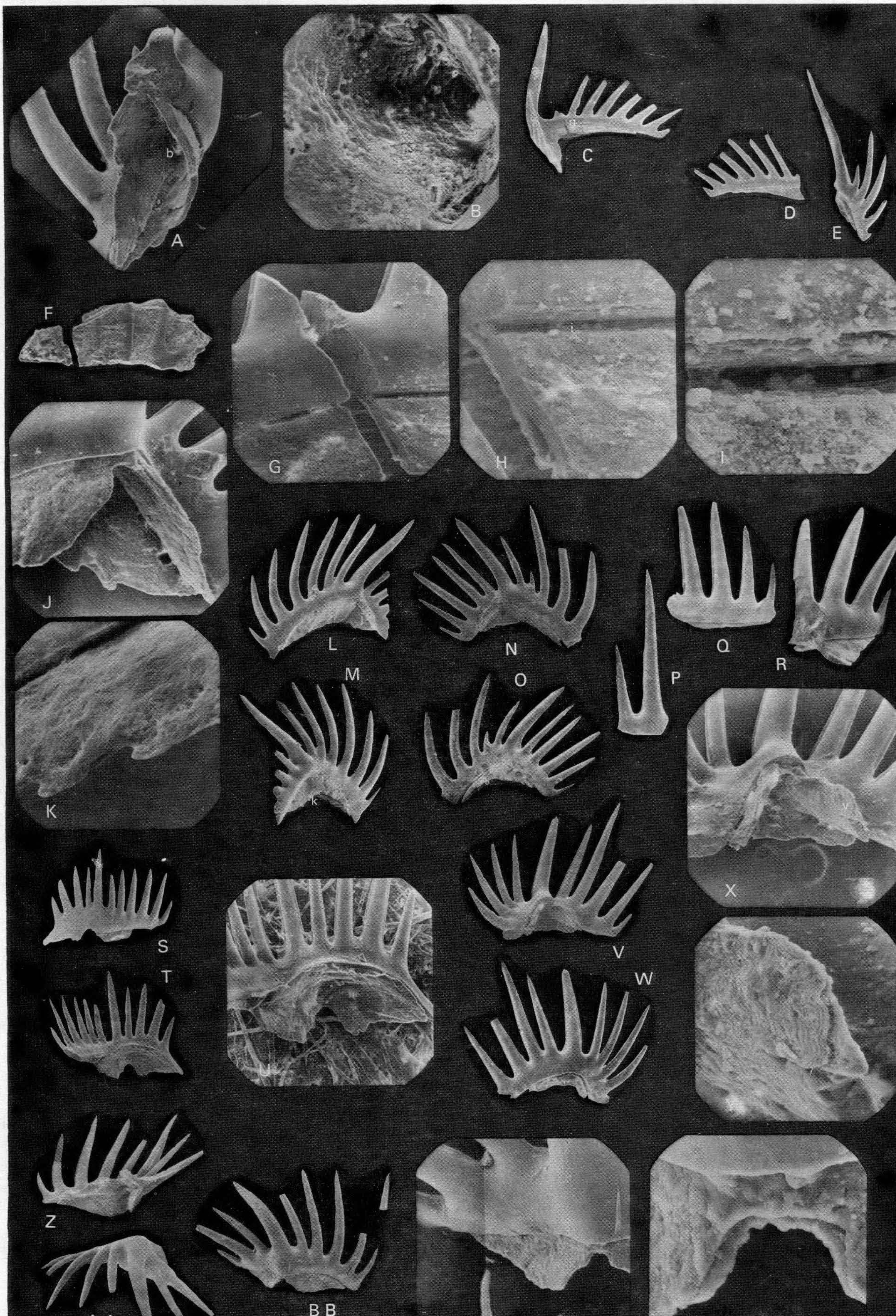
Stauffer does not appear to have recognised any M_2 elements.

Remarks:

Four I elements were recovered. These show a size gradation from the smallest with only one pair of lateral row denticles to, the largest specimen with 4 pairs of lateral row denticles. The lateral denticles are curved outward and upward, and there is no ridge between them and denticles of the middle row. The posterior denticle is the largest denticle and is morphologically very similar to the S_2 element. In the smallest specimen (Fig. 7A-E) the posterior denticle is striated. Middle row denticles range from 3 to 7 in number.

The 6 S_2 elements recovered show a range of morphology. All are laterally compressed with a slight flare of both the anterior and posterior margins a short distance above the base of the crown. Two of the specimens (Fig. 7V, W, Z-CC) were joined by the basal cone when found; however in moving them on the SEM stub the elements separated. The two elements are recurved posteriorly, and the axial plane slightly twisted so that there is a slight en echelon arrangement. The tips of these elements are striated.

Figure 6. *Oulodus angulatus* **apparatus. A-E, G-I. Sc element, CPC 17196.** A. posterior view of broken anterior end showing relationship of basal plate to crown (85X). B. enlargement of the apex of the aboral surface of the basal plate (290X). C. inner lateral view (13X). D. outer lateral view of posterior process (13X). E. anterior view (13X). G. enlargement of break in posterior process (120X). H. junction of basal plate and crown showing ridged surfaces of both parts and the narrow solid connection (250X). I. closeup of area outlined in H showing ridged surfaces of crown and basal plate (500X). F. Sc element, CPC 17195. part of posterior process adhering to the inner surface of fish-scale layer (20X). **J-M, M. element, CPC 17200.** J. enlarged inner lateral view showing notch and prongs on outer lateral margin (100X).K. enlargement of outer lateral margin of basal plate showing prongs (220X). L. inner lateral view, note notch (22X). M. outer lateral view, note lack of notch (22X). **N, O, M element, CPC 17199.** N. inner lateral view (22X). O. outer lateral view (22X) **P. Sb element, CPC 17202.** fragment of posterior process (50X). **Q. Pa element, CPC 17203.** fragment of anterior process (50X). **R. Pb element, CPC 17205.** fragment of posterior process (50X). **S-U, Pa element, CPC 17204.** S. outer lateral view, note notch in basal plate (22X). T. inner lateral view (22X). U. enlargement of basal plate area, note notch on outer margin of basal plate (50X). **V-X, CC. Sb element, CPC 17201.** V. inner lateral view (26X). W. outer lateral view (26X). X. enlarged inner lateral view showing notch area (65X). Y. enlargement of margin of basal plate showing edge and laminae (130X). **Z-DD, Pb element, CPC 17206.** Z. aboral view (17X). AA. oral view (17X). BB. outer lateral view (17X). CC. enlarged outer lateral view showing notch development (29X). DD. enlargement of area shown in AA to show tip of notch (160X).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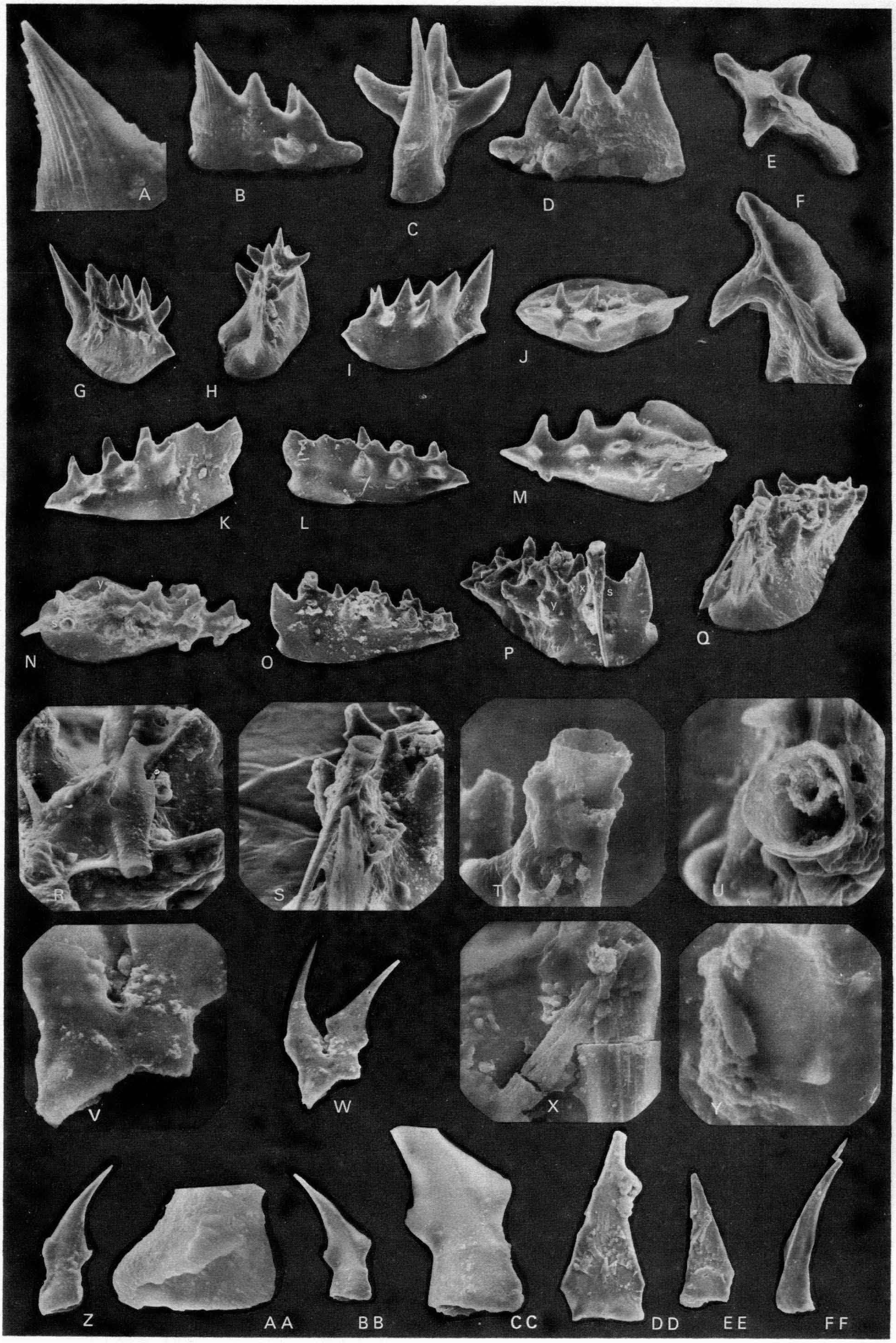
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Only three M_2 elements were recovered. Two were adhering to the side of the largest I element (Fig. 7P), and the third was free in the sediment. The elements have sub-rounded cross sections of the lower part of the crown, and the basal cone continues this outline. The crown is striate for most of its length.

Lange (1968) assumed a model of 1 pair of I elements to 30 cone elements for the *Icriodus* apparatus. Bultynck (1972) however has argued that the I element was not associated with any cone element. From this study it appears that the *Icriodus* apparatus has at least three distinct morphologic elements; the I element, a laterally compressed S_2 element, and a rounded to subround M_2 element. All element types show a broad range of morphologic variation. There were at least 4 I elements, 6 S_2 elements and 3 M_2 elements in the *Icriodus brevis* apparatus. As none of the I elements is paired it is probable that there were at least 8 I elements, i.e. 4 pairs, in the original organism, and an undetermined number of S_2 and M_2 elements.

Interpretation of the conodont elements

Oulodus apparatus

The elements of the *Oulodus angulatus* apparatus allow an interpretation of the position of elements within the conodont organism and of their possible function. This interpretation is based on the complete or nearly complete basal plates found on all elements of the apparatus, as well as the morphology of the crown and the relative position of the elements.

The elements assigned to the *Oulodus angulatus* apparatus represent the only hard parts of that conodont organism. Despite the presence of what is thought to be post-mortem mineralisation of the muscle tissue of the fish, there were no structures observed during the etching process that could be related to the elements. This is a clear indication that the conodont organism was, with the exception of the elements, composed only of non-mineralised tissue. The conodont elements must have been attached to soft tissue.

Three distinct tissue types were in contact with different surfaces of the element (Fig. 8). These are the smooth crown surface, the rough boss-covered upper basal plate surface, and the parallel ribs of the aboral basal plate surface. Functionally the ribbed surface of the lower part of the basal plate would have been excellent for attachment of the element to the supporting tissue of the organism because of the greatly increased area of the attachment surface. The surface of the crown is smooth when compared with the upper surface of the basal plate that is marked with boss structures. The upper surface of the basal plate was probably embedded in supporting tissue—which may have included muscle fibres, regulating the fine movement of the element, that were attached to the boss structures.

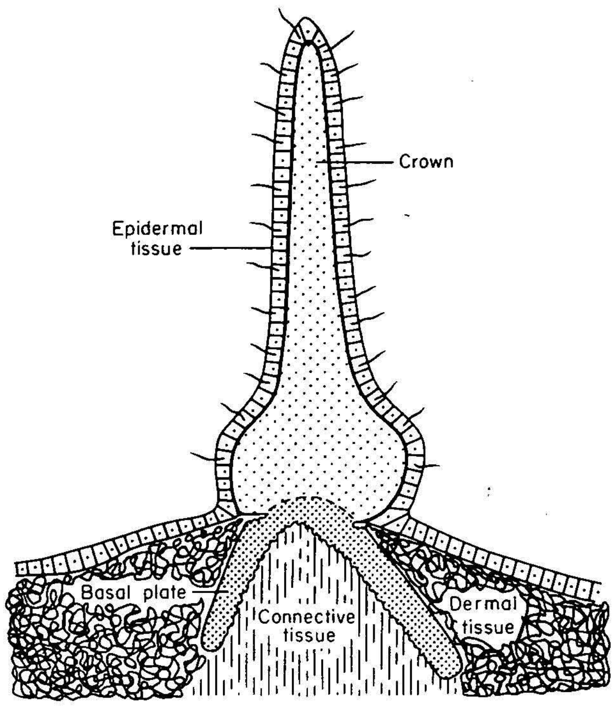

Figure 8. Cross-section of element showing hypothetical soft tissue relationships.

Bengston (1976, 1977) suggested that the crown was not tissue-covered, and that growth took place when the element was withdrawn into a pocket while not functioning. I disagree with Bengston and believe that the crown surface was tissue-covered, and that growth took place by precipitation from the inner surface of this tissue layer. Lindstom (1973, 1974) has argued this to be the case, and Morris (1976) suggests that the 'teeth' of *Odontogriphus omalus*, which may be conodont elements, were covered by tentacles. Conceptually it is hard to envisage the growth of the more complex platform elements by the process put forward by Bengtson.

The furrow structures on the basal plate surfaces may be the impression of nerve or circulatory pathways. Similar features are common on vertebrate bones, especially those of the head region.

Icriodus apparatus

Two aspects of the *Icriodus* apparatus require comment. One is the pair of S_2 elements (Fig. 7W) that were fused by the basal cones, the other is the size disparity shown by both the S_2 and I elements.

As stated earlier the basal cones of two of the S_2 elements (Fig. 7Z, BB) were fused when first observed (Fig. 7V, W). The crown portions of these elements had a slight en echelon arrangement. After separation it can be seen that the basal cone of the left element (Fig. 7AA) is modified to fit over the leading edge of the basal cone of the right element

Figure 7. *Icriodus brevis* **apparatus. A-F, I element, CPC 17207.** A. enlargement of ribbed posterior denticle (270X). B. right-lateral view (185X). C. posterior view (250X). D. left-lateral view (215X). E. oral view (200X). F. oblique-aboral view (225X). **G-J, I element, CPC 17208.** G. oblique right-lateral view (110X). H. posterior view (110X). I. oblique left lateral view (110X). J oral view (110X). **K-M, I element, CPC 17209.** K. oblique left-lateral view (90X). L. oblique right-lateral view (90X). M. oral view (110X). **N-Q, I element, CPC 17210.** N. oral view, the M_2 elements CPC 17216 is located near the posterior denticle; the S_2 element CPC 17218 is located on the large posterior left denticle; and the S_2 element CPC 17215 is located between the second pair of lateral row denticles (105X). O. right-lateral view (90X). P. oblique left-lateral view (120X). Q. oblique posterior view (120X). **R. S_2 element, CPC 17215.** lateral view (390X). **S-U, M_2 element, CPC 17216.** S. lateral view (240X). T. enlargement of basal cone and adjacent part of crown (375X). U. aboral view of tube-like structure inside the basal cone (400X). **V, W, Z-CC, S_2 elements; CPC 17211 and 17212.** V. enlarged view of base of fused elements (350X). W. lateral view (140X). CPC 17211. Z. lateral view (165X). AA. enlargement of basal cone (600X). CPC 17212. BB. lateral view (160X). CC. enlargement of crown and basal cone (360X). X, probable M_2 element, CPC 17219, element lying partly across M_2 element CPC 17216 and attached to I element CPC 17210 (400X). Y. S_2 element, CPC 17218. very small element attached to posterior left-lateral denticle of I element CPC 17210 (680X). **DD. S_2 element, CPC 17213.** lateral view (140X). **EE. S_2 element, CPC 17214.** lateral view (145X). **FF. M_2 element, CPC 17217.** lateral view (250X).

(Fig. 7CC). The relationship of these cone elements is similar to specimens illustrated by Walliser (1964, text fig. 2; plate 10, figs 1-4, *non* fig. 9).

The relationship of the two S_2 elements may indicate that rather than functioning as discrete elements within the apparatus, several S_2 elements formed an elongate structure. This format would mean that cone elements, for some apparatuses, had a similar function to bar-type elements. I do not, however, think that these bar-type structures are similar to those described by Bischoff (1973) as conodont-supporting elements.

This fused relationship may also have a bearing on the origin of the double tip of the basal cavity that has been observed in most I elements. There is a close similarity between the morphology of the large posterior denticle of the I element and the associated S_2 element. In some cases the I element is constricted between the ultimate and penultimate denticles (Fig. 7F). This may be an ontogenetic demonstration of the fusion of an S_2 element to the I element at some point in the early phylogeny of the genus *Icriodus*. This view may be supported by the lack of lateral denticles associated with the posterior denticle of many I elements.

Both the I and S_2 elements show a considerable size range. The I elements also show progressive addition of middle and lateral row denticles. This is in marked contrast to the relatively uniform size and appearance of the elements of the *Oulodus* apparatus. The size range and denticle addition may indicate that elements are progressively added to the *Icriodus* apparatus during the ontogeny of the organism, or at least until maturity is reached. Thus a juvenile specimen of *Icriodus* might have only one pair of I elements, and a mature specimen could have 4 or more pairs of I elements. A similar addition of S_2 and M_2 elements would be expected.

Arrangement of elements in the *Oulodus* apparatus

There have been two basic models of the arrangement of the elements in this apparatus. Early reconstructions by Schmidt (1934), and studies by Scott (1934), and Rhodes (1952), indicated an elongated, bilaterally symmetrical arrangement of the elements. Later studies, such as those of Lange (1968), Jeppsson (1971), and Mashkova (1972), have tended to confirm the above interpretation. Lindstrom (1964, 1973, 1974) has proposed a number of models of the arrangement which culminated in his 1974 paper, in which he presented a hypothetical reconstruction of the conodont animal with the elements, supporting a lophophore, located externally and radially about an anterior mouth.

The *Oulodus angulatus* apparatus is best interpreted as an elongated, bilaterally symmetrical arrangement (Figs. 9, 10). Supporting this interpretation are the numerous occurrences of clusters of elements that have been recovered on rock surfaces, especially those of Scott (1934), Schmidt (1934) and Rhodes (1952), that have this basic linear arrangement. A linear arrangement of structures associated with ingestion of food particles in bilaterally symmetrical organisms, as we believe the conodont to have been, is the norm in the modern biological world. No living organism resembles the Lindstrom's hypothetical reconstruction.

In this study only the *Oulodus angulatus* apparatus has contributed information concerning the arrangement and function of the conodont organism. There is a basic linear arrangement of the elements (Fig. 4), although some of the elements have been skewed relative to their original orientation.

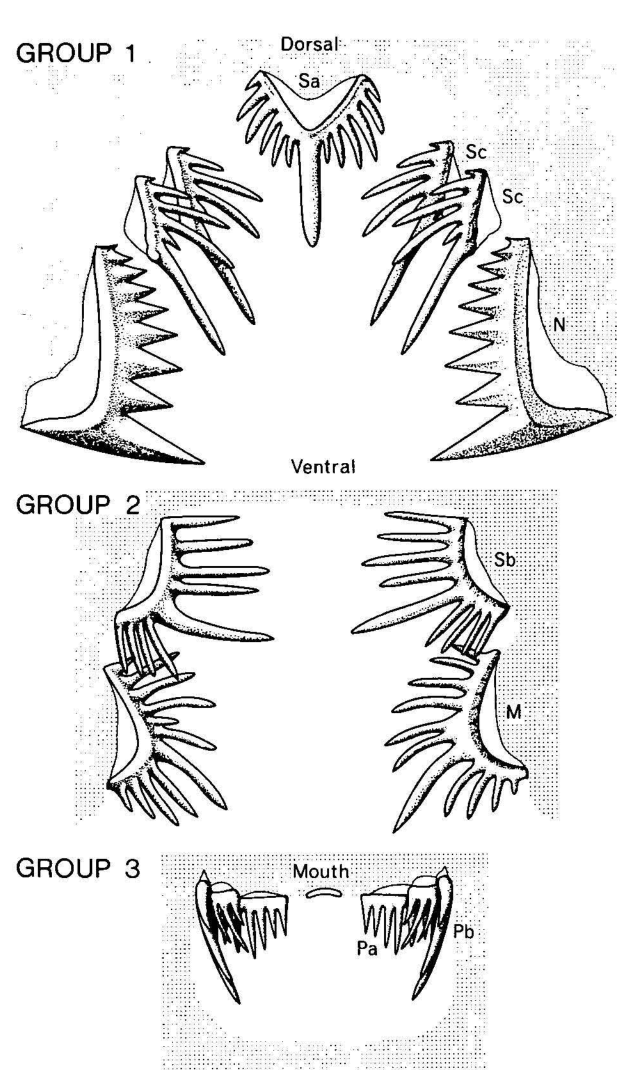

Figure 9. Hypothetical reconstruction showing the anterior views of the three groups of elements of the *Oulodus angulatus* apparatus.

The elements are separated into 3 morphologic groups and, using denticle curvature, the N, Sa and Sc elements are assigned to an anterior position. This group is followed by a transverse-oriented group composed of Sb and M elements. In the last group, the Pa and Pb elements have a posterior position. If the elements are located as shown in Figure 10, then the length of the apparatus, from the N element to the Pa element, must have been between 5.0 and 5.5 mm; this is based on a length of the Sa element of 2.5 mm and of the Pa and Pb elements of about 1.0 mm each. Thus, had the apparatus occupied about 1/10 of the body length, the conodont organism would have been 50 mm long. The Sa element is just over 2.0 mm wide and if it was flanked by the Sc and N elements, the organism was at least 4 mm wide.

Some speculative comments on the function of the conodont apparatus and the nature of the conodont organism

Association of conodont elements with various types of organisms have still failed conclusively to link the conodont organism with any described animal, vertebrate or invertebrate (Lindstrom, 1973). The proposed conodont-bearing organism of Melton & Scott (1973) is dismissed by Lindstrom (1974), and I concur, as more probably representing an organism that ate conodonts.

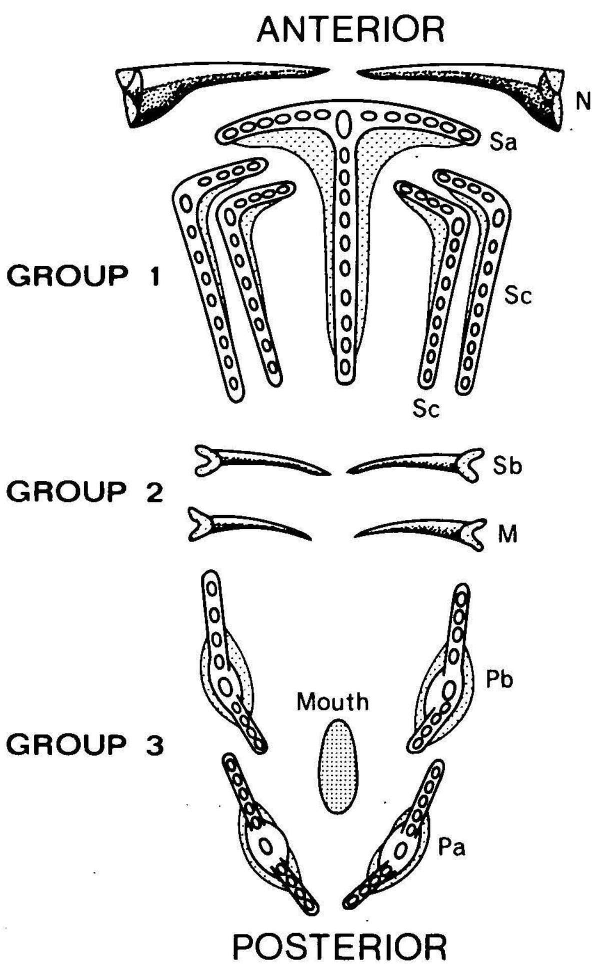

Figure 10. Hypothetical plan view of the elements of the *Oulodus angulatus* apparatus. Overall length is about 5 mm. Elements viewed from ventral surface.

Morris (1976, p. 200) describes his *Odontogriphus omalus* from the Middle Cambrian Burgess Shale as a 'bilaterally symmetrical, dorso-ventrally compressed lophophorate. Body tapering at posterior, head poorly differentiated from the annulated trunk. Head bears double-looped lophophoral apparatus containing tooth-like elements and a pair of lateral palps. Gut straight, mouth ventral, anus probably terminal. Lateral longitudinal muscles running along edges of trunk'.

The lophophore structure of *O. omalus* is poorly preserved but there were about 25 'teeth' that bore a strong resemblance to upper Cambrian cone-type conodont elements. *O. omalus* is about 60 mm in length, and has a width of about 25 mm. *O. omalus* fills most of the theoretical attributes that workers have speculated must be present in the conodont animal: marine, bilaterally symmetrical, lacking in skeletal members except for the conodont elements, and a body length of less than 100 mm.

The mouth or feeding apparatus of most vagrant organisms is located either ventrally or anteriorly. If the conodont organism was either a nektonic or a vagrant benthonic dweller, then the mouth was most probably located near the anterior end of the body and on the ventral surface. A possible reconstruction of the *Oulodus angulatus* apparatus has the elements located in a groove on the ventral surface (Figs. 9, 10). To work effectively elements of group 1 would probably have to have been exposed to the outer surfaces. Elements of group 2 may also have been exposed, but the elements of group 3 might have been partly covered. It would be interesting to examine regeneration of elements statistically to determine if there is a significant difference between specimens showing regeneration between the three groups.

I suggest that the conodont apparatus operated to pick up food particles and direct them toward the mouth region. The three groups enumerated above for the *Oulodus* apparatus would have performed different functions in the food acquisition process. Elements of group 1 could have specialised in picking up food material. Group 2, with its palmate shape, may have directed a water current toward the mouth, and group 3 directed the food particles into the mouth opening.

The denticles of individual elements may have served as supports for tentacles or have been completely, or partially, covered by cilia. I think that the presence of tentacles is unlikely, because the flexibility usually associated with tentacles would have been limited by the rigidity of the denticle. J. W. Pickett (pers. comm., 1977) has pointed out that organisms with ciliated lophophore structures usually are not associated with the vagrant benthonic organisms whose feeding operations may required the movement of large volumes of silt. This leaves an impasse on the mechanism of operation of the elements.

The conodont animal probably fed mostly on micro-organisms and fine organic detrital material. It has generally been assumed (Lindstrom, 1973) that conodont elements, with some exception, are not robust enough to have been employed in an active food gathering operation. However, it is possible that the elements of group 1 are robust enough to have been used to stir up mud and organic sediments from the bottom, and that these and other element served, at least in part, as filter mechanisms to keep inorganic particles out of the alimentary tract.

I suggest that the conodont organism lived a vagrant benthonic or nektonic existence, feeding on micro-organisms and organic detritus collected by the apparatus, possibly ciliated, located near the anterior end of the ventral surface. The conodont organism probably had a length of 30 to 80 mm. Except for the elements, the organism lacked mineralised structures.

The conodont organism was of sufficient size to have been attractive to a palaeoniscoid fish as food. The recovery of two different types of conodont apparatuses from a single fish may mean that the conodont organism was a choice food for fish in shallow marine seas. No precise information about the local environment has been gained from the fish other than it was a free-swimming type, and probably fed over a considerable depth range. The mouth structure of the fish is probably indicative of an organism that did not feed on muddy bottoms, and thus it is likely that the fish caught the conodont when it was swimming some distance above the sea floor.

Acknowledgements

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Evidence on the radius of the Precambrian Earth*

A. Y. Glikson

It is suggested that the early and middle Proterozoic crustal record is inconsistent with, and can not be explained on, an Earth of present-day dimensions (Glikson, in prep.). Stratigraphic, isotopic and geochemical data from terrains of the above age range in Australia, South Africa, Canada and other regions are diagnostic of intrasialic crustal environments—disclosing evidence neither for simatic crust nor for volcanic products of its partial fusion. The sima-to-sial transformation processes which have dominated Archaean evolution (Engel, 1968; Viljoen & Viljoen, 1969; Glikson, 1970, 1972; Anhaeusser, 1973; Arth & Hanson, 1975) ceased by ca 2.6 aeons ago, and all available data indicate that both cratonic and mobile Proterozoic domains have, in the main, been founded on sialic basement. An extended tectonic hiatus existed between 2.6 and 2.0 aeons ago, and the onset of development of Proterozoic intrasialic mobile belts is thought to have essentially postdated the latter age.

On the basis of the spatial relations between Proterozoic mobile belts and the Archaean and/or Proterozoic cratons, three types of belts are distinguished: (1) intercratonic mobile belts; (2) marginal mobile belts, and (3) external mobile belts. Polar wander data, stratigraphic continuities and intercratonic correlations suggest that little or no relative motion of cratons has occurred across intercratonic mobile belts—examples being the Rhodesia-Kaapvaal and Pilbara-Yilgarn pairs (McElhinny and others, 1968; McElhinny & Embleton, 1976). Marginal mobile belts are defined as those flanked on one side by an Archaean or Proterozoic craton, and include thick wedges of flysch and molasse sediments—examples being the Coronation geosyncline of NW Canada (Hoffman, 1973), and possibly the Cloncurry belt of NW Queensland (Glikson and others, 1976). The circum-Ungava geosyncline in Canada (Dimroth and others, 1970) is an Alpine-type trough—including an eugeosynclinal-miogeosynclinal division, low-LIL (large-ion-lithophile) element tholeiitic basalts, and turbidites—flanked on both sides, and resting on, Archaean sial. Likewise, the Ophthalmian mobile zone which separates the Pilbara and Yilgarn cratons contains lower Proterozoic turbidites and olistostromes (R. C. Horwitz, pers. comm., 1976) which rest on granitic basement. These examples are regarded as evidence that Alpine-type Proterozoic belts were in at least some instances founded on sialic crust, and their presence does not therefore necessarily indicate an existence of sima. In external mobile belts—namely, those belts whose spatial relations to the Archaean crust and to Proterozoic cratonic domains can not be directly observed, the ensialic nature of the volcanic and sedimentary assemblages and the generally high initial Sr^{87}/Sr^{86} ratios of acid igneous rocks (Fig. 1) indicate a sialic basement. Ophiolites are unknown, and ocean-floor-type tholeiite, andesite and LIL-element depleted dacite are rare, in systems formed during 2.6-1.0 aeons ago.

The stratigraphic and palaeomagnetic coherence of the Proterozoic sialic crust suggests that, on an Earth with present-day surface area, had simatic crust existed it must have occupied a vast and continuous 'palaeo-Pacific' regime. The operation of sea-floor spreading, subduction and partial melting processes in this regime should have given rise to at least 500 x 10^6 km^3 volume of sima-derived crustal materials—namely, island-arc and/or Cordillera-type associations. However, no evidence for such crust has to date been encountered. Moreover, data on the secular evolution of Sr^{87}/Sr^{86} ratio of sea water, based the minimal ratio in carbonates of different ages (Veizer & Compston, 1976) (Fig. 2), and on the evolution of K/Na ratios in clastic sediments (Engel and others, 1974) (Fig. 2), suggest that between 2.6 and 0.6 aeons ago sediments were, in the main, derived by denudation of isotopically and geochemically evolved and differentiated source rocks, such as the Proterozoic acid igneous rocks plotted in Figure 1. The sedimentary geochemical record is thus inconsistent with an exposure of simatic crustal rocks to atmospheric and hydrospheric denudation—in contrast to either the Archaean or the Phanerozoic eras, during which extensive contribution of geochemically immature sediments are represented by corresponding 'lows' on Figure 2.

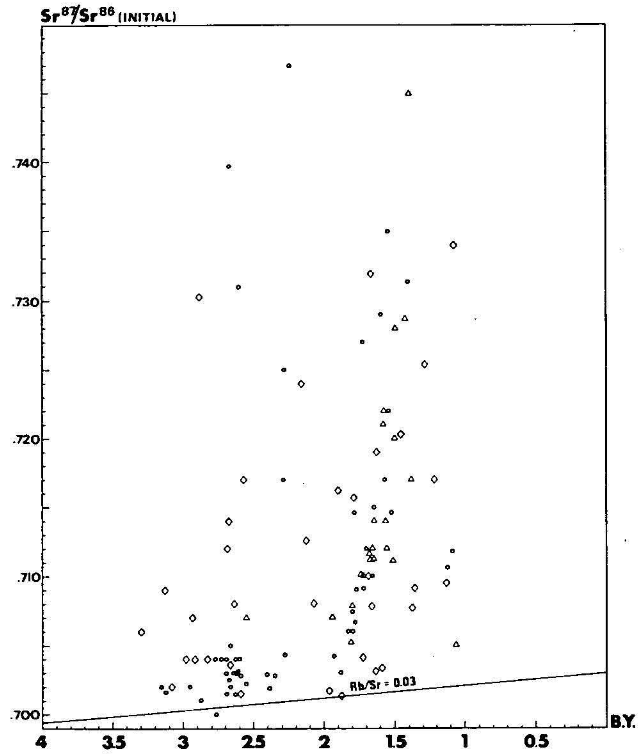

Figure 1 Initial Sr^{87}/Sr^{86} of acid igneous rocks of the Australian Precambrian Shield plotted against corresponding whole rock Rb-Sr isochron ages. Circles—granitic rocks; triangles—acid volcanic rocks; diamonds—acid gneisses (after Glikson, in prep.).

The preceding observations require that, unless all evidence for simatic crust during some 1600 x 10^6 years of Earth history has been inexplicably eliminated from the geological record, the crust must have been, in the main, sialic. However, had sima been present it is inconceivable that no record would have been preserved—bearing in mind the abundance of greenstones in Archaean systems on the one hand, and ophiolites in Appalachian, Hercynian and Alpine orogenic belts on the other hand. It is highly unlikely that a geodynamically inert and geochemically cryptic simatic crust existed during the Proterozoic (thus leaving no trace in the geological record), because this can not be reconciled with the intense tectonic and igneous activity in the contemporaneous ensialic mobile belts—ensimatic and

*** an extended summary of a paper by Glikson (in prep.)**

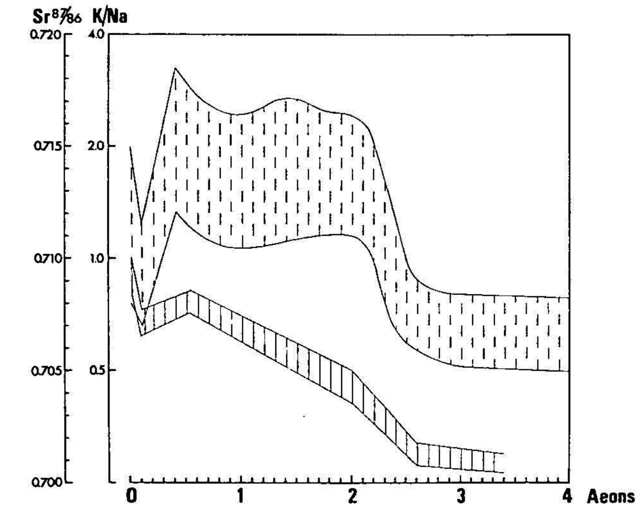

Figure 2 **Secular evolution of Sr^{87}/Sr^{86} of carbonate sediments (minimal values, thought to represent sea-water values) (vertically ruled) (after Veizer and Compston, 1976) and of K/Na ratios in clastic sediments (vertically dashed) (after Engel and others, 1974).**

sima-sial boundary domains being inherently less stable than sialic crust. Nor is it possible that a Proterozoic Earth of present-day dimensions was covered by a global sialic crust of continental thickness (ca 35 km), as this would have tripled the present-day volume of sial—which due to its buoyancy must stay at the surface. It is equally unlikely that a globally-thin sialic crust existed (which could account for the volume problem), because an accretion of this crust into the present-day thick sial is contradicted by palaeomagnetic pole data and structural constraints such as the preservation of the primary dimensions of dykes and cratonic volcanic-sedimentary blankets. The enigma, namely, the nature of the 'missing' geological record for two-thirds of the Proterozoic crust on an Earth of present-day dimensions, cannot be resolved by these models, nor can I think of any other conceivable solution except that *the Earth's surface area itself has increased with time*—namely, a Proterozoic global sialic crust existed which is represented by the present-day Precambrian crust, occupying about 80 percent of the continental crust. Accordingly, the Earth's radius must have been about half of the present value before the late Proterozoic. The appearance of ophiolites about 1.0 aeons ago in Arabia, Egypt, the Atlas and the Urals (Greenwood and others, 1976; Piper, 1976) signifies the onset of plate-tectonic processes—for which no evidence exists prior to this stage (Piper, 1976). It appears, in agreement with Carey (1976), that plate tectonics are a unique expression of radial expansion and genetically related formation of new simatic crust.

The concept of early terrestrial crustal evolution, following on earlier work (Glikson, 1972, 1976a, 1976b; Glikson & Lambert, 1976), is diagramatically illustrated in Figure 3, summarised below in terms of six evolutionary stages:

Stage I—About 4.1-3.9 aeons ago the terrestrial planets were subjected to major meteorite bombardments, responsible for the formation of the lunar mare (Schmitt, 1975). It is considered highly unlikely that the Earth alone has escaped these collisions. Ultramafic to mafic xenoliths and outliers contained in and intruded by the isotopically-oldest gneisses in southwestern Greenland, Labrador, Rhodesia, eastern Transvaal, southern India and the Pilbara region (Western Australia) are considered to be relicts of long-acting, originally impact-triggered, volcanic activity (Green, 1972; Glikson, 1976a).

Stage II—During 3.9-2.6 aeons ago, the volcanic crust, and minor volumes of associated sediments, generated during stage I, were subjected in different regions to deformation—namely, downbuckling, rifting and possibly subduction. This resulted in partial melting of the volcanic crust, particularly above ascending mantle diapirs, with consequent generation of large volumes of tonalitic to granodioritic magma. The ascent of the latter resulted in the formation of the diapiric 'gregarious batholiths' characteristic of Archaean terrains and deformation of the volcanic crust into linear troughs—the greenstone belts. Coeval dacitic volcanic activity and the persistence of partial melting in subjacent mantle diapirs resulted in the formation of stratigraphically high volcanic and associated sedimentary units within the greenstone belts. Thus, *early greenstones* (terrestrial mare equivalents) and *late greenstones* (which postdate granites) are distinguished (Glikson, 1976a). These processes resulted in a progressive, geographically diachronous, transformation of an early Archaean simatic crust into a global sialic crust.

Stage III—An acceleration of sima-to-sial cratonisation processes toward the end of stage II culminated with a world-wide crustal thermal rise about 2.6 aeons ago, reflected by regional metamorphism in the greenstone belts, formation of anatectic ensialic K-high adamellite and granite, and late acid volcanic centres and derived sediments. These events terminated the evolution of greenstone belts, which are unknown in the Proterozoic.

Stage IV—The 2.6-2.0 aeons range constituted the longest tectonic hiatus recorded in Earth history. There is evidence for neither greenstone belt-type activity nor mobile belt-type activity during this time. The principal features of this era are the development of platform-type to epicontinental volcanic and sedimentary blankets, intrusion of major dykes and stratiform basic to ultrabasic bodies (e.g., Bushveld, Great Dyke, and the Millindina, Widgiemooltha and Jimberlana intrusions in Western Australia), and minor ensialic high-level granitic intrusions. Principal examples of early Proterozoic intrasialic basins are the Hamersley, Transvaal and Huronian systems.

Stage V—From about 2.0 aeons ago a world-wide network of intrasialic mobile belts developed, possibly as an expression of a world-wide tensional phase and consequent formation of intrasialic rifts—the precursors of mobile belts. Concomitant anatexis at the root zones of subsiding linear zones of sialic crust and partial melting in subjacent mantle diapirs (in analogy with modern continental rifts, such as the east African rifts and underlying mantle domes indicated by seismic data, Baker and others, 1972), resulted in extensive volcanic, plutonic, tectonic and sedimentary activity along these belts. These developments peaked about 1.8-1.7 aeons ago, but continued intermittently in subsequent periods, including the 0.6 aeons old pan-African thermal events.

Stage VI—About 1.0 aeons ago increasing tensional stress resulting in splitting of the sialic crust along some of the older mobile belts—the loci of continental breakdown. The opening and closing of simatic gaps at that stage and in later times are reflected by occurrences of ophiolites and calc-alkaline volcanic complexes (Greenwood and others, 1976; Piper, 1976). Some of the major crustal tensional structures whose onset dates back to this stage are the Grenville belt, Keweenawan mid-continent rift, Amadeus Basin and Adelaide Geosyncline. Thermal rises and igneous activity associated with the rifting are represented by a peak on age distribution histograms (Dearnley, 1966).

According to this concept of crustal evolution, while analogous elements of structure, lithology and geochemistry

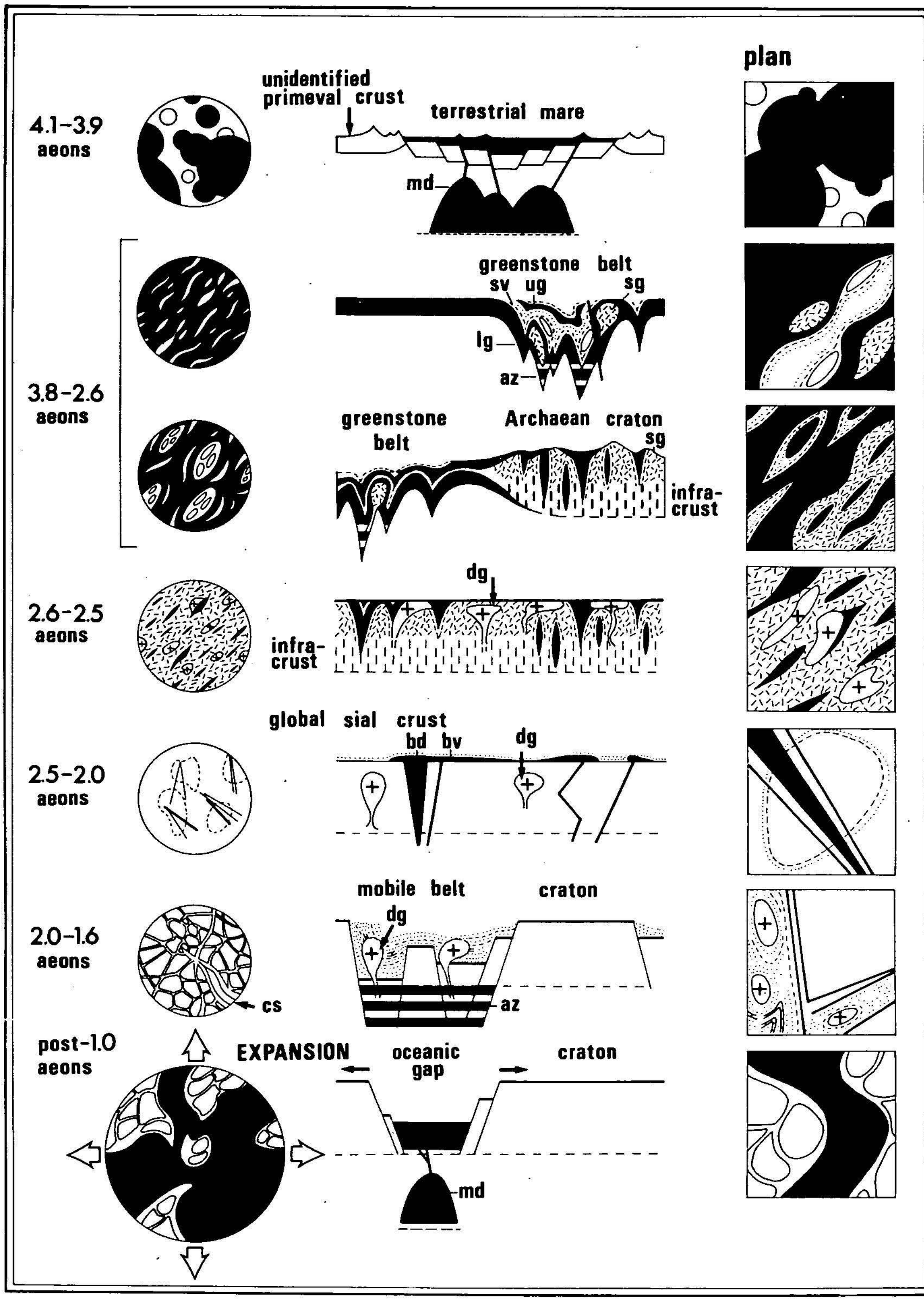

Figure 3 Diagrammatic illustration of the concept on Precambrian crustal evolution (from Glikson, in prep.). For explanation of the stages refer to the text. md—mantle diapirs; lg—lower greenstones; sg—sodic granites; sv—sediments and acid volcanics; ug—upper greenstones; az—anatectic zone; dg—differentiated granites; bd—basic dykes; bv—basic volcanics; cs—crustal suture.

can be found at each stage, their combinations have never been repeated, namely, each stage has been characterised by a set of temporally unique peculiarities—resulting in an irreversible trend, in contrast to uniformitarian models. The major Precambrian isotopic age peaks—i.e., at ca 2.6, 1.8 and 1.0 aeons ago (Dearnley, 1966) are interpreted, respectively, in terms of a culmination of sima-to-sial transformation, a major tensional phase, and the onset of radial expansion and consequent plate tectonics. In agreement with the expanding Earth theory (Dearnley, 1966; Carey, 1976), and in harmony with universal expansion (McDougall and others, 1963), it is suggested that the Precambrian Earth was significantly smaller than the present and that the opening of oceanic gaps and radial expansion have, in the main, commenced only since about 1.0 aeons ago.

Acknowledgements

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Chemistry of manganese nodules from the Cape Leeuwin field off Western Australia

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

A preliminary report on the manganese nodule field southwest of Western Australia published in this Journal recently (Frakes, Exon & Granath, 1977) quoted chemical analyses which were carried out on air-dried material. Significantly higher metal values have been recorded in some later analyses done on nodules dried at 105°C.

Tests have shown that the ground, air-dried material retains considerable moisture, which accounts for the higher metal values of the later analyses. The average water content (after drying at 105°C) has been determined at 16 percent.

The relevant chemical data now available on this material are summarised in the accompanying table: in this table metal values (by atomic absorption spectrophotometry) have been recalculated assuming a moisture content of 16 percent. Correspondence between the analytical results from different laboratories using different methods is good; Cu values determined by X-ray fluorescence appear to be consistently slightly lower than the AAS results, whereas Ni, Fe and Mn values by XRF are slightly higher than the AAS figures from the other two laboratories. The analyses were not carried out on the same nodules and, except in the case of Station 9, the spread of

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values is less than might be expected from natural differences in composition between individual nodules in a single dredge haul.

The overall average value of Ni + Cu + Co from all 8 stations taken from the analyses given here is 1.53 percent, compared with the figure of 1.18 percent quoted in the preliminary account.

Acknowledgement

We thank H. A. Jones for his assistance during this reassessment.

Station	*Position*	*Laboratory*	*Metal content—weight percent, dry basis*					
			Fe	*Mn*	*Ni*	*Cu*	*Co*	*Ni + Cu + Co (Average)*
2	40°03'S 114°10'E	1	6.5	19.3	1.12	.57	.065	1.76
3	41°53'S 113°57'E	1	11.2	24.0	1.05	.50	.077	1.55
		3	13.3	25.14	1.04	.36	ND	
4	37°57'S 103°09'E	1	12.1	21.7	.90	.40	.13	
		2	ND	ND	.95	.38	.14	
		3	13.08	24.86	1.00	.34	ND	1.46
5	37°00'S 102°55'E	1	11.0	23.9	.96	.49	.15	
		2	ND	ND	1.00	.45	.15	1.60
		3	11.75	25.17	1.05	.39	ND	
6	36°00'S 102°00'E	1	11.7	21.5	.84	.42	.15	
		2	ND	ND	.88	.38	.20	1.44
		3	12.59	24.08	.93	.35	ND	
7	35°54'S 99°03'E	1	12.3	22.0	.88	.37	.18	
		2	ND	ND	.92	.38	.19	1.47
		3	13.36	24.01	.98	.33	ND	
8	34°58'S 98°58'E	1	10.4	23.5	1.00	.49	.19	
		2	ND	ND	1.00	.43	.20	1.65
		3	11.47	25.01	1.05	.40	ND	
9	34°38'S 101°00'E	1	14.2	19.1	.61	.26	.18	
		2	ND	ND	.90	.38	.23	1.27
		3	15.32	22.38	.75	.28	ND	

ND—not determined.

1. **Australian Mineral Development Laboratories, Adelaide. Average of two analyses from each station, except station 2 (1 analysis). Analyses by atomic absorbtion spectrophotometry.**
2. **Bureau of Mineral Resources, Canberra. Analyses by atomic absorbtion spectrophotometry.**
3. **Monash University, Clayton, Victoria. 5—8 analyses from Stations 4—9; 1 analysis from Station 3. Analyses by X-ray fluorescence. (Data from Frakes & O'Brien, in press; and O'Brien, unpubl. data).**

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Sixth BMR Symposium

The BMR Symposia are annual events stressing work relevant to industry. The Sixth Symposium was held in Canberra between 3 and 5 May 1977, and was officially opened by the Minister for Science, Senator the Hon. J. J. Webster.

On 3 and 4 May, sessions were held at the Academy of Science Building. Talks presented, abstracts of which are given below, included results of completed projects, of work in progress, and some more general topics. A panel discussion, entitled 'What maps are needed now?' was held on earth-science maps in Australia. The contributions of the members of the panel, and an edited version of the discussion, will be published in the December issue of this Journal.

An innovation this year was a one-day workshop, held at the Administration Building of CSIRO on 5 May 1977; the subject was the Pine Creek Geosyncline. Specific topics were discussed under broad headings of regional studies, uranium mineralization, and mapping and exploration techniques. 140 were present at the workshop, many of whom took part in discussion.

Mineral resource assessment

L. C. Ranford

Australia has become a major source of minerals to the industrial nations of the world and the importance of this mineral trade will increase in the future. With about 5 percent of the land surface of the Earth and only about 0.3 percent of the population, we have a relative abundance of many minerals important in modern industrial society and it is imperative that we recognise the international implications and responsibilities of this endowment. Australia is the world's largest exporter of bauxite, mineral sands and iron ore, the second largest exporter of lead and zinc, and the third-largest exporter of coal and nickel. We have about one-quarter of the world's low-cost uranium reserves and the potential to become the world's principal exporter of uranium.

It is recognised in BMR that Australia's mineral endowment will focus increasing international attention on our country at a time when it is widely appreciated that the supply of non-renewable mineral resources may well prove to be a limiting factor in attempts to raise the general standard of living to that currently enjoyed in parts of the industrialised world.

To ensure that the Australian people obtain maximum benefit from our mineral resources, and that, subject to our own strategic requirements, supplies are made available to other consumers, it is essential that we have adequate data on which to base decisions concerning the mineral industry, decisions that may have far-reaching implications.

The prime requirement is for accurate assessments of our identified resources and of their likely availability through time. A start has already been made in BMR in this direction and preliminary assessments have been made of reserves of iron ore, tin, coal, mineral sands, and antimony, and we are attempting to update and publish each year estimates of demonstrated reserves of all major mineral commodities, and place these reserves in the context of world reserves and of Australian and world production. We are also undertaking more comprehensive appraisals of identified resources of certain minerals including copper, nickel, tungsten, arsenic and asbestos and are attempting to develop methods of expressing quantitatively the inferred extensions of identified resources.

While we recognise that data on identified resources are the prime requisite for short-term and medium-term planning, we are now facing an increasing requirement for information that will enable us to anticipate problems of longer-term mineral supply and land use. To provide the data required we need to tackle the problem of estimating undiscovered mineral potential. This is a relatively new subject, but assessments of undiscovered potential have already been undertaken in other countries, and research into the subject is increasing rapidly. BMR is already engaged in a program designed to assess the nation's total petroleum resources, and we are studying the various approaches which might be used to estimate undiscovered resources of other minerals. Our objective will be to provide properly documented and carefully explained quantitative estimates in a form which reflects both the degree of certainty of occurrence and the economic feasibility of extraction of the nation's total mineral resources. To achieve this objective will require increased expertise in certain fields in BMR, as well as co-operation and assistance from industry and other government agencies. We are aware of the problems involved in producing worthwhile estimates of undiscovered resources, and of the risk of misuse of the results, but we believe that where there is a demand, estimates will be made and it is our responsibility to ensure that the best possible assessments and appraisals are available.

Assessment of undiscovered petroleum resources

D. J. Forman

It is important for Government to consider and implement long-term policies to lessen the effects of forthcoming shortages of oil and gas. In addition to information on our discovered resources planners in Government need to know: the likely amount of oil and gas that may be discovered in the future; the probable distribution of new discoveries; the effort required to make the discoveries; the economic and technological conditions under which the discoveries may be exploited.

Resource assessment is the only process that will give probable answers to these questions.

There are two problems to be solved in estimating the resources of undiscovered petroleum. One is to calculate the probability of discovery; the other is to estimate the type and volume of any petroleum that may be found.

In estimating the probability of petroleum discovery in an area the rock types and their burial and deformation history are examined and compared with models based on knowledge of the occurrence of petroleum. For instance, a petroliferous area must have source and reservoir beds, a favourable thermal and structural history, and adequate sealed traps that have been preserved from subsequent destruction by deformation or erosion and from flushing.

At least three methods may be used to estimate the volume of petroleum that is likely to be discovered. Selection of the method or methods depends on how much is known about the geology.

The 'volumetric' method has been extensively used by government geological organisations in USA and Canada. The likely yield of petroleum per unit volume is determined by comparison with fully explored petroleum provinces elsewhere, and total ultimate recovery is determined by multiplying this yield factor by the volume of sediments in the area to be assessed.

The 'play' methods are more detailed (a 'play' is a set of geological circumstances under which petroleum may originate and be preserved in one or more traps). In one method a field-size distribution pattern is established for similar plays elsewhere. Total ultimate recovery is determined by adding up the resources of the individual fields in the section of this distribution that best matches the play to be assessed.

The 'prospect by prospect' method is the most detailed. A prospect is a trap, such as an anticline or dome, within which petroleum may occur. After recognition of the prospects, estimates are made of the volume and type of petroleum that may be trapped in each, based on a knowledge of the geology of the area itself.

Monte Carlo simulation is used extensively in all methods, to calculate the probabilities of discovering various amounts of petroleum in an area, and to add up the amounts and probabilities for each area to arrive at a total for a region.

A small group was formed by BMR in 1976 to undertake assessment of Australian oil and gas resources. So far the group has developed a computer program to meet present requirements and has used the 'prospect-by-prospect' method to make preliminary assessments of the undiscovered resources of several areas of offshore Western Australia.

Two other small basin study groups were included in the assessment task in 1977. The three groups are currently planning to complete a first assessment of Australia's undiscovered petroleum resources in a few years. To achieve this, they will be seeking co-operation from State Geological Surveys, companies, CSIRO, and other areas of BMR.

Ore reserves and cost inflation and escalation

J. Erskine

When, over a long period, metal prices fall or mining costs rise, ore which had been in the category of mineral reserves is degraded in value into the category of subeconomic mineral resources. Over the past ten years the prices of the base metals copper, lead, and zinc, measured in constant money terms, have been falling for copper; more or less level for lead; and rising slightly for zinc. Over the same ten-year period mining costs have been rising faster than monetary inflation, or expressed in constant money terms mining costs have been rising—an escalation of mining costs. In the case of copper mines, with falling prices and rising costs the effect has been to make revenue less than working costs—certain deposits of copper minerals which had in the past been economic are therefore now uneconomic and must be reclassified from reserves to sub-economic resources.

Although the falling copper price has been significant, the single most important factor which has caused reserves to be degraded to resources has been cost inflation and escalation. Graphs are presented of cost inflation over the past ten years for fuel oil and distillate, for mine employees' wages compared with non-mine employees, and for heavy mobile mining equipment compared with equipment items such as the family car.

We then look at a hypothetical open pit copper mining project with 1 percent Cu ore and compare the costs of constructing and operating it in 1967 with the same costs in each of the ten years 1967 to 1976. A graph is presented of the Australian producer copper price over those years (a slightly downward trending line, compared with fuel, wages and equipment which trend upward).

Charts are presented which show, for each year from 1967 to 1976, operating costs for mine and mill, concentrate transport costs, smelting and refining costs, State royalty costs, and interest charges on borrowed capital. The graphs show the copper price that would have been needed in the first year of production for a mine started in each year during the recent ten year period to be profitable, and this copper price is compared with the actual price received. For a start up in any year after 1970 all costs plus return of capital and 10 percent profit would not have been recovered. Finally, there is a chart showing what grade of copper would have been needed each year, given the actual copper price that year, to cover all costs plus return of capital and 10 percent profit.

Using the TEM method for geoelectric sounding

B. R. Spies

A knowledge of the resistivity of rocks at depth is invaluable in exploring for groundwater, oil and mineral deposits, and for geological mapping. The most common technique for electrical sounding of the earth is the electrical resistivity method. Resistivity depth soundings can be slow because of the need to dig electrode holes and lay out long lengths of wire.

The electromagnetic method can also be used for depth soundings. Present techniques involve varying the separation between transmitter and receiver, while keeping the frequency constant ("geometric sounding"); or alternatively varying the frequency while employing a fixed transmitter-receiver configuration ("parametric sounding"). Depth sounding using the transient electromagnetic, or TEM, method is also possible.

TEM measurements can be converted into apparent conductivity values that vary with sample time. This process is analogous to converting electrical resistivity data to apparent resistivity values which vary with electrode separation. The main advantage of TEM depth sounding compared to conventional methods is the speed and ease of measurement. The time taken for an average TEM reading (including laying out the loop) is about ten minutes.

Although master curves for quantitative interpretation of TEM soundings are yet to be developed, model studies over layered and finite structures show that apparent conductivity curves derived from TEM soundings can be used to interpret geoelectric sections qualitatively.

TEM depth soundings have been used to interpret geophysical surveys at Woodlawn, NSW, and in the Alligator Rivers area, NT. At Woodlawn TEM soundings indicate that the orebody has a conductivity of 20 s/m and this result is consistent with conductivity measurements made by other methods. In the Alligator Rivers area, TEM soundings were used to aid geological mapping of carbonaceous rocks covered by up to 100 m of alluvium. The TEM soundings in the Alligator Rivers area permitted anomalies caused by bedrock conductors to be distinguished from those caused by conducting surface clays.

An assessment of the fixed-source, downhole EM method

R. D. Ogilvy

The possibilities of using EM techniques for off-hole mineral exploration have long been recognised. Early attempts were made over 20 years ago but relatively little has been published concerning the effectiveness of these techniques. In 1974, BMR purchased a Scintrex DHP-4 fixed-source downhole EM system. Field tests started in 1975, and were followed up with model studies in 1976. The model studies were carried out in conjunction with CSIRO Mineral Research Laboratories. Analysis of the model data is still at a preliminary stage.

Field trials made over the ore deposit at Woodlawn, NSW, indicate that the DHP-4 has only limited applications in its present form. Detectibility depends upon the mutual EM coupling relationships between the transmitter, conductor and downhole receiver, and varies significantly for differing geometrical situations. For optimum EM coupling the detection limit was shown to be of the order of 30 m for the Woodlawn orebody. A quantitative interpretation of field results is currently hindered by the lack of an effective normalisation procedure and a generalised interpretation scheme.

Theoretical and model studies highlight difficulties in the interpretation and development of fixed-source downhole EM systems. However, model studies indicate that an improvement in detectibility could be achieved by measuring orthogonal and differential components of the subsurface magnetic field. In addition, fixed-source systems offer several advantages over alternative systems, including the possibility of directional information, the utilisation of complex surface instrumentation, and the minimal expense involved for lost probes.

Guidelines for geophysical exploration in the Cobar area, New South Wales

P. G. Wilkes

Because of deep weathering and scarcity of outcrop, exploration in the Cobar area relies increasingly on geophysical methods. Although orebodies in this area are generally good geophysical targets the surface weathering makes them difficult to detect. The effective use of geophysics requires very careful selection of methods, survey design, and an unusually detailed interpretation. An exploration strategy is presented which integrates the use of magnetic, electrical, electromagnetic and gravity methods in the search for magnetic and non-magnetic ore bodies.

Magnetite and/or pyrrhotite are present in most of the deposits discovered to date. Accordingly the aeromagnetic method is regarded as the primary exploration method. If this yields exploration targets these can be followed up with ground magnetics and gravity, and drilling if warranted. The gravity and magnetic anomalies produced by pipelike orebody models and surficial sources have been computed, and the results used to produce guidelines for the use of these two methods. If the magnetic results are inconclusive it may be necessary to carry out electrical or electromagnetic work prior to gravity.

The search for orebodies which do not have a suitable magnetic expression is very difficult and a strategy of regional and detailed electrical surveys followed by detailed gravity and drill-hole geophysics is proposed. The response of electrical surveys in this area is illustrated by model studies and field examples of TEM surveys, resistivity soundings and borehole resistivity measurements. The results of the field surveys and model studies show that the deep weathering severely attenuates resistivity, IP, and electromagnetic responses of conductive-chargeable sources in the unweathered rock. To overcome the effects of weathering, the importance of understanding the geo-electric section before designing and interpreting electrical surveys in this area is stressed, and it is recommended that methods used should be capable of distinguishing the response caused by the overburden from the response due to conductors in the unweathered rock.

Proterozoic patterns of sedimentation north and northeast of Mount Isa

G. M. Derrick

North and northeast of Mount Isa relations between the Haslingden Group, Surprise Creek Beds, Mary Kathleen Group and Mount Isa Group are examined.

Basalt and epicontinental sands of the Eastern Creek Volcanics and Myally Subgroup thin eastwards onto the Kalkadoon-Leichhardt and Ewen blocks, and a shoreline is proposed coincident with the long-acting Gorge Creek-Quilalar hinge zone.

A disconformity is postulated between the Myally Sub-group and the lower Surprise Creek Beds. Gentle epeirogenic uplift of Haslingden Group rocks was followed by onlap from the east and northeast.

Transgressive sandstone sheets of the lower Surprise Creek Beds were deposited in a coastal shelf-alluvial plain environment. It is proposed that the basal Surprise Creek Beds and Mary Kathleen Group are equivalent, that sedimentation was probably continuous across the basement block, and that the long-held concept of separate eastern and western depositional basins is probably not valid for this period. The broad shelf area is marked by at least two major lineaments, one extending north of Mary Kathleen, the other a broad anticlinal rise between Gunpowder and Mount Isa. Marked east-west facies changes are characteristic of some of the lithostratigraphic units.

A regional unconformity separates lower from upper Surprise Creek Beds, and may represent crustal disturbance associated with extrusion of the Fiery Creek Volcanics to the west. The basal unit of the upper Surprise Creek Beds is a fluvial and shallow shelf sand possibly equivalent to the Deighton Quartzite, and it grades upwards into flysch-like sandstone and siltstone in which some copper was concentrated.

Slight regional uplift terminated this cycle and resulted in deposition of the Warrina Park Quartzite blanket. Further transgression, then quiescence culminated in the deposition of Pb-Zn ores at Mount Isa.

Apparently dissimilar copper deposits at Mammoth and Mount Isa share many sedimentological and tectonic features, such as proximity to basement highs, thinning and/or erosion of older units—particularly the regionally cupriferous upper Surprise Creek Beds—and deposition of ore in a structurally prepared host. Mount Isa copper may represent the optimum extension of the processes operative at Mammoth.

Geophysical mapping of buried Precambrian rocks in the Cloncurry area, northwest Queensland

A. J. Mutton

A program of geophysical mapping was carried out during 1975 by BMR in an area of 1700 km², located 50 km northeast of Cloncurry in northwest Queensland. The aim of the mapping was to determine the depth of burial, lithology, and structure of the Precambrian Cloncurry Complex in a region where the results of previous regional geophysical surveys indicated that such rocks are covered by only a thin veneer of younger sediments. Detailed gravity and ground magnetic work, combined with geological mapping, appraisal of drilling results, physical property analyses of rock samples, and a reinterpretation of regional aeromagnetic data proved to be a suitable combination of techniques for mapping the basement rocks in this area.

The results of the mapping indicate that the Cloncurry Complex extends beneath sediments of the Carpentaria basin for approximately 40 km beyond the eastern limit of outcrop of the complex. The eastern limit of the buried complex is marked by a major fault at which the complex ends abruptly and gives way to a less dense granitic basement. Interpreted depths to the buried complex indicate that in much of the survey area the young sedimentary cover is no more than 50 metres thick.

The mapping indicates that the buried Precambrian complex is composed of granites and metamorphic rocks belonging to the Corella Formation and the Soldiers Cap Group. The distribution of these rock types can be outlined by their geophysical response. Where granites have intruded rocks of the Corella Formation a distinctive magnetic aureole is evident and is the locus for concentrations of magnetite and hematite.

The area is structurally complex. Apparent fold patterns are more complex than that suggested by the regional geophysical response. Several major magnetic lineaments interpreted within the buried Precambrian basement appear to reflect granite boundaries rather than major faulting.

The effective use of geophysical techniques for mapping shallow-buried basement rocks in the region could substantially expand the area of Cloncurry Complex available for prospecting.

Predicting the existence of diamonds in kimberlites from their inclusion

J. Ferguson

Kimberlites contain a wide variety of ultramafic nodules. It is now generally accepted that these ultramafic nodules represent xenoliths that have been erupted from the upper mantle. By far the commonest of these xenolithic upper mantle nodules are lherzolites. There are two varieties of these xenoliths; in addition to olivine and two pyroxenes the stable aluminous phase is either spinel or garnet, giving rise to spinel and garnet lherzolites respectively. In that these lherzolite nodules are direct representatives of the upper mantle and hence the parent to most of the igneous rocks, they have been the subject of intense investigation. Experimental phase studies combined with thermo-dynamic considerations indicate that the compositional variations in the mineral assemblages present in these lherzolites are sensitive to temperature and pressure. Provided that equilibrium is preserved it is possible to estimate temperature and pressure from the mineral assemblages of the xenoliths. These temperature-pressure estimates define a palaeogeotherm allowing predictions to be made concerning the possibility of finding diamonds in individual kimberlites. Where there is a low geothermal gradient the graphite-diamond stability curve is intersected at a shallower level compared to a high geothermal gradient. Evidence is presented to show that the fossil Cainozoic geothermal gradient in southeastern New South Wales is similar to the present-day high geothermal gradient—making the prospect of finding diamondiferous kimberlites, of Cainozoic age, in this part of Australia highly unlikely.

The Mordor Complex, Northern Territory

A. Langworthy

The Mordor Complex in central Australia consists of a suite of highly fractionated potassic rocks ranging from phlogopite dunite, through phlogopite-rich wehrlite, lherzolite, shonkinite, and pyroxenite to melamonzonite, monzonite, and syenite. The syenite and monzonite are intruded by mafic differentiates (phlogopite shonkinite and melamonzonite) which are in turn intruded by numerous plug-like bodies (up to 200 m across) of ultramafic rock (phlogopite-rich peridotite and pyroxenite), pegmatite, and dykes of carbonate-rich breccia.

Whole-rock chemical analyses indicate that the ultramafic rocks are unusually enriched in large-ion lithophile (LIL) elements: K (up to 1.47 percent), Rb (up to 100 ppm), Ba (up to 3030 ppm), La (up to 70 ppm), and Sr (up to 464 ppm). In addition the analyses, when compared to those of normal ultramafic rocks, are typically low in Mg, and high in Al, Ca, K, and Ti. The syenite is low in Si and Na, and rich in Ca, K, and Mg relative to average syenite. All the rocks have very high K_2O/Na_2O ratios (3 to 7), and low K/Rb (110 to 280) and $MgO/(FeO + Fe_2O_3)$ (typically 2 in the ultramafic rocks). Rb-Sr data from whole-rock and mineral systems indicate an age of about 1150-1200 m.y., and relatively high initial $^{87}Sr/^{86}Sr$ (0.711).

The unusual chemical features of the rocks of the Complex indicate an affinity with rocks of the 'ultrapotassic series', a classification used by Carmichael *et al.* (1974) for world-wide occurrences of highly potassic mafic lavas ($K_2O/Na_2O > 3$). In a similar manner to several of the extreme members of the ultrapotassic series elsewhere, the Complex mirrors many of the unusual features that isolate kimberlite from the mainstream of ultrapotassic mafic rocks.

Petrogenesis of the Complex possibly involved zone refining of deep-mantle partial melt, or partial melting of a phlogopite-bearing atypical upper-mantle source rock. Evolution of the liquid during uprise was followed by extreme magmatic differentiation in an intermediate-level magma chamber prior to intrusion of the products of differentiation to a high level in the crust. Evidence suggesting that the upper mantle may be heterogeneous is discussed.

Access to BMR information

E. P. Shelley

The wide range of BMR Activities results in the production of information ranging from raw field observations to published reports and maps. This information is made available to industry in a variety of ways.

BMR's formal *publication* series include Bulletins, Reports, Geological and Geophysical maps, Australian Mineral Industry Quarterly and Annual Reviews, and the BMR Journal. Catalogues of publications are readily available and new releases are advised by means of a quarterly list. Unpublished *Records* are produced in limited numbers and contain, among other things, reports of geophysical surveys and progress reports of geological surveys; most are available on open file. Company reports of geophysical and drilling operations subsidised under the Petroleum Search Subsidy Acts are also available for inspection and copying.

Preliminary results from geological and geophysical surveys may be discussed with BMR staff and when results have reached a suitable compilation stage they are released through the Australian Government Printer copy service. This facility enables companies and individuals to obtain and use information that usually takes considerable time to reach formal publication status.

Cores and cuttings received under the Petroleum Search Subsidy Acts, the Petroleum (Submerged Lands) Act, and from BMR stratigraphic drilling operations are stored, and much of the material is available for inspection and non-destructive testing.

The *BMR Library* is the largest and most comprehensive geoscience library in Australia. Industry personnel are always welcome to use the library's collections, and its inter-library loan and reference services are available.

It is the policy of BMR to make its information freely available as quickly as possible; company representatives and individuals have always been welcome to use BMR information services and to consult with BMR officers on subjects in which they are interested.

This paper will explain in more detail the various services mentioned above and describe a number of other services such as the Stratigraphic Index and the National Gravity Data Repository, and the availability of primary geophysical data.

Geophysical mapping of a porphyry copper prospect at Mount Turner, Georgetown area, Queensland

J. A. Major

As part of BMR's evaluation of the mineral resources of the Georgetown region a program of geophysical mapping was conducted over a porphyry copper-molybdenum prospect at Mount Turner near Georgetown. Methods employed in the mapping program were resistivity/IP depth soundings, drilling, down-hole logging, magnetics and gamma spectrometry. The aims of the mapping program were to assist in determining the geological setting and economic potential of porphyry copper prospects in the Georgetown area; and to establish what geophysical techniques might be useful in exploring for and evaluating similar prospects in the region.

Gamma spectrometry was used to determine the radio-element concentration within the geologically mapped alteration system at Mount Turner. No correlation between radio-element concentration and alteration zoning was observed. Extensive ground magnetic traverses also failed to outline the alteration system.

The resistivity/IP work comprised vertical electrical soundings on a one kilometre square grid over an area of 30 km^2. Interpretation of the soundings was used to build a three-dimensional picture of resistivity and chargeability to a depth of approximately 200 m. Chargeability layering, predicted from the soundings, generally compared well with the results from down-hole logs, but resistivity logs compared less well. A comparison of the electrical soundings with surface geological mapping shows that a region of high chargeability and low resistivity appears to correlate with a zone of phyllic alteration; and near Mount Turner there is a correspondence between low chargeability and potassic alteration.

The distribution of chargeability and resistivity in conjunction with detailed geological work, provides a guide to the distribution of sulphides, alteration zoning and the level of erosion in the porphyry system.

Buried reef structures in the Lennard Shelf, Canning Basin, Western Australia

J. Rasidi

Upper Devonian reefs in the Canning Basin occur in the Lennard Shelf where they are found mostly at the surface. The recovery of a small quantity of oil from a structure associated with a buried Devonian reef in Meda 1 highlighted the importance of reef structures in the basin as prospective drilling targets. Indeed petroleum exploration in the Lennard Shelf between 1959 and 1970 was directed almost exclusively to testing Upper Devonian reef structures. However, difficulties in identifying these structures appear to have been largely responsible for the disappointing result.

The successful use of geophysical methods for identifying reef structures is due mainly to the physical characteristics of reefs and their effect on the overlying sediment. The reef geometry, the decrease in thickness and the increase in seismic wave velocity within sediments above a reef structure give rise to many expressions on seismic data recorded above the structure. An important, but often neglected one is the increase in the frequency of seismic reflections due to velocity anomalies and the thinning of sedimentary layers above the structure. These frequency variations are usually very small but can conveniently be observed using a "Laser Scan". The result of a frequency analysis on two seismic records for the Meda structure supports the application of this method in identifying reef structures in the Lennard Shelf.

Several seismic records indicating possible reef structures were analysed and the result shows at least 6 undrilled structures, similar to that in Meda 1, exist in the area at a depth of about 1500 m below the surface.

Playing with the 'GABHYD' hydraulic model of the Great Artesian Basin

G. E. Seidel

The GABHYD model consists of a group of computer programs designed to simulate by numerical methods the flow of water in the Great Artesian Basin. Its purpose is to predict how yields of artesian groundwater from the Great Artesian Basin would respond to different management interventions.

To demonstrate the accuracy of model predictions the model was run for a time period for which data were available, but without using these data in the model. The model's predictions were then compared to these data after the run. It was shown that the model is suitable for investigating large-scale regional effects of management interventions throughout the basin and small to medium-scale effects throughout most of the currently developed areas of the basin.

Based on these results and on model characteristics operating rules are defined for the model and the presently available management options are listed. Their use is explained by example of two model runs for the period 1970 to 1999, both with management interventions postulated for 1980. The first intervention is a selective conservation measure, the second is the provision of extra water in a newly developed area. The model's predictions are shown to be reasonable and in the expected order—but offering detail, which could not have been obtained by conventional methods.

Submarine fans and their hydrocarbon potential

R. V. Burne

Hydrocarbon search in deeper marine environments has focused mainly on sunken rift basins on continental margins of separation. The sediments of these basins were generally deposited in water far shallower than their present depths. The only other major hydrocarbon prospects of the deep marine environment are the thick sedimentary wedges that accumulate at the base of the continental slope and in depressions on the slope, the so-called submarine fans. These sedimentary features may be classified according to their supposed hydrocarbon potential.

Oil has been recovered from ancient fan deposits at a variety of locations, for example the North Sea, Barbados, California, and Venezuela, but the potential of present-day fans has yet to be established. Sedimentary processes operating on present-day fans show great variety, ranging from mass transport processes through to hemipelagic sedimentation. These present-day processes, may not necessarily be similar to those responsible for the major accumulation of these types of deposits in the past. These processes are reviewed and the generative conditions of potential source and reservoir rocks in the fan system are outlined.

Studies of ancient fan sequences, coupled with an analysis of the distribution of environments on present-day fans, have led to the proposition of typical sedimentary facies associations. These associations are presented, their significance to stratigraphic trap formation is analysed, and the probability of optimum juxtaposition of source and reservoir beds is assessed.

The geothermal gradient of the continental margins is not well known, but available data are used in an attempt to indicate the depth-time parameters for hydrocarbon formation in fan sediments.

It is possible to assign probabilities to the factors, source rock, maturation, reservoir, and migration and entrapment timing for the model fan situations. This approach helped to delineate several areas where the acquisition of additional data will greatly refine the models, thereby providing further justification for continued funding of deep-sea fan studies.

The margin south of Australia and the problem of initial rifting

J. C. Mutter

Recently acquired seismic refraction measurements made on the southern continental margin of Australia have been combined with studies of the gravity and magnetic fields to reveal a crustal structure which is considerably at variance with generalised models of Atlantic margin structure.

The transition from continent to ocean, rather than being achieved by a gradual diminution of crustal thickness from shelf to abyssal plain, appears to take place across two discrete boundaries. These boundaries coincide with the landward and seaward limits of the magnetic smooth or quiet zone which occupies most of the continental margin. The crust flooring of the quiet zone can most usefully be treated as unique in its own right, being neither continental nor oceanic. The two crustal boundaries represent the juxtaposition of continental with quiet-zone crust, and oceanic with quiet-zone crust.

The observation of a spacially discontinuous crustal structure appears to be difficult to reconcile with models of Atlantic margin formation. Such models indicate the gradual thinning and modification of a continental crustal section going hand-in-hand with the development of a major rift-valley system on the earth's surface. The scheme culminates with sea-floor generation in the axial zone of the rift valley.

We suggest that continuous evolution of the deep crust and mantle structure is not necessarily the logical corollary of the continuous evolution of surface features. We propose that the deep structure of a rift system forms fairly quickly, then remains in a relatively steady-state situation while the surface structure evolves in response to the new stress conditions set up by the deep crustal changes. The unique quiet-zone crust is generated within the sharply defined borders of the rift zone; upon continental dispersal it formed the basement complex of much of the continental margin.

Note

The work presented here is not entirely that of the author. It was carried out at the Lamont-Doherty Geological Observatory, Palisades, New York in collaboration with Prof. Manik Talwani, and Dr Robert Houtz, and followed a co-operative marine geophysical investigation of the southern margin of Australia by Lamont and BMR.

Investigations of the copper-bearing breccia pipes at Redbank, Northern Territory

T. D. Donnelly, John Ferguson, J. Knutson, I. B. Lambert and W. M. B. Roberts

Any model to explain the origin of the approximately fifty breccia pipes in a volcano-sedimentary sequence of Carpentarian age in the Redbank area has to take the following features into consideration:

1—steep to vertical disposition and cylindrical form;

2—limited diameter, with a maximum of 130 m;

3—almost entirely *in situ* brecciation, whereby mappable units in the undisturbed host rocks can commonly be traced through the breccia pipes;

4—minor tabular breccia zones of allochthonous material present in some of the pipes;

5—a small volume increase—the *in situ* brecciation usually being less than 10 percent;

6—cementing matrix of the breccia zones comprises any or all of the following: microbreccia, dolomite, ankerite-siderite, quartz, and, less frequently or in minor amounts, barite, pyrobitumen, chalcopyrite, apatite, leucoxene, rutile and galena;

7—magmatic, marine and "mixed" isotopic values for C and O from carbonates in breccia matrix and veinlets;

8—magmatic sulphur isotopic values for galena and relatively heavy values for chalcopyrite, pyrite and barite;

9—partly unfilled framework between the breccia fragments;

10—extensive K-metasomatism of breccia fragments, in cases producing near-monomineralic K-feldspar aggregates;

11—no alteration of the roof rocks other than minor brittle fracturing filled by dolomite, ankerite-siderite and accessory chalcopyrite;

12—location of pipes along northeast and east-trending lineaments;

13—apparent pre-Masterson Sandstone age.

It is suggested that a carbonated K-rich trachytic magma rose to a shallow depth below surface where a vapour phase was produced that was capable of carbonate and potash metasomatism. Conditions contributing to an overpressure situation resulted from a moderately impervious roof, sealing of isolated pores by K-rich metasomatising vapours, and drastic gas expansion. Any inherent weakness in the tectonic fabric of the overlying rocks would have been the focus of the pressure activity. Explosive pressure release would have taken place by hydraulic fracturing of the roof rocks. This sudden loss of high pore-fluid pressure created an implosion. This event is correlated with the formation of the breccia pipes, in which there is only a small volume expansion produced by the essentially *in situ* brecciation process. That further activity of a different style took place is indicated by the minor tabular zones within some of the pipes containing allochthonous breccias.

Following pressure release and brecciation, solids were precipitated from the vapour phase in the open cavities caused by the brecciation—where they were not already filled by micro-breccia rock flour. The isotopic data suggest temperatures of precipitation of the order of 250-350°C, and that the ascending fluid incorporated some connate water. The present-day open framework of the breccia columns indicates that there were insufficient dissolved solids in the magmatic vapour phase to entirely fill these cavities. "Non-magmatic" carbonates in the breccia pipes probably represent subsequent precipitation from heated connate brines which dissolved sedimentary carbonate from the surrounding (sedimentary) dolomites, and magmatic carbonate from the breccia pipes. In a similar manner the "non-magmatic" sulphur in the bulk of the chalcopyrite mineralisation can be explained in terms of precipitation from connate brines which dissolved magmatic copper sulphides from the breccia pipes and possibly leached copper from sedimentary and igneous rocks, at sufficiently high temperatures for sulphur isotopic exchange or/and abiological sulphate reduction to occur. Pyrobitumen in the breccia pipes could represent oxidation of magmatic methane or leaching of organic matter from the sedimentary rocks.

Factors affecting reef formation, southern Great Barrier Reef

Peter J. Davies and John F. Marshall

The Capricorn and Bunker Reefs in the southern Great Barrier Reef show a diversity of morphological development. While most are roundly triangular in plan and have well developed algal rims (One Tree Reef, Lady Musgrave) others are elongate along one axis (Sykes Reef). Lagoons are present in some but not all reefs. Patch reefs within lagoons are either sparsely or densely developed. Lagoons are being infilled with prograding sand sheets. Some, e.g. Fairfax, have been almost completely infilled, but the outlines of patch reefs are still visible. Cays are present on both windward (shingle) and leeward (sand) reef margins. Lithification processes are evident around the edges of the cays.

Opinion is divided on the origin of Holocene coral reefs. The organic control theory (Maxwell, 1968) states that a thick Holocene reef sequence has developed by upwards and outwards growth as a result of biological and sedimentological processes. Alternatively, in the antecedent karst theory (Purdy, 1974), emphasis is placed on the development of a thin Holocene Reef sequence overlying a karst surface.

Echo sounding and seismic refraction profiling, underwater drilling of windward and leeward reef slopes, sedimentological studies, and water monitoring studies, have been conducted to test these alternative hypotheses. Results show that the Holocene reefs are thin and have grown on the upper surface of previously exposed and eroded limestone knolls, the tops of which vary in depth below sea level from 7 m to 20 m. The shape of the modern reefs is controlled by the overall shape of the limestone knolls. Both the shape and depth of lagoons, and the shape and density of patch reefs within lagoons are mainly controlled by the detailed physiography of the top of the karst surface.

Holocene reef growth began around 8-9000 BP and was dominantly vertical on perimeter zones at a rate of 3 mm/year. Reefs growing from different depths have therefore reached sea level at different times, and as a result they have spent varying lengths of time in the surf zone. Modification of original reef shape has occurred as a result of interactions between the surface reef and the wave regime. Such interactions have led to lagoon infill and massive leeward growth of the reef as a result of the accumulation of calcium carbonate at a rate equal to or greater than that produced in windward situations.

A model of reef growth in the Great Barrier Reef is proposed involving *a.* vertical reef growth during transgressive marine phases, and *b.* leeward growth during marine stillstands. Two principal consequences arise from the model. *1.* Sediment shed in leeward directions is of sufficient quantity, and the diagenetic environment sufficiently favourable, to suggest the possibility of petroleum accumulation in such sequences. *2.* The reefs are at different stages of development i.e. some are juvenile, some are mature, while others are senile. Such reefs are likely to react differently to natural and unnatural perturbations.

Two other BMR publications

AUSTRALIAN MINERAL INDUSTRY 1975 REVIEW

The latest edition of the Annual Review is expected to be available in September 1977. The Annual Review has been issued regularly since 1948; the latest edition presents a comprehensive coverage of developments in mineral commodities, including fuels, both in Australia and overseas, in 1975 and the first half of 1976.

Part 1, 'General Review', includes salient statistics of the Australian mineral industry as a whole, and summarises recent developments in the industry, both national and international, under the headings: The Industry in the National Economy, Important Recent Developments, Production, Overseas Trade, Prices, Exploration Expenditure, New Capital Expenditure, Overseas Investment, Mining Census Summary, Wages and Salaries, Industrial Disputes, Taxation, Royalty Receipts, and Government Assistance, Legislation, and Controls.

Part 2, 'Commodity Review', covers Australian production, processing, consumption, trade, and exploration of individual mineral commodities from Abrasives to Zirconium, and summarises prices and developments around the world.

Part 3, 'Mining C… Census, and some mineral processi…

Part 4, 'Misc… out provided by State Departm…

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Part 1 (BMR… ncipal mineral commodities in … 5', and a list of metal, ore, and …

Part 2 (ABS) … for the quarter ended 31 Sep… and refinery production of … r 1976 are also included.

A revised for… e article in this issue is 'Coppe… reserves', by B. G. Elliott.

The price of the 1975 Annual Review is $18; the price of one volume (4 numbers) of the Quarterly is $8.00. Subscription forms may be obtained by writing to the Director, Bureau of Mineral Resources, Geology and Geophysics, PO Box 378, Canberra City, ACT 2601.

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