DEPARTMENT OF NATIONAL DEVELOPMENT
BUREAU OF MINERAL RESOURCES, GEOLOGY AND GEOPHYSICS

BULLETIN 138

Geology of the Middle Cambrian Phosphorites and Associated Sediments of Northwestern Queensland

BY

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AUSTRALIAN GOVERNMENT PUBLISHING SERVICE
CANBERRA 1972

BUREAU OF MINERAL RESOURCES, GEOLOGY AND GEOPHYSICS

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Published for the Minister for National Development,
the Hon. Sir Reginald Swartz, K.B.E., E.D., M.P.,
by the Australian Government Publishing Service

ISBN 0 642 00188

Manuscript received: 1971
Revised manuscript received: January 1972
Issued: January 1973

Printed by Graphic Services Pty. Ltd., 60 Wyatt Street, Adelaide 5000

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SUMMARY

Remapping of the Middle Cambrian sediments of the eastern portion of the Georgina Basin has revealed new information on the distribution and relationships of rock units in north-western Queensland. Many of the pre-existing biostratigraphic units have been found to be rather unsatisfactory mapping units. It is possible to group all the various sediments into six lithosomes:

The *basal sandstone-conglomerate lithosome* comprises the Mount Birnie Beds and its equivalents, and is composed of tillite, conglomerate, quartzose and arkosic sandstone, and mudstone. It ranges in age from late Precambrian to Lower Cambrian, and was probably deposited under a variety of conditions including marine glacial, very shallow marine, marine deltaic, and fluviatile.

The *dolomite lithosome* is made up of the Thorntonia Limestone, the Camooweal Dolomite, and the Age Creek Formation, with a range in age from lower Middle Cambrian to Ordovician (the Camooweal Dolomite is not, as has been previously suggested, Precambrian). Hypersaline supratidal conditions probably prevailed during deposition.

The *chert-siltstone-limestone-phosphorite lithosome* comprises the richly fossiliferous Beetle Creek Formation and its equivalents; it is everywhere Middle Cambrian in age. Although thin, it is extremely widespread. Because of its high phosphate content in many areas, this is economically the most important lithosome in the Georgina Basin. It is believed to have been deposited under a variety of shallow water conditions, including lagoonal, estuarine, sub-littoral, and littoral environments.

The *silt-shale-chert lithosome* is composed of the Inca Formation and its equivalents. It ranges in age from lower Middle to upper Middle Cambrian and has a rich agnostid fauna. The depositional environment was probably shallow marine or paralic.

The *limestone lithosome* is up to 900 m thick, and consists of calcarenite, calcilutite, oolitic limestone, and dolomitic limestone, interbedded with marl, mudstone, and chert, of Middle to Upper Cambrian age. It is believed to have been deposited in warm, agitated water in a shallow marine environment.

The *sandstone-siltstone lithosome,* which ranges in age from late Middle to Upper Cambrian, is only developed close to the inferred strandline. It probably formed in very shallow seas, possibly as intertidal or beach deposits in places. In some areas, particularly the Burke River Outlier, there is evidence of contemporaneous faulting. The effects were, however, only local, and in most areas sedimentation continued through most of the Cambrian with only minor breaks.

The distribution of the lithosomes reveals a regional pattern of deposition, with dolomites in the central part of the basin surrounded by a rim of limestone deposition, and sandstone-mudstone-chert-phosphorite deposition nearer to the shore.

Exploration for phosphorites, using such techniques as visual recognition, field chemical testing, logging of drill holes, and, most recently, airborne radiometry, has so far revealed six main areas of phosphate deposits in Queensland with ore reserves in excess of 2 000 million tonnes. The Duchess area (Burke River Outlier) contains the largest deposits, with proven reserves of 1 100 million tonnes of beneficiation grade ore, using a cut-off grade of 17 percent P_2O_5. Most of the phosphate is found in a narrow belt extending for 25 km along the west side of the outlier. It occurs predominantly as pelletal material, and is concentrated in the Monastery Creek Phosphorite Member, which is up to 40 m thick in places.

The Lady Annie area also contains extensive phosphate deposits, with announced reserves of 250 million tonnes of ore with a cut-off grade of 18 percent P_2O_5. The phosphorites are very fine-grained non-pelletal and coarse pelletal types. So are those of the Thorntonia area 20 km west of Lady Annie, where 250 million tonnes of fine-grained phosphate rock, averaging 18.6 percent P_2O_5, have been proved in the D Tree deposit. South of Yelvertoft homestead substantial reserves have been proved in the Sherrin Creek area.

There are a number of deposits, whose total reserves are probably more than 200 million tonnes, in the northeast corner of the Georgina Basin, extending from Lawn Hill to Border Waterhole. In these deposits secondary phosphorites are abundant.

Rich phosphorites (predominantly pelletal) are known to occur in the Ardmore Outlier, and are up to 12 m thick in places. Reserves have not been announced, but are probably

substantial. Several small deposits have also been located in the Quita Creek region; both pelletal and fine-grained varieties are present. Reserves are small.

The Wonarah area, Northern Territory, contains reserves of 970 million tonnes of phosphate averaging 15.7 percent P_2O_5. They occur in the Wonarah Beds, and are related to a basement high. The phosphate occurs as a fine-grained non-pelletal material in a bed up to 19 m thick.

There are several types of phosphorite in the Georgina Basin. The most common variety, particularly in the southern deposits, is pelletal phosphorite, which is composed of ovules (mostly structureless but with fossil fragments forming the core of some), with a diameter of 0.06 to 0.60 mm. Some of the pelletal phosphorites show scour-and-fill structures and cross-laminations.

'Argillaceous phosphorite' is composed of abundant detrital grains of silt size and finer, with a fine-grained phosphatic matrix. Where the detrital grains are almost completely absent the name 'collophane mudstone' or 'phospholutite' is suitable. The term 'microsphorite' has been applied to both these types of phosphorite. The third most abundant type is believed to be of secondary origin, resulting from the remobilization of apatite in groundwaters, probably in response to tropical or subtropical weathering. The name 'phoscrete' is suggested for it. It is believed to be primarily of Cainozoic age, but some may be as old as Cambrian. Phosphatic breccias of both primary and secondary origin are present in places.

Diagenesis is a feature of many of the Georgina Basin phosphorites, and includes phosphatization, silicification, calcitization, alunitization, and fluoritization as well as the development of various secondary phosphate minerals such as wavellite, variscite, and crandallite. The origin of phosphatic calcareous nodules in siliceous phosphorites in the Mount Murray area is controversial: de Keyser suggests that they are remnants of an original calcareous phosphorite, which has been upgraded (from 7 percent P_2O_5 to 20 percent P_2O_5) by silicification; but Cook believes them to be of secondary concretionary origin, locally downgraded by calcitization.

The major element composition of the phosphorites appears to be somewhat similar to the Phosphoria phosphorites of the United States, particularly in their low CO_2 content. The minor element composition is rather different, owing primarily to their lack of organic matter. The pelletal phosphorites are comparatively rich in lanthanides, but show a marked cerium deficiency. The argillaceous phosphorites and phoscretes are significantly depleted in lanthanides, but not in cerium.

A superficial comparison with other phosphorites suggests that no other deposit is precisely the same, but there are some similarities with the so-called 'east-coast' phosphorites; there are also some notable similarities with the Karatau phosphorites in Russia and it is conceivable that there was an Austral-Asiatic phosphogenic province during the Cambrian period.

Some of the phosphate may be a primary precipitate. The argillaceous phosphorites may in part have formed by the early diagenetic replacement of muds below the sediment-water interface. The most important single process was probably the post-depositional phosphatization of rounded biogenic calcareous fragments. Localized upwelling and estuaries are thought to have been the main sources of phosphate, although the evidence is rather inconclusive. The depositional environment was probably very shallow marine or paralic. The pelletal material is thought to have formed under rather turbulent shallow marine conditions, whereas the finer-grained non-pelletal phosphorites were formed under more paralic conditions.

INTRODUCTION

Following the discovery of large phosphate deposits in the eastern part of the Georgina Basin in 1966 by Broken Hill South Limited, the Bureau of Mineral Resources embarked on a detailed stratigraphical and palaeontological study of the Cambrian sediments of the area in 1967. Particular attention was given to the phosphatic part of the section, but new information on the associated Cambrian units was also gained. In 1967, F. de Keyser, J. H. Shergold, C. G. Gatehouse, R. Thieme, and C. Murray (Geological Survey of Queensland) mapped the Burke River Outlier, and in 1968 de Keyser and Thieme mapped the Cambrian of the northeastern corner of the Barkly Tableland. In 1969 de Keyser and P. J. Cook completed the mapping of the known phosphogenic areas in Queensland when they mapped the eastern margin of the Georgina Basin in the Mount Isa/Urandangi area. Associated palaeontological, petrological, and geochemical studies were also carried out.

The resignation of de Keyser from the Bureau of Mineral Resources in January 1970 unfortunately prevented him from writing a comprehensive bulletin on the Georgina Basin work. Consequently Cook undertook the writing of this Bulletin, basing it on his own observations, and on several unpublished reports and numerous discussions with de Keyser. Where the two authors differ significantly in their interpretations, this is clearly stated in the text.

The area of the Georgina Basin covered by this investigation lies mostly within the State of Queensland, between latitudes 18°30′ and 22°30′S and longitudes 138° and 141°E (Fig. 1). The detailed field mapping was limited mainly to the northern and eastern margins of the basin, where the phosphatic Middle Cambrian units crop out. Several Middle Cambrian outliers within the Precambrian basement were also examined in some detail. BMR drilled a number of stratigraphic holes in the Burke River Outlier and also in the central part of the basin (mainly in the Northern Territory) in order to test the Beetle Creek Formation at depth.

The area is sparsely settled; the only large town is Mount Isa, with a population of approximately 20 000. The small townships of Duchess, Dajarra, Urandangi, and Camooweal have populations of less than a hundred. Sealed roads link Mount Isa with Camooweal and Dajarra; the Mount Isa/Townsville railway runs through Duchess, with a branch line to Dajarra. There are regular passenger flights into and from Mount Isa, with some connecting flights to the smaller townships and homesteads. Access in most parts of the area is by dirt roads, and away from the tracks a four-wheel-drive vehicle is necessary.

The climate is semi-arid savannah, with most of the rain falling during the summer. The annual rainfall ranges from about 380 mm in the south to about 620 mm in the north. The summers are hot, and temperatures frequently rise above 36°C. In the winters, day temperatures are about 24°C, but at night frosts are sometimes recorded.

The relief ranges from low to moderate. Outcrops of Precambrian basement provide the largest relief, where some of the ranges rise 150 m above the surrounding plain. In places, some of the more resistant Middle Cambrian units form prominent scarps and mesas 30 to 60 m high, while the softer units weather to form broad shallow valleys. The Camooweal Dolomite characteristically forms exceptionally flat featureless tablelands (the Barkly Tableland), where there is little

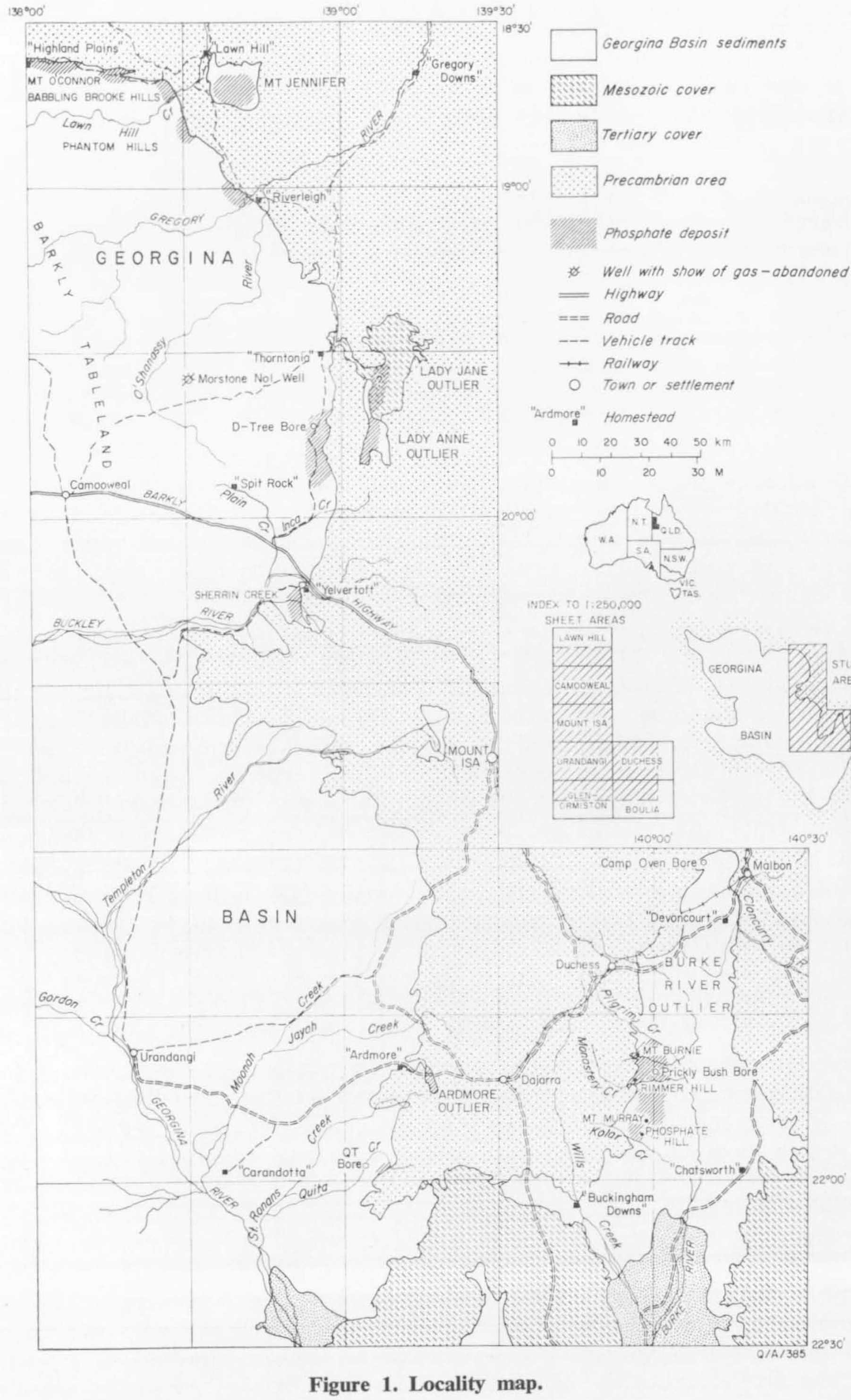

Figure 1. Locality map.

or no outcrop, but it is well exposed on the deeply incised northeast margin of the Barkly Tableland.

Around the edge of the Barkly Tableland, there are a number of permanent watercourses, but elsewhere the rivers only run during the wet season.

Previous Investigations

Smith (1972) gives a comprehensive review of earlier work in the Georgina Basin, which it is unnecessary to repeat here. Öpik began detailed studies of the Cambrian sediments of the eastern part of the Georgina Basin in 1950. In a series of publications (Öpik, 1954, 1956a, b, 1960, 1961, 1967a, b, 1968, 1970; Öpik et al., 1961; Carter & Öpik, 1961, 1963), the Cambrian stratigraphic nomenclature was established and the succession subdivided on the basis of age and lithology. Lithostratigraphic studies have subsequently been undertaken by Brown (1962), Brown (1968), Nichols (1966), and Randal & Brown (1962), who used the stratigraphic succession established by Öpik as a basis for their investigations.

In 1965, the Bureau of Mineral Resources invited R. P. Sheldon of the United States Geological Survey to assess the phosphate potential of Australian sedimentary basins as part of a programme to assist the search for phosphate deposits in Australia. On the basis of the known empirical relationship of phosphorites with black shales and cherts one of the areas which he indicated as potentially prospective for phosphate was that of the Cambrian sediments of the eastern part of the Georgina Basin. Systematic analysis of oil-well samples by Broken Hill South Limited established the presence of comparatively high concentrations of phosphate in the lower Middle Cambrian Beetle Creek Formation in the Black Mountain No. 1 Well, in the southeastern corner of the Georgina Basin. Subsequently, field investigations in the Burke River Outlier in 1966 by the Company's geologists confirmed the presence of major phosphate deposits in the Beetle Creek Formation (Russell, 1967). Since that time, Broken Hill South Limited, IMC Development Corporation (a subsidiary of International Minerals and Chemicals Corporation), and Continental Oil Company of Australia have conducted extensive drilling and mapping programmes in the search for phosphate deposits. Many reports have been written by the companies on their activities, but most are confidential.

Since 1967, the Bureau of Mineral Resources has made a detailed study of the Cambrian sediments, with particular attention to the potentially phosphatic parts of the section (de Keyser, 1968, 1969a, b). Cook & Armstrong (1972) investigated the clay mineralogy of the Beetle Creek Formation and the variation in clay mineralogy with phosphate content. Bastian & Thieme (1970) undertook a detailed laboratory study of the cores and cuttings obtained in the Bureau of Mineral Resources drilling programme in the central part of the Georgina Basin. The detailed mapping has also led to a re-evaluation of the thinking underlying the Cambrian stratigraphic nomenclature; de Keyser (1972) advocates a number of changes in the present scheme to clarify problems which have arisen in the Georgina Basin as a result of confusion of lithostratigraphic with biostratigraphic units.

Acknowledgments

The work of the several Bureau of Mineral Resources and Queensland Geological Survey geologists who have taken part in this investigation has been incorporated into this publication, and the authors wish to acknowledge the debt they owe them. The technical and administrative assistance received from Mr K. A. Armstrong throughout this project has been outstanding.

The co-operation of the Director and staff of the Geological Survey of Queensland at all stages in the investigation is greatly appreciated.

Throughout the mapping programme, and subsequently, the relationship between the Bureau of Mineral Resources and all the companies exploring for phosphate in the Georgina Basin has been excellent; the numerous discussions held with the company geologists have been a constant source of assistance and stimulation. Comments on the manuscript of this bulletin by Professor P. F. Howard of Macquarie University and Mr R. T. Russell of Broken Hill South Limited were most helpful.

General Geology

Smith (1972) defines the Georgina Basin as 'the sedimentary basin containing lower and middle Palaeozoic sediments, which extend in a belt trending northwest from western Queensland to the northern part of the Northern Territory; it is bounded on the east, west, southwest, and north by Precambrian rocks, but the northwestern and southeastern margins are covered by Mesozoic sediments'.

This definition is not entirely satisfactory, as the coarse basal clastic sediments of the Mount Birnie Beds range in age from late Precambrian into the Lower Cambrian. There is little change in type of sedimentation within the unit, yet Smith's definition excludes the lower part of the formation from the Georgina Basin sediments. This is obviously unsatisfactory, and the definition could perhaps be modified to 'the sedimentary basin containing late Precambrian, lower and middle Palaeozoic sediments'.

The geology of the Queensland portion of the Georgina Basin has been the subject of a number of the publications already mentioned, and therefore this discussion will be primarily concerned with amendments to the stratigraphy and earlier geological maps.

The most important changes to the stratigraphic scheme have already been detailed by de Keyser (in press). He points out that earlier schemes were in fact unsatisfactory mixtures of lithostratigraphic and biostratigraphic units of little value to the field geologist. As an alternative he advocates that many of the names first suggested by Öpik should be retained, but that they be fitted into a framework composed of magnafacies and parvafacies (see Krumbein & Sloss, 1963, pp. 316-26). Although this is not a radical departure from the existing nomenclature, it clarifies considerably the interrelationships of the various rock units and highlights their diachronous nature. He also recognizes six basic lithosomes*, and wherever possible subsequent discussions of the Cambrian stratigraphy will be on this basis. The relationships of the lithosomes, the time zones, magnafacies, and parvafacies are shown schematically in Figure 2. In general, the detailed sediments of the eastern margin of the basin are replaced westwards by limestones, and ultimately by massive dolomites in the central part. In most of the Georgina Basin outcrop is poor and stratigraphic information can only be obtained by drilling. Around the eastern perimeter, however, outcrop is good and consequently the information given on

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* Krumbein & Sloss (1963, p. 301) use the term lithosome for 'masses of essentially uniform lithologic character which have intertonguing relationships with adjacent masses of different lithology'.

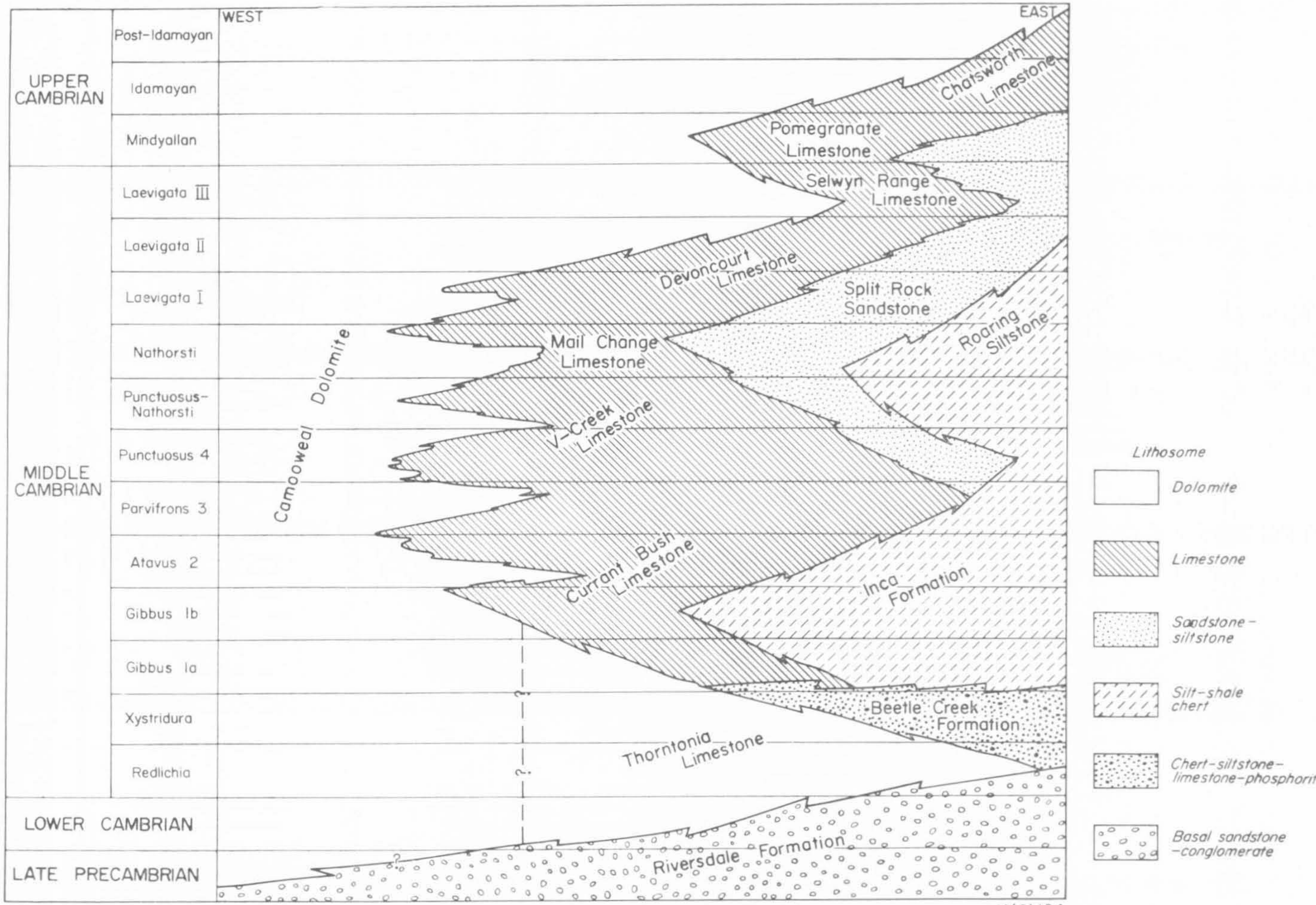

Figure 2. Rock and time relationship diagram for the eastern margin of the Georgina Basin.

the various units came primarily from this region. Some subsurface information was obtained from the Barkly Tableland (Bastian, 1970) and is also incorporated in the discussion. In addition to the main basin, there are several outliers of Cambrian sediments within the Precambrian basement; the most important are the Burke River, Ardmore, and Lady Annie Outliers (Fig. 1). Outcrops within them range from moderate to good; some drill holes were also put down in the Burke River Outlier.

Precambrian Basement

Precambrian basement rocks of the Cloncurry Complex form the eastern margin of the basin and unconformably underlie the Cambrian sequence. They have been described in some detail by Carter et al. (1961); Carter & Öpik (1961, 1963); Noakes et al. (1959); Öpik et al. (1961); and Smith & Roberts (1963). The Cloncurry Complex comprises migmatite, gneiss, schist, metaquartzite, basalt, granite, conglomerate, sandstone, siltstone, carbonates, shale, slate, calc-silicate rocks, tuff, and agglomerate. It has a complex depositional and structural history. The major igneous masses, the Sybella and Kalkadoon Granites, have a minimum age of 1 400 m.y. (Richards et al., 1963).

The Colless Volcanics

In most areas, the Cloncurry Complex is overlain by Cambrian sediments, but on the northeast margin of the basin, in the vicinity of Border Waterhole, it is unconformably overlain by the Lower Cambrian Colless Volcanics, which have a maximum thickness of about 60 m (Fig. 3). Similar volcanics have also been encountered at the base of the Cambrian section in a number of drill holes in the Northern Territory, and are present in outcrop (the Peaker Piker Volcanics). They are probably also equivalent to the Antrim Plateau Volcanics of Western Australia and the Helen Springs Volcanics of the Tennant Creek area. It is apparent that the Lower Cambrian was a time of quite extensive volcanic activity.

The Colless Volcanics are primarily basic, or rarely intermediate, in composition. They are generally strongly weathered to a red-brown or grey-brown colour. They are vesicular or amygdaloidal, with chlorite commonly filling the amygdales. A typical sample of basalt is composed of 55 percent plagioclase feldspar (forming phenocrysts in places), 40 percent monoclinic pyroxene, and 5 percent magnetite and hematite. The intermediate volcanics are composed primarily of sanidine; they tend to be concentrated in the upper more vesicular part of the sequence. Bands of chalcedony are present in places; towards the top there are some tongues and lenses of red-brown silicified sandstone, possibly grading up into a medium to fine-grained yellow sandstone. Where the volcanics are directly overlain by Middle Cambrian dolomites, the contact is gradational in places.

THE SEDIMENTARY SEQUENCE

Basal Sandstone-Conglomerate Lithosome

The sandstone-conglomerate lithosome forms the base of the sedimentary sequence in most areas, resting unconformably on the Precambrian basement. It is composed primarily of coarse detrital sediments, and is best developed in the Burke River Outlier (Fig. 4).

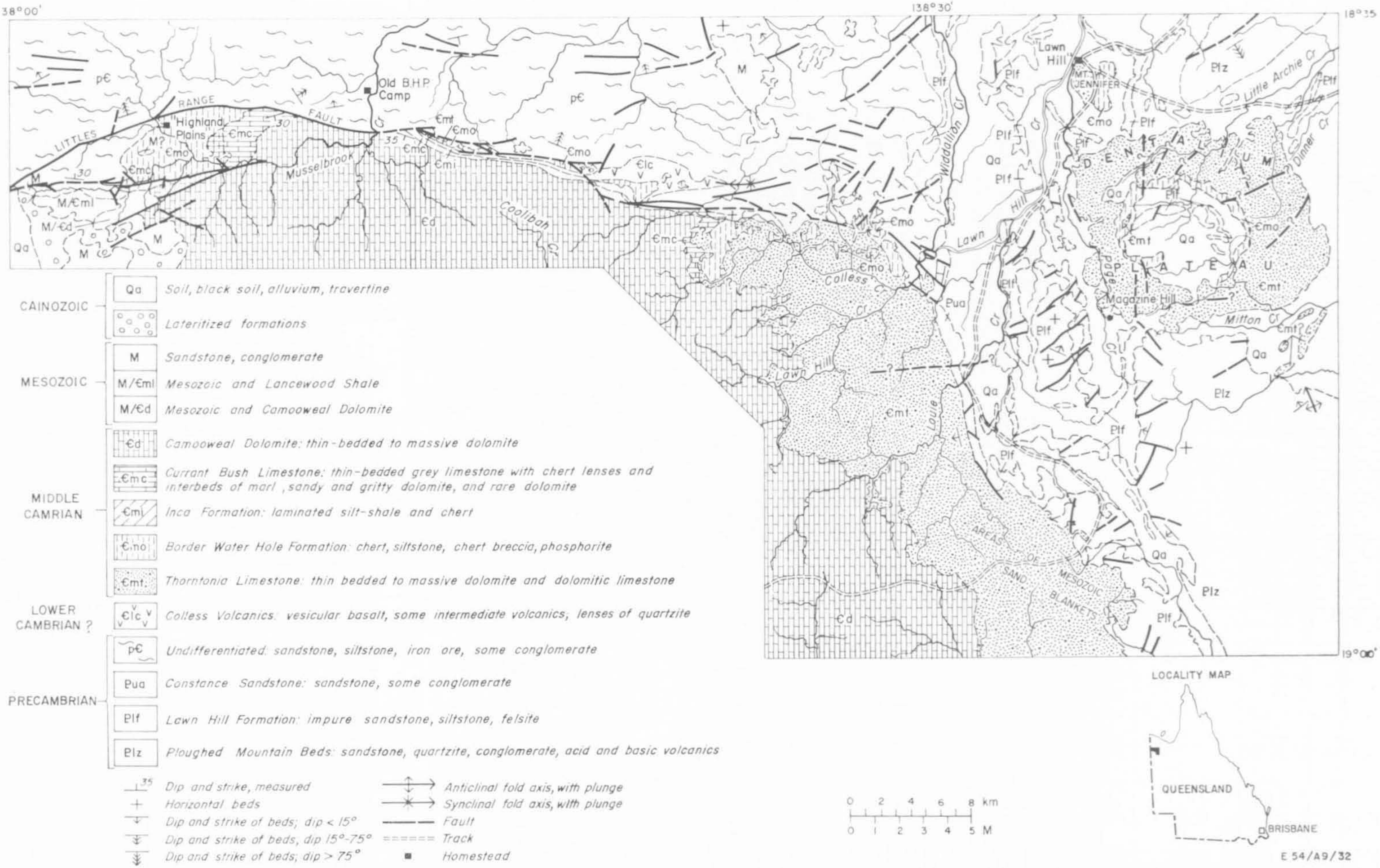

Figure 3. Cambrian geology of the Border Waterhole/Lawn Hill area, northwest Queensland.

Mount Birnie Beds

The name Mount Birnie Beds was given by Öpik (1960) to a 'sequence of conglomerate, sandstone, green shale, and arkose' underlying the fossiliferous Middle Cambrian succession in the Burke River Outlier, Duchess district. The 1967 mapping programme in the area considerably increased our knowledge of this formation (Figs 5-8).

On the west side of the Burke River Outlier, the unit, where complete, includes a tillite up to 20 m thick (de Keyser, 1970) (Pl. 1, fig. 1), overlain by 10 m of bedded dolomite, and then by 40 m of massive dark red-brown ferruginous sandstone, thick and thin-bedded sandstone, and silty sandstone. This is followed by up to 100 m of sandy micaceous shale and siltstone, red and green fissile micaceous shale, and sandy siltstone (Pl. 1, fig. 2), overlain by 20 m of cross-bedded orthoquartzite and quartz conglomerate (Pl. 2, figs 1, 2). The top of the unit is marked by massive mudstone up to 20 m thick. Lithology and thickness vary laterally quite considerably. Along the eastern margin of the Burke River Outlier the formation is much thinner and the tillite is absent: arkose forms the basal member, followed by sandstone and siltstone and, at the top, massive mudstone. Trace fossils are present in the upper part of the sequence (Pl. 3, fig. 1).

The Mount Birnie Beds were thought to be Lower Cambrian, but it now appears that they range from late Proterozoic (the basal tillite) to probable Lower Cambrian (the top mudstone). The boundary between the orthoquartzite/conglomerate member and the underlying massive ferruginous sandstone and shale complex is very sharp, and the two were obviously deposited in different environments. This is also shown by the distribution of the members on either side of the Pilgrim Fault, a meridional fault which forms the western boundary of the outlier (Figs 5-8): the massive ferruginous sandstone complex is missing on the western side of the fault, but is well developed immediately east of it, whereas the quartzite and conglomerate are present on both sides. In many places, the top of the Mount Birnie Beds is marked by a fossil soil in the shape of a hard ferruginous capping up to 1 m thick.

Riversdale Formation

The Riversdale Formation has much in common lithologically with the Mount Birnie Beds. It is scattered along the margin of the Cambrian outcrop area between Mount Isa and the Quita Creek region, and includes red sandstone and sandy siltstone, polymictic conglomerate, sedimentary breccia, silicified feldspathic sandstone, and massive porcellanitic siltstone or mudstone. The maximum thickness observed was about 30 m, but it is only a few metres thick in the south. The top of the Riversdale Formation is quite dolomitic, and this sandy dolomite or dolomitic sandstone seems to grade into the basal parts of the dolomite of Thorntonia Limestone age in many places.

The informal term 'Mount Hendry Formation' is used by geologists of Broken Hill South Limited in the Lady Annie area for a conglomerate and sandstone unit underlying the fossiliferous Middle Cambrian formations. It comprises polymictic conglomerate with sandstone interbeds, gritty to fine-conglomeratic dolomitic sandstone, brown ferruginous sandstone, and pockets of massive earthy siltstone. The sandstones are generally quite immature, and reflect the nature of the nearby Precambrian basement rocks (Pl. 3, fig. 2; Pl. 4, fig. 1). Cross-bedding is common, as is imbricate structure in the conglomerates. The unit is characterized by the

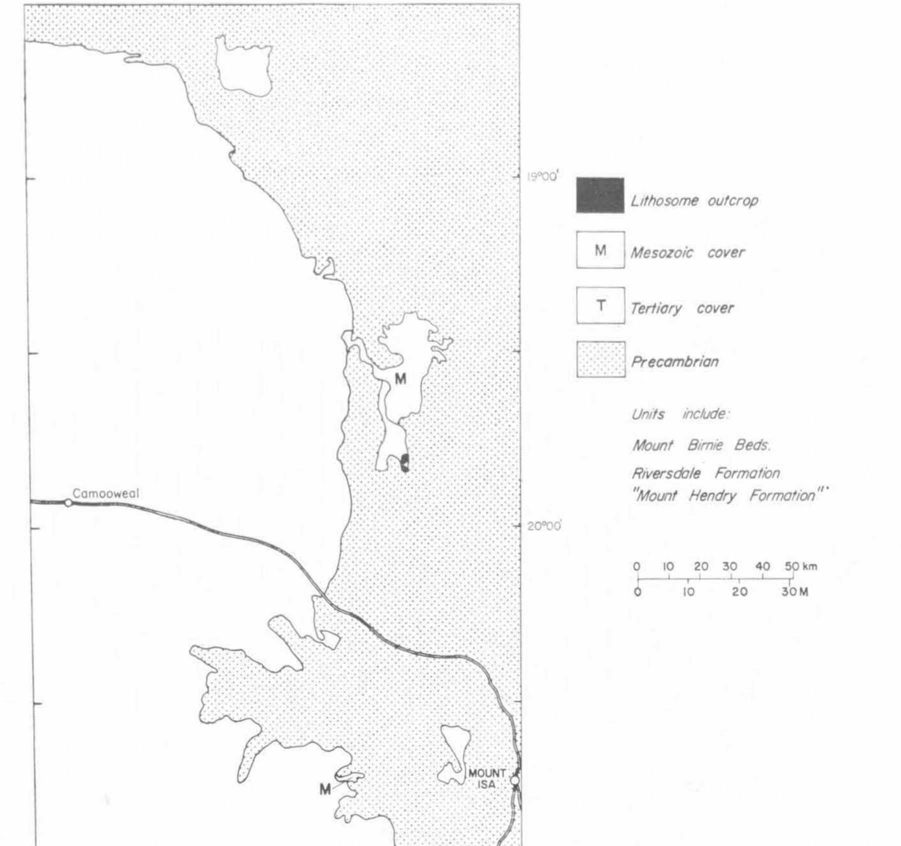

Figure 4. Distribution of the basal sandstone-conglomerate lithosome.

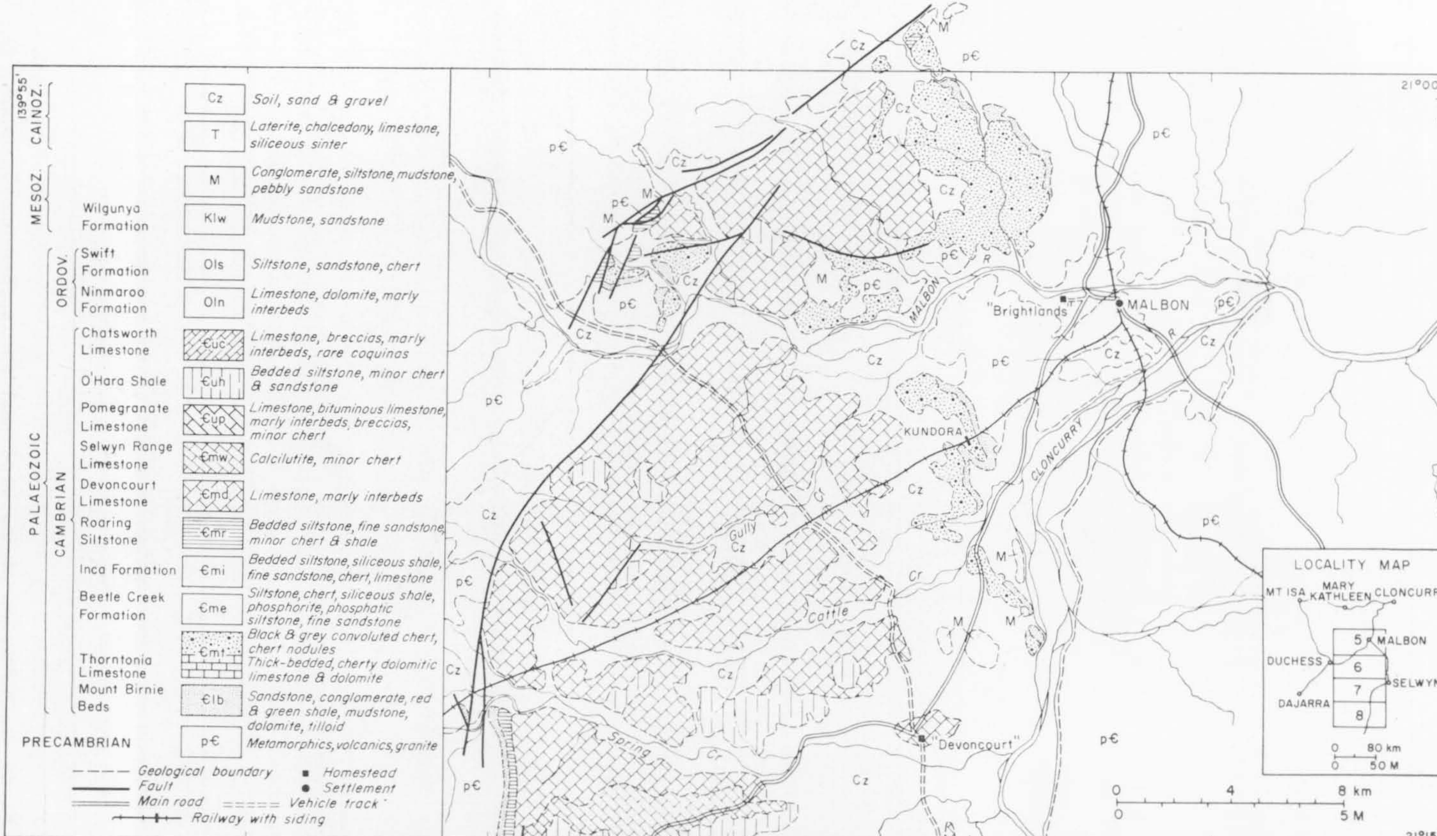

Figure 5. Geology of the northern part of the Burke River Outlier.

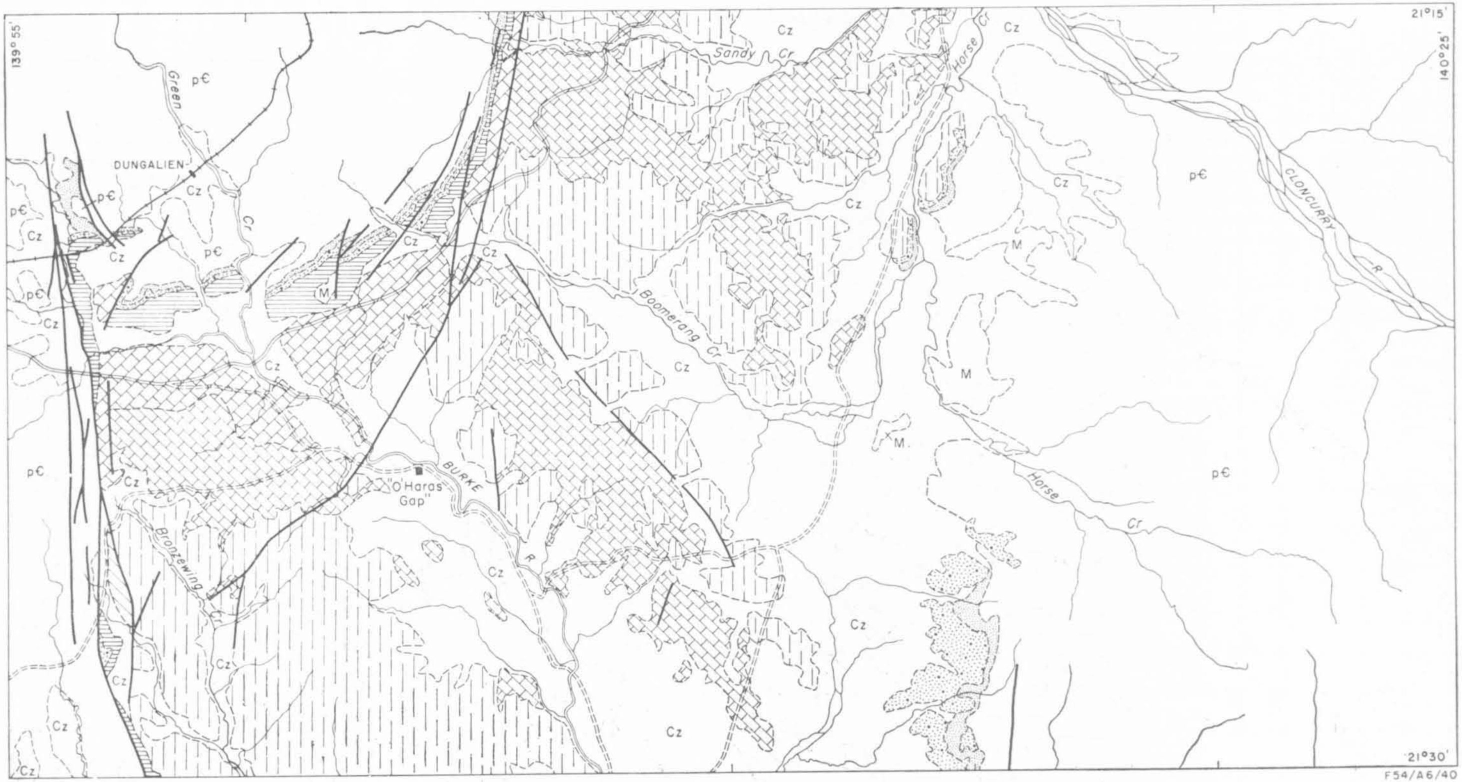

Figure 6. Geology of the north-central part of the Burke River Outlier.

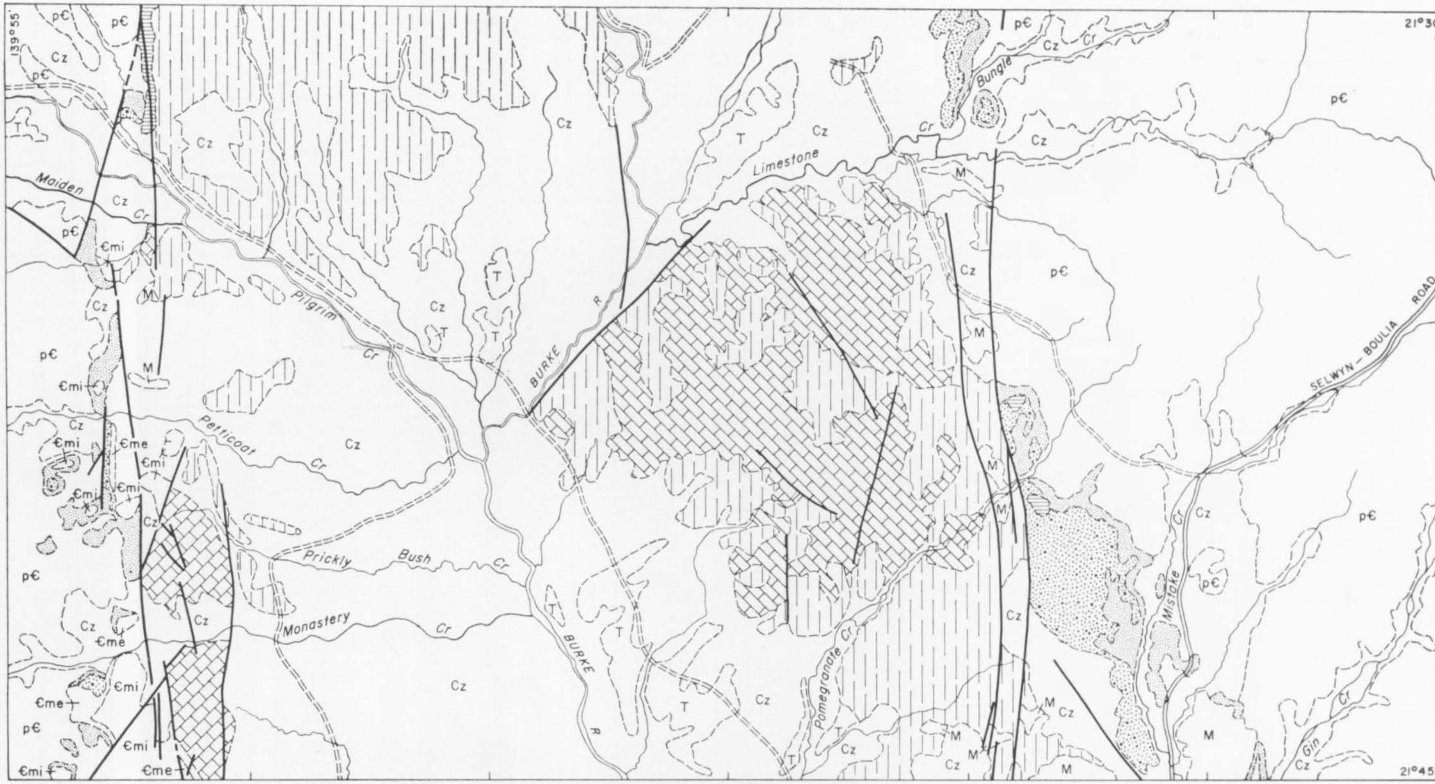

Figure 7. Geology of the south-central part of the Burke River Outlier.

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Figure 8. Geology of the southern part of the Burke River Outlier.

irregularity of its thickness, distribution, and lithological composition, and the widely varying degree of sorting, rounding, and size of grains and clasts. Towards the top, the 'Mount Hendry Formation' becomes strongly dolomitic, and locally grades upwards into the dolomite of the Thorntonia Limestone.

In the north, near Riversleigh homestead, the formation appears to be represented by a thin pebbly and sandy unit at the base of the Thorntonia Limestone. To the south, in the Yelvertoft/Thorntonia area, the basal sandstone at the head of Lily Creek in the Ogilvie Range, previously considered to be Split Rock Sandstone overlying the Beetle Creek Formation, underlies the Beetle Creek Formation, and unconformably overlies strongly dipping Precambrian siltstone. Cross-bedding, with sets up to 2 m thick, is a noteworthy feature of this sandstone (Pl. 4, fig. 2).

The overall grey colour of the 'Mount Hendry Formation' is rather different from the red-brown colour of the Mount Birnie Beds and the Riversdale Formation. Nevertheless, the 'Mount Hendry' and Riversdale Formations are lithologically similar in many ways, for example in the increasing dolomite content in the top beds.

Depositional Environment

In the Burke River Outlier, the sandstone-conglomerate lithosome was probably deposited in highly variable environments. The basal tillite could perhaps be a 'tilloid' deposited as a mudflow or turbidity current, but it seems more likely from the evidence given by de Keyser that it is a true periglacial marine tillite. It can probably be correlated with other late Upper Proterozoic tillites such as the Field River Beds of the western part of the Georgina Basin and the tillites of the Pertatataka Formation of the Amadeus Basin (Wells et al., 1967). After the tillite was laid down, the climate became warmer and more arid, as is indicated by the presence of halite pseudomorphs; periodical high-energy currents can be inferred from the coarse, strongly cross-bedded arkose. The most likely depositional environment at this time was perhaps very shallow marine, marine deltaic, or fluviatile. The subsequent transgression of a shallow sea deposited a mature orthoquartzite over most of the Burke River Outlier; trace fossils such as *Diplocraterion* and *Crossochordia* are present in this unit. Finally, the mudstone was laid down in a regressing tranquil sea. The overlying unit, a widespread ferruginous crust associated with a bleached zone, is thought to be an ancient soil profile.

North and west of the Burke River Outlier, the sandstone-conglomerate lithosome is much thinner and consists mainly of red-brown arkosic sandstone and conglomerate deposited in a delta or very shallow sea. This creates something of an enigma in that the unit thought to have been deposited from the shallowest sea is also the most widespread. Possibly therefore this unit is in part a continental deposit formed by a system of braided streams.

The Riversdale Formation and the 'Mount Hendry Formation' appear to have been laid down at much the same time as the upper part of the Mount Birnie Beds. They are lithologically almost indistinguishable from the upper part and therefore it is recommended that the terms Riversdale Formation and 'Mount Hendry Formation' be discontinued.

Dolomite Lithosome

The dolomite lithosome is the most widespread and thickest unit of the eastern part of the Georgina Basin (Fig. 9) and includes such formations as the Thorn-

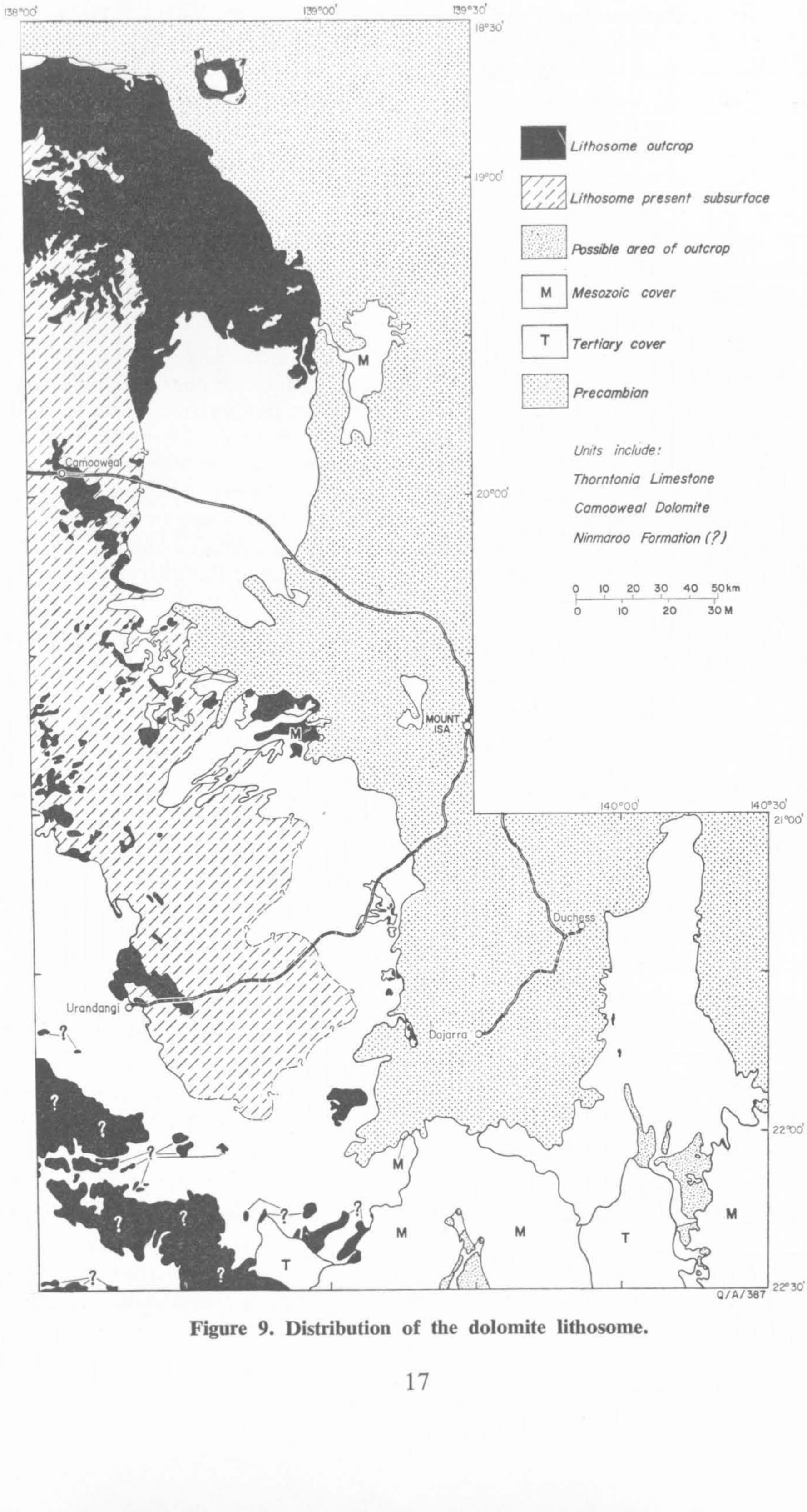

Figure 9. Distribution of the dolomite lithosome.

tonia Limestone, the Age Creek Formation, and the Camooweal Dolomite. It ranges in age from lower Middle Cambrian (perhaps older in places) to Upper Cambrian and possibly Ordovician. On the margins of the basin, it is generally less than 100 m thick, but in the central part of the basin it is up to 700 m thick.

The Age Creek Formation was not examined during the present investigation; Smith (1972) considers that its pelletal nature distinguishes it from the predominantly coarsely crystalline Camooweal Dolomite. If this is so, then it would seem to be a valid rock unit worthy of retention. The Thorntonia Limestone and the Camooweal Dolomite are lithologically identical, and their boundary is an arbitrary cut-off. However, as the two names are established in the literature they were retained during our investigation. Both were mapped in some detail.

Thorntonia Limestone

Mapping during the course of the present investigation considerably extended the known distribution of the Thorntonia Limestone, particularly in the Lawn Hill 1:250 000 Sheet area (Fig. 3), and to a lesser extent in the Burke River Outlier (Figs 5-8). The Thorntonia Limestone is composed predominantly of dolomite, with some minor limestone. At the base it is sandy and rarely conglomeratic, grading upwards from the basal sandstone-conglomerate lithosome. In places where it overlies the Colless Volcanics (and its equivalents), it contains angular fragments of volcanic material. It grades vertically and laterally into the chert-siltstone-limestone-phosphorite lithosome.

The carbonate rocks are thin-bedded to massive; their grainsize ranges from microcrystalline to coarsely crystalline. They are white, pink, fawn, or yellow when fresh, but generally grey or yellow-brown when weathered. Irregular patches, layers, and nodules of silica occur in places. Towards the top of the formation chert becomes particularly common. This *Chert Member* of the Thorntonia Limestone is a persistent and very distinctive non-carbonate unit. It is well developed in the Quita Creek/Mount Isa area, and to a lesser extent in the Duchess district. Thinner and smaller outcrops are also found farther north. The type area is the margin of the Georgina Basin between the headwaters of Quita Creek and St Ronans Creek, some 10 to 30 km south of Ardmore homestead. Here, black-and-white banded chert rubble beds, ranging in thickness from 2 to 15 m, overlie the Precambrian basement (Fig. 15).

Several types of chert can be recognized:

Black-and-white banded chert is the commonest type in the Ardmore area and to a lesser extent in the Duchess area. The bands are from 1 to 10 mm thick, and are commonly convoluted.

Algal chert—both wavy-laminated and spheroidal—is the commonest type in the Mount Isa and Camooweal Sheet areas. The diameter of the spheroids ('algal balls') ranges from pea-size to about 2 cm.

Vuggy grey quartzitic chert in places grades into spheroidal algal chert, and is common in the Duchess area. A well bedded variety also occurs in the Thorntonia area. The quartzitic chert contains hyolithids and *Redlichia*.

'Yelvertoft'-type chert is found mainly in the Thorntonia/Yelvertoft area and is a yellow, lumpy, nodular chert, usually weathered to a porcellanitic rock. Fragments of *Redlichia* are common.

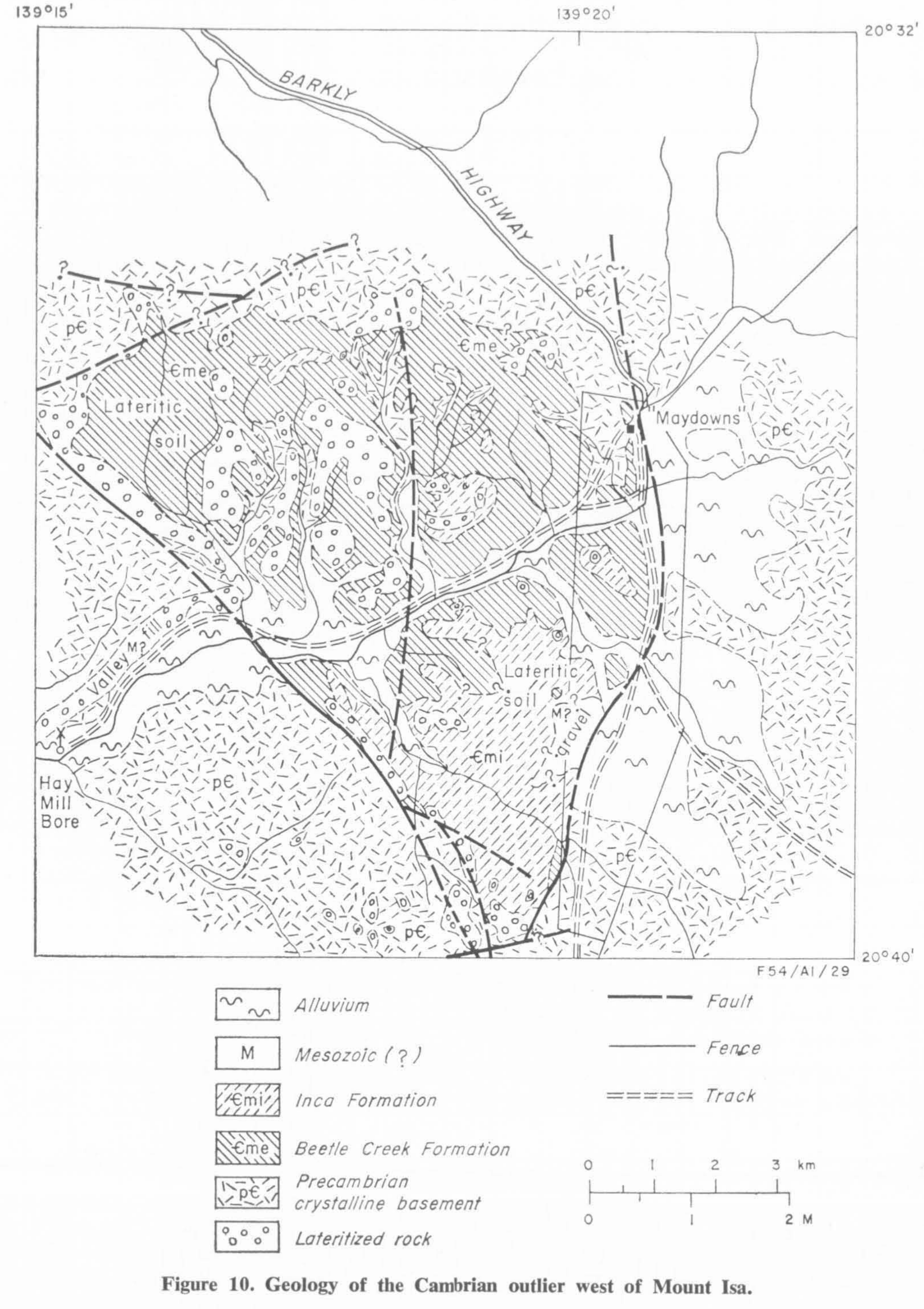

Figure 10. Geology of the Cambrian outlier west of Mount Isa.

Lumpy chert is white or yellow and has an irregular lumpy appearance with a glazed surface. It is present in the Duchess area.

Chert nodules are spheroidal or ovoidal and concentrically laminated. They are found in the Duchess and Ardmore areas.

The Chert Member is normally underlain by the Thorntonia Limestone and overlain by the Beetle Creek Formation, but in places, e.g. west of Mount Isa (Fig. 10), it occurs intercalated as lenses and interbeds in the base of the Beetle Creek Formation. In the Duchess area it may be traced laterally into Thorntonia Limestone. It is notable that the Chert Member almost invariably occurs as a rubble horizon only, and is best developed where outcrops of Thorntonia Limestone are scarce or insignificant. This suggests that the chert member is in part a residual concentration of silicified portions of Thorntonia Limestone, after most, or all, of the carbonate has been leached out or replaced. Other evidence of the original carbonate rock, such as clouds of fine carbonate dust and outlines of dolomite rhombs, may be seen in thin sections of the chert. The siliceous wavy and spheroidal algal structures, and the presence of concentrically laminated chert nodules of a type similar to those enclosed in dolomite of the Thorntonia Limestone, support the hypothesis that the member is of diagenetic origin.

It is somewhat uncertain whether the Chert Member of the Thorntonia Limestone should be included in the dolomite lithosome. De Keyser favours its association with the dolomite lithosome because of the evidence that it is silicified Thorntonia Limestone. Cook on the other hand feels that it should be included in the overlying chert-rich lithosome despite its diagenetic characters, as he considers that it is possible that not all of the chert is diagenetic, and that, conversely, much of the chert in the overlying chert-rich lithosome is diagenetic.

Fossils are fairly rare throughout most of the Thorntonia Limestone, but are present in some of the siliceous layers. They include *Biconulites* sp., *Redlichia* spp., *Helcionella* sp., *Hyolithus,* echinoderm fragments, archeocyathids, phosphatic brachiopods, *Girvanella,* and sponge spicules (Pl. 5, figs 1, 2; Pl. 6, fig. 1). Algal structures are common in places.

Camooweal Dolomite

To the west, in the central part of the basin, the dolomite lithosome thickens considerably and is there known as the Camooweal Dolomite. Lithologically it is very similar to the Thorntonia Limestone. It is composed of buff, yellow, cream, white, or mottled dolomites, which weather to dark grey. Intercalations of sandy dolomite, dolopelmicrite, oolitic dolomite, dolarenite, and penecontemporaneous breccia are present. Karren surfaces commonly form on the Camooweal Dolomite (Pl. 6, fig. 2). Bedding is generally thick to massive, but thin-bedded dolomite is also present in places; some units are cross-bedded. Stylolites are common locally.

The age of the Camooweal Dolomite and its relationship to other units have been a matter of considerable speculation for some time. Primarily because of the apparent lack of fossils, Öpik (1956a) suggested that the unit was either Lower Cambrian or late Precambrian. He considered that the Camooweal Dolomite probably formed a topographic high in Middle and Upper Cambrian time, which acted as a faunal barrier and so produced the differences which are evident between Cambrian faunas of Queensland and those of the Northern Territory. Subsequent workers, notably Mulder (1962), Randal & Brown (1962), Smith & Roberts (1963), and de Keyser (1971) contested Öpik's interpretation. During the present investigations, lower Middle Cambrian fossils were collected from a number of localities previously mapped as Camooweal Dolomite. In addition, in the Colless Creek area (Fig. 3), the upper Middle Cambrian Currant Bush parvafacies is overlain by the Camooweal Dolomite. While the Camooweal Dolomite is lithologically indistinguishable from the Thorntonia Limestone in outcrop, one can nevertheless trace the boundary between them on the air-photographs in the Colless Creek area (Fig. 3) and in places the Camooweal Dolomite overlies the Thorntonia Limestone. This is further evidence that part of the Camooweal Dolomite is at least as young as Middle Cambrian. It could conceivably range in age from Lower Cambrian to Ordovician.

Although the Camooweal Dolomite does not generally contain identifiable fossils, thin sections commonly contain 'ghosts' partly obscured by the dolomitization (Pl. 7, fig. 2). Algal remnants are also present in places.

Depositional Environment

The depositional history of the dolomite lithosome is somewhat uncertain owing to the effects of coarse recrystallization, but it seems probably that the unit represents early* dolomitization of aragonitic or calcitic sediments. The hypothesis of Adams & Rhodes (1960) involving dolomitization by seepage reflexion from a hypersaline lagoon could be applied to the Camooweal Dolomite. However, a more likely mechanism is that suggested by Shinn et al. (1965) from their work in the Bahamas. They found that dolomitization occurred very soon after deposition in the supratidal zone. Features in the dolomite lithosome such as cross-bedding, penecontemporaneous brecciation, and the presence of stromatolite biostromes and bioherms (Pl. 8, figs 1, 2) are all consistent with a supratidal environment. The Camooweal Dolomite, which is in the middle of the basin rather than around the margins as would be expected for an intertidal zone, was probably laid down as an extensive supratidal shoal, comparable in some respects to the present-day Bahama Banks, and surrounded on all sides by deeper more normal marine conditions.

The Georgina Basin is known to have lain near the Cambrian equator, and consequently the supratidal zone is likely to have been hypersaline. Such conditions were likely to have been inimical to most organisms and could have formed a faunal barrier. The presence of fossils indicates either that some forms may have been able to withstand the high salinities or that marine incursions may have mitigated the environment. In addition the fossil assemblage may be in part thanatocoenosic.

CHERT-SILTSTONE-LIMESTONE-PHOSPHORITE LITHOSOME

The chert-siltstone-limestone-phosphorite lithosome is thin but widespread and comprises the Beetle Creek and Border Waterhole Formations in Queensland and the Burton and Wonarah Beds in the Northern Territory (Fig. 11). It is everywhere of lower Middle Cambrian age. There is little justification for the various rock unit names used for this interval, and it is recommended that only

* Throughout this text terms related to diagenesis are commonly qualified by the prefix 'early' or 'late'. The term 'early' is used to denote a diagenetic change which took place very soon after deposition, in some cases before the complete lithification of the original sediment. The term 'late' indicates diagenesis which occurred some considerable time after the original sediment was deposited and the rock lithified.

the name Beetle Creek Formation should be retained, as all four units are lithologically identical and of the same age.

As indicated in Figure 2, this lithosome generally overlies and laterally replaces the dolomite lithosome (Thorntonia Limestone), but in some places it rests directly on the basal sandstone-conglomerate lithosome (Mount Birnie Beds). A prominent chert unit (Pl. 9, fig. 1) commonly underlies the Beetle Creek Formation. In general it is overlain by the silt-shale-chert lithosome (Inca Formation). Our investigations modified somewhat the distribution of the lithosome (compare, for instance, the distribution of the Border Waterhole Formation shown on the published Lawn Hill 1:250 000 geological Sheet with that in Figure 3). The lithosome was also studied in some detail both in the field and the laboratory, because of the economic importance of the phosphatic part of the section. Only general aspects of the geology will be considered here; the phosphorites will be described in more detail later.

Beetle Creek Formation (and Border Waterhole Formation)

The area in which the formation has been most studied is the Burke River Outlier (Figs 5-8), because of the known phosphate deposits. There, the formation consists of siliceous shale, chert, siltstone, phosphatic siltstone, phosphatic limestone, limestone, and phosphorite. Russell (1967) subdivided the formation into three members: Lower Siltstone Member, Lower Breccia Member, and Monastery Creek Phosphorite Member. This stratigraphic scheme was subsequently modified by Thomson & Russell (1971) and Russell & Trueman (1972), who suggest, on the basis of improved subsurface data, that the Lower Breccia Member is not a bonafide stratigraphic unit and should be deleted. Their twofold stratigraphic division is as follows:

The *Lower Siltstone Member,* which is present only in the southern half of the Burke River Outlier, consists of siltstone, chert, and minor phosphorite. It has a maximum thickness of about 60 m.

The *Monastery Creek Phosphorite Member* is well developed throughout the Burke River Outlier and particularly in the Mount Murray area. It reaches a maximum thickness of 40 m. It comprises white, grey, or brown phosphorite, phosphatic siltstone, chert, and minor light grey limestone (Pl. 9, fig. 2). Below the zone of oxidation all the rocks are black. Bedding ranges from thin to medium, cross-laminations are common, and cut-and-fill structures are present in places.

Elsewhere, the Beetle Creek Formation has not been formally subdivided, and the exceptionally rapid facies changes within the formation make it highly unlikely that any such subunits would be of regional significance. It is often impossible to correlate rock types between drill holes a few hundred metres apart.

In the Lawn Hill/Border Waterhole area (Fig. 3) the Beetle Creek Formation (named the Border Waterhole Formation in this corner of the Georgina Basin by Carter & Öpik, 1961) is up to 70 m thick. It consists of irregularly bedded and nodular chert, silicified microcoquinites, chert breccia, chert conglomerate, siltstone, siliceous shale, and phosphorite. East of Highland Plains homestead, these sediments grade upwards, and also in places laterally, into fine-grained fine to medium bedded grey cherty fetid limestone. The chert breccia contains rare rounded pebbles of Precambrian quartzite in places, and occasional clasts of chert are round or subround, indicating some reworking of the chert.

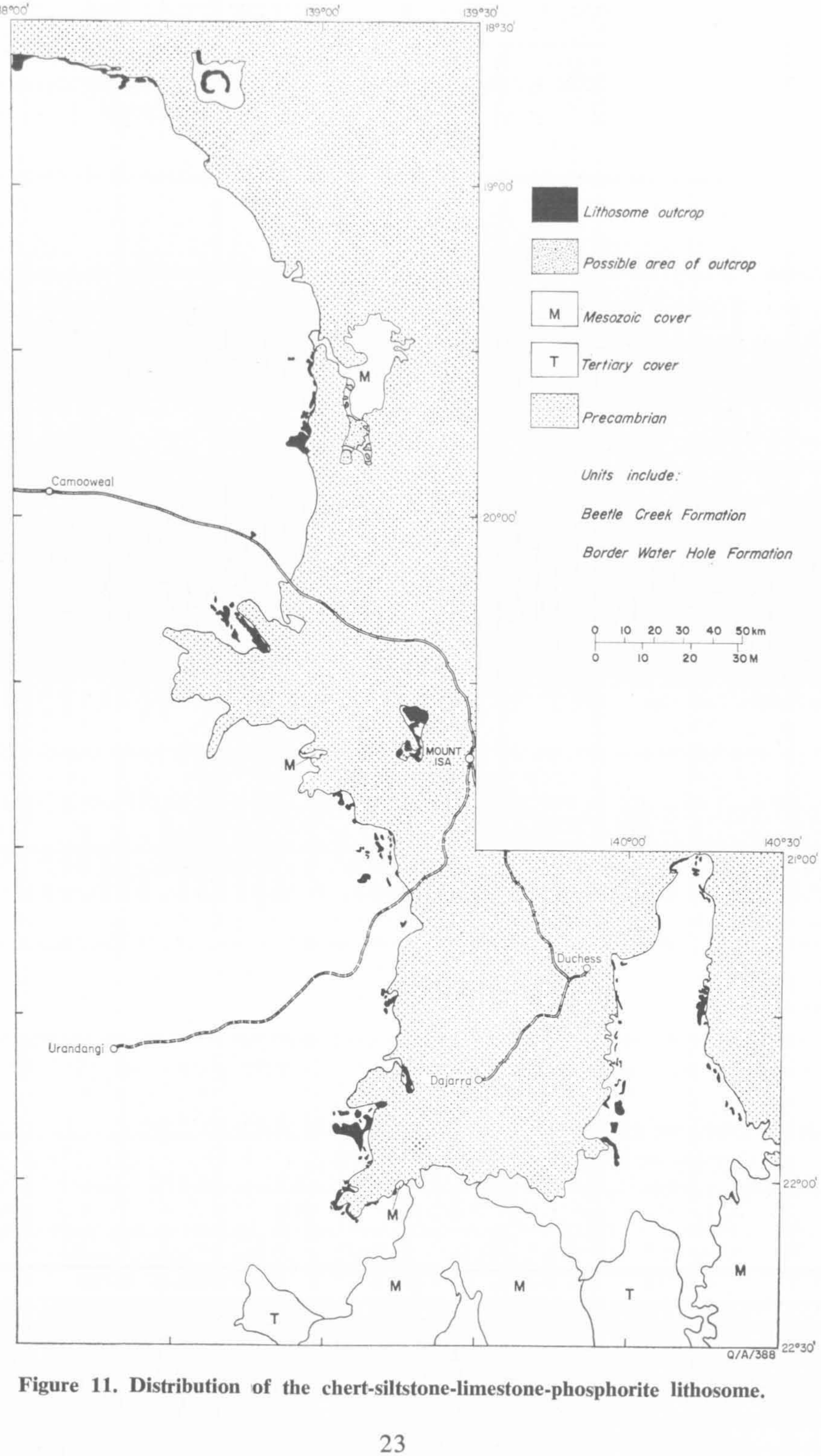

Figure 11. Distribution of the chert-siltstone-limestone-phosphorite lithosome.

In the Lady Annie/Lady Jane district (Fig. 12) the Beetle Creek Formation consists of poorly bedded chert, chert breccia and conglomerate, silicified micro-coquinite, white and yellow phosphatic siltstone or silty phosphorite, pelletal phosphorite, and fine sandstone (Pl. 10, figs 1, 2). Ferruginous and manganiferous breccia layers within the formation are thought to have formed during diastems. The boundary between the Beetle Creek Formation and the underlying Thorntonia Limestone is particularly interesting in this area. In the vicinity of Hilary Creek the contact is highly irregular, and resembles a karst surface. Pockets and depressions in the dolomite are filled with chert-phosphorite breccia, phosphatic siltstone, and silty phosphorite, and the sides are lined with iron and manganese oxides, and somewhat enriched in Zn, Ni, and Co. It is reasonable to conclude that in this area the Thorntonia Limestone emerged and was eroded before the Beetle Creek Formation was laid down in a further marine transgression. It is also possible that a little of the phosphate is derived from the solution of slightly phosphatic Thorntonia Limestone.

West of the Lady Annie Outlier, in the Thorntonia area (Figs 13-14), the Beetle Creek Formation is poorly exposed. The rock types are much the same as those of the Lady Annie area, except that pelletal phosphorites are almost completely absent, and cherts, silty phosphorites, and mudstones predominate.

In the type section in the small unnamed outlier west of Mount Isa, chert and mudstone predominate, and phosphorite appears to be completely absent. The formation is also non-phosphatic southwest of Mount Isa. However, south of Ardmore (Fig. 15), and also in the Ardmore Outlier (Fig. 16), both pelletal and non-pelletal phosphorites (silty phosphorite and phosphatic siltstone) are well developed. Chert and mudstone and thin limestone bands are again present. In the northern part of the Ardmore Outlier breccia is well developed; in a newly made road-cut it was apparent that the breccia is composed of angular siltstone clasts, but the weathered samples were silicified and would have been regarded as chert breccia. The siltstone breccia is restricted to particular beds and had probably formed penecontemporaneously with sedimentation, without lateral movement. Some of the breccias associated with the Beetle Creek Formation are thought to have formed by post-depositional weathering, so that it is misleading to attempt to correlate many of them.

Fossils are common and well preserved in the Beetle Creek Formation. The siltstone and mudstone contain a particularly rich fauna, and many of the Lower Middle Cambrian type fossils (especially trilobites) were collected from this part of the section. Fossils include trilobites (*Xystridura* and *Pagetia* are particularly common), brachiopods, bivalves, echinoderms, sponge spicules, and hyolithids.

Depositional Environment

The abundance of fossils indicate that the lithosome was deposited mainly under marine or paralic conditions. The complex facies variations suggest a highly variable environment such as would be encountered nearshore. Features such as cross-bedding and trough-and-fill structures imply moderately high-energy conditions at times. The phosphorites and cherts indicate that nutrients were abundant. However, the abundance of non-phosphatic mudstones also shows that there was periodically an abundant supply of fine detritus into a low-energy environment. The clay mineralogy of the Beetle Creek Formation shows no simple pattern; the clays consist mainly of kaolinite, with minor illite and montmorillonite, as could be

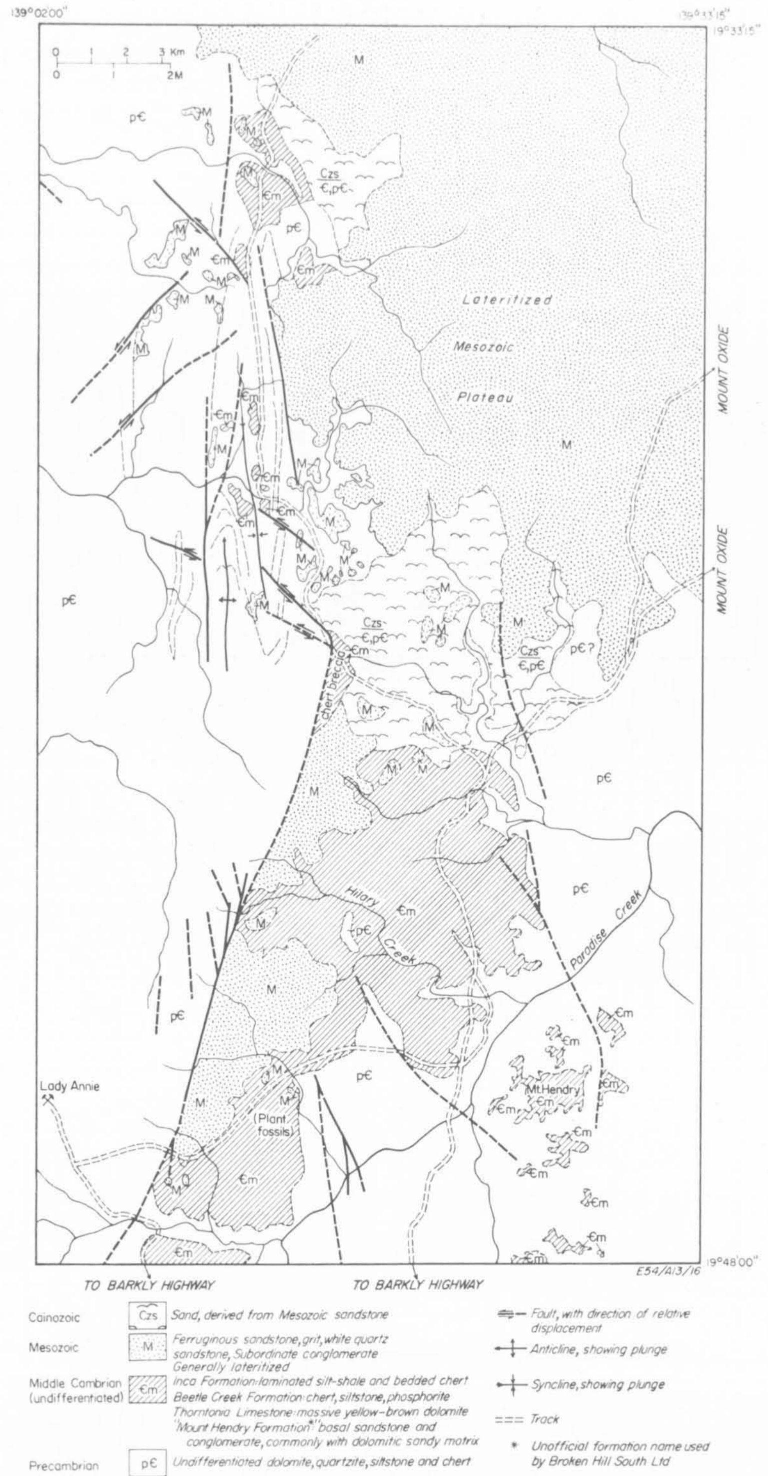

Figure 12. Reconnaissance geology of the Lady Annie phosphate district.

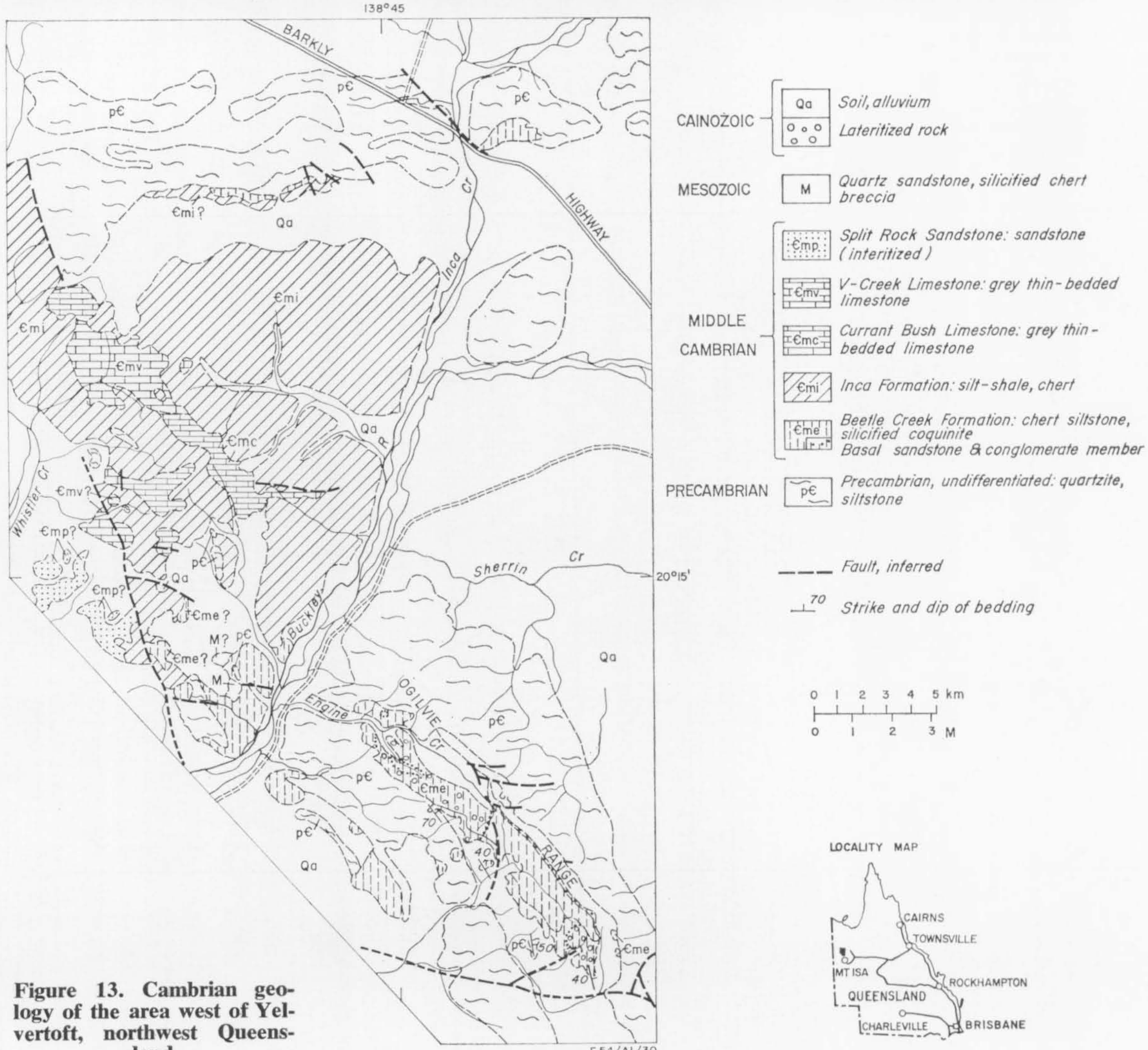

Figure 13. Cambrian geology of the area west of Yelvertoft, northwest Queensland.

Plate 1, fig. 1. Tillite in Mount Birnie Beds, 10 km east-northeast of Duchess.

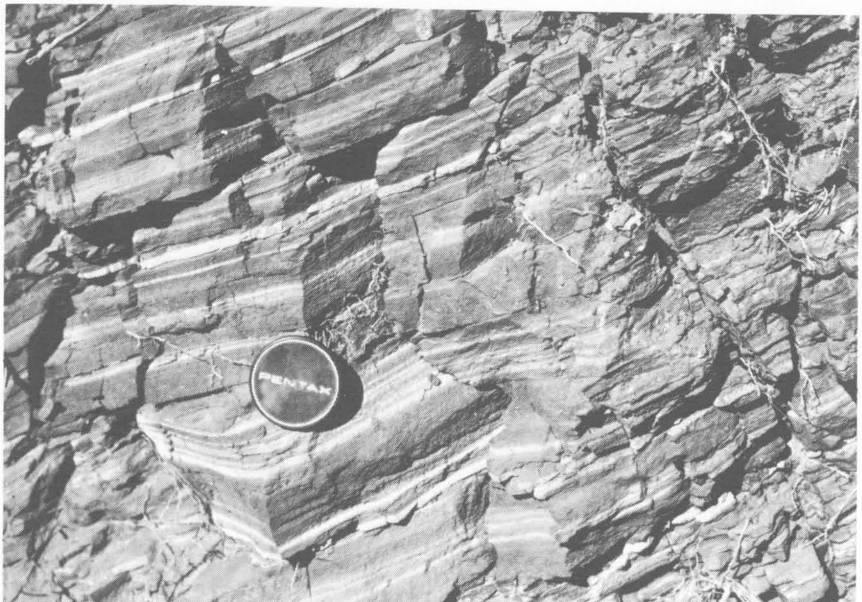

Plate 1, fig. 2. Red and green shale in Mount Birnie Beds, 10 km east-northeast of Duchess.

Plate 2, fig. 1. Cross-bedded orthoquartzite overlying quartz-pebble conglomerate. Mount Birnie Beds.

Plate 2, fig. 2. Quartz pebble conglomerate in Mount Birnie Beds, southwest of Bundy Bore.

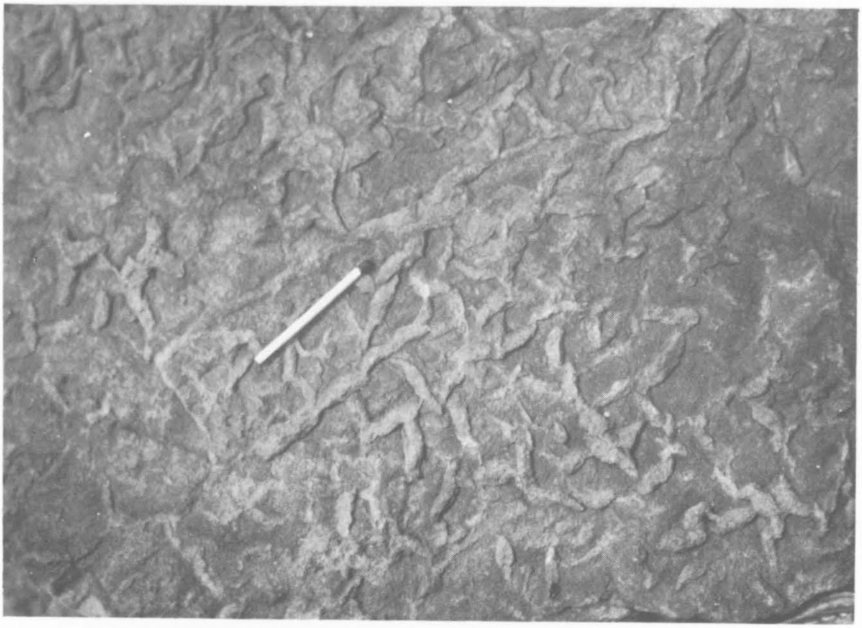

Plate 3, fig. 1. Trace fossils on a bedding-plane surface of quartzose sandstone. Mount Birnie Beds at Mount Birnie.

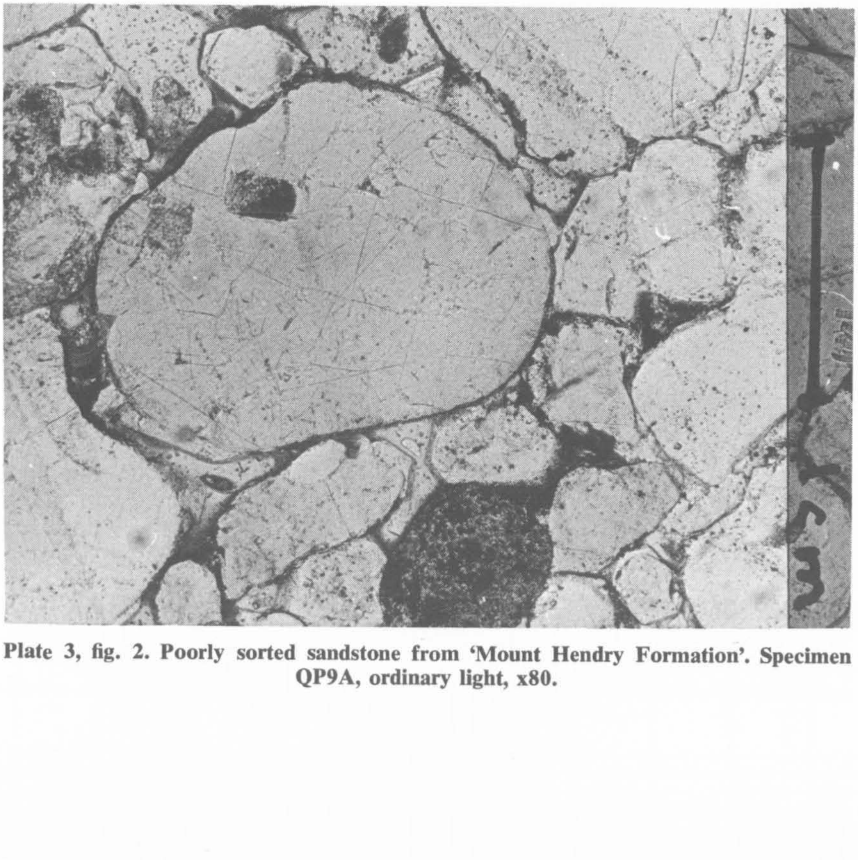

Plate 3, fig. 2. Poorly sorted sandstone from 'Mount Hendry Formation'. Specimen QP9A, ordinary light, x80.

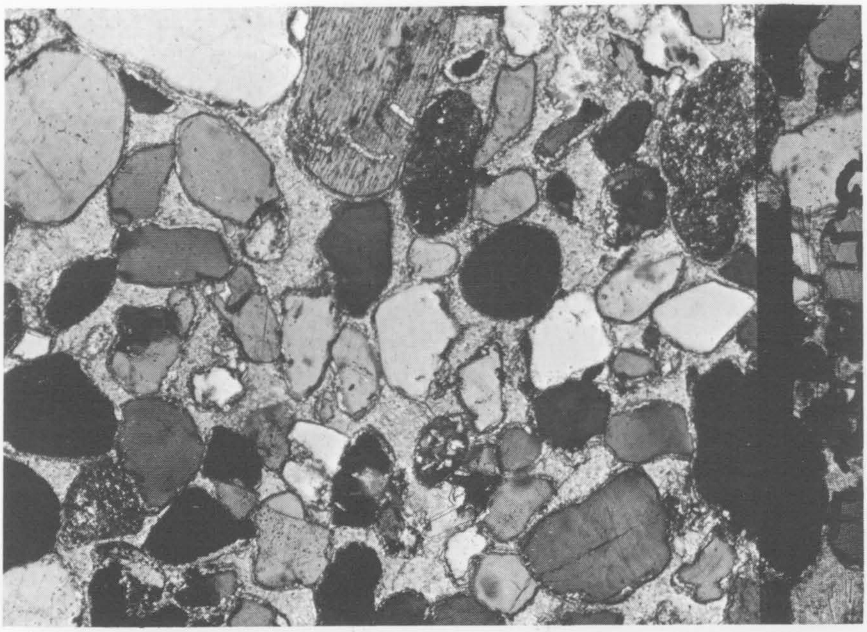

Plate 4, fig. 1. Poorly sorted sandstone with a calcitic matrix. Riversdale Formation. Specimen QP28C4, crossed nicols, x80.

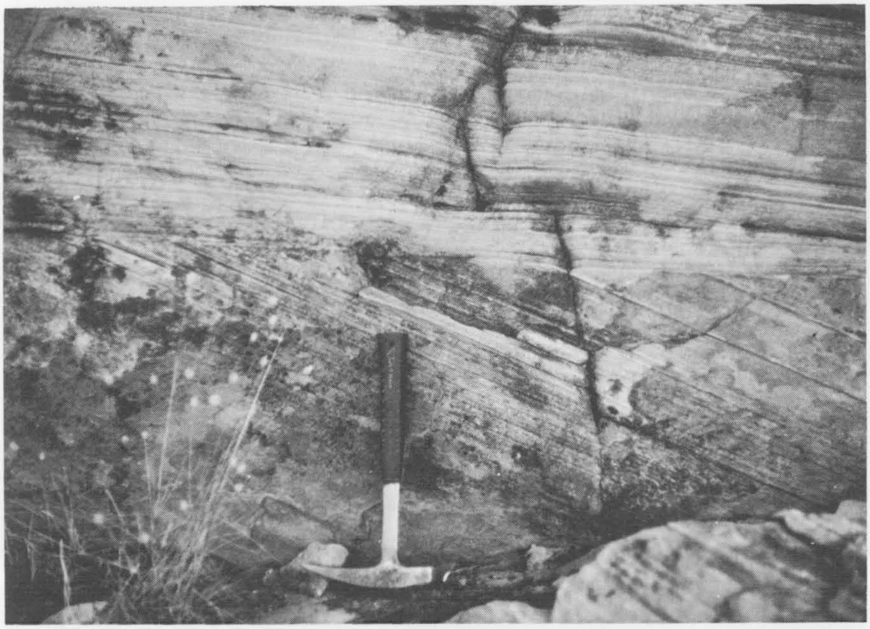

Plate 4, fig. 2. Cross-bedding in basal sandstone-conglomerate of Lily Creek area 21 km south-southwest of Yelvertoft homestead.

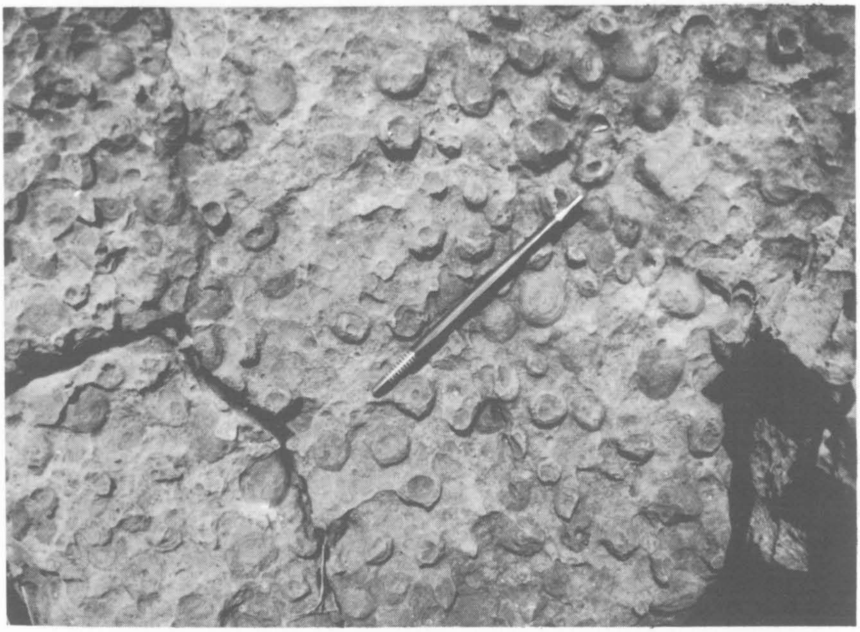

Plate 5, fig. 1. *Girvanella* in Thorntonia Limestone.

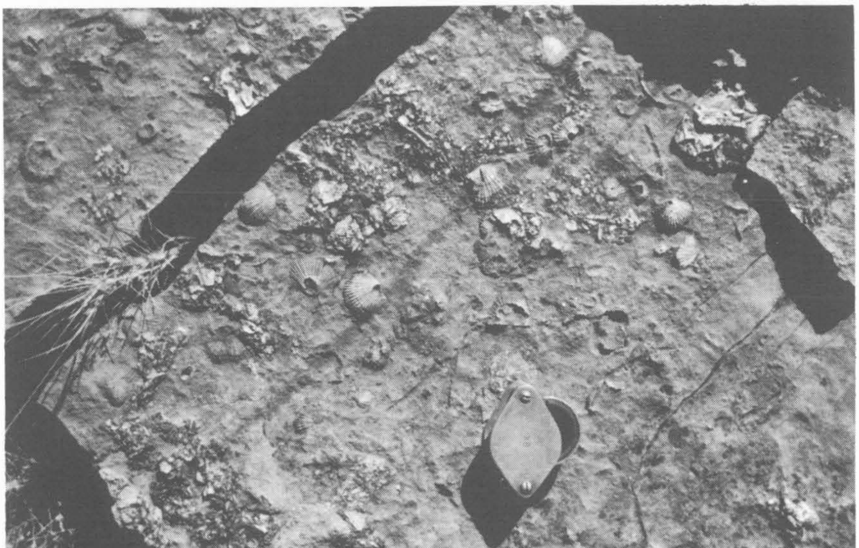

Plate 5, fig. 2. Bedding plane of Thorntonia Limestone with numerous brachiopods.

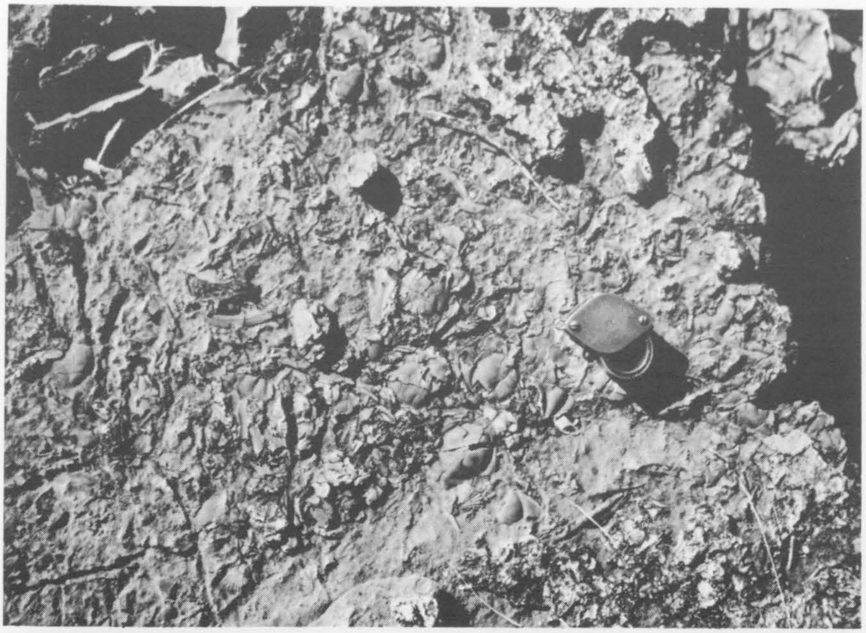

Plate 6, fig. 1. Bedding-plane surface with abundant trilobite fragments, particularly *Xystridura* and *Nisusia* sp.

Plate 6, fig. 2. Karren surface on Camooweal Dolomite, Colless Creek area.

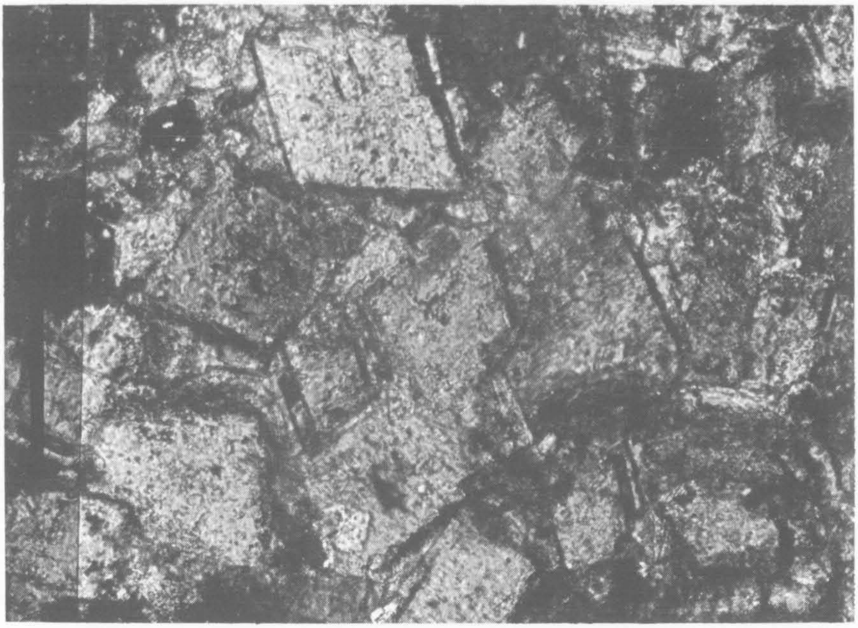

Plate 7, fig. 1. Strongly recrystallized Thorntonia Limestone with abundant dolomite rhombs. Specimen 2C3. Polarized light, x250.

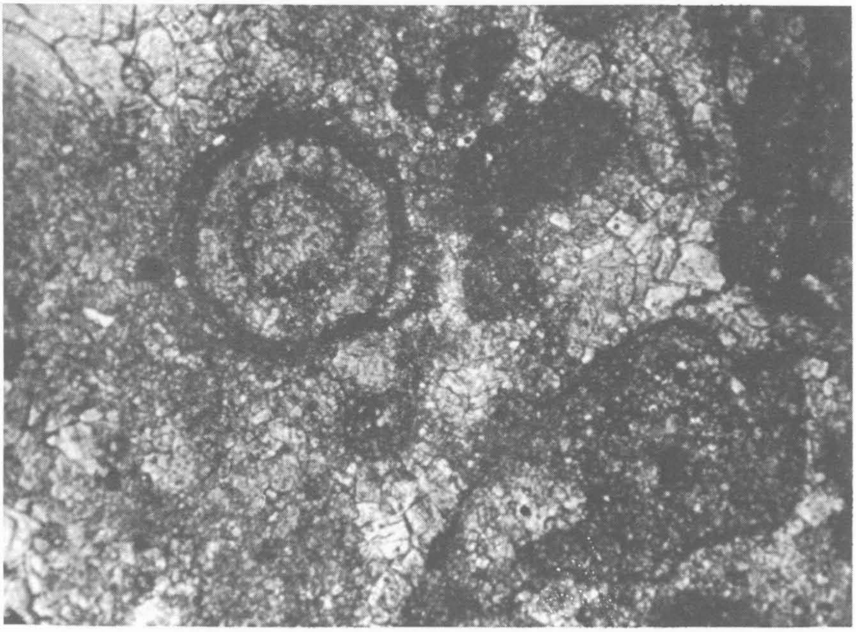

Plate 7, fig. 2. Strongly recrystallized Camooweal Dolomite with 'ghosts' of fossils. Ordinary light, x35.

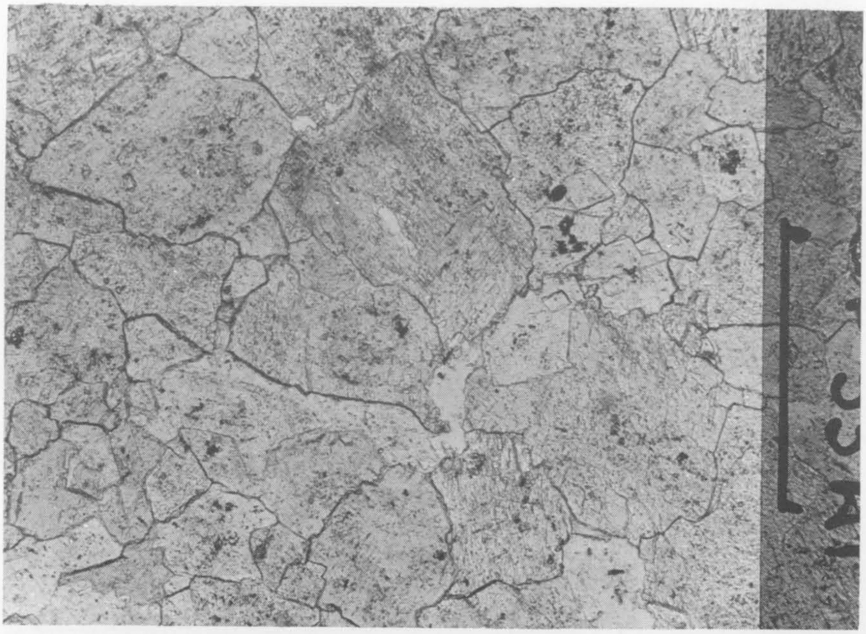

Plate 8, fig. 1. Coarsely crystalline biohermal material from Thorntonia Limestone. Sample QP 53A1. Ordinary light, x80.

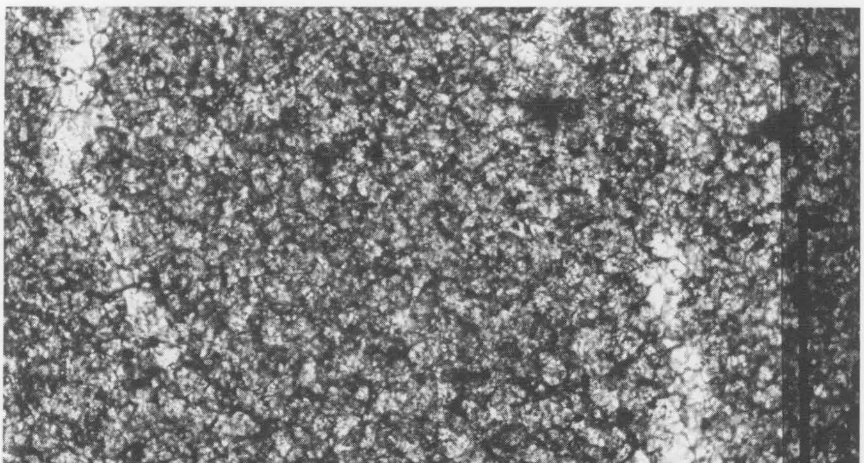

Plate 8, fig. 2. Finely crystalline biostromal material from Thorntonia Limestone. Sample QP 53A2. Ordinary light, x80.

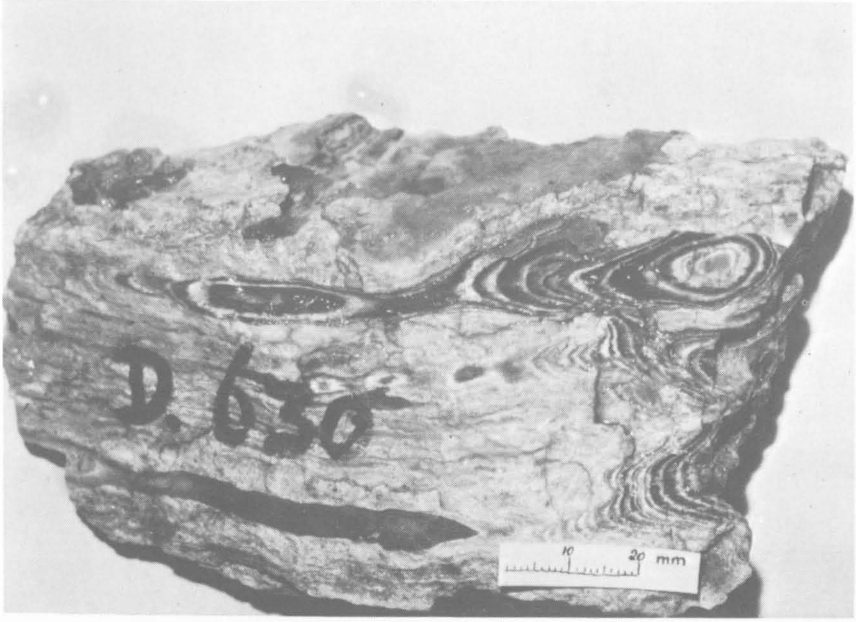

Plate 9, fig. 1. Convoluted black and white chert characteristic of chert unit of Thorntonia Limestone.

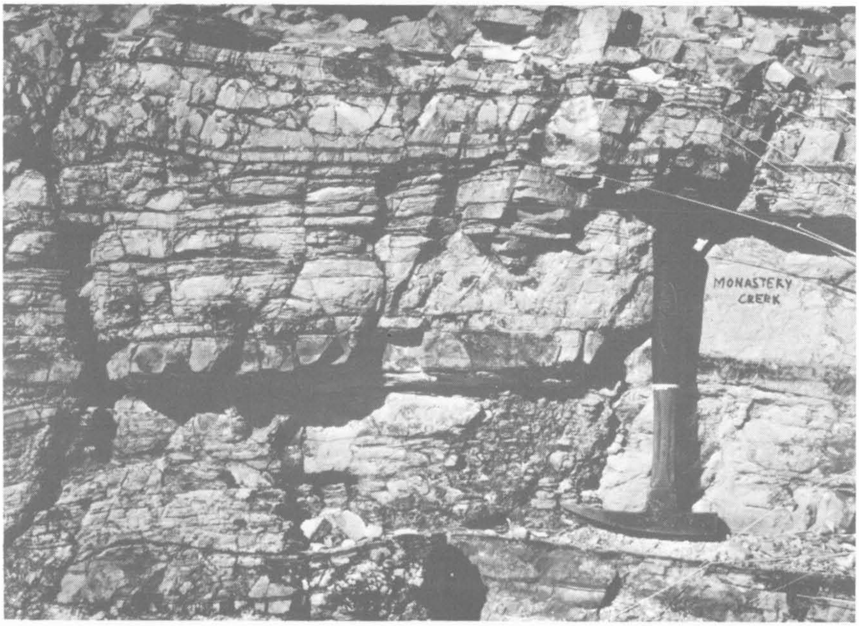

Plate 9, fig. 2. Typical outcrop of pelletal phosphorite in the Duchess district. Siliceous phosphorite and phosphatic siltstone are interbedded with chert.

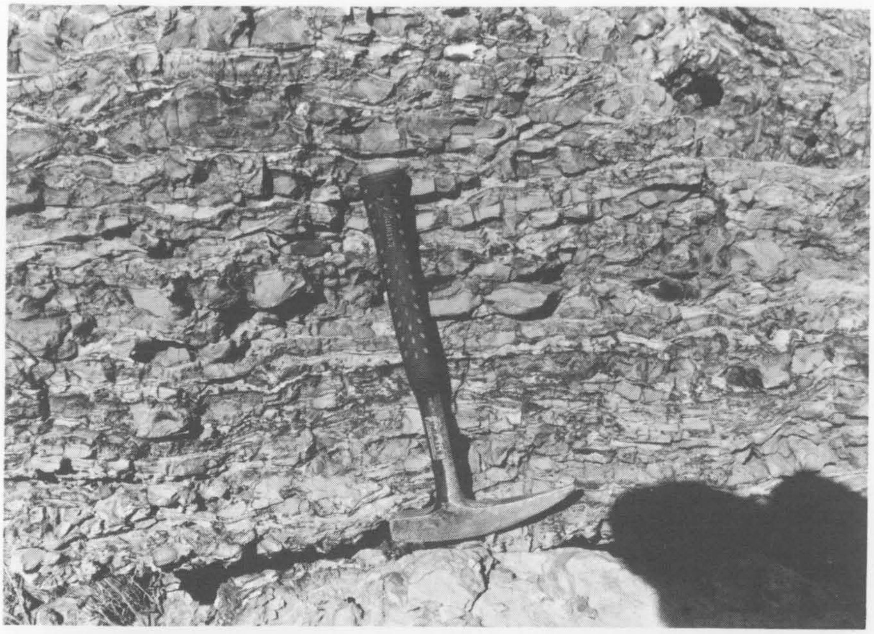

Plate 10, fig. 1. Typical Beetle Creek Formation in the Lady Annie area.

Plate 10, fig. 2. Nodular chert in the Beetle Creek Formation ('Yelvertoft Beds') of the Lady Annie area.

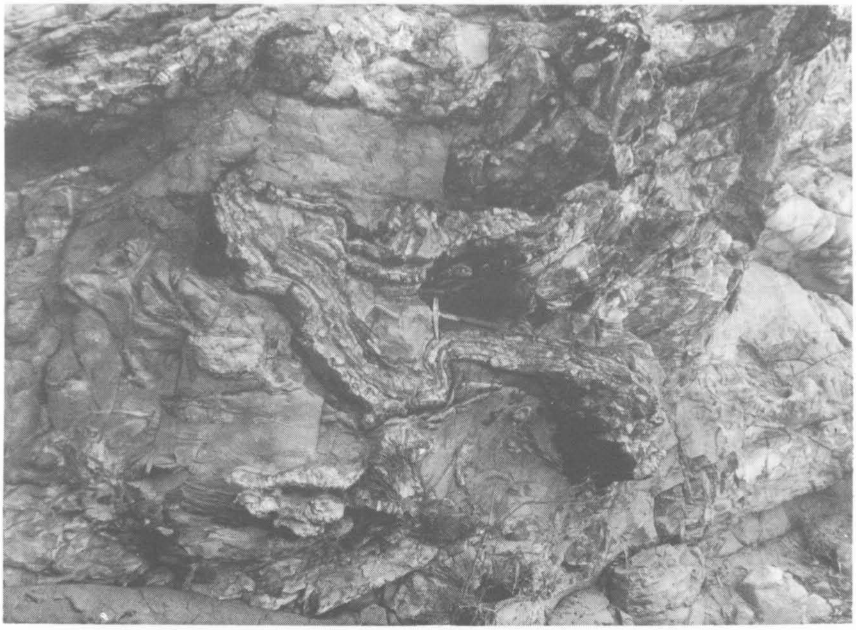

Plate 11, fig. 1. Slump fold in the Inca Formation.

Plate 11, fig. 2. Intraformational breccia in the Inca Formation 32 km south of Thorntonia homestead.

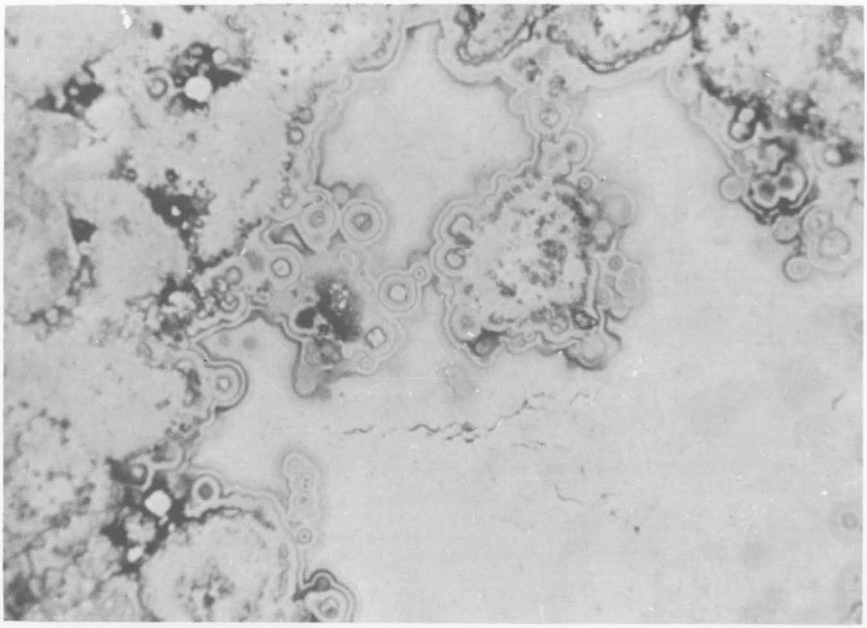

Plate 12, fig. 1. Silicified limestone from the cherty unit of the Thorntonia Limestone showing chalcedonic colloform banding. Ordinary light, x35.

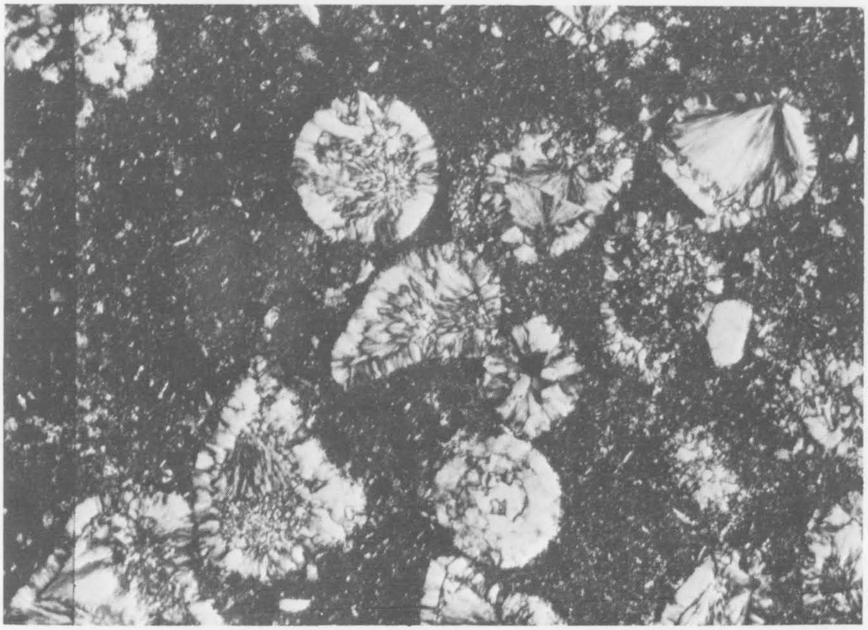

Plate 12, fig. 2. Abundant siliceous sponge spicules in transverse section in a cherty unit of the Inca Formation. Polarized light, x100.

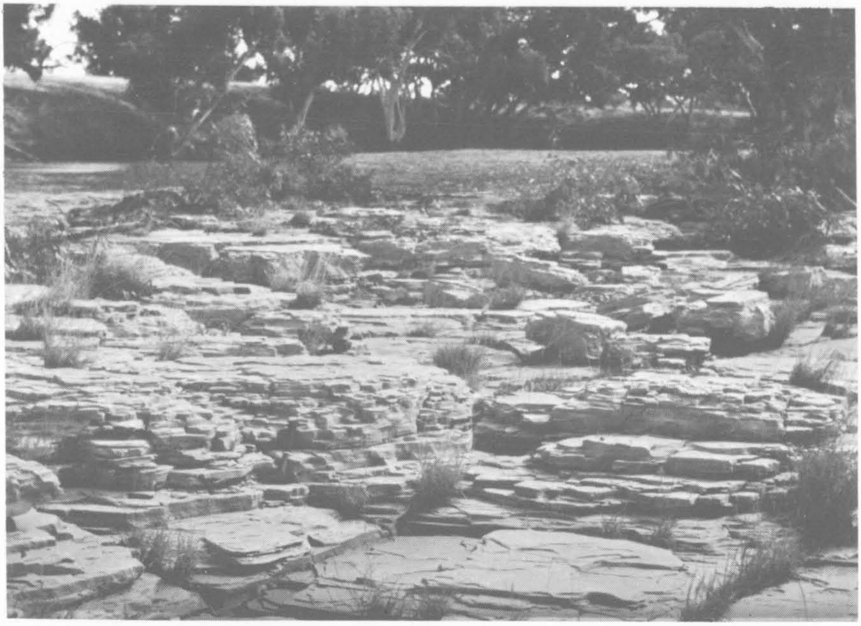

Plate 13, fig. 1. Selwyn Range Limestone in the Burke River 5 km southeast of O'Haras Gap homestead.

Plate 13, fig. 2. Laminated calcilutites with disc-like and platy chert nodules. Selwyn Range Limestone, 6.5 km southeast of Pilgrim Bore.

Plate 14, fig. 1. Typical outcrop of Devoncourt Limestone showing resistant silty calcilutite with soft marly interbeds, 13 km east of Duchess.

Plate 14, fig. 2. Typical outcrop of Quita Formation in the Quita Creek area.

Plate 15, fig. 1. Nodular bed of calcilutite within the Devoncourt Limestone, 11 km east of Duchess.

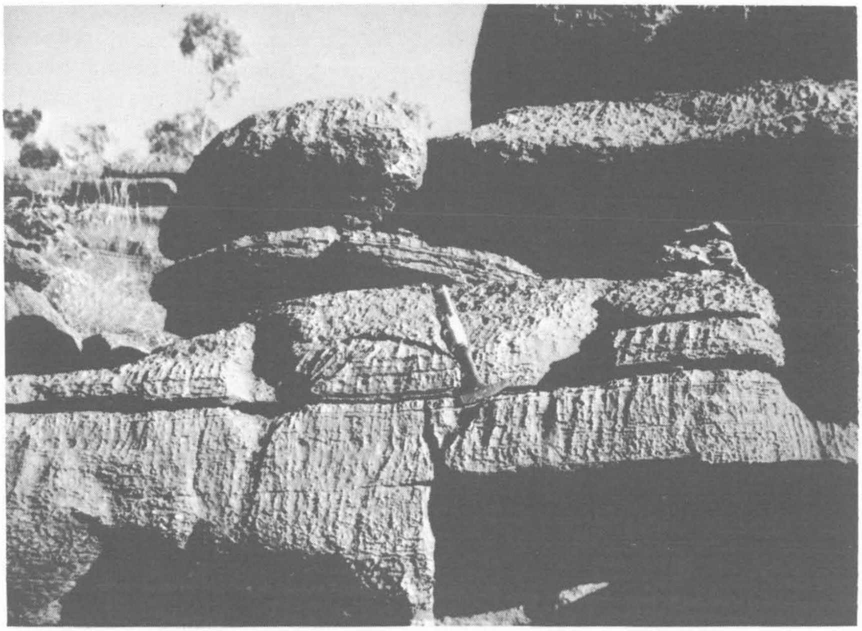

Plate 15, fig. 2. Dark grey bed of dolomite within the upper part of the Currant Bush Limestone, east of Highland Plains homestead.

Plate 16, fig. 1. Split Rock Sandstone disconformably overlying Mail Change Limestone, 40 km east of Camooweal.

Plate 16, fig. 2. Typical Split Rock Sandstone at Split Rock Waterhole.

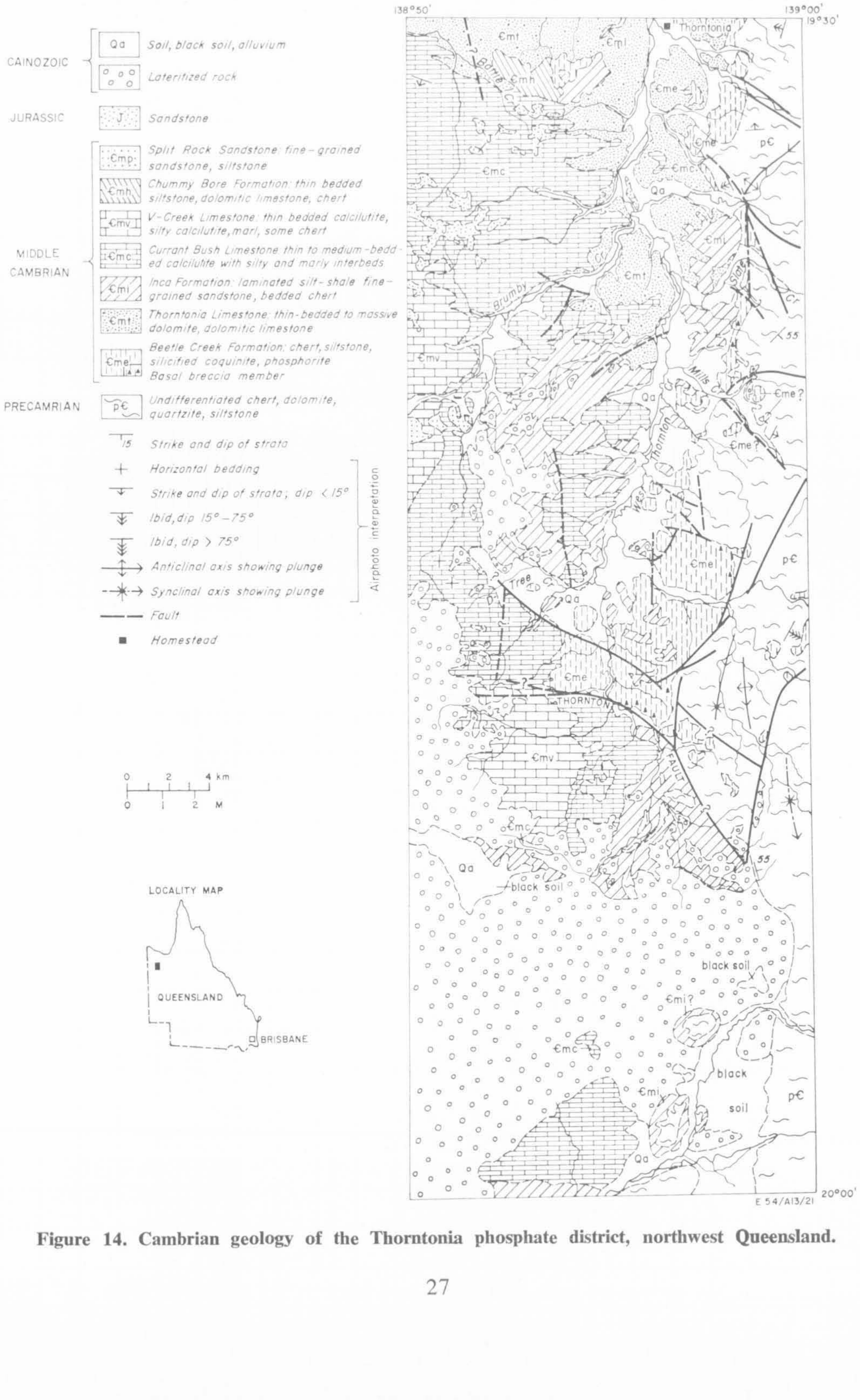

Figure 14. Cambrian geology of the Thorntonia phosphate district, northwest Queensland.

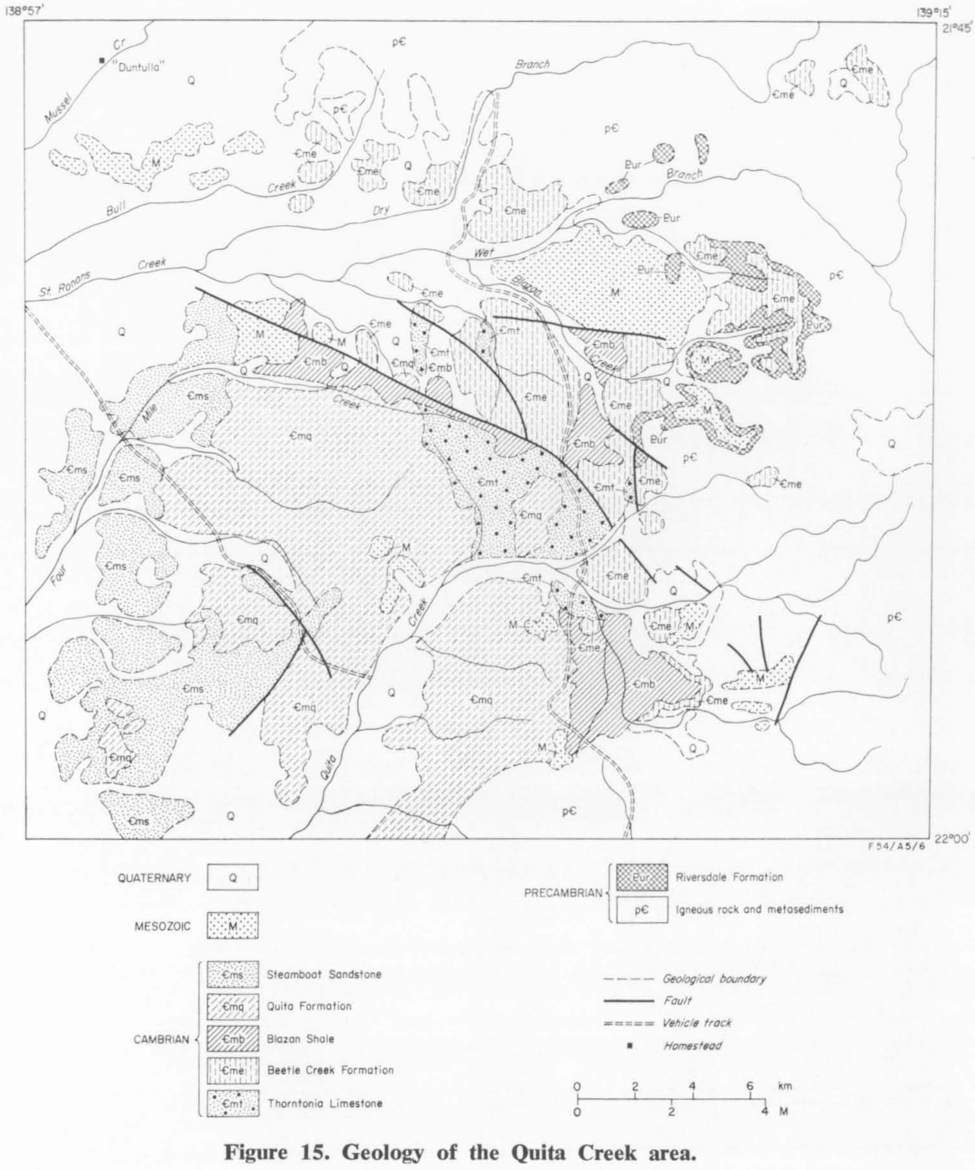

Figure 15. Geology of the Quita Creek area.

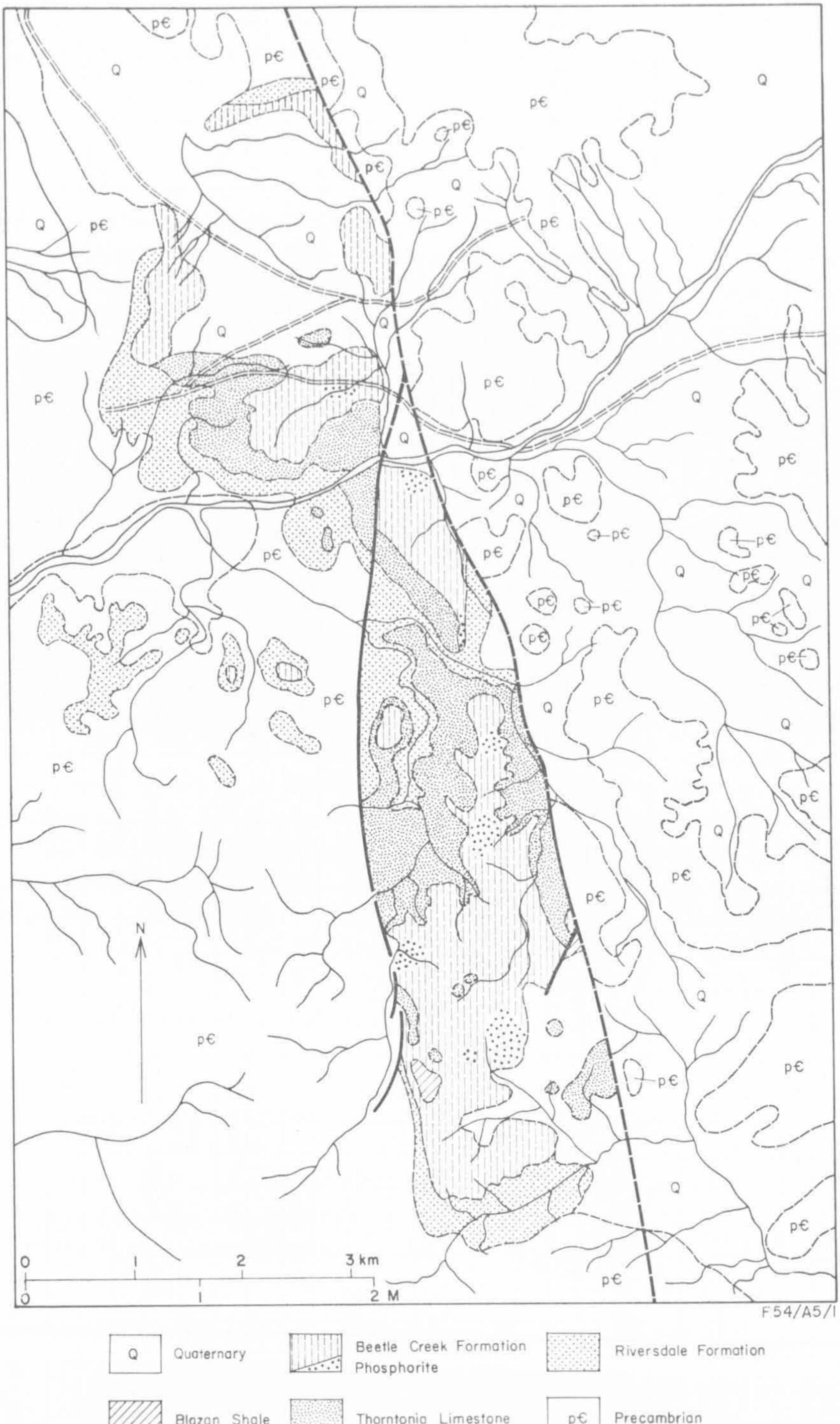

Figure 16. Geology of the Ardmore Outlier.

expected in a nearshore deposit. The formation was probably laid down, not in a single basin, but in several separate sub-basins which ultimately coalesced. The possible range of environments includes lagoonal, estuarine, littoral, and sublittoral.

Silt-Shale-Chert Lithosome

The silt-shale-chert lithosome includes such previously defined units as the Inca Formation, the Blazan Shale, the Lancewood Shale, and the Roaring Siltstone. All these units are lithologically almost identical and have been separated solely by their fossils; that is, they are parvafacies units. Even some of these time units are unnecessary, and there is, for instance, little justification for separating the Inca Formation and the Blazan Shale.

This lithosome ranges in age from lower to upper Middle Cambrian. It overlies the chert-siltstone-limestone-phosphorite lithosome and intertongues laterally with the limestone lithosome. It also intertongues with, and is overlain by, the sandstone-siltstone lithosome. The authors differ on whether or not the chert-siltstone-limestone-phosphorite lithofacies represented by, for instance, the Beetle Creek Formation, should be separated from the overlying silt-shale-chert lithosome represented by the Inca Formation. De Keyser feels that the latter may be distinguished by the thin angular platy fragments that make up the chert rubble, in contrast with the rounded nodular cherts of the Beetle Creek Formation, and by the agnostid and sponge spicule fauna, in contrast with the dominantly polymerid fauna of the Beetle Creek Formation. Cook questions whether these differences are really significant, and in particular has reservations on the validity of the faunal assemblage as a criterion for the recognition of lithosomes. He suggests that a single chert-siltstone lithosome including both the Beetle Creek Formation and the Inca Shale might be more satisfactory, and that possibly a small phosphorite lithosome should be separated out. However, throughout this discussion, the published scheme of de Keyser (in press) is followed.

The present mapping programme extended somewhat the known distribution of the various units of the silt-shale-chert lithosome (Fig. 17). In the Burke River Outlier (Figs 5-8) the lithosome is composed of the Inca Formation parvafacies, which is up to 150 m thick, and the Roaring Siltstone parvafacies, which has a maximum thickness of about 70 m. Both units consist of light grey to dark grey shaly siltstone, siliceous shale, thin-bedded chert, fine-grained silty sandstone, and thin bituminous limestone (calcilutite). Russell (1967) subdivided the Inca Formation into a lower shale member and an upper limestone member. However, the large mass of limestone west of Prickly Bush Bore, which he regarded as the upper limestone member and which does contain Inca Formation fossils, is lithologically almost indistinguishable from the Devoncourt Limestone.

In the Ardmore/Quita Creek area (Fig. 15), the sole representative of the lithosome is the Blazan Shale, which is lithologically identical with the Inca Formation. The Blazan Shale, which is 40 to 50 m thick, clearly intertongues with the limestone lithosome (represented by the Quita Limestone). Öpik (1956a) reports a disconformity at the base of the Blazan Shale, marked by the irregular nature of the boundary with the underlying Thorntonia Limestone.

Inca Formation and its equivalents are also known to be present in the Ardmore Outlier (Fig. 16), in the outlier west of Mount Isa (Fig. 10), and in the Lady Annie Outlier. Throughout these widely scattered localities the lithosome retains

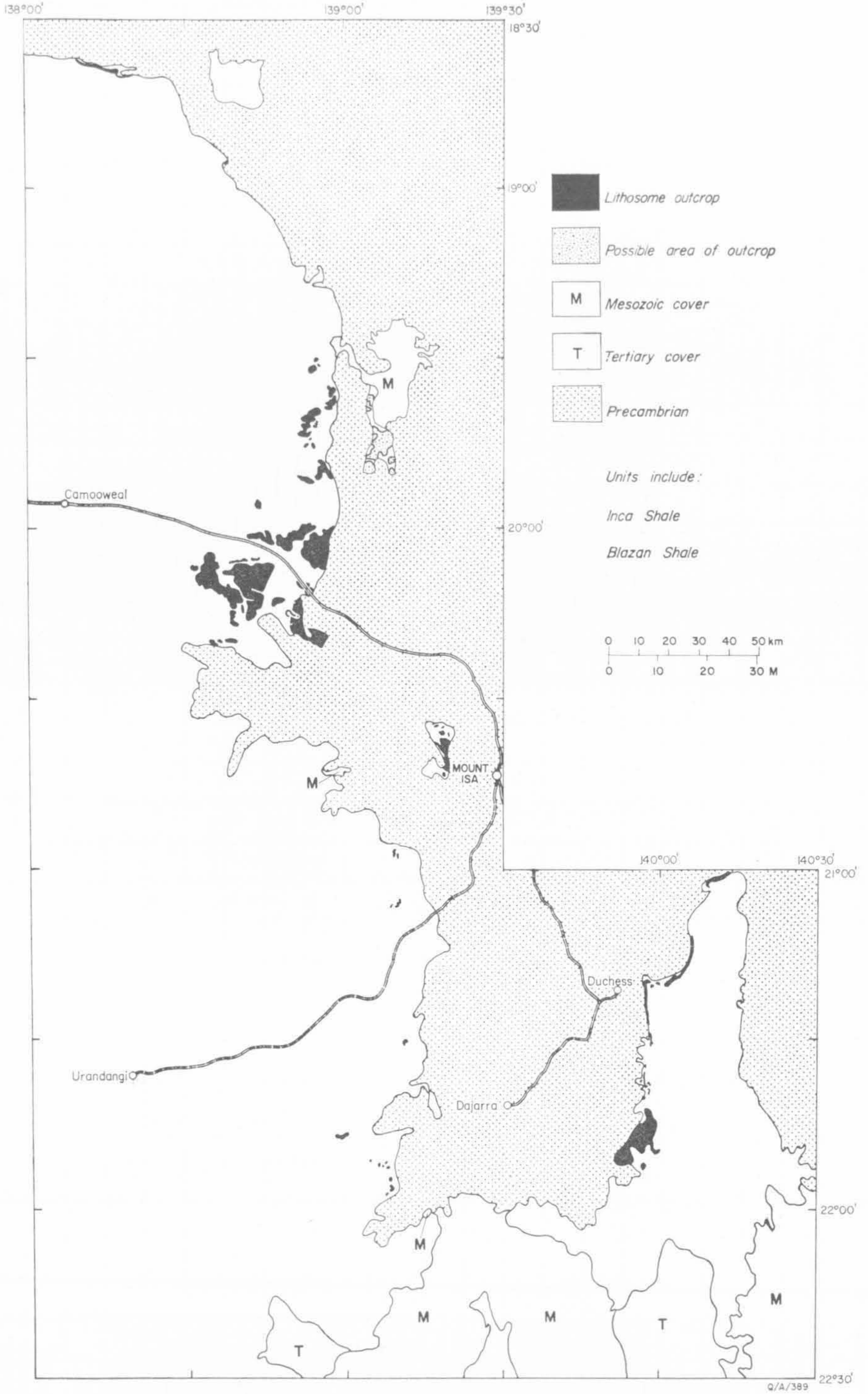

Figure 17. Distribution of the silt-shale-chert lithosome.

its essentially uniform character. In the Yelvertoft/Thorntonia area, the Inca Formation is well developed, and in places has a thin phosphorite at the base. Some of the siltstones and cherts are strongly contorted (Pl. 11, fig. 1). The contortions are probably the result of submarine slumping before consolidation. In places there are intraformational chert breccias (Pl. 11, fig. 2).

In the Border Waterhole/Lawn Hill area the distribution of the Inca Formation has been extensively modified from the earlier map. It occurs along a 15-km zone (Fig. 3) and has a maximum thickness of 30 to 60 m. The unit here consists of thin-bedded platy or flaggy red shaly siltstone and very fine sandstone, with occasional thin chert laminae.

The silt-shale-chert lithosome is also developed in the Lady Annie Outlier, but was not mapped in detail.

In the Inca Formation, *Ptychagnostus gibbus,* the diagnostic fossil, is fairly common and agnostid trilobites in general are sparsely scattered throughout the lithosome. Various trilobites, phosphatic brachiopods, and sponge spicules are also present. In contrast with the cherts of, for instance, the Thorntonia Limestone, which appear to be of diagenetic origin (Pl. 12, fig. 1), many of the cherts of the Inca Formation are believed to be of primary origin; some horizons are composed almost entirely of siliceous sponge spicules (Pl. 12, fig. 2). The more elongate spicules indicate a current lineation in places.

Depositional Environment

The silt-shale-chert lithosome is lithologically uniform over an extensive area of the Georgina Basin; however, it is considered unlikely that a single depositional environment covered thousands of square kilometres at the one time. It is probable that, as in the Beetle Creek Formation, there were numerous small areas of sedimentation which ultimately coalesced. They were all essentially of very shallow marine or transitional character, as indicated by the abundant marine fauna. Cross-bedding and current lineations suggest that there were fairly strong currents at times. The abundance of spicules is likely to have been environmentally controlled, and suggests cool or cold water conditions or some other situation, such as upwelling, likely to cause high concentrations of silica. De Keyser (1972) suggests that at times the depositional environment of this lithosome may have been toxic. Such a situation may have been analogous to present-day red-tides and blooms, when dinoflagellates become excessively abundant and create toxic conditions. These conditions can occur in a variety of situations, but appear to be most common in areas of upwelling or in estuaries.

Limestone Lithosome

The limestone lithosome (Fig. 18) includes a large number of units (parvafacies) ranging in age from Middle to Upper Cambrian. Many of the parvafacies are indicated in Figure 2. The limestone lithosome overlies the chert-siltstone-limestone-phosphorite lithosome; it intertongues with the dolomite lithosome in the west and the silt-shale-chert and sandstone-siltstone lithosomes in the east. Our investigation did not greatly modify the boundaries of this lithosome, but did clarify the intertonguing relationship with the Camooweal Dolomite.

The lithosome is best developed in the Burke River Outlier, where it is up to 900 m thick. It has been divided into several 'formations' (parvafacies) by Carter

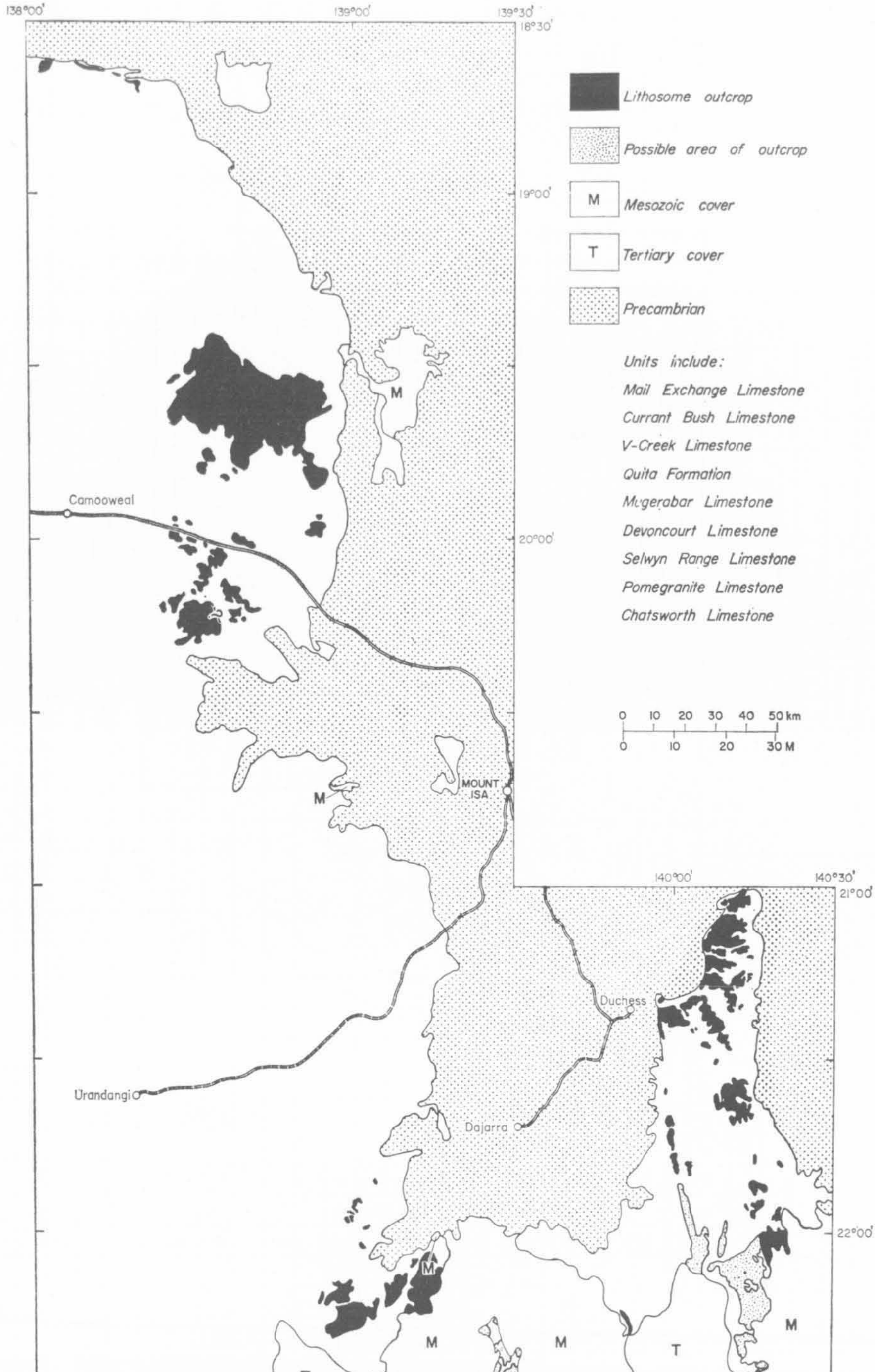

Figure 18. Distribution of the limestone lithosome.

& Öpik (1963): Devoncourt Limestone, Selwyn Range Limestone, Pomegranate Limestone, and Chatsworth Limestone. The lower three are generally thin, with maximum thicknesses of about 100 m. The uppermost unit, by contrast, is about 600 m thick at the extreme southern end of the outlier according to Öpik (1960). The distribution of the various units is indicated in Figures 5 to 8. The four parvafacies are lithologically identical, and can only be distinguished by their fossils; consequently it is unnecessary to describe each individually.

There is a variety of limestones, including calcarenite, calcilutite, sandy limestone, oolitic limestone, dolomitic limestone, siliceous limestone, and slightly phosphatic limestone. Interbedded with the limestone are marl, calcareous mudstone, calcareous intraformational breccia, and chert. The limestone is dark grey when fresh, bituminous, brittle, and typically laminate to medium bedded (Pl. 13, 14). Cross-laminations indicating a source area to the northwest of the Burke River Outlier, ripple marks, and current troughs are present in places. Non-calcareous grains present in the limestone include quartz, feldspar, pyrite, mica, glauconite, phosphate pellets, tourmaline, and zircon.

Diagenesis is common, including the development of coarse recrystallized calcite, marginal replacement of detrital non-carbonate grains, and the formation of dolomite rhombs. Some of the chert bands may be primary, but most of the nodules are believed to be secondary, formed by the replacement of limestone. Some of the calcilutites weather to a characteristic nodular form (Pl. 15, fig. 1).

In the northeast corner of the basin (Border Waterhole/Lawn Hill area), the limestone lithosome is represented by the Currant Bush Limestone, which comprises yellow to dark grey, fetid, silty or sandy limestone, marl, and dolomitic limestone (Pl. 15, fig. 2). Bedding is thin to medium, but in places the limestone weathers to a nodular form. A few intervals are cross-bedded. Chert layers and patches are present in places. The formation has a maximum thickness of 100 m.

The upper boundary of the formation has been a matter of some dispute since Öpik's original statement that it was faulted. In fact (Fig. 3), the Currant Bush Limestone is conformably overlain by the Camooweal Dolomite. The upper part of the Currant Bush Limestone is characterized by a progressive increase upward in the percentage of dolomite (Pl. 15, fig. 2). The top of the formation is for convenience taken at a particularly prominent gritty dolomite, which contains angular fragments of chert and rounded carbonate pellets in a fine-grained dolomite matrix.

Farther south, in the Yelvertoft/Thorntonia area (Figs 13-14), the limestone lithosome is divided into: Currant Bush Limestone, V-Creek Limestone, and Mail Change Limestone.

These three units are lithologically very similar, although Öpik (1960) considers that the Mail Change Limestone is distinguishable from the underlying units because it is more thickly bedded. However, they are distinguished primarily on the basis of their fossil assemblages. The combined thickness of the three units probably does not exceed 100 m.

In the Ardmore/Quita Creek area, the sole representative of the limestone lithosome is the Quita Formation, which has a thickness of 60 to 70 m. It clearly intertongues with the Blazan Shale (Fig. 15) and is overlain by the Steamboat Sandstone. It consists of light grey to dark grey bituminous thin bedded to laminate limestone with recessively weathering interbeds of light grey to yellow-grey marl

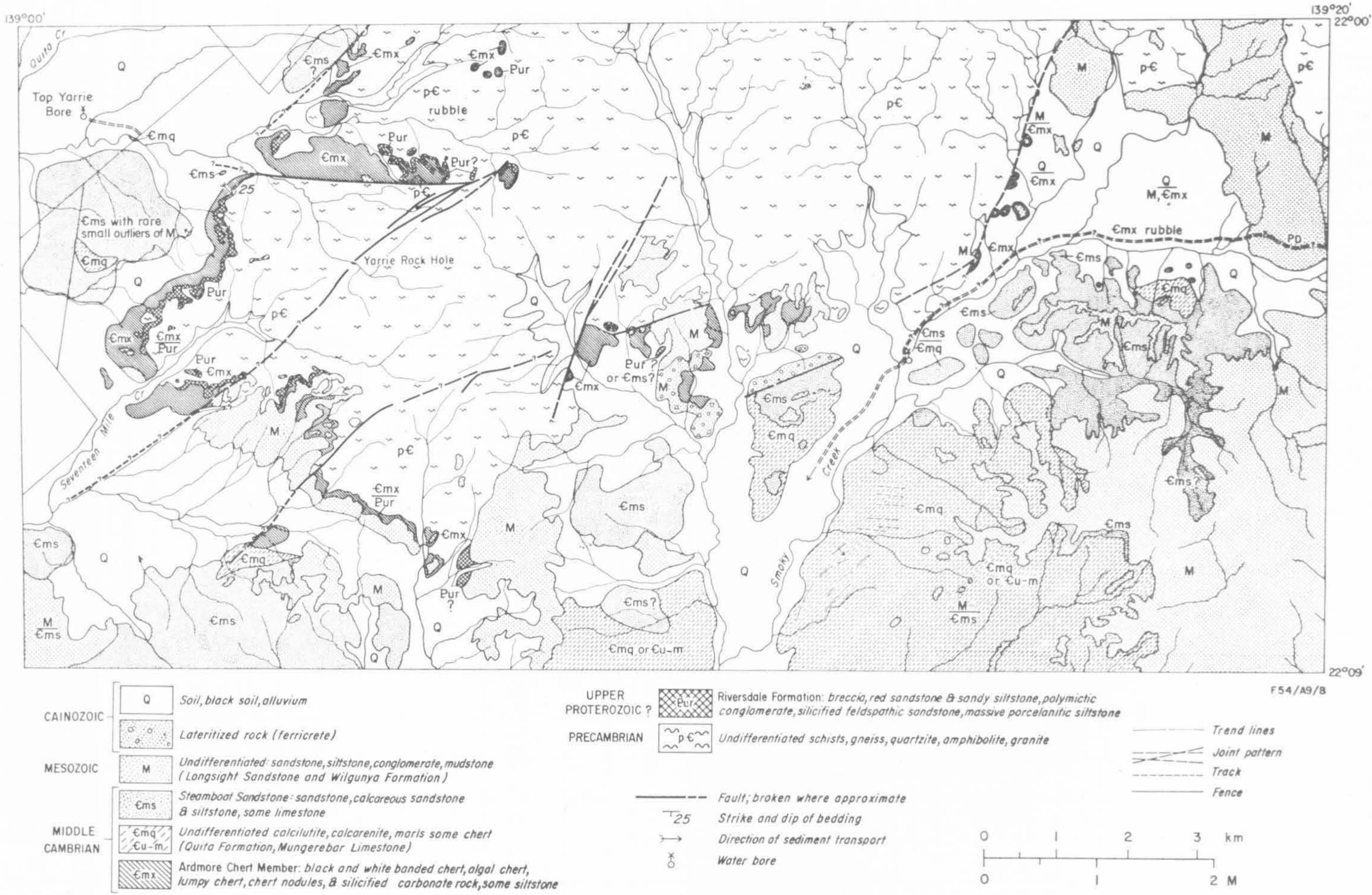

Figure 19. Geology of the northern part of the Glenormiston 1:250 000 Sheet area.

and mudstone and some irregular chert laminae and nodules. The limestone consists mainly of fine-grained calcarenite (cross-bedded in places), calcilutite, and oolitic limestone; some intervals are coquinitic. Calcareous intraformational breccia is present in places. Towards the top of the Quita Formation, the percentage of detrital quartz progressively increases, and there is a gradational contact with the overlying Steamboat Sandstone.

Farther south, in the Glenormiston 1:250 000 Sheet area (Fig. 19), the Quita Formation is well developed, but Reynolds (1965) somewhat surprisingly includes it with the Steamboat Sandstone. There is an additional limestone unit, the Mungerebar Limestone, which conformably overlies the Steamboat Sandstone. It is a typical limestone lithosome unit and is lithologically very similar to the Quita Formation. It has a maximum thickness of 30 m.

Fossils are common throughout much of the limestone lithosome, particularly in the more siliceous horizons. Most of the fossils are fragmentary. They include trilobites, brachiopods, echinoderms, and sponge spicules.

Depositional Environment

The predominance of calcareous rock and the abundance of fossils indicate that the sequence is marine. The current troughs, ripple marks, and cross-laminae, the comminution of many of the fossils, and the intraformational breccias, indicate that at times high-energy conditions were prevalent. However, conditions were obviously rather variable, for calcilutites are common, indicating local placidity, though this can be achieved in a generally vigorous environment by the protective effect of, for instance, reefs or sea-grass meadows. The oolitic units are taken to indicate rather shallow seas subject to gentle agitation. The decrease in the amount of detrital material in the limestone lithosome, compared to the adjacent lithosome to the east, suggests that it formed in a more open sea, in an area in which terrigenous sediment was not abundant. The temperature was probably warm to hot. Much, perhaps most, of the material in the limestone lithosome is detrital carbonate; it may have been derived locally or, conceivably, from a large carbonate deposit such as the region occupied by the dolomite lithosome, but before dolomitization.

SANDSTONE-SILTSTONE LITHOSOME

The sandstone-siltstone lithosome, which ranges in age from late Middle to Upper Cambrian, is only developed on the margins of the Georgina Basin (Fig. 20), and consists of red ferruginized quartz sandstone, siltstone, mudstone, and minor chert laminae. It overlies the silt-shale-chert lithosome (probably disconformably in places); to the west, it intertongues with the limestone lithosome.

In the Burke River Outlier the lithosome is known as the O'Hara Shale, which has a maximum thickness of about 100 m, and consists of shaly mudstone and siltstone (calcareous in part) and fine sandstone. Carter & Öpik (1963) record conglomerate in the O'Hara Shale, but it was not observed during our mapping. In the central-eastern and northwestern parts of the outlier there are beds of chert 1 to 4 cm thick. Limestone (calcilutite) nodules are present in places. The O'Hara Shale is difficult to distinguish from the Roaring Siltstone and Inca Formation of the silt-shale-chert lithosome, but tends to be more coarsely micaceous; the chert is also commonly red, olive green, and brown in contrast with the grey and white of the silt-shale lithosome. It also forms a distinctive landscape of incised plateaux

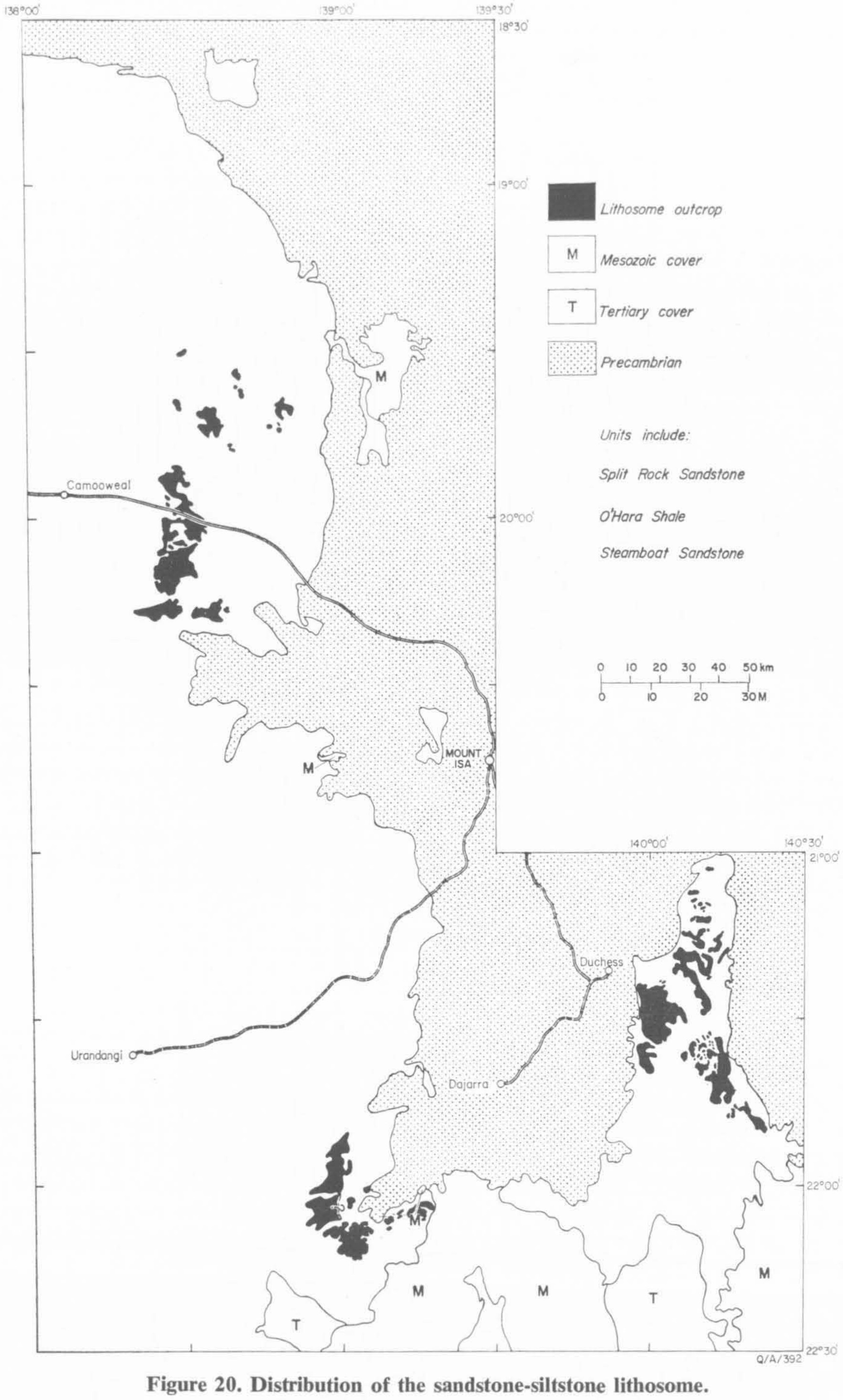

Figure 20. Distribution of the sandstone-siltstone lithosome.

and mesas. These differences are, however, somewhat superficial, and a case could be made in the Burke River Outlier for including all the lutaceous units from the Inca Formation to the O'Hara Shale in a single mudstone lithosome.

By contrast, in the Quita Creek area (Fig. 15), the lithosome consists of a rather distinctive sandstone unit, the Steamboat Sandstone. This formation, which has a maximum thickness of 100 m, in many places rests with a gradational contact on the Quita Formation; in the Glenormiston area it interfingers with the Mungerebar Limestone. Locally, in the vicinity of QT bore in the Quita Creek area (Fig. 1), the contact with the Quita Formation appears to be an irregular surface of erosion. The top of the formation is everywhere eroded. The Steamboat Sandstone consists of yellow white, brown, and red-brown fine to coarse-grained sandstone, silty sandstone, and siltstone. Bedding is thin to medium; cross-beds and ripple marks are abundant. Most of the sandstone is a mature well sorted orthoquartzite with a high percentage of clayey matrix in places. Thin cherty bands are also present in places. At the base of the formation, beds of sandy limestone and limy sandstone and lenses of limestone are present. In the Thorntonia area, the lithosome is represented by the Split Rock Sandstone, which is very similar in appearance to the Steamboat Sandstone, and is about 25 m thick. It consists of thin to medium bedded fine-grained friable quartz sandstone with some siltstone interbeds; cross-bedding is common (Pl. 16, figs 1, 2). The unit is of limited distribution and is found only in the vicinity of Undilla homestead.

The sandstone-siltstone lithosome contains a rich trilobite fauna, which has been described in some detail by Öpik (1967). Fossils are particularly common in the siliceous horizons.

Depositional Environment

Fossils indicate that the sandstone-siltstone lithosome is marine; the abundance of cross-beds and ripple marks suggests turbulent water. This, together with the ferruginous detritus and the position of the lithosome on the margins of the Georgina Basin, suggests very shallow marine deposition close to the strand-line. Deposition perhaps took place in the littoral zone in places, but in general below low-water level, possibly in the form of extensive submarine sandbanks.

STRUCTURE

The regional structure of the eastern part of the Georgina Basin is indicated in a rather general way by the magnetic basement contours (Fig. 21). Although the horizon indicated is not necessarily the base of the sandstone-conglomerate lithosome (Mount Birnie Beds), it nevertheless suggests a north-south structural trend in the Cambrian sediment in most areas, except in the Lawn Hill region, where the trend becomes more east-west. Smith (1972) considers that the southwest corner of the Basin was deformed during the Devonian-Carboniferous Alice Springs Orogeny, but there is no evidence that the region studied during this investigation was affected. Similarly, Smith reports that in the Burke River structural belt tectonism reached a climax in the Lower Ordovician, but as there are, in general, no Palaeozoic sediments younger than Cambrian within the study area, there is little evidence of movement between the Cambrian and the Mesozoic. It was, however, possible to prove the presence of several Cambrian-Precambrian movements. Normal faulting has been responsible for the development of the various outliers around the margins of the basin; all the main outliers are downfaulted grabens. There is no evidence of lateral movement along any of the faults.

Faulting is particularly prominent in the Burke River Outlier; vertical displacements are up to 350 m on the Pilgrim Fault and 250 m on the Roaring Fault (Fig. 22). Displacement is greatest on the western side of the graben, and the trough shows a pronounced tilt and some associated folding. The Lady Annie Outlier (Fig. 12) also has an asymmetric cross-section, with the greatest displacement on the west side. Both these outliers are thought to be basins of deposition throughout most of the Cambrian, with the present faulted margins close to the Cambrian basin margin. This is not true for the outlier west of Mount Isa (Fig. 10) and the Ardmore Outlier (Fig. 16), in both of which parts of the sedimentary sequence overlap the fault boundaries with no change in rock type or thickness across the faults.

On the margins of the Barkly Tableland (Fig. 3) there is fairly extensive faulting and some minor folding; along the Littles Range Fault, dips are vertical close to the fault, but almost horizontal a short distance away. Within the fault zone, the Border Waterhole Formation is severely crushed and sheared. In the vicinity of Lancewood Creek, Currant Bush Limestone and Camooweal Dolomite are faulted against the Border Waterhole Formation and each other. It was this feature which led to the mistaken belief that the Camooweal Dolomite was thrust over the Currant Bush Limestone. Steep dips in the vicinity of Lawn Hill Creek may also be indicative of some faulting in the area.

On the Dentalium Plateau (south of Lawn Hill homestead), Thorntonia Limestone is haphazardly and severely folded, but no regular pattern of folding is apparent. The plateau lies in a region where east, northeast, and southeast trending fault systems converge (cf. Carter & Öpik, 1961, fig. 2), and this could have given rise to complex block fracturing in the subsurface. Recumbent folding in the Inca Formation of the Yelvertoft-Thorntonia area (Figs 13-14) is thought to be the result of slumping before the sediments were completely lithified; it may have been triggered by faulting. Another possible effect of the faulting is more speculative; the faults may have provided channelways for the hydrothermal submarine springs and solfataras that are assumed to have been the last expression of the widespread Lower Cambrian volcanism represented by the Colless Volcanics in the Border Waterhole area, the Peaker Piker Volcanics in the Northern Territory, the Antrim Plateau Volcanics in Western Australia, and the basalt encountered in a number of drill holes in the Northern Territory. There are indications of hydrothermal alteration along some of the fault zones, including silicification, alunitization, the formation of secondary phosphate minerals (variscite, turquoise, possibly evansite, and other undetermined varieties), and perhaps some fluoritization.

There is evidence of several periods of faulting and also of recurrent movements on faults. An example of this is the West Thornton Fault, which runs in an east-southeasterly direction about 30 km south of Thorntonia homestead. To the south, the Beetle Creek Formation is extremely thin or completely absent, but to the north it is normally developed, starting with a basal breccia and conglomerate up to 10 m thick evidently derived from a cliff formed by the uplifted southern block. The Inca Formation on both sides is not affected; so the sea level had apparently risen sufficiently during its deposition to cover the uplifted block. At present, however, the Inca Formation in the southern block is at a lower topo-

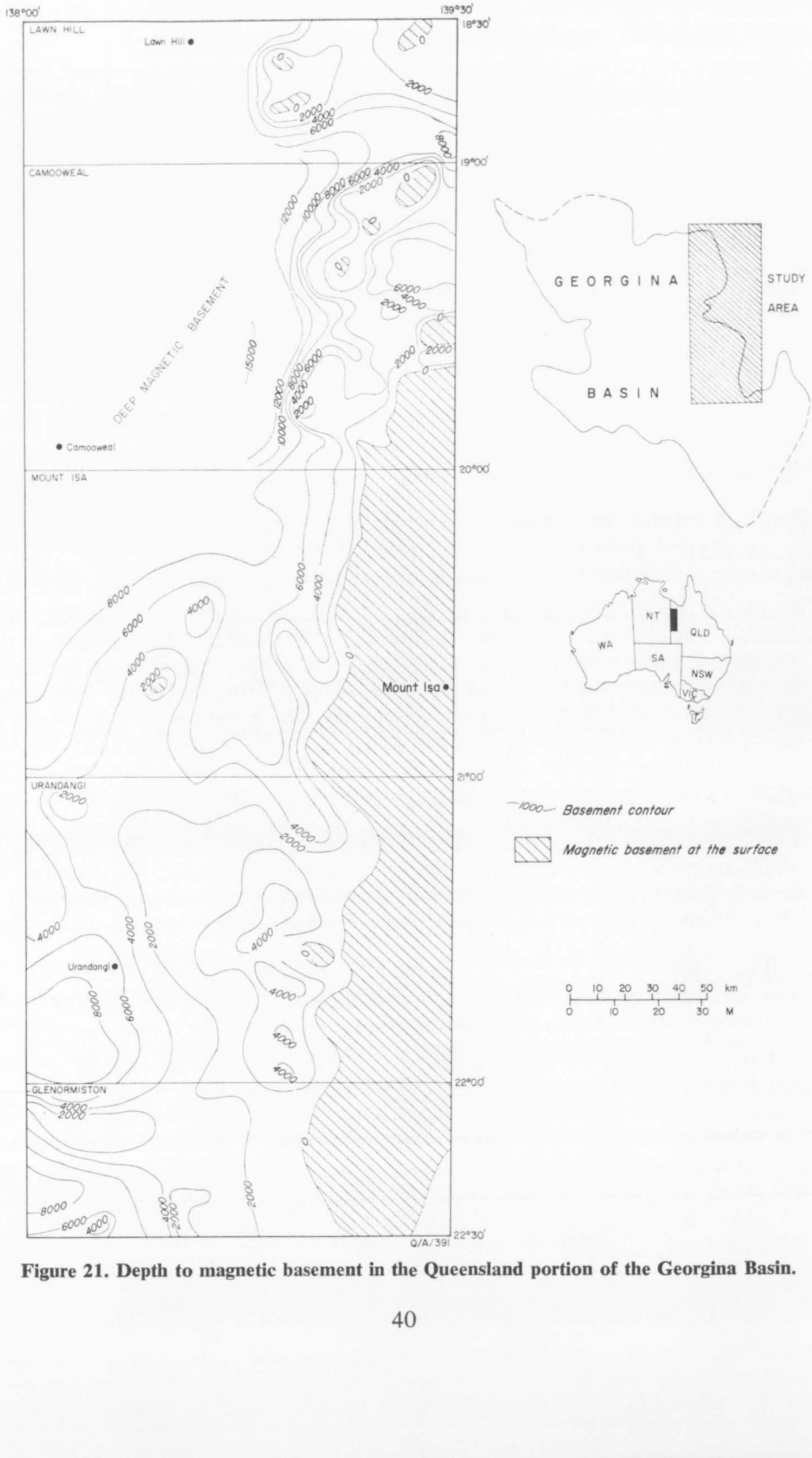

Figure 21. Depth to magnetic basement in the Queensland portion of the Georgina Basin.

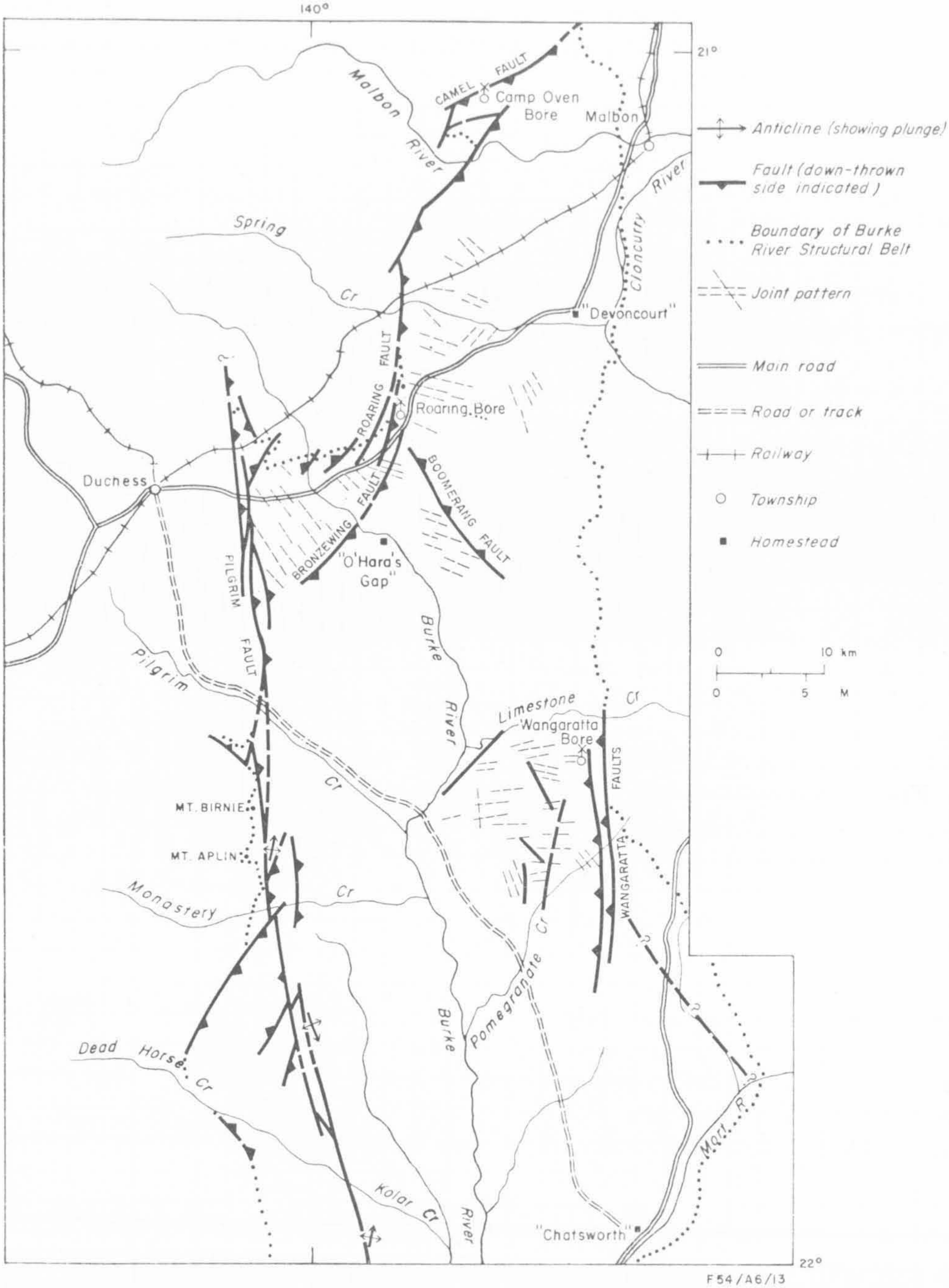

Figure 22. Structural elements in the Burke River Outlier.

graphical level than in the northern block, so that the relative fault movements must have reversed some time after the deposition of the Inca Formation.

Evidence of repeated faulting is also found in the Burke River Outlier at Mount Birnie and near Camp Oven Bore in the Camel Fault Zone. The attitudes of the units at Mount Birnie are interpreted as indicating three separate episodes of faulting, in the Lower Cambrian, post-Middle Cambrian, and Cainozoic. The third inferred movement is perhaps the one most open to doubt as it is only based on the fact that on the east side of the fault the silcrete ('billy') capping is dipping at an angle of 3°; the dip could be that of the surface on which the silcrete formed. The geology of the Mount Birnie area is illustrated in Figure 23.

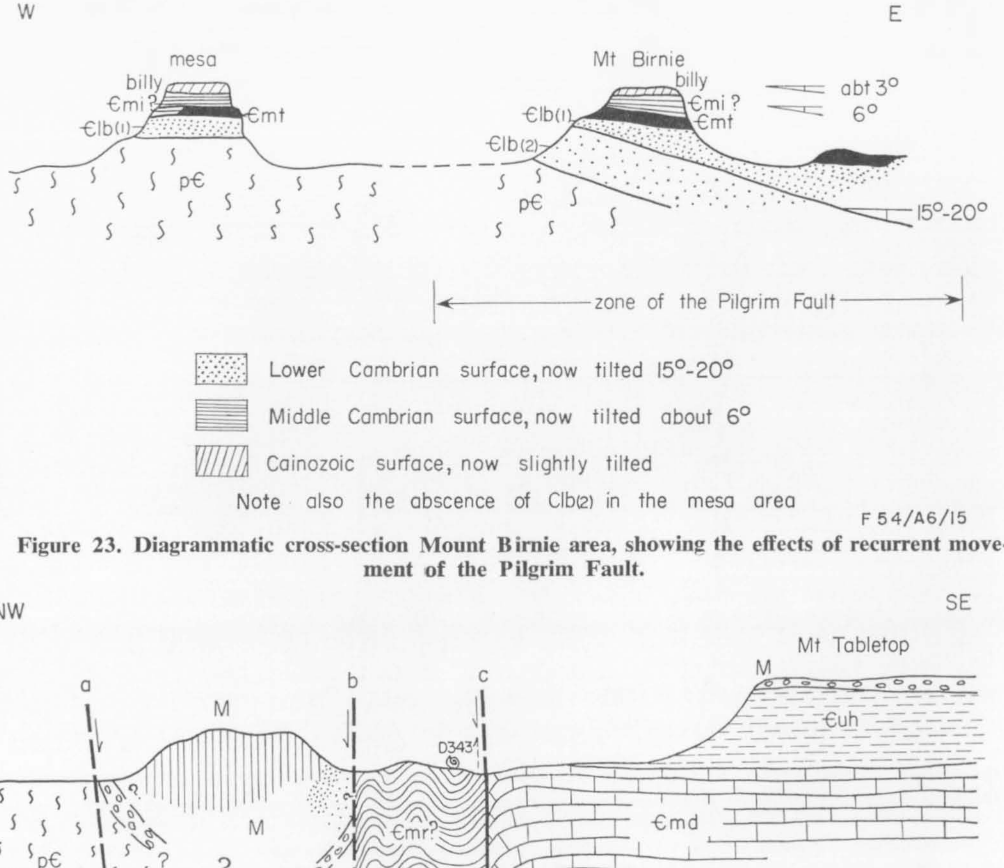

Figure 23. Diagrammatic cross-section Mount Birnie area, showing the effects of recurrent movement of the Pilgrim Fault.

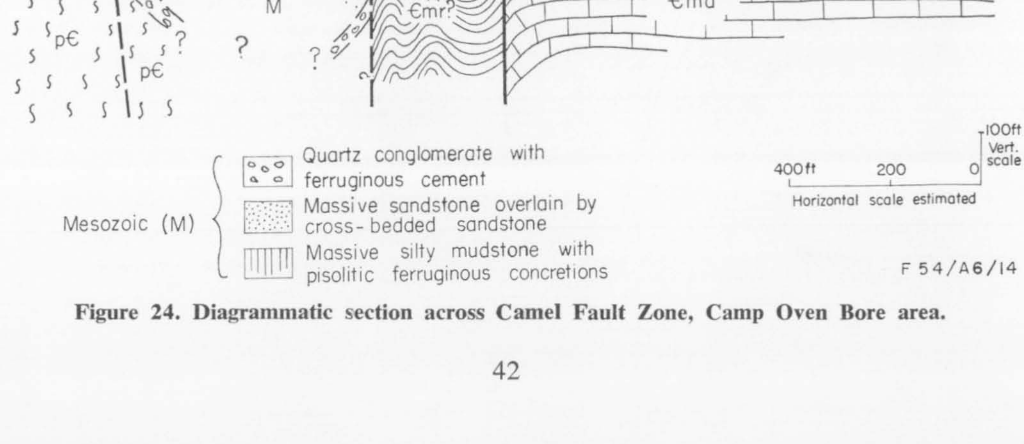

Figure 24. Diagrammatic section across Camel Fault Zone, Camp Oven Bore area.

In the vicinity of Camp Oven Bore, Roaring Siltstone is preserved in a narrow graben (Fig. 24). The most easterly fault is thought first to have down-faulted the Siltstone and later reversed, to give rise to a strong drag fault. Post-Mesozoic movements along the western and central (a and b) faults downfaulted the Mesozoic sediments. Similarly, southwest of Camp Oven Bore Mesozoic conglomerate dips at 45° adjacent to the Camel Fault and unconformably overlies almost vertical Cambrian siltstones. The history of the Camel Fault probably extends back into the Precambrian, as quartz-filled fault-lines alongside the Pilgrim Fault are truncated by the unconformity at the base of the Mount Birnie Beds.

Many localities around the margin of the Georgina Basin, therefore, show evidence of several periods of faulting, including Precambrian, early Middle Cambrian, Upper Cambrian, post-Cretaceous, and possibly Cainozoic.

HISTORY OF CAMBRIAN SEDIMENTATION

Sedimentation in the Queensland portion of the Georgina Basin began in the late Upper Proterozoic when fluvioglacial and marine glacial sediments were deposited in the Burke River Outlier. To the south and west in the Northern Territory the glacial deposits thicken considerably, and are particularly well developed in the Field River Beds; elsewhere they either were not deposited or have since been eroded away. The temperature rose after the glacial episode, and coarse sandstone, conglomerate, and calcareous sandstone were laid down over a wide area from a shallow sea (as indicated by trace fossils). Some of the unfossiliferous sandstones could be fluvial or alluvial fan deposits. The coarseness of the sandstone indicates high-energy conditions; their mineralogical and textural immaturity points to a nearby source area in the Cloncurry Complex. At the same time, lavas up to 60 m thick point to volcanism in the north. Some faulting may have been associated with the volcanism, and fumarolic activity probably continued for some time along many of the fault zones, such as those on the west side of the Burke River Outlier.

After volcanic activity and sandstone-conglomerate deposition ceased in the late Lower Cambrian or early Middle Cambrian, a widespread dolomite lithosome was laid down in the early Middle Cambrian as a prograding body of shallow marine sediments (possibly intertidal or supratidal in part). Biohermal and biostromal limestone bodies formed, but were dolomitized soon after deposition. The climate was probably warm to hot and the water (particularly the pore water) highly saline at times.

Subsequently, these biohermal-biostromal supratidal(?) hypersaline deposits became less widespread as the sea spread into the margins of the area, and initiated deposition of the chert-siltstone-limestone-phosphorite lithosome. This established a deposition pattern which persisted throughout the remainder of the Cambrian, with more normal conditions of marine sedimentation around the perimeter of the basin in the east, and more saline water in the central part of the basin to the west (Fig. 25). This is undoubtedly an abnormal pattern of sedimentation. A similar situation occurs in the late Palaeozoic central Colorado Basin of the Rocky Mountains, where evaporites were deposited in the centre of the basin and normal marine carbonate on the margins of the basin immediately adjacent to the ancient land masses of the Uncompahgre Highlands and the ancestral Rockies.

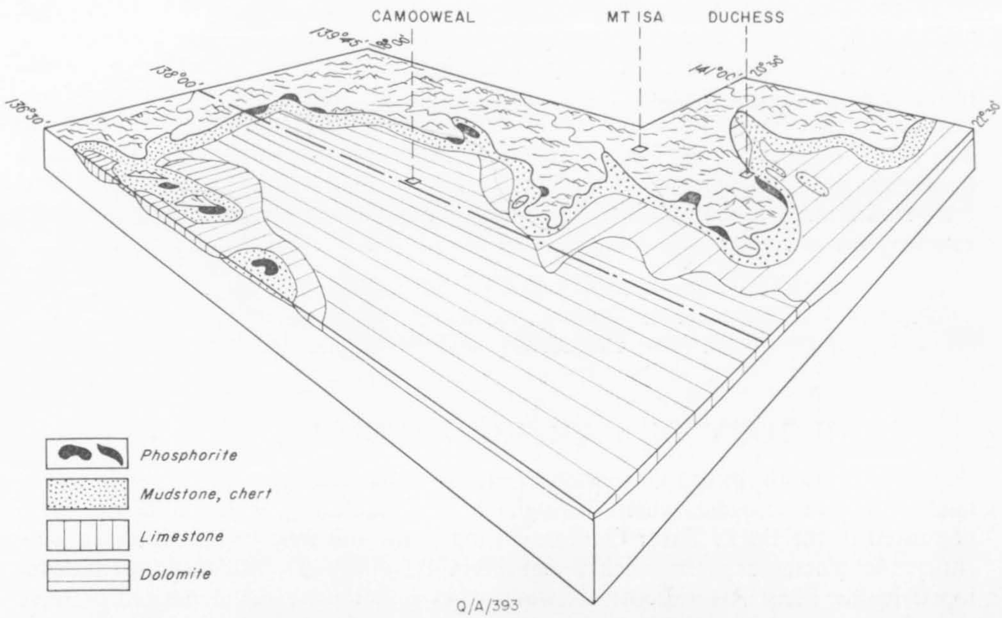

Figure 25. Facies distribution during the Cambrian.

The initial Beetle Creek transgression deposited fine-grained sediments over a wide area, although dolomite sedimentation continued in the centre of the basin. Rich phosphorites and numerous fossils indicate an abundant supply of nutrients at times. The presence of thick siltstones suggests that the shoreline was nearby. Much of the sedimentation probably took place fairly close inshore, in lagoons, estuaries, and bays.

As the marginal seas deepened (perhaps in response to marginal downwarping or faulting), pelagic conditions prevailed over much of the basin, as suggested by the richly siliceous spicular sedimentation of the Inca Formation and other associated units of the silt-shale-chert lithosome. The associated pelagic fauna was prolific but somewhat restricted; the large trilobites of the earlier part of the Middle Cambrian are replaced by agnostids. Possibly while surface conditions were conducive to the formation of abundant marine life, the bottom conditions were anaerobic, and unable to support benthonic forms.

To the west, and in parts of the Burke River Outlier farther from the shore, there was little terrigenous sedimentation; and in the warm shallow waters thick carbonates could accumulate. In the central part of the basin, highly saline conditions with associated dolomitization continued without interruption.

As the marginal trough filled with sediments the perimeter water shallowed until eventually very shallow seas covered almost the entire area. The limestone lithosome was able to prograde from west to east across the main part of the basin (and from east to west within the Burke River Outlier) almost to the shoreline. With the marginal trough completely filled, the perimeter became a site for terrigenous sedimentation; as a result, the siltstone-sandstone lithosome advanced seawards across the area depositing a regressive body of shallow marine sand (such as the Steamboat Sandstone) in many places. Seaward of the siltstone-sandstone lithosome, limestone sedimentation continued; in the centre of the basin, deposition of the Camooweal Dolomite also continued. This pattern of sedimentation persisted for the remainder of the Cambrian and possibly into the early Ordovician, until finally it was brought to a close by tectonism, epeirogenic movements, or perhaps a eustatic lowering of sea-level.

PHOSPHATE DEPOSITS

Since the discovery of phosphate in the Georgina Basin in 1966 (Russell, 1967), several companies have been active in northwest Queensland. The most extensive exploration programmes have been conducted by Broken Hill South Limited (Thomson & Russell, 1971) and by International Minerals and Chemicals Development Corporation (Howard, 1971); Continental Oil Company of Australia and Clutha Development have carried out some drilling. The deposits located in Queensland are situated on the west side of the Burke River Outlier, at the southern end of the Ardmore Outlier, in the Quita Creek area, in the Lady Annie Outlier, in the Thorntonia area, south of Yelvertoft homestead, and throughout the Lawn Hill/Border Waterhole area (Fig. 1). In the Northern Territory deposits have been discovered in the Wonarah and Alexandria areas.

Primary phosphorites are restricted to the Beetle Creek Formation (chert-siltstone-limestone-phosphorite lithosome), but some secondary phosphorites are found in overlying weathering profiles. The lower part of the Inca Formation contains small phosphorite bodies. A number of other Middle Cambrian units, such as the Thorntonia Limestone and Devoncourt Limestone, are slightly phosphatic.

The phosphorites have various forms. The most abundant type (particularly in the Burke River Outlier) is pelletal; other forms include phosphorites composed of clay-size phosphate particles, dense fine-grained secondary phosphorite, phosphatic mudstone, phosphatic sandstone, and phosphatic limestone.

Because much of the drilling data is confidential, only a brief outline of the various deposits can be given. For the same reason, our conclusions regarding the nature and origin of the phosphorites are mainly based on the study of surface material.

EXPLORATION

Drawing on his experience of the Rocky Mountain and other phosphorites, Sheldon (1966) undertook a literature and field review of phosphate potentialities. He concentrated on suites of rocks deposited between palaeolatitudes of 40°N and 40°S, which contain black shale and chert assemblages. The Lower Palaeozoic of eastern Australia fulfilled these general conditions, and he singled out the Undilla Basin (the name then used for the eastern part of the Georgina Basin) for particular mention. He stated (Sheldon, 1966, p. 8): 'The Undilla Basin has a particularly interesting section of Cambrian rocks. The Inca Formation comprises spicular chert and mudstone that probably is dark and carbonaceous in the subsurface, but weathers light-coloured in outcrop. No phosphate rock was found in outcrop in a brief examination, but in the Morestone No. 1 bore just to the west of the outcrop cuttings from one 10-foot interval analysed about 4 percent P_2O_5 and 80 feet of rock analysed about 0.5 percent P_2O_5'.

As a result of these observations, Broken Hill South Limited conducted a systematic search of all available Cambrian oil well samples from the eastern part of the Georgina Basin. They noted higher than average phosphate values in the lower Middle Cambrian sediments and particularly high values in the Beetle Creek Formation in Black Mountain No. 1 bore, The Brothers No. 1, and other wells. As a result of this, the company decided to carry out field investigations of the Beetle Creek Formation in the Burke River Outlier and within three days of the start of the field work, outcropping phosphorites were located (Russell, 1967).

Since then a great deal of exploration work has been undertaken by various companies, and several techniques have been applied to the search for phosphate in the Georgina Basin. These are: the visual recognition of phosphorites; field chemical testing; geophysical, geochemical, and visual logging of drill holes and cuttings; and airborne radiometric surveys.

Visual Recognition

Pelletal phosphorite is the only readily recognizable form of phosphate rock in the Georgina Basin (Pl. 17, fig. 1). The pellets can generally be seen with the naked eye, but a hand-lens facilitates recognition. However, as oolitic carbonates have a similar appearance the identification must be verified by chemical analysis. Many of the Georgina Basin phosphorites, both pelletal and secondary, acquire a very characteristic convoluted appearance on weathered surfaces. Phosphorites may have a variety of colours, but a white or blue-white phosphate 'bloom' is rather common. The high specific gravity of the high-grade phosphorites also may give a clue to the identity of the rock.

In some areas there seems to be an association between certain plants and phosphatic soil.

Field chemical testing

The most widely used material for testing for phosphate is ammonium molybdate, which gives a yellow stain in the presence of even small quantities of phosphate. The test is purely qualitative and has its drawbacks; it may give a strong positive reaction even where very little phosphate is present, especially when the sample is calcareous, and in cold weather the reaction may be very slow. In addition, some types of high-grade rock give a deceptively weak or slow reaction, while on the other hand some of the cherts associated with the Duchess deposits react strongly. Moreover, barren Tertiary opaline silica and some altered silicified Thorntonia Limestone in places reacted positively to the test, although in thin section not a trace of phosphate minerals could be detected. The test is therefore not necessarily specific: amorphous or cryptocrystalline silica seems to give the same effect, perhaps by the formation of yellow silicon molybdate. By the same token, test solution deteriorates much faster in glass than in plastic bottles.

A semiquantitative method described by Shapiro (1952) gives a rather more reliable result. The yellow phosphovanadomolybdate colour is used as the basis for the estimation of phosphate content, and reference solutions allow estimate of P_2O_5 content to within about 5 percent. The method is rather more complex than the simple molybdate test; in addition, as only a very small amount of material is taken, the result can be unrepresentative unless extreme care is taken with the grading and splitting of the sample. The solutions are also rather unstable and unless kept under refrigeration are only usable for a few days. This problem can be particularly critical in the Georgina Basin, as high temperatures are common, even during the winter months.

Logging of drill holes and cuttings

In the eastern part of the Georgina Basin, outcrop is generally poor and subsurface data must be obtained. Costeans and shafts have been used for this purpose, but rotary and percussion drill holes were more commonly used. The cores or cuttings were logged by visual examination and semiqualitative chemical analysis. Any phosphatic intervals were analysed qualitatively.

In addition, these holes, and any other accessible wells were gamma-ray logged. A qualitative correlation is found in many other phosphate deposits between gamma-ray peaks and intervals with high P_2O_5 values (see Hales, 1967); and some holes yielded useful data in the Georgina Basin. Gamma-ray logs from the Yelvertoft area (kindly made available by Continental Oil Company) show a good qualitative correlation with the P_2O_5 content in 70 percent of the drill holes.

Figure 26 shows a number of representative logs from the D Tree deposit area. Section 1 shows in general a good correlation between the gamma-ray and P_2O_5 logs except that at about the 15 m level there is a large peak in the gamma log without a corresponding increase in the P_2O_5 content. This may be due to a secondary crandallite zone at the base of the Inca Formation, and is a feature shown by many of the logs. Section 2 again indicates a good correlation, but illustrates that the technique is useful only in a qualitative way, for the size of the gamma-ray peak bears no relationship to the actual P_2O_5 content. Section 3 shows an excellent qualitative correlation between the two logs, but Section 4 does not correlate at all: there are comparatively high P_2O_5 values between 40 m and 50 m, but no corresponding increase in the gamma log. Conversely, down to about 25 m a shaly sequence has high gamma-log values yet the P_2O_5 content is negligible.

Even under the best conditions, the gamma-ray logging technique is only qualitative. Changes in lithology such as from limestone to black shale can produce very large changes in the gamma log completely unrelated to any change in the P_2O_5 content. However, the value of the method has been fully demonstrated in the Georgina Basin, particularly in obtaining some information from water-bores, from which no reliable samples or driller's logs have been preserved.

Airborne radiometric surveys

As a result of the general correlation in drill holes between gamma-ray logs and P_2O_5 content, and also because of the occurrence of a radiometric anomaly in the Ardmore Outlier over an area where thick phosphorites outcrop, the Bureau of Mineral Resources undertook an experimental airborne radiometric survey over several areas containing known phosphorites. The purpose of this survey was to evaluate the method as a possible prospecting tool for phosphorites using the recently developed airborne gamma-ray spectrometer, which is capable of distinguishing, within certain limits, the source of the radiation.

In the Thorntonia district thorium channel anomalies appear to correlate with areas of outcropping laterite. There is, however, a correlation between the uranium channel response and the Beetle Creek Formation in the same area. In particular, known phosphate deposits give rise to clearly defined anomalies. The Geophysical Branch of the Bureau of Mineral Resources is currently analysing the results of the programme, and a report will be issued when analysis is complete.

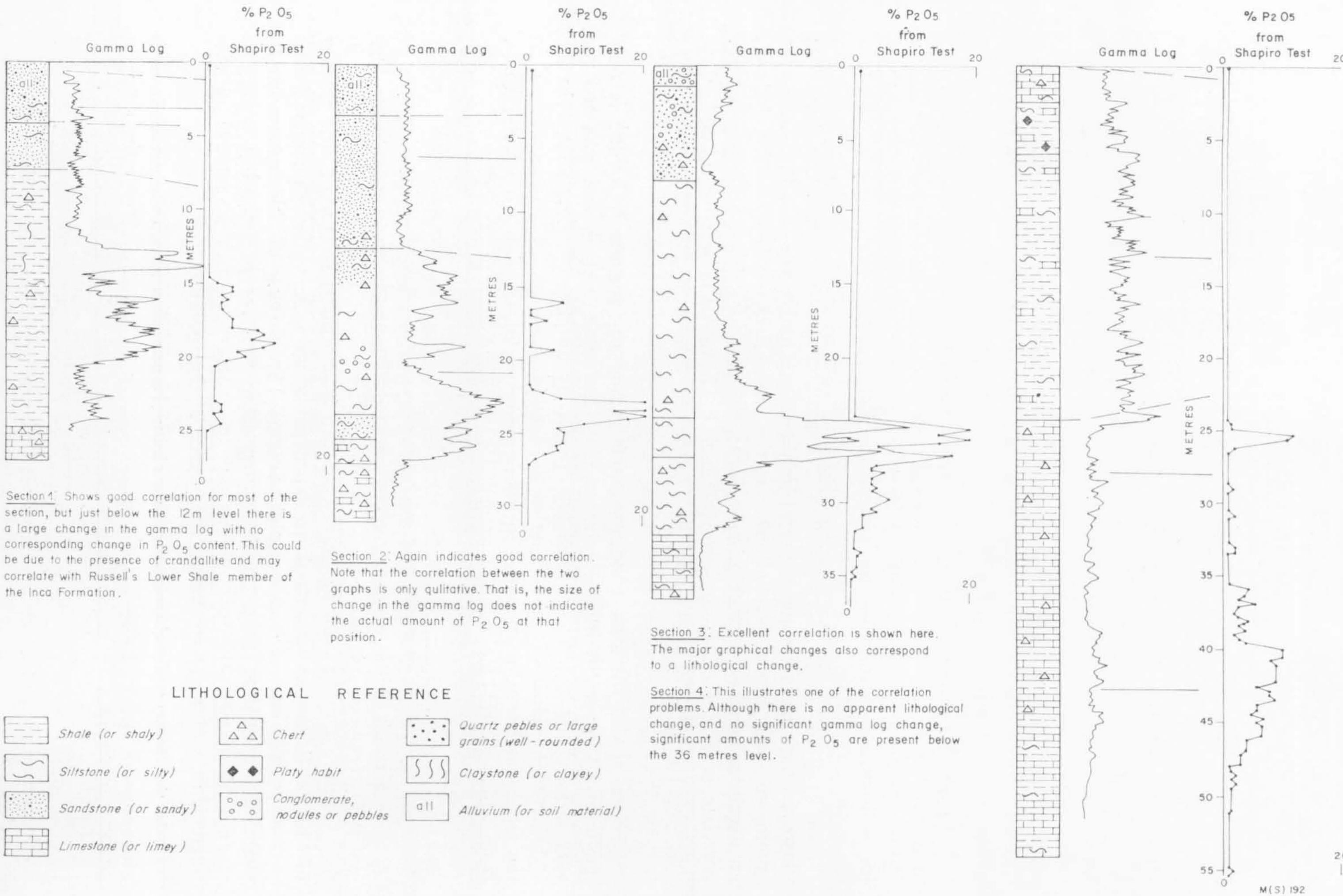

Figure 26. Correlation between gamma logs and phosphate in the Yelvertoft area, northwest Queensland.

DEPOSITS

With the exception of the Yelvertoft-Thorntonia area, all known phosphate deposits in northwest Queensland are at present held by Broken Hill South Limited, exploration being conducted by their subsidiary, Mines Exploration Pty Limited (Thomson & Russell, 1971). In the Thorntonia area, the D Tree deposit is held by International Minerals and Chemical Development Corporation, and in the Yelvertoft area the Sherrin Creek deposit is shared by Continental Oil Company of Australia Limited and IMC Development Corporation. Large exploration leases are held by these and other companies in the Northern Territory portion of the Georgina Basin. In this area, deposits have been discovered by IMC Development at Wonarah and near Alexandria homestead (Howard, 1971).

Duchess

Since the initial discovery of phosphorites in the Duchess area in 1966, Broken Hill South Limited has carried out an extremely comprehensive program of drilling and detailed mapping of the Burke River Outlier. Several deposits have been found on the west side of the outlier, stretching from Mount Birnie south for about 25 km to Phosphate Hill (Fig. 27). Within the drilled area, reserves of beneficiation-grade ore (using a cut-off grade of 18% P_2O_5) are known to total about 1 100 million tonnes (BHS, Chairman's address for 1968).

The Roaring Siltstone, the Inca Formation, the Devoncourt Limestone, and the Thorntonia Limestone contain small phosphorite occurrences of no economic importance, but the vast majority of the phosphorites occur in the Beetle Creek Formation. Russell (1967) divided this formation into three units, but this was subsequently modified to a twofold subdivision by Thomson & Russell (1971) and Russell & Trueman (1972).

2. Monastery Creek Phosphorite Member: pelletal phosphorite, chert; phosphatic siltstone; shale and sandstone; minor phosphatic limestone (generally 10 to 15 m thick).

1. Lower Siltstone Member: siltstone, with thin interbeds of chert and minor pelletal phosphorite (50 to 60 m thick).

The Monastery Creek Phosphorite Member is the most important phosphatic unit (Pl. 17, fig. 1). Its outcrop or subcrop covers an area of more than 25 km^2. The type section at Monastery Creek is made up of the following sequence (after Russell, 1967):

Top of Sequence	Stratigraphic Thickness (m)
Phosphorite, minor phosphatic siltstone, shale and chert	1.0
Phosphatic siltstone, shale and minor chert	1.8
Phosphorite, phosphatic siltstone, minor shale and chert	1.2
Phosphorite, minor phosphatic siltstone	4.6
Phosphatic siltstone, shale and chert	1.4
Phosphorite, minor phosphatic siltstone	0.8
Phosphatic siltstone, chert, minor phosphorite	1.2

Phosphorites are present in the basal Lower Siltstone Member, but are comparatively minor compared with those in the other member.

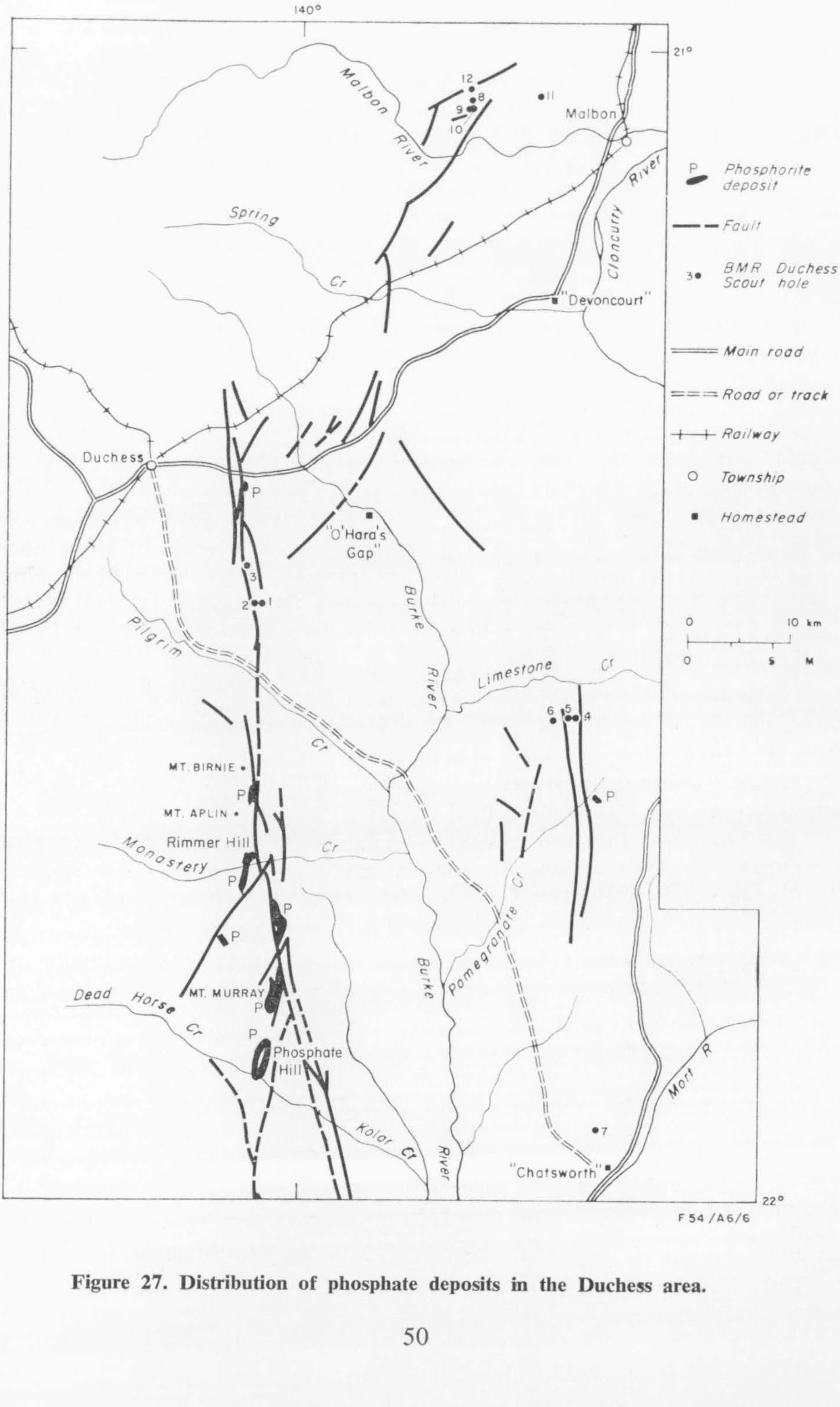

Figure 27. Distribution of phosphate deposits in the Duchess area.

In the Rimmer Hill area the Monastery Creek Phosphorite Member has an average thickness of about 19 m of phosphate rock averaging 22.5 percent P_2O_5. At Mount Murray, phosphorites averaging 19 percent P_2O_5 occur over an interval of about 10 m. Farther south, at Phosphate Hill, there is approximately 9 m of phosphate rock averaging 21 percent P_2O_5. Thomson & Russell (1971) report a maximum thickness of 40 m of phosphate rock in the Monastery Creek Phosphorite Member. Russell & Trueman (1972) discuss the geology of the Duchess deposit in some detail.

In general the Beetle Creek Formation is flat-lying, or gently dipping at 5 to 10°; however, near some of the larger faults (Fig. 22) the chert and shale beds are severely drag-folded. In places, this folding has resulted in the repetition of some phosphorite horizons. Broken Hill South Limited are still evaluating the Duchess deposits and other deposits in northwest Queensland for the determination of reserves, beneficiation, mining methods, water supply, port facilities, transportation, and marketing.

Lady Annie/Lady Jane

The Lady Annie/Lady Jane area, which is leased by Broken Hill South Limited, was first found to contain phosphorites in 1967. By June 1970, the company reported that 1 382 holes had been drilled with a total footage of more than 30 000 m (Thomson & Russell, 1971). In addition 30 exploration shafts were sunk to obtain representative samples of phosphate rock for beneficiation testing. Ore reserves of 250 million tonnes with a cut-off grade of 18 percent P_2O_5 have so far been proved at Lady Annie. Farther north the Lady Jane deposit is covered by a thin veneer of Mesozoic sediments and the phosphorites do not crop out (Fig. 12). They are essentially an extension of the Lady Annie deposit, and are believed to be similar geologically. The phosphorites of the Lady Annie area consist of both pelletal and very fine-grained varieties. The fine-grained phosphorites are in part secondary weathering products; others are mudstones and siltstones with a fine phosphatic cement. Phosphatic chert breccias are also present in places.

Obvious pelletal phosphorite varieties, such as are found in the Duchess district, were not generally observed at the surface. However, drilling revealed widespread pelletal phosphorite in the subsurface in the western and northern portions of the outlier, and pelletal phosphorite was also reported from some creek outcrops by the company geologists.

The deposits vary in grade and thickness over short distances, and were therefore drilled on a 500-foot grid. This revealed that the phosphorites were deposited over a karst-type surface of Thorntonia Limestone, which explains the variation in thickness of the Beetle Creek Formation. In the Hilary Creek area the ancient karst surface is exposed, and the depressions are filled with chert-phosphorite breccia, phosphatic siltstone, and silty phosphorite (Pl. 18, figs 1, 2; Pl. 19, fig. 1).

Phosphate beds average 6 m in thickness, and have a maximum thickness of 20 m in the Lady Annie deposit. In the Lady Jane deposit the phosphorites average 4 m in thickness, and have a maximum thickness of 22 m.

Lawn Hill/Border Waterhole

A number of phosphate deposits have been found by Broken Hill South Limited associated with Beetle Creek equivalent along the northeast margin of the Georgina Basin (Fig. 3). The more important areas are in the vicinity of

Highland Plains homestead, Mount O'Connor, Babbling Brooke Hills, Riversleigh, Mount Jennifer, and Phantom Hills. Reserves have not been announced by the company, but are probably in excess of 200 million tonnes. The phosphorites, which have a cream or yellow-brown earthy appearance, are mainly phosphatic chert breccia, silty phosphorite, and dense secondary phosphorite. Pelletal phosphorite appears to be completely absent. The average thickness of the phosphatic units ranges from approximately 2.5 m in the Riversleigh deposit to 10 m in the Phantom Hills deposit. The maximum thickness so far encountered is approximately 30 m in the Phantom Hills area (Thomson & Russell, 1971).

The phosphorites of this area and the Lady Annie district are rather less extensive than those of the Duchess area, but are 300 km nearer to the Gulf of Carpentaria and in an area of abundant rainfall. Consequently this northern area may come into production earlier than the southern deposits.

The Lawn Hill/Border Waterhole deposits extend across the Northern Territory border into the Carrara Ranges. In February 1969, Macmine Pty Ltd announced reserves in this area of 67.5 million tonnes of phosphate rock averaging 20.9 percent P_2O_5 and inferred reserves of 14.7 million tonnes averaging 20.5 percent P_2O_5.

Yelvertoft-Thorntonia

IMC Development Corporation and Continental Oil Company of Australia Limited have reported deposits of phosphate rock north and south of Yelvertoft homestead at D Tree and Sherrin Creek respectively (Figs 13-14). An announcement by IMC in October 1967 indicated reserves of 500 million tonnes averaging 16 percent P_2O_5 in the D Tree deposit, 15 km west of Lady Annie. The bed was stated to average 5 m in thickness and cover an area of at least 30 km^2. During 1968 and 1969, intensive grid drilling, pitting, and slotting were carried out on the deposits, and bulk samples were subjected to mineralogical, beneficiation, and phosphoric acid production tests. The application of stringent specifications in terms of cut-off grade, recovery, product quality, and mining ratios have reduced the reserves to 250 million tonnes averaging 18.6 percent P_2O_5.

The D Tree deposit covers an area of at least 38 km^2 and occurs in association with siltstone and chert of the Beetle Creek Formation, with local development of the basal sandstone-conglomerate lithosome. Phosphorite beds lie within a phosphatic unit, which has a maximum thickness of 35 m. The top of the exposed unit dips gently to the west at the southern end of the deposit, but forms a pronounced trough trending north-northeast at the northern end. The base has a similar structure, and onlaps Precambrian basement along the eastern edge of the deposit. Along the western edge, phosphorite-chert and siltstone-chert facies both overlie and intertongue with the Thorntonia Limestone. Small outliers of phosphorite also occur between D Tree and Lady Annie. The phosphorites of this area are again the fine-grained varieties; pelletal phosphorites are extremely rare or absent. In places on the west side of the area cliffs up to 10 m high and composed of dense secondary phosphate are present.

Barkly Tableland (Northern Territory)

IMC Development Corporation holds Prospecting Authorities for large areas in the Northern Territory extending from Creswell Downs in the north through Alexandria station to the Barkly Highway in the south, while Continental Oil Company of Australia Ltd holds adjacent Prospecting Authorities to the south and west.

In October 1967, IMC Development Corporation geologists discovered non-outcropping phosphorite in the Alexandria-Wonarah area of the Barkly Tableland, at two points 24 km east and 18 km southeast of Alexandria homestead, and also straddling the Barkly Highway. During 1968 and 1969, a regional mapping programme covering 60 000 km^2, a ground radiometric survey, study of subsurface data contained in water bore logs, and gamma logging of selected holes were followed by extensive wildcat and subsequent grid-drilling programs. In the Wonarah area, phosphate reserves amount to 970 million tonnes, averaging 15.7 percent P_2O_5 contained in a bed up to 19 m thick. The deposits near Alexandria homestead occur as a bed up to 6 m thick and though they have not been extensively drilled, they appear to be too deep for economic consideration.

The phosphorites in the Barkly Tableland are in general fine-grained varieties similar to those of the D Tree deposit; they also exhibit the same lateral changes in lithology, grade, and thickness. They occur in the Burton Beds near Alexandria homestead and the Wonarah Beds at Wonarah. Both units have similar lithology, comprising siltstone, phosphatic siltstone, phosphorite, chert, sandstone, limestone, and dolomite. They are lithologically very similar to the Beetle Creek Formation to the east.

In the Wonarah area, the phosphatic unit occurs beneath Cainozoic sand. It is flat-lying to gently dipping. Drilling has indicated extensive volcanics (possibly equivalent to the Peaker Piker Volcanics) underlying, and areally coincident with, the phosphatic Wonarah Beds. In addition, one drill hole bottomed in suspected Precambrian quartzite at a depth of 20 m. It is believed that the phosphate deposits are located on a Precambrian high (Howard, 1971).

Ardmore

The Ardmore Outlier is a small downfaulted block of Cambrian sediments, about 10 km east of Ardmore homestead (Fig. 16). The Beetle Creek Formation is up to 50 m thick and contains some rich phosphorite horizons, particularly in the southern half of the outlier. Pelletal phosphorite is the dominant phosphate, but there are fine silty phosphorites in places. Some dense secondary phosphate has developed locally. The phosphorites probably underlie an area of several square kilometres. Broken Hill South Limited has carried out a drilling program and a detailed mapping program, but, so far, little information has been released. The phosphorites are known to have an average thickness of 7 m, with a maximum thickness of about 12 m (Thomson & Russell, 1971).

Quita Creek Area

The Quita Creek area, which is 35 km south of the Ardmore deposits, contains three small phosphate deposits (Fig. 15). Broken Hill South Limited has carried out a small exploration program, but has not as yet released any details of probable reserves.

The most easterly deposit crops out on the flanks of a mesa capped by ferricrete, and consists of various phosphorite types with a total thickness of several metres. The phosphorites are most commonly pelletal, but sandy phosphorites, nodular phosphorites, silty phosphorites, and the fine-grained dense secondary variety are all present.

Farther west near Blazan Creek the phosphorites are of the phosphatic chert breccia and dense secondary varieties only. Approximately 6 km south, by the track (Fig. 15), there is another small area (approximately 100 m square) of outcropping pelletal phosphorites. It is suspected that in this area the phosphorites overlie a karst-type surface on the Thorntonia Limestone, similar to, though on a much smaller scale than, that found in the Lady Annie area. Some of the phosphorite horizons have been strongly ferruginized. If the ferruginization continues to any appreciable depth, it is likely to have adversely affected the grade of the phosphate rock.

Types of Phosphorite

It is apparent from the description of the various phosphate deposits that there are several types of phosphorite. Morphologically they are distinguished by such features as the presence or absence of pellets, the grainsize of the phosphatic material, the presence of included clasts or grains, and whether clasts are phosphatic or non-phosphatic. Where possible, the nomenclature suggested by Mabie & Hess (1964) is used in the following descriptions.

Pelletal Phosphorite

Pelletal phosphorite is the commonest type, particularly in the southern deposits. It is composed of rounded phosphate ovules ranging in colour from dark brown to colourless (in thin section). A few of the pelletal phosphorites are cross-bedded (Pl. 19, fig. 2). On some specimens the matrix is composed of fine-grained phosphatic material, but generally it is siliceous or calcareous, or more rarely composed of detrital silt and clay particles. There is every gradation from siliceous and calcareous pelletal phosphorite to phosphatic and slightly phosphatic chert and limestone.

The ovules range in size from 0.06 to 0.60 mm in diameter. They generally have little or no internal structure, except rare included fossil fragments or detrital grains (Pl. 20, figs 1, 2). There is a notable lack of any concentric banding in most of the ovules, although a few show a well developed oolitic form (Pl. 21, fig. 1). Rare compound pellets analogous to carbonate grapestone (Pl. 21, fig. 2) are present. A few ovules have a nucleus of either a silt-size detrital grain or a fossil fragment, but many lack evidence of growth by accretion around a nucleus. Many pellets are not concentrically banded, and are therefore 'ovules' rather than 'oolites'.

The pelletal phosphorites are generally thinly bedded or laminate; a few units show scour-and-fill structures; some show cross-bedding. Sedimentary structures such as these suggest agitated shallow water. The matrix surrounding the ovules may consist of sand, silt, or clay-size detrital material, but more normally the matrix is made up of sparry calcite or cryptocrystalline chert of both primary and secondary origin.

Argillaceous Phosphorite

Mabie & Hess (1964, p. 58) suggest the term argillaceous phosphorite (or quartzitic phosphorite for sand-size material) for rocks composed of 45 to 80 percent collophane (approximately equivalent to 18 to 31 percent P_2O_5) and less than 55 percent detrital grains. For 10 to 45 percent collophane they suggest the term phosphatic siltstone or phosphatic sandstone. There is of course every gradation from a slightly phosphatic siltstone containing perhaps only 3 percent P_2O_5 to an argillaceous phosphorite containing 31 percent P_2O_5.

Argillaceous phosphorite and phosphatic mudstone are particularly common in the Yelvertoft/Lady Annie district (Pl. 22, figs 1, 2). They consist of angular to subangular silt-size quartz grains set in a structureless collophane matrix or cement. Bedding is thin-bedded to laminate; current laminations are lacking. Ovules were observed in a few samples, but in general were rather rare. It would seem that the argillaceous phosphorites were deposited in a much quieter environment than the pelletal phosphorites. Because of the fine grain of the rock it is difficult to distinguish these phosphorites from a kaolinitic mudstone. This is particularly true of fresh rock, and the only certain way of distinguishing the two is by chemical testing. Trueman (1971) points out that this phosphorite type is comparable with the microsphorite beds of the Florida phosphate fields which Riggs & Freas (1965) believe to be parent material for much of the pelletal phosphorites. As the term microsphorite would appear to have some genetic connotations, the simpler more descriptive term 'argillaceous phosphorite' is perhaps more desirable. Difficulties arise with terminology when there is little or no included detrital material, as Mabie & Hess (op. cit.) suggest no name for fine-grained phosphate rock with greater than 80 percent collophane (31% P_2O_5) apart from the general term 'phosphorite'. The term 'microsphorite' is perhaps useful for a fine-grained primary phosphorite such as this, although a more suitable name might be 'collophane mudstone' as suggested by Russell & Trueman (1972), or alternatively 'phospholutite' (analogous to calcilutite in carbonate terminology).

Secondary Phosphorite

Secondary phosphorite is commonest in the north, but occurs to a limited extent in all the deposits. It consists of massive structureless very finely crystalline or cryptocrystalline collophane (Pl. 23, fig. 1). It is generally pale brown or yellow, and in places such as the Yelvertoft and Mount O'Connor areas it forms prominent scarps 5 to 10 m high. Colloform banding is present in places, and staining by iron and manganese is common. Inclusions of silica, calcite, iron oxides, and pyrolusite are abundant in places. The weathered surface is commonly convoluted. Some of the secondary phosphorite is definitely encrusting, but in many cases the relationship with underlying material is unknown. It is commonly associated with silcrete and ferricrete produced in the Tertiary lateritic weathered profile; for this reason the name 'phoscrete' is proposed for this type of secondary phosphorite. The phoscrete did not, however, only form as a result of Tertiary weathering. It is probably forming at the present day; and some contemporaneous—that is, Cambrian—thin iron and manganese-stained phoscrete is interbedded with more normal Beetle Creek sediments in places. The term 'microsphorite' has probably been applied to such phosphorites, but the term (or the alternative phospholutite) should only be used for the primary, or perhaps very early diagenetic, phosphorite, and not for a phosphatic weathering product.

Lack of subsurface data precludes any estimate of the abundance, grade, and distribution of subsurface phoscrete.

In places, the phoscrete has no inclusions, and has the appearance of having formed at the surface by precipitation. Elsewhere, the presence of inclusions suggest that it has formed by replacement, particularly replacement of carbonates. Extensive phoscrete-type deposits have not, to the authors' knowledge, been described previously; however, some hand specimens of phosphorites kindly supplied by G. I. Bushinski of the Geological Institute of the Academy of Science of the USSR and called 'Karst phosphorites' are rather similar in appearance and may well have formed by a similar mechanism.

Phosphorite Breccia

The phosphorite breccia is believed to be in part a secondary weathering product, for which the name 'phoscrete breccia' is appropriate, analogous to the breccias common in Cainozoic silcretes and ferricretes. Clasts may be of pelletal phosphorite (as at Rimmer Hill, see Pl. 17, fig. 1 and Pl. 23, fig. 2) or chert (as at Mount O'Connor) or limestone. The matrix is generally of cryptocrystalline structureless collophane, but is pelletal in places. Russell (1967) suggests that the brecciation at Rimmer Hill resulted from tectonic pulses before the Monastery Creek Phosphorite was laid down. As the unit is near the Pilgrim Fault Zone, the 'fault breccia' hypothesis is reasonable. Slumping due to the leaching out of underlying carbonate, ultimately leading to a collapse breccia, is another possible explanation (Russell & Trueman, 1972). Some of the breccias are undoubtedly of Cambrian age, formed by the penecontemporaneous brecciation of finely laminate phosphorites. The break-up of such beds probably occurred in regions of agitated shallow water.

Composition of the Phosphorites

Only a very limited program of major and minor element analyses has so far been undertaken by the Bureau of Mineral Resources. Some of the analyses are summarized in Tables 1 to 7.

The phosphorites are composed primarily of carbonate-fluorapatite with variable quantities of gangue material such as quartz, microcrystalline quartz, clay minerals, calcite, dolomite, iron oxides, and less commonly heavy minerals and fluorite, all of which can significantly modify major and minor element analyses.

The carbonate-fluorapatite has the approximate formula $Ca_5(PO_4)_3(F, CO_3)$, but as Gulbrandsen (1966) points out, numerous substitutions into the lattice are possible, the principal ones being Na, Sr, U, Th, and the lanthanides for calcium, and SO_4 for PO_4. The few major element analyses so far carried out on Georgina phosphorite appear to give values somewhat comparable with those given by Gulbrandsen for Phosphoria phosphorites.

The Georgina phosphorites contain only 1 to 2 percent of CO_2 (see Table 1 for major element analyses). This is similar to values given for the Phosphoria phosphorites (Gulbrandsen, 1967), but is considerably less than the values of CO_2 (4 to 7 percent) found in North African phosphorites.

The minor element analyses are given in Tables 2 to 5 and average mean values for the three major types of phosphorite are given in Table 6. Again the small number of analyses makes any conclusions somewhat speculative at this stage, but there do appear to be notable differences in minor element concentrations in the three main types of phosphorite. Manganese, for instance, is significantly more abundant in the phoscrete than in the pelletal phosphorite, which is precisely what one would expect of a weathering product, for many of the ferricretes in northern Queensland contain abundant manganese. Conversely, values of Ag, Cr, Sr, V, and Y are considerably higher in pelletal material than in phoscrete and argillaceous phosphorite. This may be due to a slightly higher content of organic matter in the pelletal phosphorites than in the other types. In all three types of Georgina Basin phosphorite however, the concentration of many of the minor elements, such as Ag, Cr, Cu, Ni, and V, is appreciably less than those of the Meade Peak phosphorites (Table 6) due to high organic matter content of the

Meade Peak phosphorites. Conversely there are significantly greater concentrations of Ba, Mn, and Pb in the Georgina Basin phosphorites compared to those of the Meade Peak. The manganese is probably a function of the greater degree of weathering of the Georgina phosphorites (note the high Mn values for some of the weathered nonphosphatic sediments in Table 7). The abundance of Ba may be a reflection of the gangue material; the apparent abundance of lead in the Georgina phosphorites is still unexplained.

The distribution of rare earths in the Georgina phosphorites is of some interest. Figures 28 and 29 indicate the usual variation of relative abundances of odd and even lanthanides, but of more significance is the cerium deficiency. This has been detected in a number of other phosphorites by Altschuler et al. (1967), and is believed by them to be a feature characterizing marine apatite. The relative lack of cerium compared with the abundance of lanthanum in pelletal phosphorites is apparent from Figure 28. If this diagram is compared with Figure 29, it is evident that lanthanides are less abundant in the phoscretes and argillaceous phosphorites than in the pelletal phosphorites. The low concentration in phoscretes is particularly marked, and cannot be attributed to a decrease in P_2O_5 content. This suggests that during weathering the lanthanides are either leached out or left as a residual. It is difficult to understand how such selective removal could have occurred as the lanthanides (RE^{+++}) are generally considered to undergo diadochic substitution for Ca^{++} in the apatite lattice, charge balance being retained by the coupled substitution of Na^{+} (Gulbrandsen, 1966). They are not considered to exist as a separate mineral phase as might be suggested by their apparent readiness to be preferentially leached during weathering.

TABLE 1. MAJOR ELEMENT ANALYSES OF SOME GEORGINA BASIN PHOSPHORITES

Sample	1	2	3	4
SiO_2	9.35	3.65	4.15	4.75
Al_2O_3	1.66	0.29	0.81	0.39
Fe_2O_3	0.29	1.46	2.30	0.83
FeO	<0.01	0.07	0.23	0.14
MgO	0.07	0.03	0.21	0.38
CaO	46.3	51.6	48.3	50.6
Na_2O	0.11	0.11	0.63	0.50
K_2O	0.23	0.02	0.11	0.11
CO_2	0.70	0.90	2.00	1.70
P_2O_5	34.6	38.4	33.9	36.6
MnO	1.77	0.05	0.04	0.03

1. QP10a1 Phoscrete (?Cambrian) Galah Creek area.
2. QP11 Phoscrete (?Cainozoic) Galah Creek area.
3. QP45a3 Pelletal phosphorite. Ardmore outlier.
4. QP96a1 Pelletal phosphorite. Quita Creek area.

Analyses by the Analytical Section of the Australian Mineral Development Laboratories (A. B. Timms, Officer-in-Charge.)

TABLE 2. P_2O_5% AND MINOR ELEMENT ANALYSES (PPM) OF SOME PELLETAL PHOSPHORITES

	1 * (a)	2 (a)	3 (a)	4 (a)	5 (a)	6 (a)	7 (a)	8 (a)	9 (a)	10 (a)	11 (a)	12 (a)	13 (b)	14 (b)	15 (b)	16 (b)	17 (b)	18 (b)	19 (a)	20 (a)*	21 (b)	Av.
Ag		1.5		2	8															0.8		3.8
Ba	400	250	250	100	50	100	5000	50	50	300	200	500							200	400		604
Cu	60	80	10	10	10	50	30	80	100	30	30	30	45	33	50	70	20	45	20	100	45	43
Co	5	30	x	5	5	5	x	5	x	x	x	x	2–	2–	6	7.5	16	5	150	150	78	5
Cr	100	150	100	100	50	150	80	100	100	100	100	100	90	135	98	280	x	128	80	20	75	110
K	800		500			1000	5000	1000	500	500	800	800							1000	1000		1090
Li	8	5	5	5	5	5	8	6	5	6	10	8							5	5		6
Mn	2000	400	300	300		500	300	300	300	300	300	300	306	63	93	238	675	275	2000	10000	2460	480
Mo		10		3																5		7
Na	10		1000			1500	500	800	1000	1000	1500	1000	22	21	23	20	33	23	4500	500	228	920
Ni	10	100	5	15	10	10	x	5	20	20	30	30							200	250		21
Pb	30	250	10	50	50	10	30	10	10	10	10	10	28	5–	50	8	78	5–	100	100	98	40
Rb	20		x			10	250	x		10	10	10							20	30		38
Sr	250	600	250	300	300	100	5000	250	250	600	250	800							150	400		745
Ti	300	500	x	100	100	300	1500	300	100	100	100	200							300	800		300
V	200	300	80	30	10	100	80	150	200	50	50	80							80	300		110
Y		1500		800	1000															200		1100
Zn	100	500	50	20	20	x	x	200	300	150	150	150	35	45	70	95	568	74	200	500	41	125
P_2O_5	36.4	34.4	36.9	36.4	35.4	37.4	18.2	35.6	36.9	34.6	35.4	35.2	29.7	20.4	32.3	8.3	26.0	15.2	30.9		21.8	34.4

1. QP43 Pelletal phosphorite. Ardmore Outlier.
2. QP45a3 Pelletal phosphorite. Ardmore Outlier.
3. QP49 Pelletal phosphorite. Ardmore Outlier.
4. QP96a1 Pelletal phosphorite. Quita Creek area.
5. QP106a1 Pelletal phosphorite. Quita Creek area.
6. QP107 Pelletal phosphorite. Quita Creek area.
7. QP108a1 Pelletal phosphorite. Quita Creek area.
8. QP110a1 Pelletal phosphorite. Monastery Creek, Burke River Outlier.
9. QP110a3 Pelletal phosphorite. Monastery Creek, Burke River Outlier.
10. QP114 Pelletal phosphorite. Phosphate Hill, Burke River Outlier.
11. QP114a1 Pelletal phosphorite. Phosphate Hill, Burke River Outlier.
12. QP114a2 Pelletal phosphorite. Phosphate Hill, Burke River Outlier.
13. MM Pelletal phosphorite. Mount Murray, Burke River Outlier.
14. D640d Pelletal phosphorite.
15. AM Pelletal phosphorite. Ardmore Outlier.
16. MC Pelletal phosphorite. Monastery Creek, Burke River Outlier.
17. GP293 Pelletal phosphorite.
18. 1127C Siliceous pelletal phosphorite. Burke River Outlier.
19. QP106a2 Ferruginized pelletal phosphorite. Quita Creek area.
20. QP106a4 Ferruginous pelletal phosphorite. Quita Creek area.
21. GP228 Ferruginous pelletal phosphorite.

Av. Average value for analyses 1-17.

* (a) Analyses by semi-quantitative emission spectroscopy, Analytical Section of Australian Mineral Development Laboratories (A. B. Timms, Officer-in-Charge).
* (b) Analyses by atomic absorption spectrophotometry, BMR, by H. R. Lord.

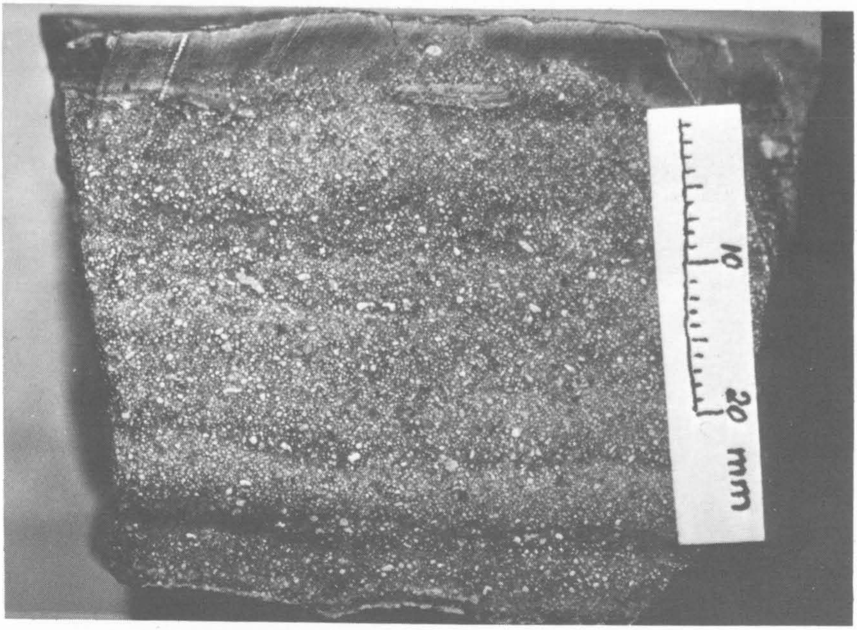

Plate 17, fig. 1. Typical pelletal phosphorite from 3 km north of Mount Murray.

Plate 17, fig. 2. Phosphatic breccia at Rimmer Hill.

Plate 18, fig. 1. Pocket of phosphatic siltstone (light-coloured) within Thorntonia Limestone, Hilary Creek area.

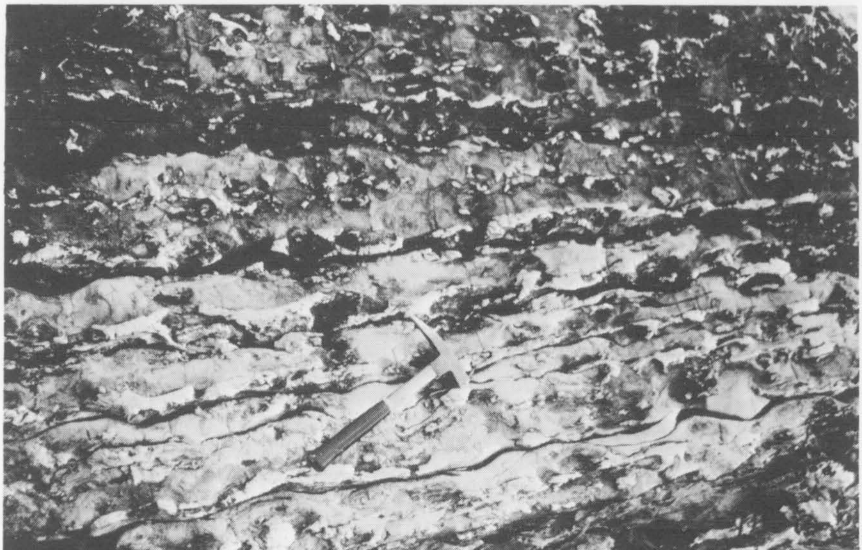

Plate 18, fig. 2. Chert layers and nodules in Thorntonia Limestone, Hilary Creek area.

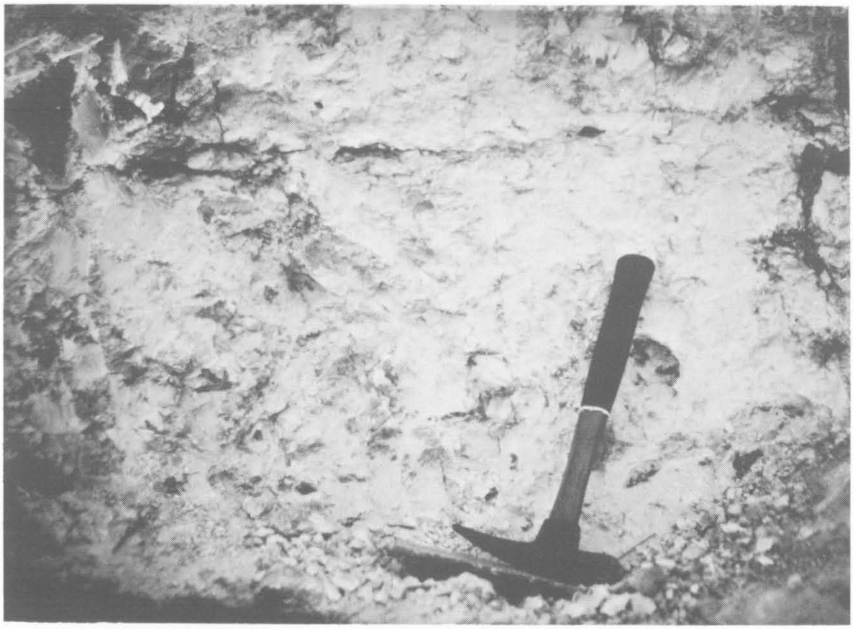

Plate 19, fig. 1. Close up of the phosphatic siltstone in Plate 18, figure 1, showing the leached structureless nature of the sediment. Some chert fragments (derived from the Thorntonia Limestone) are visible within the siltstone.

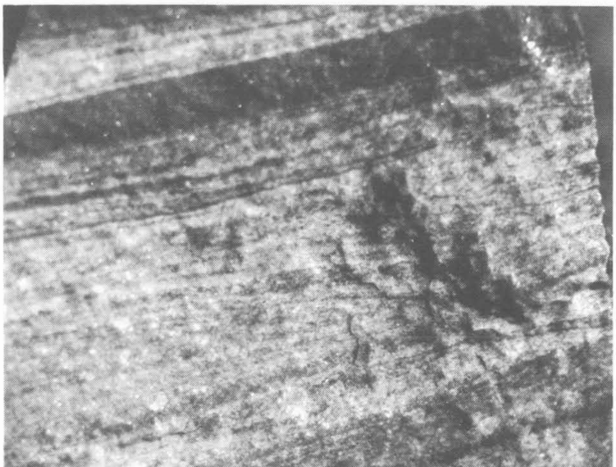

Plate 19, fig. 2. Cross-bedded calcareous pelletal phosphorite, from 3 km north of Mount Murray. The arrow in the lower right corner is approximately 2.5 cm long.

Plate 20, fig. 1. High grade pelletal phosphorite from the Mount Murray area. Ordinary light, x100.

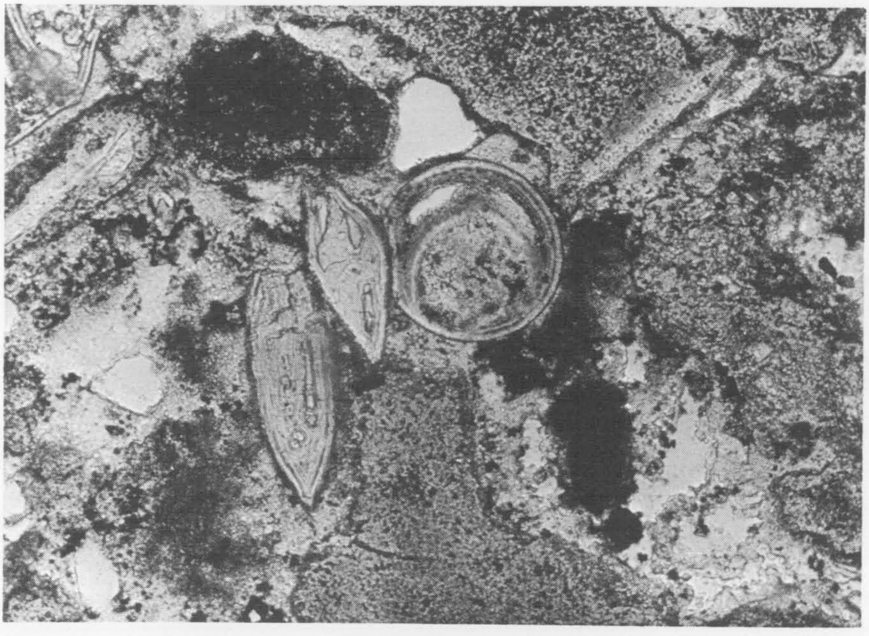

Plate 20, fig. 2. Phosphorite from the Ardmore Outlier, composed in part of phosphatized fossil fragments. Ordinary light, x80.

Plate 21, fig. 1. Phosphatic oolith with a core of partly recrystallized or remnant material. Quita Creek area. Ordinary light, x250.

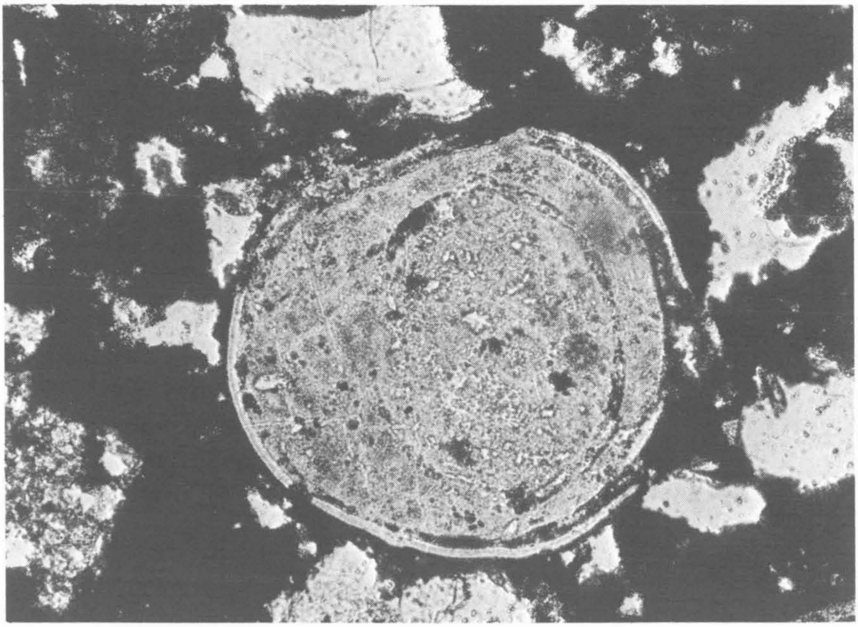

Plate 21, fig. 2. Compound phosphate pellet in a phosphorite from the northern margin of the Georgina Basin. Ordinary light, x250.

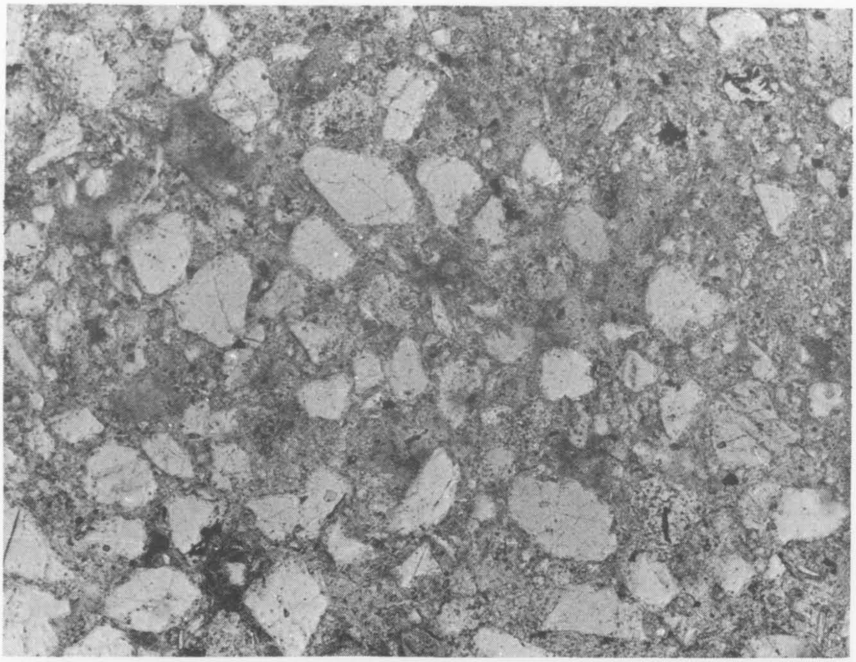

Plate 22, fig. 1. Sand-size quartz grains (light) in a matrix of dark collophane. Ardmore Outlier. Ordinary light, x80.

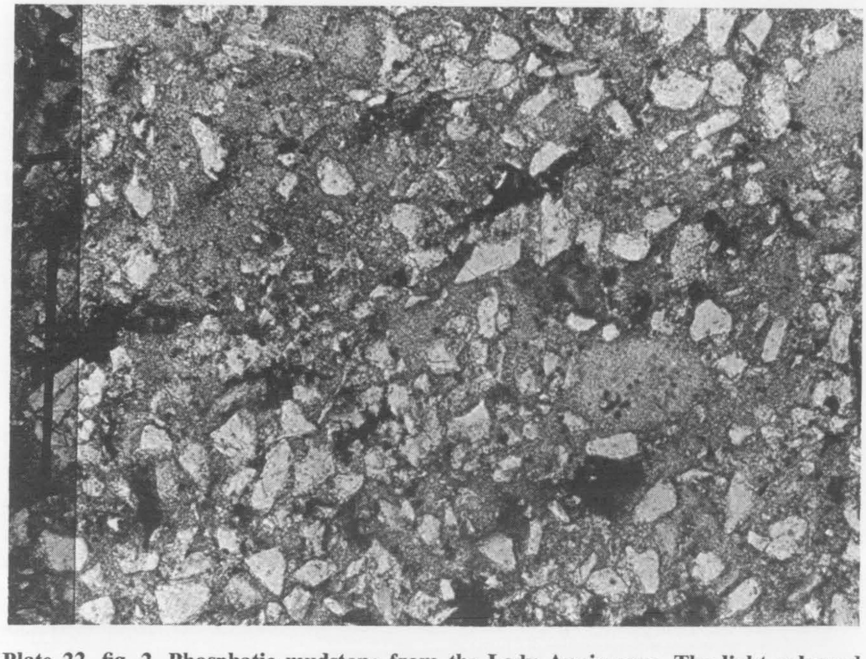

Plate 22, fig. 2. Phosphatic mudstone from the Lady Annie area. The light coloured grains are primarily detrital quartz. Ordinary light, x80.

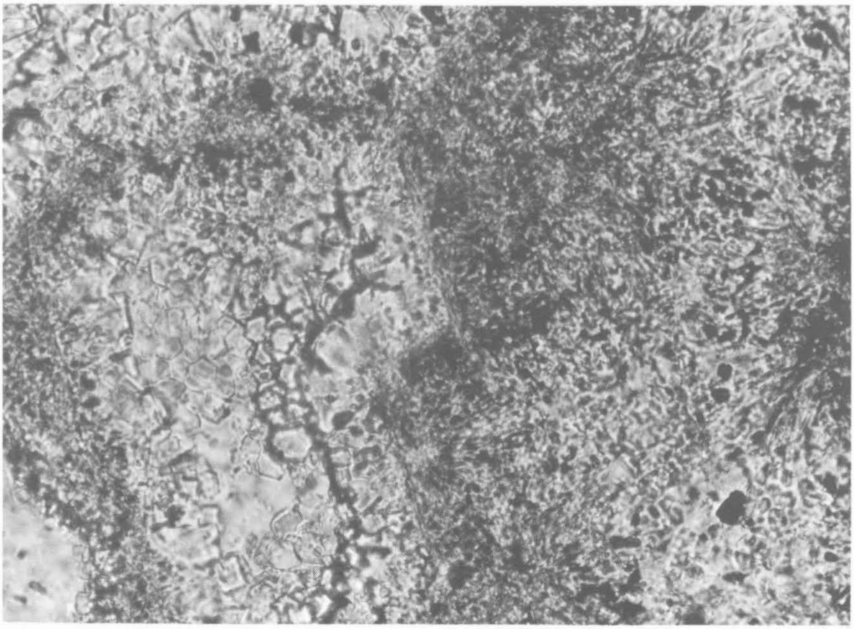

Plate 23, fig. 1. Small hexagonal crystals of apatite in phoscrete from the Ardmore Outlier. Ordinary light, x400.

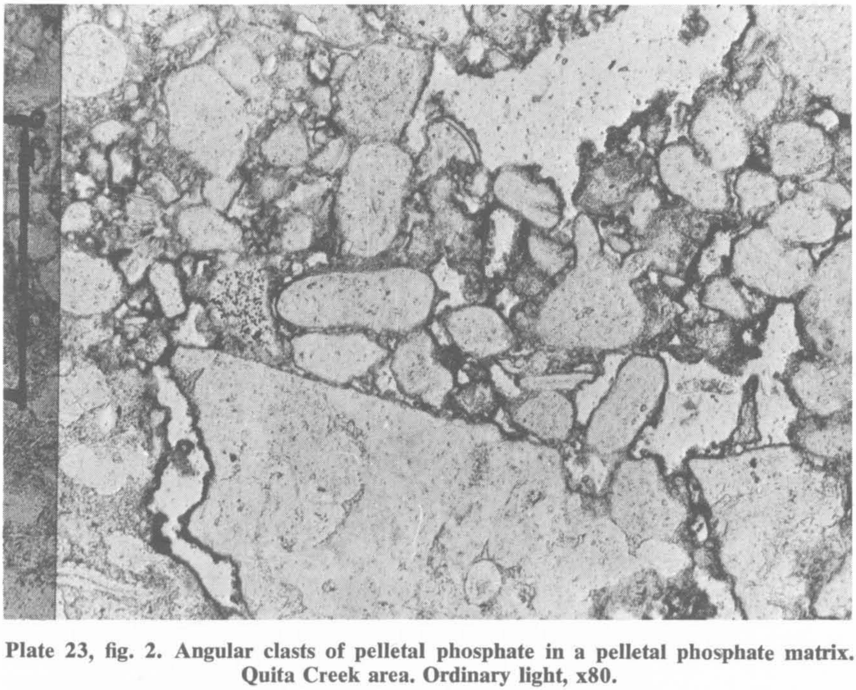

Plate 23, fig. 2. Angular clasts of pelletal phosphate in a pelletal phosphate matrix. Quita Creek area. Ordinary light, x80.

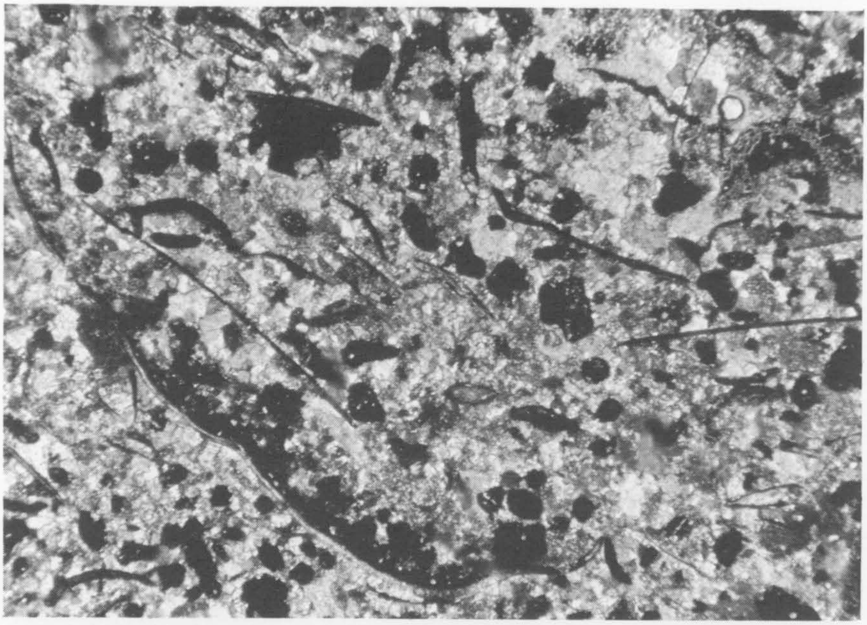

Plate 24, fig. 1. Collophane pellets and phosphatized fossil fragments (black), in a sparry calcite matrix (light). 3 km north of Mount Murray. Crossed nicols, x35.

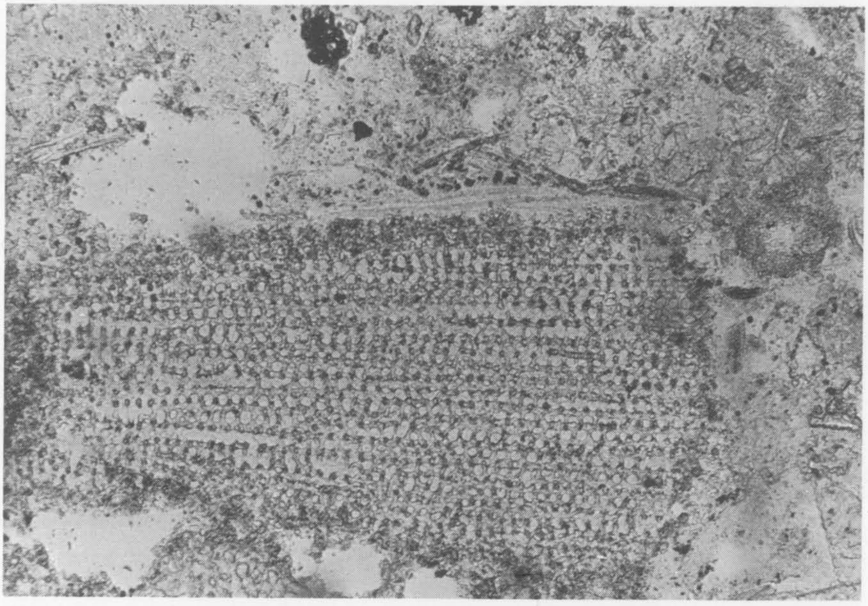

Plate 24, fig. 2. Partly phosphatized fossil fragment in biopelsparite. 3 km north of Mount Murray. Ordinary light, x100.

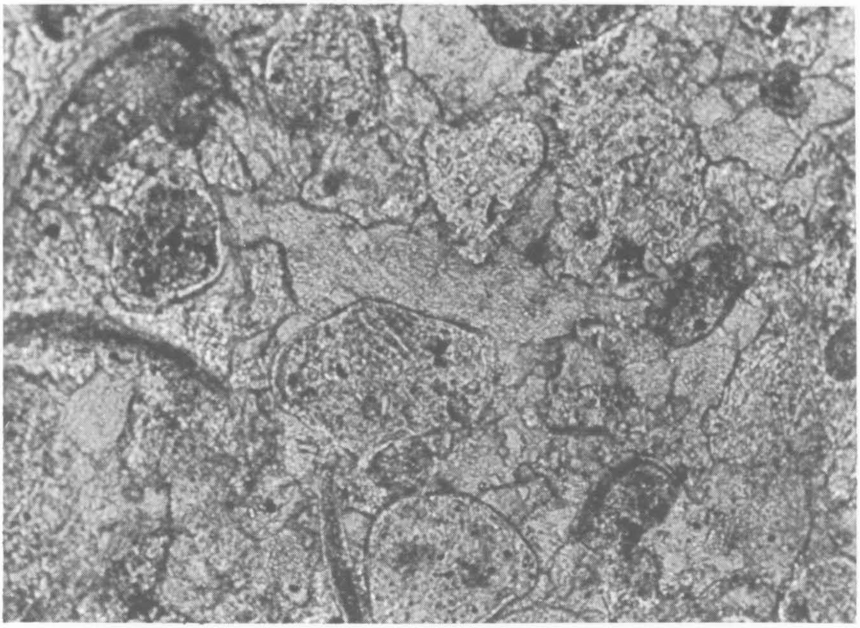

Plate 25, fig. 1. Phosphatic biopelsparite containing collophane pellets and fossil fragments in a sparry calcite cement. 3 km north of Mount Murray. Ordinary light, x100.

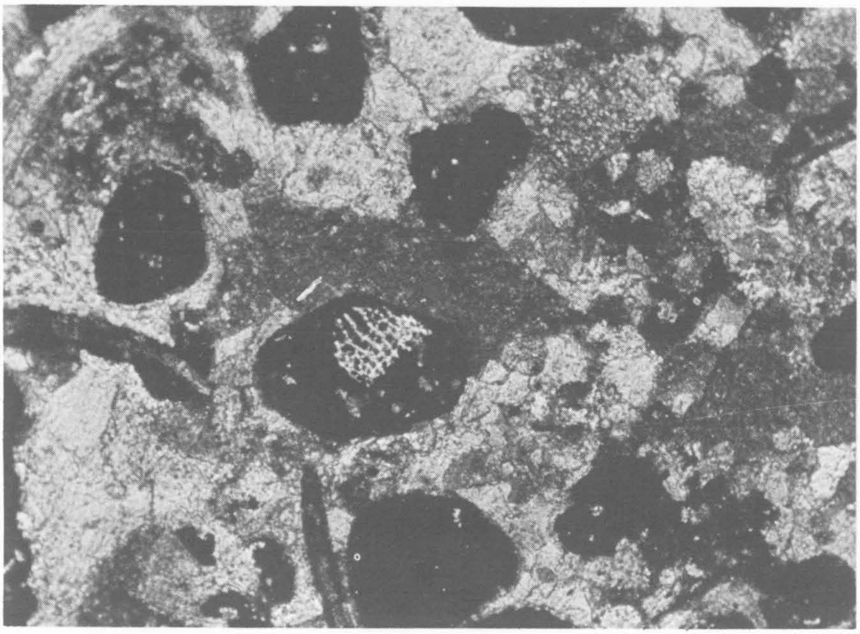

Plate 25, fig. 2. Same view as Figure 1 but with nicols crossed. The phosphate pellets (black) are now evident. The calcitic remnant of a fossil fragment is clearly visible in the central pellet, x100.

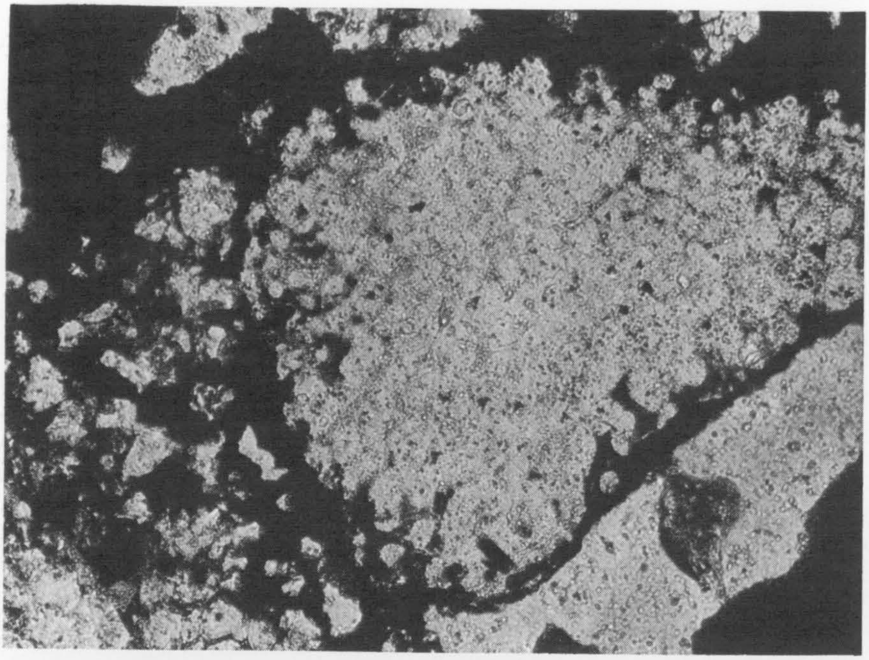

Plate 26, fig. 1. Phosphate pellet showing phosphatized remnants of echinoderm fragment. Ordinary light, x250.

Plate 26, fig. 2. Hexagonal quartz crystals replacing cryptocrystalline apatite. Northern margin of Georgina Basin. Ordinary light, x250.

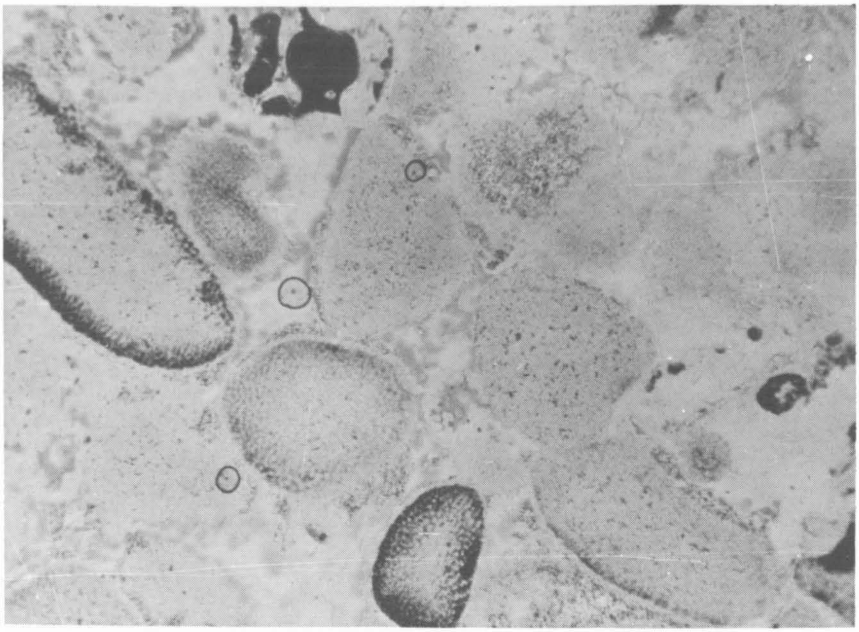

Plate 27, fig. 1. Silicified coquinite from the cherty interval in the Beetle Creek Formation. Phosphatized skeletal fragments (dark) are visible within some of the pellets. Ordinary light, x35.

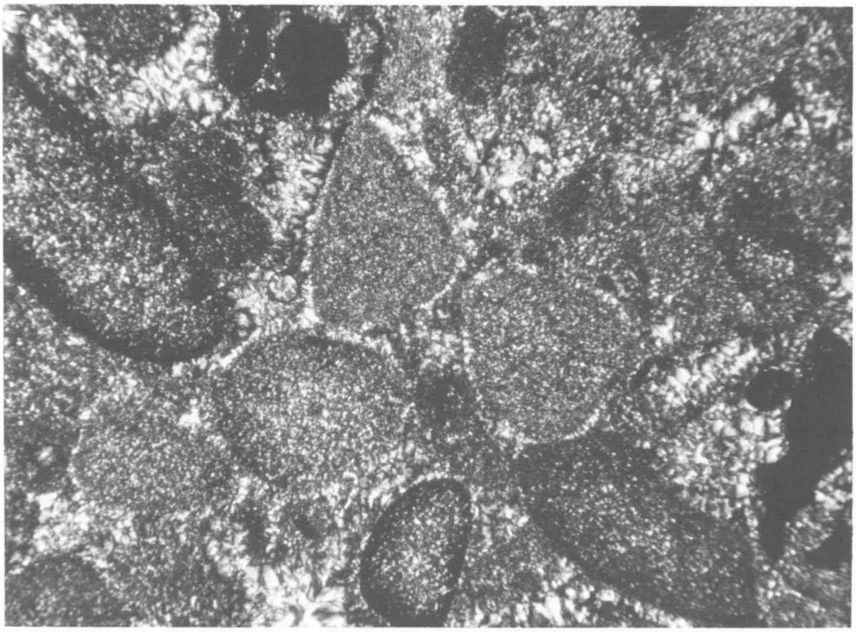

Plate 27, fig. 2. Same field of view as Figure 1 but with crossed nicols. The cherty nature of the sediment is apparent. x35.

Plate 28. Bed of siliceous pelletal phosphorite in the Mount Murray area with two calcareous spherical remnants of unaltered phosphatic limestone (de Keyser) or alternatively two nodules resulting from post-depositional calcitization (Cook).

TABLE 3. P_2O_5% AND MINOR ELEMENT ANALYSES (PPM) OF ARGILLACEOUS AND SANDY PHOSPHORITES, AND SILTSTONE FROM THE BEETLE CREEK FORMATION

	1 * (a)	2 (a)	3 (a)	4 (a)	5 (b)	6 (b)	7 (b)	8 (a)	9 (a)	10 (b)	11 (b)	12 (b)	13 (b)	14 (b)	Av.
Ag	2	0.2	2	2				2	0.2						1.6
Ba	200	100	100					200	250						130
Cu	10	50	10	10	45	40	43	30	50	58	135	13	13	105	30
Co	5	5	5	10	183	5	31	5	x	325	21	5	10	93	35
Cr	30	30	30	30	55	98	63	150	100	175	63	48	103	3	48
K	400	600	400					400	400						470
Li	10	15	15	3				8	8						10
Mn	2000	500	300		41300	575	575	300	100	5780	1380	130	315	4730	7540
Mo			150	200				3	100						175
Na	200	300	300		108	21	134	200	200	588	58	20	19	168	177
Ni	10	5	10	10				20	x						9
Pb	100	100	50	80	578	120	138	30	5	2120	145	38	58	23	170
Rb	10	20	10	10				20	20						13
Sr	100	100	100					100	100						100
Ti	1500	1000	2500					800	1000						1670
V	30	10	30	20				30	10						23
Y	40	20	200					50	x						87
Zn	600	400	200	30	3430	213	475	30	100	796	455	56	107	718	764
P_2O_5			13.1	37.1	38.3	22.7	21.5	16.0	0.7	1.9	3.3	5.1	27.8	2.8	26.6

1. QP2A4 Argillaceous phosphorite. Hilary Creek area.
2. QP2B1 Argillaceous phosphorite. Hilary Creek area.
3. QP3 Argillaceous phosphorite. Lady Annie Outlier.
4. QP96A8 Argillaceous phosphorite. Quita Creek area.
5. 3b Argillaceous phosphorite.
6. 4c Argillaceous phosphorite.
7. 5a Argillaceous phosphorite.
8. QP96a3 Sandy phosphorite. Quita Creek area.
9. QP4 Siltstone. Lady Annie area.
10. 8C-2 Siltstone.
11. 3d Siltstone.
12. 4a Phosphatic siltstone.
13. 4a Sandy phosphorite.
14. 4b Ferruginized phosphatic siltstone.

av. Average of analyses 1-7.

* (a) Analyses by semi-quantitative emission spectroscopy, Analytical Section of Australian Mineral Development Laboratories (A. B. Timms, Officer-in-Charge).

(b) Analyses by atomic absorption spectrophotometry, BMR, by H. R. Lord.

TABLE 4. P_2O_5% AND MINOR ELEMENT ANALYSES (PPM) OF MISCELLANEOUS (PRIMARILY PELLETAL) PHOSPHORITES

	Cu	Co	Cr	Mn	Ni	Pb	Zn	P_2O_5
GP 72	15	15	33	2750	88	185	300	37.4
GP 74A	10	3	28	355	13	80	600	29.3
GP 74C	15	58	10	55000	90	x	2100	3.0
GP 74D	10	3	13	300	5	25	975	34.8
GP 75A	3	3	45	150	5	25	123	15.2
GP 75B	18	5	28	380	13	30	213	10.7
GP 75C	130	270	210	24250	110	10	2500	4.7
GP 90	15	15	40	770	48	25	150	32.2
GP 93	45	3	50	490	18	470	143	26.0
GP 95	15	3	38	670	8	5	38	34.3
GP 97A	3	10	28	2630	30	15	150	37.9
GP 97B	3	10	40	1320	40	55	200	28.5
GP 120A	48	18	15	3700	38	115	400	36.2
GP 120B	10	5	20	580	10	120	190	36.4
GP 121	153	40	55	350	30	15	300	0.5
GP 143	8	10	13	3700	25	25	775	35.2
Mt O_2	5	13	13	3400	23	120	200	31.5
Mon Ck A	75	7	55	190	15	18	103	33.4
Mon Ck B	80	4	166	180	15	11	68	14.8
Mon Ck C	115	26	177	660	34	11	97	23.1
Phos Hill A	25	4	59	160	18	24	46	36.5
Phos Hill B	20	11	51	600	24	18	32	37.2
Mt Murray A	43	4	39	70	24	12	79	20.8
Mt Murray B	46	4	260	45	26	5	36	5.9
67632022/1	20	<4	3	115	13	35	30	6.8
67632022/2	27	4	66	60	15	12	37	20.6
Little Phos. Hill	154	15	63	1900	15	18	82	35.5
Duchess 623	136	30	39	2200	29	20	100	37.5
Duchess 624	83	8	63	160	18	34	68	37.2
Duchess 626	320	46	75	520	36	24	114	36.4
Duchess 627	38	<4	66	60	9	9	68	38.1
Duchess 640A	27	4	79	20	9	11	48	19.2
Duchess 640B	23	4	17	40	10	12	26	16.9
Duchess 640C	61	4	110	40	12	12	126	21.1
Duchess 663	31	<4	51	20	13	10	64	23.2
Duchess 675A	27	<4	55	40	15	38	600	38.2
Duchess 675B	25	<4	21	40	9	43	800	37.8
Duchess 687A	80	8	79	140	12	34	76	36.4
Duchess 687B	80	8	96	60	15	48	60	35.3
Uran 1A	15	<4	79	140	15	14	26	36.4
Uran 1B	25	4	39	160	15	6	30	34.6
Uran 1C	29	<4	55	40	9	12	24	38.0
Uran 1D	20	<4	28	40	6	12	22	38.4
Uran 1E	27	<4	35	160	18	12	30	37.0
Uran 1F	29	<4	83	60	12	9	126	22.2
Rimmer Hill	29	<4	63	40	9	58	112	35.8
Mean	48	15	60	2364	23	41	271	27.9

Analyses by atomic absorption spectrophotometry. Analysts H. R. Lord and P. M. Rew, BMR.

TABLE 5. P_2O_5(%) AND MINOR ELEMENT ANALYSES (PPM) OF SOME PHOSCRETES AND PHOSCRETE BRECCIAS

	1 * (a)	2 (a)	3 (a)	4 (a)	5 (a)	6 (a)	7 (a)	8 (b)	9 (b)	10 (b)	11 (b)	12 (b)	13 (b)	14 (a)	15 (a)	16 (a)	17 (a)	18 (a)	Av.
Ag	0.4	0.6	0.4	0.6		2	1										2		1.0
Ba	800	50	150	100	100	600	100							150	150	200	150	250	271
Cu	10	60	50	10	20	30	10	45	15	40	30	45	28	15	10	10	30	50	30
Co	150	5	30	10	x	10	10	15	9	10	775	179	18	30	15	5	10	x	94
Cr	20	30	30	30	100	150	30	85	20	98	73	85	80	20	20	20	100	100	64
K			100		800	400	200							2000	2000	1000		800	375
Li	160	3	1	3	3	5	1							10	8	5	8	6	25
Mn	17700	2000	3000	700	300	300	600	10300	552	700	33200	63000	875	3000	1500	2000	400	100	1025
Mo	x		5	3		5	x												2.6
Na			30		100	100	30	48	20	33	497	114	5	300	300	100		1500	97
Ni	150	10	100	15	10	20	10							30	40	20	30	x	45
Pb	500	250	10	50	60	50	50	323	425	40	243	150	80	100	100	200	50	10	170
Rb	10	x			10	10	x							30	20	20		20	6
Sr	100	40	150	100	100	30								100	100	100	20	600	89
Ti	500	x		x	300	800	100							500	300	300	200	400	283
V	20	20	100	30	20	50	50							200	150	100	30	50	41
Y	40	10	x	60		50	20												30
Zn	600	300	300	x	30	150	30	1240	1155	63	725	890	145	3000	1000	500	100	150	432
P_2O_5	34.6	32.3	35.8	38.5	38.0		31.9	31.2	31.0	37.6	17.0	21.2	31.0	31.2	28.0	32.6	31.5	33.4	31.7

1. QP10a1 Manganiferous phoscrete. Yelvertoft-Thorntonia area.
2. QP11 Phoscrete. Yelvertoft-Thorntonia area.
3. QP45a2 Phoscrete. Ardmore Outlier.
4. QP96a2 Phoscrete. Quita Creek area.
5. QP97 Phoscrete. Quita Creek area.
6. QP100a1 Phoscrete. Quita Creek area.
7. QP100a2 Phoscrete. Quita Creek area.
8. GP29—1 Phoscrete.
9. GP29—2 Phoscrete.
10. GP90 Phoscrete.
11. GP97 Phoscrete.
12. GP120 Phoscrete.
13. GP141 Phoscrete.
14. QP21a5 Phoscrete breccia. Mount O'Connor area.
15. QP22a3 Phoscrete breccia. Mount O'Connor area.
16. QP2297 Phoscrete breccia. Mount O'Connor area.
17. QP100a5 Phoscrete breccia. Quita Creek area.
18. QP115 Phoscrete breccia. Rimmer Hill, Burke River Outlier.

Av. Average mean value for analyses 1-13.

* (a) Analyses by semi-quantitative emission spectroscopy, Analytical Section of Australian Mineral Development Laboratories (A. B. Timms, Officer-in-Charge).
(b) Analyses by atomic absorption spectrophotometry, by H. R. Lord, BMR.

TABLE 6. MEAN MINOR ELEMENT CONTENT OF GEORGINA BASIN PHOSPHORITES AND MEADE CREEK PHOSPHORITES

	Pelletal Phosphorite (17)		*Phoscrete* (13)		*Argillaceous Phosphorite* (7)		*Average value for Meade Peak (after Gulbrandsen)*
	Mean	*Range*	*Mean*	*Range*	*Mean*	*Range*	
Ag	3.8	1.5-8	1.0	0.4-2	1.6	0.2-2	3-100
Ba	604	50-5000	271	50-800	130	100-200	100
Cu	43	10-80	30	10-45	30	10-50	100
Co	5	0-30	94	0-775	35	5-183	<10
Cr	110	0-280	64	30-150	48	30-98	1000
K	1090	500-5000	375	100-800	470	400-600	
Li	6	5-10	25	1-160	10	3-15	
Mn	480	93-2000	1025	300-63000	7540	300-41300	30
Mo	7	3-10	2.6	0-5	175	150-200	100
Na	920	10-1500	97	5-497	177	21-300	
Ni	21	0-100	45	10-150	9	5-10	100
Pb	40	5-78	170	10-500	170	50-578	<10
Rb	38	0-250	6	0-10	13	10-20	
Sr	745	250-5000	89	30-150	100	100-100	1000
Ti	300	0-1500	283	0-800	1670	1000-2500	
V	110	30-300	41	20-100	23	10-30	300
Y	1100	800-1500	30	0-60	87	20-200	300
Zn	125	0-568	432	0-1155	764	30-3430	300
P_2O_5	34.4	8.3-37.4	31.7	17.0-38.5	26.6	13.1-38.3	29.8

TABLE 7. P_2O_5(%) AND MINOR ELEMENT ANALYSES (PPM) OF MISCELLANEOUS DOLOMITES AND LATERITES FROM THE GEORGINA BASIN

	1 (a)	2 (a)	3 (a)	4 (a)	5 (a)	6 (a)	7 (a)
Ag	0.1	0.1	0.2	0.2	0.6	0.2	2
Ba	200	50	x	100	1000	600	1000
Cu	10	10	10	80	100	10	20
Co	5	5	10	100	20	5	x
Cr	50		30	30	100	600	80
K	200		150	500			800
Li	2	2	1	3	8	3	8
Mn	3000	600	2000	1000	500	300	30
Mo		x	x	10			
Ng	200		300	100			300
Ni	5	x	30	150	50	10	5
Pb	20	3	5	10	30	10	30
Rb	x	x	x	10	10		20
Sr	60	100	100	30	300	100	60
Ti	x	x	x	1500	1500	x	5000
V	10	x	10	200	50	x	10
Y	x	20	50	20	40	x	10
Zn	400	x	x	500	300	x	x
P_2O_5		1.2		2.0	1.0	1.2	0.2

1. QP2C2 Dolomite. Thorntonia Limestone, Hilary Creek.
2. QP106a6 Dolomite. Thorntonia Limestone, Quita Creek area.
3. QP106a7 Phosphatic(?) Dolomite. Thorntonia Limestone, Quita Creek area.
4. QP106a6 Ferricrete. Quita Creek area.
5. QP100a7 Ferricrete breccia. Quita Creek area.
6. QP100a9 Silcrete. Quita Creek area.
7. QP100a8 Silcrete breccia. Quita Creek area.

* (a) Analyses by semi-quantitative emission spectroscopy, Analytical Section of Australian Mineral Development Laboratories (A. B. Timms, Officer-in-Charge).

(b) Analyses by atomic absorption spectrophotometry, by H. R. Lord, BMR.

The cerium deficiency is considerably less marked in Figure 28 than in Figure 29 except, surprisingly, in the phosphatic silcrete (QP21A1), which shows a marked deficiency. The argillaceous phosphorite (QP3A3) on the other hand shows an appreciable enrichment in cerium, which may be attributable to its non-phosphatic lutaceous content or might indicate that the phosphate is of non-marine origin; this could be checked by separating out the apatite, and analysing the concentrate for lanthanides.

One can only conclude that the geochemical data available on the Georgina phosphorites are too few at present to allow firm conclusions to be drawn. It does appear, however, that the Georgina phosphorites have a low CO_2 content, and

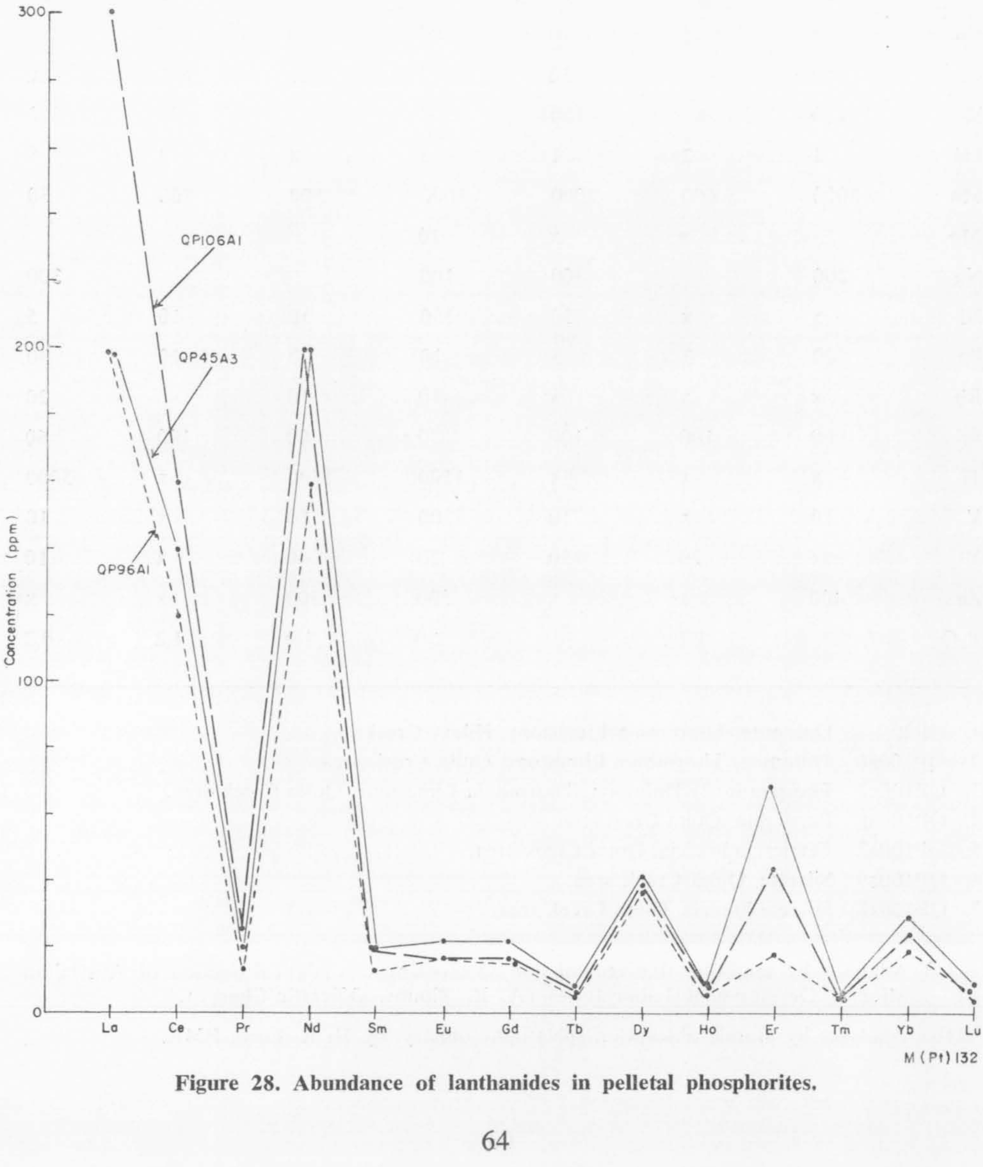

Figure 28. Abundance of lanthanides in pelletal phosphorites.

that their composition is rather similar to the Meade Peak phosphorites. There is a marked deficiency in a number of minor elements such as Ag, Cr, Cu, Ni, and V, which is probably attributable to the relative paucity of organic matter in the Georgina Basin. The comparative abundance of Mn in the Georgina phosphorites is thought to be a result of deep lateritic weathering.

There are some marked differences in minor element concentrations between the primary (pelletal) phosphorites and the secondary (phoscrete) phosphorites resulting from the remobilization of apatite.

DIAGENESIS IN THE PHOSPHORITES

Diagenesis in phosphorites has until recently received little attention, but it is now becoming apparent that a variety of post-depositional changes commonly take place in phosphate-rich rocks. Cook (1970) observed a six-stage diagenetic sequence in the Phosphoria Formation and suggested that most of the reactions were pH-dependent. Post-depositional changes have also occurred in the phosphorites of the Beetle Creek Formation. These include: (1) phosphatization of calcareous material (fossil fragments, lime mud) and possibly fine-grained terrigenous material; (ii) the silicification of carbonate and phosphate; (iii) the recrystallization of the carbonate cement; (iv) the calcitization of collophane; (v) fluoritization; (vi) the development of alunite and secondary phosphate minerals such as wavellite, variscite, meta-variscite, evansite(?), and crandallite.

Figure 29. Abundance of lanthanides in various phosphatic rocks.

Some of these replacements may in part be related to fault-zone mineralization, and accompanying submarine exhalative processes may have played a role. In the Mount Murray area, veinlets of wavellite, or more rarely variscite, cut through pelletal phosphorites; these veins are generally flanked by a zone of secondary silicification. Secondary aluminium phosphates may also appear as zoned crystals, which have evidently grown progressively outwards. Turquoise occurs in thin seams and joints apparently restricted to areas adjacent to faults. Similarly fluoritization and perhaps alunitization in both pseudomorphic and automorphic forms occur primarily in fault zones. Crandallite on the other hand appears to be fairly widespread, and is believed to be related to weathering processes in which crandallite is deposited as a secondary mineral immediately above the primary phosphorites. Similarly, under the right physicochemical conditions apatite (strictly carbonate fluorapatite) can become comparatively mobile, replacing calcite, dolomite, and chert, and forming a zone of secondary enrichment within the soil profile; this process has already been mentioned in the discussion on secondary phosphorites. Secondary apatite crystals also precipitate in voids within some rocks.

In addition to this comparatively late-stage phosphatization, there was also a diagenetic phosphatization stage occurring very soon after deposition, primarily involving replacement of calcite (mainly of biogenic origin). Examination of thin sections reveals phosphate pellets containing calcareous fossil fragments (especially echinoderm fragments) in various stages of phosphatization (Pl. 24, figs 1, 2; Pl. 25, figs 1, 2; Pl. 26, fig. 1). Fine-grained calcareous and siliceous muds may have also been phosphatized in places. A great deal of controversy revolves around the relative importance of this early phosphatization, and this question is considered in more detail later.

Recrystallization of carbonates and also calcitization of phosphorites and associated sediments probably occurred at various stages in the history of the sediments. Diagenetic textures developed in the carbonates include grain-growth mosaic, syntaxial overgrowth, drusy textures in cavities, caries textures, and pseudomorphic and automorphic replacement. Dolomitization, generally in the form of well developed dolomite rhombs, is also common in many places, particularly in the massive biohermal carbonates.

Silicification was probably also a multi-stage diagenetic process. In places, silica partly replaces phoscrete believed to be of Cainozoic origin. Conversely, silicification was probably also a very early diagenetic process, possibly taking place in part before lithification. The silica may have the form of coarsely crystallized quartz such as in veins or as hexagonal crystals (Pl. 26, fig. 2). More commonly, it occurs as chalcedony or chert; these forms in places show pseudomorphic replacement (Pl. 27, figs 1, 2), but commonly have a spherulitic form which completely destroys any pre-existing textures.

Some controversy over diagenetic processes has centred on the interpretation placed on nodules of calcareous phosphorite (containing about 7 percent P_2O_5) which occur in a bed of siliceous phosphorite (containing 20 to 21 percent P_2O_5) in the Mount Murray area (Pl. 28). The situation is shown schematically in Figure 30. A number of features are shown by these structures: bedding and cross-laminations are much more clearly visible in the limestone bodies than in the cherty rock; separate bedding planes in adjoining nodules can be correlated; bedding planes wrap around the limestone nodules. In some nodules the bedding may be inclined to that in the surrounding cherty bed; carbonate laminae a few millimetres thick, free of pellets in the limestone nodules, usually correspond to thinner chert laminae in the siliceous bed (Fig. 31), except at the lower and upper edge of the nodules, where the deflection of the wrap-around bedding planes in the cherty bed becomes so strong that the continuity is disrupted. Collophane pellets in the limestone bodies are commonly marginally replaced by calcite, whereas in the cherty bed the pellets appear to be relatively unaffected. Thin zones of collophane pellets in the cherty rock are replaced by a moderately birefringent, optically positive, secondary calcium phosphate mineral, whereas no such replacement has been observed in the limestone bodies.

The two authors differ in their interpretation of the observed facts concerning the origin of the nodules, and as this matter has important implications on the diagenetic history of the deposits as a whole, the argument is set out in some detail below.

One explanation which has been put forward is that the nodules were formed elsewhere by unspecified processes in shallow water, and then they rolled down the slope, coming to rest in the siliceous phosphorites. This rather unlikely mechanism is rejected because of the continuity shown by laminae in the nodules with laminae in the enclosing rock.

The more likely alternative is that the nodules are autochthonous, but whereas de Keyser believes that the nodules represent the remnants of an originally calcareous bed, which has now been silicified, Cook considers that the nodules result from calcitization of the siliceous phosphorite.

The main points at issue are the following:

De Keyser suggests that the partial solution of calcite during silicification results in a volume decrease of the matrix which effectively upgrades the phos-

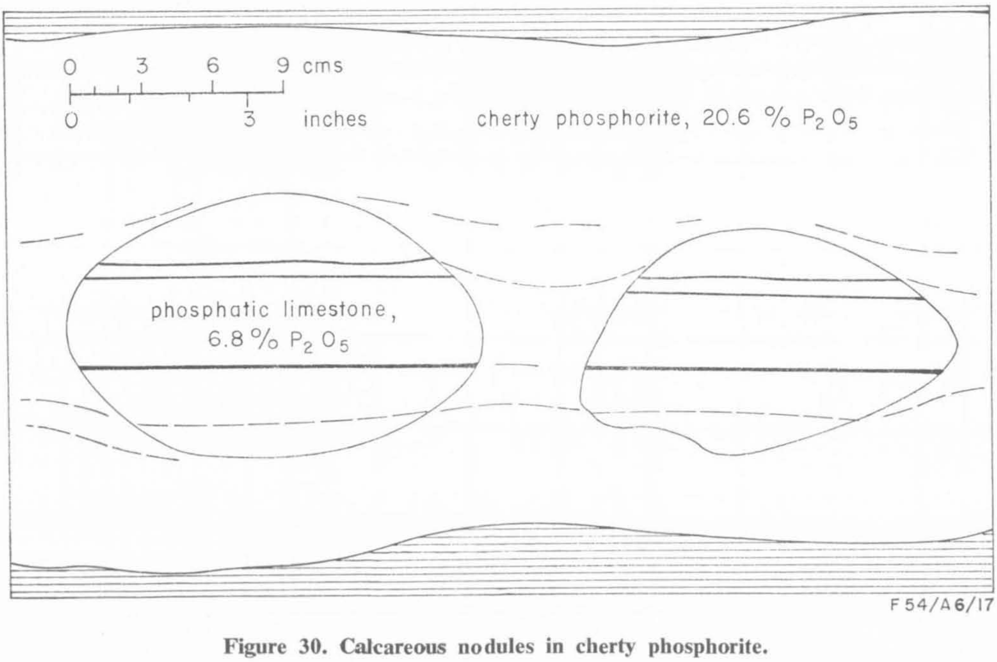

Figure 30. Calcareous nodules in cherty phosphorite.

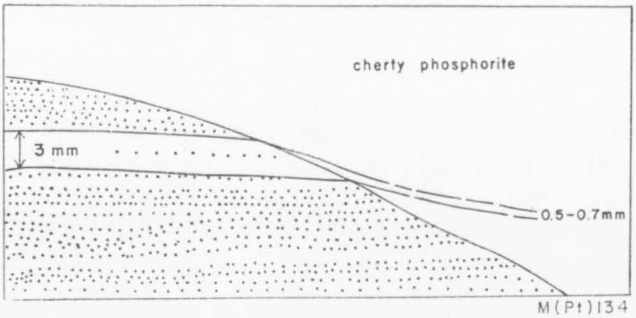

Figure 31. Detail of Plate 28 showing decrease in thickness of pellet-free laminae at transition from limestone to chert.

phorite from about 7 percent P_2O_5, in the original nodules, to 21 percent P_2O_5 in the surrounding siliceous phosphorite. This is supported by the observed difference in thickness of the pellet-free laminae in the nodules and their matching counterparts in the enclosing rock, which is of the order of 4 to 6 times (Fig. 31). A change in volume is also suggested by the deflection and wrapping around of the bedding planes in the siliceous phosphorite around the nodules. Cook, however, points out that the replacement of calcite by silica would result in a decrease in volume of only 5 percent, 60 times less than that required to upgrade the calcareous phosphorite from 7 percent P_2O_5 to a siliceous phosphorite containing 21 percent P_2O_5 (an upgrading of 300 percent). He suggests, on the other hand, that down-grading of a siliceous phosphorite to a calcareous phosphorite by calcitization of pelletal material is easily achieved.

De Keyser states that bedding structures are more prominent in the nodules, both in outcrop and in thin section and in both fresh and weathered rock, and that a replacement process involving calcitization could not accentuate bedding. Cook, however, believes that bedding is made more prominent by calcitization owing to the fact that calcite weathers more easily than chert. He considers that the fresh material cited by de Keyser has, in fact, suffered some weathering.

Fossils are more prominent in the calcareous nodules and de Keyser claims that this prominence is a true reflection of their greater abundance; it is unlikely that calcitization could result in an increase in the number of fossils. Cook, on the other hand, claims that their greater abundance in the nodules is apparent rather than real, and that their prominence, which is not disputed, is brought about by calcitization and subsequent weathering. He also suggests, if fossils are in fact more abundant in the nodules, that calcitization could possibly have occurred preferentially where calcareous fossils were slightly more plentiful. On this point de Keyser claims that such preferential calcitization would be more likely to occur in a stratiform rather than a nodular form. De Keyser also doubts whether a process involving the silicification of calcareous fossils, followed by calcitization, could restore the perfect form of the fossils observed in the nodules.

Marginal replacement of phosphate pellets by calcite within the nodules has undoubtedly occurred, and Cook cites this as clear evidence in support of formation of the nodules by calcitization. De Keyser, however, claims that identical marginal replacement occurs in all the primary carbonate beds, and suggests that this is a late-stage process, which is inevitably less pronounced in previously silicified rocks.

In summary, it must be admitted that there are arguments supporting both hypotheses, and that resolution of the problem must await a more detailed field, textural, and mineralogical examination than it has been possible to carry out in the present study.

Comparison of the Georgina Basin Phosphorites with Other Phosphate Deposits

Although no two phosphate deposits are exactly the same, common features in various deposits can be recognized. A number of classification schemes have been suggested; at the 1967 ECAFE conference in Bangkok, the USSR delegation suggested the classification:

1. Geosyncline
   (a) Miogeosyncline
   (b) Eugeosyncline
2. Platform
3. Foredeep

The Georgina phosphorites would fall into the miogeosynclinal type in such a classification. Some of the criteria listed by the Soviet delegation for this type include 'evidence of diagenetic regeneration and mechanical reworking', 'bedded oolitic grained phosphorite', 'widespread phosphorus-bearing series of carbonate-siliceous rocks (700-120 km) of great thickness (75-120 m)', and 'the thickness of productive strata runs into tens of metres'. The miogeosynclinal group includes such phosphorites as the Phosphoria Formation and the Karatau deposits. Superficially, there are some similarities between the Georgina Basin phosphorites and the Phosphoria Formation; in particular, the abundance of bedded cherts in both units and the pelletal form of the phosphate. The differences are, however, equally significant; the facies relationships (and the inferred depositional environments) of the two deposits appear to be completely unlike each other, and the mode of formation of the phosphorites was rather different. There are, however, some interesting similarities with the Karatau phosphorites of the USSR (Bushinski, 1969), in particular the fact that both are Cambrian; there is some doubt whether the Karatau phosphorites are Middle or Lower Cambrian, but the former seems to be the most generally accepted age. There are some surprising similarities in the associated sediments. In the Karatau area tillites (cf. the Mount Birnie Beds) and volcanics (cf. the Colless Volcanics) underlie the sequence in places; the phosphorites are also underlain by a Cambrian dolomite (cf. the Thorntonia Limestone and Camooweal Dolomite). The phosphorites are predominantly pelletal and generally have a siliceous or calcareous cement. Smirnov & Tushina (1960) observed that in places the phosphorites have been dissolved and redeposited as thinly bedded manganiferous and brecciated phosphate (cf. phoscrete). All these similarities can be taken as purely coincidental. An alternative hypothesis is that there was a Cambrian Austral-Asiatic phosphogenic province. This might seem extremely unlikely, but it should be remembered that the Cambrian faunas of Australia and parts of mainland Asia are rather similar. Öpik (1966, p. 14) stated that 'Multiprovincial Middle and Upper Cambrian faunas of Australia and Siberia are evidence of open seaways and commingling of faunas'. In addition phosphogenic provinces of great lateral extent are known from other epochs; the Upper Cretaceous-Eocene Tethyan phosphogenic province, for instance, had a lateral extent of at least 6000 km.

Turning to other phosphorites, some comparisons may be drawn between the Georgina Basin phosphorites and the so-called east-coast type phosphorites of the United States. The Tennessee brown rock phosphorite deposits, which are Ordovician in age, are described by Collette (1968) as being 'marine in origin and residual in occurrence'. They are associated with the Bigsby Formation, and lie on the flanks of a regional anticline. They were deposited in shallow seas as calcareous pelletal phosphorites or phosphatic limestones. Subsequent weathering of the limestone has left a residual concentration of phosphorite on the karst surfaces overlain by phosphorite in the vicinity of Colombia, Tennessee, which are very similar in the phosphatic karst surfaces in the Hilary Creek area of the Georgina Basin. There is, however, no evidence to suggest that the Georgina phosphorites are a residual deposit, although, locally, weathering of slightly phosphatic Thorntonia Limestone may have resulted in thin phosphorites. The so-called white-rock of Tennessee is a secondary phosphorite, which occurs as an irregular near-surface deposit. It is believed to have formed within a tropical or subtropical soil profile, and both in appearance and genesis it is comparable with Georgina Basin phoscrete.

The phosphorites of the Hawthorn and Bone Valley Formations (Cainozoic) of Florida have some similarities with the Georgina phosphorites; they are believed to have formed on very shallow marine banks, or in bays, estuaries, or lagoons (Freas, 1968). There are abundant fossils and abraded fossil fragments, and facies changes are numerous. In the land-pebble deposits, coarse pelletal phosphorites tend to accumulate on submarine ridges, and the finer particles (which have been removed from the ridges by winnowing) are concentrated in the depressions. The North Florida deposits are found in basins on the flanks of anticlines, which were rising as deposition occurred (Cathcart, 1968). Similarly the Israeli phosphate deposits are found in synclines, which formed Cretaceous-Eocene valleys. This is in direct contrast to the Georgina phosphorites, which are believed to be concentrated on ridges, although the evidence for this is by no means conclusive. Russell & Trueman (1972) present evidence from the Duchess deposit which clearly indicates that a close relationship existed in the Georgina Basin between phosphate deposition and basinal topography. No single phosphate deposit, however, bears a close resemblance to Georgina Basin Phosphorites. There are similarities with Karatau phosphorites, and it is interesting to speculate on the possibility of a Cambrian Austral-Asiatic phosphogenic province. There are also a number of common features shown by the Georgina, the Tethyan and the so-called east-coast phosphorites.

Genesis of the Phosphorites

Whether the phosphate was a primary precipitate or an early diagenetic form is a question common to all phosphorite deposits.

As mentioned previously, the so-called phoscrete probably has a completely distinct origin from the more usual phosphorites. It is believed to be a weathering product resulting from the remobilization of apatite in the groundwater and subsequent reprecipitation in the weathering profile. In some cases limestone was also replaced by the apatite-rich groundwater. The phoscretes are thought to be primarily a Cainozoic phenomenon, but there are also examples of probable Cambrian age, which presumably formed at times of subaerial exposure of the phosphorites.

Much of the phosphatic material gives no clue to its genesis, for it occurs as ovules showing no internal structure or as a fine-grained groundmass. Such structureless material could be precisely what one would expect of a primary precipitate of cryptocrystalline apatite; nevertheless, this only constitutes rather weak negative evidence for such a theory. There is, on the other hand, abundant evidence of phosphatization of biogenic calcareous material, in particular echinoderm fragments. Many examples were observed of skeletal fossil fragments ranging in mineralogy from almost wholly calcareous to almost wholly phosphatic, with the amount of recognizable skeletal structure decreasing as the degree of phosphatization increases. It is a small step to postulate that all structureless ovules were formed in the same way, with every trace of the original skeletal material lost owing to the intensity of phosphatization. Similarly the phospholutite and the argillaceous phosphorite could have originally been calcilutite and argillaceous (or sandy) limestone respectively. D'Anglejan (1967) considers that such processes were important in the formation of the Cainozoic Baja California phosphorites.

There is, however, some evidence of primary precipitation of phosphate, for unphosphatized fossil fragments commonly show infillings of fine collophane, which is identical in appearance with thin laminae and lenses which occur in the sediments. This collophane is in some instances completely surrounded by non-phosphatic calcite. Cook believes that it is most unlikely that a diagenetic hypothesis is tenable for such material; de Keyser suggests that the parent material may have been lime mud, which was preferentially phosphatized because of its fine grainsize. The fine collophane could possibly be the result of direct biogenic precipitation; it contains abundant fine brown inclusions perhaps resulting from the decay and decomposition of organic (algal) matter, which locally created the right pH conditions for precipitation of phosphate.

If this process could happen on a small scale, then why not on a larger scale? Cook suggests that the possibility of direct precipitation of phosphate cannot be ignored for those phosphorites completely lacking any evidence of calcite parent material. Some of the pelletal phosphorites might fall into this category. A number of the argillaceous phosphorites do; for these, there is the alternative hypothesis that they were formed by the phosphatization of non-calcareous muds. This is believed to be an important process in a number of other phosphorites (Bushinski, 1964; Cook, 1968), and may conceivably have been important in the northeastern corner of the Georgina Basin, where argillaceous phosphorites are so abundant. Any such phosphatization would have occurred immediately below the sediment-water interface within the 'ooze', where favourable local physicochemical conditions were set up.

So far, the question of the formation of the pellets has not been considered. Emigh (1958, 1967) believes that all phosphorites form by the phosphatization of calcareous deposits analogous to the Bahamian oolites, and that the phosphatic ooliths are pseudomorphs after calcareous ooliths. There are some problems posed by this hypothesis, one being that phosphorites are not, in general, geographically closely related to such carbonate deposits, although this may not be true of the Georgina Basin. Other difficulties include the significant difference in size between calcareous ooliths and the smaller phosphatic pellets, the absence of a calcitic core (apart from biogenic fragments), and the scarcity of phosphatic ooliths with well developed concentric banding compared with their abundance in calcareous deposits. In the Georgina Basin phosphorite there is no doubt that many of the pellets result from the attrition of biogenic fragments, particularly echinoid, or less commonly brachiopod shells. All stages from the completely unmodified angular fragment to the highly abraded pellet may be found. Many of these pellets were then phosphatized. There is evidence from the presence of compound pellets, i.e., pellets composed of two or smaller pellets, that there was later cementation and further rounding. Owing to a slow rate of deposition, material was probably being constantly reworked and further abraded, possibly as phosphatization proceeded.

In conclusion it seems there is little doubt that many of the pelletal phosphorites formed as a result of the abrasion and later phosphatization of calcareous biogenic (particularly echinoid) fragments. Phosphatization of calcilutites, or non-calcareous lutaceous material, may also have been important in the formation of the argillaceous phosphorites and phospholutites. Phoscretes, whether Cambrian or Cainozoic in age, are believed to have formed by the mobilization and subsequent precipitation (or replacement in some instances) of apatite. In addition, Cook believes that some of the fine-grained collophane, such as that filling fossils, is most probably a primary precipitate. This still leaves a great deal of phosphatic material, such as the pelletal material lacking any internal structure, the origin of which is unknown. Undoubtedly the Georgina Basin phosphorites have a rather complex history, including possibly both primary precipitation and secondary replacement of calcareous (and probably also siliceous) material. Overall, it would seem that the phosphatization of rounded biogenic calcareous fragments was the most important single mechanism.

Source of the Phosphate

Whether the phosphates of the Georgina Basin formed as a primary precipitate or as a result of early diagenesis, abnormally large amounts of phosphate were undoubtedly available. A further indication of abundant nutrients comes from the extremely rich fauna of the Beetle Creek Formation and the development of bedded spicular cherts. The possible sources of the phosphate are volcanoes, rivers, the biota, or upwelling ocean waters.

Mansfield (1940), Bidaut (1953), and Rooney & Kerr (1967) have all suggested that volcanism may be an important source of phosphate. Brodskaya (pers. comm.) in particular has pointed out the number of phosphatic sequences which are underlain by volcanics. In this respect, the Beetle Creek Formation is no exception, as it is underlain (in some places directly, elsewhere with the Thorntonia Limestone intervening) by the Colless Volcanics, or in the Northern Territory by the Peaker Piker Volcanics. In addition the effects of this volcanism may have continued into the early Middle Cambrian as submarine fumarolic activity along fault-lines. Mineralization in the vicinity of the faults suggests some hydrothermal activity, but such exhalative effects are likely to have only locally influenced the precipitation of phosphate. The volcanics are rather more widespread and are particularly well developed in the northeastern and extreme western portions of the basin. Most of the major phosphorite deposits are, however, found where the volcanics are absent. In addition it is unlikely that the vast tonnages of phosphate present in the Georgina Basin could be produced by the relatively minor amount of volcanic activity required for the 20 to 60 m of basalts represented by the Colless

Volcanics. Therefore, volcanism is not considered to be the major source of the phosphate.

A biogenic source for phosphate has been suggested by Murray & Renard (1891), Blackwelder (1916), and Mansfield (1918), who considered that mass mortalities of organisms produced saturation of seawater with phosphate, ultimately leading to the formation of phosphate pellets. The Beetle Creek Formation as a whole is extremely fossiliferous, and fossil fragments are also common particularly in the phosphorites. This suggests that the biota might have played some role in the precipitation of phosphate. However, there is no evidence that the amount of phosphate increases as fossils become more abundant, because some highly fossiliferous beds contain only very minor phosphate, and vice-versa. Consequently, abundance of fossils alone is not proof of a biogenic origin for the phosphate; in addition, abundance of fossils is largely dependent on abundant nutrients, so that the problem of the source of the phosphate nutrient still remains.

Upwelling of oceanic water was first suggested as a major source of phosphate by Kazakov (1938) and was subsequently applied to many phosphate deposits (e.g. the Phosphoria Formation: McKelvey et al., 1953). There are, however, some difficulties in the application of this concept to the Georgina Basin, in particular the strong evidence that the sediments were deposited in very shallow water. It is difficult to imagine how upwelling could occur in, or perhaps penetrate, a region of very shallow water. In addition, the probable palaeogeography indicates comparatively restricted areas of phosphate deposition, again posing a problem to the upwelling hypothesis.

It is for reasons such as these that a number of authors, notably Bushinski (1964) and Pevear (1965), have rejected an upwelling origin for phosphorites and postulate instead an estuarine origin. Pevear applies his ideas to Cainozoic phosphates on the east coast of the United States and Bushinski to the Phosphoria Formation. Undoubtedly rivers carry large quantities of phosphate in solution and features such as algal blooms, abundant nutrients, and rich faunas are commonly found in estuaries. However, there is also a considerable amount of terrigenous sedimentation in most estuaries, which tends to mask any phosphate deposition. Consequently abnormal estuarine conditions involving an abundant supply of fresh nutrient-bearing waters, but almost no sediment, must be postulated. It is difficult to imagine an estuarine environment fulfilling those conditions, so it seems that here also there is no completely satisfactory explanation.

In conclusion, none of the four potential sources of phosphate mentioned can be dismissed as impossible, nor is any entirely acceptable on its own. The volcanic source is regarded as probably the least important. There was undoubtedly a flourishing biota, but this might have been a result of the abundance of phosphate rather than its cause. The two remaining hypotheses have points both for and against them. Oceanic upwelling seems an unlikely mechanism, but there may have been shallow localized upwelling, influenced by perhaps a topographic high standing in the path of a current. This would seem the most likely mechanism for the Wonarah-Alexandria phosphorites of the Northern Territory, which are located on a basement high (Howard, 1971).

De Keyser favours an estuarine origin for the majority of the Georgina phosphate, whereas Cook believes that estuaries and localized dynamic upwelling may both have been important.

Depositional Environment

The depositional environment of the chert-siltstone-limestone-phosphorite lithosome as a whole has been discussed earlier. It was concluded that deposition occurred in shallow marine or paralic environments, and lagoonal, estuarine, littoral, and sub-littoral environments were specifically mentioned. Moreover, it is probable that the phosphorites formed in particular sedimentary environments. Let us briefly examine what is known about the depositional conditions for other phosphorites. They are known to form primarily between latitudes 40°N and 40°S. A pH of 7.1 to 7.8 is believed to be necessary (Krumbein & Garrels, 1952), but the Eh is not critical and may range from positive to negative without affecting the precipitation of phosphate. Deposits are predominantly, though not exclusively, laid down under marine conditions and are commonly associated with cherts. The water must be fairly shallow, but there is no concensus as to the exact depth limitations. In addition, there must be a higher-than-average concentration of phosphate, though how much higher is uncertain.

In general the Georgina Basin phosphorites seem to conform with these rather broad limits. It is possible to be more specific by looking closely at the phosphorites. Features such as cut-and-fill structures and cross-laminations are common in the pelletal phosphorites. The fossil fragments are abraded and well rounded. In addition, the resultant pelletal units are well sorted, and there is little or no fine material in many beds; this suggests winnowing action. All these features are consistent with shallow water accompanied by moderately vigorous current and wave action. The sediment was probably constantly reworked, as indicated by the presence of some compound pellets. The rate of deposition of terrigenous sediments must have been very slow, and at times probably ceased altogether, so that the sequence is condensed with numerous diastems. Therefore it is necessary to suggest an environment largely cut off from any major source of terrigenous sedimentation. Such an area might have an arid peneplaned hinterland, or alternatively be cut off from the source of sedimentation by, for instance, a barrier bar. The area cannot, however, be cut off from the source of nutrient, so any barrier must not be subaerial. An alternative suggestion is that the area was surrounded by a trough, which acted as a sediment trap. One possible way in which the phosphorites might have formed is that material from shallow carbonate banks is swept down as abraded pelletal carbonate debris into the surrounding slightly deeper water, which was colder and contained a higher concentration of phosphate. Under such conditions the phosphatization of the pelletal biogenic material would have taken place rather rapidly. Where only fine material was winnowed from the banks, then only argillaceous phosphorite would be formed in the troughs. Such a mechanism would result in the major phosphate deposits occurring in troughs. One cannot exclude the possibility that, for instance, the Ardmore and Lady Annie Outliers were troughs, with the Middle Cambrian seas extending over the basement. However, in some areas subsurface information suggests that the phosphorites are concentrated over Middle Cambrian rises. Further investigation of this point is necessary, as it is of considerable importance in understanding the depositional environment of the phosphorites, and has a direct bearing on future exploration programs.

The Mount Murray area was possibly a carbonate bank composed primarily of biogenic carbonate, which ultimately formed a biopelsparite, elevated above wave base (Fig. 32). It was influenced by phosphate-bearing waters, by which the

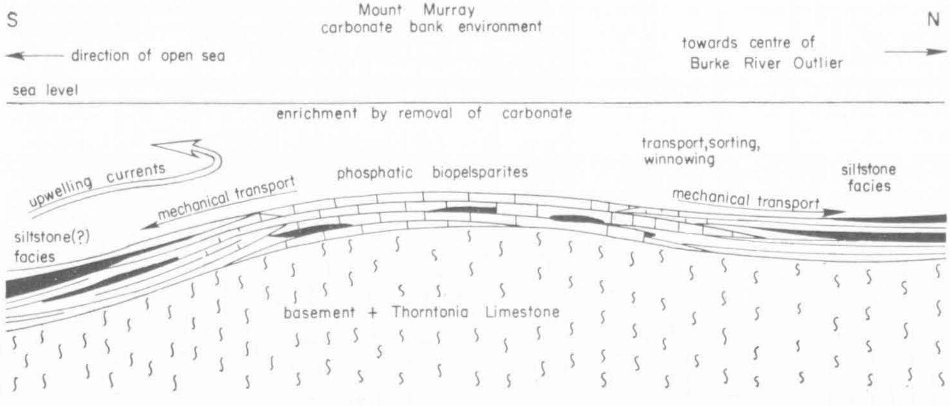

Figure 32. Possible mechanism for the development of phosphorites in the vicinity of Mount Murray.

calcitic material was phosphatized. Whether the phosphate came from upwelling of deep oceanic water or from localized upwelling is uncertain, although the latter possibility is preferred. Winnowing of fine material upgraded the phosphorites further; de Keyser also feels that partial solution during the later silicification of the matrix upgraded the deposits, but Cook disagrees.

Studies by Broken Hill South Ltd have shown that the facies distribution at the time of phosphate deposition was probably as follows: a silty to sandy facies close to the old shorelines, siliceous phosphorites on the more elevated parts of the shelf and on the crests of submarine banks, and the limestone lithosome in the troughs. The 'trough limestones' are represented by the dark, micritic, fetid limestones, and the coarser-grained biopelsparites probably formed on the more aerated elevated shelf areas and the crests of banks. It is notable that the richest phosphorites in the Duchess district are the siliceous phosphorites; Cook suggests that this may possibly result from upwelling producing 'blooms' of siliceous organisms with an associated abundance of phosphate. De Keyser on the other hand feels that the association of the richest phosphorites with the siliceous units results from upgrading of the phosphorites by the silicification.

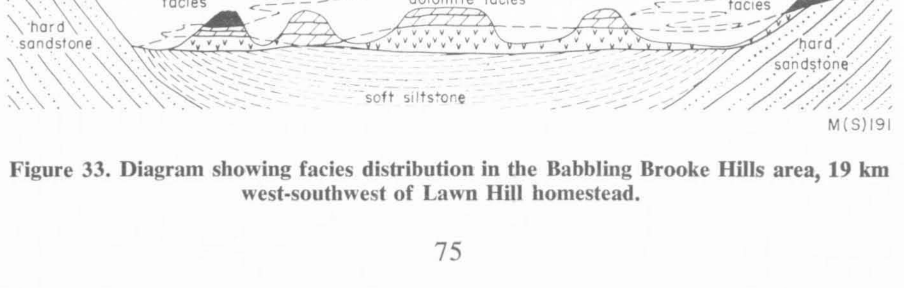

Figure 33. Diagram showing facies distribution in the Babbling Brooke Hills area, 19 km west-southwest of Lawn Hill homestead.

In the Northern Territory, the phosphate is found over basement highs; similarly the phosphate is also concentrated around the margin of the Precambrian basement complex. This is illustrated by the facies distribution in the Lawn Hill area (Fig. 33), where the phosphatic part of the sequence occurs immediately adjacent to the basement. Therefore in most areas there is apparently a near-shore sequence of the phosphorites and associated sediments grading seaward into limestones and dolomites. In places in the Northern Territory, there is a suggestion of a red-bed facies beyond the carbonates. Such a facies distribution is present in the Phosphoria Formation and might conceivably also be present in the Georgina Basin, representing a shallowing sequence once again.

As mentioned earlier, in the Queensland portion of the Georgina Basin the phosphorites of the south are primarily pelletal, whereas those of the north, with the exception of Lady Annie, are predominantly the very fine-grained non-pelletal varieties. Environmental changes were probably a significant factor in controlling this distribution. The abundance of phosphorite composed of abraded biogenic material, together with cross-beds and scour structures, suggests more vigorous conditions in the south, perhaps corresponding to a fairly open shelf-type environment. In addition the environment was evidently very shallow; it was certainly above wave base, and from the abundance of probable benthonic fossils, was aerobic. The lack of terrigenous detritus, despite the fact that the phosphate deposits were laid down near to the shoreline, indicates that there was some form of sediment trap such as a barrier island, a subaqueous bar, or a marginal trough, which at times prevented terrigenous sediments reaching much of the shelf.

In the north, the phosphorites are finer grained and non-pelletal, and current structures are absent; this suggests a rather less vigorous environment. There are also in this area a number of possible Cambrian phoscrete horizons, formed presumably as a result of penecontemporaneous weathering and implying very shallow water, with at times subaerial exposure. The northern phosphorites also contain more detrital (predominantly quartzose) silt grains than do the pelletal phosphorites, suggesting that the northern area was not cut off from all terrigenous sedimentation. All these considerations suggest somewhat variable depositional environments; estuaries, bays, and lagoons are all possible sites of deposition. The estuarine environment, in particular, would seem a favourable site for the formation of phosphorites, for not only would the rivers carry down the fine detrital material, but in addition they would have been capable of supplying abundant nutrients.

In conclusion, the Georgina Basin phosphorites were not deposited in one environment, but in a number of coalescing shallow marine or paralic areas including bays, lagoons, estuaries, and shallow submarine banks. Everywhere the water was shallow, probably considerably shallower than 100 m in many areas. The water was particularly turbulent in the south, but tranquil in the north.

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