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THE GEOLOGY OF THE CARNARVON BASIN, WESTERN AUSTRALIA

Part 3

Post-Permian Stratigraphy; Structure; Economic Geology

by

M.A. Condon

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Preface

The report on the Geology of the Carnarvon Basin is issued in three separate Parts. Each Part treats a section of the subject and is accompanied by a Summary and an appropriate list of references.

Part 1 (published 1965) deals with the pre-Permian stratigraphy and also includes a General Summary and introductory information. Part 2 (published 1967) deals with the Permian stratigraphy, and Part 3 gives the post-Permian stratigraphy and describes the structure and economic geology.

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CARNARVON BULLETIN PART 3

TEXT FIGURES

Text Figures No. 144 - 162 have been omitted from the hardcopy of 1967/124.

SUMMARY

A period of uplift and erosion followed the Permian regression. Triassic sediments were deposited only in a small area and Jurassic in a slightly larger area in the north-west of the basin and in a small area in the south. The next main sedimentation occurred in the Lower Cretaceous, when a major transgression occurred and a basal sandstone and mainly fine-grained terrigenous and organic sediments were deposited. These were followed after a small hiatus by mainly carbonate sediments of Upper Cretaceous and Tertiary age.

The Carnarvon Basin is a compound basin. It is divided meridionally by a basement ridge (mainly subsurface) and on either side of this ridge are several smaller basins that developed at different times from late Precambrian to Cretaceous. The main structural style results from the basin downwarps rather than from major tangential compression.

The basin is regarded as having a good potential for petroleum - the Barrow Island oil and gas field is at its northern end.

The underground water potential is outlined and an indication given of the occurrence of barite, bauxite, bentonite, clays, glauconite, gypsum, limestone, and radiolarite.

TABLE I: MESOZOIC AND CAINOZOIC STRATIGRAPHY

AGE	GROUP	FORMATION	THICKNESS (feet)	FOSSILS
QUATERNARY			to 300	Forams, Mollusca, Corals
MIOCENE	CAPE RANGE GROUP	Pilgramunna Formation	70 to 100	Forams, Mollusca, Corals calcareous algae, echinoids
		Trealla Limestone	to 200	
		Tulki Limestone	to 430	
		Mandu Calcarenite	to 350	
		Lamont Sandstone	to 30	Forams
EOCENE		Giralia Calcarenite	to 225	Forams, bryozoa, echinoids brachiopods, mollusca
		Merlinleigh Sandstone	to 50	Mollusca, corals, forams wood
		Pindilya Formation	to 90	
EOCENE-PALAEOCENE	CARDABIA GROUP	Jubilee Calcarenite Cashin Calcarenite Pirie Calcarenite Wadera Calcarenite Boongerooda Greensand	to 400	Forams, bryozoa, echinoids brachiopods, mollusca corals.
UPPER CRETACEOUS		Miria Marl Korojon Calcarenite Toolonga Calcilutite	to 895	Forams, echinoids, ammonites, mollusca, crinoids.
LOWER CRETACEOUS		Alinga Greensand	20 to 50	Forams, radiolaria, belemnites
	WINNING GROUP	Gearle Siltstone	to 1922	Forams, radiolaria, belemnites, pelecypods Ammonites, wood
		Windalia Radiolarite	to 425	
		Muderong Shale	to 705	
		Birdrong Formation	to 388	
		Un-named formation in Barrow No. 1 Well	2507	
CRETACEOUS AND/OR JURASSIC		Nanutarra Beds	81	Pelecypods, plants
		Yarraloola Beds		Leaves
		Wittecarra Beds	122	Leaves
JURASSIC		Learmonth Beds	2210	Ammonite, belemnite, brachiopod, mollusca
		Dingo Claystone	11,313	Mollusca, forams, ammonites, belemnites
		Woodleigh Beds	to 298	Spores & pollens
TRIASSIC		Un-named sequence in Learmonth No. 2 Well	432	

MESOZOIC

One of the main sedimentary, tectonic, and erosional breaks in the Carnarvon Basin sequence followed the regression at the end of Permian sedimentation. The basin was uplifted, the sediments were folded and faulted, and dissection by erosion set in, and continued through the Triassic and into the Jurassic.

Triassic sediments are known only in the Exmouth Basin, where they were found in WAPET's Learmonth No. 2 Well from 5705 feet to Total Depth 6137 feet (WAPET, 1964).

Lower Jurassic sediments were deposited in the southern part of the Gascoyne Basin, Middle and Upper Jurassic in the Exmouth Basin, and Upper Jurassic in the Onslow Basin. Lower Cretaceous sediments cover the Gascoyne, Exmouth and Onslow Basins and Upper Cretaceous the western part of the Gascoyne Basin and the Exmouth and Onslow Basins (Table 1 and Fig. 144).

JURASSIC

Woodleigh Beds

The Woodleigh Beds (McWhae, Playford, Lindner, Glenister, & Balme, 1958, p. 142) consist of soft grey pyritic shale with spores and pollens of Lower Jurassic affinities. They are known only in water bores on Woodleigh Station about 200 miles south-east of Carnarvon and seem most likely to be a restricted lake deposit, since there is no evidence of their presence in outcrop nor in water bores elsewhere in the basin.

In the Woodleigh bores, the Woodleigh Beds are overlain by Lower Cretaceous Birdrong Formation, but the base was not reached. The greatest thickness drilled was 298 feet.

The Woodleigh Beds have microfloral affinities with the Cockleshell Gully Formation of the Perth Basin and may tentatively be correlated with that unit; it is also possible that they are equivalent in age to the lower part of the Dingo Claystone.

Dingo Claystone

The Dingo Claystone (McWhae et al., 1958, p. 90) consists of dark grey micaceous silty claystone unconformably underlying the Lower Cretaceous Birdrong Formation or Muderong Shale in the subsurface of the Cape Range area. Its base has not been reached except perhaps in WAPET's Cape Range No. 2 Bore, where the lithology of the lowermost 150 feet is silty greywacke. As this is thick enough to indicate a different formation the thickness of the Dingo Claystone in Cape Range No. 2 Bore is 11,313 feet.

All or part of the Dingo Claystone is laterally equivalent to and probably grades into the Learmonth Beds.

The Dingo Claystone contains a marine fauna of uncertain age affinities, including elements that appear to give contradictory indications. The general consensus of opinion now gives the age of the formation as Middle to Upper Jurassic, but the lower 3000 feet, in which no fossils have been found, may extend into the Lower Jurassic, and the upper part may extend into the Lower Cretaceous.

The Dingo Claystone is of strikingly uniform lithology over a very great thickness but is remarkably close, geographically, to a quite different and much thinner equivalent sequence. The meagre evidence suggests that the two facies are separated by a mobile hinge, the 'Learmonth Hinge', active during the Jurassic but not thereafter. On the landward side sands and silts were deposited in a shallow marine environment, while on the seaward side, clay was deposited in a sinking basin or graben. The total sediment supply must have been predominantly clay and silt and therefore was probably derived from a mature land surface and transported by a sluggish drainage. In many respects the environment of deposition is similar to that of the Triassic Kockatea Shale of the northern Perth Basin.

Traces of hydrocarbon were reported from much of the Dingo Claystone and it seems likely that this should be a large source formation for petroleum and that drainage into the sands of the Learmonth and Birdong Formations must have occurred. Whether pools, either structural or stratigraphic, can be found in these remains to be seen. The oil found in the Cretaceous Birdrong Formation in WAPET's Rough Range No. 1 Well may have migrated from the Dingo Claystone.

Learmonth Beds

The name 'Learmonth Formation' was proposed by McWhae et al (1958, p. 81) for a sequence of silty micaceous sandstone, kaolinitic sandstone, conglomerate, siltstone, and carbonaceous shale, unconformable on the Permian and overlain probably disconformably by the Birdrong Formation. It is probably laterally equivalent to and may grade laterally into the Dingo Claystone. It is known only in the subsurface of the Rough Range and Learmonth areas.

The 'Learmonth Formation' at present is not a valid stratigraphic rock unit, since it has been intersected in only one bore and possibly in another. I suggest, therefore, that for the present the sequence be called 'Learmonth Beds' until it can be adequately established as a significant rock body.

The 'type section' is in the Rough Range No. 1 Well between depths of 3990 and 6200 feet; but as samples from this interval are not available in a public depository and no log of the interval has been published, this is not a valid type section.

The thickness (or rather the depth interval, since no indication is given of dip) is 2210 feet. Although Rough Range No. 10 was described before drilling as a test of the Jurassic its total depth of 3750 feet indicates that it did not enter the Learmonth Beds.

The Learmonth includes beds with marine fossils and beds of strongly carbonaceous shale; it appears to have been deposited in a paralic environment.

A few similarities of fauna suggest a correlation with the Dingo Claystone.

The sandstone of the Learmonth Beds includes porous and permeable beds suitable for accumulating petroleum. In WAPET's Rough Range No. 1 Well the Learmonth Beds may not have been within an area of structural or stratigraphic closure. Much more exploration of this formation appears justified to determine areas of structural closure and of sedimentary pinchout where oil derived from the Dingo Claystone may have a accumulated.

No indication can be given of its areal extent, its variations in thickness and lithology, or its structure. Its fauna and flora and therefore its age are imprecisely known. It does, however, have prospects of containing oil accumulations, and therefore its exploration should be one of the many good reasons for continuing a vigorous exploration of the north-western area of the Basin.

In WAPET's Learmonth No. 2 Well (at Lat. 22° 17' 35"S., Long. 114° 03' 48" E.), 802 feet of sandstone and siltstone with carbonaceous material was identified as 'Wogatti Sandstone' (WAPET, 1964). This may be an equivalent of the Learmonth Beds, although its microflora is of Lower Cretaceous age.

'Wogatti Sandstone'

The name 'Wogatti Sandstone' was proposed by McWhae et al. (1958, p. 92) for argillaceous sandstone between the Birdrong Formation above and the Learmonth Beds below. The authors did not indicate how the 'Wogatti' is differentiated from the Birdrong either lithologically or palaeontologically. They claim that the contact between the 'Wogatti' and the Birdrong is either a disconformity or an angular unconformity, but as it has only certainly been penetrated in Rough Range No. 1 no such relationships can have been established.

I consider that there is no evidence at present to separate this interval in the Rough Range bore from the Birdrong Formation, which is of similar age and includes the reported lithology. The Rough Range occurrence will therefore be considered in the section on the Birdrong Formation.

'Curdamuda Sandstone'

In 1940 Teichert described a small exposure of sandstone with marine fossils in and adjoining the south bank of the Minilya River near Curdamuda Well (north of Wandagee Hill). He determined several species and stated that the fauna indicated a Middle Jurassic age because of faunal affinities with species from the Middle Jurassic of the Perth Basin. In 1952 Teichert confirmed his age determination, although he indicated that the specific determinations were not indubitable.

Teichert (1952) named the sequence 'Curdamuda Sandstone' and described it as occurring between faults. I examined the outcrop (locality 3, Fig. 156); the exposure is quite adequate to show quite clearly that the fossiliferous sandstone rests unconformably on an uneven surface of the Permian and is in conformable gradational sequence with the Aptian Muderong Shale.

The forms so far named are not such that any precise age can be ascribed to them. For the present there seems no good reason to separate the 'Curdamuda Sandstone' from the Birdrong Formation.

Wittecarra Beds

The name 'Wittecarra Formation' was proposed in 1958 by Johnstone and Playford (in McWhae et al, 1958, p. 94) for a sequence of sandstone, siltstone, claystone, and conglomerate cropping out in a small area of coastal cliff between Red Bluff and Bluff Point, south of the mouth of the Murchison River. The only fossils are a few leaves considered by Walkom to be 'probably of Upper Jurassic age'.

The rock types of this sequence are different from those of the Birdrong Formation, with which it may possibly be correlated. Its limited known extent and the absence of certainty as to its age and spatial relationships preclude its establishment as a formation in the proper sense. For the present, therefore, this sequence should be referred to as the Wittecarra Beds, of possible Jurassic age.

Yarraloola Beds

The name 'Yarraloola Conglomerate' was proposed by Hoelscher & McKellar (in McWhae et al., 1958, p. 93) for 'a few discontinuous exposures of poorly sorted conglomerate and sandstone overlying Precambrian rocks' near the north-eastern margin of the Carnarvon Basin.

Fossil leaves were considered by Walkom to indicate a probable Upper Jurassic age, but this cannot be regarded as indubitable and requires confirmation by spores and pollens.

In any case, the outcrops as described do not form a proper rock unit and the occurrences should preferably be called Yarraloola Beds until their age, extent, and spatial relationships can be established.

Nanutarra Beds

The name 'Nanutarra Formation' was proposed by Hoelscher & McKellar (in McWhae et al., 1958, p. 93) for a sequence of micaceous sandstone and siltstone resting on Precambrian rocks near the north-eastern margin of the Carnarvon Basin. The beds contain marine fossils and fossil leaves.

The marine fossils are regarded by Cox (1961) as having probable Lower Cretaceous affinities with some possibility of Upper Jurassic. Walkom considered the plant fossils to be of probable Upper Jurassic age.

Skwarko (1966) reviewed Cox's faunal list and by comparing the Nanutarra pelecypod species with species from Northern Australia concluded that the Nanutarra Beds are probably of late Neocomian age.

The rock types are similar to those of the Birdrong Formation, and the probable age does not preclude the possibility that these beds are part of the Birdrong Formation.

As the extent and spatial relationships of this sequence is not established it should preferably be called Nanutarra Beds until its relationships are established.

BARROW ISLAND

WAPET's Barrow Island No. 1 Well drilled an Upper Jurassic sequence of sandstone and siltstone with minor limestone from about 5600 feet depth to total depth of 9785 feet. There is no obvious change in lithology between the Cretaceous and Jurassic and there is also a continuous sequence of microfossils (McTavish, 1965).

The environment of deposition of these sediments is paralic to neritic.

None of the sequence penetrated in wells in the Carnarvon Basin or southern Canning Basin can be identified in this sequence, although parts of it may correlate with part of the Dingo Claystone, the Learmonth Beds, the Frezier Sandstone, and the Callawa Formation (Bastian, 1963).

Oil and gas were discovered in several intervals within the Jurassic sequence. This discovery gives further point to the need for additional exploration of the Learmonth Beds.

CRETACEOUS

The Cretaceous sequence of the Carnarvon Basin consists of marine sediments ranging in age from Neocomian to Maestrichtian, but with two important disconformities within the sequence.

The Cretaceous extends from Barrow Island (subsurface) in the north over the Onslow and Exmouth Basins and a large part of the Gascoyne Basin; it overlaps the Permian of the northern and western parts of the Merlinleigh Basin.

It reaches its greatest known thickness at Barrow Island, where its thickness is about 4800 feet. It has an aggregate thickness of about 3000 feet in the Rough Range area. Around the outcrop the thickness is much less - 180 feet near Lyndon River, 800 feet west of Kennedy Range, 500 feet at Wooramel River, and 320 feet at Murchison River.

The Cretaceous System in the Carnarvon Basin is made up of three main sedimentary units - a paralic terrigenous lower unit, a neritic mainly terrigenous middle unit (the Winning Group), and a carbonate upper unit (the Cardabia Group). The two upper units are separated by an important disconformity with an hiatus representing most of the Turonian and Coniacian Stages.

Jurassic sedimentation in the Exmouth and Onslow Basins continued into the Cretaceous with the deposition of regressive (deltaic) sandstones. A widespread transgression, probably in the late Neocomian, resulted in the deposition of a blanket sand unit followed by finer grained terrigenous and organic-siliceous sediments. After a strong regression and some erosion a quiet transgression was followed by deposition of organic-carbonate sediments with only minor terrigenous sediment.

NEOCOMIAN

In WAPET's Barrow No. 1 Well, a sequence, dominantly of quartzwacke with some siltstone and minor limestone, contains abundant Neocomian microplankton and spores and pollen (Balme, 1964, in McTavish, 1965). This sequence is penetrated between 3093 feet and about 5600 feet depth (a drilled interval of about 2507 feet).

The environment of deposition is near littoral and probably deltaic.

This sequence may be the same unit as the 'Wogatti Sandstone' (p. 6) in WAPET's Rough Range No. 1 Well. In Barrow No. 1 Well the Neocomian unit is distinguishable from the overlying Bridrong Formation by having coarser-grained pebbly quartzwacke, more siltstone, and little glauconite. The Barrow No. 1 sequence may perhaps be identified with the Frezier Sandstone of the southern Canning Basin (Lindner & Drew, in McWhae et al., 1958, 108), which was identified in Bore BMR4 Wallal (Bastian, 1963).

No significant traces of hydrocarbon have been reported from this unit.

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WINNING GROUP

The Winning Group (Raggatt, 1936; amended Johnstone, Condon, and Playford, 1958) is the largely terrigenous sedimentary unit resting disconformably on Neocomian sediments or unconformably on Jurassic, Permian, Devonian, Lower Palaeozoic, and Precambrian rocks (Fig. 145) and overlain disconformably by Upper Cretaceous and Eocene sediments. It includes the basal Birdrong Formation, the Muderong Shale, the Windalia Radiolarite, the Gearle Siltstone, and in the southern area the Alinga Formation. The Winning Group ranges in age from probably Neocomian to Turonian. Each of the formation boundaries within the Group is gradational, and the inference, supported by the rather meagre fossil record, is that there is no important hiatus within the Group.

Information from water bores can be used to show the main trends of thickening of the Winning Group (Fig. 146), even though the drillers' logs cannot everywhere be interpreted with certainty. There is little doubt that, regionally, the Winning Group thickens from south to north and that the trend of greatest thickness is in the central part of the Gascoyne Basin from the mouth of the Murchison through Marron, Minilya, Cardabia, and Exmouth. The isopachs suggest that the present edge of outcrop is near to the original edge of the basin of deposition except in the area between Kennedy Range and Lyndon River, where dissection has removed the Winning Group almost completely. This is confirmed by the rocks, which are coarser and more glauconitic at Murchison River and Lyndon River than along the Western side of Kennedy Range and much coarser than in the Giralia Anticline. The isopachs indicate thinning westward at the coast; this may point to the distal limit of the basin, produced either by an originally high sea floor, by subaerial exposure of the pre-Cretaceous rocks during the lower Cretaceous in the offshore area, by erosion of the Winning Group following post-depositional uplift, or by some combination of these. It certainly points to the coastal and offshore area as likely to include beds with high porosity and permeability and to be favourably placed for receiving primary migrating petroleum.

The basin of deposition appears to have been open to the north beyond Exmouth Gulf; so in this area there appears to be a very favourable relation between a thick central section with good source beds and the likelihood of good porosity on the basin flanks in the position of primary migration. WAPET's Yanrey No. 1 was drilled in this favourable area, but the basal sands were absent; there remains a distinct possibility that pools may be developed in the Birdrong where it is overlapped on the flanks of the Precambrian basement ridge on which Yanrey No. 1 is located.

There is a marked local thinning of the Winning Group over the Giralia Anticline, suggesting that in this area there was a high ridge in the Lower Cretaceous sea floor. BMR seismic work at Giralia (Chamberlain et al., 1954) indicated that the Giralia Anticline was underlain by synclinal sediment shown by BMR 5 to be Permian.

The top of the Birdrong Formation can be used as a fairly reliable marker to show regional structure (Fig. 146). South of the Gascoyne River the regional dip is gently westward. There is a regional high between Giralia and the south end of Salt Lake in the area where numerous small anticlines as well as the large Giralia Anticline are evident at the surface. The surface Cape Range Anticline appears to continue down to the Birdrong, but the Rough Range Anticline does not: beneath it there appears to be little more than a terrace in the westward dip into the Dingo Syncline. The structure, like the isopachs, is open to the north, and attractive stratigraphic and perhaps structural prospects may occur if northward thinning and southward regional plunge are developed together. South and North Muiron Islands and Long Island are in good positions to test this possibility.

The Winning Group may almost certainly be correlated with the Blythesdale 'Group' and the Roma 'Formation' of the Great Artesian Basin. The Lower Cretaceous transgression was very widespread over Australia, reaching as far inland as the vicinity of Alice Springs. In many areas throughout Australia the similarity in the lithological sequence is quite remarkable, suggesting very uniform conditions of sedimentation. Such conditions are most readily explained by an eustatic rise of sea level. If this inference is correct the present positions of Lower Cretaceous sediments must present useful information on relative tectonic movements since the Lower Cretaceous.

The Winning Group includes the sandstone that contains the oil produced at the rate of 500 barrels a day from WAPET's Rough Range No. 1 Well; although no extension of this pool has yet been proved very little drilling of the Cretaceous sequence has been undertaken. Its marine shales appear to be good source beds and its basal sand certainly is a good reservoir formation. There is likely to be much more variability in the Birdrong Formation than is obvious, and such variability may have produced stratigraphic trap pools not flushed by artesian water flow. The artesian water is a valuable continuing resource to the pastoral industry and it would seem appropriate for pastoral and oil exploration interests to co-operate in drilling the Birdrong to obtain information about its variations and its fluid content. Where it contains potable water this could be developed and used (and the bore paid for) by the pastoralist or the State Government; where no useful water is found the cost could be borne by the oil exploration company with or without Commonwealth Government subsidy.

In considering oil derived from underlying rocks the main problem at present is that there is very little reliable information about the age of the pre-Cretaceous sedimentary rocks, although their lithology is known from many water bores. WAPET's Rough Range No. 1, Giralia No. 1, Warroora No. 1, and Yanrey No. 1 and Dirk Hartog No. 17B gave useful information (McWhae et al., 1958) and BMR 5 Giralia and Pelican Hill Bore (Carnarvon) also gave reliable age data. Using these as datum points, and estimating regional dip of the Palaeozoic sediments from basin shape deduced from gravity and aeromagnetic data, a geological map of the unconformity below the Winning Group can be drawn (Fig. 145). This suggests, regionally, a very gently north-plunging syncline, broad at the south end of the Gascoyne

Basin and narrowing, with steeper flank dips, to the north. The boundary between the Lower Palaeozoic Tumblagooda Sandstone and Dirk Hartog Limestone and the Devonian is placed between Dirk Hartog Island and Peron Peninsula and swings around to the south end of Shark Bay, around the north end of the Ajana Ridge, and there disappears under the Lyons Group. This boundary is placed here because of the differences in lithology between the ?Lower Silurian Dirk Hartog Limestone in the Dirk Hartog Bore and the Limestone in the Shark Bay town bore. Sandstone and shale in water bores between the Wooramel and Gascoyne Rivers are regarded by WAPET geologists (McWhae et al., 1958) as Tumblagooda Sandstone. However, limestone has been reported in some of them and it seems at least as likely that these sediments are equivalents of the Devonian and Carboniferous sediments exposed in the north-east of the Merlinleigh Basin and consisting of carbonate rocks, quartz sandstone and red shale, quartzwacke and conglomerate.

If this were so, there would be good prospects for secondary migration across the unconformity into Cretaceous structural or stratigraphic traps, and even poor indications of structural highs such as that at Pimbie are worth drilling to obtain reliable information about the lithology, age, and dip of the Palaeozoic sediments and to test for the presence of oil. The Permian Lyons Group may not reach to the Gascoyne River, but there is some possibility that it may extend in a fairly narrow syncline to the Wooramel and across into the Byro and Coolcalalaya Basins. It probably extends over much of the northern part of the Gascoyne and Merlinleigh Basins and most of the Onslow Basin. Artinskian (Permian) sediments occupy a syncline from Minilya into Exmouth Gulf and an area west of Kennedy Range. Precambrian gneiss inliers may occur at Binthalya and Marrilla as well as that established at Yanrey No. 1. It is very likely that structures will be found in the Palaeozoic sediments and these will present drilling targets in themselves, but much mor information on the distribution of the Palaeozoic systems and formations is required before adequate assessments can be made. It is very evident at this time that there is no more than fortuitous coincidence between structures in Palaeozoic sediments and those in the Mesozoic and Tertiary, so that the older structures must be sought by subsurface exploration (seismic surveys and drilling).

BIRDRONG FORMATION

The Birdrong Formation (Condon, 1954) consists of quartz sandstone, glauconitic sandstone, quartzwacke, and siltstone, and rests disconformably on Neocomian sediments or unconformably on Jurassic, Permian, probably Carboniferous, Devonian, Lower Palaeozoic and Precambrian rocks and is overlain conformably and gradationally by the Muderong Shale and the Windalia Radiolarite. It is probable that in places it grades laterally into the Muderong Shale.

The type locality (Fig. 147) is in a scarp at the north end of a mesa half a mile south-west of Birdrong Spring on Hill Springs Station 22 miles north-east of the homestead.

The Birdrong Formation crops out along the western side of Kennedy Range, in the Minilya River near Curdamuda Well, in the south-eastern part of Winning Pool Station, and in the valley of the lower Murchison River. Because it forms the main aquifer of the Gascoyne Basin it has been penetrated by many water bores; it has also been the main target of exploration drilling for oil to date. These subsurface data establish the Birdrong Formation as extending throughout the Gascoyne Basin from the Cape Range and Barrow Island in the north to the Murchison River in the south.

Although other names had been given earlier to scattered outcrops of parts of the Birdrong Formation - 'Butte Sandstone' (Clarke & Teichert, 1948) amended to 'Tutula Sandstone' (Fairbridge, 1953), 'Curdamuda Sandstone' (Teichert, 1952) - Johnstone et al., (1958) in recognizing the identity of the Birdrong Formation and the 'Tutula Sandstone' proposed to retain the name Birdrong for the formation over its full extent because it was then well established by usage even in general publications. McWhae et al. (1958) and Playford & Johnstone (1959) supported this proposal. Apart from consideration of usage, however, the formation as exposed on the west side of Kennedy Range is more representative of the rock body as a whole than are the Murchison River outcrops.

The type section, measured by M.H. Johnstone, is 97 feet thick and displays the several rock types characteristic of the formation (Fig. 148).

The lowermost beds are commonly coarse-grained and contain fragments of the underlying rock; the upper boundary is gradational into the sandy bottom part of the Muderong Shale. As might be expected in such a widespread sandy formation above an unconformity, there is quite a variation from place to place in lithology and thickness. In the Murchison River area the rock is almost entirely clean quartz sandstone and the formation is 200 feet thick. It contains fragments of the Tumblagooda Sandstone in the lowermost beds. Drillers' logs of bores on Coburn suggest a thickness of about 200 feet also, but the lithological variation is much closer to the typical Birdrong than the Murchison outcrop. In Woodleigh No. 7 Bore, McWhae et al. (1958, p. 142) reported 332 feet of sandstone with minor siltstone, with plant microfossils of Lower Cretaceous affinities - this is almost certainly the Birdrong Formation, here overlying the possibly Lower Jurassic Woodleigh Beds. In the Shark Bay Town Bore the Birdrong Formation is only about 40 feet thick and in Dirk Hartog No. 17B only about 10 feet (written communication - WAPET). On Wooramel Station the Birdrong Formation is, apparently, mainly absent, but in the northern part of the station it reaches about 100 feet in thickness. On Yalbalgo Station the Birdrong is absent or very thin (up to about 20 feet). Near Carnarvon it is thin (50 feet at Pelican Hill and up to 40 feet on Brickhouse Station). In outcrop along the west side of Kennedy Range, it ranges from 5 to 105 feet in thickness. At Manberry it is about 67 feet thick and on Minilya from 40 to 150 feet. In WAPET's Grierson Bores it is about 200 feet thick (written communication - WAPET), in Warroora No. 1 (WAPET) about 60 feet, and in Giralia No. 1 (WAPET) about 40 feet. In BMR 5 Giralia the Birdrong is about 70 feet thick. In WAPET's Rough Range No. 1 McWhae et al. separated the 'Wogatti Sandstone' from the Birdrong Formation; there appear no good grounds, either lithological, palaeontological, or regional relationships, to distinguish this unit, which I suggest should be included in the Birdrong Formation. Apparently WAPET geologists have regarded the Birdrong as predominantly a sandstone unit; whereas typically it has a sand/shale ratio of 4 to about 10. I consider that the Birdrong Formation in Rough Range No. 1 is 388 feet thick and quite typical of the Birdrong in many places, with a glauconitic upper part and a clean quartz sandstone lower part with fragmentary plant fossils. In Cape Range Bores (WAPET) the Birdrong is absent in the south and up to about 150 feet thick in the north. In Yanrey No. 1 the Birdrong is absent (WAPET - written communication). On Winning Station, in the outcrop area between Lyndon River and Kialiwibry Creek, the glauconitic upper part of the Birdrong is very well developed although the thickness is only 20 to 40 feet. McTavish (1965) did not identify the Birdrong Formation in Barrow No. 1, but the interval from 2875 feet to 3093 feet (218 feet drilled interval) has all the characteristics of the Birdrong Formation and I would identify it as such.

The variations in thickness of the Birdrong Formation appear to have very little regional significance in relation to the shape of the depositional surface: they appear to be related to local irregularities in that surface. It is evident that the local relief on that surface was at least 400 feet and may have been much more. The greatest thickness, in the Rough Range bores, is in the area where the Lower Cretaceous as a whole is very thick and may represent the deepest and first submerged part of the Lower Cretaceous basin (or at least of the present subaerial parts of that basin).

The only large fossils so far found in the Birdrong Formation are poorly preserved pelecypods in the Murchison River area, the pelecypods and calcareous algae in the 'Curdamuda Sandstone' (lowermost Birdrong) on the Minilya River, and fossil wood in several places along the west side of Kennedy Range. Microplankton and plant microfossils have been found in a few bores, but the age significance of these cannot be established at this time since the ranges of the forms have not been fixed in relation to well-established marine sequences. The indications are for an age between Neocomian and Aptian and it may indeed range over this interval: it grades upwards (and probably laterally) into the Muderong Shale of fairly definite Aptian age and some of the fossils from the base appear to have Jurassic affinities. In this respect it is similar to the Blythesdale 'Group' of the Great Artesian Basin, which also appears to have about this range in age and to be, also, of variable thickness and lithology.

The Birdrong Formation is mainly a transgressive marine sand, undoubtedly with some paralic and continental parts. It probably represents the marine clean-up of residual soils during the transgression rather than a flush supply of river-borne sediment, since the succeeding formations show only fine-grained terrigenous sediment, almost certainly derived from a very mature land surface. It probably filled the shallower hollows in the pre-existing surface but was not deposited on the higher ridges.

At present it is impossible to determine how much of the structural form of the Birdrong is inherited directly from its depositional form and how much is related to positive tectonic activity. The regional structural relief of more than 4000 feet indicates, at least, regional tilting or warping. The BMR seismic profile along the Bullara-Giralia road shows very clearly that the Cretaceous of the Giralia Anticline in this area is deposited over a ridge in the underlying Palaeozoic, which has a synclinal structure. In several areas along the west side of the Kennedy Range (in particular the area south-west of Muderong Bores, Middalya) relationships that were thought to indicate faulting of the Cretaceous against the Permian have been shown to be steep (sea-cliff) unconformities with the Cretaceous abutting against the old cliff and draping over and against it. Sequence repetition in one bore (Rough Range South No. 5) has been taken (WAPET - written communication) to indicate complex faulting, but could more readily be explained by slump movement off a steep slope.

The Birdrong Formation forms a homocline dipping gently to the west-north-west. This is interrupted by regional anticlines in the areas between Giralia and Quobba, and in Cape Range, and along the Wandagee basement ridge between Lyndon River and Point Locker.

Several local culminations have been indicated along these regional highs, which appear, on the basis of isopachs of the Winning Group, to have been high during its deposition. Anticlinal structures are suggested in the Pimbie area by bore records and the course of the Wooramel River. There is possibly a large anticline in the Binthalya area and small folds in the northern part of Hill Springs Station.

The Birdrong Formation is the main artesian aquifer of the Carnarvon Basin but is by no means completely flushed. In many areas particularly towards the north-west, the water is brackish and in some places (as at Rough Range) quite saline. This variation in salinity of its waters may be related to porosity barriers that may also form traps for petroleum.

The knowledge of the Birdrong Formation at present is very unsatisfactory; its age-range has not been established and must await both more precise determination of the micro-faunas and floras of the Jurassic and Cretaceous of Western Australia and more fossiliferous material from the Birdrong itself. Its detailed thickness, lithology, and structure, and the detailed interpretation of its sedimentary environments, must await additional drilling; present data from water bores could be improved by gamma-ray logging of available bores. Useful and possibly important information may be available in the detailed analysis of bore water, which would help to indicate porosity barriers; pressure data in the area of artesian flow and water level data from non-flowing bores can assist in this also; the combined pressure and salinity data can provide essential data on the hydrodynamic environment. Geochemical testing for trace hydrocarbons may give important indications of migration paths of oil and gas. Precise information is required on the lithology, age, and structure of the underlying rocks.

Muderong Shale

The Muderong Shale (Condon, 1954, p. 106) is the formation of shale and claystone (bentonitic in places) and siltstone conformable between the Birdrong Formation below and the Windalia Radiolarite above. Both boundaries are gradational and there is some evidence that the Muderong grades laterally as well as vertically into the Birdrong.

The type locality (Fig. 149) is 1.3 miles west-south-west of Muderong Bore, Middalya Station, in the slopes of a butte (Lat. 24°08'03" S., Long. 114°45'49" E.). The Muderong is identified only north of the Gascoyne River; along the west side of Kennedy Range it is 3 to 50 feet thick, in the south-western part of Winning Station it is 15 to about 40 feet thick, and on the Minilya River near Curdamuda Well it is absent. It is not clearly distinguishable in most drillers' logs of water bores, but appears to range in thickness from 0 to 50 feet on Boolathanna, from 80 to 160 on Minilya, from 40 to about 200 in the western part of Mia Mia and Winning and 100 to 130 on Cardabia. In BMR 5 Giralia, the Muderong is 225 feet thick, and in WAPET's Giralia No. 1 243 feet (McWhae et al., 1958, p. 112). In WAPET's Barrow No. 1 Well, McTavish (1965) regards the interval from 2747 feet to 2981 feet as Muderong Shale. I have examined the cores and cuttings from the well and would identify as Muderong Shale the interval from 2170 feet to 2875 feet (705 feet drilled). Within this interval the rock types typical of the Muderong are present but the proportion of quartzwacke is higher than in the type locality.

The type section (Fig. 150) displays the characteristic rock types of the areas of outcrop. In the subsurface there appear to be areas where glauconite is relatively abundant and some places where sandstone beds are reported by drillers. Subsurface information, even in the area where WAPET has drilled, is not sufficiently precise to establish lithological ratios.

Only microfossils have been found in the Muderong. Foraminifera have been determined by Crespin (1955) and by Glaessner (1955). Cookson & Eisensack (1958) described microplankton from bores in the Muderong.

The Muderong is a marine shale probably deposited in an open sea of only moderate depth. The main control on the lithology appears to have been a low rate of supply of mainly fine-grained sediment from a reduced hinterland. There is some indication of reducing conditions in the sediment (disseminated pyrite is reported from some bores).

It seems likely that the Muderong is a source formation for oil, and if in fact it grades laterally into the Birdrong the conditions for primary migration of petroleum should have been good. Moreover, the Muderong has generally provided a cap-rock for the Birdrong. Any original structures involving both the Muderong and Birdrong almost certainly accumulated oil immediately. Artesian water flow may have moved this oil from some structures into other, later-developed structures or to outcrop. In WAPET's Barrow No. 1 Well, oil-stained quartzwacke of low porosity and permeability was found in the upper part of the Muderong Shale (as I regard it) from 2180 feet to 2330 feet. This is the oil sand called 'Windalia' in newspaper reports.

Windalia Radiolarite

The Windalia Radiolarite was named by Condon (1954), who cited a definition from manuscript by Condon et al. that was published in 1956. Information from bores requires that this definition be revised. The Windalia Radiolarite is re-defined as the formation of laminated to thin-bedded radiolarite, radiolarian claystone and chert, and minor limestone, greensand, and siderite, conformably between the Muderong Shale or Birdrong Formation below and the Gearle Siltstone above. In bores it is usually light to medium grey, but in outcrop is varicoloured, mainly pale, because of leaching by weathering.

The type locality (Fig. 151) is at Windalia Hill north of the Lyndon River in the south-western part of Winning Station, at Lat. 23°16' S., Long. 114°48' E., where only the lower part of the formation is exposed. The type section (Fig. 152) is in weathered rock. The upper part of the formation is well exposed only in the Giralia Anticline; a reference section is described by Condon et al. (1956) from the eastern flank of the Giralia Anticline at Lat. 23°04'15" S., Long. 114°08'45" E.

Complete sections of the Windalia Radiolarite have been penetrated in the WAPET bores between Onslow and Cape Cuvier and in BMR 5 Giralia.

The lithology of the Windalia is of a somewhat rare type, although it is widespread in Australia in Lower Cretaceous sequences. Most of the outcrops of this rock type throughout Australia are strongly leached and commonly opalized by movement of its silica. It is commonly hard to distinguish from other fine-grained leached rocks, but can be determined even in leached examples by its very high proportion of silica (85 to 99%), its very fine grain, and the isotropic character of the grains, which can be distinguished under high power as consisting of rods and fragments of rings and stars of opaline silica. In fresh rock the same debris is present but a smaller or larger part of the rock consists of tests of radiolaria, which may not be seen unless the microscope tube is raised and lowered, when the form of the tests becomes apparent. I have had slides described to me as not being radiolarite 'because there are no radiolaria' when this simple technique has revealed the slide to be completely crowded with whole tests, filled and surrounded by the fragmental material which, of course, tends to hide the tests because it is of the same colour and refractive index. Radiolarite has been called 'siliceous siltstone', but this name is inappropriate because siltstone is generally regarded as terrigenous whereas radiolarite is an organic sediment. In weathered outcrop it is light in weight and colour, may be opalized in part, and disintegrates in conchoidal blocks of larger size than leached shale. In fresh rock the distinguishing features are light weight and colour for a fine-grained sediment, strong capillary porosity, and in electric logs a moderate self-potential and resistivity. It may form a good seismic reflector.

In the Murchison River area Johnstone et al. (1958) proposed the name 'Thirindine Formation' for a sequence of radiolarian claystone and radiolarite conformably overlying the Birdrong Formation. This sequence is clearly identical with the Windalia which can be traced in water bores from Onslow to the Murchison. It is proposed therefore to refer to this unit by the older name, Windalia Radiolarite.

The base of the Windalia Radiolarite is placed at the change from shale or sandstone below to thin-bedded or laminated radiolarite above. In either case there is a marked break in electric logs at the boundary. The top of the Windalia is placed at the gradational change from radiolarite below to siltstone above; this boundary, also is reasonably well marked on electric logs.

The Windalia Radiolarite crops out in the south-eastern part of Winning Station; in a continuous belt from the Minilya River near Curdamuda Well, past Wandagee Woolshed, along the western side of Kennedy Range, across the Gascoyne River to the south end of Jimba Jimba Station; in the scarps on the north side of the Murchison Valley from near Murchison House to the north-east corner of Murchison House Station; and in the central part of the Giralia Anticline.

Most of the outcrops expose part-sections only; those on Murchison House Station are complete and range in thickness from 40 to 80 feet. In the subsurface, water bores indicate thicknesses of 150 feet on Yaringa North, 100 feet around Carnarvon and Yalbalgo, 30 to 60 on Minilya, 130 to 170 in the western part of Mia Mia, and 300 to 425 on Cardabia. McWhae et al. give thicknesses of about 150 feet in the Giralia Anticline (probably combining the outcrop thickness with the intersected thickness in WAPET's Giralia No. 1) and 402 feet in WAPET's Cape Range No. 2 bore. BMR 5 Giralia penetrated 251 feet of the Windalia. In WAPET's Barrow No. 1 Well, McTavish (1965) places the interval from 2060 feet to 2747 feet in the Windalia Radiolarite. Ditch samples show radiolarite only over the interval fram 2110 feet to 2170 feet and this interval I regard as the Windalia Radiolarite. These differences in formation identification appear to stem from difficulties in recognizing the radiolarite and in distinguishing it from siltstone and shale in an unweathered state.

There is thus no simple thickness relationship, although in general the thicker sections are in the north-western part of the Carnarvon Basin.

Radiolaria are abundant in the Windalia, but very few species have been determined. Less abundant forms include foraminifera, ostracods, ammonites (Brunnschweiler, 1959) belemnites, and pelecypods. The age of the Windalia is not well established but appears to be within the Aptian - Albian Stages.

Formations of similar lithology, faunas, and general stratigraphic position are widespread in Australia; in the coastal cliffs at Darwin, in the Wilgunya Formation of the Boulia area of western Queensland, and in parts of the Roma Formation of the eastern part of the Great Artesian Basin. These occurrences may be tentatively correlated with the Windalia.

The large volume of siliceous organic sediment represented by the Windalia Radiolarite and other similar formations in northern Australia indicates that the sea during the deposition of this material must have been abnormally high in silica and probably also in nutrients. Terrigenous clays were deposited at the same time as the organic debris, but the debris was produced in sufficient quantity to dominate the resulting sediment. The run-off from the hinterland must have carried mainly clay and solutions, including soluble silica. A mature land surface under a humid climate would provide this sort of run-off; the sediment may indicate the establishment of the conditions of terrain and climate that produced the deep weathering (lateritization) that characterizes the present surface of much of northern Australia. Although the sediment is fine-grained the presence of pelecypods and the inclusion of minor beds of sandstone indicate that the Windalia was deposited in water of no more than moderate depth (in the neritic environment).

The leached rock at outcrop forms an attractive building stone with excellent insulating properties. This rock may be used as a source of fine abrasive, for filtering, and as an inert filler; tests to establish its usefulness have not yet been carried out.

The Windalia forms a marker, at a convenient distance above the Birdrong Formation, in drilling to targets in the Birdrong. It also is probably one of the good seismic reflectors found near the base of the Cretaceous.

Much work remains to be done on the details of the fauna of the Windalia so that its age may be established; probably the best hope of establishing affinities with the European stages lies in additional collections, from outcrop, of ammonites. Brunnschweiler (1959) made satisfactory small collections during a quite short visit and there is little doubt that more material could be found. The study of the microfauna would help in future subsurface exploration as well as in the precise correlation with other Australian formations.

There is some possibility that the Windalia may have been a source bed for oil, and geochemical analyses are required to determine trace hydrocarbons and heavy metals. In some places near Carnarvon the

Windalia appears to rest directly on the Birdrong; if this relationship is present in areas where structural or stratigraphic traps are developed in the Birdrong any oil generated in the Windalia would have had excellent primary migration possibilities through the Windalia into the Birdrong. Some information on this problem could be obtained by gamma-ray logging of existing water bores.

Gearle Siltstone

The Gearle Siltstone was named by Condon, Johnstone, Prichard, & Johnstone (cited in Condon, 1954). It consists of soft dark grey bentonitic siltstone and claystone with few thin beds, particularly in the lower and upper parts, of radiolarite and barite. It is gradationally conformably on the Windalia Radiolarite and is overlain with erosional unconformity by the Korojon Clacarenite; it appears to grade laterally into the Alinga Greensand.

Only the uppermost part of the formation is well exposed in the type section in C-Y Creek (Lat. 22°54'S.; Long. 114°09'E.). A reference section (Fig. 153) was measured east-north-east of Remarkable Hill.

The base of the Gearle is placed at the change from firm radiolarite somewhat resistant to weathering to softer and darker bentonitic siltstone and claystone; the top is an erosional unconformity and therefore the detailed lithology below it varies, from dominant radiolarite to bentonitic shale or siltstone. This is overlain by carbonate rocks of the Korojon Calcarenite, usually a member of soft calcilutite. A lag gravel, including pebbles up to about 1½ inches diameter of quartz, phosphate, and ironstone, commonly rests on the unconformity surface of the Gearle and shed from its outcrop can be used to establish the position of the boundary.

In outcrop the rocks of the Gearle tend to disintegrate on weathering so that the surface material is soft and commonly gypseous. Beneath this layer the rock is firm, as it is also in bores. The bentonite content of the shale, siltstone, and claystone varies and the more bentonitic varieties appear to disintegrate to greater depths than the less bentonitic. White specks up to about 1 mm in diameter include foraminifera and radiolaria; many were not identified but appeared to consist of a fine white powder. The beds of barite, generally less than 6 inches thick, consist of barite crystals about 1 mm in diameter. They certainly form sedimentary beds, well exposed in the cliff face of Cardabia Creek 3½ miles north of Cardabia Pool. It would appear that the barite has precipitated as a thin layer directly from the sea water; siderite also has been found in the Gearle in BMR 5 Giralia. The interbedded radiolarite at the top of the reference section had not been observed previously: it should form a useful lithological marker in drilling since it should have distinctive electric log characteristics. Subsurface material from the

Gearle contains much disseminated pyrite and glauconite. Beds of glauconite have been found in outcrop.

The Gearle Siltstone is known to extend subsurface from Cape Range and Barrow Island to Yaringa North Station; somewhere between there and Murchison River it grades into the Alinga Greensand. The Gearle crops out in the Giralia and Marrilla Anticlines (Condon et al., 1956) and in a few places between Minilya River and Gascoyne River west of Wandagee Hill and Kennedy Range. It has a wide range of thickness from 80 feet in No. 18 Bore, Yaringa North, to 1922 feet in WAPET's Rough Range No. 1 Well (McWhae et al., 1958, p. 112). Information from drillers' logs of water bores indicate that the Gearle is 130 to 335 feet thick around Carnarvon, 170 to 470 feet on Minilya Station, 540 to 790 feet in the western part of Mia Mia Station, and 1040 to 1135 on Cardabia Station. In BMR 5 Giralia, the Gearle is 770 feet thick. At outcrop the Gearle is 400 to 565 feet thick in the central area of the Giralia Anticline and about 300 feet thick in the area west of Kennedy Range. The Gearle Siltstone is 1184 feet thick (drilled interval from 926 feet to 2110 feet) in WAPET's Barrow No. 1 Well (McTavish, 1965).

It is evident that there is a regional increase in thickness from south to north and in the northern area a thickening into the Bullara Syncline. Locally there appear to be significant variations in thickness that may relate either to structural relief in the Winning Group or to erosional relief on the post-Gearle unconformity. Because of this unconformity, it cannot be assumed that structures developed in the Upper Cretaceous or Tertiary continue down into the Winning Group: the drilling of the Rough Range anticline (developed in Miocene limestone) showed very clearly that the structure of the Birdrong had no essential relationship to the surface structure.

Abundant foraminifera are found in many parts of the Gearle Siltstone. Belford (1958) concluded that the assemblage indicates an Albian to Turonian age. This rather lengthy period is consistent with the thickness and fine-grained lithology of the formation. The few large fossils that have been found - a pectinid and belemnite guards - are of little value in fixing a precise age.

The Gearle Siltstone may be correlated in a general way with the Wilgunya Formation and with parts of the Roma and Tambo Formations of the Great Artesian Basin.

The Gearle Silstone was deposited in conditions not unlike those of the Windalia Radiolarite: a neritic marine environment with reduced supply of fine-grained terrigenous sediment. The main change appears to have been a reduction in the amount of silica in solution in the sea. Nutrients were still available to support a vigorous growth of micro-organisms.

The Gearle has the same structure as the rest of the Winning Group but may be strongly discordant in relation to the overlying strata. On the other hand in the larger structures such as Giralia and Cape Range Anticlines the Gearle and the younger sediments are generally concordant.

The Gearle Siltstone has the characteristics generally regarded as indicating a source rock for petroleum - abundant microfossils but few large fossils, a non-oxidizing environment in the sediment, indicated by pyrite, glauconite, and carbon, and shaly lithology. Its large volume should have generated impressive amounts of oil. Much of this may have moved laterally to outcrop or into overlying rocks, but some should have moved laterally and vertically downwards into the Birdrong Formation. In its present state it forms an adequate cap rock for any older oil.

If oil drilling increases considerably in Australia the Gearle may be a useful source of bentonite or bentonitic clay for use in mixing drilling mud.

The barite beds are unlikely to constitute an economic source in the foreseeable future but, like the bentonite, may possibly be useable for adding weight to drilling muds.

The palaeontology of the Gearle needs to be studied in detail to provide a standard for this part of the Cretaceous System in Australia, particularly as it apparently includes part of the Albian, the Cenomanian, and part of the Turonian Stages. The ammonites can probably provide the main correlation with the European succession, but the microfauna will be of most value within Australia, especially for subsurface exploration.

No information has yet been obtained on the geochemistry of the Gearle; data on its carbon, organic matter, and hydrocarbon content and on its heavy metal association are required to assess its petroleum source potential and to provide urgently needed data on the sedimentary deposition of metallic ores. Barite has been regarded as a common associate of high-temperature metallic minerals; it is here occurring in evident sedimentary relationships. It is necessary that the barite beds be fully investigated from the point of view of sedimentary ore genesis - its atomic structure and its trace associates - so that, in orebodies, this association may be recognized.

Information on the thickness and detailed lithology of the Gearle may be obtained in the course of drilling for deeper targets, but it is important to realize that precise data on these parameters can provide essential indications of palaeogeographic and structural trends not otherwise available.

The glauconite contained in the Gearle may be used to calibrate the Cretaceous time-scale by isotopic age determinations.

Alinga Formation

The Alinga Formation was named (as Alinga Beds) by Clarke & Teichert (1948), renamed 'Alinga Greensand' by Fairbridge (1935), and renamed 'Alinga Formation' and re-defined by Johnstone et al. (1958). The Alinga Formation consists of dark green glauconitic and in places carbonaceous siltstone, glauconitic fine-grained sandstone, and dark green greensand, conformably overlying the Windalia Radiolarite and disconformably overlain by the Toolonga Calcilutite; it almost certainly grades laterally into the Gearle Siltstone.

The type locality is at Alinga Point in the lower Murchison River valley; the type section (Johnstone et al., 1958, p. 15) is 50 feet thick.

In the scarps along the northern side of the lower Murchison River the outcrop of the Alinga Formation is complicated by landslides. In the few places where the thickness can be neasured it ranges from 20 to 50 feet (Condon & Henderson, 1955). The Alinga Formation apparently does not extend very far from outcrop: Murchison House bores No. 4 and 5 are the only bores that passed through green rock below the chalky Toolonga.

The thinness of the formation and its high glauconite content suggest a winnowing of clay and fine silt from the Gearle Siltstone, probably in a shallower part of the basin of deposition.

Fossils in the Alinga include foraminifera, radiolaria, belemnites, and fish remains, but the poor faunas available have not yielded firm correlations. Its position between the Windalia and Toolonga indicates a correlation with part of the Gearle Siltstone. Hoelscher & McKellar (in McWhae et al., 1958 p. 116) made a tentative correlation between their 'Peepingee Greensand' and the Alinga Formation, but as the Peepingee is reported to be disconformable on the Windalia it is likely to be younger than the Alinga.

The upper part of the Cretaceous System in the Carnarvon Basin has been included on the 'Cardabia Group'. This is discussed further on p. 29; the respective formations are here discussed separately and not combined in any group.

Korojon Calcarenite

The Korojon Calcarenite was named by Condon (1954) and defined by Condon et al. (1956, p. 21). That definition needs to be modified slightly. The Korojon Calcarenite is the formation of friable calcarenite, hard coquinoid calcarenite with abundant shells and fragments of giant Inoceramus, and soft calcilutite, resting, in outcrop, unconformably on the Gearle Siltstone and disconformably below the Miria Marl and grading laterally into the Toolonga Calcilutite.

The type section, at Lat. 22°53'S., Long. 114°07'E. (Condon et al., 1956, p. 23 and pl. 3), is 126 feet thick.

The base of the Korojon is at the marked change in lithology from fine-grained terrigenous sediment below to carbonate sediment, commonly fine-grained, above. The lateral boundary between the Korojon and the Toolonga must be arbitrary and might be placed where the overall grainsize changes from fine to medium.

The top of the Korojon is at a marked change of lithology from a pure carbonate rock to a clayey marl. The boundary is generally marked by a bed of phosphatic nodules.

The Korojon crops out from the north end of the Giralia Anticline to the Gascoyne River. In the subsurface it is evident from Cape Range and Onslow to the Wooramel River. The proportion of calcilutite increases southward, and near the Wooramel River the Korojon grades into the Toolonga.

The Korojon is about 150 feet thick at the north end of Giralia Anticline, 126 feet at C-Y Creek, and 75 feet at the south end of the Anticline, where its top is eroded. It is about 235 feet thick in Centenary Bore, Cardabia, about 200 feet in the Hill Springs area, and about 200 feet in Brickhouse No. 4 Bore. Elsewhere in water bores it is not possible to distinguish the Korojon from the Toolonga. The very distinctive feature of the lithology of the Korojon is the shells and shell fragments of a giant Inoceramus, the aragonite prisms of which can be recognized in bore cuttings. In outcrop the Korojon is white to cream, but in deeper intersections in the subsurface it may be blue-grey.

Apart from the characteristic Inoceramus, the Korojon contains a rich fauna of Foraminifera, some other pelecypods, and some ammonites. Edgell (1957) and Belford (1958) consider that the Foraminifera indicate a Campanian to Lower Maestrichtian age. Although Edgell (1954) had determined Bolivinoides decorata (Jones) australis Edgell as having close affinities to the upper Campanian B. decorata decorata, Brunnschweiler (in Condon et al., 1956) considered the Korojon to be of Santonian age on the evidence of the ammonites. As the overlying Miria Marl is more certainly Maestrichtian and as there is certainly a disconformity between it and the Korojon it seems likely that the Korojon is Santonian to Campanian in age. From water-bore evidence it seems possible that the Korojon and Toolonga in their masimum developments are laterally equivalent.

The Korojon Calcarenite was deposited in the open sea in fairly shallow water with an abundant supply of nutrients and lime but very little terrigenous material. Some of the coquinoid beds of Inoceramus have the appearance of shell banks, and may have developed on shoal banks in the Upper Cretaceous sea.

It is possible that in spite of the abundant marine life some of the resulting organic matter, apart from the tests, may have been preserved in the sediment and there formed oil. The horizontal and vertical variations from fine to coarse grain would favour primary migration and the porous shell beds and banks should have formed excellent reservoirs. In the Giralia Anticline the Korojon is sufficiently permeable to be an important shallow aquifer: it should not be overlooked as a possible oil-bearing formation and in suitable situations may have drained oil into the permeable Boongerooda Greensand.

The Korojon Calcarenite is anticlinal and conformable with the Tertiary limestone in the coastal anticlines between Cape Range and Grierson Anticline, and synclinal between them. East of this trend it is probably mainly gently west-dipping, but may include folds not evident because of superficial deposits.

Additional work on the Foraminifera, better collections and more palaeontological work on the ammonites, and new work on the microplankton may establish firmly the age range of the Korojon Calcarenite and whether or not it is anywhere fully equivalent to the Toolonga Calcilutite.

Detailed subsurface studies may indicate areas of porosity and permeability that may be regarded as drilling targets for oil.

Toolonga Calcilutite

Clarke & Teichert (1948) named the 'Toolonga Chalk' but excluded the overlying 'Second Gully Shale'. Johnstone et al. (1958) showed that this upper material was calcilutite and could not be separated for mapping purposes from the Toolonga. They proposed that the name Toolonga Calcilutite be used for the whole calcareous sequence. The Toolonga Calcilutite consists of calcilutite and fine-grained calcarenite, mainly soft, with abundant marine fossils; it rests disconformably on the Alinga Formation and Gearle Siltstone, grades laterally into the Korojon Calcarenite, and is overlain unconformably by Tertiary limestone. In large areas in the southern part of the Gascoyne Basin its eroded top is at the present land surface, and more or less travertinized.

Its base is placed at the very marked change in lithology from terrigenous siltstone below to fine-grained carbonate rock above. This change is obvious where the rocks are fresh in outcrop, but may be obscure where both are leached. In the subsurface the best means of distinguishing the formations is the calcilog. The Toolonga can be distinguished from the Korojon in electric logs and gamma ray logs but not in calcilogs. The top of the Toolonga is marked by a change from soft calcilutite below to hard and friable calcarenite above; this is distinctive in outcrop, in electric logs, and by a drilling break.

The type locality is the Toolonga Hills on the northern side of the lower Murchison valley. The type section (Johnstone et al., 1958, p. 16) is 85 feet thick.

The Toolonga Calcilutite cannot readily be distinguished from the Korojon or the Tertiary limestones in water bores except where these have been carefully logged during drilling by a geologist. McWhae et al. (1958 p. 113) report a thickness of 895 feet in WAPET's Dirk Hartog No. 17B bore. In the new No. 4 bore Brickhouse (23½ miles south-south-east of Carnarvon) Toolonga Calcilutite was penetrated between 353 and 1155 feet (802 feet drilled thickness); this included a thick member of calcarenite near the bottom, indicating that the Korojon Calcarenite probably extends downwards as far as does the Toolonga. In this bore the Toolonga is overlain by the Korojon Calcarenite. The only other well-identified occurrence for which the thickness is available is in BMR 5 Giralia, where the Toolonga was penetrated between 114 and 264 feet (150 feet drilled depth); it is overlain by the Korojon and underlain by the Gearle Siltstone. McWhae et.al. (1958, p. 113) report its presence 'in some of the bores in the Rough Range area'. The Korojon Calcarenite in outcrop on the Giralia Anticline in places rests on the Toolonga Calcilutite; in C-Y Creek the type section of the Korojon rests on 100 feet of Toolonga - not directly on the Gearle Siltstone as reported by Condon et al. (1956).

Taking the Korojon and Toolonga together, it is a little easier to obtain the regional thickness variations, undoubtedly the unit thins in the south end of the Gascoyne Basin and is thickest in the area between Dirk Hartog Island and Carnarvon; north of Minilya River it is mainly between 200 and 300 feet thick. This thinner area is of course the area of development of the Korojon and probably indicates a shallower area of the depositional basin. The Toolonga probably was deposited in the deeper parts of the Upper Cretaceous basin in an infraneritic environment with abundant pelagic life and some benthos.

It seems likely that the marine basin in which the Toolonga Calcilutite and Korojon Calcurenite were deposited was completely open and deepening to the west; this contrast strongly with the restricted north-opening basins of the Lower Cretaceous and Palaeozoic.

The Toolonga Calcilutite rests unconformably on the Winning Group; the surface of unconformity is an erosion surface of moderate relief and probably is itself folded. The Tertiary limestones are concordant with this surface and with the Upper Cretaceous and therefore it is difficult to separate the sedimentary parts of the folds from tectonic. In such large gentle folds as the Cape Range and Giralia Anticlines the fold arch could not be formed by tangential stress and must be related either to draping over topographic ridges or to vertical uplift (e.g. by faulting). We do not yet know enough about the subsurface configuration to decide this question, although some of the smaller anticlines in Tertiary limestone in the Minilya River area appear on seismic evidence to be related to older faults.

The Toolonga Calcilutite has a fairly rich fossil fauna of foraminifera, crinoids, and pelecypods. These are regarded by Belford (1960) as indicating a Santonian to Campanian age for the Toolonga, in outcrop. A range into lower Maestrichtian is claimed by McWhae et al. (1958, p. 113): as no basis for this is presented it cannot be examined. However, as there is an established hiatus between the Korojon and the Miria Marl it is possible that there was erosion or non-deposition in topographically higher areas of the basin where the Korojon was deposited while deposition continued in deeper parts where the Toolonga was deposited.

Additional work is required on the faunas of the Toolonga and Korojon in order to refine the faunal control of the Upper Cretaceous in Australia; microplankton and spores and pollens may be particularly useful in effecting correlations with sequences in Eastern Australia.

Miria Marl

The Miria Marl (named by Condon, 1954; defined by Condon et al., 1956) consists of fossiliferous marl and calcarenite disconformable on the Korojon Calcarenite below and disconformably overlain by the Boogerooda Greensand.

The base of the Miria Marl is commonly marked by a thin bed of small phosphatic nodules reworked from the Korojon Calcarenite; the top is placed at the sharp change of lithology from marl or calcarenite to greensand.

The Miria Marl is a thin persistent unit that crops out in dissected anticlines from the northern end of Giralia Anticline to the north end of Salt Lake. It has not been recognized in the subsurface as it has not been cored and is not thick enough to appear separately in cuttings.

Its fauna includes abundant foraminifera, echinoids, pelecypods, ammonites, gastropods, corals, brachiopods, and shark teeth. The foraminifera assemblage strongly suggests a Maestrichtian age for the Miria Marl (Edgell, 1957), but affinities of the Ammonite fauna suggest an upper Campanian to lower Maestrichtian age (Brunnschweiler, in Condon et al., 1956; and 1966).

More work is required on both microfossils and megafossils to resolve the question of the age of the Miria Marl.

CAINOZOIC

Cardabia Group

Raggatt (1936) used the name 'Cardabia Series' for the whole carbonate sequence in the eastern scarp of the 'Giralia-Cardabia Range'. Condon (1954) and Condon et al. (1956) followed Raggatt by referring to the whole sequence as Cardabia Group even though it was recognized that there were important disconformities in the sequence. I agree with McWhae et al. (1958, p. 110) that the 'Cardabia Group' is an unsatisfactory unit; the name should be restricted to one lithogenitic unit or the other, and I propose, because the outcrop is restricted to the area around Cardabia Station, to restrict the name Cardabia Group to the upper part of the sequence.

The Cardabia Group, then, may be re-defined as the sequence of fossiliferous carbonate rocks with minor sandstone and greensand disconformably overlying the Miria Marl and disconformably overlain by the Giralia Calcarenite. It consists of the basal Boogerooda Greensand, Wadera Calcarenite, Pirie Calcarenite, Cashin Calcarenite, and Jubilee Calcarenite (Condon et al., 1956).

As the formations can be recognized only in outcrop by means of minor changes of lithology, only the Group as a whole will be considered.

The Cardabia Group as here amended crops out on the Giralia and Marrilla Anticlines and on the Chargoo and Warroora Anticlines at the north end of Salt Lake.

In bores the Cardabia Group can be identified from Cape Range to Dirk Hartog and appears to range in thickness from about 50 feet on Chargoo Anticline and 30 feet in Grierson's Tank bore to 280 feet in Peron No. 1 Bore and about 400 feet in Centenary Bore, Cardabia. It cannot be identified east of the North-west Coastal Highway. It appears to thicken westward in general agreement with the Toolonga-Korojon.

The Cardabia Group contains an abundant marine fauna including foraminifera, radiolaria, corals, echinoids, brachiopods, bryozoa, pelecypods, cephalopods, and gastropods. Edgell regarded the foraminifera as indicating a Palaeocene to lower Eocene age, while Brunnschweiler considered the echinoids to suggest a Danian age for the main part and a lower Eocene age for the uppermost part (both cited in Condon et al., 1956). On the evidence of the Foraminifera there appears to be no large hiatus within the Group and its age appears to be Palaeocene to lower Eocene.

The Cardabia Group appears to be generally structurally concordant with the Miocene and Eocene above and the Upper Cretaceous below in the anticlines where it is exposed. It certainly thins across the axis of the Giralia Anticline near Korojon Pool and this may indicate convergence onto a pre-existing high.

Much more work might be done on the fossil assemblages in order to improve the understanding of the fossil sequence of the Lower Tertiary and to allow correlation with sequences in the Otway Basin and Papua-New Guinea.

The Cardabia Group has very little economic potential. The Boogerooda Greensand is a source of potable subartesian water and the carbonates may provide a source for lime and for road and concrete aggregate. The sediments of the Group are likely to have been original sources of oil, but it is doubtful that this oil would have been retained in the on-shore area.

EOCENE

Giralia Calcarenite

The Giralia Calcarenite (Singleton, 1941, p. 36; defined Condon et al., 1956) is the formation consisting of friable and recrystallized calcarenite, commonly with glauconite and limonite oolites, resting unconformably on the Cardabia Group or the Toolonga Calcilutite and overlain disconformably by formations of the Cape Range Group.

The type locality is in the creek near No. 10 Bore Cardabia and the type section at Lat. 22°55½'E., Long. 114°02½'E. is 200 feet thick (Condon et al., 1956, p. 46).

The Giralia Calcarenite crops out in the Giralia, Chargoo, Warroora, Chirrida, and Cuvier Anticlines and in an area between the Wooramel River and Yaringa North Homestead.

It ranges in thickness from 50 feet on Chirrida Anticline and about 30 feet on Wooramel to about 200 feet in Peron No. 1 bore and 225 feet on Giralia Anticline (west flank). On Giralia Anticline an uneven surface at its base and uneven erosion of its upper part produce a wide variation in thickness - from 20 feet on the central east flank to 225 feet on the west flank at the Bullara-Giralia road. McWhae et al. (1958) report a thickness of 740 feet in Rough Range South No. 1 Bore.

The rich marine fauna includes larger foraminifera (Nummulites, Discocyclina, Asterocyclina, and Assilina) (Edgell in Condon et al., 1956 p. 47) and Aturia, Aturoidea, and Teichertia (Glenister et al., 1956). The foraminifera indicate a middle to upper Eocene age.

Definite correlation has now been established with the Merlinleigh Sandstone of the eastern part of the Carnarvon Basin because of the presence in both formations of Aturia clarkei. The Giralia Calcarenite probably correlates with the Knight Group of the Otway Basin (Glaessner & Parkin, 1958, p. 105) and certainly has equivalents among the Eocene limestones of Western Papua (the Australasian Petroleum Co. 1961, pp. 47-56).

The Giralia Calcarenite was laid down in an open shallow sea; the quartz sand and limonite pellets possibly were derived from the dissection of a lateritic surface and there is good evidence that such a surface had developed in the eastern part of the Carnarvon Basin before the Eocene.

As the Giralia Calcarenite is bounded above and below by unconformities there remains a possibility of structural discordances at one or other of these surfaces.

The Giralia has no present economic significance, but it is porous and permeable enough in places to have potential as a groundwater reservoir; if one of the unconformities intersects source beds the Giralia could hold oil, particularly where it is capped by the impermeable Miocene calcilutite.

Comparatively little work has been done on the fossils from the Giralia. The fauna is rich and varied enough to provide useful correlation links between the Indo-Pacific assemblages and the southern Australian.

Merlinleigh Sandstone

The Merlinleigh Sandstone was named by Teichert (1950) and defined by Condon (1954). It consists of quartz sandstone with minor siltstone and conglomerate and rests unconformably on the Permian of the Merlinleigh Basin. Its upper surface is a deeply weathered Tertiary land surface.

The type locality is in the scarp and mesas near Merlinleigh homestead (now abandoned); the type section (Condon, 1954, p. 119) is 30 feet thick.

The Merlinleigh Sandstone crops out intermittently from the western part of Lyndon Station to the northern part of Carey Downs Station. Its maximum thickness is 50 feet; in detail its thickness is determined largely by the shape of the underlying surface.

The fossils in the Merlinleigh are commonly opalized and are quite distinct in their preservation from Permian forms with which they may be found in wash from a scarp. Molluscs, including nautiloids, are fairly common, and corals, echinoids, foraminifera, and fossil wood with molluscan borings are found in some places. These fossils establish the age as middle to upper Eocene and establish certain correlation with the Giralia Calcarenite.

The Merlinleigh Sandstone has no present or potential economic significance.

Pindilya Formation

The Pindilya Formation (Konecki, Condon, Dickins, & Quinlan in McWhae et al., 1958, p. 130) consists of quartz sandstone, quartzwacke, conglomerate, and micaceous siltstone; it rests unconformably on Permian formations in the Byro Basin and perhaps southward into the Coolcalay Basin.

Around the northern end of the Carrandibby Range, the Pindilya Formation grades laterally into the dominant quartz sandstone lithology of the Merlinleigh Sandstone; there is no continuity in outcrop, but the gradual change from mesa to mesa is quite evident. Apart from this the only evidence of the age of the Pindilya are some bryozoans and corals in the same opaline preservation as the Merlinleigh fossils found loose on the surface of Permian outcrop below a scarp with Pindilya Formation at the top. The species of fossils are not determined, but the distinctive preservation gives support to the spatial evidence for the correlation of the Pindilya with the Merlinleigh.

Like the Merlinleigh, the Pindilya Formation is deeply weathered with a duricrusted surface. Its thickness is quite variable and related to the shape of the underlying surface. The maximum known thickness is 90 feet.

The Pindilya has no present economic value and no potential. It masks the older formations in the area south of the Wooramel River and makes seismic surveying difficult by providing strong velocity contrasts close to the surface.

MIOCENE

Although there is no record of Oligocene rocks in outcrop in the Carnarvon Basin the presence of about 600 feet of sediments below the lowermost exposed beds (which are lowest Miocene) and above the Eocene suggests that Oligocene beds may be present in the subsurface of Cape Range. As no palaeontological work has been reported from these beds no further information is available.

The Miocene of the Carnarvon Basin consists mainly of limestone named by Clapp (1925) and defined by Condon et al. (1953) as Cape Range Group. This comprised the Mandu Calcarenite, Tulki Limestone, and Trealla Limestone. Other possibly Miocene formations are the Pilgramunna Formation and the Lamont Sandstone.

Cape Range Group

Although in the Cape Range no obvious unconformity can be established between the Trealla and Tulki and no large faunal break is evident, the wide regional extent of the Trealla compared with the very restricted occurrence of the Tulki and Mandu indicate a significant change in the palaeogeography. It is proposed therefore to restrict the Cape Range Group to the Mandu and Tulki formations.

The Cape Range Group is re-defined as the predominantly carbonate sediments resting unconformably on the Giralia Calcarenite and overlain conformably or unconformably by the Trealla Limestone, disconformably by the Pilgramunna Formation, or unconformably by the Exmouth Sandstone. It includes the Tulki Limestone and the Mandu Calcarenite.

The formations of the Group are described adequately in Condon et al. (1953).

Very little useful information on the lithology, faunas, thickness, or structure of the subsurface parts of the Group was obtained by the drilling in the Cape Range area. McWhae et al. (1958) report a total thickness of about 800 feet for the Mandu Calcarenite, but do not give any information about the subsurface part of the formation.

It is evident from the information reported by Condon et al. (1953) that the Mandu in places grades laterally into the lower part of the Tulki and that the Trealla rests on an eroded surface of the Mandu in the Rough Range.

Within Cape Range the groundwater level appears to be very little above sea level, and this suggests that the whole of the Range at least down to sea level is permeable, probably on account of solution cavities. This makes the Range a good source of groundwater but eliminates any possibility of oil accumulation down to that level.

In areas where solution has not been effective, and particularly in offshore areas, there is some possiblity of the Tulki forming a cap and the Mandu providing reservoir for the accumulation of indigenous oil.

The limestone in outcrop forms a large potential source of raw material for lime, portland cement, and road and concrete aggregate.

Before any worthwhile appreciation can be made of the oil potential of the Cape Range Group, reliable data on its subsurface extensions must be obtained. In any drilling carried out in the area the importance of this group should not be ignored merely because in outcrop it has no potential for oil.

Trealla Limestone

The Trealla Limestone (Condon et al., 1953, p. 28) is here redefined as the formation of hard foraminiferal calcilutite resting disconformably or unconformably on Tulki Limestone, Mandu Calcarenite, Giralia Calcarenite, or older formations, grading laterally into the Pilgramunna Formation, and overlain unconformably by the Vlaming sandstone, Exmouth Sandstone, and Quaternary deposits.

The Trealla Limestone extends from Barrow Island (McWhae et al., 1958, p. 128) to Yaringa North Station, and formations of similar lithology and fauna are known in the Eucla Basin (Nullarbor Limestone) and in the Darai uplift of Western Papua (the Australasian Petroleum Co., 1961). The age of the Trealla is certainly stage $f_1 - f_2$ of the Indo-Pacific Tertiary (van der Vlerk, 1950), and this is probably roughly equivalent to the Burdigalian of Europe.

The Trealla Limestone was laid down in an open sea of moderate depth with a very reduced supply of terrigenous sediment (mainly quartz sand). Algal growths occur high on the Cape Range Anticline, and this indication of shallow-water environment suggests a topographic high over the Cape Range area during the deposition of the Trealla.

On the north plunge and western flank of the Cape Range Anticline the Trealla Limestone grades laterally into the Pilgramunna Formation.

The Trealla Limestone is up to about 200 feet thick on Cape Range (east flank), 70 feet on the west flank of Giralia Anticline and 4 to 20 feet on the east flank, 50 feet on Chargoo Anticline, 40 feet on Yankie Tank Anticline, 50 feet on Chirrida Anticline, about 60 feet on Warroora Anticline, and 25 feet on Yaringa North Station.

Although in outcrop the Trealla is extremely permeable because of solution cavities, in the subsurface where it has not been exposed to weathering, and especially offshore, it may be a very good impermeable cap-rock and as such improve the oil potential of all the older sequence.

Pilgramunna Formation

The Pilgramunna Formation (Condon et al., 1955) consists of coarse-grained and medium-grained quartz sandstone, sandy limestone, and limestone; it rests unconformably on the Tulki Limestone or conformably on Trealla Limestone and grades laterally into the Trealla. Is is disconformably overlain by the Vlaming Sandstone and probably by the Exmouth Sandstone.

The Pilgramunna Formation and the Vlaming Sandstone were included by Condon et al. (1955) in the 'Yardie Group', but this group has no validity as it includes an important disconformity.

Only the Lower 97 feet of the section described as the type section (Condon et al., 1955, p. 31) actually belongs to the Pilgramunna Formation: re-examination of this section revealed a well-exposed erosional unconformity at this point with freshwater gastropods immediately above.

The Pilgramunna Formation includes beds of limestone breccia and tongues of limestone of the lithology of the Trealla Limestone. The reduced thickness as compared with the equivalent Trealla Limestone, the obvious erosional unconformity at the base, and the dominance of quartz sand, indicate an environment strongly affected by wave and current action where limestone was broken up after deposition, quartz sand was well rounded and sorted, and much of the finer-grained sediment was not deposited. This environment is likely to be the open ocean side of a submarine bank or island.

The Pilgramunna Formation crops out only on the west flank and north plunge of the Cape Range Anticline, where it ranges in thickness from 70 to 100 feet.

Lamont Sandstone

The Lamont Sandstone (Condon et al., 1956) is the formation of quartz sandstone, calcareous in places, resting unconformably on the Giralia Calcarenite and overlain unconformably by the Trealla Limestone.

The Lamont Sandstone crops out in lenticular bodies along the western flank, north plunge, and north-east flank of the Giralia Anticline, on the flanks and north nose of the Marrilla Anticline, and on the Chargoo Anticline. It ranges in thickness up to 30 feet.

It contains only rare foraminifera, of lower Miocene type. These and its relationships to the other formations establish it as lower Miocene in age and probably to be correlated with the Mandu Calcarenite.

The presence of the Lamont Sandstone in outcrop suggests that in the subsurface the Mandu may grade laterally into such sandstone and, with its probable source characteristics, may have produced oil into traps in that sand either on structures (as exposed) or on homoclines in favourable environments. The western flank and north and south noses of the Cape Range Anticline are possible areas of such sand development.

QUATERNARY

No detailed work has been attempted on the Quaternary deposits, although they cover a large part of the surface of the Carnarvon Basin. Only a few notes commenting on previous statements are included here.

'Vlaming Sandstone'

The 'Vlaming Sandstone' was named by Condon et al. (1955, p. 33) and included by them in the invalid 'Yardie Group'. However, it rests unconformably on the Pilgramunna Formation and is therefore significantly younger. Although Condon et al. claimed 'on structural grounds' that the 'Vlaming' was older than the Exmouth Sandstone they both dip at about the same angles on the west flank of Cape Range Anticline. The lithology of the two units is similar and there seems little doubt of their identivy. For this reason the name Vlaming should be dropped in favour of the older Exmouth Sandstone (Craig, 1950)

NADARRA FORMATION

The Nadarra Formation (Condon, 1962d) consists of chalcedonic limestone, fine-grained grey limestone with some siltstone, and fine-grained sandstone. It appears to be a freshwater deposit, laid down in stream valleys (and possibly lakes or swamps).

The old valleys containing the Nadarra Formation were eroded in the laterite. This suggests that the deposition of the Nadarra post-dates a marked environmental change that had the effect of producing significant erosion of the previously stable lateritic surface.

Lateritization certainly developed after the deposition of the middle Eocene Merlinleigh Sandstone. Its development was probably allied to the stable climatic conditions of the Tertiary.

There is no evidence of strong tectonic events in the Tertiary in the eastern area of the Basin.

It seems likely that the significant change in environment was a change in climate from stable (and probably humid) to unstable (varying from wet to arid). Such a change, in a lateritic terrain, would cause severe dissection such as is apparent beneath the Nadarra.

The significant change in world climate from stable to unstable came at the end of the Piocene, heralding the Pleistocene ice-age.

It is probable, therefore, that the Nadarra Formation is Pleistocene in age.

Laterite

Laterite, in the sense of a complete weathered profile, is widespread at or near the surface of the Carnarvon Basin and the adjoining Precambrian areas.

It has some real importance in the search for oil and other minerals for the following reasons; it completely masks the underlying rocks and in many cases cannot readily be related to its parent rock, so that laterite-covered areas cannot be geologically mapped even where there is minor dissection of the laterite; it completely hides any traces of petroleum seepage or wax seal that might be present; it makes very difficult the obtaining of seismic records of usable quality because its high- and low- velocity layers produce noise, surface refraction, and multiples, and reduce the emergy input and return; it changes the lithological character and colour of rocks so that subsurface characteristics including porosity, permeability, and mineralogy cannot be predicted; it destroys fossils including spores and pollens so that outcropping rocks cannot be fixed in stratigraphic position.

Sections of laterite of various types are described in Condon (1954). The main correction to that description is the age of the Merlinleigh Sandstone, which should be Eocene. As a result of this revision it may be stated with certainty that no rocks younger than Eocene have been lateritized in the Carnarvon Basin area. It is significant that a separate laterite profile is developed below the Eocene and also most probably below the Lower Cretaceous. The only age that can be determined with some certainty therefore is the end of the lateritization process. If it is accepted that lateritization develops only under stable humid climate conditions the best information on this should come from global climatic data. It has now been established (Charlesworth, 1957) that world temperatures gradually dropped during the late Tertiary, but the very abrupt change in temperature coincided closely with the end of the Pliocene and was of course the precursor to the Pleistocene ice-age. This marked change in temperature must certainly have affected world climate and it seems likely that the end of the lateritization process and the beginning of strong dissection, produced by alternations of dry and wet periods, occurred at about that time. For this reason the laterite has been referred to on the maps as Upper Tertiary, although in some areas it may have developed, either intermittently or continuously, from about the Jurassic to the Upper Tertiary.

Much, but not all, of the red sand on both the high-level plain and the western low-level plain is derived from the upper zone of the laterite profile, moved, generally a short distance, into seif or hummocky dunes.

No detailed examination of the laterite has been attempted, but areas that are likely to have been developed over shales, limestones, or dirty sandstones or igneous rocks in the Precambrian would be worth sampling for bauxite.

Where the lateritized surface is intact, as in the area of the upper Wooramel River, it is seen to be gently to strongly undulating with major relief of about 500 feet in 18 miles. Local relief of more than 100 feet is fairly common. Steep slopes in the lateritized surface have been seen south of Plant Well, Daurie Creek, where a partly dissected laterite surface includes a flat mesa top and a lateritized side slope of 15°; and west of Birdrong Spring, Hill Springs Station, lateritized side slopes on a long mesa reach 18° in places.

STRUCTURE

REGIONAL STRUCTURE

The regional structure of the Carnarvon Basin is known in a general way only; the shape of the Precambrian basement floor may be deduced from gravity and airborne magnetometer data calibrated and confirmed by outcrop geology and the few bores and seismic traverses available.

These data indicate that the Carnarvon Basin is subdivided into a number of minor basins separated by basement ridges (Fig. 154). These minor basins are diverse in their depositional and structural history, but appear to approximate to the basinal downwarps where sedimentation took place.

The basement ridges are structurally high at present and most of them appear to have been structurally high for much of the time since the inception of the Carnarvon Basin.

Basement Ridges

The northern part of the Carnarvon Basin is divided into two main parts by the Wandagee Ridge, which runs from the coast at Point Locker, past Marrilla homestead, Mia Mia homestead, west of Wandagee Hill, Hill Springs homestead, Binthalya homestead, to the Wooramel River at Meedo Pool. The data are insufficient to establish the relationships clearly in the area south of Wooramel River: the Wandagee Ridge may or may not be continuous with the Ajana Ridge, which extends from the eastern part of Woodleigh Station through Meadow homestead to the outcrop of Precambrian gneiss at Galena and Northhampton.

WAPET's Yanrey No. 1 Bore is the only bore that has reached basement along the Wandagee Ridge.

The Carrandibby Ridge may or may not develop out of the south end of Wandagee Ridge or the north end of Ajana Ridge; it includes the Precambrian inlier of the Carrandibby Range and from there extends north to the margin of the basin at latitude 25° south. The Weedarra Ridge extends from the north-western end of the Carrandibby inlier northward to Mount Sandiman.

Less well defined are the Yallalong Ridge extending North from the Basin margin near the Woodrarrung Range, the Yanrey Ridge running east-west through Yanrey homestead, and the Bullara Ridge running north-north-east through Bullara homestead.

There are several low saddles on and between these ridges; these were called 'sills' in Condon (1956), but this term implies too much palaeogeographic significance and the descriptive term is preferred. On the Wandagee Ridge the Mardathuna and Winnemia Saddles are prominent features. There may also be a saddle near Mia Mia homestead; the Wooramel Saddle separates the Ajana Ridge from the Wandagee and/or the Carrandibby Ridge. The Muggon Saddle joins the north end of the Ajana Ridge to the Yallalong Ridge. There may be another saddle between the south ends of the Wandagee and Carrandibby Ridges, in the Pimbie area.

Basins

To the west of Wandagee and Ajana Ridges is the north-plunging Gascoyne Basin containing Lower and Upper Palaeozoic, Jurassic, Cretaceous, and Tertiary sediments. There is some suggestion, in gravity, magnetic, and bore data, that the Bullara Ridge extends as the western limit of the Gascoyne Basin past Bernier, Dorre, and Dirk Hartog Islands. West of Bullara Ridge the deep but poorly defined Exmouth Basin contains Upper Palaeozoic, Triassic, Jurassic, Cretaceous, and Tertiary sediments. East of Wandagee Ridge and north of Yanrey Ridge the Onslow Basin is known to contain Jurassic, Cretaceous and Tertiary sediments, and may also contain older sediments. The Merlinleigh Basin extends east of the Wandagee Ridge from the Yanrey Ridge to Pimbie; it is bounded on the east by the margin of the Basin, and in the southern part by the Weedarra Ridge. It is known to contain Devonian to Permian sediments but may also contain Lower Palaeozoic sediments (Pearson, 1964). The Bidgemia Basin, between the Weedarra and Carrandibby Ridges, contains Devonian to Permian sediments. The north part of the Byro Basin, between the Carrandibby Ridge and the basin margin, is known to contain only Permian sediments. It is not clear whether the Byro Basin extends south into the Badgerradda Syncline, south-west to the Muggon Saddle, west to the Wooramel Saddle, or all of these. In any case it appears closely linked to the Coolcalalaya Basin, between the Ajana Ridge and the Yallalong Ridge, which is the northern extension of the Perth Basin and contains Lower Palaeozoic and Permian sediments.

It is obvious that there is no very clear boundary between the Carnarvon Basin and the Perth Basin: the boundary is certainly the Ajana Ridge and probably the Muggon Saddle and Yallalong Ridge. It is possible that the Carrandibby Ridge may be sensibly continuous with the Ajana Ridge, in which case it should logically form part of the boundary between the Perth and Carnarvon Basins and the Byro Basin would form part of the Perth Basin.

Hinges

There are several hinge areas where at different times downwarping has been concentrated in a relatively mobile belt. The west side of the Yallalong Ridge is part of the very old Darling Hinge (usually referred to as the 'Darling Fault') which has produced the deepest downwarping in the Perth Basin. On the east side of the Ajana Ridge the Yandi Hinge is less well developed than the Darling. The Yandi Hinge has the same trend as, and is roughly in line with, the Madeline Hinge on the east side of the Carrandibby Ridge. The hinge on the east side of Wandagee Ridge, for which the name 'Mooka Hinge' is proposed, was active only during the Palaeozoic. The 'Learmonth Hinge' developed mainly during the Mesozoic on the western side of the Bullara Ridge.

The mechanics of hinge development are poorly understood and very little discussed. In the hinge area, crystalline basement is displaced vertically by large amounts (several miles) without any evidence of significant faulting. The basement apparently flows in this area to produce an effect of a steep monoclinal fold. Sedimentary strata laid down over this hinge area are not stretched or faulted by the downwarping of the basement, although strata deposited across the area before the hinge movement started will be monoclinally folded. The downwarping is progressive and is commonly associated with sedimentation mainly in the downwarped area, although sediments may be deposited across the hinge at times. As there is usually a difference in depth of water across the hinge, it becomes the area of rapid facies and thickness variation.

No evidence of a hinge has been obtained in the eastern part of the Merlinleigh Basin, except the occurrence of stable-shelf sediments in the eastern area (Munabia Sandstone, Moogooree Limestone, Harris Sandstone, Moogooloo Sandstone) and basinal sediments in the central part. This lithofacies distribution suggests that a minor hinge may be present not far west of the outcrop of the Moogooloo Sandstone.

STRUCTURAL DETAIL

Present information on details of structures is restricted almost entirely to outcrop, since very little detailed seismic survey has not been attempted.

Unconformities

Several major and minor unconformities have been recognized in the outcropping sequence. As any unconformity is likely to vary in character from place to place they are here described in order of age, from oldest to youngest.

The Badgerradda Group laps on to the Precambrian metamorphic rocks in a very marked angular unconformity. The surface of the older rocks has moderate relief so that the overlying strata wedge out against slopes and drape over ridges.

The Tumblagooda Sandstone laps on to Precambrian gneiss in a very marked angular and erosional unconformity (Fig. 155). The old surface of the gneiss has fairly strong relief and the Tumblagooda drapes over ridges in this surface, e.g., near Hardabut Pool, Murchison River (locality 12, Fig. 156). The unconformity on the east side of the Ajana Ridge is exposed in the region of the Yandi Hinge; because the surface is now steeply dipping, it has been interpreted as a fault, but there is no evidence of major faulting at this contact.

The Devonian sediments lap on to the Precambrian schist and granite with a strong angular unconformity. The unconformity surface has moderate to large relief, and the Devonian sediments abut against steep slopes and drape over ridges e.g., south of Williambury (locality 5, Fig. 156).

The Carboniferous sediments rest on a surface eroded into the Devonian sediments and in places (e.g. north of Williambury, locality 5, Fig. 156) abut against a steep slope of Precambrian schist. Six miles south-south-east of Moogooree Homestead (locality 13), the Carboniferous Moogooree Limestone is deposited in a steep valley eroded in the Devonian Munabia Sandstone - the Devonian Willaraddie Formation has been entirely removed at this place (Fig. 157).

The Sakmarian glacigene sediments rest on an erosional surface of strong relief developed in Carboniferous and Devonian sediments and Precambrian schist and granite. Parts of this surface were subject to ice erosion (e.g. Carrandibby Range). The Sakmarian sediments overlap a truncated surface of the Carboniferous and Devonian between Moogooree and Mount Sandiman, abut against Precambrian schist on the east side of Weedarra and Carrandibby Ridges, and lap onto Precambrian schist between Mount Sandiman and Narryer.

Artinskian marine sediments rest on an erosional unconformity of large relief cut mainly in the Sakmarian sediments; in places (e.g. on the east side of Weedarra Ridge, locality 6) the Artinskian sediments abut against a steep slope on the Precambrian schist.

A minor erosional unconformity separates the Wooramel Group from the Callytharra Formation. The surface of the Callytharra is eroded into rock-stack topography in places (e.g. near Arthur River and in Pells Range) and the sandstone is deposited around and over the stacks (Fig. 158).

A disconformity with some indication of regional truncation separates the Bulgadoo Shale and the overlying Cundlego Formation. This unconformity is very marked in the area between Minilya River and Barrabiddy Creek, where a gentle east-west syncline in the Cundlego overlies north-south folds and faults in the Bulgadoo and older formations.

The Kennedy Group rests on a surface of the Byro Group that has been eroded in some places.

The Jurassic appears to wedge out against Sakmarian and older rocks at the Learmonth Hinge.

The Cretaceous sediments lap over the Permian, Carboniferous, Devonian, Ordovician, and Proterozoic sediments and Precambrian schist and granite. In some places (e.g. along the west side of Kennedy Range and possibly at Rough Range) the Cretaceous abuts against a sea cliff eroded in the older rocks.

There is a disconformity between the Winning Group and the Upper Createaceous sediments, with some truncation of the Winning Group.

Tertiary sediments are disconformable on the Cretaceous, and there are disconformities with more or less erosion between the Eocene and Miocene, Miocene and Pliocene and Pliocene and Pleistocene.

Condon (1956) described angle of rest unconformities where marine sediments were deposited over a surface of strong relief. These features are common in both the Sakmarian (related to the relief of the underlying unconformity) and the Artinskian (where deep strike valleys eroded into the Sakmarian sediments produce striking angle of rest unconformities in the area between Moogooree and Lyons River). These features may be important for oil accumulation as they extend for miles and provide a possibility of facies variation and particularly of sand clean-up over the ridges; this variation is well shown in BMR 6 and BMR 7 (Perry, 1965), which were drilled to provide information about such features. My interpretation of the structure is shown in Figure 159.

There is good correlation on all three logs between the intervals (BMR 6) 215 to 335 feet and (BMR 7) 50 to 190 feet. The resistivity log shows sharp peaks (from calcareous beds) at different places, but this agrees with the known lenticular nature of the calcareous beds in the Coolkilya.

This correlation confirms the continuity of the Coolkilya at surface between the two bores - they are the only fully correlatable intervals in the two bores.

The absence of correlation between the underlying intervals implies a discontinuity of some sort in one or both of the bores. Core 4, BMR 6 (295 - 303 feet) exhibits core dips of 20° to 30° in slightly contorted and brecciated fine-grained quartzwacke; Core 2, BMR 7 (204 - 214 feet) shows dip of about 5°. It is likely therefore that a discontinuity occurs in BMR 6.

The next main log-break in BMR 7 is at 485 feet. Core 6 (498 - 508 feet) is in bedded fossiliferous quartzwacke with core dip of 6°. This is typical Norton Greywacke; typical Baker Formation occupies the interval from 190 to 485 feet. No interval in BMR 6 can be correlated with the Baker Formation of BMR 7.

The next main log break (all logs) in BMR 7 is at 900 feet. Logs, cores, and cuttings indicate that the interval 485 to 900 feet is predominantly quartzwacke. A siltstone interval from 740 feet to 755 feet may be taken as indicating the base of the Norton Greywacke at 740 feet.

The section below 740 feet is certainly not the normal full section of the Wandagee Formation. Core 9 (704 - 709 feet) shows core dips of 13° to 20°, core 10 (766 - 776 feet) shows core dips of 12° to 15°. These high core dips and the absence of typical Wandagee Formation suggest a discontinuity at about 740 feet.

The shaly interval from 900 to about 1215 feet could possibly be Baker Formation, the upper part of Wandagee Formation, Quinnanie Shale, or the lower part of the Coyrie Formation. The interval from 1215 feet to TD is a single formation of interbedded (and interlaminated) quartzwacke and siltstone/shale with calcareous beds; this can only be Cundlego Formation and the overlying unit therefore is Quinnanie Shale (with a typical quartzwacke member).

In BMR 6 below 335 feet there is no obvious correlation with large parts of BMR 7. This implies either very sharp facies and/or thickness change in a very short distance (not supported by normal outcrop relationships), or a fault of throw large enough to prevent repetition of the sequence.

In seeking to identify the formations the areal geology to the west of the bore should be of value. There, Norton, Baker, and Coolkilya dip gently westward into a syncline (Kennedy Range Sheet, Condon, 1962a). The bore sequence should therefore be examined to see if Norton can be recognized immediately beneath the Coolkilya (as suggested by outcrop distribution in the vicinity of the bore). There is a quartzwacke unit from 335 to 470 feet. This unit is underlain by a unit of quartzwacke (some beds calcareous) and siltstone between 470 and 850 feet. Beneath this is a shale siltstone unit with a quartzwacke member, between 850 and TD 1002. I interpret the middle unit as Wandagee Formation equivalent (with less siltstone than usual), the upper unit as Norton Greywacke, and the lower unit as Quinnanie Shale with a quartzwacke member rather more prominent than usual.

This interpretation does require significantfacies change between the two bores. This could have been caused by penecontemporaneous faulting along a fault between the two bores or by deposition over a surface of strong relief including an angle of rest unconformity.

A fault interpretation requires two normal faults each of about 200 feet throw. There is no evidence for these in the outcrop geology.

An angle of rest unconformity is the structure most likely to explain the discontinuities, the facies variations, the abundant evidence of slumping, and the outcrop geology.

Faults

Very few major faults have been established. There are many major stratigraphic contacts that other workers have regarded as faults, but these have mainly been established as unconformities, in some cases in the hinge area.

There is good evidence (in joint and cleavage patterns and stratal geometry) of a major reverse fault to the west of the outcrop area of the Badgerradda Group; however, this evidence places its outcrop trace some 5 miles to the west of the inferred fault shown by Perry & Dickins (1960, p. 1).

Within the Palaeozoic sediments only minor faulting, mainly associated with aliding and compaction along the hinge-line slope, has been established. Of this type are the many small faults in the Wandagee Hill area and along the western side of Kennedy Range (both related to the slope off the Mooka Hinge into the Merlinleigh Basin), at the south end of Carrandibby Range (related to the Madeline Hinge), and between Minilya River and Kennedy Range (possibly related to the eastern hinge of the Merlinleigh Basin).

The indications are very strong that all the downwarping and associated faulting and folding were penecontemporanceous with sedimentation and that no strong positive movements, apart from the epeirogenic uplift, occurred after deposition. This suggests that the main petroleum traps are likely to be primary traps in sedimentary and drape structures and at porosity barriers.

Folds

The major folds in the Carnarvon Basin are the synclinal basin downwarps and the anticlinal drapes over the basement ridges. Only those strata that were deposited over the ridge before the downwarps developed are likely to be anticlinal right across the ridge, although sediments deposited during the hinge movement may have some anticlinal form.

The Tumblagooda Sandstone is likely to be anticlinal over the Ajana and Wandagee Ridges and the Dirk Hartog Limestone may be anticlinal over the southern extension of the Bullara Ridge and over the Wandagee Ridge.

The whole of the Palaeozoic may be anticlinal over the Bullara Ridge.

The Devonian is partly anticlinal over the south-plunging ridges south of Williambury and probably over parts of the Weedarra Ridge. It may be anticlinal on parts of the Wandagee Ridge.

The Sakmarian is anticlinal on the Weedarra Ridge, Carrandibby Ridge, parts of the Wandagee Ridge, and possibly on the Yanrey Ridge.

The Artinskian is anticlinal over the northern end of the Bullara Ridge.

In the western part of the Merlinleigh Basin several moderately large anticlines are developed in the Artinskian sediments (e.g. at Barrabiddy Creek, Gascoyne River, and along the western part of Kennedy Range). Poor surface evidence and equally poor seismic data suggest that these folds may have been produced by the sliding down the hinge slope of larger or smaller thicknesses of sediments at an early stage of induration.

Folds to the east of the Weedarra Ridge and the Madeline Hinge may also be of this type.

Such gravity-slide structures continue downwards only as far as the slide surface. Folds and faults result from the rotation of the upper block and from bulking of incompetent beds. The form and maximum depth of the slide surface cannot be estimated unless its dip at outcrop can be measured and the outcrop width of the slide movement effects can be established.

Anticlines have been formed in many parts of the basin by draping over pre-existing topographic ridges: the Artinskian and Cretaceous of the

Giralia Anticline; the Artinskian in the anticlines south of Gap Pool, Wooramel River; the Cretaceous south of Barrabiddy Creek; the Cretaceous and Tertiary of the coastal anticlines from Cape Range to Grierson Anticline.

It is not impossible that some folds and faults have been developed in the basin by major tectonic stresses, but the bulk of the available evidence at this time denies this. It is of critical importance that this be kept clearly in mind in examining seismic records and preparing structural interpretations from them; there may be no vertical continuity in folds (see Fig. 160) and stratigraphic breaks interpreted as faults may be unconformities that continue neither upwards nor downwards. The structural form of each major sediementary unit (between unconformities) is likely to be quite distinct from all other units and to require separate exploration.

PALAEOGEOGRAPHY

The palaeogeography of the period of deposition of each formation has been indicated in the section on Stratigraphy, but the basin-wide picture is important enough to justify summarizing.

Sedimentation in the area of the Carnarvon Basin began in the Proterozoic with the deposition of the sediments of the Badgeradda Group. Their present extent beyond the area of outcrop is entirely unknown. The present outcrop area includes a hinge line between shelf sediments to the east and basinal sediments to the west; the supply of sediment was from the south and east and it may be inferred that the sediment was derived from a terrain of moderate relief some distance to the east and south; no northern or western limit to the basin of sedimentation can be indicated.

Before the Ordovician and/or Silurian sediments were deposited the Badgerradda Group was strongly faulted.

The Ordovician sediments were deposited probably over the greater part of the present area of the Carnarvon Basin, except perhaps its eastern part. Sediment was carried from the east, from a terrain of low relief from which quartz sand, clay and lime, and iron in solution were derived. The Ajana Ridge and possibly the Wandagee Ridge were in existence as topographic highs, but the whole area was part of a slowly subsiding shelf on which sedimentation kept pace with subsidence to maintain a shallow-water environment. It seems likely that the Coolcalaya Basin started differential downwarping along the Darling and Yandi Hinges during the deposition of the Tumblagooda Sandstone.

In the Devonian, downwarping of the Merlinleigh and Gascoyne Basins started, the sea transgressed into these downwarped areas, and sediments derived from the east were deposited during the Middle and Upper

Devonian and Lower Carboniferous. Basin relief varied from fairly large to very small and supply of sediment from torrential to very little. Continental to shallow-water marine sediments were deposited in the eastern part of the Merlinleigh Basin, deeper-water marine sediments over the Wandagee Ridge, which was almost certainly a topographically high area of the sea floor, and deep-water basinal shale and limestone in the western part of the Gascoyne Basin. It seems likely that the sea deepened westward into the Merlinleigh Basin and that basinal shale and calcilutite were deposited in its central part and also over most of the Gascoyne Basin.

Towards the end of the Devonian Period the area was uplifted so that at least the eastern edge of the Basin was exposed to erosion for a short time. This was followed early in the Lower Carboniferous by rapid subsidence and transgression by the sea, but little differential downwarping. Shallow-water marine limestone was deposited over large areas and reefs may have developed on submarine shoals such as over the Wandagee Ridge. A change of climate to semi-arid, or a marked uplift of the hinterland, or both, produced a large supply of terrigenous sediment deposited in deltas at the eastern edge of the Basin and spreading as marine sands and silts as far at least as the Rough Range area. It seems likely that by this time the long gulf-like form of the sea had been established, bounded to the west and south by land or shoals. From time to time there probably was continuous sea from the Merlinleigh Basin through southward to the Perth Basin. No Carboniferous or Devonian sediments have yet been found in the Perth Basin, but it seems very probable that marine sediments were deposited there during the Devonian and Carboniferous and probably are preserved in the deeper parts of the basin.

During the Upper Carboniferous, the area of the Carnarvon Basin was uplifted above sea level and subjected to erosion so that the sediments were stripped off the marginal area. The material produced by this erosion were carried beyond the limits of the Carnarvon Basin.

Towards the end of the Carboniferous a marked change in climate developed until the Permian ice age was established. Snow and ice precipitation produced first valley glaciers and later ice sheets. Partly as a result of the load of ice the area of the Carnarvon Basin subsided beneath sea level. The continental glaciers brought rock debris from the hinterland to the east and deposited either in outwash plains, from where it was partly carried by melt-water into the lake or sea, or directly into the lake or sea from icebergs. It is evident that at times areas of the Carnarvon Basin were covered by essentially freshwater lakes, perhaps developed behind barriers either of ice or of moraine material. The whole area was mainly marine most of the time. There were a number of glacial and interglacial stages that are indicated by the variations in dominant lithology of the associated sediment - tillitic during the glacial stages when the ice reached the sea and more normal terrigenous sediments during interglacial stages. The Austin Formation, Dumbardo Siltstone, Koomeran Greywacke, Mundarie Siltstone, and parts of the Weedarra Shale were deposited during glacial stages; there may have been minor interglacials within some of these major glacial stages. At times the sea supported large populations of cold-water species that formed shell banks in some places.

The ice age in this area finished towards the end of the Sakmarian Age. With the removal of the ice-load the area rose above sea level and strong dissection of the glacigene sediments began.

The next important subsidence and marine transgression began in the early Artinskian, when mixed terrigenous and carbonate sediments were deposited in the marginal areas of the basin. Downwarping was re-established in the Merlinleigh, Byro, and northern Gascoyne Basins and probably in the Onslow Basin, and marine shales were deposited in their deeper parts. After a minor regression and transgression the sediments of the Byro Group were deposited in intermittently downwarping basins where sedimentation filled each successive downwarp. Sediment was supplied into the Artinskian gulfs from east (Precambrian provenance), west (Palaeozoic sedimentary provenance) and south (mainly sedimentary provenance). The topography of the pre-Artinskian landsurface produced drape folds, angle of rest and abutment unconformities, and slump structures in the sediments.

After a minor retreat and re-advance of the sea at the end of Artinskian time sandy sediments were deposited in a shallow Kungurian sea in the central part of the Merlinleigh Basin, probably with an outlet to the north. The sediment came mainly from the western area.

The area was then uplifted and eroded until the Jurassic Period, when the north-western area subsided, forming the Exmouth Basin, and terrigenous sediments were deposited in a rapidly down-warping basin.

After a minor retreat of the sea a major transgression covered a large part of the area of the Carnarvon Basin in the lowermost Cretaceous (Fig. 146). A basal sand was deposited, followed by shale and organic siliceous sediments. The sea retreated in Turonian time and from then to the Pliocene advanced and retreated several times over the present coastal area.

ECONOMIC GEOLOGY

PETROLEUM

As the Carnarvon Basin contains at least 100,000 cubic miles of sediments most of which are marine, and large structural relief much of which started to develop during sedimentation, the likelihood of the occurrence of petroleum in useful amounts is very great.

It can be assumed that the central area of the Merlinleigh Basin, the western part of the Gascoyne Basin, and the central area of the Byro Basin contain mainly shales that should have generated large quantities of petroleum. Also the Jurassic siltstone of the Exmouth Basin and the Lower

Cretaceous shale of the Gascoyne, Onslow, and Exmouth Basins were almost certainly petroleum source rocks.

Reservoir rocks in suitable relationship to source rocks and with structural and hydraulic histories that favour accumulation and retention of oil are the sought-after targets for drilling. Some such areas can be indicated with some assurance and other areas can be suggested as likely but requiring additional subsurface data to decide prospects.

The carbonate facies of the Ordovician-Silurian will certainly include adequate reservoir characteristics in places and is likely to be in hydraulic contact with marine shale in the deeper parts of the Ordovician-Silurian basin. The carbonate facies probably extends from Dirk Hartog Island northward perhaps as far as the Cape Range area and possibly extends southward beyond the Houtman Abrolhos.

Anticlinal form is indicated at the south end of Cape Range. Much of the prospective area is offshore; its east-west width has not been established. Similar facies has been established on Wandagee Ridge and probably extends along this ridge perhaps from about Mia Mia to Pimbie. In places along the ridge this facies will be unconformable under Devonian and younger sediments and may have received oil from any of the younger source beds.

It is likely to have large anticlinal structure at Binthalya and fault or unconformity closure elsewhere. It is not known whether the Wandagee Ridge carbonates are continuous with the coastal, but it seems likely that no basinal sediments intervene.

The Tumblagooda Sandstone has adequate porosity and permeability, but there is no strong indication of its association with source beds. It probably extends from the Murchison to about the Wooramel River.

Sand reservoir facies in the Devonian is known only in outcrop on the eastern side of the Merlinleigh Basin - it may be present, capped and in contact with source beds, in the Bidgemia Basin and along the Weedarra Ridge. Stromatoporoid reefs may have developed along the Wandagee and Weedarra Ridges. Stratigraphic traps in sandstone and carbonate reservoirs are likely along the west flank of the Wandagee Ridge between Marrilla and Point Locker.

In the Lower Carboniferous, carbonate reservoir facies is developed in outcrop in the eastern part of the Merlinleigh Basin and probably in the western part of the Gascoyne Basin (Wapet's Grierson bores). Sands may be developed along the east side of the Wandagee Ridge between Lyndon River and Gascoyne River and sands or reefs or both around the north and south ends of the Merlinleigh Basin at Lyndon River and near Pells Range south of Gascoyne River; stratigraphic and structural traps may be found in these areas.

Although the section of the Sakmarian penetrated in Wapet's Rough Range No. 1 was not prospective, sands at its base contained a good gas show. In bores BMR 8 and 9 in the Byro Basin good marine shales and porous carbonates were encountered in the Sakmarian. Because of the unusual (marine glacial) environment, the facies distribution is not evident. BMR 8 and the outcrop over Jimba Jimba (Gascoyne River) suggest that good reservoir sand (or calcarenite or both) facies may be found along the eastern flank of the Wandagee, Carrandibby, and Weedarra Ridges, mainly in stratigraphic traps. Structural traps may be available over Weedarra Ridge south of Gascoyne River, and possibly over Wandagee Ridge at Binthalya and Pimbie. The sand at Rough Range No. 1 is probably also folded over the Bullara Ridge, but this is probably a late fold (Jurassic); it could have received oil from Permian source beds mobilized by the deep downwarping during the Jurassic sedimentation. Because of likely lateral variations in porosity, stratigraphic traps may be developed in any of the sand formations, and as all of them are, in part at least, marine they must all be considered to have good prospects for oil accumulation. Drilling might well follow such leads as the porosity and fluorescence encountered in BMR 8.

Because the Artinskian was deposited over a surface of very strong relief it is very likely that many original anticlinal structures and stratigraphic traps were developed over the hills and valleys of that surface. These features are very evident in the outcrop area of the Callytharra and Moogooloo Formations between the Minilya and Gascoyne Rivers, and this area is certainly worth drilling, particularly where the Moogooloo is capped or overlapped as in the Donellys Well area, Williambury Station, the Mount Sandiman Woolshed area, and around Lyons River homestead. Anticlines in the western part of the Merlinleigh Basin, as at Salt Gully, Jimba Jimba Station, and Quail Anticline (Barrabiddy Creek), are probably developed by draping over ridges in the pre-Artinskian surface. This is very strongly suggested in the seismic sections of the Quail Anticline, which show anticlinal structure only down to 0.3 seconds on the crest (i.e. about 2000 feet depth and probably the base of the Artinskian). Along seismic traverse P (WAPET, 1963) the [illegible] flank of the Quail Anticline is draped over an unconformity surface eroded in the Sakmarian and pre-Permian sediments (Fig. 161).

Large stratigraphic traps are likely to be present in the sand formations of the Artinskian (Moogooloo, Billidee, Mallens, and Norton) on the east side of the Wandagee Ridge between Lyndon and Gascoyne Rivers and on the west side between Lyndon River and Point Locker. The Giralia Anticline appears to be developed in Artinskian sediments, draped over hills in the surface of the Sakmarian (Fig. 160), and the sands show porosity. More subsurface data are required to indicate prospective areas for structural traps. The anticlines indicated by marine seismic survey in Exmouth Gulf may include prospective sands of the Artinskian, but drilling is required to establish the stratigraphy.

The Jurassic of the Cape Range area includes a thick source-bed sequence (under Cape Range) grading rapidly into a paralic facies in the Learmonth/Rough Range area. The Bullara Ridge (on which Wapet's Learmonth No. 1 was drilled) is the most prospective area; Learmonth No. 1 found lime-cemented sands with no porosity, but these may change laterally into porous sands ideally situated to receive oil from the thick source beds.

Good flows of gas and oil have been obtained from Jurassic paralic to deltaic sands at Barrow Island. These results confirm that the Jurassic sequence in both the Caranrvon and Canning Basins must be regarded as prospective even where they are not dominantly marine.

The Lower Cretaceous has a very good reservoir sand (in the Birdrong Formation) and a potential reservoir formation (with fracturing development) - the Windalia Radiolarite.

The Birdrong produced oil in Rough Range 1, but the pool, so far, is a one-hole pool. Seismic surveys have confirmed the indications of the eighteen bores in the Rough Range area that the Rough Range Structure is mainly a sedimentary drape structure with different originating surfaces at the base of the Upper Cretaceous and Lower Cretaceous - at Rough Range 1 and 10 these are both anticlinal. The seismic survey shows very clearly that the Lower Cretaceous is draped over an east-facing erosion scarp cut in the Jurassic (Fig. 162) which dips westward, unconformable over an anticline in the Sakmarian to Devonian. It has been pointed out (Chamberlain et al., 1954) that the Bouguer gravity anomaly derives from a density contrast at about 4000 feet, and this anomaly (which includes the Rough Range 1 and 10 wells but no others) may indicate the shape of the erosional ridge in the Jurassic and by inference the structure of the overlying Bridrong. The oil show in Rough Range 10 indicates that this interpretation is not impossible and justifies the inference that an oilfield of commercial size may extend eastward and southward away from Rough Range 1.

As no oil has been found in other closed structures where the Jurassic is absent, it is a reasonable working hypothesis that the Rough Range oil migrated from the Jurassic. This provides an exploration target - to find similar drapes over the Jurassic - but these will only be looked for and found if the geological history is understood and not interpreted in terms of simple tectonics.

The Birdrong and Windalia are important targets for indigenous oil. Some gentle structures may have been flushed by groundwater movement (although data are not yet available to assess the possibility of this). In any case, stratigraphic and structural traps are likely to be of greater prospective value towards the eastern margin of the Cretaceous (along the Wandagee Ridge from Winning Pool to Worramel River). Anticlines are known in the Cretaceous at Hill Springs and suggested along the Wooramel River.

The carbonates of the Upper Cretaceous probably include source beds in deeper water facies away from present outcrop. They are known to have sufficient porosity to provide groundwater storage. They cannot, therefore, be disregarded and should be critically examined in drilling through them, particularly on any near-surface structure. In some of the drilling to date (Cape Range and Dirk Hartog) little positive information was obtained in these rocks because of lost circulation.

The Tertiary carbonates are not prospective on land because they are open (by groundwater solution) down to sea level. In offshore areas, however, the Tertiary is prospective since it has good source beds in the lower Miocene (and probably also in the Eocene in deeper water facies), and the late Tertiary and Quaternary sediments may provide cap rocks.

At this stage in its exploration, there have been few basins with more evident oil prospects and exploration targets, and it can confidently be expected that large oil reserves will be found in this basin when sufficient drilling is undertaken fully to examine and reveal the many known and possible prospective areas.

Water

Because there are practically no permanent streams in the area, underground water is of limiting importance in the pastoral industry, the main industry of the region, and in the agricultural development of the Gascoyne delta.

During the course of the field work information was gathered on the results of drilling for water over much of the area, but no special study of underground water was attempted. Therefore, only the main aquifers can be identified, and they can be described only in general terms.

As an areal appreciation is considered more realistic than a stratigraphic, an attempt is made to establish groundwater provinces characterized by particular aquifers.

1. Shallow groundwater: Unconfined shallow groundwater is important in the following areas:

(a) Stream Beds: The sandy beds of the Ashburton, Yannarie, Lyndon, Minilya and Gascoyne Rivers.

The bed of the Ashburton carries water in the lower part of its course, but the precise length of water-bearing sand and the quality of water were not determined.

In the Yannarie River, the sandy bed extends from near Yanrey homestead to about the junction with Caroline Creek. The water is potable after floods but becomes brackish after a few months.

The Lyndon River has water-bearing sandy bed from near Mia Mia homestead to about the North-west Coastal Highway. The total amount of water stored is small and quality deteriorates a few months after flood flows.

The Minilya River has deep sandy bed carrying potable water between Curdamuda Well and Salt Lake. This water becomes slightly brackish about six months after flood flows, when supplies also are reduced.

In the Gascoyne River shallow sand with potable water extends from about Winnemia Woolshed upstream beyond the margin of the Carnarvon Basin, and in tributaries this sand extends up the Lyons River to Minnie Creek, up Daurie Creek to Coor-de-Wandy homestead, up Bush Creek to Glenburgh homestead, and up Dalgetty Brook to Dalgetty Downs homestead. This water becomes slightly brackish about 6 months after a flood flow and quite brackish if the dry period lasts more than 12 months.

Between Winnemia Woolshed and Carnarvon the sand in the bed is thicker and forms a reservoir of large volume. The water is very low in salts for about 12 months after flood flow, but then becomes slightly brackish and reduced in supply. Near Carnarvon, too, sea water moves upstream through the sand when use reduces the flow of fresh water.

This sand-bed aquifer is important, also, in feeding clean fresh water into confined aquifers in the Gascoyne delta.

A shallow sand bed with potable water extends in the Wooramel River from Byro Plains almost to the mouth. The water becomes slightly brackish 6 months after flood flows.

The sand bed of the Murchison is generally too thin to provide useful storage of water, except near Murchison House.

(b) Alluvium. Useful supplies of water of potable to stock water quality are available in the alluvial flats of the major streams. The aquifers are sand beds that may be of restricted width and therefore not easy to locate by drilling or well-sinking. In general terms the area close to the junction between the flat and the valley side is more likely to contain such beds than the central area of a flat.

The delta of the Gascoyne River has useful sand aquifers in the area upstream from Carnarvon. The water is low in salts and is used for irrigating bananas and vegetables. After a long dry period the supply drops and the salt content rises.

Some drilling has been done to find aquifers in other areas of the delta. In such a large area the sand bodies that form useful aquifers are not easy to locate. Electrical and shallow seismic surveys have proved useful in some such areas elsewhere in locating sand bodies.

The delta of the Minilya River probably contains sand aquifers, but these have not yet been located; they are likely to be small and their water may be somewhat brackish.

(c) Laterite. The deeply weathered rock produced by the process of lateritization may be very porous and permeable and very inert. In a suitable position this material can form a useful aquifer. Much of the sand plain west of the Kennedy and Carrandibby Ranges is underlain by 'laterite', the porosity of which is the main reason for the virtual absence of surface drainage. Valleys in the 'laterite' are indicated by vegetation patterns that are evident in air-photographs (see Wooramel Sheet); these should commonly hold underground water at depths of 50 to 400 feet. Both quality and supply should be good in these laterite aquifers, which have been little used as yet.

(d) Coastal Limestone. The Cainozoic limestone of the coastal area commonly has very effective joint and solution porosity as a result of which the groundwater over large areas is available in useful quantities at or near sea level - the porosity is open to the coast and the level of the groundwater, therefore, is determined by the level of its outlet, the sea. The water is hard but otherwise good.

2. Confined Groundwater: Confined groundwater is important over a large part of the Basin. At the outcrop of the aquifer, of course, the water is not confined but is not treated separately.

(a) Cretaceous Sands. Throughout the area underlain by Cretaceous sediments, from Onslow in the north to near the Murchison River in the south, and from the coast to Mia Mia, Wandagee Hill, the west side of Kennedy Range, Pimbie and Meadow, a sandstone formation at the base of the Cretaceous sequence forms the most widespread single aquifer in the region.

Water from this aquifer reaches the surface in bores west of an irregular line through Winning Pool, Manberry, Mardathuna, Yalbalgo, Yaringa South, and Tamala, and flows of more than 2 million gallons a day have been reported.

The water has few salts in the eastern parts of the area, but the salt content increases westward. Generally the water is suitable for stock after the hydrogen sulphide (which is commonly present in the water from the deeper bores) has escaped.

In the Rough Range area the water in this Birdrong Formation aquifer is quite saline.

The depth of this aquifer increases westward from its outcrop and in the coastal area reaches 2100 feet at Dirk Hartog Bore No. 17B (WAPET), 1393 feet at Brickhouse, 2374 feet at Cardabia, and 3604 feet at Rough Range.

Some drillers, in the past, have been discouraged from drilling to the Birdrong aquifer by the thick black shale that overlies it, mainly because fairly deep drilling in Permian shale had been unsuccessful (as at Wandagee). Within the area of Cretaceous sediments indicated above, the shale forms the cap to the artesian water.

(b) <u>Palaeozoic Formations</u>. From the Lyndon River to the Murchison River in the area of outcrop of Palaeozoic sedimentary rocks there are many aquifers in sandstone formations and a few in limestone.

These aquifers have mainly been drilled only to relatively shallow depths (about 500 feet), where the water is subartesian (it rises in the bore but does not reach the surface).

As it is impracticable to indicate precise areas where individual aquifers may be found, general indications are given in Table 2.

At the eastern margin of the basin dips are commonly fairly steep so that aquifers reach depths beyond normal water-drilling depths in the region in relatively short distances. This has the effect of strictly limiting the area within which any one aquifer may be developed. As an example the Munabia Sandstone on Williambury Station dips at 20° to 27°. Assuming the water table at 300 feet, the aquifer 1000 feet thick, and drilling to 1000 feet, the potential development zone is only about $\frac{3}{4}$ mile wide - only about twice the outcrop width of the formation. On the other hand the Moogooloo Sandstone, with a dip of 2° to 4° but only about 200 feet thick, has a potential development width (to 1000 feet depth) of $2\frac{1}{2}$ to 4 miles.

The total effect, considering all Palaeozoic aquifers, is that in the Palaeozoic outcrop area from Lyndon River to Murchison River there are roughly parallel bands that are alternately prospective and non-prospective for underground water.

If drilling for water could be undertaken to 2000 feet where necessary, most of the outcrop area would be prospective; the only large non-prospective areas would be the eastern margin (a belt about 2 to 4 miles wide), Wandagee Station south of Minilya River, and the central part of Byro Plain.

TABLE 2. PALAEOZOIC AQUIFERS OF THE CARNARVON BASIN

Formation	Lithology	Thickness of aquifer (ft)	Water Quality	Water Supply	General Areas Where Less Than 1000 Feet Deep
Mungadan	Sandstone	70 - 200	Fair	Fair to good	Kennedy Range (feeds springs)
Norton	Sandstone	130 - 400	Stock	Fair to poor	Wandagee Hill; E and S of Kennedy Range
Mallens	Sandstone	400 - 600	Stock	Fair to good	Burna Burna Hill to Norton Creek across N E Kennedy Range; E of Kennedy; Jimba Jimba Station
Moogooloo	Sandstone	30 - 500	Good to stock	Fair to very good	W side of Moogooloo Range; to W of ridge running from K55 (Middalya) to Arthur River; margin of Byro Plain
Weedarra	Sandstone	Up to 400	Stock	Fair to poor	Bidgemia Station; Byro Plain
Thambrong	Sandstone	Several beds total up to 500	Stock	Fair to poor	Lyons River Station (E part); E of Moogooloo Range; Carey Downs Station (W part) W part of Coordewandy
Coyango	Sandstone	200 - 1700	Fair to stock	Fair to poor	E part of Middalya Station: E part of Lyons River Station; E margin of Byro Plain
Moogooree	Limestone	200 - 500	Fair stock	Fair to poor	Between Williamburry and Moogooree
Munabia	Sandstone	1000	Good	Fair to good	Between Williamburry and Moogooree

Other Minerals

Barite

On the Giralia Anticline a bed of barite crops out in the right bank of Cardabia Creek 3½ miles north-north-east of Cardabia Pool (Condon et al., 1956, p. 83). The bed is about 1 foot thick, in bentonitic siltstone and shale of the Gearle Siltstone; it consists of loose crystals of barite about 1 mm in diameter.

At this place the bed is in the upper part of the Gearle Siltstone. In a similar stratigraphic position on the western flank of the anticline, east of Remarkable Hill, large nodules of barite are found at the surface. These are up to a foot in diameter, mainly spherical, and with radiating crystalline structure. It seems likely that these have been formed by re-crystallization near the surface of the barite bed.

Form the nature of the occurrence, in unmetamorphosed soft marine shale, it appears likely that the barite was deposited as a precipitate during sedimentation.

The two occurrences are 15 miles apart. If the bed is continuous the total quantity of barite near surface in the anticline would be fairly large, but no attempt has been made to determine its extent.

Bauxite

No occurrence of bauxite has been reported from the Carnarvon Basin, but the wide extent of lateritic surfaces, some of which are developed over shale formations, warrants attention in the search for bauxite. Areas where laterite may overlie shale include: the area west of Mia Mia between the North-West Coastal Highway and Lyndon River; the area between Hill Springs and Mooka; the area between Winnemia, Winderie, and Callytharra; and the area between Wooramel River and Curbur station, east of Byro Plains.

Areas where laterite overlies Precambrian igneous and metamorphic areas, and where bauxite may have developed, are shown (symbol Tul) on the geological map.

Bentonite

The Gearle Siltstone cropping out in the Giralia and Marrilla Anticlines and along the west fall of Chinkia Creek includes much bentonitic shale (Condon et al., 1956, p. 83). Some analyses have been carried out that confirm the presence of bentonite, but no systematic sampling has been attempted to determine whether any of the material is suitable as a source of bentonite (for drilling mud, etc.).

Clays

Many of the shale formations are so little indurated that they will pug into clay with very little working. The industrial potential of the shale formations for ceramics, cement manufacture, fillers, etc., has not been investigated. The Gearle Siltstone (Giralia and Marrilla Anticline, Chinkia Creek, Hill Springs to Mardathuna) is a soft bentonitic shale (Condon et al., 1956, p. 18 and pl. 3).

The Muderong Shale (west side of Kennedy Range) is a soft bentonitic shale (Condon, 1954, p. 106).

Shales in the Byro Group (Wandagee, southern Middalya, western Mount Sandiman, western Lyons River Stations, and Byro Plains) are firm carbonaceous shales.

Shales in the Lyons Group (south-eastern Winning, western to southern Williambury, Moogooree, Mount Sandiman, Lyons River, Bidgemia, Dairy Creek, Coordewandy, Byro, Curbur, and Narryer Stations) are slightly indurated and generally contain some sand.

In the bottom part of the laterite, leached clay is developed over shale and some igneous and metamorphic parent rocks - areas of interest are the same as those indicated for bauxite.

Glauconite

Glauconite greensand crops out in a thin formation (up to about 10 feet thick) around the Giralia and Marrilla Anticlines. The material is loose to friable and contains a high proportion of glauconite - generally about 40%. As it generally dips very gently it could be excavated very readily. No analyses of the material have been made and no economic investigation has been undertaken (Condon et al., 1956, pp. 29 and 84).

Gypsum

Gypsum is interbedded with clay in the bed of Salt Lake. Similar deposits have been investigated immediately north of the lake, in an area of former extension of the lake (Symbol Ql on pl. 3, Condon et al., 1956). Other deposits may be found in the coastal marine marshes.

Primary sedimentary gypsum crops out in the bed of Minilya River (left bank) upstream from Curdamuda Well, Wandagee. Here it is part of the Quinnanie Shale. Gypsum is known also in the Bulgadoo Shale (outcrop in the western part of Mount Sandiman Station) and in the Madeline Formation (in the creek running south to Gap Pool, Wooramel River).

Little is known about the thickness or extent of these gypsum occurrences.

Limestone

Hard dense limestone, potentially of use as road and concrete aggregate and for lime and portland cement manufacture, crops out in the coastal area from North-west Cape (Condon et al., 1953) to Cape Cuvier (Condon et al., 1956), in Moogooloo Range, the ridge that runs from Thambrong Pool, Minilya River, to Arthur River through Lyons River homestead (Condon, 1954), and in Pells Range (Condon, 1962a, p. 16 and fig. 2).

Another formation runs from north of Williambury homestead (Condon 1954, 1955, and 1962a).

Friable limestone for lime and cement manufacture crops out in the Giralia Anticline (Korojon Calcarenite - Condon et al., 1956, pp. 21-26) and between Hill Springs and Gascoyne River (Condon 1962a, p. 19 and fig. 2). Friable and hard shaly limestone in the Callytharra Formation may be suitable for manufacture of portland cement; it crops out from the Lyndon River to Gascoyne River in a belt through Mia Mia, Middalya, Williambury, Moogooree, Mount Sandiman, Lyons River, and Bidgemia Stations and another in Coordewandy and Innouendy Stations (Condon, 1955; 1962a, b).

Radiolarite

The Windalia Radiolarite is an almost pure silica rock composed of tests of radiolaria more or less disintegrated. This rock, which is of low density, high porosity, moderate permeability and fine grain, can be used in filtration, as a light-weight filler, for insulation, as an abrasive, and as a source of pure silica.

In outcrops it is commonly leached and hardened by secondary deposition of silica. The leached but not hardened form is particularly useful for filtration.

It crops out in low hills in the central part of Giralia Anticline, in the low scarps west of Winning Pool, in mesas in the south-eastern parts of Winning and Mia Mia Stations, along the west side of Kennedy Range from Barrabiddy Creek to Gascoyne River, and from Gascoyne River near Winnamia to near the southern boundary of Jimba Jimba station.

Hitherto it has been used only as a building stone (e.g. in Winning homestead).

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