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THE STRATIGRAPHY, SEDIMENTOLOGY AND URANIUM DEPOSITS OF TERTIARY ROCKS: LAKE FROME AREA, SOUTH AUSTRALIA

by

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SUMMARY

The Tertiary rocks of the Tarkarooloo Basin in the Lake Frome area rest disconformably on Cretaceous strata of the Great Artesian Basin (Frome Embayment). Total thickness varies from 300 m in the Poontana Sub-basin flanking the Flinders Ranges to 50 m on the Benagerie Ridge in the central southern part of the basin. The sequence is divided into the Eyre Formation (Paleocene to Eocene), the Namba Formation (two members; Miocene), and Willawortina Formation (late Tertiary - ?Pleistocene). The Namba Formation, resting disconformably on the Eyre Formation, intertongues in its upper part with the Willawortina Formation. Marginally, a disconformity exists between the two younger Formations. The Namba Formation is equivalent and similar to the Etadunna Formation of the Lake Eyre Basin. The Oligocene to Lower Miocene was a period of non-deposition. Silcrete formed marginal to uplands during this period, and probably during deposition of the Eyre Formation.

Changes in clay mineralogy occur across disconformities and boundaries between rock units. These variations are explained primarily in terms of climatic change, secondarily in terms of tectonism. The clay mineral changes form approximate time markers, assisting stratigraphic differentiation and correlation in atypical or lithologically homogenous sequences.

The Eyre Formation, of mature moderately sorted carbonaceous crossbedded sand and minor kaolinite, was deposited in a fluviatile environment. Braided streams and coalescing low angle fans prevailed, with sands deposited in bars. Drainage was external. The sequence fines upward, Eocene sediments being mainly carbonaceous silts, probably partly lacustrine. Deeply weathered rocks of the Olary Region provided sediments in the south, Mesozoic rocks supplied the north. Channelling is more evident in the southern regions, and

hosts uranium mineralization. Climate was tropical to sub-tropical with high rainfall, supporting rainforest vegetation.

The contrasting Namba Formation is a fine grained sequence of smectite:randomly-interstratified-clay, olive and grey, with thin pale yellow sand beds in the lower member, changing abruptly to illite:randomly-interstratified-clay in the upper member. Persistent beds of dolomite and palygorskite are characteristic. These sediments are texturally and mineralogically immature low energy deposits, accumulated in a low relief environment. Sub-environments were irregularly distributed.

Deposition began in a fresh to hyposaline lake with stagnant bottom conditions, west of modern Lake Frome. The Lake shallowed and broadened, becoming hypersaline, and dolomite was deposited. Dolomite and calcite alternated as the groundwater-saline lake water interface fluctuated. Algal mats were present. Fluctuating lacustrine and fluviatile conditions followed, with regressive shorelines and river avulsion producing rather poorly defined cyclic sequences. Streams were probably deep and constantly flowing. Incipient soil formation took place under swampy conditions. Next, well-sorted fine sands accumulated in river channels and lacustrine offshore bars, in which uranium was later deposited. After deposition of more clay, a second phase of carbonate deposition occurred at the base of the upper member, subsequently locally calcreted.

Sedimentary structures resulting from thixotropic behaviour are common. Bioturbation is prevalent, especially associated with carbonates and laminated silt. Many beds have been homogenized, mixing ooliths with micrite mud. Bioturbation distribution indicates intermittent relatively rapid deposition.

A marine connection with the Murray Basin via a large river is indicated from vertebrate evidence. Although an inland lake and floodplain is preferred, a lagoonal environment marginal to an epeiric sea cannot be eliminated, particularly during carbonate deposition.

Climate was warm temperate to subtropical, with periods of seasonal aridity. Gallery rainforest flanked rivers and lakes; savannah was elsewhere. Considered in relation to Australia's latitude during the Miocene, an expanded subtropical climatic zone is required. Widespread distribution of similar Tertiary deposits in Australia supports this. The change from smectite-degraded illite to kaolinite-mica clays in the upper Namba Formation and Willawortina Formation is attributed to uplift of the Flinders Ranges, though a similar widespread change in Tertiary southern hemisphere oceanic sediments suggests a more basic climatic cause.

Uplift of the Flinders Ranges is recorded by deposition of a flanking wedge of poorly sorted green and brown mottled illitic clay-silt, sand and conglomerate of the Willawortina Formation. The fan environment of channel and floodplain was accompanied by deposition from mud flows and related transport processes near the ranges. A change to smectite clay in the upper part of the sequence in one bore may indicate a marked increase in aridity.

Uranium could have been introduced at any time during the medial to late Cainozoic, and takes the form of roll front or sheet deposits of the geochemical cell type, still actively migrating. The Eyre Formation in the southern part of the basin is potentially most productive. Certain areas require further exploration though very large deposits are not expected, and mineralization is probably restricted to the margins of the basin.

STATEMENT

This thesis contains no material which has been accepted for the award of any other degree or diploma in any university, and the thesis contains, to the best of my knowledge, no material previously published or written by another person, except where due reference is made in the text of the thesis.

Signed . . .

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The petrophysical logs and core were provided by private companies listed in Appendix 6 and Bibliography. Most of their reports are available to the public in South Australian Mines Department files. Those providing confidential data were:

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INTRODUCTION

BACKGROUND

The studies reported here were carried out whilst the writer was employed by the South Australian Department of Mines during the period 1972-5 and are included in this thesis with the permission of the Director of Mines. The stratigraphy was deduced as a consequence of mapping COPLEY, FROME, and CURNAMONA 1:250,000 geological sheet areas, and the project initiated by Mr. B.P. Thomson of the Geological Survey. Extensive exploration for uranium by private companies provided an opportunity to undertake a basic study of that portion of the Cainozoic sequence of economic significance. The area was the first to be investigated for sedimentary uranium of the "geochemical cell" type in South Australia. Approximately 3,000 open holes averaging 120 m depth were drilled, with self potential, point resistivity and gamma ray logs. Cuttings were collected. In addition, several holes were cored, some throughout, three of these being stratigraphic bores drilled by the South Australian Department of Mines in a programme designed by the writer.

GENERAL DESCRIPTION OF THE AREA

The Lake Frome area is defined as the region between the Flinders, Barrier and Olary Ranges, bounded (approximately) to the north by latitude $29^{o}55'$. The central western portion is occupied by Lake Frome and its surrounding plains. Alluvial fans flank the Flinders Ranges and extend towards the western shore of Lake Frome, whereas the east is occupied by longitudinal dunes. Smaller fans occur along the western edge of the Barrier Ranges. The physiography is described in detail in Callen (1974).

Three sides of the area are flanked by low mountain ranges of Cambrian and Precambrian rocks of the Adelaide Geosyncline and Olary Arc, and crystalline basement inliers. To the north it is continuous with the flat lying sediments of the Great Artesian basin which underlies the vast inland plains of the north east.

The Tertiary strata are covered for more than 98% of the area by Quaternary sediments. Main outcrops occur along the flanks of the Flinders and Barrier Ranges, along watercourses, and the steep western banks of ephemeral lakes. Most is of the younger strata. The most intensively studied area was on the Eurinilla, Coonarbine and Siccus 1:63,360 geological sheets.

SCOPE AND OBJECTIVES

Objectives were to ascertain the stratigraphy and environment of deposition of the uranium bearing Cainozoic sediments, and determine large scale parameters of sedimentary uranium localization. Stratigraphic aspects involved:

1. Correlation of rock units, if possible with biostratigraphic control, followed by formal definition.
2. Definition of Tertiary boundaries.
3. Correlation with units outside the basin.

Environmental objectives were to:

1. Determine mode of transport and deposition.
2. Evaluate the role of tectonism in deposition.
3. Delineate the shape and limits of the basin, and palaeogeography.
4. Ascertain the climate on a local and regional basis.
5. Determine effects of diagenesis.
6. Determine provenance.

With respect to uranium, it was intended to

1. Place uranium deposits in their stratigraphic context.
2. Determine any sedimentological control, on the scale of the basin.
3. Determine tectonic control.
4. Deduce periods of groundwater chemistry and movement appropriate to uranium deposition. Since the uranium was not necessarily

introduced during the Tertiary, this might involve consideration of Quaternary conditions.

5. Deduce palaeogeography during expected times of deposition.
6. Predict new areas for exploration.

Additional, more theoretical objectives were to describe and interpret sedimentary structure, and investigate fine grained sediments as an exercise in utilizing information from this oft neglected source.

METHODS

The area was initially field mapped on 1:50,000 scale black and white and 1:83,900 colour photographs. Marginal areas were studied, including a brief examination of the New South Wales portion of the basin. Type sections of Cainozoic units in South Australia were visited. Over 100 sections were measured, and examined by trenching. Special attention was given to soils and their use as stratigraphic markers. This was supplemented by detailed mapping in key areas, and photo-interpretation. The surface mapping gave data on the Quaternary sequence, and uppermost Tertiary.

Thirteen cored holes in the Cainozoic provided most of the subsurface data. The information was supplemented by cuttings from water bores, and a selection from uranium exploration company drilling. Most had petrophysical logs, of varying quality. Cored holes were logged in detail in the laboratory.

The rocks were investigated under binocular microscope, and in thin sections. Xray analysis and grain size analyses were made, supplemented by chemical analysis. Peels were used to study sedimentary structures and carbonates.

In thin section, attention was concentrated on textures, chert, quartz and feldspars.

Initial clay mineralogy revealed an apparent stratigraphic association, further investigated by sampling all cored and some uncored holes at regular intervals.

Sampling methods were designed to reveal all variations in rock types, with regard to lithology, clay mineralogy and grain size, and to reveal systematic vertical variations. All outcrops were sampled, to assist in placing isolated patches in their stratigraphic context, and assist comparison with subsurface. Initially, uncored holes and outcrop were sampled in more detail than later proved necessary as cored holes became available. Sampling of the first cored hole, SADM Yalkalpo No. 1 bore, was at 2 m intervals, but revealed a constant mineralogy. Hence subsequent holes were sampled at wider intervals, but xray analyses showed much greater variation. Thus further resampling was required.

NUMBERING

The South Australian Dept. Mines numbering system is used, viz.

P1043/73 P = petrological (microscopic examination, xray or grain size analysis)

A101/72 A = chemical analysis.

/72 and /73 refer to the year in which the sample was submitted.

For specimens EUR3/4393/17, EUR = 1st three letters of 1:63,360 sheet (Eurinilla)

3 = Photo run number

4393 = Photo number

17 = sample point on photo.

CHAPTER 1

GENERAL GEOLOGY, PRE-CAINOZOIC HISTORY

1. GEOLOGY OF LAKE FROME AREA

1.1 ROCK TYPES

The Lake Frome area is the region between the Flinders, Olary and Barrier Ranges, northwards to latitude 29°55' (Figs. 1, 2). It is low lying, mostly less than 100 m above sea level, descending to below sea level in Lake Frome. Within the area are Cainozoic and Mesozoic sediments averaging 280 m thick, of which about one third is Cainozoic. The Mesozoic sediments are continuous with those of the Great Artesian Basin, forming a lobe known as the Frome Embayment. Following the nomenclature of Wopfner (1969), this term cannot be applied to the Cainozoic sequence, which has a disconformable relationship with the Mesozoic, and belongs to a different tectonic cycle. The name Tarkarooloo Basin is proposed, after the lake of the same name where the most extensive Tertiary outcrop occurs.

Within this basin several structural features (Figs. 1, 3) are recognised. The western portion is occupied by a thicker section of Tertiary sediments than east of Lake Frome, forming a shallow 'trough' parallel to the Flinders Ranges named the Poontana Sub-Basin (after Poontana Creek). It extends at least as far as "Mooloowatana" to the north, and Reaphook Hill to the south. On CURNAMONA, a well established ridge of slightly metamorphosed Precambrian sediments and granitic basement extends north at least as far as Lake Culberta on FROME. It is called the Benagerie Ridge, after Benagerie outstation on the Benagerie 1:63,360 map area.

The Cainozoic and Mesozoic strata overlie flat to gently dipping sediments of the Middle Cambrian Lake Frome Group, Wirrealpa Limestone and Billy Creek Formation (Daily, 1956) south of Lake Frome. These comprise at least 605 m of red beds and minor carbonates, part of which crop out in an anticlinal structure southwest of "Wertaloona". The structure is here referred to as the Wertaloona Anticline.* Limestone from Yalkalpo 1 bore is Cambrian (pers. comm. B. Daily 1974) and similar rocks occur in bores to the north of this on FROME (see Callen 1974). All these sediments resemble the Middle Cambrian sequence, suggesting they form a continuous relatively undeformed blanket beneath the Mesozoic. Similar ideas have been expressed by Daily et al. (1973).

Probable older rocks occur on the Benagerie Ridge, cropping out as isolated low hills (Fig. 1). These include slightly metamorphosed greywacke, arkose (with graded bedding), shale, and coarse conglomerate. The conglomerate includes pebbles from older crystalline basement rocks, but is tourmalinized and slightly metamorphosed. Carbonaceous slate has been intersected in K69 bore (Fig. 4), and is steeply dipping. These rocks probably represent low grade metamorphic sediments of the Willyama Complex, similar to those of the Broken Hill region, since they are steeply dipping, contrasting with the flat lying Cambrian.

Between Lake Tarkarooloo and Dud Bore on Eurinilla Creek, drilling has revealed the presence of an extensive porphyry body of similar type to the Gawler Range Porphyry. The thickness and affinities of this porphyry are unknown, but relationships revealed during sedimentary uranium drilling by Tricentrol N.L. indicate that it is older than Jurassic, and probably older than Middle Cambrian.

In the Northwestern portion of the basin, Ordovician rocks crop out (Wopfner 1966), and presumably exist beneath the eastern Frome Embayment.

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* This anticline is situated within a 'reentrant' of essentially Cainozoic sediments projecting into the Flinders Ranges. It forms a roughly triangular segment which has not received the same amount of uplift as the remainder of the Ranges, now expressed as an area of high level plains. This area is referred to as the Balcanoona High Plain, after "Balcoona" on the Balcanoona 1:63,360 map area. A similar area in the vicinity of Paralana Hot Springs is called the Paralana High Plain.

Lower Cambrian rocks have been suggested to lie under the basin, west of Lake Frome (Wopfner 1970).

The geology of the surrounding ranges is better known. The rocks constitute three crystalline basement areas, known as the Mount Painter, Willyama and Denison Inliers (Thomson 1973), and Adelaide Geosyncline sediments of the Flinders Ranges, Olary and Barrier Ranges region (Olary Arc). They are discussed by Thomson and Wopfner in Parkin (1969).

The Mount Painter area has been mapped by Coats & Blissett (1971), and the Olary region by Campana (Campana & King 1958), and more recently by Pitt (1971) and Forbes (1970), whose unpublished data has been utilized in the preparation of the base map (Fig. 1).

The mapping in the Broken Hill region was compiled by Rose (1968), from work by various persons, and the northern Barrier Ranges by Brunker (1967). Recently a portion of this area has been remapped by Cooper & Tuckwell (1971, & unpublished data N.S.W. Dept. of Mines). The Barrier Ranges sedimentary sequence is comparable with that of the Adelaide Geosyncline (Thomson et al. 1970). The Adelaide Geosyncline rocks west of Lake Frome were mapped by Coats (1973) COPLEY 1:250,000 sheet, Forbes (1972) PARACHILNA 1:250,000 sheet, and Binks (1971) ORROROO 1:250,000 sheet.

In the Adelaide Geosyncline the sediments are mainly fine grained silts, carbonates and shales with about 30% of sand or coarser in the Burra and Wilpena Groups and about 10-15% coarse material in the Umberatana Group. A similar situation exists for the Olary and Barrier Ranges. The lower Cambrian consists essentially of carbonates, and the Middle Cambrian of about 50% sand and 50% shale or siltstone.

Diapirs are associated with tight anticlines in the central northern part of the Adelaide Geosyncline (Coats & Blissett 1971, Stewart & Mount 1972). Metamorphism is mainly of lower greenschist facies, but locally reaches amphibolite grade near the Mount Painter and Willyama Inliers.

1.2 FAULTING (Fig. 3)

The Frome Embayment is at present bounded by reverse and thrust faults (Callen 1975 in press) along its western edge, and by a normal fault system along its eastern edge, separating the basin rocks from the Flinders and Barrier Ranges respectively. The age of origin of these faults is unknown but much movement has occurred during Cainozoic times. To the south Cambrian sediments appear to lap onto the crystalline basement of the Olary Block without any major structural discontinuity.

The major structure dominating the basin is the system of vertical faults referred to as the Poontana Structure by Callen 1974, (Fig. 1) following Coats (Coats & Blissett 1971), and defined by seismic work of Crusader Oil N.L. (refer United Geophysical Corp. 1966). The structure was initially interpreted as a basic dyke by United Geophysical Corp., who later modified this idea to suggest a narrow horst-like fault combination. Whilst nearer the true configuration than a dyke, this structure is rather unusual in geological terms. Total movement on the two faults is east block down.

A second parallel fault was located to the east, with a similar trend, in the southern part of Lake Frome. Other faults have been suggested (Callen 1975, Fig. 1; Fig. 3, this report) also with northerly trends. The only other definite fault in the basin area is that assumed to be associated with the steeply dipping ?Tertiary rocks on the NSW-SA border on Thurlooka 1:63,360 Map sheet.

A probable set of northwesterly trending structures is also suggested on the sketch (Fig. 3).

2. DEVELOPMENT OF THE CRETACEOUS FROME EMBAYMENT

The history of the basin is described in Callen (1974) and further clarified here. The tectonic foundations of the basin originated during the sequence of events which led to formation of the Adelaide Geosyncline and Olary Arc.

A stable cratonic block exists beneath the Frome Embayment (Thomson 1974) with a thin Proterozoic cover (Tucker 1972) and relatively unfolded Cambrian sequences (Daily et al. 1973, Callen 1974).

During Upper Cambrian and Ordovician times, the major folding episode of Adelaidean rocks and re-folding of basement inliers occurred. This event terminated deposition in these mobile belts, much of which have since become areas of positive relief and active erosion. This phase of folding apparently did not affect the Curnamona Cratonic Nucleus.

Following Cambro-Ordovician and ?Permian-?Triassic deposition in the Lake Frome area (Wopfner 1966), epeirogenic movements were initiated in Lower Jurassic times (Wopfner 1969). This resulted in crustal sagging over a large area of South Australia, New South Wales and Queensland and permitted a thick sequence of non-marine sediments to accumulate during the Jurassic, followed by a marine transgression in Lower Cretaceous times. Over much of the Great Artesian Basin, Cenomanian non-marine sedimentation took place, but this did not occur in the marginal Frome Embayment.

The earliest movements recorded on the Benagerie Ridge are indicated by the presence of granite and porphyry pebbles in ?Jurassic rocks near the base of Yalkalpo No. 1 bore (Callen 1974; pers. comm. Morgan 1974).

There is a tendency for the Mesozoic strata to thicken in the Poontana Sub-Basin, suggesting this feature was also active. In the upper part of the Marree Formation the sediments were dominantly silt and mudstone, indicating the surrounding highlands had been eroded down, probably forming a peneplain by the end of this depositional event.

This writer disagrees with Wopfner's contention (in Parkin 1969) that the Murray Basin and Great Artesian Basin were freely interconnected through the Frome Embayment during Mesozoic times, which has as its corollary the development of the Olary Ranges during the early Tertiary. There is no evidence for the erosion of large volumes of Cretaceous from the Olary Ranges region when they were uplifted during Eyre Formation times. Rather, evidence suggests basement was already exposed.

3. LANDSCAPE OF UPPER CRETACEOUS TIMES

At the end of Cretaceous deposition, terminated by epeirogenic uplift and regression of the sea, relief was probably subdued. The present day Flinders, Olary and Barrier Ranges were low and partially covered by Cretaceous sediments (except for the Olary Ranges region). Erosion and deposition ceased and stable conditions prevailed.

Evidence from Yalkalpo No. 1 bore (pers. comm. Morgan 1974) suggests the upper part of the Cretaceous sequence has been eroded, indicating there was a phase of uplift during this otherwise quiescent period, accompanied, presumably, by transport to the north. The Mt. Howie Sandstone (Wopfner 1963) perhaps represents this material, no other Cenomanian and Tertiary rocks are known, and there are no equivalents of the Mt. Howie Sandstone in the Lake Frome area.

Thus at the end of Cretaceous times the Lake Frome area formed a basin infilled by Cretaceous sediments, and surrounded by low hills of Cambrian, Adelaidean and older Precambrian rocks. The Flinders Ranges were virtually non-existent, and probably the Lower Cambrian limestones and Middle Cambrian red-beds covered a greater area of the palaeo-surface. Numerous basement clasts in the Cretaceous strata in the northern Flinders Ranges (Mt. Babbage area) indicate crystalline basement was exposed, and therefore would have had thin or no cover at the end of Cretaceous deposition. To the south and east the Precambrian metamorphic basement of the Willyama Complex (including the Benagerie Ridge) was exposed. The Cretaceous strata have onlap relationship to the older rocks. It has been suggested that the coastline was very close to Yalkalpo 1 bore during Cretaceous deposition, therefore the southern limit of Cretaceous would not be too different from that of the present.

Middle Cambrian red beds and limestone probably cropped out along the northern margin of the Olary Ranges and Benagerie Ridge.

The sporadic outcrops of slightly metamorphosed conglomerate, greywacke and arkose of the Benagerie Ridge are probably remnants of rock types more extensively exposed during Upper Cretaceous times. They may represent the thin Proterozoic cover of the old Curnamona Craton ('Paralania' of Sprigg 1952) but their steep dip and lithology suggests they represent relatively unmetamorphosed Carpentarian rocks. West of the Benagerie high, probably continuous with the Mt. Victoria Granite, was a large granite body (Tucker 1972), Probably exposed, judging from rocks encountered in sedimentary uranium drillholes in the vicinity (EAR3, Fig. 5). Along the Barrier Ranges, equivalents of the Adelaidean strata were presumably more extensive, probably with an exposed core of crystalline basement rocks in the vicinity of Broken Hill, and possibly Ordovician and Cambrian to the north and at Mount Arrowsmith. Between the NSW-SA border and the Benagerie Ridge was an area of soft black carbonaceous shale of pre-Cretaceous age (Fig. 4), but the Cretaceous may have covered this.

The centre of the basin was occupied by fine-grained silt and clay of the Marree Formation, whereas the coarse ?Cadna-owie Formation cropped out around the edges.

This landscape was somewhat modified by the pre-Tertiary erosional event mentioned earlier, which would have stripped some of the finer grained Marree Formation (Forbes 1966), exposing the coarser Cadna-owie Formation (Wopfner *et al*. 1970) and Algebuckina Sandstone (Sprigg *et al*. 1958) equivalents over a wide area of the marginal basin.

This was therefore the situation immediately preceeding Lower Paleocene deposition.

CHAPTER II

CAINOZOIC STRATIGRAPHY

The Tertiary sediments have been divided into three rock units: the Eyre Formation, Namba Formation and Willawortina Formation. The Eyre Formation (including the former Murnpeowie Formation of Forbes 1966) was defined in Wopfner, Callen & Harris (1974) and further discussed in Callen (1975). The other units are defined in Callen & Tedford (*in prep*. see volume 2), which also defines the Quaternary units: Eurinilla Formation, Coonarbine Formation, and Millyera Formation. The relationships between these units are shown in Tables 2 & 4 of Callen & Tedford. Material is here confined to a brief description of each unit followed by comments not in the paper. The following should be read in conjunction with Callen & Tedford (see Vol. II).

1. EYRE FORMATION

1.1 DESCRIPTION

1.1.1 General

This unit is best displayed in the Reedy Springs - "Murnpeowie" area as outcrop (Fig. 24) and in Yalkalpo 1, PMX24a, K69, EAR6, EAR3 and B240C3 bores (Figs. 4-14). It consists of very coarse sand (Fig. 91) with pebble lenses at the base, grading up to very fine sand. The large grains are frequently polished, of irregular shape and subrounded to rounded. Maturity is high: clays are kaolinite, and feldspars (orthoclase only) and other unstable minerals scarce. Carbonaceous matter and pyrite are common in the matrix, rarely occurring as cement. Black chert, porphyry, agate, milky quartz, and fossil wood are relatively common, especially in the basal pebbly beds.

Medium and small-scale cross-bedding are common. Bedding generally lenses out over a few dekametres or less. The lower contact is gently undulating, and locally has groove casts, the unit being disconformable on Cretaceous or older sediments. The upper contact is generally difficult to pick when sands are present in the basal Namba Formation or Etadunna Fromation.

1.1.2 Thickness and lithological variation

Thickness is generally about 15-20 m but varies, sometimes rapidly, from 0 to 150 m. The unit forms a widespread thin sand blanket covering much of the Great Artesian Basin in South Australia, lapping onto the basement at the margins. A more detailed description of the lithology and its variations is given in Wopfner et al. (1974), a reprint of which is enclosed in Vol. II. An appendix to the S. Aust. Dept. Mines report forming the basis for this paper, has also been included. Distribution of outcrop is in Fig. 1.

The major lithological differences are between the area south of Lake Frome, north of the Olary Ranges, and the remainder of the basin. In the southern areas chert pebbles are rare or absent, quartz grains are angular, and mica and kaolinite clay form a much higher proportion of the consistuents. This is interpreted as indicating uplift of the Olary Ranges during deposition. The more northerly material derived its chert pebbles from uplifted Jurassic and Cretaceous sediments (Wopfner et al. 1974), whereas deeply weathered granitic crystalline basement supplied the south.

A possible example of weathered basement can be observed in EAR3 bore (Figs. 5, 11) southwest of "Curnamona". Here the basement, interpreted as weathered granite, can only be distinguished from the Eyre Formation by the persistent steep dips of the layering, and the presence of small siderite nodules, coupled with a different petrophysical log response. Petrologically this material is identical to the micaceous clayey layers with angular quartz grains observed between 110 and 113 m in B240 C3 bore (Fig. 9).

In one bore (Mundi Mundi No. 1) a polished chiastolite pebble was found in the basal Eyre Formation.

Thus sediment was transported in a northerly and easterly direction from the Olary Ranges region, and in the vicinity of latitude 31°00', becomes intermingled with material of the northern Mesozoic provenance.

The Eyre Formation has been adequately described in the above references. Detailed descriptions of the sections are available in Vol. II.

1.2 STRATIGRAPHIC RELATIONSHIPS

1.2.1 Murnpeowie Formation and Eyre Formation

The Murnpeowie Formation (Forbes 1966) type section has been the basis of geological mapping on several 1:250,000 map sheet areas surrounding MARREE 1:250,000 sheet, the type area, including COPLEY (Coats 1973, Coats & Blissett 1971) and FROME (see Vol. II).

As mapping proceeded and various oil wells and bores were drilled, it became evident that a very similar sequence was developed over a wide area of the Great Artesian Basin. For this reason it was decided to abandon the name Murnpeowie Formation, regarded as having local connotations, and use Eyre Formation in the sense of earlier workers (see references in Wopfner et al. 1974). Forbes had earlier rejected the name Eyre Formation on the advice of H. Wopfner and N.H. Ludbrook of the S. Aust. Dept. Mines, this name having been associated with the Tertiary silcrete and the Cretaceous of Mt. Babbage. However, Wopfner et al (1974) have given a convincing argument for its reinstatement, regarding their work as a clarification and addition to earlier studies of Woolnough & David (1926) and David & Browne (1950).

The type section for the Murnpeowie Formation was not used as the type for the Eyre Formation, a new section being set up near Innamincka (Fig. 2 of Wopfner et al. 1974). This is better exposed than that at Reedy Springs and more representative of the major region of development of the unit, though it has the disadvantage of not exhibiting the relationship with equivalents of the Etadunna Formation. A more fundamental problem is the use of a silcrete to define the top of the Eyre Formation: all sediments below this silcrete and above the basal pebble beds of the Eyre Formation are regarded as part of the Eyre Formation. It will be shown in subsequent discussions (section 2, this Chapter) that there are at least two similar silcretes, which could easily be confused, one of which is younger than the Namba Formation. There is also the possibility of existence of units younger than the Eyre Formation, with a disconformable relationship, but beneath the silcrete. At the Reedy Springs section these problems can be avoided by reference to the adjacent drilling results of Mines Administration, and the palynological control. Here one can observe the disconformable relationship with the Namba Formation, which is a proved equivalent of the Etadunna Formation (Callen & Tedford _in prep_.). Both Miocene, Eocene and Paleocene flora are present in LC1A bore, and correlation between LB19 and the Reedy Springs outcrop is clear (Fig. 15, 24).

It is therefore proposed the Reedy Springs—Mooloowatana region be regarded as the type area, and the former type section for the Murnpeowie Formation at Reedy Springs as the type section of the Eyre Formation (The name Eyre Formation is still retained, on the basis of the arguments presented by Wopfner _et al_. 1974). This section also has the advantage of being the basis of all mapping of Murnpeowie Formation and Eyre Formation on maps of the Geological Atlas Series of the S. Aust. Dept. Mines. Until such time as these ideas are formalized in publication it will be necessary to use the terminology and type section of Wopfner _et al_.(1974).

1.2.2 Subdivision of the Eyre Formation

Within the Lake Frome area the formation can be divided into four units on the basis of LB19 bore. (Fig. 15).

These are:

4. 26.5 m of medium to fine sand with pebbles at the base and carbonaceous silt lenses around 100 m in depth
3. 8.5 m of carbonaceous silt
2. 30.0 m of medium sand with clay lenses near the base
1. 27.5 m of coarse pebbly and granule rich sand

Units 1 and 2 are Paleocene, and units 3 and 4 are of unknown age though a poorly preserved sample from unit 3 has ?Eocene characteristics (W.K. Harris pers. comm., 1973 South Australian Department of Mines).

In LC1A bore, unit 1 can be further subdivided into three parts: an upper and lower coarse pebbly sand, separated by fine sand about 10 m thick at 205 m depth. This sequence is comparable with that of Yalkalpo 1 bore adjacent to the Benagerie Ridge, where the fine grained unit is represented by carbonaceous silt, but unit 2, 3 and 4 are not present. Investigation of bores drilled by Union Corporation and Chevron Exploration Pty. Ltd. (Randell 1973, Morgan 1973) indicates the full sequence can be recognized to the northeast, and this is confirmed by Harris' record of Eocene spores in QDH18 bore, a short distance east-northeast of Yalkalpo 1 bore (p. 145 & Fig. 1 of Wopfner et al. 1974). South of Lake Frome, west of the Benagerie Ridge, the sequence is identical to that at Yalkalpo 1 bore, and Harris (in Wopfner et al. 1974) shows that both Eocene and Paleocene spores are present. Therefore the reduced sequence is the result of slower or more intermittent deposition rather than erosion. This suggests the Benagerie Ridge and "Curnamona" - "Frome Downs" area was a high region.

In LC12, LB12 and LB18 (Fig. 15) unit 1 is thinner than in LC1A and LB19 bores, suggesting uplift and reduced deposition, as in Yalkalpo 1 bore. The other units show minor variation, if one ignores the palynological evidence for a disconformity and accepts the physical correlation.

The sequence in LB19 is directly comparable to that of the Reedy Springs supplementary type section. It has been suggested that the shallow dipping outcrops at the eastern end of this section (Fig. 12 of Wopfner et al. 1974), originally included by Forbes (1966) in the Murnpeowie Formation, represent the upfaulted top of the ?Eocene sequence in LB19 bore.

1.2.3 Relationship to Other Rock Units - Upper and Lower Boundaries

That the lower boundary is a disconformity is demonstrated by the absence of Upper Cretaceous rocks beneath the lowest Paleocene in many bore holes (e.g. LB19 and LB 12 bores Fig. 15; Yalkalpo 1 bore: pers. comm. Morgan 1974, N.S.W. Dept. Mines), and the onlapping relationship (exhibited in the fence diagram sections Figs. 16, 2) and detailed correlation in the "Mooloowatana" - Reedy Springs area (Fig. 15).

The lithology is also markedly different, the Cretaceous being represented by dull greenish-grey coloured silts and shales, often carbonaceous, contrasting with the coarse sandy Eyre Formation. Occasionally carbonaceous silts in the Eyre Formation may appear texturally similar to those of the Cretaceous, but colour suffices to distinguish them in hand specimen.

The surface of the Cretaceous is unweathered, suggesting erosion prior to deposition of the Eyre Formation.

The upper boundary is also a disconformity, which is demonstrated by the absence of the Eyre Formation beneath the Namba Formation on parts of the Benagerie Ridge, and by spore and pollen analyses. This disconformity is much more difficult to detect on lithological criteria, because fine sand may be present in both units. The criteria are discussed in Callen (in press) (Vol. II).

1.2.4 Disconformity within Eyre Formation

Note Harris (in Wopfner et al. 1974) indicates a disconformity may be present in LC1A bore, in Lake Cootabarlow 2 bore and in Lake Eyre bore 20, between the Paleocene and Eocene. He believes his Cupaniedites orthoteichus Zone is missing. The data presented in Fig. 15 are relevant: this chart was drawn using lithological and petrophysical log criteria, supplemented by palynological data. Two alternative correlations are presented assuming (1) that the palynological data are a firmer basis for correlation, and petrophysical logs a secondary consideration (2) that the reverse is true.

The interpretation (1) requires erosion to have occurred with less effect near the ranges than further out in LB8 and LB19 bores between deposition of Paleocene and Eocene sediments. An Eocene sequence very similar to that of the Paleocene was deposited in the vicinity of LC8 and LB 19 bores. This area had become a basin of accumulation, whereas the former site of thick Paleocene deposition (LC12-LB12-LB18 bores) became a positive area. This reversal of roles seems artificial, and suggests that either the correlation or the palynological deductions are incorrect.

Examination of the electric logs supports a subtle lithologic difference between the Paleocene interval in LC12, LB12 and LB18 bores, and the ?Eocene sequence in LB19 and LC8. The carbonaceous silt between 113 and 122 m (?Eocene) in LB19 and the equivalent horizon (158-168 m) in LC8 react on the self-potential log with a strong positive departure, which is not observed in the other three bores. However, using purely lithological criteria, and assuming no great variation in thickness, the palynological discontinuity would not have been drawn.

The differences in log response could also be explained by differing drilling fluid electrical properties, common in this area of variable groundwater salinity. If the questionable Middle Eocene sample in LB19 is eliminated from the argument, the only reconciliation between palynological and physical criteria is to suggest a petrophysical mis-correlation between LC1A and LC2 or between LC2 and LC8. The alternative is that palynological criteria for separating Paleocene and Eocene are insufficient - perhaps the environmental factor has not been eliminated. The non-recognition of the C. orthoteichus zone may be the result of environmental differences in floral content.

Further discontinuity between palynological and physical criteria is present in LC1A, where several Eocene samples are recorded in a sequence which would be Paleocene by lithological criteria and also from palynological results in adjacent bores. These samples are regarded by Harris as the result of uphole contamination (pers. comm. 1974), which is a feasible explanation in an open hole where cores are not available.

However, some doubt is associated with the idea that a disconformity exists within the Eyre Formation.

The discontinuity has not been identified in the northern districts, though this may be the result of inadequate sampling.

1.3 REGIONAL CORRELATION

The equivalents of the Eyre Formation have been discussed in Wopfner et al. (1974). The unit occurs over a very wide area of the Great Artesian Basin, including most of the non-marine Lower Tertiary in South Australia.

The older Tertiary sediments in the Pirie-Torrens Basin are similar, but younger (Johns 1968, Harris 1972) and probably equivalent to those intersected by Carpentaria Exploration Pty. Ltd. immediately west of the Ediacara Fault (Binks 1972, Callen & Tedford in press.).

Sediments probably equivalent to the Eyre Formation have also been described by Senior (1972) in southwestern Queensland. This author assigns them to the Glendower Formation and states they are of early to medial Tertiary age. The Glendower Formation was first described by Whitehouse (1940) from the upper reaches of Flinders River, west of Charters Towers, Queensland. Here the unit is overlain by basalts which have since been dated as medial Pliocene (Wyatt & Webb 1970). By correlating a laterite present in this sequence with a similar horizon in southern Queensland described by Exon et al. (1970), Wyatt & Webb assign it a Miocene age. Therefore the Glendower Formation is presumably early Tertiary. This correlation may not be valid since no detailed work in intervening areas has been made to ascertain whether it is in fact the same laterite. The two units are not regarded as equivalent in Wopfner et al. (1974) on the basis that silcrete pebbles are supposed not to be present in the Eyre Formation.

From the papers quoted above, it is also evident that pre-Pliocene and (?equivalent) pre-Miocene grey-billy silcretes exist, in the same region.

In the Eucla Basin, recent work has shown that outcrops of Pidinga Formation (Blissett & Vitols 1974), exist at Lake Bring near the northeastern corner of the Eucla Basin. These are the most western occurrence of Eyre Formation equivalents (most northeasterly occurrence of Pidinga Formation), and important when considering the external nature of the drainage system which must have existed at this time. The Lake Bring deposits are not far removed from other sediments, equated with the Eyre Formation, in the northern Gawler Block region.

2. SILCRETES AND THE KAOLINITE "BLEACHED" ZONE

2.1 DEFINITION OF SILCRETE

Silcrete was defined by Lamplugh (1902) as the siliceous equivalent of calcrete: "Sporadic masses in loose material of the 'grey-wether' type, indurated by siliceous cement". He thought of these siliceous masses as forming from loose rock by solution and redeposition of silica, through the agency of infiltrating waters, and regards them as superficial deposits. He also uses the term silcrust, a duricrust indurated by silica of diverse structural form: quartz, often chalcedonic silica, or opal. Types of siliceous duricrust are quartzite silcrete and porcellanite (siliceous shales); botryoidal forms are known as 'greybilly' or 'greywether'. He therefore regards silcrete as a particular type of silcrust, which is in turn a type of duricrust. The term duricrust was introduced into Australia by Woolnough (1927).

The definition is further clarified by Fairbridge (1968) who defines duricrust as: "Any indurated surface formed above or within a soil. May consist of limonite, bauxite, silica, limestone etc.". Other names used are hardpan, billy, boral (Africa), carapace or curasse (France). Three types of duricrust are ferricrete, silcrete and calcrete. All are rock-like paleosols.

Thus Fairbridge's definition is both more specific and more general than that of Lamplugh: he regards duricrusts as soils, and he includes all types of siliceous duricrust under the term silcrete. His definition of a soil is a broad one and would include the conditions set down by Lamplugh. The writer prefers to eliminate any suggestion of genesis from the definition conjured up by the term 'soil', but accepts Fairbridge's broader view of silcretes to include porcellanite and all forms of siliceous duricrust. Silicified materials not formed surficially, either in the present or in the past, are not regarded as silcretes.

The term silcrete is used by Wopfner in a more restricted sense for 'grey billy' silcrete, often displaying columnar structure, and developed as a single horizon on top of the Eyre Formation. For example Wopfner would not regard the botryoidal grey billy of the "post-folding silcrete" in Callen's Fig. 8 of Wopfner et al. (1974) as true silcrete.

2.2 RELATIONSHIP TO EYRE FORMATION

Continuous silcrete crusts are best displayed in the Tarkarooloo Basin at Reedy Springs in S. Australia and near Mt. Woowoolahra in N.S.W.

Previous workers have regarded all grey massive silcretes with detrital quartz grains and showing columnar structure ('grey billy') as being the same age (Woolnough 1927, Wopfner & Twidale 1967, Wopfner in

Parkin (ed.) 1969, Wopfner et al. 1974, Stirton et al. 1961). This has been widely accepted in discussions of South Australian stratigraphy. Two stages of silcrete are present at the Murnpeowie Type Section (Fig. 8 of Wopfner et al. 1974) and there is no evidence for a pre-Etadunna Formation silcrete, except at the Lake Palankarinna Type Section. The following is relevant:

(1) A pre and post folding silcrete occurs at the Reedy Springs Type Section, both are younger than the Eyre Formation (Wopfner et al. 1974).

(2) In the Lake Eyre Basin, Wopfner & Twidale (1967 p. 139 and Fig. XIIIb) show two silcretes at Mt. Harvey, one of which is steeply dipping, separated by a sequence of sediments resembling the Etadunna Formation. These two silcretes are both grey billy types, and the younger one has columnar structure.

(3) No silcrete has been recognised at the contact between Eyre Formation and Etadunna Formation in any drillhole in the Great Artesian Basin.

(4) No silcrete is known between the Etadunna Formation and Eyre Formation in any outcrop, except at Lake Palankarinna, and here the evidence can be disputed. Firstly one could argue that the sequence at Lake Palankarinna is equivalent to the Upper part of the sequence at Lake Frome (Namba Formation). At this site there is no definite evidence that the rocks on the lake bed are Winton Formation - they could be Eyre Formation or even sandy black clays equivalent to member 1 of the Namba Formation. Secondly the silcrete at this section could have been formed at the base of a channel, the sediments of which have since been eroded out to produce the present lake, i.e. the silcrete does not persist beneath the

Etadunna Formation in the cliffs along the edge of the lake. One only observes patchy silcrete on the lake bed, geographically lower than or at the base of the Etadunna Formation, but not necessarily stratigraphically lower.

(5) Evidence of a silcrete older than the Namba Formation (?Etadunna Formation equivalent in lake Frome area) is found in Yalkalpo 1 Bore (Fig. 7), where silcrete pebbles and incipient silcretization are found at the top of the Eyre Formation.

Thus there are few localities where it is possible to say there is a silcrete older than the Namba Formation and Etadunna Formation. Even if it could be proved that there was a silcrete of this age which was widespread, it would not exclude the possibility of younger silcretes of identical lithology. In fact the evidence supports the presence of at least two silcretes of similar appearance, separated by a period of sedimentation of unknown duration, lithologically unlike the Eyre Formation.

Evidence collected by members of the Geological Survey Branch of the S. Aust. Mines Dept. further clarifies the situation:

(1) On WINTINNA and MURLOOCOPPIE Barnes & Pitt (*pers. comm.* 1975 S. Aust. Dept. Mines) have described channel deposits which contain silcrete cobbles and *in situ* nodules and layers. A basal conglomerate in these channels contains well rounded and polished silcrete pebbles mixed with milky quartz and other rocks in a sand matrix. Such beds have been found cemented by a second phase of silcrete elsewhere. The cobbles resemble typical grey billy silcrete, and yet the sequence is invariably capped by a well developed grey billy silcrete layer (sometimes columnar) resembling the silcrete described by Wopfner as forming a cap to the Eyre Formation. The writer has seen these

specimens and is satisfied that the silcrete clasts are transported silcrete pebbles, in a silcrete matrix, not nodules of silcrete. The channel sands are angular grained, but otherwise resemble Eyre Formation in having polished milky quartz and chert pebbles near the base.

(2) On the east side of the Dalhousie Dome area and Mt. Sarah, W. Krieg and L.C. Barnes (pers. comm. 1974 S.A. Dept. Mines) have described sections which resemble the Eyre Formation, but which contain pebbles of grey billy silcrete. These sections are quite close to the Mt. Alexander supplementary section of Wopfner et al. (1974), and there is no reason to suppose that they would not have been included in the Eyre Formation, because the sequence is capped by the same silcrete that occurs on the Mt. Alexander section.

These workers have therefore presented evidence for reworking of silcrete. Apparently it has been forming during deposition of the channel sands. Further, Wopfner excludes the Glendower Formation from his definition of the Eyre Formation largely on the basis that it contains silcrete clasts, thus it is evident he would not include Krieg and Barnes' silcrete pebble bearing sediments in the Eyre Formation.

Therefore silcrete horizons should not be used to define the top of the Eyre Formation since this may result in the inclusion of younger (or older) units, capped by similar silcrete. Many units containing silcrete pebbles could be younger than the Eyre Formation.

Alternatively (or additionally) the sediments containing the silcrete pebbles are Eyre Formation, and there was an older silcrete, in which case silcrete still cannot be used to define the top of the unit, since it was forming continuously with sedimentation.

2.3 RELATIONSHIP TO KAOLINITE BLEACHED ZONE

The kaolinitic bleached horizon commonly occurring beneath grey billy silcrete is regarded by some (Wopfner & Twidale 1967) as genetically related to the silcrete and by others (Firman in Parkin 1969) and earlier references therein (Jessup & Norris 1971) as a distinct unit of older age.

The problem can be resolved by examining the distribution of the horizons throughout the State. If the horizons are unrelated it should be possible to find:

(1) Silcretes developed directly on rocks without a bleached horizon beneath.

(2) Sediments intercolated between the two horizons.

(3) Portions of eroded bleached zone beneath silcrete.

(4) If the bleached zone is not found in sediments younger than the oldest silcrete cemented sediments, then it must be older than the oldest silcrete.

(5) Any discussion must take into account the possibility of at least two identical silcrete horizons. This could be complicated by partial erosion of older bleached horizons. Under these circumstances it would be possible to satisfy all the previous conditions. The only way of resolving this would be to carefully differentiate the uppermost and least eroded silcrete, and study its relationship to the bleached material.

To the writer's knowledge, after extensive enquiries of those involved in mapping in the South Australian Department of Mines, silcrete of the grey billy type is invariably accompanied by a bleached horizon beneath, though bleached horizons may be seen that are unrelated to any known silcrete (e.g. within the Cretaceous sequence: Wopfner 1964). No areas of eroded bleached zone are known immediately beneath silcretes.

There is a theoretical argument against regarding those bleached zones occurring beneath silcrete as distinct from the silcrete. In most examples of silcrete 'profiles' silicification occurs within transported sands, frequently showing sedimentary structures. These sands are often quite coarse, and any process involved in their transportation would lead to erosion of the loose kaolinized material beneath, had this been formed previously. This assumes the kaolinite zone could not have formed after deposition of the sediment.

Considering distribution of silcretes and the bleached zones in northern South Australia, they are frequently widely developed on the margins of anticlines in the Great Artesian Basin, but never found in bores penetrating identical stratigraphic horizons in deeper parts of the basins. An example is the Lake Frome area where the deepest silcrete encountered is at 15.5 m below the top of Glenmore 1 bore and an incipient silcrete in Yalkalpo 1 bore at 58.9 metres. Silcretes are developed sporadically around the entire margin of the basin, particularly on the flanks of the Flinders and Barrier Ranges. Similarly brilliant white bleached horizons are developed, beneath silcrete, in the same areas.

If the bleached horizon is independent of silcrete, and originated as a weathered horizon, one would expect it to form an extensive zone, best developed in the deeper parts of the basins where it had been preserved from erosion by subsequent sedimentation. Beneath the Eyre Formation in the Frome Embayment the Cretaceous is unweathered, though the Willyama Complex and Cambrian rocks are deeply weathered beneath the Tertiary sequence in the northern part of the Olary Block. This suggests two possibilities: (1) the bleached horizon is pre-Cretaceous and post Cambrian (Wopfner 1964, Daily et al. 1973), (2) the horizon has only developed on upland areas, because these are above the water table and permit weathering, and therefore is pre-Eyre Formation (or at least pre-Namba Formation, accepting the possibility that weathering processes can operate through a blanket of porous Eyre Formation sands).

The youngest sediments showing signs of bleaching in the Lake Frome area are those of the Eyre Formation, and it is concluded that the younger silcrete developed on this unit is probably genetically associated with bleaching. Silcretes of the grey billy type are associated with a bleached zone, probably genetically, but such zones may also occur independently in earlier horizons.

2.4 SILCRETE AND SUBSTRATE

The controlling factor in the physical appearance and petrology of silcrete is the substrate in which it is developed. If variations with maturity or stratigraphic position are being considered, the effects of substrate must first be eliminated by comparing silcretes developed within similar materials.

An example of substrate control is exhibited by the 'Murnpeowie'-Reedy Springs silcretes. On sands of the Eyre Formation, massive botryoidal and columnar grey billy silcrete sheets, containing numerous quartz grains, are developed. This material is cemented by cryptocrystalline microquartz and quartz overgrowths. On the clays and clayey silts of the Namba Formation the silcrete sheet is pale grey with red blotches and much more glassy texture, with the appearance of a breccia or 'terrazo' stone paving (puddingstone silcrete). In thin section this material consists of fibrous chalcedony and opal.

A series of holes were drilled by Pechiney (Australia) Exploration Pty. Ltd. (Mannoni & Barral 1972) between Murnpeowie, where the puddingstone silcrete is developed, and Reedy Springs, where the grey billy is best exhibited. Their section shows an erosional surface truncating the gently folded Tertiary sequence, which includes the Eyre Formation medium sands and Namba Formation clay and fine sand. This surface has a thin puddingstone silcrete developed upon it where the surface is of impervious clays, and a thick grey billy silcrete where folding has brought the Eyre Formation into contact with the truncation surface. Outcrop profiles are also shown by Mannoni & Barral in which silicified Eyre Formation clearly overlies puddingstone silcrete developed in the Cretaceous sediments. The writer has carried out field work in the area, and is satisfied with their interpretation.

Again, in the central Lake Frome area, massive brown silcretes with quartz overgrowth cement and some microquartz chert cement are developed in coarse sands. These sands form channels in the top of the lower unit of the Namba Formation in outcrop east of Lake Frome, (section 3, 4, this Chapter) and are much younger than the lithologically identical Eyre Formation with its grey billy silcrete at Reedy Springs. The two silcretes are very similar in external appearance, except for the brown colour, which results from an earlier period of ferruginization. However, there is a lesser development of microquartz cement in the younger silcrete, which may have some stratigraphic significance.

It is concluded siliceous duricrust cementation results in the following forms:

	Appearance	Petrology
(1) sand ↓	Columnar, nodular or botryoidal grey billy silcrete.	Microquartz chert, quartz overgrowths, anatase, all cementing corroded quartz grains.
gradation ↓		
(2) clay	Glassy porcellanite silcrete, sometimes with spherular structures.	Fibrous & chalcedonic chert, opal. Rare quartz grains.

The development of ferruginization on the surface to be silicified, either before or during silicification, results in yellow to dark brown silcretes in the case of (1) and red-brown mottled, or brown silcretes in (2). The red-brown mottled variety of (2) is known as puddingstone silcrete.

2.5 CONCLUSIONS

(1) There are at least two massive grey billy silcretes of Tertiary age. Silcrete formed both during and after deposition of the Eyre Formation - propensity to form this material therefore existed over a long period, but could not be expressed to its full extent unless there was a period of no sedimentation.

(2) Grey billy silcretes are generally accompanied by a kaolinitic brilliant white bleached zone directly beneath the siliceous crust, but similar bleached zones may be developed independently at other times.

(3) The physical appearance and petrology of silcretes is primarily dependent on the substrate and especially determined by its porosity.

(4) There is a silcrete at the top of the Eyre Formation, of the grey billy type, and with columnar structure, but it was locally developed and/or has been largely eroded. The best developed horizon is no older than Middle Miocene, from relationships with the Etadunna Formation and equivalent.

(5) The kaolinite horizon, preserved in valleys within the Olary Ranges on crystalline basement of the Willyama complex, is a bleached horizon originally associated with silcrete, remnants of which remain in the Mingary area.

(6) Silcrete tends to form at the margins of highlands. It may have been eroded from the tops, but has not been found in the deeper parts of sedimentary basins.

3. NAMBA FORMATION (new name)

This unit has its type section in Yalkalpo 1 bore (Figs. 7, 13), a subsurface reference section in Wooltana 1 bore (Figs. 17, 25) where it intertongues with the Willawortina Formation, and outcrop reference section at Lake Tarkarooloo (Figs. 1, 3 of Callen & Tedford <u>in prep</u>. &

Fig. 24 this thesis). Lithology has been described in detail by Callen & Tedford, and Callen (1975 <u>in press</u>; see Vol. II). Further details are to be found in the borehole logs cited above. The name is derived from Lake Namba on the CURNAMONA geological sheet (Fig. 1) which is the location of a major vertebrate discovery in this unit. It can also be observed in the bores shown in the fence diagram (Fig. 16) except K69, B240C3 and PMX24a.. The detailed logs are given in Figs. 6, 7, 17-23, 24). A coarser grained facies widespread in the region west of Lake Frome has been defined as a formal member, the Wertaloona Member, with a type section in Wooltana 1 bore.

3.1 LITHOLOGY

3.1.1 General

Briefly the formation consists of green, olive and grey or black clays with interbeds of pale yellowish laminated silt and very fine sand, and white fine to medium sand. Interbeds of oolitic dolomicrite and palygorskite clay (Figs. 146, 130) occur in several positions in the sequence. Broadly there are two informal members, which can be divided into a number of units. The lower member is dominated by dark sandy clays with irregular shiny or slickensided fractures (<u>c.f.</u> skew planes of Brewer 1964), whereas the upper member does not contain these clays, and shows more evidence of burrowing.

The lower member is divisible into four units in Wooltana 1 bore, described by Callen & Tedford. This subdivision was facilitated by reference to the petrophysical logs (Fig. 17), particularly the neutron log. The neutron log is particularly sensitive to changes in hydrogen ion content and hence porosity, and is independent of salinity. Note this and other logs have been moved down 1-3 m to correspond with the resistivity logs and lithology. These discrepancies are the result of incorrect recording depth on the logger's chart. The black clays of the Namba Formation were earlier regarded by others working in the Lake

Callabonna region, and further north, as part of the Eyre Formation. The Namba Formation clays can be distinguished by tough texture, irregular fractures, lack of visible carbonaceous material, and absence of lamination, whereas the clays of the Eyre Formation are silty, laminated, soft, carbonaceous and pyritic. There are also differences in mineralogy, discussed in Chapter 3.

Occasionally fine sands of the Namba Formation rest on fine sand of the Eyre Formation, but can be distinguished by the preponderance of kaolinite in the latter unit, and smectite in the Namba Formation (Yalkalpo 1 bore, Fig. 13).

3.1.2 Lithological and thickness variations

Gross thickness variations are depicted in the cross-sections accompanying the FROME geological sheet (Fig. 2), and show a shallow trough west of the mound springs trend in Lake Frome, and a gentle arch to the east. This arch becomes localized into a well-defined Precambrian basement high, the Benagerie Ridge, in the vicinity of Yalkalpo 1 bore, and is a prominent feature of the CURNAMONA geological map area. The Namba Formation thins out over the southern portion, though not as much as does the Eyre Formation.

During deposition of the Namba Formation, a number of erosional remnants of basement rock project above base level, and now appear as low mounds almost buried by the Tertiary deposits (Low Stony Hill, Mooleulooloo Hill, Kalkaroo Hill, Nancatee Hill, Little Nancatee Hill, and a patch of float north of Benagerie outstation, Fig. 1).

The fossiliferous black clay of the lower unit in Wooltana 1 bore has also been detected in Poontana Bore and in exploration drillholes of Central Pacific Minerals N.L. (Schindlmayr 1970, of which some were logged by the writer (F 22/26, E23/15, A 6.05/10). The facies is restricted to the Poontana Sub Basin. Little is known of its equivalents or relationship to the Eyre Formation. It is thought to rest directly on the Eyre Formation, from evidence in Poontana Bore (Fig. 2).

As in the Poontana Sub Basin the lower carbonate zone in the eastern side of Lake Frome (Fig. 16) is in contact with the Eyre Formation, but is absent south of the Lake. The carbonates are interbedded with light porous clay (palygorskite) near Wooltana 1 bore (Fig. 17). They consist of alternating beds of very fine grained dolomite and limestone. The beds lens to the east and south.

The upper carbonate in member 2 is more extensively developed than the lower, though absent from the eastern side of the Benagerie Ridge. It is best developed in the Poontana Sub Basin, where it has a similar thickness to the lower carbonate, and is interbedded with clay. South of Lake Frome the probable equivalents of these beds are well developed as a thin persistent unit extending from south of Curnamona to the Benagerie Ridge in the east.

The boundary between this carbonate and that of the Poontana Sub Basin, coincides approximately with the Poontana Structure (Figs. 2, 3, 16).

No carbonates are present east of the Benagerie Ridge, though some appear near the top of the sequence in Glenmore 1 bore (Fig. 34). The description of these suggests they are probably groundwater calcretes (unpublished data of Bunny 1968, N.S.W. Dept. Mines).

On approaching the Flinders Ranges, there is no evidence for thinning of any of the above units (see logs in Ryan 1969, Wecker 1972, cross-sections in Fig. 2) indicating the sequence once extended across the eastern edge of the Flinders Ranges, and has since been upfaulted and eroded.

Sandy beds are best developed in Glenmore 1, and EAR3 bores (Figs. 34, 5) both close to the Willyama Complex outcrop. Sands are also abundant in a northerly trending zone midway between the N.S.W. border and the eastern shore of Lake Frome and are interpreted by Randell (1973)* as an offshore bar developed in a lake.

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* The author of this report has included the sands in the Eyre Formation, not being aware of the presence of a disconformity.

In the Poontana Sub Basin cross-bedded fine to medium well sorted sands form a persistent horizon at the base of member 1, but it is not known whether they thicken towards the ranges. These sand beds also persist north of Mooloowatana and Mt. Hopeless. A high percentage of coarse sand is thought to represent proximity to source rocks, though the beds located by Randell (1973) may have some other origin.

3.2 RELATIONSHIP WITH OTHER UNITS

3.2.1. Eyre Formation

As described in Callen & Tedford the Namba Formation is disconformable on the Eyre Formation. This is demonstrated by (1) the absence of the Eyre Formation on the basement highs (e.g. Benagerie Ridge): Namba Formation rests directly on Cretaceous or older rocks, (2) by the presence of silcrete between the two units in marginal areas, (3) by the palynological data, which indicates that most of the Oligocene and Lower Miocene are unrepresented by sediments.

3.2.2 Willawortina Formation (new name)

In the Poontana Sub Basin adjacent to the Flinders Ranges, is developed a unit named the Willawortina Formation (Callen & Tedford *in prep.*) intertonguing with member 2 of the Namba Formation.

3.2.3 Other Units

In the Pechiney Exploration bores mentioned previously (Mannoni & Barral 1972) and in Minad LB12 bore (Fig. 15) puddingstone silcrete is developed on the upper surface of a sequence resembling the Namba Formation. It is here overlain by reddish brown clayey sand or conglomerate assigned to the Willawortina Formation.

East of Lake Frome the oldest unit (disconformably) overlying the Namba Formation is the Millyera Formation which is believed to be equivalent to the *Diprotodon* bearing beds of Lake Callabonna (Callen in Callen & Tedford).

3.3 INTERNAL DISCONFORMITY

The lower and upper members (1 and 2) of the Namba Formation appear to have a disconformable relationship with one another, particularly near the margins of the basin. This is deduced from the following:

(1) Member 2 rests with a sharp contact of slightly erosional character on the black clays of member 1, observable in outcrop at Lake Tarkarooloo.

(2) On the high plains area at Paralana, the top of the black clay of member 1 contains one or more well-developed alunite horizons. The irregular nodular distribution, decrease in intensity with depth, and columnar ped-like structure suggest weathering on an erosional surface. Similarly alunite occurs in black clays at the same horizon in C15 bore (Fig. 22) and in outcrop at Lakes Bumbarlow and Starvation (Figs. 1, 2). At Lake Bumbarlow it occurs within black clays about 2 m beneath a zone of silicified clay. The intervening material is bleached and kaolinized (the black clays normally have high smectite content). The nodules are too irregular and intergrown with the clay to have originated by transportation (Fig. 145) and show well developed columnar structure. Resemblance to a soil profile is striking.

(3) The alunite horizon, and the base of the upper carbonate (Fig. 16) mark the change from smectite dominated to illite-kaolinite dominated clays, described in the section on clay mineralogy, and observed in Fig. 36. The lack of physical evidence for a disconformity in the deeper parts of the Poontana Sub Basin (other than differences in clay mineralogy) suggests deposition was virtually continuous here, whereas the surrounding areas were subjected to uplift and weathering.

3.4 'COARSE, MATURE SAND UNIT'

Scattered over a wide area of the district east and southeast of Lake Frome are coarse grained well-sorted mature sands, cross bedded, lens-like in cross section, geometrically resembling channels. From the regional dip of 1^{o}-2^{o} west (Fig. 17) it is evident that they should occur at various stratigraphic levels in the Namba Formation if they are part of this unit (excluding the possible complexities of faulting). If this is the case, one would expect to encounter a similar lithology in some of the bores. Possibly polished medium sands in the black clays of units 3 and 4 (Callen & Tedford *in prep.*) may represent them, but none are as coarse or as thick. Some bores drilled by Tricentrol Aust. Ltd. (Middleton 1973, 1974) also contain mature polished sands, in lenses near the base of the sequence (LT2, LT28 and LT20 bores). These closely resemble the Eyre Formation, and are thought to have been reworked from this unit, which cropped out on the Benagerie Ridge during deposition of the lower Namba Formation.

If the coarse sands are assumed to be part of the Namba Formation then the outcrops must be placed stratigraphically near the top of member 1. However, it appears there was no source of coarse sands at this time in the centre of the basin. Strongly flowing, streams with coarse sandy beds are out of character in the Namba Formation (Chapter 5). The other feature making it difficult to place them in this Formation is their maturity, described in the section on petrology, and contrasting strongly with the commoner feldspar rich sands.

The sands are usually cemented by two or more stages of duricrust: ferricrete, silcrete and calcrete, in that order. These processes have modified the mineralogy and are discussed in Chapter 3. The finer grained sands are also cemented, but intertongue with green and grey silty muds at Billeroo Creek, never observed in the case of the coarse sands. Further, the coarse sands are invariably associated with massive pieces of partially silicified and ferruginized fossil wood (though this has never been seen in situ).

The presence of rounded fossil wood pebbles in the overlying basal Millyera Formation and Eurinilla Formation, indicates the coarse mature sand unit is older than these units.

Drilling east of Lake Frome by Chevron Exploration Corp. Pty. Ltd. (Morgan 1973) showed numerous bands of similar sand were cut into the Namba Formation clays, but never appeared as lenses within them, suggesting they were younger channel deposits.

3.5 STRATIGRAPHY OF VERTEBRATE OCCURRENCES

Before proceeding with a discussion of regional correlatives, it is necessary to place the varied vertebrate fauna from the Lake Frome area in its stratigraphic context.

Vertebrates were first collected by the writer from float on a small claypan north of Eurinilla Creek, at Grid Ref. 344147 (?Lake Hurd of early pastoralists in the area). An expedition led by R.H. Tedford located vertebrates at Lake Yantawena, Lake Tarkarooloo, Lake Namba and Lake Pinpa, on the northern part of the CURNAMONA sheet area. The writer located another occurrence at Lake Yanda. A large number of detailed sections were measured in the vicinity of a main occurrence at Lake Namba, and were placed in context with drilling by Tricentrol (Aust.) Ltd. (Middleton 1973, 1974). The drillholes were logged by the writer, and bores and sections levelled using a hand held barometer. Corrections for atmospheric fluctuation and frequent closures to Dept. Lands bench marks were made, giving an accuracy about ± 2 m. The data is summarised in the fence diagram (Fig. 33) which includes three key outcrop sections.

A regional dip of 2° west was obtained on the upper carbonate (in member 2 of the Namba Formation) in the area west and southwest of

Lake Tarkarooloo, by Paciminex Pty. Ltd. (Langron & Marshall 1973, Appendix 6) which accounts for the presence of the carbonate in outcrop at the south end of Lake Tarkarooloo, and its absence to the east. The fence diagram (Fig. 37) shows a northerly dip, suggesting faulting has been active in the vicinity of the Benagerie Ridge. It is evident from the diagram that the vertebrates occur high in the sequence, and from the detailed correlation (also on Fig. 37) it appears they are located above and below the disconformity between members 1 and 2. Alternatively all may occur beneath the carbonate in member 1, separated by an hiatus.

In Callen & Tedford it is concluded that the correlation shown in Fig. 2 of Callen (1975 in press) and Wopfner et al. (1974) between Yalkalpo 1 bore and Lake Tarkarooloo vertebrate horizons, though feasible, needs further confirmation. Possibly the vertebrate fossil in Yalkalpo 1 bore represents an older horizon.

Another fossil vertebrate horizon has already been mentioned - that of the basal laminated black carbonaceous clay in the Poontana Sub Basin, which contains fish remains. There are therefore three, or four, horizons containing vertebrates, the two major horizons with land vertebrates being at the top of member 1 and base of member 2.

3.6 AGE

A microflora extracted from Cootabarlow No. 2 bore (Harris 1970) gave a Miocene age. Further samples submitted by the writer from Wooltana 1, LC1A and Glenmore 1 bores yielded a similar flora (pers. comm. W.K. Harris 1975). This work is discussed in Callen & Tedford. A similar flora is also present in bores MT6 and MT30 of Tricentrol (Aust.) Pty. Ltd. in the northern margin of the Murray Basin, just south of Mutooroo (Lindsay & Harris 1973). The Tricentrol bores provide a detailed tie-in with foraminiferal stages, though some samples had been mixed and the conclusions regarding the upper marine transgression are not valid. A similar flora has also been found in the basal Etadunna Formation of Lake Eyre 20 bore.

The microflora occurs near the base of member 2 in all cases, hence there is no evidence for a minimum age of the Namba Formation from this source. However the vertebrate fauna is present near the top of member 2, and Tedford (pers. comm. 28th March 1973) believes this is Longfordian?, or at the latest, Mitchellian.

3.7 REGIONAL CORRELATION

3.7.1 Lake Eyre Basin - Etadunna Formation

The more obvious affinities of the Namba Formation are with the Etadunna Formation (Stirton et al 1961). The carbonates, grey-green clays and silts are identical to those of the type area at Lake Palankarinna, and palygorskite is abundant (P1136/72 to P1145/73). The vertebrates are also remarkably similar, Diprotodon ngapakaldii is significant as it has only been found previously in the Etadunna Formation (Tedford pers. comm. 1974).

In the Lake Palankarinna section vertebrates occur over a greater interval than at Lake Pinpa and surrounding areas.

Further evidence is provided by Lake Eyre 20 bore (Fig. 35), which has been correlated with the Etadunna Formation on lithological grounds (Johns & Ludbrook 1963). This bore contains the microflora mentioned earlier, equivalent to that of Wooltana 1 bore. It also has a very closely comparable clay mineral suite (Taylor & Pickering 1962) shown superimposed on the clay mineral fence diagram of Lake Frome (Fig. 36). The sequence is dominated by carbonates, contrasting with Lake Frome and Lake Palankarinna, but the lithology is basically identical, differences reflecting the dominance of lacustrine evaporitic sedimentation in the Lake Eyre Basin. It is of interest that the black clay and medium sands in Lake Eyre 20 bore are restricted to a very thin sequence at the base, whereas in the Namba Formation of Lake Frome they are extensively developed in member 1. The sequence at Lake Eyre also has a ferruginized horizon and alunite associated with it, as at the top of member 1 in the Namba Formation. Therefore the carbonates in Lake Eyre may be equivalent to member 2 of the Namba Formation.

At Lake Eyre, carbonates and green grey clays with palygorskite (pers. comm. B. Daily 1975 University of Adelaide) crop out around Madigans Gulf on Hunt and Baggage Peninsulas and were initially described by King (1956). These rocks have been assigned to the Etadunna Formation by Johns (Johns & Ludbrook 1963), Tedford (pers. comm. 1973) and Williams (1975) but are thought to be a younger unit by Daily.

3.7.4 Eucla Basin

In the Eucla Basin, the Nullarbor Limestone is partly contemporaneous with deposition of the Etadunna and Namba Formations (Ludbrook in Parkin 1969, p. 169 & Fig. 84).

3.7.5 St. Vincent Basin

Munno Para Clay Member - see Callen & Tedford (Vol. II).

3.7.6 Northern and eastern Great Artesian Basin

Rocks regarded as equivalent to the Etadunna Formation have been described by Townsend (1967) from Moomba No. 4 petroleum well.

In the Northern Territory the Waite Formation (Woodburn 1967) has been shown to be part of (or perhaps disconformable on?) a subsurface sequence (Senior 1972) which has a strong resemblance to the Etadunna Formation. The lower lacustrine beds contain the Alcoota Fauna of Stirton et al. (1968), which is placed in the medial to late Mitchellian stage by Tedford (pers. comm. 1973).

The Waite Formation consists of two units: an upper fluviatile red coloured sandstone and conglomerate capped by chalcedonic limestone, and a lower green, siltstone sequence of lacustrine origin containing vertebrate remains. The lower part of the unit was further correlated by Senior (1972) with the entire subsurface sequence identified in BMR

Alcoota 1, 2 & 3 bores. The writer does not agree with his correlation in its entirety: other interpretations are possible, and it is likely that there is a disconformity within the sequence. The stratigraphic position of the 'laterite' has not been confirmed because it is not recorded in the bores (though it could have been missed), and in outcrop occurs directly on folded basement beneath the sequence originally defined by Woodburn. It is suggested the sequence in the lower part of the Alcoota bores could be stratigraphically equivalent to the uppermost Namba Formation.

In South Australia on WINTINNA and MURLOOCOPPIE channel sands (pers. comm. L.C. Barnes 1975) are overlain disconformably by a sequence equivalent to the Doonbara Formation (Wopfner 1974) and Mangatitja Limestone (Major 1973), which have a strong resemblance to the upper part of the Waite Formation as described in Woodburn (1967). Note (Firman <u>pers. comm</u>. 1974, L.C. Barnes <u>pers. comm</u>. 1975 S. Aust. Dept. Mines) that the Doonbara Formation can no longer be regarded as entirely older than the Etadunna Formation.

3.7.7 <u>Queensland</u>

Extensive deposits of non-marine limestones occur over a wide area of Queensland (Whitehouse 1940). Many are siliceous limestones developed over ferruginous pisolite sequences, similar to the Cadelga Limestone and Doonbara Formation of Wopfner (1974) and the Mangatitja Limestone of Major (1973). Some of these limestones are Pliocene in age, since they are younger than the basalts developed in the region (Wyatt & Webb 1970), but others are older. The Carl Creek Limestone near Riversleigh contains a fauna believed to be of Miocene age (Tedford 1968, <u>pers. comm</u>. Tedford 1975).

Another sequence of interest is the palygorskite-bearing 'Silkstone Series' (Cameron 1923) which has been examined for clay minerals by Rogers <u>et al</u>. (1954). The Etadunna Formation and Namba formation contain similar clays and are lithologically similar (Whitehouse 1940). The sequence is interbedded with and intruded by basalts, the intrusions having been dated by Webb et al. (1967) as early Miocene and late Oligocene. The rocks are therefore older than the very similar South Australian deposits.

Other equivalent non-marine early Miocene deposits have been examined palynologically and summarized in Hekel (1972).

3.7.8 Gambier-Otway Basin

See Callen & Tedford.

3.8 ALUNITE IN SOUTH AUSTRALIA

A literature survey of 8 south Australian alunite occurrences revealed that all but the Yorke Peninsula deposits are located beneath "laterite" horizons, often associated with some form of silcrete. In some examples such as the Pidinga Lakes area described by King (1953) the ferruginous horizon has been referred to the Karoonda Surface (Firman 1966, Gill 1973) by J.B. Firman (pers. comm., 1974, Geol. Surv. of South Australia). Tentatively there seem to be several widespread ferruginous and siliceous horizons which have regional stratigraphic significance, and are associated with alunite. At this stage it is not possible to show these can be used across the whole state.

3.9 CONCLUSIONS

Regional correlation indicates that during deposition of the Namba Formation, marine limestones and clastics were being deposited south of the Olary Ranges in the Murray Basin, just as in the Eucla Basin, marine limestones were laid down whilst the Etadunna Formation accumulated in the Lake Eyre Basin. To the north there appears little change in facies, of equivalents of the Namba or Etadunna Formations.

The Namba Formation was deposited at a time of maximum marine transgression (Lindsay 1970), thus one might expect some marine influence. The possibility of a connection to the sea must be considered since it is evident that the Olary Range was very low at this time. The presence of a Platanistid dolphin requires this (Tedford, in Callen & Tedford in prep.), which should be borne in mind when the final discussion of palaeogeography is made.

Considering this, it is not too difficult to explain Ludbrook's record (Johns & Ludbrook 1963) of foraminifera from the basal Etadunna Formation* in Lake Eyre 20 bore in terms of transportation by sea birds. This is especially feasible in the light of recent work by Resig (1974) whose data suggests foraminifera are often abundant and varied, and probably ubiquitous, in salt lakes.

Relationships with other units in the Lake Frome area and elsewhere are shown in Callen & Tedford in prep. (Tables 2, 4, Fig. 24).

4. YOUNGER SILCRETE

4.1 BROWN SILCRETE

Brown silcrete, varying from honey coloured to very dark brown, is widespread east of Lake Frome. Typically it forms a capping to isolated mesas of medium to coarse sand, partly buried by Quaternary deposits, cropping out around the edges of large depressions. Some of these sands are referred to the coarse mature sand unit of section 3.4, others are the fine sands of the Namba Formation. The widespread distribution of these outcrops suggests a siliceous and ferruginous duricrust which has developed selectively on sands.

In thin section (Chapter 3, section 4.3) it is observed that the ferruginous matter (hematite and goethite) invariably coats the sand grains, and predates silicification. Pure specimens of ferricrete consist of dense black or very dark brown hematite, cementing sand grains. The silcrete and iron crust have not yet been found separated by intervening sediments, as would be expected if they were of differing age. Presumably

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* She did not include it in the Etadunna Formation, but it has since been shown on palynological evidence to be equivalent to the basal Namba Formation, see previous discussion in this thesis.

the area was not one of sedimentation in this district, during this interval, or the time involved was short.

These duricrust layers occur beneath channel deposits included in the Millyera Formation in Lake Tarkarooloo. At Billeroo Creek, east of Lake Pinpa, the same horizon is overlain by bone beds containing *Diprotodon* and other forms partly comparable with the Lake Callabonna fossil fauna (Callen & Tedford *in prep*).

4.2 PUDDINGSTONE SILCRETE

As stated in section ~~3~~2.4, this layer is younger than the Namba Formation. It is interpreted as silicified ferruginous soil. The layer is widespread in this district and the northern part of the State, where the corresponding horizon is probably silicified Paisley Pedoderm *c.f.* Jessup & Norris (1971) and silicified Doonbara Formation or Mangatitja Limestone (in part).

A profile which could be used as a 'type' section, occurs at the "Murnpeowie" homestead rubbish dump. Here the silcrete overlies grey Namba Formation clay.

In LB19 bore (10 m - 20 m) and LB12 bore (20 m - 30 m) puddingstone silcrete is present. It is therefore younger than member 2 of the Namba Formation, but it is uncertain whether it is above or below the lower part of the Willawortina Formation.

4.3 TIME OF EROSION OF FERRICRETE AND SILCRETE

In Wooltana 1 and WC2 bores, sand sized grains, interpreted as laterized siltstone, ?silcrete and other rock fragments (P1113/73 and P1079/73) occur in the basal part of the Willawortina Formation. Silcrete boulders and ferricrete pebbles occur in the "Wertaloona" section and at Munyallina Creek, but major erosion of ferricrete and silcrete apparently did not occur until the upper part of the Willawortina Formation was laid down (WC2 bore 7 - 71 m, Fig. 23).

It is concluded that ferricrete, and probably silcrete, has formed, or was forming, prior to deposition of the lower part of the Willawortina Formation and the upper part of the Namba Formation. It is uncertain whether this was the silcrete beneath the Millyera Formation east of Lake Frome, or the older silcrete associated with the Eyre Formation.

Ferricrete pebbles have also been observed at the base of the Balcanoona High Plains Tertiary section (Wertaloona section of Callen & Tedford) in the conglomerate interpreted as equivalent to the Eyre Formation. This suggests there is a pre Tertiary ferricrete, or that the whole of the Wertaloona section is equivalent to member 1 of the Namba Formation or younger.

5. WILLAWORTINA FORMATION

This unit is defined in Callen & Tedford (in prep.) with a type section in WC2 bore on the Paralana High Plain (Figs. 23, 31). Supplementary sections are at the dipping outcrop sequences south of "Wertaloona", on the Balcanoona High Plain and in Wooltana 1 bore (Fig. 25). Another subsurface section is present in Wertaloona 1 bore (Fig. 26).

5.1 DESCRIPTION

5.1.1 General

The formation is dominated by pebbly and bouldery clayey silts and sands with extremely poor to moderate sorting. The grains are suspended in clay matrix, rarely in contact. Feldspar and granitic rock fragments are abundant. Bedding is generally poorly developed, though thin bedding and lens-like bedding can be seen in outcrop at Balcanoona Creek. Sand lenses are cross-bedded. The clays are greenish coloured, but are frequently mottled in shades of red-brown and yellow-brown (Fig. 144 shows typical outcrop).

Thin fine grained dolomite and limestone lenses occur in

Wooltana 1 bore and along Balcanoona Creek.

The lower part of the section can be lithologically differentiated by the preponderance of matrix over framework, better sorting in the sands, and a lower proportion of coarse fraction (pebbles). Oxidation is less well developed. However, these properties still differ markedly from the major portion of the Namba Formation, and are in accord with the Willawortina Formation.

5.1.2 Lithological and thickness variations

The unit reaches its maximum thickness adjacent to the Flinders Ranges and wedges out rapidly to the east.

The lower unit in WC2 bore near the Ranges is almost identical to the upper unit, except that clay matrix is dominant, but in Wooltana 1 bore it is interbedded with moderately well sorted sand and carbonates. In WC2 bore the lower unit is quite thin, attributed to erosion during uplift of the Paralana High Plain area.

The upper unit is represented in the section at "Wertaloona" and the interval in WC2 bore, where it dominates the sequence. It is virtually absent in Wertaloona 1 and Wooltana 1 bores. Most of the material above the silcrete in the Pechiney exploration Co. Ltd. drill-holes is assigned to it, on the basis of high percentage of framework. All outcrop shown on the FROME 1:250,000 map area (Fig. 2) belongs to the upper unit.

In the bores of Eric Rudd and Associates Pty. Ltd. (prefixed 'EAR' Figs. 5, 6, 11, 12, 19-21, 27-29, 32) similar facies to the Willawortina Formation have been recognised, and are correlated with the sequence in Wertaloona 1 bore with the assistance of petrophysical log characteristics. In N.S.W. Glenmore 1 bore (Fig. 34, 0-16 m) a similar sequence occurs above a silcrete of the grey billy type.

The outcrop in Balcanoona Creek shows channels and bedded silts interpreted as river and flood plain deposits. Occasional large boulders in the channels were probably transported in tree roots, or mud flows.

In the Wertaloona section most of the coarser beds consist of quartzite boulders resembling Pound Sandstone and A.B.C. Range Quartzite, plus some metaquartzite, but interbeds and scattered boulders of dark blue grey cobbles of Cambrian and Proterozoic limestones are present in the upper part of the section. The homogenous nature of the clasts suggests headward erosion by streams supplying the detritus cutting through successive ridges of folded strata. The limestone does not appear until the upper part of the sequence, yet limestone (of Cambrian age) should be more extensive in the source area during the earlier times. This again supports headward erosion, since downcutting would produce the opposite sequence, with initially abundant limestone.

5.2 STRATIGRAPHIC RELATIONSHIPS

These are discussed in Callen & Tedford (in prep., see Vol. II)

5.3 AGE

The upper unit of the Willawortina Formation in the Wertaloona section is overlain with angular disconformity by a small patch of the basal conglomerate of the ?Millyera Formation equivalent. It is therefore older than 40,000 years B.P. The carbonate cementing this conglomerate also forms a cement to all the outcropping sandy or conglomeratic rocks of the dipping Tertiary sequence and Willawortina Formation, but does not persist at depth. It thus post-dates folding.

The older unit has been shown to intertongue with member 2 of the Namba Formation, and is therefore Middle Miocene or younger.

Relationships between the Doonbara Formation, Waite Formation and Namba Formation were discussed by Callen & Tedford and in section 3.7.6. They indicate equivalence with the basal Willawortina Formation, which is therefore tentatively Mitchellian (Late Miocene) or younger.

Thus the formation may range from medial Miocene to early Pleistocene, or span part of this time.

6. UPPER LIMIT OF THE TERTIARY

In Lake Callabonna carbonized wood (Tedford 1973) gave an age of >39,000 years B.P. (I - 5 479 SIAM86) from the Diprotodon bearing beds, which are probably equivalents of the basal Millyera Formation (Callen & Tedford, in prep.). Diprotodon is known to range from Pliocene to early Pleistocene, therefore these beds could include the late Tertiary.

In Lake Tarkarooloo the Millyera Formation overlies ferruginized and silicified sands developed on the Namba Formation. The equivalent secondarily cemented horizon in the Paralana High Plains is developed between Willawortina Formation and the Namba Formation. This ferruginized and silicified surface is taken as the upper limit of essentially Tertiary deposition.

Thus the 'coarse mature sand unit' and lower part of the Willawortina Formation are regarded as the youngest definite Tertiary deposits. For convenience, the upper unit of the Willawortina Formation is also discussed in this thesis. It is evident that the Namba Formation could extend into the Pliocene, though this is considered unlikely.

The top of the Tertiary is difficult to place, in the absence of suitable fossils. The oldest overlying sediments have an age obtained from dating shell affected by pedogenesis. This material was derived from a profile opposite the mouth of Poontana Creek in the channel joining Lake Callabonna and Lake Frome. The shell material was extracted from three horizons in the Millyera Formation (Callen & Tedford) and had suffered varying degrees of pedogenesis. The least affected material, which showed no signs of replacement in thin section, contained 81% aragonite. Most non-marine shells contain 100% aragonite, so some exchange of younger calcium has apparently taken place, assuming all calcite is pedogenic. Therefore the age of 35,200 ± 1,200 years (Gak-4948) for this material is a minimum. It is of interest that totally pedogenic material (replacement and moulds of shell) has given an age >33,400 (Gak-4949) and of 26,340 ± 1,230 (Gak-4953) respectively. The age is therefore considerably >33,200 years B.P. It is considered unlikely the Namba Formation is younger than Bairnsdalian at its top.

CHAPTER 3

PETROLOGY AND ORIGIN OF CLASTIC SEDIMENTS

1. INTRODUCTION

Methodology is discussed in Appendix 2. Selected petrological descriptions given in Appendix 1.

1.1 NOMENCLATURE

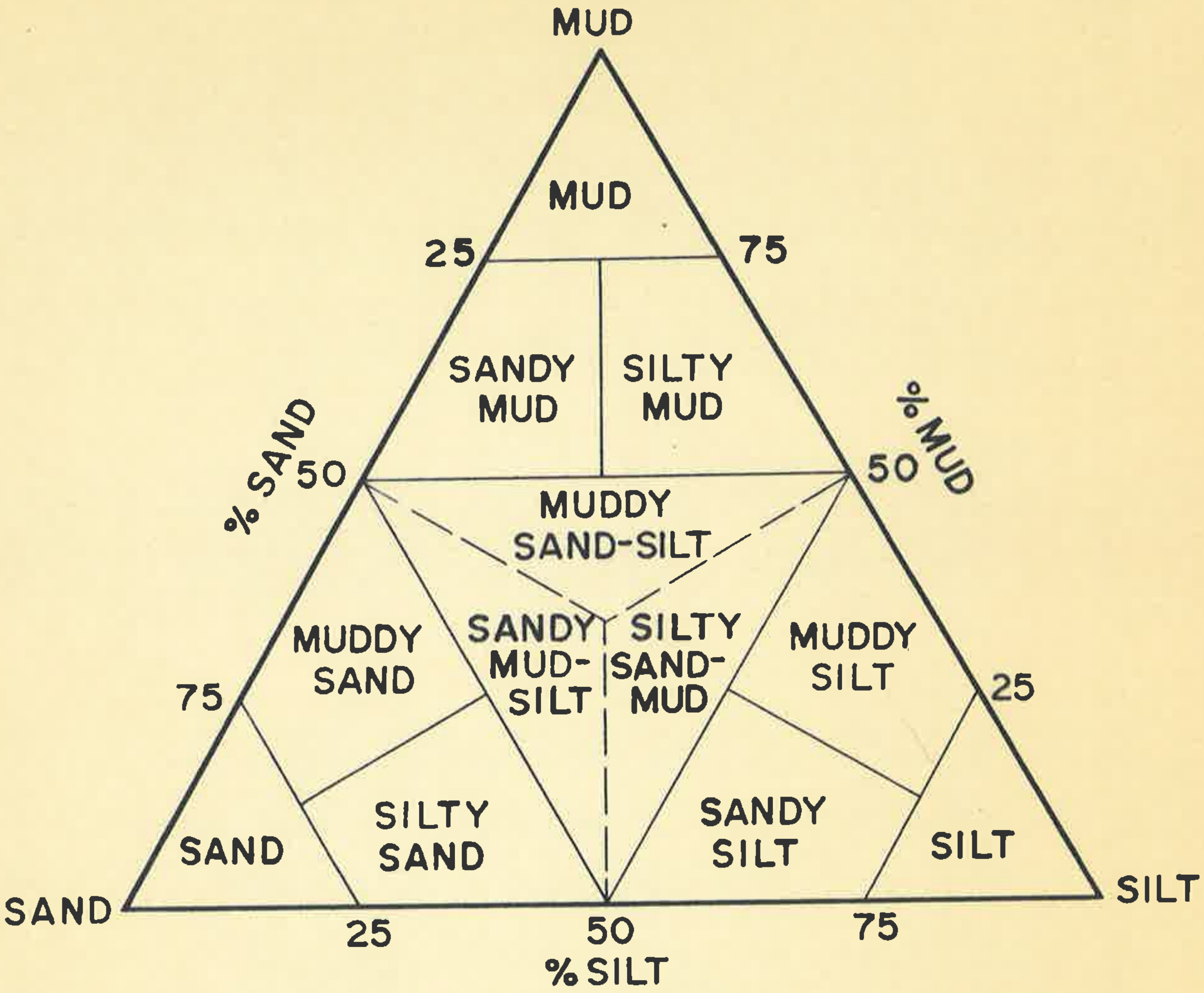
The techniques and nomenclature used were largely those of Folk (1968). This was supplemented in the fine grained rocks by the textural classification of Picard (1971), modified (Fig. 38) to avoid the confusing use of mud and clay as textural terms. Throughout this thesis "clay" is used to describe a particular type of mud consisting of clay minerals (one can also have pure quartz mud, or carbonate mud), following Folk's recommendation (Folk et al. 1970). Though mud is here used in a more restricted sense than Folk, corresponding to material $>8\phi$ (3.9μ, Wentworth's "clay"). Both Picard and Folk use the 3.9μ size as the division between mud and silt, and this is used here. The use of $<2\mu$ fraction for xray diffraction avoided including any non-clay minerals, and facilitated comparison with other results, since many analyses of this fraction have been made.

In practice estimates of silt percentage were made using a 15 x wide field eye piece and 3.5 x occular with a graticule graduated in 100'ths of a millimetre. At this magnification approximately three divisions on the graticule = 4μ. Percentage estimates were made using grain percentage comparator charts of various formats.

All gradations between silt, sand, clay and carbonate have been observed. Clay and carbonate are both muds, and can be grouped together, with silt and sand at the other end of the scale. Those rocks with 50% carbonate are classified using Folk's terminology (Folk 1959, 1968). Silts are treated in the same manner as sands (Picard 1971) using the

TEXTURAL CLASSIFICATION OF SEDIMENTS (FINE GRAINED)

MODIFIED FROM PICARD (1971)



SILT-SAND BOUNDARY 62·5 μ OR 4 Ø
SILT-MUD BOUNDARY 3·9 μ OR 8 Ø

Mud = clay, carbonate, quartz etc.
Carbonate muds classified according to *Folk*.
Sands and silts classified according to arenite scheme of *Folk*.
Muds ≡ lutites (excluding carbonate muds) classified by analogous scheme to arenites.

R. A. Callen 1975 S. A. Dept of Mines S 11513 terminology of Folk et al. (1970)

The petrology of each rock unit is discussed under the broad headings Framework and Matrix. Secondary rocks like silcrete, alunite etc. are considered separately. Carbonates are discussed in Chapter 4.

Rocks with 50% clay are termed lutites, this being the mineral compositional equivalent of the textural term mud, just as arenite is the compositional equivalent of sand and silt. Those rocks with equal quantities of two components are classified according to arenites, or in the case of carbonate and clay, as carbonates (a special case of lutite). Thus, the mud fraction vs the sand plus silt fraction is estimated. If the latter predominates, or quantities are equal, arenite terminology is used, if the former, then lutite is used. This avoids the three component system and accompanying terminology of Picard (1971). If carbonate is dominant within the mud, the carbonate classification is used. In complex mixtures, that fraction which is in next greatest abundance can be classified as though it were the prime component, and the resulting name placed in parenthesis.

Example P1085/73

SILT = 10-15% (Quartz
SAND = 25% (Feldspar & Rock 35-40%
(Fragments

Clay 45-50%) Mud dominant,
Carbonate 10-20%) therefore a lutite.
clay > carbonate,
therefore not classified
as a carbonate.

Picard: very fine sandy mud = texture term

Folk: calcareous (dolomite microspar) quartz -
kaolinite - RI - smectite lucite = mineralogical terms

i.e. very fine sandy mud: calcareous(dolomite microspar) quartz
(quartzarenite) kaolinite - RI - smectite lutite.

The minerals are listed in order of abundance, with mineral composition of clays and carbonate ideally being obtained from xray diffraction of the $< 4 \mu$ size.

The name can be abbreviated to sandy mud: calcareous quartz clay lutite (or smectite lutite, since smectite is dominant).

In practice, most specimens had one component dominant.

In classifying silts with arenites, there will be a paucity of silty litharenites compared with sands, since rock fragments are scarcer. Plagioclase would show a higher proportion of untwinned grains (only recognised with difficulty) and might lead to an apparent reduced proportion of plagarenites in comparison with sands.

1.2 MINERALOGY OF SOURCE ROCKS

1.2.1 General

Considering the area of various rock types exposed in the vicinity of the Lake Frome area at the end of Cretaceous times, ignoring mud, the detrital grains available should compose the following, in approximate order of abundance:

(1) Adelaidean - abundant fine quartz - silt and sand sized, second cycle. Durable rock fragments: chert replacements of carbonates, quartzite.

(2) Cretaceous - coarse and fine quartz sand (mixed first, second and third cycle). Chert and fossil wood, feldspar. These would be the first sediments eroded.

(3) Precambrian crystalline basement - mainly Willyama Complex - metamorphic and granitic rock fragments. Coarse quartz (metamorphic and granitic types). Feldspars and mica. Acid and basic volcanics a minor contribution. Mt. Painter Complex (smaller contribution) - similar to Willyama Complex: possibly coarser and more common potash feldspar. Minor volcanics.

(4) Lower Cambrian limestones may provide detrital grains, given the right conditions.

(5) Middle Cambrian sequence - probably a local contributor in the margins of the basin. Red-stained medium sand (second cycle grains) and fine mica would dominate. Some chert is present.

Light minerals are the most abundant, widespread components of sedimentary rocks and therefore potentially of great value in elucidating their history and provenance. Hence investigations were directed to ascertaining types of quartz, feldspar, chert, mica, clays and rock fragments in the sediments. Heavy minerals would probably also be a fruitful source of information, but their study requires special separation techniques, careful counting procedure and identification with index oils. Time did not permit their application. Percentages of light minerals are such that considerable information can be gained by simple visual quantitative estimates.

Attention was directed to feldspar, chert and clays. Feldspars and clay minerals are especially sensitive to climatic changes. Feldspars are also sensitive to tectonic events. Chert is a durable rock fragment which can give evidence of source rocks and transport processes.

As erosion proceeded during the Tertiary, the Cambrian limestones would be stripped, and crystalline basement rocks further exposed. Thus an increase of metamorphic and igneous derivatives might be expected with time, given stable climatic conditions.

1.2.2 Clay Minerals

In Table 1 the clay mineralogy of the source rocks is summarized. Data is scarce, but gives essential features, which are not expected to vary much in the Adelaidean as much of this sequence has been subject to slight regional metamorphism. The dominant minerals are illite, muscovite and chlorite, with minor kaolinite and smectite from basin margins.

TABLE 1

CLAY MINERALS IN SOURCE ROCKS

Source Rocks	Chlorite	Kaolinite	Illite/Mica ("Sericite")	Smectite	Others
1. Precambrian Crystalline basement	Tr	-	D	-	Tr biotite
2. Adelaidean	D	-	D	-	-
Lower Cambrian	?Slight, types unknown, includes illite and smectite				
3. Middle Cambrian	SD	SD	D	-	-
4. Cretaceous	-?	SD	A-SD	D	-
5. ?Precambrian	A	-	D	-	Tr biotite chloritoid
6. Unknown pre Cretaceous	SD	SD	SD	-	Graphite in some

D = Dominant, SD = Subdominant, A = accessory, Tr = trace

NOTES:

1. Estimated from writer's mapping experience and petrological investigations by AMDEL personnel.

2. Sumartojo (1974). Essentially Tapley Hill Formation and Sturt Tillite.

3. P 242/74, and P 244/72 writer's collection, and field experience.

4. None of these are in the Frome Embayment: they include specimens from the Blanchwater and Marree areas, and the Great Artesian Basin of the Innamincka and Gason domes. Winton Formation, Bulldog Shale, and Marree Formation were analyzed. Samples used are P 294/64, P 300/64, P 413/70, P 421/70, P 755/71, P 157/71, P 760/71, P 211-213/72 from Department of Mines files.

5. Possible Precambrian rocks within the Frome Embayment. Writer's collection: P 476/70B, P 480A & B/70, P 484A, B, C & D/70, P 672/70.

6. Collected by writer within Frome Embayment. P 1152/73, P1149/71, P682-4/70, P102/72.

XRD Analyses by R. Brown, Amdel

1.2.3 Feldspars

In Table 2 the composition of feldspars in the source rocks is summarized. The specimens from the Olary and Barrier Ranges region were largely collected by the author. The work was done by Amdel personnel listed in the Appendix. The object of this study was to utilize some of the observations made by Gprai (1951), Pittman (1963, 1969, 1970), Blatt et al. (1972, Chap. 8) with respect to feldspar variations in source rocks and effects of transport.

By weighting the average percentages of each unit approximately according to present day area of outcrop, it appears that in the Mount Painter Inlier, microcline (largely perthite) is about twice as abundant as orthoclase or plagioclase, which are present in equal proportions. Minor untwinned plagioclase is present. The total percentage of feldspar in rocks examined, taken by area of outcrop, is about 50-55%. The plagioclase is largely sodic, with albite twins having around 5-15 twin lamellae per individual; combined albite and pericline twinning is fairly common and many albite twins are incomplete or spindle shaped. The volcanic feldspars are considerably sericitized, except for adularia, hence these grains would probably be absent from derived sediment.

In the Olary region, unpublished mapping by G. Pitt of the S. Aust. Dept. Mines has enabled relative estimation of outcrop area of various units he defined. The Mt. Victoria area is as yet undifferentiated, and specimens from here have been grouped separately. The estimates indicate plagioclase is much more abundant than microcline (of which at least half is perthitic), untwinned plagioclase is significant and orthoclase a minor constituent. The plagioclase is more calcic than that of the Mount Painter region, being mostly andesine in composition. Complex twinning appears to be more common. Total feldspar content is about 40-50%

The Barrier Ranges region contains relatively less feldspar,

TABLE 2

FELDSPARS IN BASEMENT AREAS

MOUNT PAINTER

Source Rock	No. Specs	Probable Area of Outcrop			Feldspar Types			
		Small	Medium	Large	Twinned Plagioclase	Untwinned Plagioclase	Orthoclase	Microcline
Freeling Heights Quartzite	-			X	Known to be feldspathic; thin sections not available			
Mount Neill Granite Porphyry	4			X	6-9%/0.8 mm Alb.-Olig.	-	15%/0.6 mm some perthitic.	35%, size v. variable, usually coarse. Most perthitic.
Terrapinna Granite	9			X	8-10%/1-2 mm Alb.-Olig.	-	15-18%/0.5 mm some v.large. Turbid perthitic types common.	20-21% coarse. Some perthitic
Wooltana Volcanics	7		X		29-31%/0.2 mm long laths, very altered. Alb.-Lab.	8-9%/0.25 mm v. altered.	1%/2 mm Rhombic Adularia	-

Pepegoona Porphyry	3	X			8-10%/0.05 mm, some 1 mm. Altered or clear Alb.-Olig.	-	11%/2 mm altered	14-15%/0.03-3 mm
Mudnawatana Granite	2		X		Not examined - concentric zoned plagioclase present.			
Wattleowie Granite	1	X			Not examined.			
Yerila Granite	1	X			1-2% Intergrown musc. biot. Poorly twinned.	-	-	4-5% Poor twinning. Large sized crystals.
					OLARY RANGES			
Meta sediments (p€s)	3			X	21-23%/0.25 mm Variable, some sericitized, others clearly twinned. Albite.	-	3-5%/0.25 mm	7%/0.1 mm Poorly developed twins - Myrmekite common.
Mt. Victoria granitic rocks (p€r & p€g)	7		X		23-29%/0.4-0.5 mm. Oligoclase	Tr-2%	-	35-40%/1.2 mm inclusions common, some perthitic

Microgranite	1	X		20-25%/0.5- 1 mm Oligoclase	-	-	50-60%/3 mm Perthite and exsolved plag.
Granodiorite gneiss (p€r)	4	X		21-25%/0.7 mm Oligoclase, minor albite, minor pericline twins and carlsbad twins.	17-20%/0.6 mm Albite	$\frac{1}{2}$-2$\frac{1}{2}$%/0.3 mm	3-6%/0.7 mm mostly perthite. 6
Adamellite (p€g)	3		X	25%/1.1 mm Oligoclase, minor albite. Albite twins, minor carlsbad & pericline twins.	2-3%	-	23%/1.1 mm minor perthite. Twinning variable.
Unclassified	1	X		30%/0.6 mm Deformed.	-	-	-
Granite Conglomerate	1	X	very minor, but possibly representative of older rocks	35%/0.6 mm Bent lamellae many inclusions.	-	10%/0.4 mm Some perthite graphic intergrowths common	10%/0.5 mm Perthite

Mica schist (p∈a)	1	X	1%/0.2 mm Simple twins of albite type. Oligoclase	-	7%/0.2 mm	-
Meta-feldspathic quartzite (p∈s?)	1	X	15% Albite	-	-	-
			BENAGERIE RIDGE			
Sediments of probable Pre-Cambrian age (Of 13 specimens, only 3 contained feldspar)	1	X	80% plagioclase partly sericitized. Also feldspathic rock fragments	-	-	-
	1	X?	Percentage 60-70%? Mostly sericitized, some clear plagioclase.			
Porphyry	2	X	Total feldspar not given, but phenocrysts mostly feldspar, which is orthoclase and plagioclase. Both are considerably sericitized.			

				BARRIER RANGES			
Feldspathic gneiss and undifferentiated metasediments (Ꝑ w)	6		X	10%/0.5 mm Alb. Altered & sericitized	-	5%/0.6 mm Sericitized	5%/0.6 mm sericitized
Augen granite gneiss Ꝑ ga	1	X		5%/0.15-1 mm Albite	-	-	50%/0.4 mm clear twinning Myrmekite common.
Potosi Footwall Gneiss Ꝑ f	1	X		5%/0.3-0.4 mm in microcline.	-	-	75%/1-1.5 mm Perthite.
Granite Gneiss Ꝑ g	3	X		37-39%/0.5 mm Alb. & Pericline some Carlsbad. Fine lamellae.	-	-	6-8%/0.45 mm
Augen Gneiss Ꝑ w ?	1	X		55%/0.2 mm Alb?? Alb-Pericline twins well developed. V-clear and characteristic.	-	10-15%/0.15 mm v. clear	-

much sericitized. Sodic varieties of plagioclase are the most abundant, with microcline forming approximately 1/2-2/3, and some orthoclase.

No detailed study has been made of feldspars in other rocks, though it is known they are abundant in some Cretaceous sediments. In the Mt. Painter district the Bolla-Bollana Formation contains 45% 0.1 mm sized microcline, and no plagioclase.

It will be noted that the number of specimens is small, and variability of crystalline basement areas large, but it is thought that variability within the various units, with the exception of the undifferentiated areas, is small. Regional metamorphism may be expected to have produced relatively uniform composition in the plagioclase over large zones. Thus differences between the two crystalline basement areas are realistic.

Contribution from the Wooltana Volcanics is probably negligible, for reasons already stated, and the Pepegoona Porphyry has the composition of the enclosing granites and metamorphics. The only other possible contribution to volcanic detritus is the large porphyry body within the Benagerie Ridge and possibly sediments of Precambrian age on this same ridge, exposed during the early Tertiary. The feldspars of the sediments are plagioclase, whereas those of the prophyry are sericitized orthoclase with minor plagioclase.

Grain size of the potash feldspars is generally greater than for plagioclase. Sizes of 0.5-1.0 mm seem commonest. Microcline tends to be coarsely twinned in all the source rocks, and may therefore be difficult to distinguish from albite-pericline twinned plagioclase in small individual grains.

1.2.4 Chert

Chert occurs in the Cambrian, Adelaidean, Carpentarian and Lower Proterozoic sediments of the Flinders Ranges, as follows:-

Callana Beds	White chert
Blythe Dolomite	Present
Benbourie Dolomite	Present
Skillogalee Dolomite	Black chert
Bunyeroo Formation	Grey chert
Balcanoona Formation (limestone)	Present
Balcoracana Formation	Vitreous black chert
Lower Cambrian limestones	Pale grey and white chert nodules

Most of these cherts are replacements of limestone beds, and contain structures indicative of the original carbonate texture, Although forming a very small volume of rocks available to erosion, durability is such that they may form a significant proportion of alluvial sediment. In Depot Creek, for example, chert is abundant in the gravels 7 km from the source (which forms only a tiny percentage of detrital supply).

The most abundant source of chert would probably be Cambrian Limestone, though there is some doubt as to the age of the silicification relative to the Tertiary rocks. The next most abundant is that of the Skillogalee Dolomite, but this does not crop out close to the Lake Frome area.

Cherts from the Skillogallee Dolomite in the Depot Creek area collected by W. Preiss (S.A.D.M.) were examined. The grain size of individual quartz crystallites is quite variable. In detrital medium sand-sized grains derived from this material one would expect to observe carbonate replacement textures.

Detrital cherts from the Cretaceous and Jurassic of the Great Artesian Basin, collected by H. Wopfner (then of the South Australian Dept. of Mines) were also investigated (Fig. 77). Some examples from the Cretaceous of the Frome Embayment were included. The rocks of this period contain abundant chert as pebbles and sand sized grains. All varieties of textures were present.

Two other rocks can be confused with chert in sand sized material - recrystallized glassy parphyritic volcanics, and silcrete. Specimens of porphyries from the Gawler Range Volcanics (Figs. 81-83; collected by H. Blissett), the Benagerie Ridge and detrital grains in the Cretaceous were examined. Some of the detrital volcanic grains in the Cretaceous had been silicified. Silcretes from the Tertiary in the vicinity of the Lake Frome area, and from Lake Palankarinna were examined assuming older silcretes (at present unknown) contain similar textures.

The following differences were noted (Table 3):

TABLE 3

TEXTURES OF CHERTS AND RELATED ROCKS

Proterozoic Cherts	Mesozoic Cherts	Mesozoic Porphyry	Lake Frome area Porphyry. Gawler Range Porphyry	Tertiary Silcrete (grey billy type)
Cryptocrystalline micro quartz grading to mega quartz. Replacement textures typical of sparry limestones and shales, Some fibrous chalcedonic types as replacements of vugh infillings, or as direct infilling of voids.	As for Proterozoic Cherts, replacement textures less common, generally finer grained. Fibrous chalcedonic types (agate and fossil wood).	"Snowflake" texture, phenocrysts Red-brown stain, fuzzy appearance. Most replaced by microcrystalline quartz. Some patches of fine chert.	"Snowflake" textures, phenocrysts of feldspar and quartz.	Microcrystalline quartz, and quartz overgrowths. Embayed detrital quartz grains float in this matrix. Sedimentary textures generally destroyed, though clay texture may survive.

In fine grain sizes silcrete textures converge with cherts, and with recrystallized volcanic glassy matrix. Volcanics, however, can show fine 'snowflake' texture of chert or feldspar or both which is quite distinctive (Fig. 81, 82) and is usually accompanied by ferruginous staining. The quartz-overgrowth silcrete textures were not observed in the older rocks. In coarser grains, especially granule size and upwards, distinction between various types can generally be readily made. The fibrous chalcedony of the Cretaceous agates was indistinguishable from similar textures developed in chert replacements of carbonates, in small grains.

Both fibrous chalcedony and micro quartz chert textures can grade into those typical of recrystallized volcanic glass, which may consist of aggregates of radial fibrous chert, or of mixed quartz and feldspar with 'snowflake' texture (P1024/73B and Fig. 80). The granular microquartz type (Fig. 88) also grades into textures similar to fine grained quartzite and silcrete (c.f. Dickinson 1970).

While not a comprehensive study, these observations at least provide some data for comparison. Data are lacking on Cambrian cherts, however, which could be an important source.

2. FRAMEWORK CONSTITUENTS

2.1 EYRE FORMATION

(Figs. 4-14, 33, 24). Selected petrological descriptions (P1048/73, P1134/73, P298/72) are given in Appendix 1.

2.1.1 Arenites

Arenites are ubiquitous and dominate the sequence, being characteristic of the Eyre Formation. All (25 were examined in thin section) are classified as quartz arenites or cherty quartz arenites. The basal unit sometimes contains granule and pebble beds which fall into the rudite field, but texturally and mineralogically they are identical to the finer sands. Medium sands are commonest, ranging to coarse silts in the finest arenites. Clay generally forms less than

2% except in the finest grades. Lutites and arenites are usually sharply differentiated, with erosional contacts in many cases, though occasionally fining upwards sequences are present which show complete gradation to sandy clay at the top (B240C3, K69, Figs. 4, 9).

The dispersion ("sorting") ranges from well sorted to very poorly sorted, averaging moderately well sorted. Grains are sub-rounded to rounded, of low sphericity. In the southern areas they are sub-angular to angular.

These rocks are mineralogically supermature, and texturally mature.

2.1.1.1 Feldspar and quartz

Feldspars are rare, of untwinned orthoclase with a slightly turbid appearance, or very rare microcline. Polycrystalline quartz is rare, even in coarse grained sands: most is of semicomposite type. There is a tendency for polycrystalline grains to be commoner in the lowermost unit, which is probably a result of coarser average grain size. Most composites are simple types (P1048/73, P294/72 and Figs. 64, 80, 87) with a small proportion of stretched metamorphic quartz.

2.1.1.2 Chert

Absence of chert in the southern regions, except in Eocene silts (P243/72) is confirmed in thin section studies. The samples from PMX24a (Fig. 8), B240 C3 and K69 bores contained no chert, whereas it is abundant in Yalkalpo 1 and Reedy Springs samples. Two main types can be distinguished: radial chalcedonic forms, and granular microquartz.

Various types of microquartz chert distinguished are:-

(a) Equigranular types (Fig. 79), or

(b) Inequigranular types, subdivided into those with

  (i) Sutured contacts (anhedral)

(ii) Straight contacts (subhedral)

These may be stained or clear, and vary in grain size (Fig. 78). Grains may vary considerably in size range, average size, and texture. The commonest textures are those with equigranular matrix having coarser criss-crossing veins (Fig. 85), grading to megaquartz, patchy coarse and fine, and "porphyritic", forms.

(c) "Fuzzy" inequigranular chert - individual grains have very diffuse contacts. Often stained or full of minute inclusions (bubbles?)

No grains were found which could be conclusively assigned to silcrete. Some were suspected of being of volcanic origin, especially when "snowflake" textures, scattered large clear quartz grains, and ferruginous stain were present. However, no feldspar could be distinguished, certainly no twinned feldspars were present. Types with very fine oriented ragged quartz grains (P296/72, 295/72) are probably metamorphic quartzite.

In chert pebbles, the texture is coarser than for the sand sized grains, except "brecciated chert" in P298/72, which would produce sand sized grains of inequigranular chert with sharp boundaries between individual grains, and equigranular chert with veins of coarser size. The brecciated chert pebble is a replacement of sediment, as it contained outlines of irregular clasts with distorted structures.

Other chert pebbles displayed the following textures:-

(a) Laminated
    (i) Fine parallel laminae - banded silt or carbonate P918/71, P298/72
    (ii) Wavy laminated (Fig. 76).

(b) Banded, with megaquartz, strongly undulose extinction - crystalline limestone?

(c) Snowflake texture, with large single rounded polycrystalline quartz grains - recrystallized porphyry (Fig. 80).

No pebbles with fibrous structure were present though R.P. Coats (*pers. comm.* 1974, S. Aust. Dept. Mines) has found agate pebbles north of "Mooloowatana".

2.1.1.3 Mica

Mica is present almost entirely in the form of muscovite. Flakes frequently reach large sizes, and, as expected from the hydrodynamic properties, are coarser than other grains in the same sample, and most abundant in the silt to fine sand sizes. Many grains are bent by the pressure of surrounding quartz grains, and in clayey samples many showed fanned edges with kaolin along cleavages (P1148/73; compare Millot 1970, Plate 1). Some show rounded edges, formed by gentle abrasion.

2.1.1.4 Heavy Minerals

Characteristic heavy minerals have been described from the Eyre Formation. The only study was that of Whittle & Chebotarev (1952) who examined samples from a series of stratigraphic wells drilled by the Frome Broken Hill Co. Pty. Ltd. Their results were inconclusive, since similar grain sizes were not compared and core was discontinuous, but some general comments about mineralogy can be made using recent stratigraphic knowledge. From their results the Eyre Formation contrasts with the Namba Formation in containing staurolite and kyanite. Other heavy minerals present are zircon, tourmaline, sillimanite, andalusite, rutile, garnet, kyanite and opaques. This suite was confirmed by the writer, who observed zircon, tourmaline (often zoned, usually blue) andalusite and rutile are commonest (in order of abundance). All of these minerals show little rounding, and frequently are terminated crystals.

The suite is similar to that in the Olary Ranges crystalline basement rocks, and most abundant in the Eyre Formation near this region. The lack of change in mineralogy in the northern areas (Whittle & Chebotarev 1952) at first suggests sands from the basement were intermingled with those from the Mesozoic sediments, but the Mesozoic samples also contain a similar heavy mineral suite, which could be reworked into the Tertiary sediments. Changes in roundness and relative abundance between areas is unknown.

2.1.1.5 Rock Fragments

Fine grained quartzite and coarse grained strained granitic quartz pebbles (Fig. 86) or stretched metaquartz are the only rock fragments observed. In sand sized material the same grain types are present, though of less readily recognizable origin. In Folk's sandstone classification all polycrystalline monomineralic quartz except chert is assigned to the quartz pole of his triangle.

2.1.1.6 Grain features

The consistent subrounded-rounded low sphericity quartz sand grains of the northern areas (Figs. 85, 91) contrast with subangular varieties on the CURNAMONA map area (Fig. 64). Shape is consistent, many grains showing lath-like forms derived from quartz prism shapes or effects of parting. It is usual to explain elongation of quartz in terms of original crystal prism habit coupled with greater hardness perpendicular to the C-axis, but most grains had their C-axis at an angle of 30^{o}-40^{o} to the long axis of the grain (in thin section). It is thought that cleavage, though rarely observed or considered in quartz, is a significant shape determinant in monocrystalline grains even with incipient polycrystallinity and undulose extinction. It is suggested this is a more important factor during abrasion than strain boundaries, and probably as important as variations in hardness or original shape. These elongate grains display prominent orientation sub-parallel to lamination.

The grains in the CURNAMONA area have deep grooves, seen criss-crossing the surface under a hand lens. In thin section they appear to follow crystallographic directions, and are infilled with kaolin (Fig. 64). Sometimes they penetrate the full width of the grain, which is held together purely by kaolin. These features are thought to result from secondary weathering after deposition. Feldspars have been converted into kaolin which has recrystallised in the cracks and solution cavities. Essentially it is a soil phenomenum. Quartz more commonly shows other less extreme diagenetic features: grains being embayed, presumably through reaction with matrix or pore water.

A feature of the coarser grains in the northern areas is the surface polish, thought to result from abrasion of bed-load material by the saltation load during transportation in streams, or else by attrition within the saltation load. It does not result from incipient minute overgrowths, as far as could be optically determined.

2.1.2 Lutites

Five thin sections were examined. Carbonaceous kaolin clay with varying degrees of silt, sand and mica occur, mainly as clayey silts in the Eocene (Fig. 57),dominantly in the CURNAMONA sheet area and to a lesser degree elsewhere. The muds are distinct from the silts, since they contain a very poorly sorted sand fraction often very coarse grained. The sand grains show the deep grooves mentioned above, and are scattered singly throughout the matrix.

Polycrystalline grains are less common in lutites than the arenites, though some lutites contain a higher proporrion of quartz.

2.1.3 Conclusions

The Eyre Formation sands are texturally and mineralogically mature, though sphericity is not as high as expected. Relatively low sphericity may be caused by lack of transport, or by mode of transport, plus a tendency to cleave more readily than the average quartz grain. Lack of evidence for prolonged transport suggests a highly weathered source material already mineralogically mature, is required to supply the basin.

As indicated in Chapter 1, textures of the sand-sized cherts are identical to those found in Adelaidean rocks and Mesozoic sediments. According to Wopfner et al (1974) the Jurassic sandstones are an abundant source of cherty material. In Yalkalpo 1 bore the Cadna-Owie Formation equivalent and lower Marree Formation also contain similar cherts. A source from these units, uplifted on the northern parts of the basement blocks in the Barrier and possibly Flinders Ranges, is suggested.

Lack of chert in the CURNAMONA sheet area is indicative of a source in the chert free Willyama Complex, which has locally swamped Mesozoic debris. Ultimate sources of chert are the Adelaidean and possibly Cambrian rocks, though some of the coarse fibrous types probably originated from fossil wood and agate derived from the Mesozoic. The distribution of mica again supports an origin from the granitic Willyama Complex of the Olary Ranges.

2.2 NAMBA FORMATION

The Namba Formation is mineralogically more complex than the Eyre Formation, though dominantly fine grained. See Figs. 6-7, 17-23, 24. Examples P1090/73, 1076/73, 1086/73, 1083/73, P1269/73, CSIRO543, P1021/73, P1154/73, P1101/73 are in Appendix 1.

2.2.1 Arenites

The dominant minerals are quartz, clay, feldspar and mica, the commonest rock fragments are ?volcanics, chert, intraformational clays and carbonate. There is a strong contrast with the Eyre Formation sands, even when the grain size factor is eliminated.

The Namba Formation also has an abundance of unstable clays and feldspars. Twenty eight thin sections of arenites were examined, twelve of which are from surface outcrop, 8 sands, and 20 silts. This does not include secondarily comented varieties, not discussed here because of the modified texture and mineralogy.

The grain size ranges from very fine silt to medium sand, but coarse silt and very fine sand are commonest. The mud component is ubiquitous, and most have matrix-supported textures. They range from arkose through subarkose to quartzarenite. Gradations to sandy clay or carbonate-mud are present. Clay mineral composition and texture is identical to the muds, and discussed in section 3 (this chapter). In sands with a low proportion of matrix, skelsepic and lattisepic fabrics (Brewer 1964) tend to dominate. Most have a very poorly to poorly sorted sand fraction, the clay content then producing even lower calculated sorting values (see Chapter 6).

Grains of quartz and other minerals generally show a strong preferred orientation, with long axes sub-parallel to lamination.

2.2.1.1 Quartz

Quartz grains are generally distinctly elongate, sometimes in shard-like forms. As in the Eyre Formation, cleavage, crystal shape, and hardness variations relative to crystallographic direction appear to have been a dominant factor in shape determination, even more so than in the coarser sands. Polycrystalline grains range from trace amounts to 10% and are usually simple types with 2 or 3 individual, subhedral contacts and straight extinction. The remainder consist of variably sized individuals (Fig. 67), some of which are stretched metamorphic types (Fig. 92). Others have diffuse very small individuals with ragged outlines (Fig. 88). Some cataclastic quartz is present. Of the simple grains, up to 50% show undulose extinction, and up to 15% of these are semicomposites. Rutile and sillimanite needles, chlorite, sericite, plagioclase, tourmaline and mica have been noted as inclusions. Some varieties are observed in Fig. 71 and P1021/73, P235/72. The proportion of composite quartz grains is less than in the Eyre Formation, to be expected because of the finer grain size. However, undulose extinction and semicomposites seem to be more common, suggesting a more unstable assemblage.

The grains are often embayed by reaction between clay matrix and quartz, and in many cases this has resulted in a 0.002 - 0.005 mm fine silt size (e.g. P1083/73 and Fig. 99). Fig. 73 (P1083/73) displays quartz overgrowths, also having reacted with the matrix. Under the binocular microscope,stepped facetted surfaces and crystals faces are developed on grains, sometimes minute quartz prisms project from apparently rounded grains (see sketch in Yalkalpo 1 bore log at 17 m, Fig. 7). In many cases these facets seem to be superimposed on originally rounded grains, but in thin-section one rarely finds evidence for overgrowths. In fine grained quartz sands rounding is less prominent than in coarse sands, hence the angularity and presence of crystal facets can be explained partly by hydrodynamic properties during transport.

2.2.1.2 Feldspars

Seventeen thin sections containing feldspars were examined, and in other specimens xray diffraction records their presence,(e.g. Fig. 149). Methods of measuring feldspar composition and classifying twin types are discussed in Appendix 2.

Commonest feldspars are untwinned varieties (Fig. 65), second in abundance are albite-pericline twins (Fig. 69) with albite twins slightly less common (Figs. 66, 68). The untwinned grains are mainly orthoclase (Fig. 65 and P220/72), deduced from xray diffraction analysis of whole rocks, refractive index compared with quartz, and presence of fuzzy alteration (sericite). Plagioclase in these samples rarely shows good cleavage and is generally unaltered, except by marginal reaction with clay matrix. Albite-pericline twins can be divided into fine-cross-hatched types, undoubtedly microcline (Fig. 67), and coarser types which can be microcline or plagioclase (Fig. 69). The grid twinning may be very coarse, in the presumed source rocks and perthites can be present with exsolved plagioclase. Sometimes grains of microcline have twin effects difficult to distinguish from type 1-3 twins of Gorai (1951) on a flat stage, unless a suitable optic figure can be obtained and sign measured. Carlsbad twins are extremely rare.

The commonest forms of plagioclase are Type 1 twins of Gorai, others being rare and generally of Type 3A. Albite polysynthetic twins are most abundant, but the number of twin lamellae varies from many fine individuals to 3 or 4 coarse bands. Type 2 twins are also common.

Relative abundance of twin types is generally constant for a particular outcrop or drillhole, but variations occur between areas. There are insufficient results to analyse this statistically. In WC2, and Wooltana 1 bores, orthoclase and microcline are each equal to or more abundant than plagioclase, whereas in Wertaloona 1, EAR7 and EAR5 bores plagioclase or microcline is usually more abundant as expected from consideration of crystalline basement feldspar. This situation also applies to the northern outcrops, east of Lake Frome, but outcrop on Benagerie sheet area and material from Yalkalpo 1 bore show a consistently larger proportion of orthoclase.

Measures of plagioclase compositions, though not always producing unique results by flat stage technique, indicate varieties in the albite-oligoclase range are dominant.

Evidence for breakdown of feldspar to clay is common (Fig. 68).

2.2.1.3 Mica and chlorite

Fine mica is ubiquitous, though varying in abundance from a few flakes to 10–15%. It is most abundant in the silts and fine sands, particularly in the sands between 123 and 147 m in Wooltana 1 bore (Fig. 17) and 135 m to base of hole in Wertaloona bore (Fig. 18). Fine grained muscovite is dominant, though a few grains of biotite or chlorite may be present.

2.2.1.4 Chert

Chert varies in percentage from 0.5% to 5%. A few grains are invariably present. Varieties are similar to those of the Eyre Formation, with both fibrous-radiating chalcedony (Fig. 89) and microquartz (Figs. 65, 71, 90, 92) types present, the latter more abundant. Microquartz types may have fine criss-crossing veins of coarser texture, or irregular patches of more coarsely crystalline quartz (Fig. 71). In some grains these patches extinguish simultaneously. A few show 'snowflake' textures reminiscent of recrystallized volcanics. Some of the inequigranular fine grained varieties are almost isotropic (Fig. 71), resembling silcrete of the silicified shale variety. Several forms of radiating types occur, frequently coarser grained than microquartz varieties (which are generally finer than quartz grains). They may consist of aggregates of spherular chert (1021/73 P1027/73) and polyphase varieties (P1272/73). Most show length fast chalcedony, some have length slow chalcedony in addition.

2.2.1.5 Rock fragments other than chert

These are of two types – intraclasts and detrital grains. The intraclasts are coarsely crystalline clay (kaolin? or p~~o~~alygorskite?) and granular textured green clay (smectite?) or silty clay. Detrital grains are quartz-feldspar composites of granitic origin, or schist. Such grains are rare, even in the fine to medium sands.

2.2.1.6 Heavy minerals

Tourmaline is normally present, in small angular bluish grains. Other heavies include zircon, rutile, andalusite, opaques, epidote, garnet, sillimanite and amphibole according to Whittle & Chebotarev (1952). Zircon and tourmaline are the most abundant of the heavy minerals. Zircon, rutile, tourmaline, opaques and garnet were observed by the writer under the binocular microscope.

2.2.1.7 Conclusions

The framework minerals of the Namba Formation differ markedly from the Eyre Formation in abundance of unstable feldspar and clay, finer grain size, greater angularity and better sorting. The difference in angularity can be explained largely by grain size differences, in accord with the behaviour of fine grained sands during transport (Blatt _et al_ 1972, p. 69). This is confirmed by the presence of similar angular fine sands in the Eyre Formation (e.g. the top of the Eyre Formation in Yalkalpo 1 bore - Fig. 7) in which the mineralogical features are indicative of a mature sediment. Lack of coarse grained detritus suggests low energy conditions. Absence of rock fragments is attributed largely to the fine grain size, but those present are unstable types.

Embayed quartz and degraded feldspar provide abundant evidence for diagenesis, in which clays have reacted with the framework grains. The implications of this will be discussed in the section on matrix constituents.

Total feldspar content and grain size is low compared with abundance in the crystalline basement areas, as expected from dilution with fine clastics, and abrasion and weathering.

Before deductions about feldspar proportions can be made, effects of weathering on surface samples must be determined if these are to be included in the discussion. Comparison between surface and subsurface shows plagioclase and microcline is as abundant in both. Most of the Quaternary rocks contain abundant feldspars of both types, showing weathering has not occurred to great extent. Thus outcrop samples are little modified by later weathering. The overlying Quaternary rocks all contain abundant unstable feldspar. However, if the "coarse mature sand unit" is recognized as a distinct rock unit, and its maturity taken as indicative of humid weathering, then modification of feldspars in the Namba Formation during Plio-Pleistocene times should have occurred, as a result of these climatic effects, and should result in higher orthoclase content.

The dominance of type 1 twinned plagioclase and absence of complex twins and zoned plagioclase is consistent with an igneous and metamorphic source (Gorai 1951). Plagioclase compositions in the Lake Frome rocks are consistent with those of the crystalline basement areas. Two sets of compositions dominate in the Namba Formation at An10 or An30, and An15 or An25, averaged from 92 determinations. The few unique determinations suggest albitic compositions (An10 and An15) are commonest as does the generally lower refractive index than quartz (though it is rarely that the comparison can be made, as quartz and feldspar are generally not in contact). In the Willawortina Formation there is one dominant set at An19 or An30, being the commonest values out of 22 determinations.

The relative abundance of feldspar types is crudely consistent with existing crystalline basement feldspar content, with respect to plagioclase/orthoclase ratio. Outcrop on the Benagerie sheet area and sediment in Yalkalpo 1 bore both have high orthoclase content, perhaps attributed to the proximity of the sub-surface porphyry rich in orthoclase (P516, 517/71). There is no conclusive evidence for exposure of the Benagerie Ridge during deposition of the Namba Formation.

The decreased amount of microcline in the Namba Formation compared with the crystalline basement contrasts with the relatively unaltered orthoclase/plagioclase ratio, particularly in the area adjacent to the Mt. Painter block. This apparent lack is partly attributed to the mechanical breakdown of the rather coarsely twinned basement material so producing quite coarse albite-pericline twins, resembling plagioclase. Even accounting for this, there is a distinct reduction in the proportion of microcline compared with the presumed source rocks. According to Blatt et al., (1972 p. 304) microcline is more stable than orthoclase under surface conditions, so the lack of this mineral is difficult to explain, in view of its invariably fresh appearance in thin section. Possibly it disintegrated more easily than other feldspars during transport, and rapidly became degraded.

The relative stability of plagioclase and orthoclase was examined by Todd (1968) who found that even under humid conditions, if restricted leaching applied, plagioclase was least weathered. Presumably orthoclase would be more readily degraded under these conditions, and therefore form a lower pencentage of the resulting sediment. This situation opposed that normally quoted in textbooks, and may be applicable to the Namba Formation. It cannot be assumed that presence of "unstable" feldspars indicates arid climate. Even though plagioclase is abundant in the source area, one would have expected most of it to be weathered in a humid climate with strong leaching.

The few calcic plagioclases can be attributed to a local source in the Wooltana Volcanics or from basalt dykes. No evidence for a major addition of volcanic feldspar was found, although this period was a time of vigorous vulcanism in the east (Sutherland et al. 1972).

Some feldspar grains, particularly microcline and plagioclase (Figs. 67, 68 and P1110/72) have been partly decomposed and absorbed into the clay matrix. Thus feldspar content does not represent the original detrital component, and percentage of clay has increased. Changes were relatively minor, most grains showing only slight degradation.

It is concluded the feldspars were derived largely from nearby crystalline basement areas. Weathering and abrasion have modified the quantity and ratio of types.

Similarity of cherts between the Eyre Formation and Namba Formation suggests a similar source. They are comparable to Mesozoic cherts (c.f. Figs. 77, 90, 78). Being more resistant than other rock fragments, chert is able to survive two, perhaps more weathering and erosional cycles and could therefore be partly inherited from the Cretaceous rocks, as proposed for the Eyre Formation. The greater abundance of chert in the Namba Formation compared with the Eyre Formation could be attributed to erosion of post Eyre Formation silcrete, or to greater stability under prevailing lower energy transport conditions and less tropical climate.

2.2.2 Lutites

Forty five thin sections were examined of which 22 were from outcrop, the remainder from bores.

In general the same comments regarding texture and mineralogy apply to both lutites and arenites. Lutites exhibit uneven distribution of framework and poor sorting to a greater degree (Fig. 99) showing a variety of well-developed textures in the matrix, the predominant form being the "criss-cross" texture resembling a rectangular-grid pattern. These are discussed in section 3 of this chapter. In these rocks, grains are very rarely in contact. There is sometimes a tendency, also noted in the arenites of both Namba and

Eyre Formation, for grains of similar type to be grouped. The reason is unknown - they do not show any features indicating they belonged to a single grain. Possibly they were derived from mud clasts that originated from a particular rock type.

2.2.2.1 Quartz

Single grains are dominant and are mostly clear with straight extinction, but a high proportion have strongly undulose or slightly undulose extinction, and semicomposites may be common. The proportion of straight to undulose extinction is very variable: in EAR5 bore undulose extinction is rare. Composite grains are rare, and are mainly fine grained with diffuse borders between individuals, though some stretched metamorphic types have been observed. Various types of inclusions are common. One grain of possible volcanic quartz was noted (P871/71).

Grains with overgrowths are observed in some. Most grains are very angular and often form long triangular shapes, probably as a result of chipping from larger grains during transport. Embayed and fragmented grains are common, indicating reaction between quartz and clay (Figs. 99, 70 and P1250/73, P1085/73), and producing in an increase in fines. Grain size ranges from less than 1μ to 0.05 mm in the fragmented grains.

2.2.2.2 Feldspar

Feldspars are identical to those of the arenites, though there is a tendency for Type II Gorai twins to be commoner, expected in a fine rock by breakdown of albite twins. Plagioclase is generally equal to, or commoner than, orthoclase or slightly less common than microcline in coarser rocks, though total feldspar is lower (0.5 - 5%). This is perhaps an analogous situation to undulose extinction in quartz. However, Blatt _et al_. (1972, p. 391) suggest plagioclase should be less common in fine rocks because it is more readily broken down by reason of its twinning. Also grain size should often be less than twin lamellae width. Abundant evidence for dissolution and breakdown of a proportion of all feldspars is present (Fig. 68 and P1261/73, P871/71).

2.2.2.3 Mica

Muscovite is invariably present as minute scattered flakes, grading to illite.

2.2.2.4 Chert

As in the arenites, chert is often present and of similar textural variety, though lower average percentage. Lower percentage is the result of less framework constituents and possibly reaction with clay during diagenesis (boundaries are often diffuse). Both fibrous radiating and granular types are present. Varieties with fine granular matrix and criss-crossing coarser chert are commonest, second are granular or inequigranular types, some of which are coarser and have fuzzy brownish alteration (P1019/73) resembling porphyry matrix of the Benagerie Ridge (P516-517/71).

2.2.2.5 Rock Fragments other than chert

Some of the chert probably represents volcanic porphyry matrix or very fine metasiltstone. Other fragments, apart from minor goethite, are carbonate and clay, which is entirely intraformational. The clays are identical to the matrix, or of differently textured material such as coarse kaolinite or palygorskite. Carbonates are rounded dolomite or limestone micrites.

2.2.2.6 Conclusions

Lack of composite grains in the quartz fraction is a reflection of fine grain size and diagenetic reaction with clay matrix, so quartz gives little information regarding source. There is a tendency for undulose extinction to be commoner than in coarser grained rocks, probably the result of greater contribution to the fine fraction by older sediments, most slightly metamorphosed. This agrees with theory, as rocks with high quartz content should contain much more non-undulatory quartz than those with little quartz (Blatt <u>et al</u> 1972, p. 275).

The areal distribution of relative abundance of feldspars in lutites with respect to arenites is inconsistent, in many cases the order was reversed. In WC2 bore plagioclase > orthoclase > microcline, in Wertaloona 1 bore orthoclase > plagioclase > microcline and in EAR5 bore plagioclase > orthoclase thus reversing some of the trends determined from arenites. The only area where samples gave consistent results is adjacent to the Benagerie Ridge, showing greater orthoclase content.

Explanations are:

(1) Where abundances of feldspar types are almost equal, visual estimation cannot distinguish slightly greater amounts of one or other component - this is a common situation.

(2) The apparent abundance of plagioclase may be partly a feature of the difficulty in estimating untwinned feldspar. In thin sections of rocks in which xray diffraction showed high feldspar, often none or only low percentages could be detected. These rocks frequently contain quantities of very fine angular quartz silt, with which fine feldspar can be confused where lack of grain contacts renders refractive index comparison impossible, and presence of absorbant clays makes staining techniques useless.

(3) Estimates from coarse and fine rocks may introduce a psychological factor in grain size estimation, weighing the results in a particular direction.

(4) The grains are of variable size and irregular distribution,

making estimation difficult when percentages are low.

(5) Coarse microcline when broken down to fine size, was difficult to distinguish from plagioclase.

Allowance was made for these factors during determinations, as far as possible. It is felt that the more obvious twinned types have been slightly overestimated, and within this group microcline was slightly underestimated relative to other twinned types, being assigned to plagioclase.

No trends in abundance of chert were detected, either vertically or horizontally, but the number of samples is scattered and unevenly distributed. There is a tendency for chert to be common when abundant feldspar is present, for both lutites and arenites. This suggests chert is derived from the same general source as feldspar, assuming matrix reaction during diagenesis has affected rocks of the same types to the same degree. Thus a mixed sedimentary, igneous and metamorphic source is indicated.

2.3 'COARSE MATURE SAND UNIT'

2.3.1 Comparison with other sands in the Namba Formation: effects of secondary cementation

The possibility that the sands grouped under this unit are younger than the Namba Formation has been discussed. These sands are all medium grained, or coarser, well sorted and well rounded, containing virtually no feldspar or other unstable minerals. All have been affected by secondary cementation processes: it is in these that the sequence of secondary duricrust cementation can best be observed (Figs. 74 and P437/72, P895/71, P859/71).

Only one specimen (P435/74, a loose well washed sand) has any remaining clay matrix. Such sands do occur within the Namba Formation, but none are as coarse, or lacking in matrix. Twenty four outcrop samples were examined, to determine the effects of differing types of cementation. Of 16 showing silicification, only 4 contained plagioclase, and most no feldspar, or a few grains of orthoclase. In 2 of these (P437/72, P920/71) the feldspar is present in fine grained ferruginized silt clasts. Another (P435/74) contained one grain of remnant plagioclase. The remaining specimen (848/71C) contains abundant feldspar and mica, and has fine-grained angular quartz as the dominant constituent. This specimen shows typical Namba Formation lithology, and indicates feldspar can survive silicification, at least in the finer grained rocks.

The remaining nine specimens are cemented by calcrete and one by gypsum. All of the fine grained samples resemble typical Namba Formation and contain feldspar. The gypsum cemented specimen is a coarse sand containing plagioclase (P859/71). In the case of the coarse sands, it is difficult to determine which were originally silicified, since other specimens show calcrete destroys and replaces silcrete, eventually absorbing much of the original quartz framework (Fig. 74).

It is concluded the coarse sands either contained little or no original feldspar, and are distinct from the Namba Formation, or that silicification and calcretization destroyed the feldspar in coarse grained Namba Formation sand. There is support for the second hypothesis, because coarse sands unaffected by the above processes rarely contain some plagioclase. In many outcrops silicified silt clasts identical to the Namba Formation show evidence of intraformational deformation, demonstrating the silt beds were present within the sediment, not reworked from underlying material. Other evidence supporting classification as a distinct unit is supplied by the quartz grains, commonly simple or showing incipient polycrystallinity, thus resembling the Eyre Formation.

Therefore the coarse sands appear to represent a distinct Namba Formation lithology, only rarely encountered in sub-surface, though there is evidence that surficial silicification and calcretization have modified the rocks. These sediments are silicified in preference to the finer Namba Formation sands, probably a result of the coarser grainsize and greater primary porosity.

2.3.2 Mineralogy of Framework

The commonest forms of quartz are semicomposites and single grains with straight extinction, and grains with slightly undulose extinction and criss-crossing lines of inclusions. Composite grains are of several types including (a) Fine grained composites with elongate individuals, in which sets of individuals extinguish simultaneously (gneissic?), (b) Complex composites with granulated margins between larger grains. These exhibit strong undulose extinction and may contain differently oriented bands of inclusions (quartzite or granite). Some have quartz overgrowths, (c) Composites with straight sharp boundaries between individuals, having widely differing orientations (quartzite or granite?), (d) Grains with 1 or 2 large individuals of widely different orientation and moderate undulose extinction (granite?), (e) Irregular single grains with distorted twin-like strain lamellae when observed under crossed polars (cataclastic or intensely metamorphosed) (f) Stretched metamorphic quartz.

Some of the single grains of quartz are elongate lath-shaped and exhibit ?cleavage planes parallel to the length of the grain. These are quartz crystal prisms or cleaved grains. Inclusions take the form of minute criss-crossing needles or lines of minute opaque grains, or sometimes tourmaline laths or a yellow-green mineral.

Feldspar is present as rare grains of cloudy orthoclase, some well rounded. The only specimen containing significant plagioclase apart from those with silt clasts, show polysynthetic twinned grains. Mica is very rare. Chert is quite common (0.5% - 2%) and contains varieties identical to those in the Namba and Eyre Formation.

The commonest rock fragments other than chert are intraclasts or fine angular silt which have been almost entirely replaced by iron oxide. These generally contain feldspar, including plagioclase, resembling typical Namba Formation.

Scattered grains of tourmaline and zircon are ubiquitous, and in similar proportion throughout, though one specimen showed a laminae composed of 50% zircon.

2.3.3 Conclusions

These sands have been derived from a mixed metamorphic, sedimentary and igneous source, with igneous and metamorphic contribution dominant. The matrix has been entirely removed but it is not known whether by secondary processes or winnowing. The grains indicate a high degree of maturity, interpreted as partly resulting from secondary silicification, ferruginization and calcretization. The beds are placed in the Namba Formation, though the possibility remains that they represent a distinct unit of post Namba Formation mature sand.

2.4 WILLAWORTINA FORMATION

This formation is typified by extremely poorly sorted to very poorly sorted sediments (Figs. 60, 61), averaging silt to fine sand size, but containing detritus ranging up to very large (9.5 m) boulders near the Flinders Ranges. As in the Namba Formation, grains are supported by a matrix of clay and are rarely in contact (Fig. 61). Apart from the poorer sorting and oxidized colours, the sediments are comparable to the Namba Formation, especially in the lower part. See Figs. 23, 25, 26, 31, 5, 21, 32. An example of a petrological description is P1104/72 (Appendix 1).

2.4.1 Arenites and Rudites

Ten thin sections were examined, varying from moderately sorted medium sand quartzarenite in the lower unit in Wooltana 1 bore, to more common poorly sorted muddy silty and sandy clay-mica-subarkose, arkose, litharenite and feldspathic quartzarenite.

Composite quartz grains are common, including a high percentage with elongate oriented individuals having undulose extinction. These are probably metamorphic derivatives. Some show rounded quartz overgrowths. Composites with large simple individuals are common (Fig. 61), possibly of granitic origin or from sandstones like the Pound Sandstone. A quarter to one half of the grains are semicomposites or show undulose extinction (Fig. 61). Grains vary from very angular to well rounded, depending on the distance from the edge of the basin.

A much more varied assemblage of feldspars is present than in most other rocks and includes a greater abundance of microcline (Fig. 62), various perthites, and feldspar-quartz intergrowths. Microcline is often present in the same proportion as orthoclase and both are equal to or greater than plagioclase in abundance. Near the Mt. Painter block microcline is frequently much more abundant, and perthites commoner than elsewhere (though always the least abundant feldspar).

Grain size and angularity of feldspar is similar to quartz, though, as in the other rocks, plagioclase and microcline tend to be finer grained than orthoclase. Total percentages of 5-20% feldspar are common, and the proportion increases on approaching the Flinders Ranges. The upper unit contains a higher percentage of feldspar than the lower.

Mica is a common constituent (Fig. 61), often reaching 5%, consisting almost entirely of coarse muscovite, sometimes broken or shredded. It is most abundant near the Mt. Painter area.

Chert rock fragments (Fig. 62) are relatively less abundant than in the other units, types resembling silcrete (P1079/73), porphyry (P483/70) or quartzite (metamorphic or sedimentary) being much commoner.

Sedimentary rock fragments are sometimes the most abundant constituent, producing granule or pebble conglomerates or feldspathic sedirudite types. Sedimentary rock fragments are generally commoner than other types, except near the Mount Painter area, where granitic material is dominant. The sedimentary types are mainly quartzites and Cambrian or Precambrian limestones, with lesser amounts of silts, sandstone, clay, ferricrete and silcrete. In some samples (P1113/72) ferricrete is common, especially in the upper part of the Formation. Gneiss and schist fragments have also been recorded.

Larger rock fragment grains are usually well rounded, and boulders frequently show percussion marks, being sometimes broken, indicating vigorous transport.

2.4.2 Clay Lutites

Six thin sections were examined, showing similar characteristics to the coarser rocks, but sedimentary rock fragments were relatively less abundant, compared with granitic types. Feldspars were less abundant than in the arenites. In WC2 bore, microcline was again the dominant feldspar.

Reaction between matrix and framework was more evident than in the coarser rocks, with embayed and partly broken down quartz (Fig. 61) present.

2.4.3 Conclusions

These rocks are very immature compared to those previously discussed, showing abundant evidence of uplift of the Flinders

Ranges, especially of the Mount Painter area. The dominating microcline content of the Mount Painter Complex is reflected in the relative abundance of this feldspar.

The abundance of matrix sands and conglomerates cannot be explained by mud-filtration into pore space. Diagenesis with forcing apart and breakdown of grains may have played some part, but the characteristic is more likely related to depositional processes, discussed in Chapter 5.

2.5 SUMMARY

There is no evidence to suggest any of the rock units did not have their source in the vicinity of the Lake Frome area. During deposition of the Eyre Formation, coarse-grained Mesozoic sediments of the northern Barrier and Flinders Ranges, and crystalline basement of the Willyama and Denison Inliers were the main contributors. In the younger units the dominant source for framework grains other than quartz seems to have been the crystalline basement complexes. Quartz was derived from the same source, in addition to the Adelaide Geosyncline sediments. The northern Flinders Ranges became the major provenance during deposition of the Willawortina Formation and member 2 of the Namba Formation. Local contribution is proved beyond doubt for these latter units.

There is a prominent change in mineralogical and textural maturity between the Eyre Formation and Namba Formation. The immaturity of the Namba Formation persists in the coarser lower part of the Willawortina Formation with which it intertongues, and is therefore not entirely explained by changing grain size and energy conditions. The petrology of both framework and matrix demonstrates immaturity beyond that attributed to grain size. A change in climate is suggested during the time between deposition of the Eyre Formation and the younger units, probably from humid tropical to lower rainfall and more seasonal.

The feldspars and rock fragments in the Willawortina Formation indicate a major period of uplift in the adjacent Flinders Ranges. It was therefore during late Tertiary times that the basin attained its present structural and, presumably, drainage configuration. The variations in composition of clasts reflect the source, with granitic and gneissic forms dominating near the Mt. Painter inlier, sedimentary quartzite and carbonate to the south. Varying maturity, grain size, and sorting characteristics also record a change in energy conditions, from higher energy in the Eyre Formation to very low in the Namba Formation, back to high energy in the Willawortina Formation.

The type and relative abundance of feldspars in the Namba Formation and Willawortina Formation requires explanation, since plagioclase is generally the most or slightly less abundant component than microcline, yet regarded as unstable under most weathering conditions. Further, evidence for diagenetic decomposition of plagioclase indicates it was once more common. Plagioclase is abundant in the source rocks, especially those of the Willyama Inlier, and microcline is the second most abundant component, though dominant in the Mt. Painter Inlier. Under arid conditions these relative abundances are expected to be maintained, apparently the situation in the Willawortina Formation. In the Namba Formation there is less correspondence between source rocks and sediments: relative abundances are maintained, with a reduction in microcline caused by mechanical disintegration. The possibility that under restricted leaching conditions plagioclase can be less weathered than orthoclase in a high rainfall climate has been discussed. This type of data is lacking on other feldspars, which could show similar "anomalous" behaviour, hence the degree of weathering and inheritance of crystalline basement relative feldspar abundance is not necessarily indicative of arid climate.

Finally, there is no evidence for a volcanic component added to the sediments, in the form of windblown ash: no glass shards, basic plagioclase and volcanic quartz were noted, other than that explained by local volcanics present in the adjacent ranges and on the Benagerie Ridge.

The phenomenum of embayed quartz has been discussed by Cleary & Conolly (1972) who found these grains abundant in the root zone of soil profiles. They noted a relatively short distance of transport was required to break off and round protuberances. The degree of embayment in the Lake Frome samples is much less, but many grains have shapes indicative of in situ formation. Thus soil-forming processes may have been operative intermittently with deposition. The grains are particularly evident in the clay lutites of the Namba Formation and Willawortina Formation, many from the tough black clays.

The diagenetic process of quartz and feldspar destruction produces a new silt size fraction, but is insufficient to account for the abundant fines observed in the Namba Formation and Willawortina Formation. Many grains are unrelated to any parent grain, and soil textures are often not present. Other sources of this material are windblown dust, grains spalled from larger ones during transport, diagenetic quartz formed in situ, and attrition and corrosion during ingestion by animals. In spite of their small size, most of these fine grains show sharp boundaries and are not intergrown with clays. Many sections show grains aligned parallel to mica flakes indicating they are not diagenetic but detrital. The frequent complete gradation from fine to coarse suggests spalling and breakage of larger grains as the dominant process. Although bioturbation is often present (Chap. 5) or suspected, many undisturbed samples retain the same textural pecularities.

One of the features of the Namba Formation and Willawortina Formation is the matrix supported texture - even sands with a high percentage of framework have grains invariably separated by clay. This has partly resulted from recrystallization, producing clay films and forcing grains apart, though normal processes of sedimentation probably played the major role. Low energy conditions prevented fines from being winnowed out, and bioturbation by plants and animals mixed layers. In the coarse sediments, a mudflow or streamflood transport process is proposed, discussed in Chapter 6.

3. MATRIX CONSTITUENTS

The matrix of arenites and clay lutites is considered together. In all but the secondarily cemented rocks, the matrix is dominated by clays, except in one sample where it is micron sized quartz, thus this becomes a discussion of clay mineralogy and texture. The petrology of the Quaternary calcretes which often cement the Tertiary sands is not discussed. The silcrete, manganiferous stain, and ferruginous horizons are soil stratigraphic units or groundwater horizons and therefore treated under a separate heading, rather than as variants of matrix cement. Examples of petrological descriptions are given in Appendix 1.

3.1 TEXTURE

Few studies of clay textures have been made. Thus it is difficult to assess features of geologic significance. The only comprehensive study (relating to pedology) is that of Brewer (1964), whose analysis was directed toward the assessment of soil genesis. One problem, though partly a matter of definition is the distinction

TABLE 4

TEXTURES OF CLAY MINERALS IN MATRIX OF SILTS AND MUDS

P. Number	Mineralogy	Texture					
	$<2\mu$ fraction	grain size μ	criss cross (XX)	oriented bands	variable granular	fine granular	Flaky
1085/73	S:D,RI:A,K:A M:Tr					X	
1086/73) 1072/73)	S:D,RI&K:A		X				
1089/73) 1074/73)	RI:D,M:A–SD, S&K:A		X rare	X	X		
1090/73) 1076/73)	S:D,K:A–SD, RI&M:A	1–5					X
1246/73) 1245/73)	M≈RI M,K,RI	2.5	X				
1250/73) 1249/73) 1251/73)	 RI,M,K P,M		X rare				
1258/73	S:D,K:A,M:Tr					X	
1260/73) 1259/73)	S,RI<S&K	2–8	X				
1261/73	S,RI,K,M		X				
1262/73) 31/73)	S,+?RI		X Minor				X
1263/73	S,+?RI	8					X
1267/73) 1268/73)	S:D.K:A,M:Tr		X				
1277/73) 1278/73)	S:D,K:A,M:Tr		X	X			
1019/73 1014/73	S:D,K:A,M:Tr	4	X				
1105/73	M,S,K,RI	16			X		
1107/73	S:D,RI:A,K: Tr–A,M:Tr	1–3			X		
1108/73	S&K:CD		X 0.14– 0.15 mm		X Minor		
1110/73	S:D,K:SD,RI: A–SD,M:Tr				X 0.07 mm		
1106/73	RI:D;M,K&S:A	5	X				

P.Number	Mineralogy	Texture					
	<2μ fraction	grain size μ	criss cross (XX)	oriented bands	variable granular	fine granular	flaky
1111/72	S:D,RI:SD,K&M:Tr	15-20		X			X
1112/72	S:D,RI:SD,K&M:Tr	2.5-5		X			X
225/72	S:D,K:SD,RI:A-SD	2-5	X moderate				
227/72	P:D,M:A	<1		X strong			
238/72	S:D,R&K:A,M:Tr	5-20					X
241/72	S&RI:CD,K:A-Tr,M:Tr	30					X
231/72	RI:D,S:A-SD,M&K:A	7.5	X weak				X
233/72	S:D,RI:SD,K:Tr-A,M:Tr	5	X				
234/72	S:D,RI:SD,K&M:Tr						X
236/72	M&RI:CD,S:Tr	5-9 & 2.5				X	
237/72	S:D,RI:SD,K:A-SD,M:Tr		X weak			X	
239/72	M:D,P:SD,RI:Tr-A,K:Tr	12	X well devel.	X well devel.			X
240/72	RI:D,M&S:SD,K:Tr	0.8-3.4				X well devel.	
1134/73	K:D,M:SD				vermicular texture		
293/72	K:D,M&RI:A,S:Tr				X		
1104/72	RI:D,M:SD,S:A-SD,K:A	15	X				
1103/72	S:D,M&RI:SD,K:A				X		

of soils from original rock, and soil layers from sedimentary layers. What degree of diagenesis and weathering is required before the features developed are regarded as pedogenic? In this thesis a soil is considered to have formed when clearly differentiated cutanic textures are present (not subcutans). Many sepic textures found in soils also occur in unaltered sediments, thus the only certain diagnosis is the presence of cutans. The cutanic textures should be related to a landsurface (ancient or modern) so that variations in intensity, type chemistry, and mineralogy occur along an axis perpendicular to that surface, and homogeneity within a particular soil layer is maintained over an area of at least several hectares. In cores it is difficult to determine the relationship to a landsurface over any large area. Some of Brewer's nomenclatural terms have suitable geological equivalents, preferred in this thesis.

In the chart (Table 4) the textural classification can be related to Brewer's scheme. In his terms "broad oriented structure" (Figs. 57, 96, 98) of column 1 represents an extreme case of unistrial masepic fabric; criss-cross structure (XX structure, Figs 99, 97) includes mainly right and clino bi- or tri- masepic fabrics and lattisepic fabric (generally associated with minor vosepic fabric); variable granular fabric (Fig. 62) approximates silasepic fabric, though silt need not be common; uniformly fine granular fabric is close to argillosepic fabric, and flaky fabric includes mosepic and insepic fabrics. Another form is vermicular texture (Fig. 63) which has no equivalent in Brewer's scheme, and is best regarded as a special case of unistrial fabric.

Most of the textures are variants of the XX class (Table 4) and there is little relation between texture and clay type. Exceptions are purer forms of kaolinite, frequently showing vermicular structure or coarse variable granular structure, and palygorskite, invariably of broad oriented type. Mixtures of clays have varying texture.

One of the features of the textures is the hierarchial arrangement of grains into domains. Most clays form crystals much too small (excepting kaolinite) to be observed under the normal light microscope. According to Moon (1972) kaolinite and illite generally have a grain size in the vicinity of 0.1 - 1.0μ, whereas smectites are about 0.001 - 0.01μ. Palygorskite occurs as extremely fine grained minute needles and can only be resolved with the aid of the electron microscope (Wiersma 1970). Thus the 'grains' and 'flakes' used in this text must refer to aggregates of clay (see sizes, Table 5). Several workers have shown that clay probably sediments as aggregates (e.g. Kranck 1973), but even these are too small to observe with the light microscope. Thus the 'grains' observed here are multiple aggregates in which clays are optically oriented. The 'flakes' are larger than grains and show a distinct elongate form, with symmetrical or straight extinction. They grade into 'domains' with increase in size. Sometimes these aggregates extinguish in irregular zones which sweep across the flakes and grains in a manner analogous to undulose extinction in quartz. The aggregates may occur in 'domains' in which they may be oriented or disoriented, and these domains may be further aligned so as to produce the various coarser textures recorded above. Thus it is the size, orientation and relationship of the grain aggregates which determines the fabric.

From previous discussion it is obvious that very few samples showed clay textures which can be interpreted as detrital, through parallelism to bedding. In addition the size of the aggregates is such that flocculation must have been very extensive, if they represent true floccules (Kranck 1973, showed there was a relationship between the size of a floccule and the grain size of the clay mineral). The domain orientation, and the fact that it crosscuts all sedimentary structures (except, rarely, rheotropic structures - Chapter 5) suggests they may not be floccules at all, but phenomena of recrystallization formed during diagenesis. During this recrystallization process, stresses were set up which led to orientation of the fabrics. These stresses must have been directed towards framework grains (Fig. 99) acting as rigid centres, so that the stress subcutans was produced on the framework.

3.1.1 Eyre Formation

The commonest matrix to the arenites is carbonaceous matter (Fig. 57) and iron sulphide (marcasite and pyrite - e.g. P1165/72 in Yalkalpo 1 bore and P1135/73 in B240/C3 bore), clays forming $<4\%$ by weight.

Sulphides are present as disseminated grains, large hard nodules several centimetres in diameter, or as layers cementing quartz (P1135/73), at porosity boundaries. The solid layers are accompanied by fracturing of the quartz, with penetration of sulphide along fractures. These fractures are parallel to the bedding, suggesting crystallization pressures have been directed by weight of overburden (the beds are horizontal). The sulphides oxidise and hydrolise rapidly on exposure to the atmosphere, forming melanterite and roemerite (iron sulphates). Conditions of deposition of iron sulphides are discussed by Berner (1971).

Carbonaceous material takes the form of fine grains, and chunks of carbonized wood. Occasionally percentages are high enough to form a cement which holds the sand together (e.g. A165/72). Carbonaceous matter is also an important constituent of the silts, as fragmental plant remains on bedding planes rather than cement. Abundant carbonaceous matter indicates a vegetated source area, and reducing conditions at the site of deposition (supported by the presence of iron sulphide).

Kaolinite is the dominant clay mineral in the matrix, smectite is present only in fine sands in the uppermost part of the Eyre Formation. Most illite is well crystallised, and therefore related to mica.

In thin sections of muds kaolin is coarsely crystalline, with a banded texture (P292/73 and Fig. 63). The banding parallels bedding, and tends to encrust the upward side of detrital grains. The individual crystals of kaolin are perpendicular to the layering. This feature, combined with presence of mica with kaolinite alteration along cleavage (P1148/73) can only be explained by diagenesis. In the sands, the small amount of kaolin could be explained entirely as a diagenetic neoformation, but that of the almost pure clay beds suggests detrital kaolinite has been transformed.

Conditions for dissolving and reprecipitating kaolin were therefore operative. Reference to Fig. 9-7 of Berner (1971) indicates an acid environment with high silica content is necessary suggesting flushing of the Eyre Formation with acid groundwater. The clay beds must originally have had sufficient porosity for groundwater penetration.

In the northern areas, most clays are intermixed with up to 50% or more of carbonaceous matter and pyrite, as matrix to silt grains.

Thus the clays are mineralogically mature types, modified by diagenesis in the southern regions. The sediments are identical to weathered granitic basement (e.g. EAR 3 bore Fig. 11).

3.1.2 Namba Formation and Willawortina Formation

The textures shown in these units are more diverse than those of the Eyre Formation. This may result from the variety of clay minerals, of which kaolinite is a minor constituent, but is also attributed to much lower proportion of framework.

The development of XX texture has been discussed. In the Namba and Willawortina Formations boundaries of clay domains often coincide with irregular shiny or slickensided fractures. These fractures are the skew planes of Brewer (1964), and the associated clay fabric often fits his definition of a skew plane subcutans. The planes rarely show any signs of a true soil type cutans in the form of plasmic separation. They are regarded as diagenetic stress features, but relationship to soil genesis is unknown - they may represent an incipient soil. The fractures are characteristic of the tough black clays so common in member 1 of the Namba Formation.

3.1.2.1 Marmorization

Throughout the units, particularly within the tough black clays, are patches of orange brown, yellow and dark brown stain (see sketch at 209 m, Wooltana 1 bore Fig. 17). This stain often has a spacial relationship with the XX structure and/or skew planes, both of which may bound one or more edges of the stained area (Figs. 70, 115). Chemical analyses (Table 5) and xray diffraction (P17/74) show the stained material is hematite. In thin section minute crystallites ($<1\mu$) of transparent mineral (opaque under low power) are observed, interpreted as iron minerals.

There are three ways in which the stain distribution may be explained:

(1) It predates the skew planes and has been offset by them, producing a combination of sharp and diffuse boundaries.

(2) It is the result of oxidation along the skew planes.

(3) It is a diffusion phenomena, limited by pre-existing natural weaknesses in the rock.

The distribution indicates (1) or (3) are most feasible,

TABLE 5

ORIGIN OF DARK COLOUR: CLAYS AND SANDS, NAMBA FORMATION

			%			
SAMPLE	MUNSELL COLOUR	C (elemental & organic)	CO_2	Fe	Mn	S
A 956A/73	N8	0.20	0.05	1.95	0.004	0.10
A 930/73	2G7/1	0.09	-	2.05	0.01	-
A 928/73	5YR3/1	0.37	-	1.44	0.01	-
A 950/73	5Y5.5/1	0.33	0.16	4.9	0.03	0.05
A 927/73	N4.5	0.13	-	3.85	0.01	-
P 37/75	N4	0.07	0.10	5.10	0.33	0.67
A 932/73	N4	6.1	-	5.30	0.02	-
A 949/73	N3.5	0.18	0.05	3.2	0.015	0.07
A 929/73	N2	1.6	-	7.60	0.02	-
A 956B/73	N2	0.90	0.05	2.65	0.023	0.75
A 931/73	NO	0.34	-	3.90	<0.01	-
AN3048/70	Black nodule	1.2	-	30.3	0.001 to 0.01	Nil
A 943/73	"	9.3	-	21.7	<0.01	-
A 169/74	Black stain on sand	0.25	-	0.75	1.13	-

though in some cases further oxidation may have occurred via (2). The stain often cross-cuts domains, suggesting it postdates them.

The ferruginised patches in some rocks show a distribution (Figs. 126, 75) suggestive of ferruginisation of intraclasts and faunal burrows. In thin sections the 'intraclasts' are often coarsely crystalline clays, resembling features described as papules by pedologists. Both the iron and coarsely crystalline clay are concentrated largely on one side of these features, generally the upward side. Careful examination shows a plane of separation delineating rounded clast-like forms, bounds the area upon which the ferruginous stain is developed (Fig. 58). Domains within the clay have identical textures both within and without these structures, though portions may exhibit coarse texture as described. The sequence of events is:

(1) Deposition of sediment, followed by reworking, bioturbation and quick-flow. This produced subtle irregular structures, burrows, and small clasts, further discussed in Chapter 5.

(2) Partial destruction of pre-existing structures by recrystallization of clay.

(3) Migration of iron oxides and further crystallization of accompanying clay.

Simultaneity of these processes suggests iron oxide is released during recrystallisation,moving to the outer edge of the clasts (usually the top). The clay develops a pale orange birefringence when it recrystallizes. Analyses show above average iron in the black clays (Table 5). As the iron crusts develop, the structures show strong resemblance to ferruginous pisoliths.

Recrystallization of spherular clast 'ghosts' may be related to the same processes which produced the iron oxide rims - being a stage in the development of papules in a soil. This phenomenum of iron formation and spherular structure is analogous to the processes which operated in the formation of puddingstone silcrete. It is comparable to many similar processes in soils: nodular calcrete, ball structures in grey-billy silcrete, ferruginous and bauxitic pisolites, and others. Siliceous crusts on clay balls of pisolite size have been noted north of "Mooloowatana". Clasts of carbonate with one-sided iron crusts occur in the calcretized and ferruginized carbonate of the Willawortina Formation outcrop at Balcanoona Creek.

The horizon of ferruginous structures in Wertaloona 1 bore becomes more intense upwards (Fig. 126) terminating in a sharp planar upper margin. It is concluded the horizon is an incipient soil, resulting from brief subaerial exposure. Inspection of the detailed logs reveals numerous examples of similar ferruginous mottled zones, though none as well developed. These are separated by unoxidized intervals, and therefore formed intermittently with sedimentation. Similar structures are described by Freytet (1973, p. 43; 1971, p. 256) who calls the process 'marmorization', attributing it to soil formation under slightly dryer conditions than those producing gleyed soils. Alternatively they could represent vertisols (Mohr et al. 1972) formed under water logged conditions in a tropical climate, this being compatible with the clay mineralogy (smectite) and high iron content.

Reaction between matrix and framework has already been noted, and may be connected with incipient soil formation, especially considering production of embayed and fragmented quartz.

3.1.2.2 Palygorskite

Thin sections of palygorskite show pale birefringent masses with a high degree of orientation, probably the result of its needle prism habit and mode of formation. Carbonate-palygorskite mixtures have micritic dolomite (1-4μ) with disseminated oriented patches of palygorskite visible under crossed polars (Fig. 96).

Some specimens have carbonate ooliths suspended in a palygorskite mud (P1253/73, P1101/73). This has only been recorded previously by Wiersma (1970 p. 46 and Fig. 3).

In one sample (Fig. 98) recrystallization of palygorskite is observed.

3.2 CLAY MINERALOGY

Analytical techniques are described in Appendix 3. Included are examples of diffractogram interpretations. Results are presented in two forms: (1) complete analyses of whole rock and $< 2\mu$ fraction, shown adjacent to the summary logs (Figs. 10–14, 25–33), (2) the $< 2\mu$ fraction analyses and, where space permits, the whole rock analyses, are presented in the fence diagram in terms of a colour code (Fig. 36). To construct this diagram the scheme used by R.N. Brown (AMDEL Reports 1971–5 Appendix 3) was converted to equivalent percentages, as indicated in the Appendix. These percentages are accurate to about 10% in the case of the dominant and subdominant components, more accurate for the less abundant components. Where considerable amounts of randomly interstratified clay are present, percentage estimates may be considered a rough guide only, though order of abundance is probably correct. the essence of the study was to determine overall trends in abundance, and it is considered this has been achieved.

3.2.1 Eyre Formation

The xray diffraction analyses show kaolinite is the dominant matrix clay throughout the Eyre Formation. Minor amounts of illite are present, and traces of smectite. Smectite increases near the top of Yalkalpo 1 bore, to become the dominant constituent. Chlorite is sometimes present at the base. In Yalkalpo 1 bore the fine fraction from sieve analyses, when xrayed, indicated trace amounts of kaolinite throughout the sequence.

The genesis of kaolinite has been well established (Keller 1970; Millot 1970, p. 325; Wiersma 1970, p. 153) and requires humid weathering conditions. Granitic terrains are particularly good source rocks.

Kaolinite in the Eyre Formation could have originated in the following ways:-

(1) Detrital

(a) By inheritance from pre-existing rocks

(b) By erosion of a soil mantle

(2) Neoformation

(a) From feldspars and mica or other clays in the sediment

(b) Post Eyre Formation, pre Namba Formation weathering.

Kaolin was relatively low in all source rocks, though present to a moderate degree in Jurassic-Lower Cretaceous sands. Thus weathering at the source is required, presumably under humid climatic conditions, to supply kaolinite. The maturity of the framework mineral suite is in keeping with this concept. It remains to be determined if weathering occurred during or prior to deposition.

The Jurassic deep weathering profile has been discussed in the section on silcrete and kaolinitic bleached zones: it is likely some kaolin was available from this source. The presence of possible kaolinized basement is indicated in EAR 3 bore (Figs. 5, 11), and is ascribed to the silcrete weathering horizon. Although considerable material was probably available from preweathered sources, much would have been stripped by erosion during Late Cretaceous times. Therefore chlorite should be present. Minor amounts were found, but kaolinite and mica were most abundant, suggesting either humid climatic conditions during deposition, or transformation by post Eyre Formation weathering. Chlorite is present only at the base of the Eyre Formation probably derived from the underlying Middle Cambrian sediments or older rocks in the southern part of the Tarkarooloo Basin.

There is abundant evidence for <u>in situ</u> formation of kaolinite from muscovite. In addition, any unstable feldspar in the sediments would have hydrolized and eventually formed kaolinite. Thus a proportion of the kaolinite has formed within the sediments: probably enough to account for the low percentage of clay in the porous sands, but insufficient to produce the interbedded clays and silts in the southern part of the basin. Pre-existing weathered rocks and possibly early Cretaceous sediments must have contributed most kaolinite.

Therefore there is no need to attribute kaolinite entirely to humid weathering, though other evidence (particularly fossil flora) shows a humid climate did exist. Low percentage of mica in the drill holes adjacent to the Northern Flinders Ranges and at Reedy Springs suggests this region was not as active in supplying detritus as the Olary Ranges. Some mica, however, occurs in the Eyre Formation west of Mt. Babbage in the vicinity of Yerilina Creek, indicating its absence east of the ranges may be the result of northerly transport direction rather than absence of a source.

Increased smectite percentage near the top of the Eyre Formation in Yalkalpo 1 bore is explained by a change in climatic conditions towards that prevailing for deposition of the Namba Formation.

3.2.2 Namba Formation

The clays of this sequence can be divided thus:-

(a) Those dominated by smectite, with accessory randomly interstratified clay, and minor illite and kaolinite.

(b) Those dominated by palygorskite, in association with carbonates, with accessory illite and traces of kaolinite and randomly interstratified clay.

(c) Those dominated by illite, with accessory kaolinite and randomly interstratified clay, rare chlorite.

The smectite in these rocks is the dioctahedral variety, and in some pure examples is almost certainly montmorillonite (P1268/73: see XRD trace Fig. 149, Appendix 3). This probably applies to all the smectites. Smectite, when pure, forms blue green or pinkish coloured clay. Normally it is pale green or olive, grading to black in iron rich (or humic acid stained) clays. Hand specimens have a waxy or greasy lustre.

The clays are frequently degraded, particularly RI, illite, kaolinite (P1062/73, P1099/73), and sometimes palygorskite and smectite (P236/73). Illite is of two types - that showing sharp peaks on the diffractograms is muscovite, whereas broad peaks indicate illite (Fig. 151, Appendix 3). When illite has very broad peaks, it is called 'degraded'.

The clay mineral fence diagram (Fig. 36) shows the relationship between these assemblages. Assemblage (b) is dependent on lithology, and occurs wherever the dolomites are found, being in greatest abundance near the base of these beds. Assemblage (a) and (c) show no obvious lithological affinities, but when observed in relation to the stratigraphy, assemblage (a) corresponds to member 1 of the Namba Formation, and assemblage (b) with member 2.

Another obvious feature is the mineralogical contrast with the Eyre Formation. The change from kaolinite- to smectite-dominated rocks occurs at the disconformity between the Eyre and Namba Formations.

The change from assemblage (a) to (b) is also associated with a disconformity - the alunite zone occurs at the top of member 1. In bores where dolomite beds are present and alunite absent, the change is not readily placed: it is difficult to ascertain whether it is above or below the upper dolomite horizon. Careful inspection of those sections with suitable detail suggests the increase in illite begins immediately beneath the dolomite, supported by the analysis of the outcrop sequences at L. Namba and L. Tarkarooloo (Fig. 24).

Lateral variations occur, but sample density in the horizontal plane is such that no meaningful pattern was established. In the thin sequence of Yalkalpo 1 bore (Fig. 13), there is a very consistent mineralogy througout, in which smectite is dominant and illite and kaolinite are trace components. In this bore the mineralogy typical of member 2 is absent, though lithology is similar. When the regional westerly dip is considered, it is apparent that erosion may have caused this anomaly, having removed member 2 (see Callen & Tedford in prep.). Alternatively member 2 could be present (the eastern edge of the Benagerie Ridge is downfaulted), but for some reason not understood has different mineralogy.

Origin is best considered in relation to the Willawortina Formation, being discussed in section 3.2.4.

3.2.3 Willawortina Formation

Two of the clay assemblages defined for the Namba Formation can be recognised in this unit: assemblage (b), identical to the same assemblage in the Namba Formation, and assemblage (a), though with slightly higher illite content. Assemblage (a) is anomalous, and occurs in WC2 bore. Assemblage (b) is in sediments which intertongue with member 2 of the Namba Formation, of identical mineralogy. In WC2 bore the correlation suggests assemblage (b) ought to be expected, with illite dominant, rather than (a).

3.2.4 Genesis and environment, Willawortina Formation and Namba Formation

The abrupt change from kaolinite to smectite across the Eyre Formation - Namba Formation disconformity suggests more than a gradually decreasing availability of source material is required. The average total quantity of kaolinite in the $<2\mu$ fraction of the Namba Formation muds and silts is about 12% compared with 30% for the Eyre Formation. The sands of the Eyre Formation contain less than 1% clay, all kaolinite. Those of the Namba Formation also contain 1%

though the actual proportion of mud matrix is greater.

The effect of permeability on clay development was reviewed by Wiersma (1970, p. 153) who concluded kaolin was preferentially developed in coarse sands. Comparison of different grain sizes within the Lake Frome Tertiary units shows this process was not operative in the Namba Formation, where relative proportions in the $<2\mu$ fraction are identical for all grain ~~size~~ sizes.

3.2.4.1 Origin of assemblage (a)

Smectites (especially montmorillonite) can originate in a number of ways:-

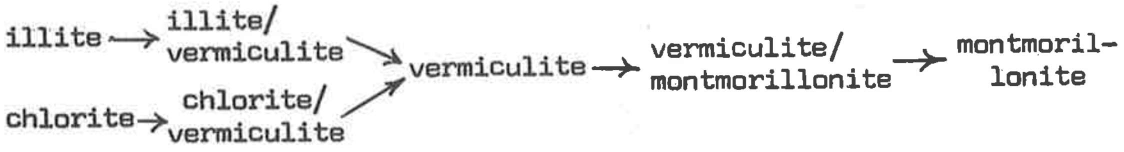
(1) In soils from illite or chlorite by virtue of low rainfall or restricted leaching (swampy soils) - Berner (1971, pp. 143-5).

(2) By neoformation in an aqueous environment rich in Mg^{2+} and Al^{3+} (Millot 1970) in a humid climate.

(3) By weathering of volcanic material under conditions as for (1), either in the source rocks or the depositional basin.

(4) As a detrital component from erosion of pre-existing rocks.

(5) By transformation of illite: Millot (1970 p. 108) gives a series of transformations from illite and chlorite to montmorillonite:



The role of source rocks will first be examined: from Section 1.2.2 of this chapter it is evident that Cretaceous rocks could supply smectite, though to achieve the concentrations found in the Namba Formation it would be necessary to transform large quantities of illite and kaolinite present in the same rocks. As there is no evidence for higher concentrations of illite and kaolinite in marginal parts of the basin, alteration at the source or within the basin by weathering is necessary. The Cambrian limestones also contain smectite, and their dissolution might produce an additional supply.

The bulk of the rocks adjacent to the Tarkarooloo Basin should have produced illite and kaolinite, which ought to be in excess of any detrital smectite. Also silcrete and accompanying kaolinization must have further transformed any pre-existing clays during Paleocene to Oligocene times. Therefore almost complete absence of chlorite and low percentage of illite and kaolinite in the actual samples indicates alteration must have occurred, at the source ~~of~~ or in the basin. The possibility of soils formed under swampy restricted leaching conditions is in accord with this idea. Kaolinite can be accounted for by degradation of illite, muscovite and feldspar.

Absence of any volcanic contribution from beyond the basin indicates weathering of externally derived material could not be invoked as a source of smectite. There is no relationship between plagioclase and smectite abundance, expected if both had a volcanic source. Therefore hypotheses (1) and (2) must apply, though detrital supply from a distant northerly source cannot be eliminated. The latter is unlikely considering the unstable minerals and angularity.

The presence of feldspars containing unstable plagioclase is controversial, as discussed earlier, and not necessarily indicative of an arid climate. The percentage of feldspar is relatively low for an arid climate sediment. It is unlikely they could survive long distance transport from the north.

The exact mineralogical nature of the randomly interstratified clay is unknown, and environmental implications uncertain. It is considered in section 3.2.4.4.

Further evidence concerning origin is provided by consideration of the other clay suites, in following sections.

The presence of high percentage of smectite in WC2 bore is unusual, since this sequence has a very coarse grained framework and is otherwise immature.

Three explanations are

(1) The Paralana High Plain, in which WC2 bore was drilled, has been upfaulted. The entire sequence may be equivalent to member 1 of the Namba Formation, member 2 having been eroded (or not deposited, depending on the age of the faulting).

(2) The sequence above about 105 m is Willawortina Formation, but the mineralogy has changed from that regarded as typical of this unit.

(3) The Willawortina Formation actually constitutes two parts, the lower equivalent to member 2 of the Namba Formation and the upper a younger sequence. This interpretation is given on the fence diagram (Fig. 39). It requires the clay mineral change to be a time marker, implying climatic change.

The stratigraphic evidence in favour of (1) is presented in Callen & Tedford (in prep.) and rejected on the basis of comparison with the Balcanoona High Plain sequences, and correlation between Wooltana 1 and WC 2 bores.

The second hypothesis requires smectite to increase near the Mount Painter region. This seems incompatible with the composition of detrital unweathered clays supplied from the crystalline basement rocks, and abundant illite and kaolin in the stratigraphic equivalents further out in the basin. Evidence for uplift of the Flinders Ranges has been presented, and would have contributed illite and kaolinite to the sediments in the basin margins if it had done so to those further out. This suggested the data may not be valid - possibly the presence of randomly interstratified clay had led to an under-estimate of illite content, but it is difficult to see why this is not consistent for all bores. Another explanation is that Namba Formation was uplifted along the edges of the ranges, where it became an abundant source of smectite, but this requires the finer grained smectite to be preferentially deposited in the margins of the basin. If assemblage (c) was the result of a major climatic change and not uplift (see section 3.2.4.3), provision of a marginal smectite supply from uplifted Namba Formation is more feasible.

The base of the upper sequence, projected horizontally, intersects Wooltana 1 bore immediately beneath the smectite rich sample at the top of the sequence. A similar increased smectite content is found at the top of Wertaloona 1 bore. Certain lithological differences have already been noted between the two parts of the Willawortina Formation in WC2 bore. Thus this horizon may mark a major climatic change during deposition of the unit.

Clay mineralogy therefore suggests the following history for the Paralana High Plain:

(i) Deposition of member 1 of the Namba Formation.

(ii) Development of alunitic ferruginous weathered surfaces, especially in uplifted areas, and silcrete.

(iii) Deposition of member 2 of the Namba Formation and the lower part of the Willawortina Formation, containing clay assemblage (c). Assemblage (b) was not developed.

(iv) Further deposition under differing climatic conditions being the upper unit of the Willawortina Formation with clay mineral assemblage (a).

The sequence is summarised in Fig. 3 of Callen & Tedford. Differences between the upper and lower parts of the Willawortina

Formation suggest a marked climatic change causing smectite and randomly interstratified clays to develop in the soils of the source area. A process requiring restricted leaching operated in an environment of vigorous erosion and high relief. This can occur in an arid climate, where coarse clastics could be mixed with smectite-rich arid soils by intermittent flash floods. These ideas need to be substantiated by more clay mineral analyses in the high plains areas.

3.2.4.2 Origin of assemblage (b)

Carbonates in the Namba Formation are accompanied by high palygorskite content, particularly near the base. Halite is detectable by xray diffraction, and has a stratigraphic consistency which suggests it is not a contaminant. Palygorskite generally occurs in pure laminae interbedded with dolomite, or in intimate mixtures with dolomite. The occurrence of dolomite ooliths in palygorskite clay has been mentioned.

These relationships indicate similar conditions for palygorskite and dolomite precipitation. The chemical stability conditions for palygorskite have been defined by Singer & Norrish (1974, Fig. 7) who indicate high magnesia and silica, and high pH are necessary. Stability of the closely related mineral sepiolite is defined by Wollast et al. (1968, Fig. 4)who shows it forms in carbonate depositional environments if alumina is absent. They suggest where alumina is combined with high silica concentrations, chlorite forms, not palygorskite. Apparently palygorskite forms in preference to chlorite at earth surface conditions: Chlorite requires more Mg, Al and less Si and generally forms under conditions verging on metamorphic (Millot 1970, p. 329). Whether palygorskite or sepiolite form depends on the Mg/Al ratio. Palygorskite has a much lower free energy of formation, explaining the relative scarcity of sepiolite in general.

Various workers have shown palygorskite can be neoformed in soils (Singer & Norrish 1974, Eswaran & Barzanji 1974). Neoformation in lake and marine sediments was proposed by Millot (1970), the climate and tectonic situation being such that high alumina and magnesia concentrations developed. Detrital supply must be low enough to prevent these chemical sediments being diluted. The work of Eswaran & Barzanji (1974) defines optimum conditions for formation in Iraqi soils: pH 7-9 and annual rainfall 100-400 mm. Loughnan (1960) suggests a pH>10, Singer & Norrish (1974) indicate a pH of 6-9 is necessary.

A high pH, high Mg^{2+} environment is also required for primary precipitation of dolomite (Von der Borch 1965). Fine grained micritic dolomite is only found in hypersaline modern environments. Halite in the Miocene Lake Frome sediments is in accord with these conditions. Palygorskite may be a chemical sediment, like dolomite.

Although the Coorong sediments in South Australia are high in silica in some areas (Peterson & Von der Borch 1965) there is no evidence of any sepiolite or palygorskite being present: clays of any description are rare. In another major carbonate precipitating environment, the Persian Gulf, palygorskite is believed to be detrital (Seibold et al. 1973). Dolomite has also been found in playa lake sediments (Bonython 1955, McLean et al. 1972, Papke 1972), often in association with palygorskite and sepiolite, but in all but one case the clays can be traced to a detrital supply. Thus there seem to be few modern palygorskite-precipitating environments, except in certain soils. It could be that this lack is apparent: there has been no systematic search in the right places. The precise chemical conditions of formation in the soils are unknown.

A climatic influence was invoked for palygorskite genesis by Millot, who requires sedimentation to occur in or near a landmass of low relief upon which a tropical climate is operative. Such a land area would have had thick vegetation and negligible detritus in its rivers. Lateritization proceeded on adjacent land, and high rainfall flushed the appropriate ions into contemporaneous seas or lakes. Similar conclusions were reached by Wiersma (1970), who added the requirement that evaporation needed to be greater than precipitation, and therefore could not explain marine occurrences (see Chapter 7).

The possibility of a detrital supply from pre-existing rocks in the Lake Frome area must be examined. No such clays are known from this source, though analyses are scarce. Certainly the Proterozoic and Precambrian rocks can be eliminated. The Cambrian is a possibility, though a survey of world palygorskite occurrences (Chapter 7) showed palygorskite is rare in pre Triassic rocks. The Cretaceous is a possible source, though palygorskite is not yet recorded therein. In any case, other clays are dominant and have diluted the palygorskite. In soils palygorskite is a minor component, rarely reaching 20% even though it may be forming within them. Thus the Lake Frome deposits may be chemical sediments deposited in a lacustrine environment.

This subject is returned to in Chapter 7.

3.2.4.3 Origin of assemblage (c)

Illite has been stated to be derived by degradation of high-temperature muscovite, or sericite, but Hower & Mowatt (1966) show the structures differ too greatly to permit this. Thus illite is presumably derived by erosion of illitic rocks in the source area. The 'illite' of R. Brown's classification actually includes muscovite as well as true illite. In the Willawortina Formation in WC2 bore it is the muscovite which dominates the sequence. Fine muscovite is ubiquitous in the Namba Formation. The change from member 1 to member 2 required that either processes converting illite to smectite were inoperative (climatic change), or the Adelaide Geosyncline rocks and Cretaceous sediments played a more prominent part as a source in the younger unit. Evidence for uplift of the Flinders Ranges suggests greater supply of detrital illite is the explanation.

Illite is unstable in an acid environment. Millot (1970), and Blatt _et al_. (1972, p. 255) indicate it forms in soils under restricted leaching conditions, as does Berner (1971). Berner also cites evidence to show diagenesis from smectite requires pressure and temperature conditions operative with several hundred metres of overburden. Modern studies of clay mineral distribution show illite is essentially a detrital mineral.

Hence the illite-kaolinite assemblage is thought to have been derived by direct erosion of uplifted source rocks, in which chlorite has been eliminated by weathering processes. It is suggested that the soils which formed on the landsurface existing during deposition of clay assemblage (a), were eroded to form at least part of the deposits of assemblage (c). The presence of laterite and silcrete clasts in the Willawortina Formation supports this. The sediments were deposited in an acid oxidizing environment largely above the water table.

As no other sequences have been analyzed for clays close to the Flinders Ranges, it is difficult to assess the significance of the isolated series of results in WC2 bore (see also 3.4.2.1 above).

3.2.4.4 Note on Randomly Interstratified Clay

This material was recognised by R. Brown from the presence of abnormally rising background at low angles on the xray diffractograms, accompanied by "hk" reflections typical of clays in the random mounts (Figs. 150, 151, Appendix 3). Clays belonging to the main clay mineral groups were in such low concentrations that the presence of some other clay-like material is necessary. In the oriented samples basal reflections were absent, or so low as to be obscured by other peaks, therefore completely random stacking of tetrahedral and octahedral layers with displacement in both a and b crystallographic directions is required. Elucidation of affinities with respect to other clay minerals is beyond the scope of this project.

The variation in smectite abundance compared with that of randomly interstratified clay is apparently an inverse relationship, at least within clay assemblage (a). Kaolinite and illite within these samples remain constant. Thus randomly interstratified clay may be structurally related to smectite.

The geological significance of randomly interstratified clay is unknown, and cannot be determined without knowledge of its chemical and structural affinities. Recently Wetherby (1973) found it was common in the soils of the Murray Valley region, accompanied by illite and kaolinite. Randomly interstratified clay and illite were dominant in pedogenic carbonates (calcite with minor dolomite and ankerite).

Roberson (1974) has shown vermiculite and montmorillonite are converted into mixed layer clays on exposure to sea water. His diffractograms are similar to those obtained from material containing randomly interstratified clays by R. Brown for the Lake Frome Tertiary sequence (Appendix 3, Figs. 150, 151). He states that weathering of vermiculite and montmorillonite in soils is sufficient to alter the silicate structure, so that when placed in a marine environment only certain layers can absorb K^+. The clay is then transformed to randomly interstratified material instead of illite. Therefore the randomly interstratified clay in the Namba Formation could have been formed from montmorillonite deposited in saline water (or perhaps permeated by saline groundwater).

3.2.4.5 Clay Colour

In Table 5 an attempt has been made to relate colour (in terms of the Munsell colour code), of the Namba Formation muds to percentages of elements known to form common black pigmenting minerals. The object was to determine whether the black colour in the tough clays with skew planes of member 1 was the result of carbonaceous content or of finely divided pyrite. Those samples from other lithologies showing very high carbon were known to contain carbonaceous matter, from hand specimen examination.

The carbon content is generally rather low compared to the average shale, manganese is very low and constant, but iron is high and tends to increase irregularly with darkness of colour. The few sediments analyzed for sulphur, have too low a percentage to allow for much iron being in the form of pyrite or marcasite.

Thus the black colour cannot be attributed to carbonaceous matter or sulphides. The higher iron content is probably caused by hematite (identified in xray diffraction) in reddish and brownish coloured patches, commonest in the black clays. A possible cause of the dark colour is humic acid staining, a situation which occurs in the Holocene sediments of Lake Frome, where very black clays contained virtually no carbon (J. Draper, pers. comm., 1974, Bureau of Mineral Resources Geology and Geophysics, Canberra).

3.3 CONCLUSIONS

The clay analysis gives a well defined vertical sequence in agreement with the stratigraphic subdivision, though it is insufficient for deductions about lateral variations. Changes in clays from one rock unit to the next are much greater than lateral variation. The mineralogy is here considered without recourse to fossil evidence, incorporated in Chapter 7.

The mineralogical difference between Eyre Formation and Namba Formation indicates a conversion from strong leaching to restricted leaching, in accord with the change from high to low energy depositional regime. The prominent change in clays is thought to be more than a tectonic effect - climatic change is postulated. The climate of the Eyre Formation has been discussed and was probably humid tropical, but climate of the Namba Formation is less clear - both tropical and arid elements seem to be present.

Smectite is present in the same proportion in the $<2\mu$ fraction of the sands of the Namba Formation, as it is in the clays and silts. Therefore much of it must have been derived from soils in the hinterland, since some of these sands are believed to be fluviatile. Transformation within the basin probably also took place, in swampy soils. A moderately alkaline depositional environment applies to assemblage (a) becoming strongly alkaline for assemblage (b).

The clay sequence in the Namba Formation from smectite through palygorskite to dolomite, is similar to that recorded by Millot (1970), though the sepiolite phase is not represented. He quotes Slansky (1959) and others, who regard the sequence as a consequence of increasing alumina and decreasing magnesia on approaching the shoreline. The land area was subject to tropical weathering, of low relief and with a dense vegetative cover. Chemical sedimentation would proceed in the above order if there were a transgression, or the reverse during a regression. The transgressive-regressive sequence does not necessarily apply to the Namba Formation, but the idea of increasing magnesia and decreasing alumina is appropriate.

Although unstable feldspars are common, the total feldspar percentage is rather low for arid climatic conditions. The significance of the presence of unstable feldspars for climatic deductions has been questioned. Thus unstable feldspar content does not eliminate the possibility of a humid tropical or semi-tropical climate. According to Birkland (1974, Fig. 1-4) the savannah is a region of deep weathering where illite and smectite predominate over kaolinite in soils, which is appropriate to member 1 of the Namba Formation.

There is a second major change in clays from smectite in member 1 of the Namba Formation to illite dominated sediments in member 2 and the Willawortina Formation, attributed largely to uplift of the Flinders Ranges. Essentially the change is from magnesium rich to potash-rich sediment. Illite and chlorite in the source rocks were no longer converted to smectite. This could be largely the result of changing leaching environment resulting from uplift, and need not be accompanied by major climatic variation. The abundance of feldspar and unstable rock fragments in the Willawortina Formation does, however, imply the climate was not hot and very humid.

Near the Flinders Ranges, during deposition of the upper part of the Willawortina Formation (rich in smectite) a semi arid climate prevailed. Intermittent floods and mudflow activity permitted mixing of smectite rich lowland soils and coarse detritus from the uplands.

Textural studies indicate recrystallization of clay, probably in association with incipient soil development, in the Namba Formation. In contrast many of the palygorskite textures have a high degree of orientation in accord with neoformation, or settling from suspension without flocculation.

The absence of a volcanic ash contribution, particularly in the Miocene, suggests a westerly wind direction, this being a time of maximum vulcanism in eastern Australia (Sutherland <u>et al</u>.

1972, Wellman & McDougall 1974). No ranges were interposed to the east, as the Kosciusco uplift had not yet begun.

The colour of the dark grey and black clays is sometimes the result of high carbonaceous content, but in the tough black clays of the Namba Formation it is attributed to staining by humic acids. It is also possible that small crystallites of ?iron oxides observed in these clays, which are opaque under low power microscopic examination, could cause the black colour. There is a tendency for the darkness of colour to increase with increasing iron content. The black sands, on the other hand have abnormally high manganese content, and their colour is caused by the presence of manganite and pyrolusite.

The black sandy clays were therefore probably formed in a swampy or marshy environment, from humic-acid stained clay interbedded with sand. Similar soils are described by Millot (1970, p. 111), as calcimorphic soils, essentially vertisols formed by leaching from a calcareous or Mg/Ca rich substrate. They are black soils composed of neoformed smectite with weak plasmic separation. It was earlier noted that carbonates tend to precede the Namba Formation black clays.

The sequence of clays for Lake Eyre 20 bore (Fig. 35) has been plotted from the data of Taylor & Pickering (1962) and superimposed on the clay mineral fence diagram (Fig. 36). The similarity with the Lake Frome sequence is clearly shown, though the smectite interval is reduced and the dolomite-palygorskite-illite assemblage dominates. The preponderance of kaolinite in the Eyre Formation is again illustrated. Clay analyses and thin section studies of the Lake Palankarinna Type Etadunna Formation section indicate an identical sequence here, as far as could be determined from limited outcrop. Thus clay variations determined for the Lake Frome region are applicable on a regional basis.

The Lake Eyre sequence demonstrates the manner in which illite increases in the dolomite-palygorskite zone, and illustrates the antipathy between palygorskite and smectite. The variation in illite may be the result of a relative abundance factor rather than increased supply to the basin. It is thought that illite was no longer being transformed to smectite - the conditions conducive to formation of palygorskite exclude smectite genesis (Millot 1970).

4. PETROLOGY OF SECONDARY CEMENTS OF STRATIGRAPHIC SIGNIFICANCE

4.1 ALUNITE

The alunite horizon stratigraphy has been discussed as part of the section on the Namba Formation. Occurrences of alunite and natroalunite in South Australia were discussed in relation to stratigraphy.

The Lake Frome material depicted in Fig. 145 shows details of the ramifying nodular form, and vertical oriented pipe structure. The texture of the other deposits varies from solid veins to nodules similar to those at Lake Frome. At L. Frome it contains 1-2% Na_2O and 6.24% K_2O (A366/74) giving an xray diffraction pattern corresponding to alunite proper (<u>pers. comm.</u> R.N. Brown 1974, Australian Mineral Development Laboratories, Frewville). In thin section it forms extremely small very low birefringent high relief grains, intergrown in column-like structures with star-shaped cross sections in clay. The Yorke Peninsula deposit differs from all others in being bedded (Crawford 1965), though it may be related to the weathered upper calcreted surface of the unit in which it is developed.

Association of alunite with weathered horizons is well known (Millot 1970, pp. 152, 272-4), It is often ascribed to reaction between weathered pyrite (iron sulphate) and a potassium (or sodium for natroalunite) bearing mineral - e.g. kaolinite or aluminite (Keller <u>et al.</u> 1967, Ross <u>et al</u>. 1968). In the case of the Lake Frome examples, the alunite is commonly developed in black iron rich smectite-illite (partly weathered to kaolinite) clays, which may once have contained sulphides. This does not explain occurrences associated with non pyritic rock types, and it seems unlikely that pyrite should be so widespread in the varied rocks recorded.

A more likely hypothesis is that sulphate derived from gypsum, a more widespread mineral, commonly associated with disconformities and porosity boundaries. The gypsum could be derived from groundwater or pedogenic sources, before or after kaolinization. The nodular form of many occurrences may result from replacement of gypsum nodules.

The source for potassium is a problem. Evaporites seem unlikely, since extreme evaporitic conditions for which there is no evidence are required for precipitation of potash salts. The black clays in the Tarkarooloo Basin in which the deposits occur are iron rich smectite with minor illite and kaolinite, but most of the alunite occurs at the transition from smectite to illite-kaolinite dominated clay assemblages at an horizon regarded as a disconformity in certain areas. Thus potassium could be derived during weathering of illite and smectite to kaolinite, or from leaching of overlying illite. The former idea is preferred, since nodules are not present above the disconformity in the illitic clays. It is assumed there was enough potash in these clays to provide the necessary requirements.

Thus the most likely hypothesis is reaction between gypsum and illite-smectite during weathering to produce kaolinite and probably iron oxides. This process is much more likely to operate in the varied rock types encountered. Similar ideas have been expressed by King (1953) and Leeson (1967). Differing clay mineral compositions would result in formation of natro-alunite, alunite or jarosite and related minerals. Connection with laterite and bauxite of humid hot climates is recorded by Millot (1970) in the Eocene of N. Africa.

4.2 BLACK STAIN AND SILICEOUS NODULES IN THE NAMBA FORMATION

The fine sands of the Namba Formation frequently have black coated grains, in the outcrops adjacent to present day depressions. Brown chert nodules are present in similar situations. Neither of these secondary products occur in boreholes.

4.2.1 Black Stain

The black coating is a manganese oxide (A169/74, Table 5) and is occasionally developed to such an extent that slabs of pyrolusite are formed (e.g. at Billeroo Waterhole). At one of the vertebrate localities (north Lake Namba) the distribution of the stain is well exposed (some is visible in Fig. 140). It affects the finer sands overlying the coarser vertebrate-bearing channels more than the channels themselves, which contain numerous layers of brown silica nodules.

The distribution suggests a geochemical control, affected by grain size - it seems that the manganese was carried in groundwater, which soaked through the sands. At the groundwater air interface in the banks of the depressions manganese was precipitated around finer grains to form a stain.

In Lake Tarkarooloo and elsewhere, black stain is often found in association with calcite cement, forming spherical structures spacially directly related to carbonate distribution, suggesting simultaneous formation. This carbonate is post Millyera Formation, pre Eurinilla Formation.

Manganese is found more widely as an impregnation, and following outlines of minute branching pores in carbonates (Fig. 85) and clays in the Namba Formation. Apparently these fine grained rocks were more suitable for precipitation than the sands in regions away from the channels (where oxidation could occur).

4.2.2 Siliceous Nodules

The presence of the nodules as clasts in the older Millyera Formation channel deposits in Lake Tarkarooloo, but not in the "coarse mature channel sands" indicates they were formed by groundwater movements prior to deposition of this unit. Thus the black stain is unrelated, though both resulted from groundwater movements localised around the depressions, actually old river valleys related to the Plio-Pleistocene topography (Callen 1974).

These groundwater movements may be linked to the same process which formed the younger silcrete duricrust and iron cement in the same stratigraphic position.

4.3 PETROLOGY OF SILCRETES

In this section textures of silcrete are briefly described so as to establish relationships between different silcrete types, ferruginization and calcretization. An example of a silcrete (P848/71) is given in Appendix 1.

4.3.1 Silcrete and Ferricrete

In the thin sections (27) iron oxides are usually present as thin crusts of hematite on quartz grains, or as matrix to silt in replaced silt clasts. This is invariably the earliest secondary cementing material. Quartz, as overgrowths, or opal and chalcedony, enclose the grains and their iron crusts (Figs. 72, 74). Iron crusts are never found in intergranular spaces left after silicification. Quartz overgrowths (Fig. 72) form best in the coarser sands, whereas fibrous chalcedony and opal or microquartz (Fig. 74 and P479/70B) form best in silts and clays, though the fibrous chalcedony is sometimes found in coarser rocks also. Rarely chalcedony and opal occur in the same specimen as quartz overgrowths (P923/71). Opal, microquartz and chalcedony may alternate, though microquartz and opal (the first formed) are generally intergrown.

The sequence P1113/72 to 1122/72 illustrates development of various forms of secondary quartz in a ferruginous clay profile. Clay several decimetres below the main silcrete profile shows the development of opal and microquartz (P1114-1115/72). Near the contact, veins of calcite are prominent. Within the silcrete profile, clay forms rounded lumps which develop during weathering. These have iron oxide crusts, and clay is completely replaced by microquartz and opal. Higher in the profile, voids between the clay pellets are infilled by banded chalcedony, any remaining space by micro- and megaquartz. Megaquartz infills gaps resembling typical soil voids described by pedologists (Brewer 1964).

In coarser specimens with quartz overgrowth cement, growth banding may occur (Fig. 72, P437/72) indicating intermittent cementation.

Hematite cement is preserved without silicification only in the fine grained rocks (P477/70B) and has been identified by xray diffraction (P479/70C).

Silcretes are frequently observed partly replaced by calcite of groundwater or soil profiles (Fig. 74). In these, fibrous chalcedony is more readily replaced than microquartz and opal. Only rare examples of replacement of quartz overgrowths were seen (P860/71). Eventually detrital quartz grains are attacked, and become greatly embayed. In some specimens sparry calcite is fractured and replaced by micrite, indicating two phases of calcretization.

Thus the sequence of replacement is:

(1) ferruginization - hematite crusts,

(2) silicification, usually with fibrous chalcedony forming last,

(3) calcretization by at least two phases of calcrete.

A common secondary mineral in the silcrete is anatase, which takes the form of semi-opaque groundmass analogous to microquartz chert, or as minute discrete grains. It has been found as a major or minor constituent in many silcretes and has been discussed by Hutton *et al.* (1972).

4.3.2 Chert Nodules

These occur in certain localities in the Namba Formation sands, consisting of irregular ellipsoidal nodules with brown crusts, of slaggy appearance. In thin section (P222/72 and Fig. 84) they consist of very clear microquartz chert, the centre of the nodule being occupied by star-shaped cracks (shrinkage cracks?) lined by quartz crystals. The size of the layers of crystals increases towards the cavity. Occasional embayed detrital quartz grains are enclosed in the chert. Sometimes silt or sparry calcite fills the cavities.

Although these nodules appear to have grown in the sediment (they show little sign of rounding) they contain virtually no clastic components.

Some show radiating structures outlined by faint ferruginous stain, centred on the central cavities. These suggest a nodule-type growth pattern (comparable to spheroidal calcrete of soil profiles?).Crumpled external appearance and shrinkage cracks suggest crystallisation from silica gel.

CHAPTER 4

CARBONATES

1. GENERAL

The dominant chemical sediments in the sequence are the dolomitic carbonates of the Namba and Willawortina Formations. There are minor sedimentary gypsum horizons. The gypsum layers form rare thin beds associated with black clays and carbonates, and are not discussed further. The carbonate sediments crop out to the west and southwest of Lakes Namba and Tarkarooloo (Figs. 143, 144), Flinders Ranges, where the Namba or Willawortina Formations have been upfaulted. The main area of exposure is in the Wertaloona Anticline and along Balcanoona Creek. In subsurface, the carbonates form persistent sheets, in three horizons in the Poontana SubBasin. The lower horizon of the Namba Formation does not extend south of Lake Frome, but the upper is widespread south of the lake and absent to the east. Neither occurs east of the Benagerie High. In the Poontana SubBasin the lower bed consists of several layers, alternating with clay over a thickness of 20 m. The upper bed is thinner (about 8 m), with fewer layers (Figs. 16, 36). The beds in the Willawortina Formation are similar, but much more sandy (Fig. 60) and have been subject to extensive subaerial exposure, and later soil processes.

The carbonates were studied in thin section, one sequence in Wooltana bore by stained acetate peels. The staining techniques of Dickson (1966) were used for thin sections, the method of Davies & Till (1968) for peels. Cores were slabbed to investigate sedimentary structures and mounted in araldite to prevent dessication. Mineralogy was checked by xray diffraction and chemical analysis (see detailed logs Figs. 17 & 8, and Table 8).

In hand specimen the carbonate is extremely fine-grained, and pure white or pale yellow. It grades into marls consisting of carbonate mixed with pale grey or greenish palygorskite, illite or smectite and randomly interstratified clay. Numerous minute branching manganese (Fig. 95 and P1070/73, 1104/72) lined pores are present. Bedding is thin and very fine laminae are common (Figs. 96 and 130). A variety of breccia structures, disturbed contacts and shrinkage phenomena are described in Chapter 5. The carbonate, though mostly dolomite, effervesces rapidly with cold 10% HCl, being the result of extremely fine grain size.

The carbonates are frequently nodular, often weathering to a rubble. In the Willawortina Formation these nodules are of secondary origin, being concentrations of carbonate in a sandy clay matrix, continuous with the enclosing rock. A black or brown stain resulting from iron and manganese oxides accompanies the nodules, which occur randomly through the sediment. They can be distinguished from the sedimentary carbonates, which have well-defined layering. In bores the distinction becomes difficult because horizontal extent is unknown, and all carbonates are affected by a brown stain. The Namba Formation carbonates, however, retain their chalky white appearance (Figs. 116, 118), whether as nodules or beds.

Analyses (Table 6) were made to check visual estimates of carbonate percent, subsequently found to be about 5% too high. The original estimates were made on the basis of colour, after dissolving some samples in hot HCl, and calculating the percent residue by weighing. In one sample (Fig. 95 ff) the dark and light grey portions were xrayed and found to differ only in the proportion of dolomite present. Analyses for Ba, Sr and Li were to determine whether the same variations in abundance occurred as in the Etadunna Formation (Johns & Ludbrook, 1963). A variable and often high barium content was found in the Namba Formation, and is also typical of the Etadunna Formation.

TABLE 6

ANALYSES OF CARBONATES

			ELEMENTS PRESENT				
			%		ppm		
A No.	Bore	Depth	Ca	Mg	Ba	Sr	Li
942/73	Wooltana	7.05	11.1	6.30	270	660	20
937/73	"	70.24	8.8	5.6	380	150	25
938/73	"	76.36	15.0	8.6	200	180	20
939/73	"	90.78	11.3	7.1	70	140	15
933/73	"	101.58	13.8	8.70	300	400	10
940/73	"	141.18	13.0	6.4	125	350	10
935/73	W	206.55	23.7	9.10	55	240	5
941/73	"	212.88	22.0	9.8	670	300	10
934/73	"	218.38	27.8	7.4	175	160	5
936/73	"	227.16	28.8	5.4	1450	150	5
947/73	Wertaloona	66.70	20.60	10.6	10	400	19
948/73	"	170.95	13.5	6.35	90	250	24
951/73	"	174.30	28.7	3.7	70	90	11

2. PETROLOGY

The carbonates are classified using the terminology of Folk (1959a, b). All are micrites, apart from a few recrystallized forms, most containing allochems in the form of intraclasts, ooliths (coated intraclasts) and pellets (actually rounded small intraclasts). Some contain quantities of detrital grains or clay and grade into clay lutites and arenties. The grain-size of the carbonate crystallites varies from 0.5-5μ, and texture is very equigranular. Xray diffraction shows nearly all are dolomicrites, though analyses indicate the lower carbonate horizon contains much calcite, confirmed by the stained acetate peels. Examples of petrological descriptions are P1081/73, P1252/73, P1154/73, P1101/73, P1103/73 (Appendix 1).

2.1 TEXTURE

The micrite grains are closely interlocking and have sutured contacts, but may grade into microspar with sharp contacts between grains (Fig. 100 and P1029/73). Frequently a clotted texture (Figs. 101, 102 and P1154/73) is present. In these respects they are similar to those of the Green River Formation in U.S.A. (Williamson & Picard 1974) though of slightly finer texture. The dolomicrites show many examples of dolomitic fossils (Figs. 100, 101), intraclasts and ooliths (Figs. 106-111 & Fig. 112), sometimes fading out into the matrix (P1081/73, P1153/73) but the calcmicrites have well preserved ostracode carapaces and sharply defined clasts (parts of Fig. 130). This at first suggests dolomite formed by alteration of pre-existing calcite or aragonite as in the Green River Formation.

In the lower carbonate beds of Wooltana 1 bore (Fig. 17) alteration must have been very selective, or else primary precipitation occurred, because dolomite containing few single ostracode carapaces alternates with limestone containing numerous articulated carapaces (Fig. 130). In neither case have the ostracodes been replaced by dolomite. The dolomite has cracked and shrunk, whilst the lime remained mobile and penetrated into these cracks. Therefore dolomite replacement must have occurred before the carbonate was fully lithified. It is difficult to explain how one layer of carbonate could have been dolomitized without the others having suffered the same fate: apparently once calcite has formed it becomes very difficult to dolomitize. This is supported by the occurrence of undolomitized ostracodes in the dolomicrite. Differing reaction to shrinkage is probably related to the type of carbonate present, indicating dolomite formed before the sediment dried out. The different ostracode habit and abundance suggest higher energy conditions, and perhaps salinity, for the dolomite bed, but this need not have been connected with actual dolomite precipitation. Alternatively drying could have caused cracking and disrupted ostracode valves, implying frequent exposure during dolomite formation.

The micrite is often dark coloured, varying in shade for differing degrees of remobilization of the sediment. The nature of this fuzzy stain is unknown, although extremely fine semiopaque crystallites, just resolved at 625X magnification, are often observed. These are the same crystallites which form a dark stain outlining pores and other discontinuities, and are therefore post lithification. They occur in dendritic forms or radiating clusters. The quantity was not large enough to be detected in xray diffraction, though analysis of insoluble residues, and crystal habit, suggests manganite or other manganese oxides.

The overall texture of these rocks is anomalous because the coarse allochems are supported by micrite, not sparry carbonate. Yet some allochems are broken, suggesting high energy conditions. A mixing process must therefore have operated, further discussed when ooliths and pellets are considered.

2.2 TERRIGENOUS GRAINS

The Willawortina Formation carbonates are often sandy or clayey micrites, and may be arkosic, unlike those of the Namba Formation which contain very rare quartz silt grains or feldspar (Fig. 102). Some unusual micrites containing large boulders derived from the Flinders Ranges region were observed in Balcanoona Creek. These are not calcretes, as they contain ostracodes. They ~~would~~ could have originated by slumping or from mudflows or avalanches entering the carbonate precipitating environment from nearby mountains. The alternative possibility of carbonate precipitating after deposition of the conglomerate, in the pore space, is eliminated by the fact that the texture is matrix supported. Boulders may have been rafted in tree roots, but no fossil wood was found, and the number of boulders is too large.

Willawortina Formation carbonates are often arkosic (P1051/73), and the proportion and abundance of feldspar is similar to that of the clay lutites. The Namba Formation carbonates contain feldspar varieties in similar proportion, but lower total (P863/71). Quartz, mica, chert, tourmaline and other mineral grains are present, as in the clay lutites of both formations. Polycrystalline grains are rare, and all grains are generally better rounded and sorted in the Namba Formation carbonates. In these the detrital silt fraction is probably wind-blown.

An intimate relationship of dolomite with palygorskite is observed in the Namba Formation carbonates (P230/73 and Fig. 96). Coarse patchy extinction of palygorskite is superimposed on the microcrystalline dolomite, implying the two minerals were sometimes precipitated simultaneously. In P214/72, palygorskite pellets are coated by dolomite layers, forming complex ooliths. Thus this clay is not detrital like illite and kaolinite, which are present to minor degree.

2.3 INTRACLASTS

These consist of normal dolomicrite, some with possible algal textures. The origin of micrite intraclasts is discussed in the chapter on sedimentary structures. Here attention is drawn to the pellets, breccia structures and related phenomena in Fig. 107 (see also P1029/73, P1103/73) in the oolite cores. Large complex clasts such as in P1153/73, resemble calcrete rather than algal forms. There is a complete gradation from irregular large intraclasts to pellets (section 2.4).

2.4 OOLITHS AND PELLETS

The ooliths (mainly coated pellets) range from 0.1-1.0 mm diameter, averaging 0.3 mm, having a constant maximum diameter of 0.8 mm in most specimens. Pellets are smaller, ranging from 0.03 to 0.3 mm, the same size as the micritic cores of the ooliths. The shape of the ooliths is irregular, ovals and rods predominating. The surface tends to be polished. Fossil fragments or algal-like material may be the nuclei, but more often large micritic pellets are present, or sometimes no visible nuclei (P1101/73, P1103/73). Generally about 10 laminae are present in the coating, the number of laminae tending to be constant for a particular sedimentary layer of ooliths. Both ooliths and pellets are composed of dolomicrite.

The pellets may show complex 'ghost' structures, delineated by different shades of grey (Fig. 107). Some are made up of micrite breccia (Fig. 106) or smaller irregular pellets (P1101/73, 1029/73) and are therefore intraclasts. They have never been observed with enclosed fossil fragments and are identical in all respects to the cores of the ooliths (Fig. 107, etc.) The larger sizes grade into abraded intraclasts, often angular. Thus the pellets are regarded as intraclasts of micrite sediment, not fecal pellets.

In coated grains the envelopes generally follow outlines of the pellets and smooth over irregularities (Fig. 106), in contrast to algal oncolites which have emphasized irregularities. Some show a columnar like wavy structure resembling algal forms (Figs. 112, 113 and P226/72). Ooliths with wavy structure in the layered portion show complete gradation into forms typical of the 'normal' irregular ooliths, suggesting genetic relationship. In better preserved ooliths the structure of the individual coating layers can be observed. The laminae consist of radially arranged carbonate crystallites such that a uniaxial cross can be obtained under crossed polars (stationary on rotating the microscope stage, Fig. 106). No organic matter was observed in the envelopes, though some of the variation in shades of grey between layers may be the result of its presence. No structures resembling fungal borings, algal cells or algal filaments were seen in the oolith envelopes.

Groups of ooliths cemented by micrite and with encompassing layered envelopes sometimes occur (Fig. 108 and P1103/73) and there are numerous examples with layers of alternating radial oriented crystallites and micrite (Figs 106, 109 and P1029/73, P1102/73). In some, spalled portions of layered envelopes have been encased with successive layers (Fig. 109). Yet others show laminae which lens within the envelope (109). Such features suggest periods of abrasion alternated with envelope formation. Some have been broken and recemented after or during envelope formation (Fig. 110).

Microspar occurs in patches within the ooliths, sometimes related to the structure of core and matrix, but often irregular. It is generally commoner within the ooliths than the surrounding matrix. It is regarded as a product of recrystallization of micrite.

2.4.1 Origin

The origin of these structures cannot be deduced without discussing overall textural peculiarities of the rocks. Accepting that micrite grain size of the matrix reflects original sediment size (Folk 1959, 1968) a quiet water low energy environment is required. True ooliths, on the other hand, are generally indicative of a high energy environment. In addition the Lake Frome specimens have broken ooliths and spalled envelopes, implying high energy conditions: there is no evidence for presence of large ingestion feeding organisms capable of crushing these grains, and such grains are rare in bioturbated zones. The intraclasts forming the centres of many ooliths also require high energy conditions. They indicate layers of micrite were torn up and abraded before being coated with oolitic envelopes. Thus, mixing of low and high energy sediment is required.

The following hypotheses are suggested to achieve this:

(1) Bioturbation - burrowing and feeding organisms can cause rapid subsidence of objects resting on sea floors (Clifton & Hunter 1973) or churning of layered sediment (Howard & Frey 1973). This could produce mixing of ooliths, formed during a phase of agitation, with underlying mud.

(2) Slumping into deeper quieter water environment.

(3) Formation of ooliths on shoals from which they are transported into deeper water by currents (Loreau & Purser 1973, Friedman et al. 1973). A widespread distribution can be achieved in a relatively short period by this method.

(4) Mixing through quasi-liquid flow (quick-flow).

In Chapter 5 on sedimentary structures it is shown that most breccias in the carbonates are not formed by slumping: most grade down into unaffected carbonate and originated by shrinkage and quick-flow.

Where quick-flow produced mixing (4 above), a more irregular distribution of ooliths would be expected. Evidence for this deformation in oolitic zones is lacking, and where it does occur there has been disruption of sediment in which ooliths were already scattered through a fine matrix. Bioturbation is a more likely process, since it can cause complete homogenization of a single bed. Traces of burrowing are quite common in the oolitic layers (P226/72, 1101/73), which lack lamination.

In the Persian Gulf (Loreau & Purser 1973) widespread distribution of ooliths was partly the result of Quaternary climatic peculiarities and changes in sea level, though currents have played a part. These authors suggest ooliths formed in a shallow tidal or lagoonal environment in which carbonates were precipitating. They were confined in it for a period because tidal currents were alternating, not undirectional. Layers of closely packed tangentially oriented carbonate crystals alternate with radial types in the cortex, as the ooliths pass from crests to troughs of ripples. It should be noted radial structure is not necessarily a diagenetic feature as was once thought: see Kahle (1974), Great Salt Lake, Utah: and Freidman et al. (1973), Red Sea.

The widespread distribution of the ooliths and lack of any ooid shoal environments is a problem if they are attributed to classical theory of formation in an agitated milieau. This may be the result of sampling deficiencies, considering the few scattered drillholes examined. One location of a possible shoal which could act as a source, is the vicinity of Tricentrol (Aust.) Pty. Ltd. bore G8, which contains large greenish dolomite (confirmed by xray analysis) ooliths mixed with fine quartz sand, small gastropods, nacreous shell fragments, fish bones and otoliths, ornamented and smooth ostracode valves and sandy agglutinated tubes (identified by J.M. Lindsay, pers. comm. 1974, S. Aust. Dept. Mines). The ooliths have a crazed cortex, suggestive of shrinkage or fracturing and recementation.

The textural relationship can also be explained by methods which avoid mixing sediments from two widely different energy environments. The widespread distribution of the ooliths and lack of evidence for transport after envelope formation suggest in situ genesis.

(1) Oncolites can form in association with algal mats. When the mats are destroyed by bioturbation, the oncolites are left suspended in micrite (Friedman et al. 1973).

(2) Concentrically laminated spherical micrite ooliths, thought to be algal oncolites, can be formed on the sea floor in quiet water conditions (Jenkyns 1972).

(3) Irregular ooliths were described by Freeman (1962) from muds

deposited in a quiet environment. They grade shorewards into normal ooliths in fine sands.

(4) Vadose pisoliths are described by Dunham (1969), Steel (1974), and similar structures of oolith size by Siesser (1973). Vadose and phreatic ooliths are discussed by James (1972).

(5) In their experiments Bubela <u>et al</u>. (1975) produced some 0.1 mm monohydrocalcite oolith-like bodies with radially oriented crystallites and concentric structure. Thus oolitic bodies can be produced by precipitation, without agitation, on a substrate of micrite sized carbonate sediment.

Discussing these proposals:

The extreme assymetry typical of oncolitic structures is absent, Those with suspected algal involvement are radially symmetrical (Figs. 112, 113) showing shrinkage features in the cores. The wavy lamination in these could also be explained by shrinkage and cracking of the oolith cortex, with subsequently infilling by micritic sediment. Later, evidence for the presence of algal mats will be presented, but these are in the lower carbonate, not associated with ooliths. The structures of Freeman's type II ooliths (his Fig. 10) are oncolitic and quite different from the Lake Frome specimens. High polish is claimed by Freeman to result from agitation in a high energy environment.

The micritic layered ooliths of Jenkyns do not have radial laminae like those of the Namba Formation. His work is of interest because he proposes an algal origin for micritic bodies.

Secondary origin as calcretes (Dunham 1969, Steel 1974) is unlikely since polygonal fitted structures, reverse grading and one sided growth with perched inclusions are very rare or absent.

However, Siesser's examples, remarkably, show none of these features, yet a calcrete origin is very likely (pers. comm. Siesser 1973, University of Cape Town, South Africa). Wind blown origin of the South African ooliths from nearby beaches is considered most unlikely, though it cannot be entirely eliminated. The ooliths differ from those described here, since they are in contact with one another and are cemented by sparry calcite. Siesser envisaged micrite coatings forming around centres of nucleation, subsequent growth forced ooliths apart, without formation of polygonal structures.

If Siesser's method of formation is invoked for the Tarkarooloo Basin samples, nucleation needs to have occurred around widely spaced centres. The presence of spalled and cracked ooliths is in accord with vadose genesis (see above papers, also Shearman et al. 1970), but is not as common as would be expected. The presence of single broken oolith fragments (P1029/73,P1253/73) though rare, cannot be readily explained by these processes.

The South African ooliths have an internal layered micrite structure. The sub-aerial ooliths of Dunham 1969 (Fig. 10) contain radially oriented crystallites. The ooliths described by James consist of alternating tangential and micritic layers. Thus none are quite like those of the Namba Formation carbonates.

Some pellets show vague concentric lamination (P1153/73) indicating they were once ooliths or that layered structure is forming within micrite lumps. Some of the oolith cores also have this structure.

The fact that Bubela et al. were able to grow ooliths in standing water, opens up entirely new possibilities for oolith genesis - no longer is it necessary to have agitated water. Those described here could equally well be formed by this method.

In conclusion, the following genesis is proposed:

(1) Micrite sediments disrupted by wave action, perhaps during storms, rounded, forming "pellets" and intraclasts.

(2) Coating of intraclasts, not necessarily during agitation.

(3) Burial and mixing with underlying micrite by burrowing organisms.

Some of the irregular ooliths associated with calcrete crusts could have originated by Siesser's method.

Transportation of ooliths and/or intraclasts, formed within numerous shoal areas, to a quiet environment where bioturbation mixing occurred is possible. Currents capable of transporting these ooliths can be expected to disrupt the underlying sediment, forming intraclasts which would be intermixed in the oolite. Absence of such clasts in many examples argues for quiet water origin, or some sort of binding agent such as algal mats in the micrite. A binding agent may not be essential if the low erodability of very fine slightly lithified carbonate sediment is considered. No quantitative studies of erodability of this type of sediment are known to the writer.

There is no direct evidence for extensive algal mats having bound the micrite, interbedded with oolite, nor is there conclusive evidence for algae being involved in growth of oolith laminae.

2.5 FOSSILS

Ostracodes are commonest, and have thin curved valves 0.1-0.18 mm long, rarely articulated (P1081/73 and Wooltana 1 bore 227.16 m - acetate peel). These valves are about 0.01-0.02 mm thick and often laminated, with about 5 alternating layers of micrite and microspar. Charophytes are locally abundant generally represented by oogonia, tubules are rare. In Fig. 100 are some tubular or plate like structures which may be charophyte stems, and unidentified fragments, perhaps representing moulds of monocotyledonous plant stems (Fig. 101). Others are high-spired gastropods of the "coxiella" variety, bivalvia, and unidentified organisms. Burrows are of various sizes, discussed in Chapter 5.

A feature of the carbonates is the presence of numerous anastomosing and branching canals 18-90μ diameter (Fig. 95). These are usually empty, but sometimes lined with microspar or filled with clay or organic matter (P1252/73). They are outlined by a zone of fuzzy micrite, stained dark grey a short distance from the canal. Zones of recrystallized coarse palygorskite clay sometimes occur adjacent to the tubes. The often branch, usually at a high angle, and these branches may cross or join. Short blind branches are common and also stellate structures and nodes (Fig. 95). They resemble fungal filaments (Edwards & Perkins 1974), common in carbonate sediments. Some contain brown-stained fibrous material which could represent the original organic matter. They do not resemble solution voids produced during soil formation. Slight recrystallization and stain occur at all discontinuities in the sediments to a varying degree and are not restricted to the channels. The dark stain was thus a later introduction, taking advantage of existing porosity.

3. LAMINITES

Stained acetate peels (6) from the lower carbonate sequence of Wooltana 1 bore (227.16 to 240.0 m, Fig. 7) were examined, and one of these (Fig. 105) revealed the presence of structures interpreted as algal laminites. They are frequently domed upwards in structures resembling stromatolites. Burrows and carbonate-filled cracks are present.

The laminae of dolomite have dried out and cracked, and water saturated calcite mud has flowed into the gaps (Fig. 150). Near the top the laminae show a microstructure of thin platelets a few microns long of unstained carbonate (dolomite) suspended in a matrix of pink-stained calcite. The platelets occasionally pass laterally into contorted finely laminated dolomite blocks. The edges of blocks splay out as they pass into the platelet layers. The structure of the platelet layers grade into continuous laminae on the one hand, and through boudinage-like structure to isolated platelets with curled edges (up or down) on the other. These structures suggest the carbonate was bound by some flexible substance, distorted by drying and subsequent rheotropic flow: mobile lime alternated with the less mobile dolomitic platelets, which were stretched and crumpled or broken. The laminae are so fine that an algal origin is likely.

At the top of this layer, the laminae alternate with palygorskite clay (Fig. 150) and eventually pass into a clay bed. The intense blue stain in the clay indicates it is iron rich.

The sequence records alternating periods of calcite and dolomite deposition (confirmed by staining, xray diffraction and chemical analysis). Ostracodes were abundant in the calcium rich phases, and rarer in the dolomite-rich periods. As the sediment dried out, the dolomitic layers cracked and mobile lime penetrated, rafting off pieces of dolomite. Algal mats assisted dolomite precipitation, and their seasonal growth produced the fine laminae.

Other possible algal structures were described in the oolites, and are known in other samples. An example is the lamination 15μ thick in P1082/73. The bed in which this occurs is more clayey than adjacent carbonate. The lamination has almost been destroyed by fungal tubules, animal burrows and brecciation. Organic activity is concentrated here, suggesting fungae and burrowers utilized organic matter produced by decaying algae. The overall scarcity of algal laminites is partly the result of grazing, burrowing organisms.

4. CALCRETE

A sequence in EAR 7 bore (Fig. 20) contains a leached zone with laminated crusts resembling calcrete of soil profiles. The crust is developed on a dolomicrite, and a thin section (Fig. 108) shows the surface below the crust is highly irregular, with pits resembling solution cavities.

One of these pits contains partly dissolved oomicrite, from which ooliths have been released. These are elongate, and have become oriented parallel to the cavity walls. The laminated crust has recemented them in place. Another pit containing an oolith has a micrite crust on its lower surface, and has then been infilled by micritic carbonate, The mouth of the cavity has been closed by a further layered micrite crust. A third pit contains a fragment of micrite with a well-developed laminated crust on its upper side, which resembles an oncolitic structure (Fig. 108). The cavities are thus interpreted as geopetal structures, and the surface at which they were formed was subjected to solution before deposition of the overlying bed.

The solution phase was followed by deposition of the pale orange laminated micrite crust (Fig. 108) which alternated to some extent with micrite sedimentation. At 625X magnification, no structure could be observed in the crust, apart from the laminae. The encrusting micrite does not emphasize protuberances, except in the case of the clast (C_1, Fig. 108). Ooliths sometimes project up into the crust, probably exposed by differential solution.

In other parts of the section there is a complex relationship between solution and deposition. A shallow cavity has been coated with a thin micrite crust, and then filled with oomicrite sediment. Infilling alternated with solution, evidence being given by truncated ooliths and scolloped surfaces with a thin micrite layer (Fig. 111) and laminated crust formation.

The distribution of ooliths, pellets and occasional quartz grains, coupled with the morphology of the structures, is indicative of infilling of cavities by sediment and alternating phases of accretion and solution, rather than stylolite pressure solution. There is no evidence for binding substances in the laminae, the geometry of the shapes is not that associated with algal forms, and they differ in being formed only on solution planes. A phreatic origin is suggested in accordance with James (1972), though tangentially oriented crystallites could not be detected. Thus there was subaerial exposure.

The relationship between crust and ooliths is interesting, considering previous comments about oolith genesis. Pellets immediately beneath the crust are not laminated, there is rare evidence for vadose pisolith structures of Dunham (1969) (Fig. 107), an abrupt boundary occurs between uncoated and coated pellet layers, and ooliths have radial structure. Thus they are not related to the crust, though solution has modified them.

5. CARBONATE IN CLASTIC LUTITES AND ARENITES

Dolomite and calcite occur in several forms in fine grained rock.

(1) Micrite clasts of very variable size (0.1 - 1.0 mm or more), generally angular, identical to the pure carbonate layers, presumably reworked from them (Fig. 118).

(2) Micrite laminae, alternating with silt and clay containing clasts in a micrite-clay-silt matrix. Examples are P1262/73, P1261/73 both showing disrupted structure involving carbonate. In P1261/73 carbonate beneath a silt layer is disrupted, probably by a gas bubble or escaping burrower, so as to produce

a zone of mixed micrite silt and clay ?above the exit hole. The top of this section is not known, hence it could be interpreted as the result of downward penetration. The clay has crystallized so that domains follow the distorted framework structure.

(3) Disseminated grains - minute carbonate rhombs scattered through silt and clay.

(4) Clustered grains (Fig. 103) in radiating aggregates 0.1 mm diameter, often centred on a ferruginous grain.

(5) Sparry carbonate in vughs or around framework grains, always fine grained (usually $<$ 0.15 mm) e.g. P1262/73.

(6) Micrite, infilling probable mudcracks or faults in laminated silt (P232/72). This has a patchy texture reminiscent of calcrete formation.

Of these, micrite clasts are commonest.

6. ORIGIN OF DOLOMITE

The rate of growth of dolomite crystals is extremely slow, from thermodynamic consideration, long periods being required for ordering of cations. Thus to dolomitize calcite or aragonite, magnesium rich alkaline waters must be in contact with the sediment for a long time (Berner 1971, p. 152). This led to development of the evaporative reflux model, first proposed by Deffeyes et al. (1965) for dolomite forming in lagoons at Bonaire Island. This model has appeared in various forms in text books (Blatt et al. 1972, p. 486; Berner 1971, p. 148) but requires dolomite formation on the seaward side of lagoons. In the Coorong area of South Australia, the situation is reversed: young dolomite precipitating lakes even occurring far inland (Von der Borch et al. 1975). Von der Borch et al. propose carbonate groundwaters are necessary - the variety of carbonates precipitating along the Coorong result from location of the groundwater seawater interface in relation to various isolated small lakes. On the side influenced by seawater, calcite and aragonite are precipitating, landward lagoons contain dolomite.

The carbonates of the southeast of South Australia have been deposited in a series of fossil "Coorong" areas associated with stranded beach ridges. Dolomite, or high magnesium calcite are precipitated in the stranded lagoons through evaporation of groundwaters in areas of groundwater discharge. One lake near Naracoorte mentioned by Von der Borch et al.is 80 km inland, but is still precipitating dolomite, because it is a site of groundwater "outcrop" and high evaporation.

The chemistry of dolomite precipitation has recently been investigated experimentally by Davies et al.(in press) who show a high carbonate to bicarbonate ion ratio is prerequisite for dolomite formation, and the Mg/Ca ratio was not as important as formerly thought, though Mg must be high. They show dolomite can precipitate under conditions of low pH and high salinity (e.g. in the Persian Gulf) or if salinity is low then a high pH (9-10) is required (the Coorong). They show decaying algae have a role, by providing high bicarbonate concentration and suggest this operates in the Coorong.

Folk & Land (1975) show how aphanitic dolomite precipitates in a hypersaline environment, whereas limpid well formed crystals crystallize from fresh groundwaters. They suggest dolomite precipitates during phases of decreasing salinity.

7. SUMMARY AND CONCLUSIONS

The Namba Formation upper carbonate was deposited over a wide area, and was not strongly transgressive or regressive, particularly in the area south of Lake Frome. This suggests it was a large scale equivalent of the inland lake situation described by Von der Borch et al. with evaporation occurring over a wider area, supplied with Mg rich groundwaters. During the Tertiary this was a time of maximum marine transgression and low relief, therefore the Tarkarooloo and Lake Eyre Basin could equally well have represented the extended supratidal environment of a shallow epeiric sea.

Groundwater formation of dolomite leads to the alternation of centimetric beds of calcite and dolomite, as in the lower carbonates of Wooltana 1 bore, by means of fluctuations in the groundwater-seawater (or saline lakewater) interface. Once calcite formed in the lacustrine or marine environment, the solutions could not convert it to dolomite, therefore a transgression produces a sequence of calcite over dolomite, a regression the reverse.

Evidence for drying of dolomite is compatible with its mode of formation from high salinity waters in a supratidal (or equivalent) environment.

In the algal laminites, death and decay of algae could have caused precipitation of dolomite, as suggested by Davies *et al*. This is compatible with evidence for drying. The alternation of laminae is then probably indicative of seasonal ~~climated~~ climatic variations, implying thicker beds (2 cm and upwards) are the result of longer term fluctuations in rainfall or water level.

Association of dolomite with palygorskite has been mentioned. A comparable occurrence of dolomite, with barite and palygorskite in the soils of the Riverina area of N.S.W. is known (Singer & Norrish 1974). Considered in terms of the model of Von der Borch *et al*., this dolomite could have originated by evaporation of groundwaters, when the soils were submerged in a playa type environment. It is conceivable that palygorskite and barite were derived by a similar process. Singer & Norrish did not consider the past history of the soil when they proposed that palygorskite forms in poorly drained semiarid soils - the palygorskite could have been remobilized from pre-existing playa lake precipitates.

Thus aerial or temporal variations in groundwater composition within a supratidal lagoon or hypersaline inland lake environment are the most likely explanation for the genesis of the Namba Formation carbonates.

With regard to tectonics, the sinking in the region of the Poontana SubBasin accounts for the greater thickness of dolomite here and the alternation with clay layers. Absence of carbonate east of the Benagerie Ridge suggests that during these times a connection with the Murray Basin, if it existed, was over the western end of the Olary Block, or via Lake Eyre or Lake Torrens, not via Cockburn.

The carbonates in the lower part of the Willawortina Formation are dolomitic, similar to those of the Namba Formation, excepting they are oxidized and sometimes affected by soil processes. The margins of alluvial fans are often a site of groundwater discharge, and in a climate with a high evaporation rate, given appropriate groundwater chemistry, this is another expected site of dolomite precipitation, in playa lakes. Dolomite does not occur in the high plains areas, where conglomerates are best developed, and is scarce in Wertaloona 1 bore, fitting this model.

The process of oolith formation under low energy conditions on shoals and in nearshore environments is possible, but evidence for the operation of currents capable of transporting them into micrite precipitating areas is lacking, particularly if the environment envisaged for dolomite formation is accepted. Mixing of micrite, intraclasts and/or ooliths must have been achieved by bioturbation. Growth of oolitic envelopes could have proceeded by the method of Bubela et al. (1975) in still water. All carbonates were disrupted by thixotropic transformation and flow, and bioturbation. Partial recrystallization of ooliths, fossils and other structures occurred during formation of microspar. The relationship between this and dolomitization is unknown, and the two need not be connected.

There is a close comparison with the lacustrine carbonates of the Green River Formation (Williamson & Picard 1974). Many Lake Frome carbonates would fit the lagoon or shoal environment of these authors, supporting a shallow, quiet water depositional environment during sedimentation. The deposits are also comparable with the lacustrine carbonates of the Tertiary in France and Switzerland (Kubler 1962, Freytet 1973), particularly considering association with palygorskite (also present in the Green River Formation). This is further considered in Chapter 7. There is an analogy with the Coorong dolomites in South Australia, though ooliths and palygorskite are absent from these.

Stained acetate peels show persistent bluish colour for dolomite and frequently purple for calcite, indicating high iron content. In one peel (Wooltana 1 bore 221.70 m) bright blue ferroan calcite clasts are present. Thus the carbonates are iron rich, as are the dark clays in the same sequence (Table 5). In detail iron tends to be concentrated within the periphery of dolomite clasts, and in the peel at 218.68 m (Wooltana 1 bore) it varies in concentration between areas delineated by stylolite boundaries. It is suggested the iron was introduced from groundwaters immediately after sedimentation whilst the carbonate was water saturated, during quick movement of the calcite interbeds. In this same peel a more intense concentration of iron also occurs in minute dendritic areas in the matrix, related to clotted microtexture. This may be the result of slight grain-size differences affecting the intensity of the stain or of concentrations of clay impurity. The black clays with which the dolomites are associated also have high Fe content.

CHAPTER 5

SEDIMENTARY STRUCTURES, CYCLIC DEPOSITION

1. INTRODUCTION

1.1 CLASSIFICATION AND NOMENCLATURE

The various types of sedimentary structures are given in Fig. 147. Criteria for differentiation follow:

Bedding (contacts between different lithotypes).

(1) Sharp bedding planes: a pencil point can be placed on the boundary. There is no gradation, the surface being a plane of discontinuity, e.g. Fig. 131, at the base of the black clay. Fig. 115, at the base of the sand-clay interbeds (light grey).

(2) Diffuse: transitional over 1 cm or less, e.g. Fig. 116 at the base of the laminated silt.

(3) Transitional over 1-10 cm., e.g. Fig.

(4) Gradational: transition >10 cm, used where there is a distinct change, usually of several properties, not where the change is imperceptible.

(5) Imperceptible changes are indicated by grading the rock symbol code.

(6) Irregular boundaries: usually sharp boundaries disrupted by bioturbation or soft sediment deformation. They are distinguished by a transitional zone of irregular blocks of sediment, or apophyses of sediment passing up into the overlying material. Flame structures, distorted mudcracks and burrows may be present. e.g. Fig. 116 at contact between carbonate and black clay.

Lamination: beds measured in thicknesses of a few millimetres, e.g. Figs. 122, 95.

Cross-stratification (cross-bedding and cross-lamination): The cross stratified sets are divided into classes according to thickness.

Interpretation must allow for erosion of the tops of these sets. In outcrop it was sometimes possible to classify in terms of Allen (1963). Examples are given in Fig. 140, 141, 95.

Slumping: can be distinguished from overturned bedding, crumpled structures etc. in outcrop, but it is rarely possible to identify it in core unless of small scale, e.g. Fig. 139.

Quick Flow Structures: Penecontemporaneous structures or rheotropic structures (Conybeare & Crook 1968) other than slumps. Distorted clasts clay wisps, intraformational breccias and various phenomena indicative of quasi-liquid flow. Those resulting from quasi-liquid flow are grouped under a general heading of "quick-flow" structures. This term is derived from the quick-clays (certain types of clay showing thixotropic properties) described by Boswell. The term has been extended in this thesis to cover any structures which arise from similar processes, e.g. Figs. 128, 130, 118.

Biogenic structures: Include both surface traces and internal structures, formed by plants or animals. The term bioturbation structure is used by Reineck & Singh (1973) in a more restricted sense, as they do not include disturbance by plants, e.g. Figs. 121, 123, 138.

Mudcracks: Rarely observed in outcrop. Some structures seen in cores are interpreted as mudcracks. Simple vertical wedge shaped forms are rare, most being complex and usually parallel-sided, e.g. Fig. 93.

Ooliths: Have been discussed under carbonates.

1.2 STRUCTURES INDUCED OR DESTROYED BY DRILLING PROCEDURE

Drilling procedure has produced structures as follows:

(1) Downturning of laminae marginal to the core periphery, resulting from downward pressure or drag as core enters the core barrel. These can be readily distinguished from sedimentary structures (Figs. 17, 18, Wooltana 1 bore, 128.19 m; ?Wertaloona 1 bore

165.60 m and Fig. 121). They are useful in providing an indicator of way up on the core, and can be removed if desired by scraping with a knife, to reveal the true structure.

(2) Those resulting from rotation of the core. Swelling clays sometimes became jammed in the bit, resulting in rotation of core segments relative to one another (Fig. 17, Wooltana 1 bore 215.60 m - sketch). This may have produced distortion of structures such as that at 205.00 m in Wooltana 1 bore which has a spiral arrangement when observed in three dimensions.

(3) Those resulting from penetration of drilling mud, producing pseudolamination (Fig. 7, Yalkalpo 1 bore 22.71 m,and Fig. 121). These are sometimes difficult to distinguish from true lamination or horizontal clastic dykes. They may be accompanied by core rotation.

(4) Structural modifications produced by swelling in the core barrel. The core cut by the bit was sometimes narrower than the inner tube, as a result of washing effects at the bit cutting edge. Many cores showed more than 100% recovery, resulting from subsequent expansion of clay after entering the inner tube. Diapiric intrusion of fluid clay into the tube, caused by overburden pressures also occurred. Thus expansion and extension are possible producing features such as the radial distortion of burrows and clasts in Fig. 7 (Yalkalpo 1 bore 12.5 m). Most examples can be distinguished from true sedimentary structures, having radial symmetry in relation to the core axis.

(5) Another consideration is the destruction of structures in water saturated sand by flowage, when removing the core from the inner tube (triple-tube wireline drilling procedures were used). This occurred in Yalkalpo 1 bore, and destroyed the cross stratification.

2. EYRE FORMATION

2.1 BEDDING

Average thickness is about 1.5–2 m, estimated from bores in the southern part of the area. The beds consist of sets of cross strata or alternations of silt, sand or clay. Bedding planes are generally sharp. In outcrop, beds lens out in a few metres. Bedding planes are flat, though the lower surface is sometimes cut by wide grooves (Wopfner _et al._ 1974, Fig. 4). Inspection of the detailed logs shows bed thickness to be bimodally distributed at 20–30 cm and 2–3 m thick.

2.2 CROSS STRATIFICATION

Both planar and trough cross-stratification were observed in outcrop. The three dimensional form was never seen well enough in cores to assign it to one of the classes of Allen (1963), except in very small scale cross lamination.

Foresets are straight or slightly concave downwards. Sets varying from 10 to 30 cm thick were recorded in the cores, and are common in outcrop. Sets of 1–2 m were also observed in the field. Dips vary from 25-34° in the coarser beds. The larger cross-stratified sets are megaripples or aqueous dunes, the smaller types probably ripples.

An araldite peel made of core (method in Appendix 4) from PMX24a bore at 111.80 m (Fig. 137) shows, in coarse sand, sets 15–20 cm thick with alternating crude coarse and fine lamellae. Subsequent sets often show opposed dips, but one cannot assign these with certainty to true herring-bone cross-stratification (De Raaf & Boersma 1971) without having determined the three dimensional form. The apparent contrasting directional properties of subsequent sets may be partly the result of orientation at an angle to true longitudinal sections. Accounting for this, there must still have been considerable variation in current direction with time. This type of variation is more common in meandering stream environments than in braided types, particularly where dunes have curved crests. Not enough measurements are available to give statistical significance.

The alternation of coarse and fine lamellae in cross-beds has been explained by Smith (1972) as the result of avalanching of ripples over the crests of dunes. Ripples are often accompanied by scours which contain coarse particles. As these migrate over the surface of the dunes, successive layers of coarse and fine particles are formed. Lamellae can be produced by shear, especially in dunes, leading to a concentration of coarse grains towards the base and outside of lamellae (Reineck & Singh, 1973, Fig. 12).

2.3 HORIZONTAL LAMINATION

Well developed fine lamination is a common occurrence in the silts and clays of the southern Lake Frome region. Large mica flakes are often present and much of the clay is shredded mica. Some of the clay beds are unusual, containing large quartz grains. The texture so produced is identical to the weathered basement material, apart from the lamination. Petrological examination showed lamination resulted partly from secondary recrystallization effects. The deposits are regarded as slumped material derived from weathered basement.

The laminated beds are generally distinct from the cross-bedded sequence, occurring more commonly near the top of the Eyre Formation (PMX24a Fig. 8). They are interpreted as flood plain deposits or upper flow regime plane beds.

2.4 BIOGENIC STRUCTURES

Rare bioturbation is observed in the upper fine grained beds. Rare burrow-like structures are present, similar to those in the Namba Formation, associated with mottled and churned structures.

2.5 CYCLIC SEQUENCES

Fining upwards sequences are well displayed in PMX24a bore (Fig. 8) and to a lesser extent in K69 and B240C3 bores (Figs. 4, 9) They were not recognised in the Reedy Springs section, though C15 bore (Fig. 22) in the northern region shows variations in the electric logs of suitable scale to be interpreted as fining upwards cycles. The neutron logs display the variations to the best advantage (e.g. Yalkalpo 1, PMX24a, Figs. 13, 14) but are not often run.

In B240 C3 bore at 116 m there is a rootlet horizon associated with the top of a cycle, which is typical of the upper parts of flood plain deposits or channel bar deposits (Reineck & Singh 1973). Another example is seen in EAR9 bore (Fig. 21) at 110 m.

There is no way of separating point bars from braided bars by criteria observed in a single vertical sequence (Reineck & Singh 1973). Gross features, like sequences with higher proportion of coarse sands than clays, and silts with isolated sand lenses, denote an essentially braided river system (Allen 1965). There is a tendency to overall upward fining through the whole of the Eyre Formation, clearly displayed in the Reedy Springs and PMX24a sequence (Figs. 24, 8). Beds near the top of the latter section alternate with fine grained floodplain type sediments. Coarse grained beds near the base show individual fining upwards characteristics less clearly or not at all compared with those higher in the sequence. This is suggestive of a tendency to meandering rivers and a channel-confined regime in the upper part of the unit. In Wopfner <u>et al</u>. (1974) this variation was stated to be typical of the Eyre Formation as a whole, and was attributed to the effect of reduction in relief in the source areas, with gradual filling of the basin.

2.6 SLUMPING

In EAR3 (Fig. 5) bore, finely laminated micaceous silt forms the weathered basement zone recorded in the lower part of the hole. The interpretation as basement is based on electric log response (Fig. 11) and subvertical lamination in the core. Careful inspection revealed the subvertical lamination was largely the result of slumping, since near horizontal clay beds were occasionally seen (Fig. 5, 135.83 m). This suggests the sequence is actually slumped weathered basement, and presumably equivalent to the Eyre Formation. This is in agreement with the depth of seismic basement determined by Nelson & Galbreath (1973, appendix 6) which is further supported by an abundance of chlorite in the basal samples at the same depth (a feature generally indicative of pre-Tertiary sediments, especially Cambrian and Precambrian).

3. NAMBA FORMATION

3.1 BEDDING

A greater variety of bedding plane types occur in the Namba Formation when compared with the Eyre Formation - gradational and irregular forms are much more common. Individual beds are more persistent and have been traced over several dekametres. In the case of the carbonates they extend for several kilometres. On a large scale the surfaces of sharp planes at the top of the black clays in member 1 are undulating. On a small scale disrupted or burrowed planes are common. No toolmarks or ripples were observed. Bedding thickness averages $1\frac{1}{2}$ m, as for the Eyre Formation, though there is greater variability in the Namba Formation. Mud beds have an average thickness of 2-2.5 m, sands 1-2 m and carbonate 1.0 m.

3.2 CROSS-STRATIFICATION AND CHANNELLING

In outcrop it was often possible to determine the three-dimensional form of cross strata, because of secondary cementation and differential weathering. Two types are present: the commonest forms are pi cross-bedding, sometimes tending toward intermediate forms of omikron cross-bedding (Fig. 140). The rarer form, identified in Lake Namba, is a well developed omikron type with straight foresets. The coarse mature sand unit has also been studied - its widespread silicification has meant that it is generally well exposed. It also exhibits pi-cross bedding.

The pi cross-bedding is in sets 1-3 m thick, cut into the underlying clays. The curvature of the cross-beds in plan view is often very marked, though foresets are straight in longitudinal section. This type is best observed near Lake Gomolara on Eurinilla Creek. Meandering channel patterns are sometimes observed.

In Lake Namba (Fig. 140) cross-beds of the omikron type are 10-30 cm thick, having straight foresets sharply cut off, top and bottom. Individual sets are a narrow wedge-shape. Large clasts are present which caved from the channel banks. The sequence is overlain by finer sands, containing small scale trough cross-lamination (Fig. 140). The whole may represent a point bar or braid bar sequence of a river. The extent of these channels is not known, they are not visible unless outcrop is trenched. Some of the structures in the bores may represent them (Fig. 136).

The pi cross-stratification was probably formed by the migration of lunate dunes in deep confined channels, whereas the omikron type resulted from migration of straight crested dunes in a shallow channel. The pi types are typical of meandering rivers, an interpretation supported by the channel plan, whereas the omikron type is commoner in shallow braided rivers (Smith 1972). However, both may occur in a variety of environments (e.g. offshore bars, chute channels on beaches, etc.).

In subsurface, medium scale cross-stratification is commonly observed. Five peels from Wooltana 1 bore, 3 from Wertaloona 1 and one from PMX24a were prepared. Most sets are 8-17 cm thick (Fig. 136), or 0.5-4 cm thick (Fig. 133, 134 and Wertaloona 1, 152.00 m). Often these two sizes of cross-strata alternate (Wooltana 1, 135.6 m). Rare larger sets 25 cm thick are present (Fig. 135). The cross-laminae probably represent migrating ripples, the cross-beds aqueous dunes (or mega-ripples). Frequently dips of successive sets or groups of sets are opposed (Fig. 133), in the manner of herringbone cross-stratification (c.f. Reineck & Singh 1973, fig. 143). It is not possible to assign the structures to this class with certainty, since three dimensional form must be observed: variable dips could result from migration of curve-crested ripples or dunes. In the absence of data on wavelength in the 10 cm sizes or thereabouts it is difficult to separate ripples and dunes, though thin lamination is indicative of ripples (Allen 1970a). The possibility of a tidal influence cannot be eliminated.

All the cross-strata are developed in silt to fine sand, often with alternating clay laminae (Fig. 134) either within or between successive sets. The clay was probably transported as small sand size clay particles or deposited from suspension during periods of slack water (e.g. following cessation of flow). Some peels show cross-lamination partly or almost completely destroyed by burrowing (Fig. 132 and Wertaloona 1 bore, 152.00 m, 165.6 m), again more typical of offshore bars or tidal channels than rivers.

Cross-stratification is thinner in the Namba Formation than in the Eyre Formation. It is also apparent that large scale trough cross-bedding (pi type of outcrop) is not a common feature of the subsurface sequence, at least in the Poontana SubBasin. No cross-strata were observed in C15 or Yalkalpo 1 bores, though difficult to detect without the aid of peels. The EAR series bores had deteriorated too much, and other bores have cored the Eyre Formation only. The preponderance of smaller scale structures in the Namba Formation need not be the result of differing stream power, since grain size controls the type of structure within a particular energy range.

During deposition of the 'coarse mature channel sand', streams ran in more confined channels than in Eyre Formation times, as can be observed from outcrop.

Fine and very fine cross-lamination is frequently observed both in outcrop and subsurface. The above peels (Figs. 132-138) and sketches on the bore logs give examples from subsurface, and the photographs (Figs. 140, 141) of outcrop (see also Callen & Tedford in prep.). These structures are among the most abundant. They are very lenticular and often trough-shaped. Individual laminae are defined by variations in proportion of clay mixed with the silt or fine sand. The structures are generally accompanied by wavy thin bedding and fine lamination. Sometimes they occur in forms resembling flaser and lenticular bedding of Reineck (Reineck & Singh 1973).

The structures described can be found in a number of environments, particularly channel deposits and tidal flats (De Raaf & Boersma 1971), or offshore bars. In Chapter 8, drilling by uranium exploration companies is described, which has revealed the presence of major channel complexes indicative of large rivers.

3.3 HORIZONTAL LAMINATION

This is the most abundant structure in the Namba Formation. It occurs in all lithologies, including the carbonates.

In Wooltana bore (Fig. 17) the basal unit 1 shows very fine varve-like lamination (Figs 58, 125) consisting of alternating carbonaceous material, dark clay, silt and calcareous matter. The calcareous laminae are of two types - (1) fossiliferous, with ostracodes and fish spines, or (2) fine chemical sediments. Very fine silt occurs on partings between lamellae, and is often only one or two grains thick. The clays vary from black to dark green, with a well developed fissility or parting, partly the result of orientation of carbonaceous matter parallel to the bedding. There are 8 lamellae per mm in some sections, but though the lamellae persist within the width of the core, there is no development of couplets as in true varves (Kirkland & Anderson 1969). Alternation of clay and ostracodes or silt occurs, possibly seasonal. The sediment contains a diverse flora (Harris *pers. comm*. 1975), no one species especially abundant. In thin section the lamellae average 10-20 m thick, within which even finer laminae 5 microns thick can be seen (Fig. 59).

The fissility of clay has been ascribed to sedimentation of clay minerals in a fresh water environment (White 1961). The varve-like laminae and presence of abundant plant material (5% C, Table 5) and pyrite and marcasite (5% Fe, Table 5 and xray diffraction) are typical of a euxinic environment. The absence of marine fossils, presence of the algae *Pediastrum*, and ostracodes, suggest this is a nonmarine deposit. The ostracodes were investigated by MacKenzie (*pers. comm*. 1974, Riverina College of Advanced Education, N.S.W.) who noted the presence of both ornamented and non-ornamented forms believed to indicate varying salinity. The data indicate this was a lacustrine environment, of great enough depth to have been thermally stratified. The layers of organisms may have been produced seasonally.

Similar sediments occur higher in Wooltana 1 bore (Fig. 131), and in Wertaloona 1 bore (Fig. 122). The lamellae in the Wertaloona section are of alternating fine silt and clay in varying shades of grey and green. The silt is slightly calcareous, grading up into clay to form couplets, with 3-4 mm in the finer parts. The width of these laminae varies more than that of classical varves, and the maximum size is greater. They may be the result of seasonal variations or settling from suspension after storms.

Lamination is common in the fine sediment of the other units, but rarely as well defined as that of unit 1 in Wooltana 1 bore. It usually results from slight differences in grain size or mineralogy of silt layers, but may be produced by alternation of clay and silt or fine sand, or by colour variations in clay. Colour variations are caused by differing quantities of carbonate or carbonaceous matter or oxidation state of the clay, or to the colour varieties of the clay itself. These laminae tend to lens out within a few centimetres, frequently interrupted by small scale faulting or soft sediment deformation. Examples are given in the sketches on the bore logs and in Figs. 94, 121, 119, 128 (Yalkalpo 1 bore, 36.15 m; Wertaloona 1 bore 161.19 m, and outcrops at THUR4/0035/1, EUR3/4393/11).

An araldite peel of PMX24a bore at 92.73 m shows diffuse wavy horizontal lamination in fine well-sorted sand. The laminae are 0.5 cm thick.

Lamination is best developed in Wooltana 1, Wertaloona 1 and Yalkalpo 1 bores. The other fully cored bore with a thick sequence of Namba Formation is C15, dominated by clay showing limited laminar development.

The lamination resembles that of flood plains, tidal deposits, lagoons or lakes. There is a strong resemblence to the "Sloef" deposits of Dutch lagoons (van Loon & Wiggers 1975). It indicates a low energy environment with a pulsating deposition. Evidence for abundant quick-flow structures and bioturbation and partly destroyed lamination suggests lamination was origianlly much more common.

The carbonate lamination is of two types - the fine algal lamination described in Chapter 4 and alternations of clay (usually palygorskite) and carbonate produced by variations in the amount of carbonate. Some of the fine lamellae are so thin (Figs. 122, 130 and Wooltana 1 bore 218.68 m) that a seasonal origin or intra-seasonal fluctuations, are proposed. The presence of laminae in these sediments contrasts strongly with their absence in the otherwise comparable Coorong area (excepting the algal stromatolite locality, Walter et al. 1973). Elsewhere agitation of the water keeps the bottom sediment stirred up and produces a deposit with the texture and appearance of yoghurt. The presence of laminae in the Namba Formation carbonates suggests some binding organisms, such as algae, were present.

3.4 SLUMPING

Slumps are rheotropic structures, demonstrating hydroplastic behaviour. They appear rare, though difficult to recognise unless considerable exposure is available. Two outcrop localities are known: one at the western cliff of Lake Tarkarooloo South (EUR3/4392/3) and the other at the northern end of Lake Namba (Fig. 139), also in the western cliff.

The structure at Lake Tarkarooloo is 0.75 m thick and 2-3 m long. It is located in a sequence having an overall westerly dip of 15-20 degrees, and is associated with an area of variable and anomalous dips (EUR3/4393/17 and 22). The region is broken into several blocks, associated with channel deposits of the Millyera Formation, and with intraformational channels. The trend of the main fracture zone was found to be parallel to the edge of the lake, which is very straight, When projected to the north it corresponded to a remarkably straight channel located in the same lake bed. This structure is thought to be a contemporaneous tectonic feature

(?linear diapir) which has to some extent controlled sedimentation. The overall flat dip and slight displacement rule out any possibility of a major structure. The slump may have resulted from movement on this structure. The Lake Namba slump is smaller and of different character.

The presence of slumps indicates the sediment was saturated with water, and there was sufficient gradient for movement. Possibly they formed by caving of stream banks collapsing into soft sediment, or by aqueous dunes migrating over water-saturated silty substrata.

Slumps are difficult to interpret from core. A possible example is in Wooltana 1 bore (Fig. 17, sketch at 205.00 m, actual scale).

3.5 BIOGENIC STRUCTURES

3.5.1 Description of burrows and bioturbation

All stages of bioturbation varying from isolated burrows to homogenized strata have been observed. Burrowing (endogenetic lebensspuren) is characteristic of the Namba Formation, and usually exhibits well defined spreiten. The spreiten take the form of concave-down lamellae with a lens-shaped cross section. Most burrows are 0.5 cm diameter (Figs. 132, 138, 95,and Wooltana 1 bore 166.79 m) and 2-3 mm (Fig. 121). They are irregular, sometimes branching (P1252/72,and Wertaloona 1 bore 58.72 m) with a tendency for alignment parallel to or perpendicular to the bedding. Vertical and subvertical burrows tend to be isolated and straight for several centimetres, whereas those concentrated in a single bed or along a bedding plane are curved, and often cross one another.

In thin section other burrows of 1.5-4 mm were observed (P1253/73), less commonly 0.3-0.4 mm (Fig.131)and 0.65 mm,(P1140/73 - Eyre Formation) diameter are also present. The larger 1 cm variety in the peels (Fig. 132) were not identified in thin section probably because of difficulty in recognizing textural relationships in so small an area.

Burrows are filled with a variety of material, frequently of differing composition to the matrix (Fig. 4 of Callen & Tedford *in prep*.) Those in Fig. 95 (P1252/73), a carbonate, were investigated in detail. The xray diffraction data showed clay was commoner in these burrows than in the matrix. The spreiten are produced by slight differences in orientation and packing of the clay and micrite grains, by slight variations in dark stain (carbonaceous matter?) on, or in, the micrite, and by alignment of minute vughs (sometimes infilled by coarsely crystalline clay). Other portions of the burrow system show irregular pelletal and granular texture. These features suggest the passage of an organism, probably an ingestion feeder, with later diagenesis.

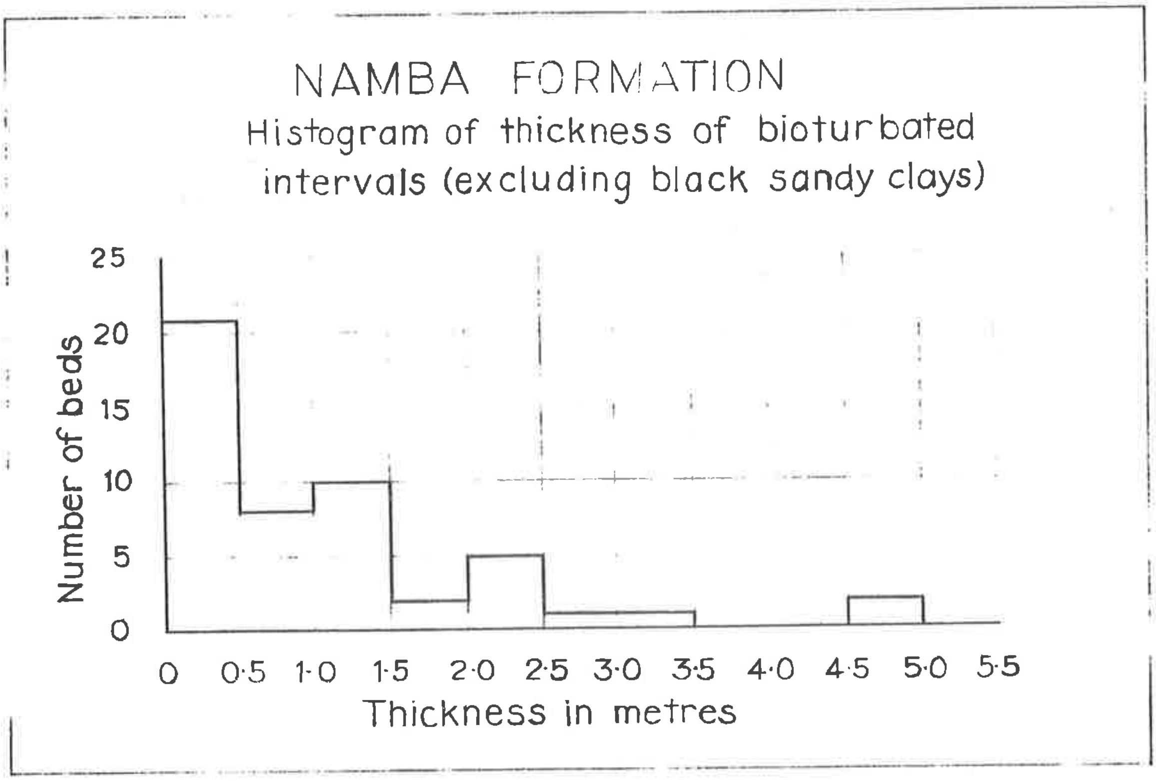
As the burrows become more densely distributed they grade into mottled structure (Fig. 132 and Wertaloona 1 bore 58.72 m) and finally homogenized sediment with churned structure in which lamination has been destroyed (Fig. 132, 121, 138 and Fig. 4 of Callen & Tedford). A similar gradation has been described by Moore & Scruton (1957) for sediments on a marine shelf, though passage from regular layers through irregular layers to mottled structure was rarely observed in a vertical sequence in the Namba Formation - an abrupt change from regular to bioturbated intervals is the rule.

Another example exhibiting spreiten is P1081/73 which has alternating micritic and clayey lamellae, convex down. The clay is present in pellets of varying size (average 0.15 mm) and angularity, sometimes coallesced into solid masses in some burrows. The lamellae are concave and 0.09-0.15 mm thick. Clay pellets of similar type are scattered through the matrix, which has a churned appearance, but larger pellets, obviously clasts, are also present. The burrowers have apparently concentrated the clay originally mixed with the carbonate, in preference to the carbonate, expelling it as pellets. This suggests the organisms gained nutrients from the clay fraction, explaining the abundance of burrows in clayey layers interbedded with the carbonate.

3.5.2 Intensity and thickness of biogenic structures

Bioturbation is commonest in muds, particularly when calcareous or interbedded with carbonate. It is less common in pure carbonates than the associated clay and may also be abundant in silty mud. Bioturbation decreases in both quantity and intensity with increasing grain size. An examination of the thickness and intensity of bioturbated intervals shows the dark sandy clays are completely homogenized. Any interlaminated sand, mud or silt beds would become sandy clays when thoroughly bioturbated. Homogenized dark sandy clays are thicker (often >3m) than other bioturbated zones, which average 1 m.

A histogram of bioturbation thickness, (see over) excluding the dark clays, shows a strongly skewed distribution towards thinner intervals. The maximum depth to which bioturbation is commonly recorded (Reineck & Singh 1973) is about 50 cm. Assuming that the burrowing organisms in the Namba Formation could operate at this depth, thicker beds can be accounted for if sedimentation was slow and continuous enough for burrowing to keep pace. The preponderance of thin bioturbated horizons and their restriction to well defined layers is interpreted in terms of rapid sedimentation, followed by a period of quiescence when the surface was subjected to burrowing. The absence of burrows in identical facies elsewhere in the sequence must therefore indicate sedimentation was too rapid to permit this activity, or burrows were destroyed by agitation.



3.5.3 Biogenic structures and lithofacies

The black sandy clays usually show intensive mottled effects, with patches of sand and clasts of clay and carbonate of various types. Occasional irregular remnants of sand beds are present. Burrows are rare (Fig. 4 of Callen & Tedford, Yalkalpo 1 bore 12.5 m is an example, in which burrows are unusually distinct), though vertically oriented streaked mottled zones are frequent (Fig. 117). The streaked zones (see sketch Wooltana 1 bore 209.0 m Fig. 7) occur at transitions from sand to silt and do not resemble burrowed zones. Close examination shows that the sand occurs in cracks between vertically elongate clay fragments.

No gradation of black clays to laminated clays with scattered burrows was observed, though the churned appearance and presence of rare burrows suggest almost complete bioturbation during slow deposition. Original sand layers could have been disrupted to produce the observed patches. An experiment by Clifton & Hunter (1973, Fig. 5) showed almost random distribution of grains was produced by burrowing organisms after one year. A soil origin was suggested in an earlier section: disruption by roots and other organisms may have produced the bioturbation, but absence of fossil roots is difficult to explain.

Other types of clays also show massive structure, without disrupted beds or signs of bioturbation. Agitation of bottom muds in shallow water, a common process in lagoons (e.g. the Coorong) and playa lakes (Holocene sediments in modern Lake Frome show no lamination) could have produced this.

Accepting the carbonates as indicating a supratidal or equivalent environment implies the burrows in clays interbedded with the carbonates formed in a nearshore facies. They do not have the features of those formed by suspension feeders, nor do they have strengthened walls, therefore quiet water is implied. Even in this situation, agitation in shallow water can be expected to destroy most structures, unless the sediment was organically bound (by algae?). Fungal or algal moulds are common (see later) but not ubiquitous or abundant enough to act as a binder. Alternatively burrowers operated at a depth beyond the reach of agitation.

Silts show burrow types similar to carbonates. They occur in thick sequences alternating with thin sand beds (Fig. 7, Yalkalpo 1 bore), or as transitional intervals within the cyclic sequences, between sands and black sandy clays (Fig. 18, Wertaloona 1 bore). Burrowed silts of this type occur most commonly in tidal flats and lakes. A flood plain environment is possible, though lack of any associated channel sands in the Yalkalpo 1 bore sequence, where silts are best developed, makes this unlikely. Intraformational brecciation is abundantly associated with the silts, and the lamination type and cross bedding resemble tidal environments.

Sands are rarely burrowed, though the peels (e.g. Fig. 132) show it is more common than apparent from hand specimens. The burrows in some examples have almost destroyed pre-existing aqueous dune and ripple cross-bedding (Fig. 132). This is typical of offshore bars, but has also been reported to less extent in bars of braided streams (Stanley & Fagerstrom 1974). Spiral burrows with concave laminae of comparable size are common in coarse pebbly channel sands of the Millyera Formation in Lake Tarkarooloo.

The black laminated carbonaceous muds of unit 1 in Wooltana 1 bore show numerous small pyrite-filled burrows, and bedding trails (Fig. 123). The trails are similar to those of gastropods. This assemblage contrasts with other types described above, and when considered in conjunction with other organisms present, indicates a biofacies intermediate between 'vital' and 'letal panostrat' types (Reineck & Singh 1973). In contrast the remainder of the sequence approaches the 'vital lipostrat' type.

3.5.4 Bioturbation as depth and facies indicators

The degree of bioturbation is a useful criteria for elucidating environment (Howard & Reineck 1972, Clifton & Hunter 1973, Moore & Scruton 1957), and is related to prevailing energy conditions. It was shown maximum bioturbation occurs in a shallow offshore zone, development facilitated by fine sediment and low wave activity. Mottling and homogenization was best developed in sheltered bays, in a zone of 4-10 m water depth along the Georgia Coast, and from 1-2 m water depth in lagoons and 15 m in open bays of the Texas Gulf and Mississippi delta regions. The depth limitation in the Georgia Coast study is the result of the presence of relict sediment on the outer shelf. However, the work of Moore & Scruton indicates extensive bioturbation may extend to the shelf edge at depths of 106 m. In higher energy coasts the bioturbation zones are shifted further offshore. Thus bioturbation is greatest in areas of quiet water. Lakes and lagoons can be expected to show very high bioturbation provided the appropriate organisms are present. The absence of traces of such organisms can be attributed to foul bottom conditions, excessive salinity, rapid sedimentation or destruction by agitation, or quasi-liquid and hydroplastic flow.

In the Namba Formation, association with carbonates indicates high salinity does not affect the organisms. No carbonaceous matter or sulphides are present to suggest foul bottom conditions, therefore absence of burrows has been attributed to the other causes. Another reason may be that, for sand beds, deposition may have occurred in a river channel where burrowing is usually absent.

The shrinkage cracks in Figs.131 and Fig. 6 of Callen & Tedford have burrows cutting across, indicating they did not form at any great distance beneath the sediment surface. The depth of burrows below the top of the bed, indicated by the position of the crack, give minimum values of 3 cm and 8 cm for the depth of bioturbation in the sediments.

3.5.5 Type of organism causing bioturbation

The works of Hertwick (1972), Seilacher (1964, 1967), Farrow (1966) Howard & Frey (1973) and others (see also Reineck & Singh 1973) discuss the use of trace fossil types for distinguishing nearshore facies in marine environments.

In his examination of trace fossils Seilacher showed how certain burrow types were associated with distinctive sediments and sedimentary structures, forming three universally recognizable facies. In the case of non-marine bioturbation, ichnofacies have not been recognized, very few studies having been made. The worm

Tubifex has been reported as a common burrower in fresh water lakes (Reineck & Singh, p. 217) and insect bioturbation occurs in river deposits (Stanley & Fagerstrom 1974).

The Namba Formation trace fossils resemble Seilacher's "facies breaking" types and so are non-diagnostic, though commonest in the zoophycos facies. Appropriately, this facies is essentially a quiet water environment. The concave lamination in the burrows and traces along bedding planes (Figs. 95, 138;Yalkalpo 1 bore, 22.61, 22.71 m) resemble Fig. 6 of Stanley & Fagerstrom, and Plate 116A of Pettijohn & Potter (1964), but the insect burrows do not branch. Polychetes tend to form lined burrows without internal lamination. No hard parts were preserved. Among the most likely organisms are crustaceans.

The lack of variety in the trace fossils through most of the Namba Formation is at first surprising, considering the high chance of preservation in quiet water sediments. Of large numbers of animals living in a marine environment, Hertweck (1972) found only a few were capable of leaving traces which had a high chance of preservation. During the carbonate cycles the chemical environment would have been harsh, with high salinity and alkalinity, which may have restricted the variety of species.

3.6 SHRINKAGE CRACKS

Shrinkage cracks are rheotropic structures demonstrating quasi-solid behaviour. They are intimately connected with quasi-liquid and hydroplastic structure in these sediments. Two types have been observed:

3.6.1 Cracks on upper surface of beds (mainly in carbonates)

These cracks are rarely vertical and often parallel sided, occurring more often in dolomites than limestone. They are invariably filled with mud or marl which has flowed under quasi-liquid conditions. The parallel sided nature (Figs. 93, 122 and Fig. 6 of Callen & Tedford) suggests they could have been syneresis cracks (Burst 1965), induced in swelling clays by changes of salinity in the water. Smectite and palygorskite are known to be abundant in carbonates but cracking is commonest in purer beds without marked swelling properties. Lack of rounding of the fragments produced by shrinkage suggests if there had been subaerial exposure, the process of exposure and subsequent recovering by water was not attended by wave action - it would need to be a very gentle process. Examples of this type of cracking are Figs. 93, 130 (also Wertaloona 1 bore, 145.5 m). Cracks often form extensive networks, sometimes penetrating the entire bed if thin (Fig. 120).

In the Coorong area hard carbonate layers occur with fluid clay beneath. If cracked, and especially if overlain with other sediment, the clay could flow into the cracks, producing structures similar to those in the Namba Formation. Similarly, penetration of mud into shrinkage cracks is commonly observed on the surface of playas (Glenny 1970).

3.6.2 Cracks within beds, not based on a bedding plane

These have well defined edges, are infilled by clay and carbonate fragments, and are generally a few millimetres wide. They often bifurcate upwards and downwards, indicating they must have been laterally filled. They have a near vertical orientation and may extend for 2 m in depth (e.g. Wooltana 1 bore, 215.2 m). The latter example shows evidence of having been formed before the sediment was dry, since it is convoluted at its base, presumably by vertical shrinkage of the enclosing clay during dewatering. A bifurcated crack is shown in Fig. 131. They must have formed during shrinkage of the clays after burial, and are therefore involved in dewatering. It is feasible that the other shrinkage cracks described in section 3.6.1 were similarly formed.

3.6.3 Origin

Contacts between clay mud beds, or between clay and silt or sand, are usually of the disturbed type, and are discussed in the section on quick-flow structures. The lack of cracks in clay muds suggests they were not exposed to the atmosphere or to syneresis processes, or if formed were destroyed by quick-flow.

It is possible they formed entirely by subsurface dewatering processes whilst covered by sediment, as suggested by Van Houten (1964) for identical features in the Triassic Lockatong Formation of New Jersey. A similar comparison has been made by Freytet (1971) for structures in similar carbonates of the Lower Eocene of Languedoc. Association with carbonates, however, suggests drying may be the dominant cause, since the swelling clays do not show cracks to the same extent.

3.7 QUICK-FLOW STRUCTURES

These structures include disturbed contacts, rafts of distorted clay, silty clay with clasts, infillings, shrinkage cracks, streaked out structure, and intraformational breccias. The disturbed contacts range from flame structures, to situations where apophyses of clay, sand or carbonate extend up into the overlying bed. Sometimes the latter may be separated from the underlying bed (Figs. 116, 118 Wertaloona 1 bore 136.72 m, 148.5 m, Wooltana 1 bore 221.7 m), and resemble Fig. 4F of van Houten (1964).

Rafts of distorted clay are common in some sections (Fig. 124 and Wooltana 1 bore 85.3 m), and show signs of cracking, flowage and burrowing. Rafting occurs in association with the shrinkage cracks in the carbonate, where blocks have become separated and buoyed upward as the overlying clay penetrated (Figs 93, 120). Streaked out sand structures (Fig. 117) are common, and can be attributed to flowage of water saturated sand into soft cracked clay, as well as burrowing.

Another example, common in the silt layers, is the complex assemblage shown in Fig. 94. Narrow wedges of sediment are bounded by fault like fractures (B, arrowed) infilled by silt and clay. The fractures often diverge from a common point (A), and the laminae at the margins of the blocks of sediment delineated by them are downturned. In some layers clay has apparently flowed downward carrying blocks of sediment (C). A structure resembling a minute thrust fault exists at E. Small diapiric-like forms of mud are at D, which have produced reverse 'flame structures'. These structures are intermediate between quasi-liquid and hydroplastic flow. Some resemble flame structures and load casts. The fractures indicate rigid body behaviour.

Intraformational breccias frequently show signs of flow. Two examples in which oxidation at an old weathering surface has picked out these are shown in Fig. 126 (and Wertaloona 1 bore, 48.2 m). All show colours resulting from the various oxidation states of iron, frequently arranged in a concentric fashion. This is so closely related to the formation of the clasts, especially in Fig. 129, that it suggests the process of diagenetic oxidation is temporaly related to dewatering. When a certain stage is reached the sediment becomes thixotropic, and any slight disturbance results in the subspherical bodies being rafted up. Alternatively a particular layer in the sediment may have been at the critical state for flow, whereas the surrounding clay was slightly more stable. When flow occurred, partial mixing of the two clays occurred along irregular curved planes. Subsequent oxidation then picked out the boundaries between these structures.

In the lower carbonate of Wooltana 1 bore stained acetate peels (Fig. 93 and also at other depths shown on Fig. 17) show the greater mobility of the calcite mud compared with dolomite, and its manner of penetrating shrinkage cracks in the dolomite. These structures are identical to Figs. 8, 12 and 13 of Van Houten (1964).

The phenomena of quick-flow and thixotropy have been mentioned. According to Leibling & Kerr (1965) quick-flow results in a sediment which has less strength than the original, whereas thixotropic transformation produces a sediment as strong as, or stronger than the original. The latter was probably the more dominant process, though it is impossible to state this definitely without knowing the properites of the original sediment. The term quick-flow, used more loosely here, includes structures formed by both quasi-liquid and hydroplastic behaviour, and exhibiting thixotropy. True quick-flow occurs in rocks with a high proportion of fine quartz (Cabrera & Smalley 1973, Liebling & Kerr 1965). Thixotropic clays contain abundant montmorillonite or other swelling clays (Liebling & Kerr). Both of these requirements are present to varying degrees in the Namba Formation, therefore both processes are possible.

The distorted clay clasts shown in Fig. 124 are identical to structures produced by Ramberg (1967) in layered painter's and silicone putties and modelling clay. Ramberg centrifuged his samples to simulate gravitational forces – he was investigating tectonic processes. His Figs. 52 and 95 show foundered blocks with wisps of distorted clay lamellae clinging to the top. Thus equivalent features in the Namba Formation examples represent laminae which were once beneath the mud clasts.

The relative movement of clasts and matrix is all that can be determined from the structures, though the higher specific gravity of dolomite (2.7-3.0) compared with smectite (2.2-2.7) and palygorskite (2.1-2.4) suggests dolomite should sink. In the case of the carbonates, the cracked portions must have sunk into the clay, being heavier.

The vertically streaked sand-clay zones are probably lower order structures than liquefaction types, more like forms produced during hydroplastic or quasi-solid behaviour. The skew planes in the black clays associated with sand-streaks resemble shredded bedding (Elliot 1965). These planes have lated acted as channels and barriers to changes occurring during dewatering and incipient soil forming processes.

The cause of liquefaction is now considered. In muds overlain by a crust of relatively hard carbonate, drying would have been prevented. Thus transformation from sol to gel or solid to liquid may not have been necessary, as the sediment was already liquid. In the other examples some shock is required to incite the transformation, and many workers have invoked earthquakes or microseismic activity. Pressure built up by rapid deposition onto water saturated sediments is also a possible cause. Subsequent dewatering would have produced further pressures. Shrinkage, with dewatering of clays beneath laminated silt beds, may have produced structures like those of Fig. 94. Another possible cause is solution of evaporites underlying soft clays, thus inducing the type of structure associated with disturbed contacts, particularly in the carbonate sequences. The relationship between bioturbation and rheotropic structures (Figs. 126, 131 and Wertaloona 1 bore 58.72 m, Wooltana 1 bore 85.3 m) indicates the sediments were in an unstable state during burrowing. Under these circumstances it is possible for intense burrowing to induce the thixotropic transformation.

3.8 CYCLIC SEQUENCES

Terminology and basic approach follow Duff *et al*. (1967)

3.8.1 Statistical Analysis

Investigation of the detailed logs suggested four types of cycles, three being simple alternations:

(1) clay - carbonate

(2) clay - sand

(3) laminated silt - clay

the other is more complex, an empirical modal cycle consists of the following sequence:

(4) black sandy clay with skew planes
(carbonate)
silt
sand

A typical example is the section between 162.00 m and 175.30 m in Wooltana 1 bore (Fig. 7).

The contacts at the top of the black clays are generally sharp, representing hiatuses of considerable extent. The contact between black clay and sand or silt is generally of the streaked variety. A thin sand bed often appears in the black clay at about half to two thirds the distance up from its base. The sand fraction differs from that of other sand beds in being coarser, frequently having polished grains.

To determine the validity of the empirical cycles, a statistical test is required, such that no prior knowledge of the top or bottom of a cycle or what constitutes a cycle is necessary. Two methods are applicable: that of Selley (1969) is a simple method having the advantage that no assumptions about the behaviour of the sequence or constraints on the type of variation are required. It is particularly applicable to situations where large quantities of data

FIG. 39

SELLEY—CYCLIC DEPOSITION ANALYSIS

Transition matrix

WOOLTANA 1

$$\begin{array}{c|ccccc|c} & A & B & C & D & E & \\ \hline A & 6 & 8 & 6 & 12 & 12 & 44 \\ B & 9 & 2 & 1 & 3 & 1 & 16 \\ C & 6 & 4 & 8 & 3 & 10 & 31 \\ D & 12 & 1 & 6 & 9 & 22 & 50 \\ E & 11 & 1 & 10 & 22 & 0 & 44 \\ \hline & & & & & & 185 \end{array}$$

YALKALPO 1

$$\left[\begin{array}{ccccc} 2 & 5 & 5 & 3 & 0 \\ 4 & 6 & 3 & 5 & 0 \\ 4 & 4 & 0 & 0 & 0 \\ 4 & 3 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 \end{array}\right] \begin{array}{c} 15 \\ 18 \\ 8 \\ 7 \\ 0 \\ \hline 48 \end{array}$$

WERTALOONA 1

$$\left[\begin{array}{ccccc} 3 & 5 & 2 & 19 & 3 \\ 6 & 1 & 5 & 4 & 2 \\ 4 & 5 & 5 & 3 & 6 \\ 18 & 5 & 3 & 7 & 9 \\ 0 & 2 & 8 & 10 & 2 \end{array}\right] \begin{array}{c} 32 \\ 18 \\ 23 \\ 42 \\ 22 \\ \hline 137 \end{array}$$

WC 2

$$\left[\begin{array}{ccccc} 0 & 2 & 0 & 1 & 0 \\ 1 & 0 & 3 & 0 & 0 \\ 1 & 2 & 3 & 1 & 0 \\ 1 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 \end{array}\right] \begin{array}{c} 3 \\ 4 \\ 7 \\ 1 \\ 0 \\ \hline 15 \end{array}$$

COMBINED DATA

$$\left[\begin{array}{ccccc} 11 & 20 & 13 & 35 & 15 \\ 20 & 9 & 12 & 12 & 3 \\ 15 & 15 & 16 & 7 & 16 \\ 35 & 9 & 9 & 16 & 31 \\ 11 & 3 & 18 & 32 & 2 \end{array}\right] \begin{array}{c} 94 \\ 56 \\ 69 \\ 100 \\ 66 \\ \hline 385 \end{array}$$

Transitions assuming random sequence

$$\left[\begin{array}{ccccc} 10 & 4 & 7 & 12 & 11 \\ 4 & 1 & 3 & 4 & 4 \\ 7 & 3 & 5 & 8 & 8 \\ 12 & 4 & 8 & 13 & 12 \\ 10 & 4 & 7 & 12 & 11 \end{array}\right] \begin{array}{c} 44 \\ 16 \\ 31 \\ 49 \\ 44 \\ \hline 184 \end{array}$$

$$\left[\begin{array}{ccccc} 4 & 5 & 3 & 3 & 0 \\ 5 & 7 & 3 & 3 & 0 \\ 3 & 3 & 1 & 1 & 0 \\ 2 & 3 & 1 & 1 & 0 \\ 0 & 0 & 0 & 0 & 0 \end{array}\right] \begin{array}{c} 15 \\ 18 \\ 8 \\ 7 \\ 0 \\ \hline 48 \end{array}$$

$$\left[\begin{array}{ccccc} 7 & 4 & 5 & 10 & 5 \\ 4 & 2 & 3 & 6 & 3 \\ 5 & 3 & 4 & 7 & 4 \\ 10 & 6 & 7 & 13 & 7 \\ 5 & 3 & 4 & 7 & 4 \end{array}\right] \begin{array}{c} 31 \\ 18 \\ 23 \\ 43 \\ 23 \\ \hline 138 \end{array}$$

—

$$\left[\begin{array}{ccccc} 22 & 14 & 17 & 17 & 25 \\ 14 & 8 & 10 & 10 & 15 \\ 16 & 10 & 12 & 18 & 12 \\ 24 & 15 & 18 & 26 & 18 \\ 16 & 10 & 12 & 17 & 12 \end{array}\right] \begin{array}{c} 95 \\ 57 \\ 68 \\ 101 \\ 67 \\ \hline 388 \end{array}$$

Residual transitions allowing for number of beds in sequence

$$\left[\begin{array}{ccccc} -4 & 4 & -1 & 0 & -1 \\ 5 & 1 & -2 & -1 & -2 \\ -1 & 1 & 3 & -5 & 2 \\ 0 & -3 & -2 & -4 & 10 \\ 1 & -3 & 3 & 10 & -11 \end{array}\right]$$

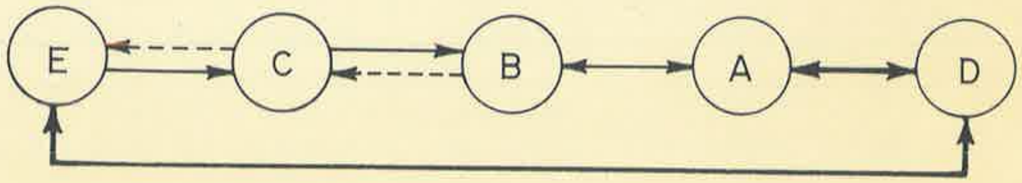
$$\left[\begin{array}{ccccc} -2 & 0 & 2 & 0 & 0 \\ -1 & -1 & 0 & 2 & 0 \\ 1 & 1 & -1 & -1 & 0 \\ 2 & 0 & -1 & -1 & 0 \\ 0 & 0 & 0 & 0 & 0 \end{array}\right]$$

$$\left[\begin{array}{ccccc} -4 & -1 & -3 & 9 & -2 \\ 2 & -1 & 2 & -2 & -1 \\ -1 & 2 & 1 & -4 & 2 \\ 8 & -1 & -4 & -6 & 2 \\ -5 & -1 & 4 & 3 & -2 \end{array}\right]$$

—

$$\left[\begin{array}{ccccc} -11 & 6 & -4 & 10 & -2 \\ 6 & 1 & 2 & -3 & -7 \\ -1 & 5 & 4 & -11 & 4 \\ 11 & -6 & -9 & -10 & 13 \\ -5 & -7 & 6 & 15 & -10 \end{array}\right]$$

TRANSITIONS ALLOWING FOR RELATIVE NUMBER OF BEDS



TRANSITIONS FROM MARKOV ANALYSIS
(MEMBER 1, NAMBA FORMATION)

GRAND DATA ARRAY

FIG. 40

Matrices

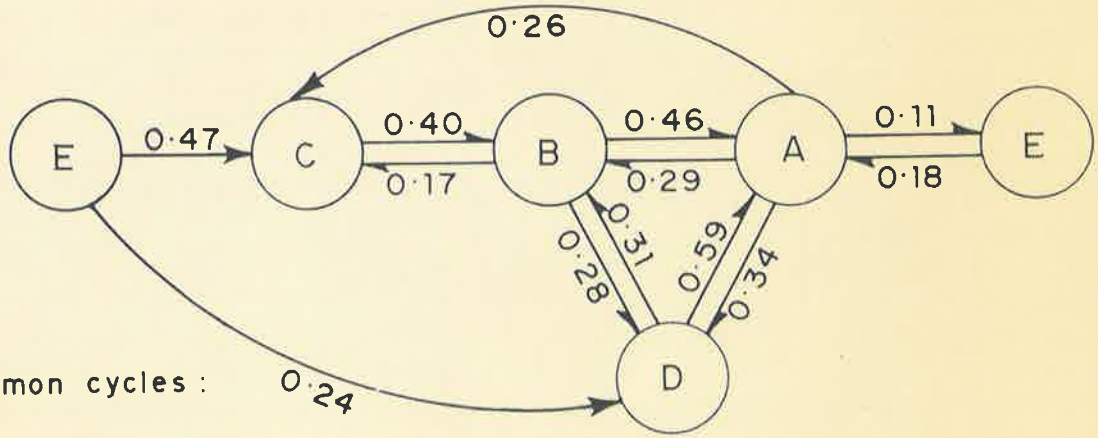
$$f_{i\,TOT} = \begin{array}{c} A \\ B \\ C \\ D \\ E \end{array} \left[\begin{array}{c} 62 \\ 46 \\ 35 \\ 39 \\ 17 \end{array} \right] \quad \underline{}\ 199$$

$$f_{ij\,TOT} = \begin{bmatrix} 0 & 18 & 16 & 21 & 7 \\ 21 & 0 & 8 & 13 & 4 \\ 16 & 14 & 0 & 2 & 3 \\ 23 & 12 & 1 & 0 & 3 \\ 3 & 2 & 8 & 4 & 0 \end{bmatrix}$$

$$p_{ij\,TOT} = \begin{bmatrix} 0{\cdot}00 & 0{\cdot}29 & 0{\cdot}26 & 0{\cdot}34 & 0{\cdot}11 \\ 0{\cdot}46 & 0{\cdot}00 & 0{\cdot}17 & 0{\cdot}28 & 0{\cdot}087 \\ 0{\cdot}46 & 0{\cdot}40 & 0{\cdot}00 & 0{\cdot}011 & 0{\cdot}085 \\ 0{\cdot}59 & 0{\cdot}31 & 0{\cdot}026 & 0{\cdot}00 & 0{\cdot}077 \\ 0{\cdot}18 & 0{\cdot}12 & 0{\cdot}47 & 0{\cdot}24 & 0{\cdot}00 \end{bmatrix}$$

A = sand; B = silt; C = black sandy clay; D = clay; E = carbonate

p transitions (upwards), $p > 0{\cdot}15$



Common cycles:

		A		
A	A	D		A
B	B	B	A	D
C	D	C	B	B
E	E	E	C	C

FIG. 41

TRANSITIONS FROM MARKOV ANALYSIS

INDIVIDUAL SECTIONS – UPWARD TRANSITIONS

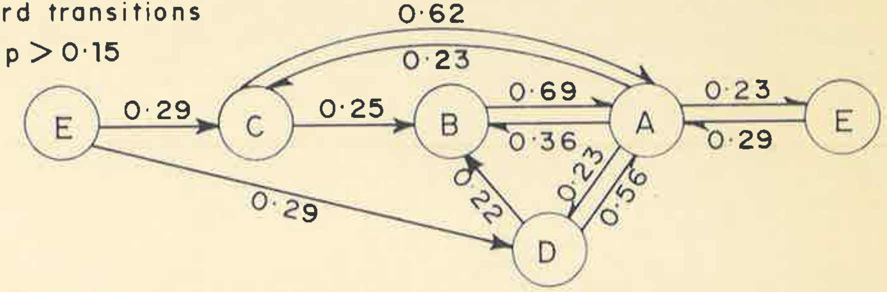
WOOLTANA 1 BORE

Matrices

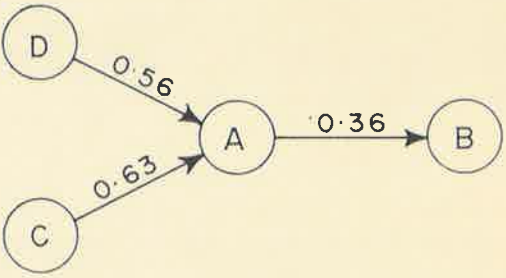
$$fi = \begin{array}{c} A\\ B\\ C\\ D\\ E \end{array} \underset{59}{\begin{bmatrix} 22\\ 13\\ 8\\ 9\\ 7 \end{bmatrix}} \qquad fij = \begin{bmatrix} 0 & 8 & 5 & 4 & 5\\ 9 & 0 & 1 & 2 & 1\\ 5 & 2 & 0 & 0 & 1\\ 5 & 2 & 0 & 0 & 1\\ 2 & 1 & 2 & 2 & 0 \end{bmatrix} \qquad pij = \begin{bmatrix} 0{\cdot}00 & 0{\cdot}36 & 0{\cdot}23 & 0{\cdot}18 & 0{\cdot}23\\ 0{\cdot}69 & 0{\cdot}00 & 0{\cdot}08 & 0{\cdot}15 & 0{\cdot}08\\ 0{\cdot}62 & 0{\cdot}25 & 0{\cdot}00 & 0{\cdot}00 & 0{\cdot}13\\ 0{\cdot}56 & 0{\cdot}22 & 0{\cdot}00 & 0{\cdot}00 & 0{\cdot}11\\ 0{\cdot}29 & 0{\cdot}14 & 0{\cdot}29 & 0{\cdot}29 & 0{\cdot}00 \end{bmatrix}$$

Upward transitions

$p > 0{\cdot}15$



$p > 0{\cdot}30$



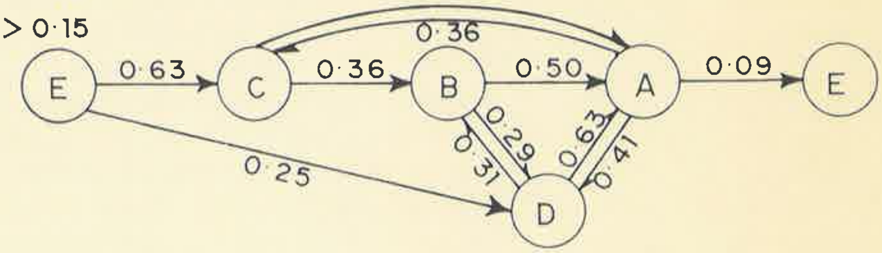
WERTALOONA 1 BORE

Matrices

$$fi = \begin{array}{c} A\\ B\\ C\\ D\\ E \end{array} \underset{74}{\begin{bmatrix} 22\\ 14\\ 14\\ 16\\ 8 \end{bmatrix}} \qquad fij = \begin{bmatrix} 0 & 3 & 8 & 9 & 2\\ 7 & 0 & 1 & 4 & 2\\ 6 & 5 & 0 & 1 & 2\\ 10 & 5 & 0 & 0 & 1\\ 0 & 1 & 5 & 2 & 0 \end{bmatrix} \qquad pij = \begin{bmatrix} 0{\cdot}00 & 0{\cdot}14 & 0{\cdot}36 & 0{\cdot}41 & 0{\cdot}09\\ 0{\cdot}50 & 0{\cdot}00 & 0{\cdot}07 & 0{\cdot}29 & 0{\cdot}14\\ 0{\cdot}43 & 0{\cdot}36 & 0{\cdot}00 & 0{\cdot}07 & 0{\cdot}14\\ 0{\cdot}63 & 0{\cdot}31 & 0{\cdot}00 & 0{\cdot}00 & 0{\cdot}06\\ 0{\cdot}00 & 0{\cdot}13 & 0{\cdot}63 & 0{\cdot}25 & 0{\cdot}00 \end{bmatrix}$$

Upward transitions

$p > 0{\cdot}15$



$p > 0{\cdot}30$

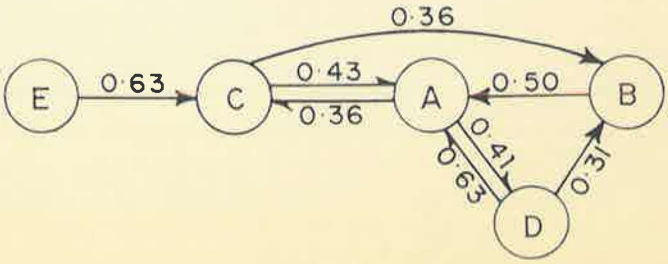


FIG. 42

TRANSITIONS FROM MARKOV ANALYSIS

INDIVIDUAL SECTIONS – UPWARD TRANSITIONS

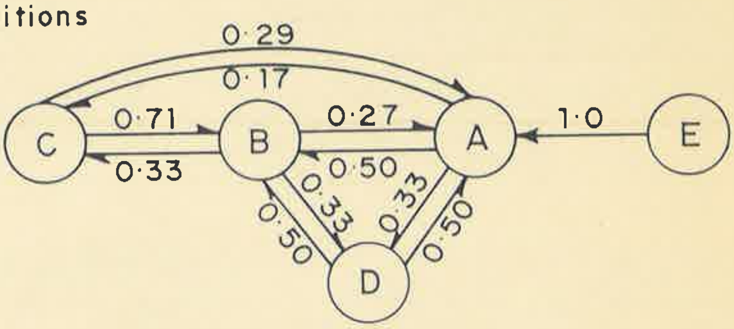
YALKALPO 1 BORE

Matrices

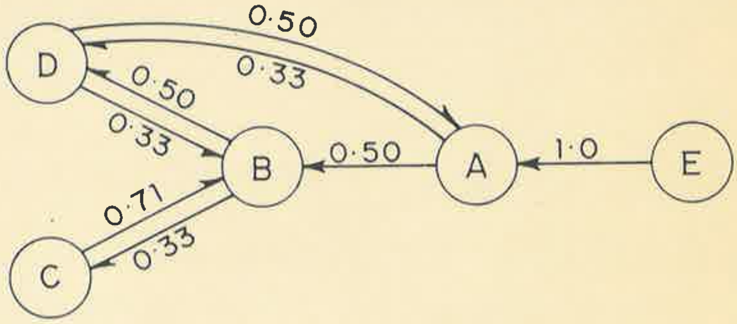
$$f_i = \begin{array}{c} A \\ B \\ C \\ D \\ E \\ \\ \end{array}\left[\begin{array}{c} 12 \\ 15 \\ 7 \\ 9 \\ \underline{1} \\ 44 \end{array}\right] \qquad f_{ij} = \begin{bmatrix} 0 & 6 & 2 & 4 & 0 \\ 4 & 0 & 5 & 5 & 1 \\ 2 & 5 & 0 & 0 & 0 \\ 4 & 4 & 0 & 0 & 0 \\ 1 & 0 & 0 & 0 & 0 \end{bmatrix} \qquad p_{ij} = \begin{bmatrix} 0.00 & 0.50 & 0.17 & 0.33 & 0.00 \\ 0.27 & 0.00 & 0.33 & 0.33 & 0.04 \\ 0.29 & 0.71 & 0.00 & 0.00 & 0.00 \\ 0.50 & 0.50 & 0.00 & 0.00 & 0.00 \\ 1.00 & 0.00 & 0.00 & 0.00 & 0.00 \end{bmatrix}$$

Upward transitions

$p > 0{\cdot}15$



$p > 0{\cdot}30$



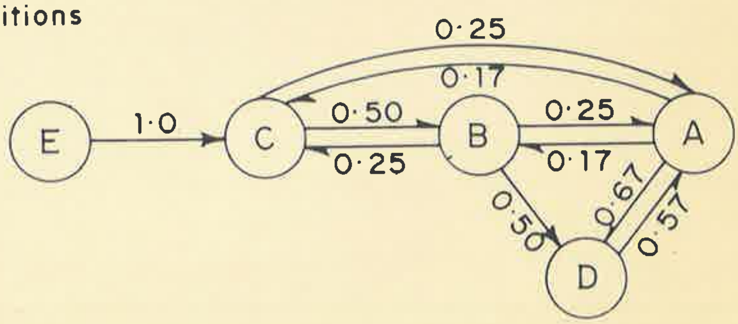
C15 BORE

Matrices

$$f_i = \begin{array}{c} A \\ B \\ C \\ D \\ E \\ \\ \end{array}\left[\begin{array}{c} 6 \\ 4 \\ 4 \\ 7 \\ \underline{1} \\ 22 \end{array}\right] \qquad f_{ij} = \begin{bmatrix} 0 & 1 & 1 & 4 & 0 \\ 1 & 0 & 1 & 2 & 0 \\ 1 & 2 & 0 & 1 & 0 \\ 4 & 1 & 1 & 0 & 1 \\ 0 & 0 & 1 & 0 & 0 \end{bmatrix} \qquad p_{ij} = \begin{bmatrix} 0.00 & 0.17 & 0.17 & 0.67 & 0.00 \\ 0.25 & 0.00 & 0.25 & 0.50 & 0.00 \\ 0.25 & 0.50 & 0.00 & 0.25 & 0.00 \\ 0.57 & 0.14 & 0.14 & 0.00 & 0.14 \\ 0.00 & 0.00 & 1.00 & 0.00 & 0.00 \end{bmatrix}$$

Upward transitions

$p > 0{\cdot}15$



$p > 0{\cdot}30$

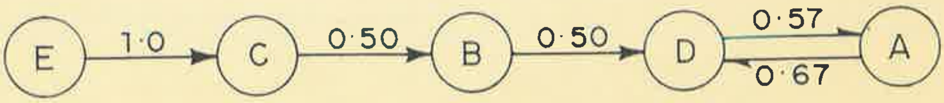
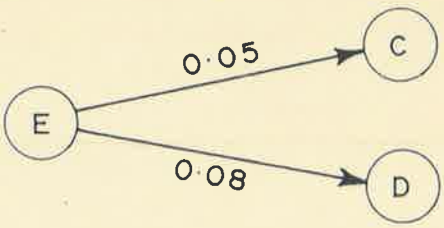


FIG. 43
TRANSITIONS FROM MARKOV ANALYSIS
SEQUENCES WITH GREATER THAN RANDOM PROBABILITY

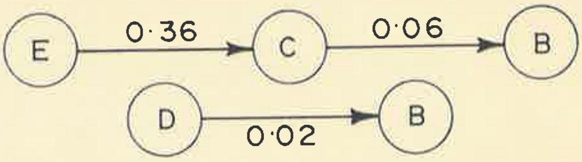
WOOLTANA 1

$$e_{ij} = \begin{bmatrix} 0{\cdot}00 & 0{\cdot}54 & 0{\cdot}28 & 0{\cdot}32 & 0{\cdot}23 \\ 0{\cdot}92 & 0{\cdot}00 & 0{\cdot}21 & 0{\cdot}24 & 0{\cdot}18 \\ 0{\cdot}76 & 0{\cdot}34 & 0{\cdot}00 & 0{\cdot}21 & 0{\cdot}21 \\ 0{\cdot}79 & 0{\cdot}35 & 0{\cdot}19 & 0{\cdot}00 & 0{\cdot}17 \\ 0{\cdot}73 & 0{\cdot}33 & 0{\cdot}24 & 0{\cdot}21 & 0{\cdot}00 \end{bmatrix} \quad p_{ij} - e_{ij} = \begin{bmatrix} 0{\cdot}00 & -0{\cdot}18 & -0{\cdot}05 & -0{\cdot}14 & 0{\cdot}00 \\ -0{\cdot}23 & 0{\cdot}00 & -0{\cdot}13 & -0{\cdot}09 & -0{\cdot}10 \\ -0{\cdot}13 & -0{\cdot}09 & 0{\cdot}00 & -0{\cdot}21 & -0{\cdot}08 \\ -0{\cdot}23 & -0{\cdot}13 & -0{\cdot}19 & 0{\cdot}00 & -0{\cdot}06 \\ -0{\cdot}44 & -0{\cdot}19 & 0{\cdot}05 & 0{\cdot}08 & 0{\cdot}00 \end{bmatrix}$$



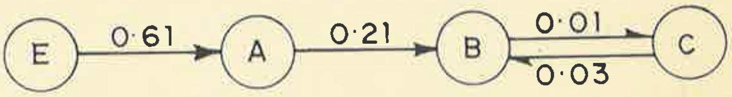
WERTALOONA 1

$$e_{ij} = \begin{bmatrix} 0{\cdot}00 & 0{\cdot}37 & 0{\cdot}37 & 0{\cdot}44 & 0{\cdot}18 \\ 0{\cdot}58 & 0{\cdot}00 & 0{\cdot}30 & 0{\cdot}36 & 0{\cdot}15 \\ 0{\cdot}58 & 0{\cdot}30 & 0{\cdot}00 & 0{\cdot}36 & 0{\cdot}15 \\ 0{\cdot}61 & 0{\cdot}32 & 0{\cdot}32 & 0{\cdot}00 & 0{\cdot}16 \\ 0{\cdot}50 & 0{\cdot}27 & 0{\cdot}27 & 0{\cdot}32 & 0{\cdot}00 \end{bmatrix} \quad p_{ij} - e_{ij} = \begin{bmatrix} 0{\cdot}00 & -0{\cdot}23 & -0{\cdot}01 & -0{\cdot}03 & -0{\cdot}09 \\ -0{\cdot}08 & 0{\cdot}00 & -0{\cdot}23 & -0{\cdot}07 & -0{\cdot}01 \\ -0{\cdot}15 & 0{\cdot}06 & 0{\cdot}00 & -0{\cdot}29 & -0{\cdot}01 \\ 0{\cdot}02 & -0{\cdot}01 & -0{\cdot}32 & 0{\cdot}00 & -0{\cdot}10 \\ -0{\cdot}50 & -0{\cdot}14 & 0{\cdot}36 & -0{\cdot}07 & 0{\cdot}00 \end{bmatrix}$$



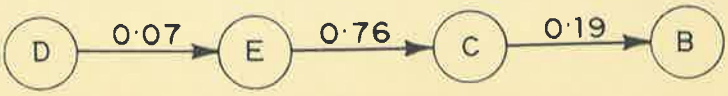
YALKALPO 1

$$e_{ij} = \begin{bmatrix} 0{\cdot}00 & 0{\cdot}29 & 0{\cdot}28 & 0{\cdot}39 & 0{\cdot}03 \\ 0{\cdot}71 & 0{\cdot}00 & 0{\cdot}32 & 0{\cdot}45 & 0{\cdot}04 \\ 0{\cdot}48 & 0{\cdot}68 & 0{\cdot}00 & 0{\cdot}32 & 0{\cdot}03 \\ 0{\cdot}52 & 0{\cdot}75 & 0{\cdot}25 & 0{\cdot}00 & 0{\cdot}03 \\ 0{\cdot}39 & 0{\cdot}54 & 0{\cdot}19 & 0{\cdot}26 & 0{\cdot}00 \end{bmatrix} \quad p_{ij} - e_{ij} = \begin{bmatrix} 0{\cdot}00 & 0{\cdot}21 & -0{\cdot}11 & -0{\cdot}06 & -0{\cdot}03 \\ -0{\cdot}44 & 0{\cdot}00 & 0{\cdot}01 & -0{\cdot}12 & 0{\cdot}00 \\ -0{\cdot}19 & 0{\cdot}03 & 0{\cdot}00 & -0{\cdot}32 & -0{\cdot}03 \\ -0{\cdot}02 & -0{\cdot}25 & -0{\cdot}25 & 0{\cdot}00 & -0{\cdot}03 \\ 0{\cdot}61 & -0{\cdot}54 & -0{\cdot}19 & -0{\cdot}26 & 0{\cdot}00 \end{bmatrix}$$



C 15

$$e_{ij} = \begin{bmatrix} 0{\cdot}00 & 0{\cdot}33 & 0{\cdot}33 & 0{\cdot}78 & 0{\cdot}07 \\ 0{\cdot}50 & 0{\cdot}00 & 0{\cdot}31 & 0{\cdot}64 & 0{\cdot}06 \\ 0{\cdot}50 & 0{\cdot}31 & 0{\cdot}00 & 0{\cdot}64 & 0{\cdot}06 \\ 0{\cdot}67 & 0{\cdot}36 & 0{\cdot}36 & 0{\cdot}00 & 0{\cdot}07 \\ 0{\cdot}40 & 0{\cdot}24 & 0{\cdot}24 & 0{\cdot}50 & 0{\cdot}00 \end{bmatrix} \quad p_{ij} - e_{ij} = \begin{bmatrix} 0{\cdot}00 & -0{\cdot}16 & -0{\cdot}16 & -0{\cdot}11 & -0{\cdot}07 \\ -0{\cdot}25 & 0{\cdot}00 & -0{\cdot}06 & -0{\cdot}14 & -0{\cdot}06 \\ -0{\cdot}25 & 0{\cdot}19 & 0{\cdot}00 & -0{\cdot}39 & -0{\cdot}06 \\ -0{\cdot}10 & -0{\cdot}22 & -0{\cdot}12 & 0{\cdot}00 & 0{\cdot}07 \\ -0{\cdot}40 & -0{\cdot}24 & 0{\cdot}76 & -0{\cdot}50 & 0{\cdot}00 \end{bmatrix}$$



are unavailable. The other method is Markovian analysis (Potter & Blakely 1968, Gingerich 1969), applied to member 1 of the Namba Formation to determine whether sequence (4) could be confirmed by more rigorous means. In this method the sequence is difficult to interpret unless it exhibits stationarity - i.e. the proportions of each lithology in the subintervals do not change, hence the application to member 1 only.

Lithofacies states used are:

(E) Carbonate - 40% carbonate, includes nodular beds.

(D) Clay - all clays other than black sandy clay.

(C) Black sandy clay - the tough dark clays with irregular shiny fractures and scattered sand patches - generally having a churned appearance and mottled with red brown iron oxides.

(B) Silt - laminated silts, often with thin clay interbeds. 50% silt.

(A) Sands - very fine grained or coarser, sometimes interbedded with thin clay layers. 50% sand.

Minimum bed thickness is 10 cm. Beds transitional between one or other state were assigned to the state with coarser grain size, or in the case of carbonate, to the carbonate lithofacies. The Markov analysis excluded the carbonate sequences, where long alternations of carbonate-clay were obvious.

Gaps resulting from core loss were filled from petrophysical log interpretation. These logs were not used for obtaining all primary data because minimum bed thickness is too small to be resolved by them in alternating sequences. Had thicker beds been chosen as the minimum, the number of beds would be insufficient for analysis. Another reason is the variable quality of the logs, and the variation in types of logs run. Five holes contained adequate detail in the lithologs.

Data arrays (using Selley's method) for the entire sequence in Wooltana 1, Wertaloona 1 and Yalkalpo 1 bores are given in Fig. 39, including a combined array, with data from the Namba Formation in WC2 bore. Whilst establishing the matrix for Wooltana 1 bore it was noted that sand-carbonate transitions were largely restricted to the portion assigned to the Willawortina Formation. Using Selley's criteria, the alternation carbonate-clay is confirmed, and so also is the less obvious alternation sand-clay. The complex cycle black clay-silt-sand-clay, is also confirmed.

The resultant sets of cycles essentially involve carbonate → clay or the sequence black clay (C) → silt → sand → clay (D).

The grand upward transition probability matrix (p values)for the Markov analysis is given in Fig. 40. The transition sequence diagrams derived from this data are shown on the same figure. From the p values the sequence carbonate → black sandy clay → silt → sand → carbonate (or silt → clay → sand instead of silt → sand)has greatest probability and is therefore the modal cycle. This is identical to the sequence derived from Selley's method, excepting the positions of sand and clay are reversed. This is caused by the inclusion of part of the Willawortina Formation sequence from Wooltana 1 bore in the Selley analysis. Note also the long carbonate-clay alternations were excluded from the Markov analysis, and Selleys analysis includes multi-story transitions.

From the Markov analysis there is an almost equal probability for alternations between beds of almost any lithology and many probabilities are not high. This implies the sequence does not have a strong 'memory'. Hence the spacial distribution of facies in the basin was probably irregular (Potter & Blakely 1968), in a low energy environment.

The p diagram shows a strong probability for alternation between silt and sand or silt and clay. The idea that the two clay types behave differently, and that it is mainly the 'normal' clays that are involved in long alternating sequences with carbonate, is borne out by the p results. The almost complete absence of transitions from carbonate to silt, suggests these facies were deposited in distinctly separate environments.

Individual p matrices calculated for each drill hole are given in Figs. 41-42. The transition diagrams are shown with probabilities of 0.15 and 0.30 respectively. "Residual" transition matrices (p-e) were also calculated (Fig. 43). These appear to indicate few transitions theoretically have a greater than random chance of occurrence. This is thought to result from insufficient data rather than implying the cycles do not occur.

The individual upward transition probability diagrams show general agreement with the combined data, though transitions through black sandy clay to sand to silt are more common than those through silt to sand, in Wooltana 1 and Wertaloona 1 bores (Fig. 41). The role of clay (D) compared with black sandy clay (C) is virtually the same.

3.8.2 Interpretation

3.8.2.1 Carbonate-clay alternations

Carbonate (E) is found almost exclusively in sequences alternating with "normal" clay (D). Accepting a supratidal or nearshore inland lake environment for carbonate deposition suggests the clay represents lacustrine or lagoonal mud. The regular alternation between the two lithologies indicates periodic fluctuation in water level, during a prolonged episode with evaporation greater than precipitation. In a large shallow lake, very slight variations in water level cause extensive transgressions and regressions. These may be the result of slight tectonic movements, periodic blockage of the lake or lagoon outlet, or minor climatic variations.

3.8.2.2 Long Cycles

Models set up by Selley (1970), Blatt et al. (1972), Rigby & Hamblin (Eds., 1972) and others form a useful basis for comparison.

Depositional processes with inherent instability will produce cyclicity, viz.:

(1) Avulsion of rivers

(2) Point bar deposition

(3) Deltaic outbuilding

Cyclic processes are also caused by external effects, viz.:

(4) Fluctuations in sea level

(5) Fluctuations in lake level through evaporation or blockage of exit drainage,

both resulting from phenomena such as

(6) Tectonic uplift of periodic type

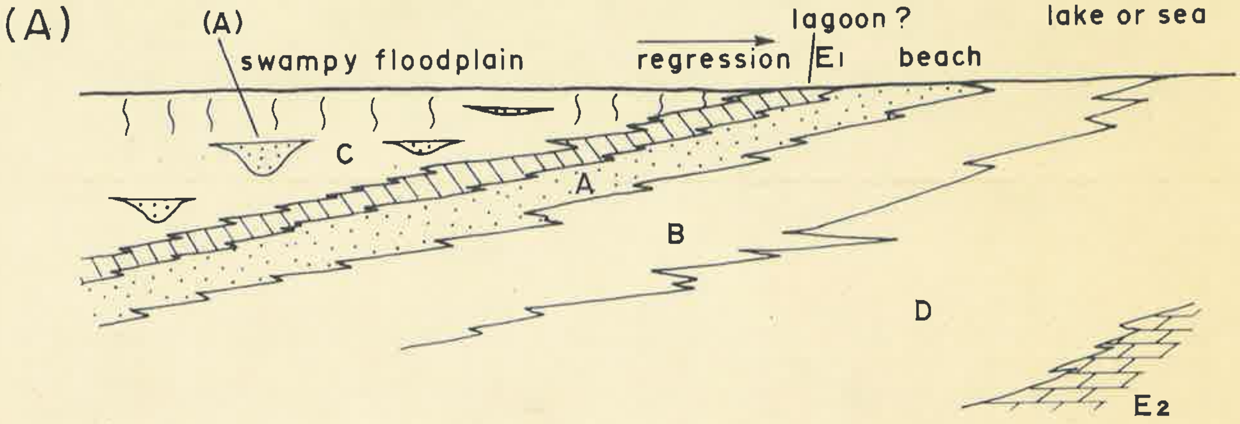
(7) Climatic fluctuations of periodic type.

Considering processes with inherent instability, (1) and (2) generally occur together, producing a fining upwards sequence of the type shown in Fig. 2.13 of Selley (1970). It is apparent this is applicable to the Namba Formation cycles where sand grades up to silt (e.g. 137-144.4 m in Wertaloona 1 bore, Fig. 13). The sharp contact between sandy black clay and sand is explained, and also the transition between sand anc clay (channel and overbank deposits). A problem arises for carbonates, which often occur between sand and black sandy clay, but not in contact with silts. It is suggested they accumulated in shallow lakes which formed subsequent to floodplain deposition. The sandy black clays represent bioturbated and waterlogged soils, or partially dried-out lake deposits. The greatest difficulty in this interpretation is the abundance of burrowing in the sediments (particularly bioturbation of cross-bedded sands), and absence of lamination in the upper clays.

Deltaic outbuilding (4) should produce a coarsening upward sequence (Fig. 5.3 of Selley 1970), supported by the tendency for silt to be followed by sand, according to the Markov analysis. In a delta the basal prodelta clays fine up into coarser subaerial

FIG. 44

REGRESSIVE SHORELINE SHOWING FLUVIATILE FACIES AND VARIOUS POSITIONS OF CARBONATE DEPOSITION



Common cycles

For E_1

(A)				
C	C	A	B	E
(E)	(E)	B	D	A
A	A	D		B
B	B			D
D	D			

For E_2

A	C	B	D
B	A	D	E
D	B	E	
E	D		
	E		

Ferruginous mottling .... ʃ ʃ ʃ ʃ

(B) RIVER FLOODPLAIN WITH INTERSPERSED LAKES

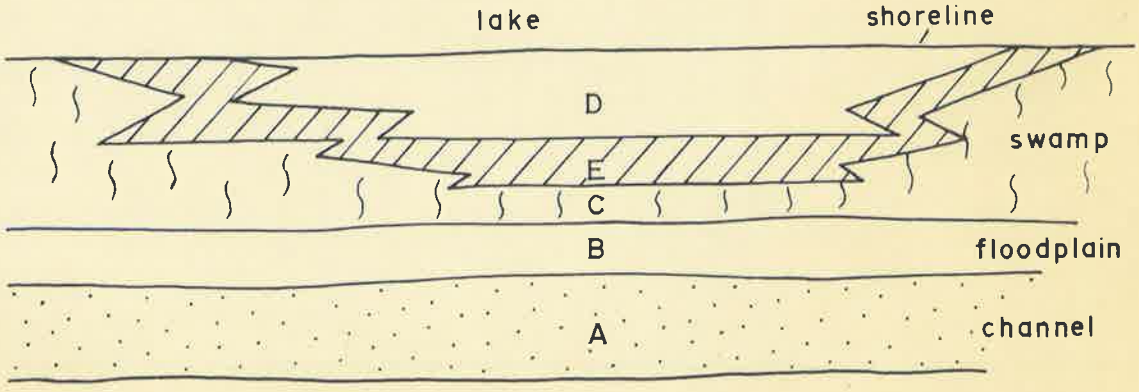
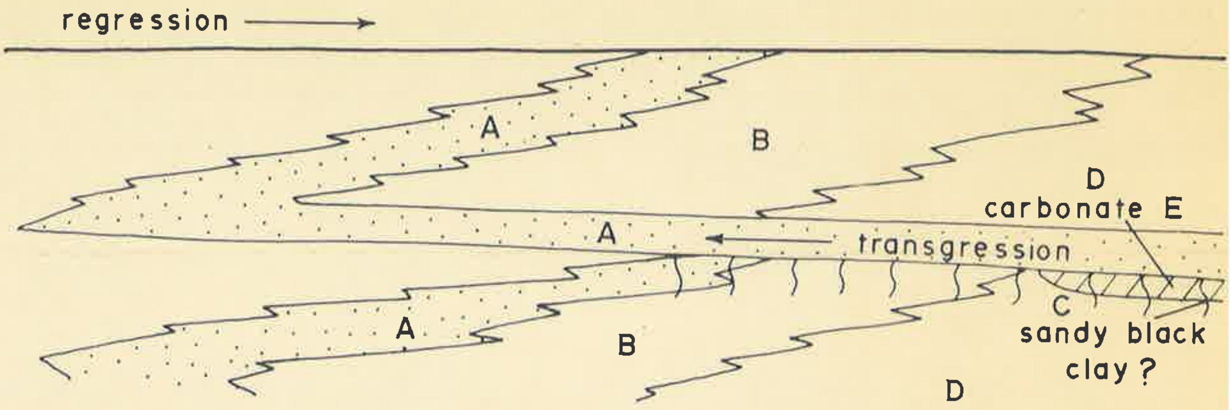


FIG. 45

SUCCESSIVE REGRESSIVE SHORELINES WITH INTERVENING TRANSGRESSION

(PRODUCTION OF MOTTLED SANDY BLACK CLAY)

(A)



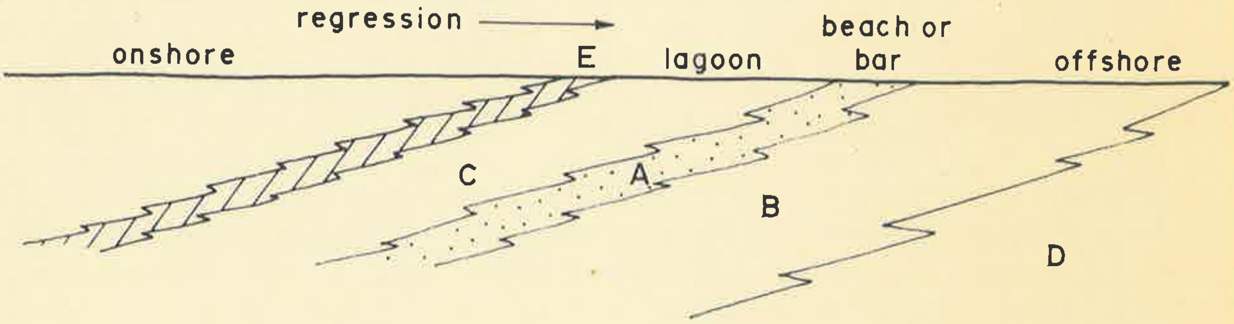
Common cycles

A	E	E	A	A	A	A	D
B	C	C	B	B	B	B	E
D	D		D	D	D	D	C
			A	A	A	A	D
			E	E	C	D	
			C	C	D		
			D	D			

Ferruginous mottling .... ∫ ∫ ∫ ∫

REGRESSIVE SHORELINE WITH LAGOON

(B)



Common cycles

				(E)	(E)		
C	C	C	C	A	A	B	D
(E)	(E)	(E)	(E)	B	B	D	D
A	A	B	B	A	D	A	
B	A	A	D		A		
D			A				
A							

facies, and there would be no opportunity for a sharp contact to develop, like that between the black sandy clays (?prodelta facies) and overlying coarser sediments, nor is there opportunity for oxidation. However, if the black sandy clays are regarded as a swamp facies at the top of the sequence, their position becomes tenable.

The processes incited by external effects all result in transgression or regression of shorelines. A simple transgressive shoreline with grain size increasing shorewards produces the opposite vertical profile to that recorded in the Markov analysis. A regressive sequence gives a better approximation, (Figs. 44-45) though the position of the black sandy clay is difficult to establish. Regarding it as an offshore lake facies does not explain the intermixed coarse sand (Fig. 45): this problem is avoided if a lagoon or swamp/marsh (Fig. 44) is accepted. Uplift or complete drying of a lake with subsequent transgression and regression (Fig. 45A) does not produce common cycles agreeing with those indicated in the p diagrams. In view of the suggested origin of carbonate, Figs. 44A(E_1), 48B, 45B are more acceptable. The models (44A, B) permit development of the soil-like phenomena. Thus a combination of two juxtaposed environments (fluviatile and regressive carbonate shoreline) provides the best solution.

The low probability of many transitions and abundance of alternations in lithology has been mentioned. The above are therefore somewhat idealistic interpretations: in reality facies distribution is much more irregular. A swampy floodplain with numerous shallow lakes, or floodplain and lagoon adjacent to an epeiric sea environment is envisaged. The lakes or lagoons were probably interconnected with the river system. The more complex cycles in member 1 results from the dominance of floodplain deposition and its interaction with the lacustrine environment. The thinness of the cycles is attributed to deposition in shallow water. Taking the Markov analysis to give a more accurate representation of the cyclic sequences in member 1 than Selley's criteria, the sequence silt → sand is accepted rather than sand → silt. Therefore, the larger scale migrating shoreline model (45A) is more acceptable than the floodplain stream model with minor lake phases (45B). During major periods of carbonate deposition, arenaceous supply was negligible and lacustrine facies dominated. Examination of the Coorong sequence shows that maximum development of dolomite sheets is likely to occur during a regression. In an inland lake the same effect can be achieved by evaporation of the lake water, which causes the carbonate rich groundwater - saline lake water interface to move towards the centre of the lake.

3.9 SUMMARY

The Namba Formation shows evidence of being deposited in a quiet water environment with little wave activity. Fine sand was deposited in alluvial channels and probably offshore bars or beaches in a lake. Streams were relatively slow moving meandering types, suggesting a mature topography. Silts accumulated in a lagoonal, lacustrine, or possibly floodplain environment, 'normal' clays in deeper water, and black sandy clays in swamps or marshes. Carbonates were precipitated in a supratidal lagoon or inland shallow lake environment, where fluctuations in the groundwater/lake water (or sea water) interface produced thin interbeds of dolomite and limestone. Algal activity formed thin laminations in some of these carbonates. In silts some other structures can be interpreted in terms of tidal effects, implying marine influence. In sands, sediment was transported by ripples and dunes, in the lower flow regime.

Bioturbation and quick-flow structures of intermittent, relatively rapid, depositional phases. There is little evidence for prolonged atmospheric exposure and lowering of the water table, sediments having remained wet, though drying and cracking of dolomites, and incipient soil formation occurred. Induration of carbonate crusts and, (in other environments) rapid deposition, trapped water in the underlying muds, inducing a thixotropic state. The operation of bioturbation and quick-flow processes caused complete homogenization of some beds. Black clays with this structure were later subjected to incipient soil forming processes, resulting in oxidation. This suggests periods of exposure, the mud apparently remaining waterlogged.

Burrowing organisms of at least two types were active, all ingestion feeders living near the sediment surface. They may have been crustaceans. Absence of hard parts may suggest they were temporary feeding burrows, not dwelling burrows. It could also mean the animals were soft-bodied (i.e. not Crustaceans).

4. WILLAWORTINA FORMATION

4.1 BEDDING

In the lower part of the Willawortina Formation (Figs. 17, 18: Wertaloona 1 and Wooltana 1 bores) bedding is clearly defined, and similar in character to that of the Namba Formation, with which it intertongues. Bedding planes are at first sight more obscure because of the effects of oxidation and soil formation. In the part of the section exposed in Balcanoona Creek the carbonates have been weathered, forming a subsurface karst profile. In the Balcanoona and Paralana High Plains area, the upper unit and the probable equivalent of the lower unit (Fig. 23, WC2 bore) have poor bedding. Examples of this are well exposed in the Wertaloona anticline, and cliffs along Hot Springs Creek. The beds lens rapidly and bedding planes are gradational or absent.

4.2 CROSS-BEDDING, UPPER FLOW REGIME PLANE BEDS, CHANNELS

Cross-stratification is best observed along Balcanoona Creek, where lenses of coarse sand cemented by carbonate crop out in the cliffs (BAL1/7598/1), and at the base of the Wertaloona anticline section. These sands show low angle cross-beds with wavy, scoured channel bottoms. The lamination in the channel is almost horizontal, virtually in phase with the undulations on the channel bed. The wavelength of the basal undulations is 60 cm, height 10 cm, therefore the sediment was deposited from currents just in the upper flow regime.

Grooves several centimetres deep were observed on the base of the channels in Wertaloona anticline section. These are interpreted as longitudinal scours eroded during flash floods, resembling similar structures observed on the north bank of Balcanoona Creek, after the catastrophic 1973 flooding.

The cross-beds described above are usually associated with well-defined channels with low depth to width ratios. Other channels of similar dimensions, infilled with conglomerate, showed no obvious bedding (BAL1/7596/2). These channels are represented by isolated sand lenses in a sequence of laminated and thin bedded silty carbonate.

4.3 CYCLIC SEQUENCES

Cycles are well developed in the lower unit, best observed in the log of Wooltana 1 bore (Figs. 17, 25). They consist of a fine-grained sand bed, rarely with a basal conglomerate, grading up to the more typical extremely poorly sorted silty clays. Frequently there is a dolomite bed at the transition zone. The poorly sorted facies cannot be interpreted in terms of channel and floodplain, since it is unlaminated and too unsorted. A mudflow type process was suggested earlier. The dolomites are lacustrine, since they contain ostracodes, in many respects resembling the Namba Formation carbonates.

The process which deposited the lower sorted sands changed gradually to one in which sorting was inoperative, suggesting a continuum from mudflow to streamflood.

Beginning with the carbonate, the cycles are explained as follows:-

(a) lacustrine carbonate sedimentation in playas or shallow lakes,

(b) mud-flows, onto playa or floodplain surfaces

(c) stream deposition, with channelling, producing a sharp basal erosional surface. In some cases this is absent, there being a gradual change to sands.

4.4 CONCLUSIONS

Channelling and cyclic deposition are well developed in the lower unit, and virtually absent in the upper, implying change from marginal lacustrine-streamflood environment to one dominated by vigorous flow mechanisms, approaching the type suggested by Davies & Walker (1974).

The trend towards increasingly high energy conditions accords with increased uplift of the Flinders Ranges. Streams were initially meandering (isolated sandy channels in laminated silty carbonates and silts), developing into braided types in the upper unit. Deposition was above the water table, or if below, was subsequently raised above, so that oxidation and soil forming processes could operate.

CHAPTER 6

GRAIN SIZE ANALYSIS

1. INTRODUCTION

1.1 PRESENTATION

Techniques are discussed in Appendix 5. Basic data (Tables 1-4 Appendix 5) has been plotted as cumulative curves on arithmetic (Figs. 153-155, Appendix 5) and probability paper (Figs. 46-50 Volume II) and as frequency curves (Figs. 10-14, 25-26, 29-31 Volume II). The arithmetic cumulative curves were used to derive the frequency curve by the technique of hand-drawn tangents (Fig. 154, Appendix 5), recommmended by Folk (1968). Frequency curves, though not often used, give an excellent pictogram of modes (the only measurable parameter on them), skewness and kurtosis. Mean size, dispersion (sorting), skewness and kurtosis were calculated from the cumulative probability curve using graphic parameters (Folk 1968), and the method of moment (Krumbein 1936), Results are given in Table 3 Appendix 5. The moments were not corrected for grouped data, since results calculated with this were not significantly different from those without. The cumulative percentages combine sieve (0.25 intervals) and pipette analyses (0.5 or 1ϕ intervals).

The parameters were plotted against one another on scatter diagrams of types claimed to differentiate for certain environments (Folk & Ward 1957; Stewart 1958; Mason & Folk 1958; Friedman 1961, 1967; Moiola & Weiser 1968; Visher 1969). Quartile deviation measures (Buller & McManus 1972, 1974) were calculated from phi cumulative statistics and plotted on similar diagrams, and C-M diagrams (Passega 1964) were prepared.

The graphic statistics are also shown on the detailed logs using the code set out in Appendix 5.

1.2 EFFECTS OF DIAGENESIS

Diagenesis is likely to have affected grain size and shape, altering grain size parameters, particularly skewness and kurtosis. In rocks older than Recent, some form of diagenesis has usually occurred, and the Tertiary sediments of Lake Frome are no exception. Modification of shape and size of detrital grains, destruction of feldspar, and production of new silt have occurred.

In Chapter 3, thin section studies indicated essentially two processes, working in opposition, modified grain size. Corrosion of quartz and production of fines dominates over quartz overgrowth formation. In some specimens, however, grain size has increased. The thin section investigations show the diagenetic effects have, in general, operated uniformly: original detrital differences should be preserved, though modified.

Much of the very fine silt size could have been produced by chipping from larger grains during transport (Riezebos & Van der Waals 1974) or by tropical weathering (Mousinho de Meis & Amador 1974). The latter process is most likely, as evidence for low energy transport processes suggests chipping was not a major factor. Weathering could have occurred both in the source areas, and the depositional basin.

The crystallization of muds has largely destroyed original clasts, and the method of dispersion to produce a suspension for analysis also breaks these down, thus the pipetted mud fraction should reflect the crystal size or domain size of the clay minerals.

1.3 TRUNCATION: EFFECT ON MOMENTS

The sizing was generally done to the point at which $>90\%$ of the material had sedimented, though some earlier analyses were terminated before this value, owing to the extreme fine grain size. An attempt was made to analyze the entire distribution in some samples, though this could rarely be achieved even at 14ϕ. The distributions are therefore truncated at different sizes, which limits comparisons of the moment measures. Approximations of the limits of distributions were made (c.f. Friedman 1968), using knowledge gained from more completely analyzed curves. The samples were grouped into classes A, B, C and 1 to 4 according to limits used. Details of the classes are in Table 3 (sheet 5) Appendix 5. Some were deliberately truncated at several values to facilitate comparison with less completely sized material and determine the effects of truncation on scatter plots.

The different classes were plotted on the various scatter diagrams, and results for one of the more sensitive parameters, kurtosis, presented (Fig. 52). Significant differences occur for high kurtosis, in fine samples, but the pattern remains unchanged. Hence other plots have been presented using the "most accurate" data from any class, assessed on the similarity of the main size and sorting to values determined from graphical measures. Wherever possible the same data class was used.

1.4 THEORY

Many studies of modern environments have been made, to differentiate by grain size parameters. Most have had some success (Friedman 1961, 1962, 1967; Mason & Folk 1958) though a limited selection of environments is used. Investigations are often restricted to sands, frequently of a narrow grain size range, thus application to a complete spectrum of unknown environments is difficult. Application to diagenetically altered older deposits presents further problems.

ADDITIONAL INFORMATION (Not for examination)

The discussion on grain size analysis (Chap. 6 Section 2. Results) benefits from consideration of the two papers cited below.

The work of Kranck (1973) was cited on p. 99 in relation to the origin of clay floccules. She has continued her research and published a paper (Kranck 1975) which explains the origin of assymmetrical non-normal curves, common for muddy sediments, and typified in the Lake Frome area by the curves in Figs. 152-3, Appendix 5 (Vol. I) and P1117/73 (Fig. 10), P1037/73 (Fig. 13), P1283/73 (Fig. 25). The discussion on p. 195 and 202-203 relating to the origin of the fine tail on the grain size distribution curves is therefore partly redundant. Kranck provides convincing evidence for the origin of the low, flat part of the frequency curves in the >4φ range (drawn on semi-logarithmic paper) by deposition of flocs, whereas the modal peak consisted of individual grains. She also suggests the break in slope found at 100 μm on many cumulative curves is the result of disaggregation during analysis of previously flocculated material. This break can be observed in several curves from the Lake Frome sediments. She concludes that modal size is a better indicator of environment than mean size for fine sediments, because it separates material deposited as floccules that deposited as single grains and the single grains are presumably not disaggregated.

Thus grain size distributions for many fine sediments reported in this thesis suggest flocculation occurred, and that fresh water carrying suspended sediment was entering saline water.

The second interesting paper is that of Sengupta (1975), who found that size distributions of particles in the range coarse silt to coarse sand in a suspended load, varied with current velocity and height above the bed (using bimodal bed material). A normal distribution thus indicates special conditions. Particularly relevant are his conclusions that (1) at low velocity the grain size distribution is skewed at all levels above the bed, being negatively skewed at low levels and positively skewed at high levels above the bed, and (2) at high velocities (around 90 cms/sec) the sediment became bimodal.

The implications are that for Tertiary sands from the Lake Frome area, deposition occurred from relatively low velocity currents at considerable height above the bed, since most sands are positively skewed. The few negatively skewed sands from the Eyre Formation suggest shallow streams, and bimodality indicates higher velocities. This further supports the conclusions on p. 208 of the thesis that the streams that deposited the Eyre Formation were shallower and of higher velocity than those that deposited the Namba Formation sands.

KRANCK, K. (1975). Sediment deposited from flocculated suspensions. Sedimentol. 22: 111-123.

SENGUPTA, S. (1975). Size-sorting during suspension transportation - lognormality and other characteristics. Sedimentol. 22: 257-273.

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The lacustrine environment is expected to have influenced deposition in the Namba Formation, but Friedman (1967) and Solohub & Klovan (1970) show that subenvironments of modern lakes are unlikely to provide suitable differentiation of sizes, probably because they are low energy situations. Solohub & Klovan believe the methods differentiate energy conditions, not specific environments.

A further difficulty in interpretation is the lack of fine sediment analyses for comparison and data on ancient sediments. This study was partly undertaken to provide such data and ascertain whether grain size parameters are a useful approach for studying fine sediments.

Interpretation of cumulative probability curves using Visher's (1969) technique was attempted. Unfortunately he considered a limited size range, and did not discuss low energy environments (lakes and lagoons), nor did he include many analyses of very coarse deposits. In the broad size range of material considered here, it was found that changes in slope were common in regions beyond those he analyzed.

2. RESULTS

2.1 FREQUENCY CURVES

Table 7 lists major, minor and dominant modes plus characteristic modes for particular units. Major modes are those showing well-defined peaks, the area under the curve representing most of the distribution. Minor modes are all others present in the same curve. Dominant modes are the commonest major modes for a particular section. Characteristic modes are those (not necessarily major) regarded as most distinctive for a rock unit, being a more subjective classification.

TABLE 7

GRAIN SIZE MODES

Rock Unit	Bore	No. Samples	Mode (in φ units)		
			Major	Dominant	Commonest Minor
Namba Formation	EAR 6	1	—	4.8	—
	PMX24a	1	2.6	(2.6)	(3.35)
	Wertaloona 1.	9	0.9,1.9,2.7,5.5,10.4,13.0	1.9,2.7,5.5 (0.9,10.4,13.0)	3.4,6.3,9.4
	Yalkalpo 1.	9	1.3,2.0,2.6,3.0,3.4,5.2,5.8,7.0,11.0,?12.5	2.0,2.6,5.8,7.0	4.2
	WC2	1	2.7,3.3	(2.7,3.3)	
	C15	2	2.65,4.1,11.1,11.8	(2.65,4.1,11.1 11.8)	(2.6,5.6)
	EAR9	2	1.2,6.3,?12.5	(1.2,6.3)	(4.8,8.2)
	Wooltana 1.	9	1.5,2.5,2.8,3.3,6.0,8.5,10.2	2.5,2.8,3.3 (1.5,6.0,8.5,10.2)	5.5
Eyre Formation	PMX24a	4*	-1.0,-0.8,1.8	1.8(-1.0,-0.8)	1.4
	Yalkalpo 1	7	0.5,0.8,1.3,1.4,2.0,2.6,4.2,9.0	1.3,2.0,2.6,(0.5,0.8,1.4,4.2,9.0)	3.0,3.4
	K69	3	-1.0,0.0,1.8,3.25	0.0,1.8,3.5 (-1.0)	1.5
	EAR3	1	3.85	(3.85)	(1.7,?3.2)
Willawortina Formation	WC2	4	-0.9,2.5,2.0,2.7	2.7(-0.9,1.7)	1.7
	EAR 9	1	3.4,3.9	(3.4,3.9)	(0.8,4.4,8.8,?10.5)
	Wooltana 1	7	-2.5,-1.0,1.5 2.5,3.3,7.0,13.0	-1.0,1.5,2.5 13.0(-1.5,3.3,7.0)	1.3,5.5

* (including P1120/73)

SUMMARY OF DOMINANT MODES

Willawortina Formation	-1.0	-0.9	1.5		
Namba Formation	3.9	4.8	5.2	5.5-5.7	11.0
Eyre Formation	0.0	1.3-1.4	6.3	12.0	

contd.

TABLE 7 cont.

	"CHARACTERISTIC MODES"	MODES COMMON TO ALL UNITS
Willawortina Formation	1.5,2.6,3.3	1.7-2.0,2.5-2.8,3.2-3.4
Namba Formation	2.0,2.2,2.4-2.6,3.4,5.5	
Eyre Formation	1.2,1.8,2.0,2.6	

In any vertical sequence each river deposit will have certain modes. Some will be the same for successive deposits because they are inherited from the source, or result from repetition of transport conditions. This may explain some of the features of the curves in Figs. 10-14, 25-26, 29-31 where modes carry through from one unit to the next. Thus any distribution is basically polymodal since grains are transported in three ways: suspension, saltation and traction.

The dominance of coarser modes in the Eyre Formation and Willawortina Formation is evident. Inspection of the listed dominant modes shows none are common to all the units, but most are repeated within a rock unit. Thus each unit was deposited by consistent and distinct transport processes. Each must have had its own characteristic source rock contribution, determined by prevailing climate and relief. The trends confirm those determined by visual inspection, though the Willawortina Formation is apparently coarser. This may result from fewer samples analysed mostly from WC2 and Wooltana 1 bores, where deposition was influenced by breakdown of granitic rocks in the Mt. Painter district.

Those modes common to all units show variations up to 0.50φ, explained by abrasion during transport, but most others are so widely separated that they could not have resulted from this process - they represent distinct size populations. The modes common to all units could have resulted from intra-basin erosion and reworking.

When mixed samples are analysed from bioturbated, brecciated or laminated beds, complex polymodal curves result. Many fine grained rocks show this, others with comparable curves originate from mixing of grains from different sources or different environments.

In PMX24a bore (Figs. 14, 8) the overall upwards fining in the Eyre Formation is the result of successive dominance of distinct finer modes, probably by action of a series of decreasingly lower energy streams. Fining upwards is not so obvious in Yalkalpo 1 bore (Fig. 13), the only other sequence having closely spaced analyses in the Eyre Formation. In Wertaloona 1 bore (Figs. 26, 18) there is a tendency towards overall upward fining in the Namba Formation, but this is not observed elsewhere.

Basinwards fining is supported by comparing major coarse modes in different bores. For example in K69 (Fig. 10), 1.8 and -0.90 φ are best developed compared with 1.25 φ in Yalkalpo 1 (Fig. 13).

There is an obvious contrast in the curve shapes between the Willawortina and Namba Formations: the former have broad low curves, often with several ill-defined peaks, whereas the latter has sharp narrow peaks (Figs. 13, 11, 25, 26, 31, 30, 29). Thus, sorting processes were less effective in the Willawortina Formation. The Namba Formation has greater kurtosis, exhibits strong skewness, and has long tails of fines. Although this is partly the result of diagenesis and bioturbation-mixing subsequent to deposition, it also indicates inability of transport processes to sort fines produced by ?humid weathering of the source rocks, or inability to transport coarse material.

Curves for the fine sands in Wertaloona 1 bore show extreme peakedness, indicating a high degree of sorting, suggesting a beach or dune deposit. The peculiar shape of curves such as P1283/73 is probably the result of burrowing activity mixing sediment.

Microscopic examination of thin sections showed quite large amounts of clay were transported as particles up to several millimetres grain size, reworked intraformationally. These particles were destroyed during sample preparation for pipetting. The muds show instead a series of peaks corresponding roughly to 8.5-9.0 φ, 11.2-11.5 φ, 10.4-10.6 φ and some around 13 φ (the limit of measurement) or greater. This suggests the actual grain sizes of the clays are being recorded, but the xray analyses show no particular clay mineral associated with any one peak. This is especially obvious in Yalkalpo 1 bore (Fig. 13) where several modes are present in a sequence with very constant mineralogy, dominated by smectite.

The sizes of some clay minerals are well known (Grim 1968, Moon 1972): kaolinite is about 0.3-0.4μ (11.5) φ diameter, montmorillonite is commonly in aggregates of 0.03μ (15.0 φ) and may range to 0.1μ (13.0 φ) or more. Other smectites are more complex, values of several microns by 0.1μ, in lath-shaped forms, are common, having more complex settling properties. Illites are commonly 0.3-0.1μ (11.5-13.0 φ) diameter, and palygorskite forms fibres which may be many microns long by 0.005-0.01μ wide. Thus one would expect the coarser modes to result from kaolinite and the finer from smectite and illite. The presence of many modes in Yalkalpo 1 bore suggests several smectites may be present or (more likely), there are a series of aggregates of relatively constant size. No more can be said without recourse to xray diffraction of individual modes. Actual sedimentation sizes of muds are probably best measured in thin section, if clasts are present, in addition to pipetting.

2.2 CUMULATIVE GRAIN SIZE PROBABILITY CURVES

2.2.1 Eyre Formation (Fig. 46)

Most of these samples are bimodal. Unimodal curves such as P1122/73, have shapes typical of material transported by strong unidirectional currents, with a well developed saltation load occupying a narrow size range (Visher 1969). The bimodal curves are essentially the same, but contain coarser populations than those considered by Visher. The shapes of some suggest traction load transport amounting to 5-10% of the load in Yalkalpo 1 bore samples. High figures for suspension load (30% in P1045/73) result from carbonaceous matter and fine secondary sulphides. The very coarse sizes, and shapes of curves for PMX24a, indicate some sediments were deposited by strong turbulent currents. Other curves resemble Visher's tidal channel types, implying confined strong currents.

Most samples were taken from a small portion of a single cross-stratified set, and therefore do not represent mixing of different sedimentation units. The alternation of coarse and fine layers in foresets was described in Chapter 5 . The suggestion that this results from avalanching of ripples over foresets of dunes is supported by the distinct separation of modes. Settling from traction load only, should produce a unimodal distribution for a sample representative of the whole cross-bed.

Sample P1117/73 from sediments originally described as laminated silts, is actually very fine sand, with a distribution resembling channel deposits. This may represent upper phase plane beds, not suspension flood-plain deposits as suggested earlier (Chapter 5).

2.2.2 Namba Formation

Samples from this unit (Figs 47-49) are dominated by mixed sediments, resulting from bioturbation, or bulk sampling of interlaminated or mixed silt and clay (Figs. 48,49). The curves are difficult to interpret, and the distribution of grain sizes is best visualized from the frequency curves. Sandy black clays with skew planes are common (Fig. 49, P1292/73, P14/74, P1267/73, P1017/73, P1037/73, P1019/73, P19/74, P1054/73, P21/74), having curves resembling Visher's turbidity current deposits, indicating their churned nature. This has been attributed to the effects of bioturbation and quick-flow. The curves are similar, generally with two main populations of grains, divided at 4.2-4.5ϕ. The portion carried in "suspension" varies from 60-95%. The sand fraction is identical to the pure sands occurring at the base of the cyclic sequences involving the black sandy clays (Fig. 47).

Bioturbated silts and sand (Figs. 47, 48) are represented by P1258/73, P20/74, P1283/73, the latter two being originally interlaminated silt and clay, by comparison with other analyses. Normal silts are P1125/73 (Fig. 49) and P1287/73, P1018/73, P1052/73 (Fig. 48), the suspension load varying from 50-80%. Sample P1125/73 resembles a levee deposit, and P1018/73 resembles the sandy black clays. The other two have a very well sorted fraction, being essentially finer versions of the well sorted sands described below. The bioturbated silts have a pattern resembling undisturbed laminated silt. All curves resemble floodplain or levee deposits, but are probably also common in lacustrine environments (not shown by Visher).

Calcareous clays (one burrowed) give a characteristic pattern, perhaps indicative of a lagoon or lake shoreline, though there are only two analyses (P1282-1284/73, P1291/73,Fig. 49). Samples P1032/73 (Fig. 49) and P1033/73 (Fig. 46) resemble them. Another calcareous clay, P21/74 (Fig. 49) is a black type with skew planes, having a distribution resembling the sandy black clays rather than the other calcareous clays. It contains 40% saltation load, wereas P1282/73 and P1291/73 are entirely "suspension" deposits.

The most readily interpreted samples are the well sorted sands (Fig. 47): p1273/73, P1269/73, P1270/73, P1266/73, P1021/73, P1053/73, P1055/73, P1115/73. Most have curves typical of stream deposits dominated by a saltation population, but some (e.g. P1053/73, P1055/73) have a higher percentage of suspension load and some traction load, resembling Visher's shallow marine bars. They are very similar to those of the Eyre Formation, though grain size is finer.

Pure clays are rare, P1248/73 is an example (not shown in diagrams).

2.2.3 Willawortina Formation (Fig. 50)

The upper unit in WC2 bore (P1111/73, P1112/73, P1113/73, P1114/73) and P1278/73, P1279-1280/73 of Wooltana 1 bore all give curves of low slope and very broad grain size range (Fig. 50). The distinction between traction, saltation and suspension load is almost non-existant, but there is a gradation to curves like those of P1049/73 and P1050/73 (Fig. 50) which are sands at the base of sand - carbonate - clay cycles in Wooltana 1 bore. This gradation was observed in the core, the two rock types being transitional. The low gradient curves are similar to those of Visher's turbidites, and there is apparently a continuum to normal streamflood types, as suggested by Davies & Walker (1974). In P1049/73 only 40% of the load was being carried by saltation at the time of deposition, the remainder being equally divided between traction and suspension. This supports deposition from a medium with properties between mud-flow and streamflood.

Sample P1051/73 is a more typical stream deposit, with a small bedload, and high saltation load. Pure clays are also present, resembling levee or floodplain types (P1281/73).

2.3 GRAIN PARAMETERS

2.3.1 Mean Size

The average mean sizes (ϕ units) for the respective rock units, calculated by the method of Folk & Ward (1957) and by the method of moments are given in Table 8.

The data confirms visual inspection sizes. Samples were chosen (i) at relatively constant intervals in certain bores, (ii) to examine specific rock types. Thus there is a slight bias to finer grain-sizes in the Willawortina and Eyre Formations, and to coarser sizes in the Namba Formation.

TABLE 8

AVERAGE OF MEDIAN DIAMETERS

Rock Unit	No Samples	ϕ Median		
		Graphic	Range (graphic)	Moment
Willawortina Formation	10	4.33	(2.84 to 5.32)	4.99
Namba Formation	31	5.64	(1.98 to 10.13)	
	28			5.47
Eyre Formation	14	1.68	(0.15 to 4.11)	1.97

Note: Samples undifferentiated with respect to rock units were excluded.

2.3.2 Sorting (See Table 3, Appendix 5)

Using the graphic measures of Folk & Ward, only six samples are moderately sorted or better, four in the Eyre Formation, and two in the Namba Formation. Most samples classify as very poorly sorted because they are bimodal or polymodal, and may contain a significant percentage of fines. Inspection of the frequency curves from sands in Wertaloona 1 bore, for example, shows extremely well sorted populations are present. Sample P1270/73 has very high kurtosis, yet the distribution of fines makes it poorly sorted.

The moment measures and classification of Friedman (1961) give consistently slightly lower sorting, probably because of the greater proportion of fines included in the calculation. Four samples are placed in a higher class, two in a lower, therefore using the verbal equivalent of the numerical values, the total number of samples in each class is unchanged. Thus there is agreement between the two methods for calculating mean size and sorting, though it must be borne in mind that the moment plots were chosen from the classes having greatest resemblance in mean size and sorting (Section 1.3) to the graphic results.

Scatter plots of sorting against mean size (Fig. 51) show an increase in sorting passing from Eyre Formation to Namba Formation to Willawortina Formation. The sorting limits are much greater in the Namba Formation than in the other two units, particularly the Eyre Formation which has a narrow range. In the Eyre Formation the fines have been separated by more efficient higher energy processes and mostly removed from the basin, as suggested in Wopfner et al (1974).

The scatter plot of sorting against mean size places most samples in a river environment, using the boundary of Friedman (1961). The areas corresponding to each rock unit have been outlined on the sorting vs. mean size plot. These outlines were not statistically based, but spacial separation indicated they have significance.

Further examination revealed an overall distribution in two fields A and B, apart from the rock unit classification. Field A includes all but two of the Eyre Formation samples and all those sands in the Namba Formation with similar and characteristic cumulative probability curves (Section 2.2.2). Field B contains all other Namba Formation samples and those of the Willawortina Formation. Two Eyre Formation samples plotting outside field A are unusual lithological types. One has a high chlorite content, suggesting it is in reality basement, or includes reworked basement, the other is a probable floodplain facies.

The Namba Formation samples from field A have been interpreted as fluviatile or bar deposits (Fig. 47), and resemble those of the Eyre Formation. Most come from the black sandy clay-silt-sand cycles. Only two of these sands plot in field B, therefore the Namba Formation samples in field A may represent fluviatile channel sands. The samples in field B are mainly bioturbated or mixed materials (excluding the Willawortina Formation for the present), the finer sizes representing low energy environments.

In their study of bimodal sediments, Folk & Ward (1957) showed sorting and mean size were related, to produce a sine curve (or something approximating it). They derived an empirical equation, assuming the segments of the curve could be represented by a straight line. The curve plotted from moments for the Tarkarooloo Basin gives a well developed sine shape (Fig. 52). It was earlier shown the results from these parameters were similar to those calculated by graphical methods, Folk's equation relating his parameters C, F and Z is therefore applicable. It should be noted that the short coarser part of the arm of the curve is produced by the Eyre Formation samples, the remainder being produced by the sands of the Namba Formation on the left arm, and the other sediments on the right arm, with Willawortina Formation plotting at the apex.

Folk's parameters were calculated, but have little relevance to this discussion since they represent "average" values for the whole Tertiary.

2.3.3 Skewness

The inclusive graphic skewness measure of Folk and moment skewness of Friedman showed no obvious relationship when plotted against one another, as expected from comments of Chappell (1967). The contrasting methods of calculation make it difficult to compare results. Another factor is the inclusion of a much greater proportion of fines in the moment calculation, which has a marked effect on skewness. These comments apply also to kurtosis. Most Skg values were in the range of commonest values recorded by Folk (1968), though a few were 0.8 or over. Most are positively skewed.

According to Gripenberg (1934) distribution of sedimented particles from a moving water layer, at a particular point on the stream bed, has a strong positive skewness and high kurtosis. Assuming (1) all grain sizes are present up to a certain radius (determined by velocity and water depth), (2) equal amounts of all grain sizes cross a particular cross section of the channel during the time considered, (3) the velocity is constant. The second requirement is unlikely to be satisfied, though it could be approached close to steep terrain with a variety of rock types, subjected to moderate weathering. Considering particles at each end of the grain size range, clays (representing the absolute lower limit of naturally occurring transported material) will probably be negatively skewed because they can only have a coarse tail. ~~Similarly~~ Conversely very coarse sediments are likely to be positively skewed. Combining these ideas, most natural sediments ought to be positively skewed and a few fine ones will be negative, unless winnowing of fines has occurred.

Most of the Tarkarooloo Basin samples are positively skewed. Nine samples show negative skewness, using the graphical measure (Fig. 51), three being coarse sands of the Eyre Formation.

Presumably these sands were subject to winnowing. The other samples are all clays, including one from the Eyre Formation. Folk's (1968) and Spencer's (1963) claim that all natural grain size assemblages obey log normal distribution may not apply. The skewness values confirm the presence of the extended tail of fines observed in thin section, and discussed at the beginning of this chapter.

Scatter plots showed no relationship between graphic skewness and mean size or sorting (Fig. 51). The boundary between Friedman's beach and river environments (Friedman 1961, 1967) was plotted on a graphic skewness vs. sorting diagram, and all samples plotted in his river field, though many had values well outside his sample range. The moment measure plots of skewness against mean size (Fig. 52) confirms the idea that skewness decreases with decreasing size, and that most samples are positively skewed. Using the data of Friedman (1967) most of these sediments again plot in his river field, and a few with coastal dunes.

The plot of moment skewness against sorting (Fig. 52) shows a tendency for sorting to increase with an increase in skewness. There is an apparent upper straight line limit to the spread of values, the meaning of which is unknown. Again, using the plot of Friedman, all the samples are fluviatile.

2.3.4 Kurtosis

Graphical kurtosis (Fig. 51) has unusually extreme values; over one third of the samples being >0.65, and several <0.40. The distinguishing feature of the Tarkarooloo Basin samples, compared with results obtained by other workers, are therefore strong positive skewness, and extreme values of kurtosis. Many of the grain size curves are bimodal, thus platykurtic not leptokurtic types, were expected.

On the mean size vs. kurtosis plot, using graphic methods, Solohub & Klovan (1970) plotted a variety of lacustrine subenvironments. The region covered by their samples on the graph corresponds best to the Eyre Formation samples, which are almost certainly from a river environment. From graphic measures (Fig. 51), skewness plotted against kurtosis gave a rather random scatter. A few samples fall within the aeolian and beach environment envelopes of Mason & Folk (1958). The moment plot of kurtosis against mean size (Fig. 52) showed an unusual J-shaped distribution. Separation in terms of rock units was not good and there seemed to be no distinct fields.

The relationship between skewness, kurtosis and mean size indicates there must be a relationship between skewness and kurtosis (third and fourth moment). The result is a partial parabolic shaped curve (Fig. 53), in which grain size decreases in an anticlockwise direction around the curve.

The relationship between moment skewness and kurtosis results partly from the method of calculation, since $Km > (Sk)^2 - 2$ (from an inequality in Kendall & Stewart 1969). Thus no values will plot outside a parabolic curve with its origin at a kurtosis of -2. The relationship is of importance when considering fields supposedly representative of certain environments. It shows up well on a plot of over 600 sandstones made by Friedman (1962, Fig. 5).

Careful inspection of Friedman's results reveals the analyses are clustered along lines parallel to the limiting parabola. The Tarkarooloo Basin samples all plot near the extreme limits of the curve. Further, the Eyre Formation samples are observed to plot on a parabola slightly inside those of the Namba Formation and concentric with the limiting parabola. Remembering the grain size variation, it is suggested that comparison of skewness and kurtosis at different mean grain sizes be made considering the parabolic curve, concentric with the limiting parabola. Therefore significant environmental comparisons should be made between different curves. This may account for the controversial results obtained by various workers attempting to differentiate environments with this plot using different sized sands, e.g. compare Friedman (1969), Solohub & Klovan (1970), Ahlbrandt (1974), Omara et al. (1974). Graphic parameters are more easily interpreted.

It was observed that the samples of the Namba Formation plotting in Fields A and B of Fig. 51 (σ vs. Mz), also plot in a distinct field in Fig. 53 (Sk vs. K). The Namba Formation and Eyre Formation plot along different parabolas, which is basically a representation of their varying degree of sorting. There is overlap between the Willawortina and Namba Formation, though the former tend to plot nearer the origin.

It is concluded that further work must be done to confirm these suggestions, and determine the environmental meaning of the differences between parabolic distributions.

2.3.5 Metric statistics (Buller & McManus 1972, 1974)

These workers claim simple metric measures of grain parameters are often better at discriminating environments than the more complex forms considered previously, partly because they are more readily understood. The envelopes they derived for different environments are shown on a plot of quartile deviation vs. median diameter (Fig. 54). Environments are differentiated using the slopes of the envelopes, but overlap makes this method useless for distinguishing an assemblage of unknown environments. However, having determined the groupings as above, they can be plotted separately to establish trends. The metric measures were computed from the phi data (Table 2) for both 75th & 25th, and 95th & 5th percentiles. The 75th & 25th percentiles are shown (Fig. 54) to facilitate comparison with Buller's & McManus' results. The metric measures do not include the fine tail, and are therefore unaffected by diagenesis or technique.

The Eyre Formation samples have a trend corresponding to fluviatile sands, with three samples plotting slightly outside the 1 standard deviation envelope. The Namba Formation sands from Field A (σ vs. Mz) in Fig. 51 show a distinctly different slope, though the number of samples is small. It corresponds to that of dune sands, though it could also be interpreted as a beach and sand bar trend. This information is significant when the position of these sands in the cyclic sequence is considered - it was suggested they might represent beach or bar environments. However, coastal dune environment is not incompatible.

The Willawortina Formation samples all plot in a group without any distinct trend, outside, or on the edge of the quiet water environment envelope. These were suggested to be mudflow or highly turbid current flow deposits, a type not considered by Buller & McManus.

Most of the other Namba Formation samples plot outside the quiet water envelope, probably a result of bioturbation and other mixing processes. Those plotting within or close to the envelope are all silty clays or clays, mostly laminated and often bioturbated. They include all the samples attributed to flood plain or lacustrine facies from analysis of cumulative probability curves. All have skewness values close to symmetrical, or slightly coarse or fine skewed.

2.3.6 C-M parameters (Passega 1964)

These plots utilize the coarsest 1 percentile in the grain size distribution, thereby being less affected by diagenesis. They are useful for differentiating fluviatile, turbidity and mudflow deposits, and different types of fans. The outline of one of the fields of Bull (1972) was plotted for comparison on Fig. 55, which shows the Tarkarooloo Basin data.

The Willawortina Formation samples all plot within Bull's mudflow envelope, and have an average trend giving C/M = 50, therefore a mudflow mode of deposition is likely.

The Eyre Formation gives a distribution close to the limiting line, indicating good sorting. A graded suspension (partly equivalent to Visher's saltation load) is well developed. The equivalent of the P-Q part of Passega's curve (Fig. 1 his paper) is not well developed, though there is a probable N-O part, representing rolled material. Some of the cumulative probability curves confirm presence of a traction load. These results provide further evidence for transportation in a braided stream environment, or at least not in deep confined channels.

The Namba Formation sands that plotted in Field A (σ vs. Mz) of Fig. 51 are shown by field X (Fig. 55). Interpreting these as stream deposits, a well defined suspension load and graded suspension are present, but no bedload of rolling grains. A deep, confined persistent flow is inferred, coupled with restricted supply of coarse detritus. The sands are rather well-sorted for stream deposits, and the other finer sediments (field Y) do not form the expected suspension load tail (though this is attributed partly to many of these deposits being mixed). Thus the beach or bar environments suggested for the same samples by the metric measures is tenable. The field Y cannot be explained, though it partly overlaps Passega's pelagic suspension (i.e. quiet water).

2.4 CONCLUSIONS

The size data confirm a fluviatile environment for the Eyre Formation, providing evidence for strong currents, probably operating in a braided stream environment. Deposition from aqueous dunes and ripples (sometimes parasitic on the dunes) is supported. At least some of the laminated silts were deposited as upper phase plane beds. The sands have been winnowed, and the fines removed to distinctly separate environments. Bimodality apparently results from the depositional processes, and is typical of the Eyre Formation.

The Namba Formation can be divided into two broad groups. The sandy sediments of one group were deposited in deep confined channels with constant flow, and/or in an offshore bar or beach situation. If a beach or bar is accepted, mixing with lagoonal or shallow lake sediments occurred, to account for the fine material. Outcrop shows channels are present, therefore both environments may be represented. The other finer grained poorly sorted class contains various types of sediments, some deposited on a levee or floodplain, and some in lakes. Most could only be assigned to a low energy environment, and many are probably mixtures of two or more deposits from juxtaposed environments, as occurs along a shoreline with lagoons or in a floodplain with irregularly distributed lacustrine and fluviatile facies.

The Willawortina Formation poorly sorted sandy and silty sediments were deposited from normal streams near the base of the unit, but turbulent flows, including mudflows, became commoner higher in the sequence. Some low energy deposits are intercolated, particularly in the lower part.

Considering the whole Tertiary sequence, sorting decreases from older to younger units, grain size decreases then increases. Energy conditions were high during deposition of the Eyre Formation, low in the Namba Formation and high again in the Willawortina Formation.

Some general conclusions can be made about methodology. Lack of knowledge about modern low energy deposits makes it difficult to resolve environments therein. The very fact that they are low energy presents theoretical difficulties. Most scatter plots are of little use in distinguishing environments in a set of unknown samples, but plotting by rock units is helpful. By a process of trial and error, the most useful plots can be found. Methods which ignore the fine fraction, such as C-M plots and metric plots are useful in sediments affected by diagenesis. Another useful scatter plot was of sorting against mean size. Parameters such as skewness and kurtosis are not well understood. The mathematical relationship between them has often been ignored when they have been plotted against one another. Few studies covering a wide range of grain sizes have been published, hence the size-dependence of skewness and kurtosis are poorly known. No natural breaks or deficiencies in certain grain sizes were found, and this has been confirmed for a large number of samples by Shea (1974).

CHAPTER 7

DEPOSITIONAL ENVIRONMENTS, PALAEOGRAPHY, PALAEOCLIMATOLOGY

(See Fig. 56)

1. EYRE FORMATION

During the late Cretaceous-Paleocene there was a marked change from quiescent conditions to a strongly erosional and depositional regime in the Lake Frome area. The sudden appearance of widespread mineralogically mature medium sands in the Paleocene is attributed to vigorous erosion of partly mature sediments from the Mesozoic and pre-weathered basement in a humid tropical climate. In the southern part of the Tarkarooloo Basin the crystalline basement areas of the Willyama Inlier contributed sediment.

The flora contains *Nothofagidites* indicating high rainfall, and includes other species suggesting subtropical to tropical climate (*Anacolosidites acutullus*, *Cupanieidites orthoteichus*). In the Eocene *Nothofagus* was commoner, suggesting increased rainfall. The area was thickly vegetated with rainforest species. The presence of *Pediastrum*, and non-marine dinoflagellates indicates a fresh water environment.

The sands were deposited from vigorously flowing braided streams, most fines being flushed from the basin. The Olary region was a source of mud, deposited in the vicinity instead of being removed as expected with vigorous stream activity. This is difficult to explain considering proximity to an uplifted area, and erosion of pre-Tertiary basement into well defined valleys (Chapter 8). Perhaps the Benagerie ridge to the east acted as a trap. The Lower Cretaceous, Jurassic and ?Permian are a suitable source of coarse sand and chert pebbles. These rocks must have formed hilly regions in the vicinity of the northern Flinders and Barrier Ranges. Some of the muds in the Olary region are slumped, suggesting unstable slopes.

Lack of any major grain size trends, and distribution of chert pebbles in the north, indicates accumulation from coallescing alluvial fans, with different provenance. There was probably reworking of intrabasin Mesozoic strata. The widespread distribution (Wopfner *et al*. 1974) cannot be explained entirely by this method. A process involving successive retreating scarps, cut into the Mesozoic or previously deposited Eyre Formation may have operated, similar to that proposed by Selley (1970, p. 44).

From Paleocene through Eocene the depositional energy conditions decreased, and fine sediments became frequent. Rainfall increased, and lakes may have been present (laminated carbonaceous silts).

2. SILCRETE

At the end of Eocene times relief was subdued and basins were partially filled by the Eyre Formation. Vegetation probably became dense, preventing erosion. Sometime during the Oligocene to early Miocene, silcrete formed, now represented by erosional remnants. The crust originated mostly in areas marginal to the eroded remnants of the ranges, but not in lowlands. It is best developed on porous sands.

The sands cemented by the silcrete have deeply corroded grains. The crusts exhibit structures similar to soil peds, and common in lateritic soils. These are features suggestive of *in situ* formation under stable conditions. In an alkaline hydrologic environment detrital quartz becomes soluble (Peterson & Von der Borch 1965) After burial, sediments containing these ions formed opal, as a result of the action of CO_2 from decaying organic matter. Aging of opal to forms of chalcedony (silcrete) is described by Berner (1971, p. 164) who states this can happen in a period of 10-100 m.y. This may account for the preponderance of microquartz chert in older silcretes, and opal and chalcedony in younger forms. Silica is also released during the weathering of smectite to kaolinite. Thus silica was dissolved from sands and shales under the conditions of strong leaching prevailing during this period, and redeposited lower in the soil profile.

It is of interest that this was a period of intermittent low temperatures (Jenkins 1974, Devereux 1968, Frakes & Kemp 1973) which suggests that silcrete formation is independent of temperature. Alternatively silcrete may have been forming during deposition of the Eyre Formation, or at least near the end of this interval, suggested by discovery of widespread silcreted abraded and sorted silcrete pebbles.

3. NAMBA FORMATION

A new phase of sedimentation set in during the medial Miocene. The fine grain size suggests this could equally well have resulted from climatic change and increased runoff, or from subdued uplift. Climatic change is supported by the clay mineralogy, and increased abundance of fossil grass pollen. Nothofagidites indicates rainfall was still high. The formation of the smectite-rich clay suite requires restricted leaching, implying transformation of chlorite and illite (or neoformation) in swamps within the basin, and/or savannah soils in the hinterland. The persistance of plagioclase in the detrital framework supports restricted leaching. The feldspar types suggest the sediments were derived from the surrounding basement areas.

As in the Eyre Formation Nothofagidites is prominent, indicating high rainfall, but there are no species diagnostic of high temperature. The fresh water algae Pediastrum is present. Grass pollen is much more abundant than in the Adelaide Plains SubBasin or at Balcombe Bay, suggesting savannah-like vegetation.

The forest species must have been limited to watercourses and lake shores, or to distant hills, to produce the mixture of families. The flora has been found only in the basal laminated black clays (see Chapter 2), though it does occur high in in LC1A and Glenmore 1 bores.

Ostracodes of non-marine affinities, both saline and fresh water, are present. Also fish spines, scales and otoliths. A permanent lake with relatively deep water and fluctuating salinity, is indicated. Trails indicate benthonic organisms could survive. No foraminifera were found in any part of the sequence, suggesting a non-marine environment throughout, or conditions unsuitable for preservation. A few foraminifera were found in the Etadunna Formation (Johns & Ludbrook 1963), all resistant to extreme conditions (taking marine as the norm). A similar restricted fauna is found in the Coorong (pers. comm. J.M. Lindsay 1975). In the carbonates charophytes, gastropods (aff. Coxiella gilesi) and non-marine bivalves are present, all of which can tolerate extremes of salinity.

The vertebrates (Callen & Tedford in prep.) occur near the top of member 1 of the Namba Formation, and possibly at the base of member 2. The presence of delicate-boned land vertebrates and partly disjointed skeletons indicate virtually no transport. Large aquatic types such as crocodiles, lungfish and turtles require an extensive body of water. Arboreal species indicate proximity to forest, wading birds and ducks suggest mudflats. This association is to be found in large rivers with gallery forest or around forested lake or lagoon shores. The presence of a riverine dolphin requires an estuarine environment, or at least a temporary connection with the sea, indicating external drainage.

The vertebrate assemblage requires a similar set of climatic conditions to the flora in the lower part of the sequence.

Thus the climate was similar throughout deposition of member 1. The similar clay mineralogy and lithology suggest no great variations from this norm occurred, except during carbonate formation.

Deposition began in the Poontana SubBasin in a thermally stratified lake. Using Reeves' (1968) formula for a closed lake basin with low relief in the drainage area, the amount of evaporation required to prevent the lake from overflowing can be derived.

$$LA' = \frac{R/BE}{1-(BP/BE)}$$

where LA' = LA/BA, B = basin; E = evaporation; L = lake; A = area;

P = precipitation; R = run-off.

The maximum Tarkarooloo Basin area (BA) approximates 66,000 sq. km., the initial deep water lake area (LA) 12,400 sq. km. A minimum figure for precipitation, from the present distribution of *Nothofagus* is 1,500 mm, and making the assumption $P \geq R \geq 0$, gives an evaporation rate between the extremes 1500 and 1785 mm/yr. This is so high (only attained in modern times in subtropical latitudes over the oceans) that the lake probably overflowed into the sea, via a river (or rivers), or else was completely open to the sea.

Subsequently the lake shallowed, and a thick sequence of drab unlaminated (churned) clays were deposited. Then came a widespread period of carbonate sedimentation, extending nearly to the New South Wales border area, but not south of Lake Frome. This change indicates further broadening and shallowing, whilst evaporation increased relative to precipitation. Tectonic processes can alter the balance between evaporation and runoff, causing depth-extent variations: a major climatic change is not essential.

The carbonates were deposited in a supratidal lagoon environment or shallow inland lake, following and accompanying an initial phase of palygorskite precipitation. High evaporation and alkaline groundwater are required for dolomite precipitation. Fluctuations in water table produced alternations of dolomite and calcite. Algal mats formed near the shoreline, whilst burrowing organisms lived in the muds. Periodic exposure occurred causing drying and cracking of the dolomite. Palygorskite, like dolomite, may have been precipitated under the influence of carbonate rich groundwater in a high Mg^{2+} high salinity, lake or lagoon. These carbonate intervals may represent protracted periods of seasonal aridity superposed on the warm temperate to subtropical climate.

In the margins of the basin, deep slow streams were active probably of meandering type. Following the carbonate phase, fluviatile and non-carbonate lake environments dominated. Floodplains were interspersed with lakes and swamps and had an irregular distribution. Successive regression of lake shorelines and migration of rivers appear to have controlled sedimentation and imposed cyclicity. Regressions could result from several causes - variation in rainfall, increased sea connections, or fluctuations in sea level (if the area is regarded as a lagoon marginal to a shallow epeiric sea). Waterlogged soils and marmorization formed in ?humic acid stained bioturbated black clays associated with these cycles. Mixing of well sorted fine sediments of different grain sizes occurred in lagoons separated from the lake or seashore by beaches or bars.

Sedimentation was intermittent, and the water table constantly high, so the muds were kept in a thixotropic state, allowing quick-flow structures to form.

In the Poontana SubBasin area there was a widespread phase of fluviatile deposition in confined channels or bar deposits, represented by a persistent fine sand bed. This was the site of uranium deposition in certain favourable areas near the Flinders Ranges (Chapter 8).

Overall, for member 1, sedimentation was in a low energy environment, with alkaline conditions and restricted leaching. Relief was low, rainfall high, and a sub-tropical savannah with gallery forests along watercourses is envisaged. Deposition occurred onto the area now occupied by the Flinders Ranges, these ranges being represented by a low range of hills.

A second phase of carbonate deposition occurred at the base of member 2, identical to the lower carbonate of member 1, though it extended south almost to the Olary Ranges. The calcrete developed on it in one of the southern bores indicates prolonged exposure here. Ooliths formed either by direct precipitation, or under algal influence, in an environment with little agitation. The intraclasts which form many oolith cores must have been created in a higher energy environment. Mixing of ooliths and carbonate mud was produced by organisms. Alternatively a binding substance such as an algal mat could have prevented strong agitation suitable for oolith formation from eroding fine muds.

4. NAMBA FORMATION AND WILLAWORTINA FORMATION

The upper member 2 of the Namba Formation marked a major change from smectite to illite-dominated clayey sediments. This accompanied an influx of detritus from the vicinity of the Flinders Ranges, represented by the lower part of the Willawortina Formation. The coarser sediments accumulated above the water table, in the margin of the basin. Silcrete and iron cursts began to be eroded from the uplands. Some of this silcrete may have formed during deposition of member 1. In the higher parts of the basin there was a break in sedimentation after deposition of member 1 of the Namba Formation and the lower part of the Willawortina Formation. Humid weathering of clays formed alunitic layers. Near the ranges silcrete and iron crusts formed. The influence of the Flinders Ranges uplift increased, sedimentation becoming dominated by an essentially fluviatile regime. The widespread lacustrine deposition of Miocene times was terminated.

The upper Willawortina Formation was deposited in a more arid climate, and the Flinders Ranges continued to be uplifted. Intermittent flash floods instigated mud-flows and high turbidity stream floods.

Throughout deposition of the Namba Formation in the Tarkarooloo Basin, the Poontana SubBasin was a region of subsidence, and sedimentation continued well onto the flanks of the present day Flinders Ranges. When these ranges developed, the western portion of the basin was cut off, uplifted and eroded. Parts of the old low relief medial Tertiary surface were uplifted and preserved as "reentrants" which acted as traps for the fan deposits of the upper Willawortina Formation. These eventually became the Paralana and Balcanoona High Plains.

5. TERTIARY CONTINENTAL SEQUENCES AND THE PALYGORSKITE-DOLOMITE ASSOCIATION

The almost identical nature of the Namba Formation and Etadunna Formation suggest the conditions just outlined prevailed over a large portion of South Australia. Other comparable deposits of similar age are widespread in the Northern Territory and Queensland. The palygorskite-dolomite suite has been recorded in the Ipswich area of Queensland (Rogers et al. 1954) in Oligocene rocks, suggesting a similar climate there during these times. Thus similar environmental and climatic conditions were common in the Tertiary over a wide area of South Australia.

There is a marked similarity to early and medial Tertiary deposits of France, Switzerland, North Africa and the Middle East.

In the L'Oehningien of the Locle Basin, Switzerland, Kubler (1962) described a sequence of Miocene rocks derived from Jurasso-Cretaceous and Alpine sediments and metamorphics. The rocks are very similar to the Namba Formation, containing the same clay mineral suite (including palygorskite), "lacustrine" dolomite, sedimentary structures, and strontium (c.f. the Etadunna Formation, Williams 1972, Johns & Ludbrook 1963). The Swiss rocks, however, contain a greater proportion of chlorite and volcanic ash, and a red colour is common (from eroded lateritic soils). Sepiolite is also present. A Mediterranean or subtropical climate was favoured by Kubler.

Several similar sequences in France and North Africa have been described by Millot (1970, pp. 174 ff, 202ff, 199ff, 262ff). All contain montmorillonite-palygorskite-sepiolite-dolomite assemblages, and are said to be lacustrine or nearshore marine. One of these sequences, in the Lower Eocene of Languedoc, was described recently in detail by Freytet (1971, 1973). The Languedoc carbonates differ in the common occurrence of sparite cement. Wiersma (1970) made a comprehensive study of the Jordon Valley, and again the sequence is comparable.

In comparing these deposits with the French basins it may be significant that the first Australian record of an Escornibovina foraminifera, previously known only from the early Miocene of Aquitaine, was made from equivalents of the Namba Formation in the northernmost Murray Basin (Lindsay & Harris 1973).

It is suggested that the climate and environment of deposition were almost identical for the European, North African, Middle East and Australian deposits.

One of the most characteristic features of the Namba Formation is the presence of palygorskite, and the related sepiolite, with dolomite. A literature search of 95* references covering 73

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* Detailed list available from the writer.

individual regions of palygorskite and/or sepiolite revealed the following distribution:

Distribution by Period		
Cambrian	1	
Triassic	3	
Cretaceous	4	
Tertiary	39	65
Quaternary	26	
	73	

Distribution by Location (Quaternary and Tertiary)	
North Africa	11
South Africa	3
Europe (mainly France)	21
Near & Middle East	13
Continental Asia	3
Far East	1
Australia	5
U.S.A.	7
	64

Most are late Cretaceous and Tertiary, especially Paleogene, occurring in the vicinity of southern Europe, North Africa and the Middle East. This is partly a reflection of where most work has been done and of bias in literature reading (mainly French and English references), but the age of most have some significance. Of the Quaternary occurrences, many are known to be derived from Tertiary rocks, and a number could have had a Tertiary source. It is frequently suspected from stratigraphy and descriptions that some of the authors have incorrectly assigned rocks to the Quaternary instead of Tertiary. Most are associated with dolomite.

The lack of palygorskite and sepiolite in Cretaceous times may be a result of instability under conditions of slight metamorphism, but the number of occurrences drops off so rapidly that possibly some other factor is operating. It is thought that during early and medial Tertiary, conditions favoured widespread development of alkaline groundwater, evaporation rate was high, relief low and extensive shallow epeiric seas and/or lakes developed. It is likely that climate was also a controlling factor.

6. TERTIARY TEMPERATURES AND CONTINENTAL DRIFT

Palaeo-temperatures can be measured from organic carbonates. Errors inherent in this method have been summarized by Bowen (1966). Several temperature curves constructed for Tertiary temperature fluctuations from a variety of calcareous organisms for New Zealand and southeastern Australia are presented by Keyes, Gill, Jenkins, Edwards & Devereux in Tuatara (1968). These results give similar curves, though there are differences in maximum temperatures and timing of peaks and lows. In the early Tertiary the temperature was around 20°C and dropped rapidly to 15°C during a short period of the late Miocene (Bairnsdalian). The air temperature corresponding to seawater of 20°C would be that of a tropical climate. Temperature fluctuations are likely to be much greater on the continents. The New Zealand temperatures are compatible with those of Victoria, and the floral content is similar over a wide area of Australia, suggesting fairly uniform climate.

There is a close correspondence between the climates deduced from these temperatures and the actual climate suggested for the Eyre Formation and the Namba Formation.

Recently Hayes et al. (1973) showed the Antarctic ice cap had already begun to form during the Miocene, implying Australia had drifted a considerable distance to the north into a higher temperature climate, as suggested by Wellman et al. (1969). A similar idea was proposed by Schwarzbach (1968) to account for the differences between the Northern and Southern hemisphere temperature curves, though the similarities between Australian and northern hemisphere Tertiary deposits are contrary evidence. Nevertheless, Australia was at a higher latitude than now, inferring the medial Miocene subtropical climatic belt was much expanded.

The change from smectite to illite clays in the $<2\mu$ fraction in the Miocene may have more than local significance, for Jacobs (1974) has shown it is widespread in the Southern Ocean. She found the change occurred at the Oligocene-Miocene boundary, whereas in the equatorial Pacific it occurs in the late Middle Miocene. It is believed to be caused by the climatic change which induced build-up of ice in Antarctica, favouring production of illite rather than smectite. It appears this widespread change may have affected the continental sediments of the Tarkarooloo Basin, though the effect of the Flinders Ranges uplift must be differentiated. The timing should be related to extent of the glacial conditions, and continental drift.

CHAPTER 8

URANIUM

1. INTRODUCTION

1.1 TYPES OF SEDIMENTARY URANIUM DEPOSITS AND CRITERIA FOR EXPLORATION

One of the largest uranium users is North America, obtaining most of its requirements from its own resources, 94% are from sandstone (McNight 1973) mostly of Cainozoic age. Thus, at present, the importance of this type of deposit far outweighs that of vein-type ore. In these sandstones, placer deposits are rare, most being of geochemical cell type (Gabelman 1971, Finch 1967, King & Austin 1965, Dall'aglioa 1971, Austin 1968, Granger & Warren 1969, Parker & Harshman 1969). Many of these are roll-front deposits, involving transportation of uranium in solution from some source rock, to its place of deposition (Hostetler & Garrels 1962).

On passing through a porous host rock, groundwaters containing uranyl ions carried in carbonate complexes may encounter reducing conditions and porosity traps, causing precipitation as uraninite or coffinite. The reducing conditions are generally supplied by carbonaceous matter, derived from plant remains deposited with the sediments, or from sedimentary sulphides. Alkaline groundwater is the transporting medium. The importance of sulphur in the process has been demonstrated by King & Austin (1965) and Granger & Warren (1969). A source of uranium is essential, generally taking the form of granitic terrain with anomalous radioactivity. Arkose and tuff in the sediments may contribute under certain circumstances (Parker & Harshman 1969). Some deposits have no evident source rocks, but it has been shown that the source need not be much above the Clarke value for uranium (Dall'aglioa 1971).

In roll-front deposits the uranium lies between oxidised and reduced zones within the particular sand bed under consideration, forming a narrow lens with a C-shaped cross section.

Certain criteria have been found useful in exploration, based on empirical and theoretical considerations.

(1) Regional

Continental Mesozoic or Cainozoic sedimentary basins with thick fill, preferably with volcanics or arkosic sediments, surrounded by Precambrian highlands. The provenance should be uraniferous. Fluviatile sediments are best.

(2) Local

Dirty carbonaceous sands, coloured shades of grey, brown or green. Well-defined channels, preferably cut into impermeable rocks, containing sands of medium grain size or coarser. A certain amount of fracturing is favourable. Radioactive groundwaters are also favourable. A roll front can be located as follows, from recognition of the altered and unaltered ground:

UNALTERED	ALTERED
Accessories such as magnetite and rutile.	Accessories absent.
Coarse discrete pyrite of variable habit.	Euhedral pyrite, discrete crystals.
	Protore is grey, with orange-brown tint and contains pyrite aggregates.
Pale grey	Yellow brown or bleached appearance.
	Low loss on ignition, Fe, SO_2 - $CaCO_3$, CO_2, org. C: low, Se: abundant.
	Mo & V high in ore

(Adapted from King & Austin 1965)

The most reliable criteria for actual location are colour (e.g. K69 bore) and gamma ray activity (e.g. WC2 bore), though gamma logs may not give true estimates of quantity.

1.2 URANIUM IN THE SOURCE ROCKS

Knowledge of the distribution of uranium in the vicinity of the Lake Frome area will be of importance when discussing the origin of uranium deposits in the Tarkarooloo Basin, whether placer or geochemical cell types. In placer deposits a former high grade uranium source is necessary, whereas geochemical cell type has less stringent requirements: a uraniferous granite, arkosic sediment or volcanic ash deposit are suitable leachants.

The source rocks for modern, and probably Cainozoic, groundwaters contain two major uranium provinces: the Mount Painter area and the Olary Ranges. The Olary Ranges have a more widespread generally lower concentration of uranium than the Mount Painter district. Three distinct areas are present within this region:

(1) The Mt. Victoria - Crockers Well - Old Glenorchy belt.

(2) The Bimba Hill - Wiperaminga Hill - Boolcoomatta belt.

(3) The Radium Hill area.

The areas (1) and (2) form a roughly East-West belt, on the northern part of the Willyama Inlier, whereas the Radium Hill area forms a distinct separate zone on the southern part of the Inlier. Of these areas, none were mined on a large scale except Radium Hill, and even this was a small deposit by world standards. Uranium is present in the Willyama Inlier in granites for areas (1) and (2) and in metamorphics for area (3). The latter resembles the Mount Painter occurrences in being associated with Lower Proterozoic metamorphics.

The Mount Painter uranium is not necessarily of Ordovician age, as suggested by Blissett (Coats & Blissett 1971) because the

Ordovician granites have average or below average uranium content for granites: all radioactivity is assoicated with the metamorphics (Youles 1972, Appendix 6). The Olary Province uranium was introduced about 1650-1700 m.y. (Thomson in Parkin (Ed.) 1969, p. 35). The primary minerals were pitchblende, davidite, absite, allanite and related minerals, weathered at the surface to secondary minerals.

Systematic sampling of crystalline basement to determine uranium content has not been accomplished anywhere, though radiometric surveys and some spot sampling are available from company work. Uranium in granites of the Olary region indicates that they at least are highly uraniferous. In the Mount Painter Inlier uranium is associated with unusual breccias, probably sedimentary (Youles 1972), or with metamorphics. A very highly anomalous radioactive zone (Young & Gerdes 1966) occurs within the Mudnawatana granite area mapped by Coats (Coats & Blissett 1971), but in detail it is found that the uranium (30-250 ppm) is associated with gneisses, in an area where pods of granite of low radioactivity are present. The only other major radioactive zones are within the Yerila Granite (Zimmerman 1969) - these are associated with linear zones which could be shears.

Thus the Mount Painter Inlier has small intensely radioactive zones associated with metamorphics and breccia bodies, with normal granite radioactivity. The Willyama Inlier has widespread highly radioactive granites, and zones within the metamorphics. In the Barrier Ranges,Willis & Stevens (1974) recorded uranium occurrences associated with the Willyama Complex, in particular the Mundi-Mundi Granite and large pegmatitic segregations. Anomalous radioactivity could be a feature of this district. The uraniferous granites of the Willyama Complex are therefore most significant as a possible source for geochemical cell type deposits in the Tertiary sediments. The localized nature of the Mount Painter radioactive anomalies makes this area a less likely source of widespread uraniferous groundwaters.

2. DEPOSITS

2.1 HISTORY OF EXPLORATION

In the Lake Frome area attention was directed to sedimentary uranium by Exoil N.L. who were undertaking exploration at Mt. Painter in crystalline basement rocks. They noted the presence of radioactive hot springs (Paralana Hot Springs Fig. 1). Examination of old water bore records (Ker 1966) indicated a Tertiary continental sequence was present, resembling that of the U.S.A. A source was immediately in evidence in the Mt. Painter and Willyama Inliers. This fitted regional requirements, except that tuffaceous beds are absent, and feldspars scarce in the early Tertiary.

A target depth of less than 110 m was required so that open cut mining was feasible for the expected size and grade of deposits for unconsolidated sediments. Nearby transport facilities were preferable: a railway exists from Adelaide to Broken Hill. Thus initial investigations were the "Paralana" and "Curnamona" districts. The first exploration was undertaken by Ker McGee Pty. Ltd. (Ryan 1969) near Mt. Painter.

Uranium was first discovered in the Paralana High Plains by the Exoil-Transoil-Petromin group of companies. It became evident only one area was mineralized, along an approximately southerly trending line from the Beverley Deposit, corresponding with the surface projection of the Poontana Structure (see Callen in press) defined at the Mesozoic - Palaeozoic unconformity surface by Crusader Oil N.L. (Proctor et al. 1966). Two more areas were found in the southern part of the basin, in the "Curnamona" - "Frome

Downs" region south of Lake Frome and in the vicinity of "Yarramba" in the southeastern corner of the Frome Embayment.

The Beverley Deposit is located in fine sands of the upper part of member 1 of the Namba Formation or perhaps in basal member 2 (Callen 1975, in press; & WC2 bore Figs. 23, 31) whereas the southern deposits are in the basal and upper parts of the Eyre Formation (K69 bore Figs. 4, 10; PMX24a bore Figs. 8, 14).

2.2 DEPOSITS

2.2.1 Beverley Deposit

This ore body occurs as a series of lenses dipping southeast at a low angle. The sands occur at the top of member 1 of the Namba Formation, and vary from 0 to 24 m thick. The upper horizon is a disconformity, and separates the Willawortina and Namba Formations, the lower is an hiatus which is quite widespread in the Beverley area (Andrus, in Bragg 1972, see Appendix 6), the sands being incised into the top of the black clay. The top of the uranium-bearing sand is flat. Interbedded black clays contain very little carbonaceous matter (Chapter 3) though pyrite occurs in this area.

Sands were deposited in a northerly trending series of channels or bars and attendant flood plains or lakes, cut off sharply to the west by a fault. Grain size fines upwards from coarse polished sand at the base to angular silt at the top, but averages fine grain-size. Clay is frequently abundant. The ore is present as finely divided uraninite at the base of the sand and within the upper part of the black clay.

The ore deposits are located at the outer edge of the Paralana High Plains area, in the vicinity of Four Mile Bore. The Poontana fault seems to be responsible for alignment of the western edges of the ore bodies, and coincides with an actively eroding slope interpreted by some as a scarp. However, the correlation shown in the fence diagram shows the upper part of the Willawortina Formation extending across the fault without much displacement. The geomorphology of the outer edge of the fan is in accord with normal fan building processes. At present this part of the fan is inactive, and is being subject to erosion by run-off from the fan surface.

According to Schindlmayr (1970) the Poontana fault increases in displacement from 25 m to 120 m near the Flinders Ranges, with east block down. Although regional dip is west, the uranium deposits dip southeast (Schindlmayr 1970, Brunt 1972). The regional dip agrees with dips established by Union Corporation east (Randell 1973), and south (Langren & Marshall 1973, see Appendix 6) of Lake Frome. A similar dip is recorded in the Cambrian Lake Frome Group and on the Mesozoic-Palaeozoic unconformity by Crusader Oil N.L. (Proctor et al. 1966). Thus dip at the Beverley Deposit is probably related to the adjacent fault.

The tabular nature of the orebodies, lack of carbonaceous matter (in unaltered sediments), and lack of equilibrium between daughter products of U are features which are not typical of roll-front deposits. Pyrite was presumably the main reducing agent, and porosity also important. Proximity to a strongly anomalous localized radioactive source in the nearby basement is obvious: the deposit is in a direct line from the Paralana Hot Springs area, and intensity of radioactivity decreases south along the fault. In the region of Paralana Hill the uranium is on the west side of the fault (Bryan 1971, appendix 6). It is suggested uranium-bearing groundwaters moved directly east, from the crystalline basement north of Paralana Hot Springs (Mudnawatana Granite), they were then constrained to the porous zone along the Poontana Fault, and moved out into adjacent sandy beds of appropriate porosity. Where impermeable pyritic clays were beneath the sands, reducing conditions prevailed and uraninite formed. Some uranium may also have been dissolved out of the Willawortina Formation, rich in feldspathic detritus derived from the Mount Painter Complex.

2.2.2 Frome Downs - Gould's Dam

This deposit is in lowermost Eyre Formation medium to coarse sands, cut into Middle Cambrian red beds. The sands occupy a channel-like feature, very straight and oriented in a northerly direction, parallel to the Poontana fault and other structures in the vicinity (Fig. 3).

The ?upstream (southern) end of the channel is located over a "reentrant" or low within the strongly positive magnetic pattern corresponding to the Benagerie Ridge. This pattern is thought to result from the presence of less magnetic sediments, which may have been more readily eroded. However, this remains conjectural until drilled in the vicinity.

The uranium in the channel is associated with carbonaceous patches and pyrite in the clay lenses and sands (Langron & Marshall 1973). According to Marshall, and confirmed by the writer, the deposit shows the attributes of typical roll-front ores in Wyoming, situated in C-shaped lenses in the oxidation reduction front.

The uranium differs from other deposits in the basin by being in equilibrium: thus gamma logs give a true record of uranium content. The ore mineral is probably uraninite (Milnes, in Webb 1971, Appendix 6) associated with a particular type of carbonaceous material and unconnected with clay.

2.2.3 Yarramba or Honeymoon Deposit

In the southeastern corner of the Frome Embayment area, Sedimentary Uranium N.L. located a uraniferous sand on the eastern edge of the Benagerie Ridge. In conjunction with Mines Administration

Pty. Ltd., a well developed channel has been outlined (Fig. 3), occurring in the upper beds of the Eyre Formation. The channel contains coarse sands and width variation (Brunt 1974a, b) suggests it had its source in the Benagerie Ridge and flowed southeast, or possibly east then north. It has been followed southeast to a point where it has been leached and oxidized and is no longer prospective. The channel is located over a magnetic trough, running northerly along the east side of the Benagerie Ridge. This trough is not associated with a great thickness of Tertiary sediment, but results from the presence of a lobe of Cretaceous shale extending south, and also from the presence of carbonaceous shale in the Precambrian rocks. The carbonaceous shale is steeply dipping and can be observed in K69 and B240/C3 bores (Figs. 4, 9). Thinning of the Eyre Formation over the Benagerie Ridge is indicative of uplift during its deposition, therefore streams should be directed away from this Ridge. This is supported by the Pacminex results and by further work of Mines Administration Pty. Ltd. north of "Yarramba" (Brunt 1973), which show the appropriate channel pattern (Fig. 3).

As in the "Frome Downs" area, the head of the Yarramba channel is located over a local magnetic low in the generally high intensity magnetic pattern of the Benagerie Ridge. This palaeovalley probably resulted from the presence of the ?weakly magnetic carbonaceous shale mentioned above, which is soft and readily eroded.

The Eyre Formation is described by Brunt (1974b, Appendix 6) as being more complex and clayey in this region. In essence his comment is correct, as outlined in Chapter 2. The sands are therefore more confined by the presence of intertonguing clay than to the north.

In the prospective channel at Yarramba, the passage of roll-front geochemical cells is marked by yellow limonite staining, which increases in intensity toward the channel banks. Near the redox boundary where the sands lens out toward the channel "bank", orange stain is frequently developed. The ore is developed in front of a rather ill-defined vertical redox boundary, and some subhorizontal boundaries are present. The situation closely resembles the "classic Wyoming types" (Brunt 1974b). The ore is in disequilibrium, as in the Beverley Deposit, but the nature of the mineralisation is not fully known. Some zippeite (hydrous uranyl sulphate) was identified.

Anomalous radioactivity also occurs in the basal Namba Formation sands, referred to as upper Eyre Formation by Brunt (1974b).

2.2.4 Other Areas

Small areas of anomalous radioactivity have been found by Central Pacific Minerals N.L. (Schindlmayr 1970) east of the Poontana Structure, by Mines Administration Pty. Ltd. near Mt. Hopeless (Brunt 1972; Jarre 1972) and by Chevron Exploration Corporation Pty. Ltd. (Morgan 1973) a few kilometres south of Kidmans No. 1 bore (Fig. 3). All are in the Namba Formation, the northerly occurrences in the same unit as the Beverley Deposit.

In the vicinity of Lake Namba, Tricentrol (Aust.) Exploration Pty. Ltd. located anomalous activity in a northerly trending channel (Middleton 1973, 1974). Very minor uranium occurred at the contact between the basal sands of the Eyre Formation and underlying carbonaceous Cretaceous sediments.

2.2.5 Summary of Deposits - Origin

All the deposits occur in carbonaceous and/or pyritic channel sands in Tertiary continental sediments. They are located at oxidation-reduction boundaries, in thin horizontal lenses in the Namba Formation at the Beverley Deposit, and in mainly irregular

C-shaped "rolls" and some horizontal layers in the Eyre Formation comparable to Wyoming deposits. Oxidized zones with yellow-brown to orange limonite and sporadic anomalous radioactivity occur up-dip of the rolls. Ore is dark blue grey, and unoxidized sediments are pale grey to buff, pyritic and non-radioactive. The ore minerals are probably very finely divided uranium oxide, forming a film over grain surfaces. In the Paralana area, Cr, Mn, Zn and V are anomalously high in radioactive zones.

These features suggest the movement of uraniferous groundwaters through the carbonaceous sands, with uranium precipitated at the oxidation front, possibly controlled by sulphate reducing bacteria and the distribution of pyrite and carbonaceous matter.

Lack of equilibrium between daughter products and uranium imply the deposits are mobile at present, but this does not imply the ore has not been accumulating over a long period of time. All that can be said is the deposits are younger than the sediments in which they formed. The uranium is though to have been derived from uranium enriched granites and metamorphics in the Mount Painter region and Olary and Barrier Ranges.

3. BASIN POTENTIAL

3.1 SOURCE AREAS

Distribution of uranium in the basement has been discussed and it is evident that the more diffuse widespread radioactivity of the Willyama Inlier is potentially a better source than the intense localised radioactivity of the Mount Painter Inlier. Balanced against this is the relative contribution of the two areas to sediments in the basin and the availability to leaching of both basement and derived sediments by groundwater.

The Olary region was more active as a source during the early Tertiary, but has since had low relief. In contrast the Flinders Ranges, particularly the northern part, have been much uplifted since the medial Tertiary but were low in early Tertiary times. This implies the Mount Painter Complex has been the main source of possible uraniferous detritus, and that the small areas of radioactivity within it have continually presented fresh material at the ground surface. The groundwater gradient would also have been steeper, and therefore more conducive to rapid leaching. The time factor must be considered: too rapid a groundwater flow may prevent uranium from reaching a suitable degree of concentration in the groundwater.

Groundwater from the Olary region had more uraniferous rock to operate upon and presumably moved more slowly.

3.2 GROUNDWATER FLOW AND CHEMISTRY

Mobilization of uranium via groundwaters from basement into Tertiary rocks is most likely to have occurred during times of active flow when slightly alkaline waters prevailed. A basin whence escape was restricted is essential. Definition of those times during the Cainozoic complying with these conditions would assist exploration.

Groundwater had two possible sources during the Cainozoic in the northern Lake Frome area: the Cretaceous aquifers, and from prevailing rainfall on the surrounding hills. Uraniferous water could be supplied by the bicarbonate rich slightly alkaline water of the Great Artesian Basin if it came into contact with uranium-bearing basement rocks. Also if the Cretaceous itself contained sedimentary uranium, introduced during late Cretaceous or early Tertiary times, it could be subsequently remobilized into the Tertiary. There is as yet no evidence for this, though waters coming into contact with uraniferous gneisses along the Paralana

Fault could carry uranium into shallower Tertiary aquifers.

The present day groundwaters have been studied by Ker (1966) and Shepherd (1960) and the modern brines and mound springs by Draper & Jensen (1974-5 pers. comm. Bureau of Mineral Resources Geology & Geophysics, ~~B.M.R.~~, Canberra). This data does not give a complete coverage for the basin and must be supplemented by deductions from present day structure and morphology. Areas of maximum groundwater flow are located along the eastern edge of the Flinders Ranges. Flow is east of southeast to east, even in the southwestern corner of the Bsrrier Ranges near Benagerie, but flow north from the Olary Ranges is apparently slight. There is a scarcity of information north of the Olary Range, though the area over the Benagerie Ridge is known to be lacking in groundwater (Shepherd 1960).

Present day groundwaters carry uranium, values of 180 to 6 800 ppb having been recorded by Oilmin N.L. (Draper & Jensen). Thus present day climatic and tectonic conditions are a guide to past periods favourable to deposition. The uranium content drops rapidly to 10 ppb adjacent to Lake Frome, supporting the idea that uranium is still being removed by deposition in Tertiary sediments close to the Flinders Ranges, and that these deposits are still forming. The waters have a variable carbonate content in the Cainozoic aquifers, being very high in carbonate adjacent to the areas of Cambrian limestone in the Flinders Ranges. The Barrier Ranges waters have high chloride and sodium compared with those of the Flinders Ranges and are therefore unlikely to be carrying uranium at present. There is no information on the pH of the waters.

Having established modern groundwater conditions, an analysis of past groundwaters follows. During Eyre Formation times drainage was exorhoeic, hence any uraniferous water would have been carried out of the basin.

In Namba Formation times an alkaline environment prevailed, and the basin was partly closed during the deposition of member 1 and probably completely during deposition of member 2. Thus conditions were conducive to solution and precipitation of uranium in the existing Eyre Formation sediments. Relief was low, but high rainfall maintained groundwater flow. Deposition would have occurred mainly north of the Olary Ranges and west of the Benagerie Ridge (and possibly east also). Connection to the Murray Basin, perhaps via the Cockburn area, would have greatly modified drainage and groundwater flow, and must be considered.

During deposition of the lower unit of the Willawortina Formation and member 2 of the Namba Formation, the Flinders Ranges were uplifted, and drainage approached that of the present. Alkaline conditions still prevailed, thus this episode is even more favourable.

Following this, formation of silcrete indicates strong leaching and alkaline groundwaters were again operative. No sediment was eroded, presumably by reason of low relief and thick plant cover, but this would not have prevented leaching of the rocks in the vadose zone and movement of groundwater. During deposition of the upper Willawortina Formation, geography was much the same as at present, though the Flinders Ranges had greater relief. Nothing is known of the groundwater composition. Rainfall was probably intermittent.

In the lakes and Plio-Pleistocene drainage channels east and southeast of Lake Frome there is abundant evidence for flushing by slightly acid groundwater (manganese and silica nodules), but carbonate was probably not of suitable concentration to form carbonate complexes with uranium, hence this interval may have been unsuitable for accumulation.

Subsequently in medial Pleistocene to Recent times, alternating with periods of fluviatile deposition, a series of calcareous soils formed (Callen & Tedford _in prep._), indicative of alkaline groundwater and high carbonate content. Conditions for uranium precipitation were then at least as favourable as now. Deposition of abundant uranium bearing detritus adjacent to the Mount Painter region further increased the quantity of leachants available. During the intervals between formation of the calcareous palaeosols, kaolinite and illite bearing sediments were deposited. These clays are stable in neutral to slightly acidic environment, thus conditions were unsuitable for transportation of uranium whilst they were deposited.

3.3 ROLE OF SEDIMENTOLOGY

3.3.1 _Eyre Formation_

The Eyre Formation is a relatively uniform blanket sand with high porosity and much carbonaceous matter, therefore it is a highly prospective horizon where suitable restrictions to groundwater flow are present. Considering palaeogeography (Fig. 3), channels can be expected to trend in a northerly direction from the Olary Ranges, with the possible exception of the "Yarramba" area, where the trend may have been southeast. To the north, the trend was southwest from the Tipooburra region, and probably south to south east in the vicinity of Mt. Painter. The general pattern was modified by radial drainage from the Benagerie Ridge, or parallel drainage if the ridge is considered to form in accompanyment to existing streams. It has been suggested braided streams dominated, with meandering more prominent later in the Eocene. Braided streams have relatively straight channels and therefore provide less constraint to migrating pore waters.

Stream directions during the Quaternary would have been approximately parallel to modern groundwater flow, except adjacent to the Flinders Ranges and in the southeastern corner of the area in the "Yarramba" district. Thus some other constraint is required for deposition in the Eyre Formation north of Mt. Victoria and vicinity (in the Olary Ranges) in order to prevent dissipation. This was provided by the abundance of locally derived fines. Porosity was lower in comparison to the northern sediments because of greater angularity. Other constraints could have been structural and are discussed in a following section.

Considered in addition to source rocks, the most suitable areas for uranium deposition are north of the Olary Ranges as far as the southern edge of Lake Frome, and in the southeastern corner of the basin east of the Benagerie Ridge, in New South Wales and South Australia. Another area lies immediately east ~~west~~ of the Flinders Ranges in the vicinity of Mt. Painter.

3.3.2 Namba Formation

In member 1, drainage was towards the area west of Lake Frome, then the deepest part of the basin. Sediments deposited from drainage west of the Poontana SubBasin have since been truncated, uplifted and eroded. There was also connection with the sea, possibly to the Murray Basin via the Cockburn area, requiring a southerly drainage pattern for part of the period. Because of the low relief, it is difficult to predict directions; rivers were meandering and a lake occupied most of the central basin. This lake appears to have expanded areally with time, reducing the region available for channelling. Channels in deltas built out into the lake may have been important.

Considering Quaternary groundwater flow, much movement would again be parallel to stream channels as in the Eyre Formation, though more restricted by lower porosity and meandering courses. In the southeastern area, drainage across the Olary block would have produced channels now directly opposed or perpendicular to modern groundwater movement.

Thus member 1 of the Namba Formation provides excellent conditions for uranium precipitation, especially in the southeastern region, but deposits are likely to have been restricted to the margins of the basin as far as the Miocene lake shores. The low porosity and rapid facies changes in the unit may be too restrictive for full development of roll fronts, hence the coarsest and highest porosity sands, such as between 130 and 150 m in Wooltana 1 are most prospective.

The upper member 2 of the Namba Formation was deposited when drainage was beginning to resemble the present, thus there was correspondence between Quaternary groundwater flow and channel directions.

3.3.3 Willawortina Formation

During the deposition of the upper part of this unit, the late Tertiary-Quaternary fanglomerate deposits of the Paralana and Balcanoona High Plains were formed, and the Miocene lacustrine era was terminated. The basin became closed and stream directions (and positions) corresponded closely to the present. Present day ground water flow through these deposits should be rapid, and directed to Lake Frome.

3.3.4 Distribution of Carbonaceous Matter and Pyrite

Carbonaceous plant material is abundant in all lithologies in the Eyre Formation, some silts approaching lignitic composition. Iron sulphides are common, some sands solidly cemented with marcasite and pyrite. In contrast carbonaceous matter is scarce in the Namba Formation, except in Glenmore 1 bore in New South Wales, and in the basal laminated clay in the Poontana SubBasin. The black clays contain only low percentages of carbon. However, iron is high, and pyrite has been recorded in the Beverley area, suggesting pyrite may have contributed the iron. Some of the sands, as in the Beverley deposit, contain some carbonaceous matter. The Willawortina Formation and member 2 of the Namba Formation contain no carbonaceous matter or pyrite.

The Eyre Formation is the most prospective unit, the lower part of the Namba Formation having limited potential, except in the vicinity of the Barrier Ranges where carbonaceous matter seems more prevalent.

3.4 STRUCTURAL CONTROL

Faulting is expected to play an important role in localizing uranium deposition, as demonstrated for deposits in North America (e.g. U.S. Atomic Energy Commission 1970, Norton 1969). The effects can be direct, by providing fractured zones for percolation, or by juxtaposing permeable and impermeable beds to form porosity barriers (as in the case of the Poontana Structure and Beverley Deposit), or indirect by influence of contemporaneous deformation on stream directions. In the Eyre Formation, faulting would be advantageous since porosity barriers are scarce.

A structure map (Fig. 3, and Appendix 6) shows all data relating to Cainozoic deposition and includes some features in older basement rocks thought to be relevant.

It is evident there are two major sets of fracture zones affecting the Cainozoic sequence. A northerly trending set exemplified by the Poontana Structure, and a northwesterly trending set, less well established for the Cainozoic though prominent in the basement rocks (e.g. the MacDonald Fault). The northerly trend of many of the Tertiary stream channels suggests structural control. In the Yarramba channel the northwesterly trend seems to have played a part.

The Poontana Structure has acted as a porosity barrier and channel, redirecting uraniferous groundwater from Mt. Painter. Other faults may have had similar roles. The Poontana Structure and related faults, if projected, meet the northwesterly trending feature of the Fitzroy Spencer Fracture Zone in the vicinity of "Curnamona". This could be an area of relatively intense fracturing. Notice the Mt. Victor uranium field occurs in the crystalline basement to the south.

The other major structural feature, the Benagerie Ridge, has controlled stream directions, apparently flowing southeast from its eastern edge. It also played a major role in influencing groundwater movements, acting as a barrier to westerly flow from the Barrier Ranges, and forcing a northwesterly deviation in the presumed northward flow from the Radium Hill area.

Finally, major Tertiary channels are localized in reentrant features, in the magnetic pattern coinciding with the Benagerie Ridge. The 'reentrant' west of the magnetic ridge associated with point (9) on the map requires investigation, particularly in the light of comments regarding fault trends.

4. CONCLUSIONS

4.1 PROSPECTIVE AREAS

The areas surrounding the Mount Painter Inlier have little potential east of the Poontana Structure. Uranium deposits along the structure have been intensively explored, except to the north of the Beverley Deposit. Prospects for uranium in other sands lower in member 1 of the Namba Formation and particularly in the

Eyre Formation adjacent to or west of the fault, are good. At present they are too deep to be economic unless of very high grade, though exploration in conjunction with exploitation of deposits in younger strata may be feasible.

The main potential of the area is in the region north of the Olary Ranges, especially in the Eyre Formation. Areas marginal to the Benagerie Ridge, and the district in the vicinity of "Curnamona" are of most interest. Most of these are being explored, though little work has been carried out northwest of "Curnamona" or east of the northern part of the Benagerie Ridge.

The region immediately west of the uranium deposits in the Denison Inlier is unexplored, and has potential both in the Eyre Formation and Namba Formation. A deep Tertiary section (O'Driscoll 1953) occurs in the southeastern part of the area on "Mundi Mundi" which is the area toward which Tertiary drainage was directed from the Benagerie Ridge. This area has not been investigated, and sediments resemble those of the "Yarramba" area.

4.2 GUIDES FOR EXPLORATION

The following is a guide to exploration derived from knowledge of the Lake Frome area, listed in order of increasing localization:

(1) Choose an area of non-marine or marginal marine Tertiary sediment flanking uraniferous basement rocks, preferably of extensive anomalously radioactive granitic type.

(2) Locate a fractured zone, preferably of northerly trend, or of a trend directed to intersect Quaternary groundwater flow.

(3) Examine pyritic and carbonaceous sands: the Eyre Formation is the most likely host in the Lake Frome area.

(4) Locate channelling: regions adjacent to basement highs active during deposition of the Eyre Formation are of most interest.

(5) Pay particular attention to 'reentrants' in the overall magnetic pattern associated with crystalline basement rocks. These may be the locus of palaeochannels.

(6) Deduce channel trends from palaeogeographic maps. Open hole drilling should initially proceed at closely spaced (0.25 km) intervals perpendicular to these directions.

(7) Choose channels cutting across the general groundwater flow or associated with faults.

(8) Drill down dip if in red-brown, yellow-brown or orange stained sands, updip when in grey pyritic and/or carbonaceous sediment. If strata are horizontal, drill nearer outcropping basement rocks when in unoxidized sands.

APPENDIX I

SELECTED PETROLOGICAL DESCRIPTIONS

WOOLTANA 1 BORE

P1081/73, A938/73. 76.36 m. NAMBA FORMATION. Microphoto 1:8-16.
(MP5074/73, 5077/73)
NAME: Bioturbated fossiliferous clayey dolomicrite.

ANALYSIS AND XRD
XRD at 78.00 m - degraded illite, kaolinite
Ca : 15%, Mg: 8.6%, Ba: 200 ppm, Sr: 180 ppm, Li: 20 ppm.
i.e. about 55% dolomite.

FRAMEWORK
Intraclasts 2-4%. Fossil fragments 0.035 x 0.12 mm. Tubes and fragments, of rectangular cross section or thin crenulated plates. Radial prismatic carbonate crystals form the cortex, surrounding the micritic core. Some tubules 0.17 x 0.01 mm - ?algae. Ostracode valves with up to 7 layers, 0.2 x 0.017 mm fragments or single valves with hinge 0.18 mm, constitute most of the fossils. Charophyte oogonia 0.10 mm, with clear internal structure. Some possible gastropod fragments.

Clay grains and pellets 15%. Brownish-orange stained, unstructured, well-rounded. Probably kaolinite or palygorskite, with some quartz grains.

Ooliths. Scattered 0.07 mm diameter concentrically layered opal and chalcedony with radial structure (may be low birefringence clay in some).

Quartz <½%. Deeply embayed, rounded, 0.1 - 0.2 mm.

MATRIX 85%
Micrite - analytically 55% of rock is dolomite, 50% of which is in the matrix. Grains 0.8 - 2.0 μ, euhedral, constant size. Clotted texture probably caused by mixing with clay, probably palygorskite or RI. Coarse-textured recognizable clay 5%, in burrowed zones.

TEXTURE
Grains scattered through fine matrix.
Burrows 1.2 - 2.3 mm diameter, with crude lamellae 0.09 - 0.15 mm thick of alternating clay and micrite. Clay pelletal (0.15 mm): illite subrounded. Grains of quartz and platelets of carbonate present. Some transverse cracks, infilled by fine micrite sand speckled with dense black <1μ opaque dust.

P1090/73. 242.22 mm. NAMBA FORMATION. Microphotos 5:25

NAME: Laminated pyritic carbonaceous kaolinite - illite - smectite lutite.

XRD: At 242.85 mm (P1076/73) gave <2μ=18%; S:D, K:A-SD, M & RI:A. A nodule of sulphide gave Py:D, Mel:SD, K:A, Q & Gt:Tr.

FRAMEWORK: none

MATRIX:
Clays. ?Smectite 60% (high birefringent), ?kaolinite 30% (low birefingent), some irregular pure patches, illite/mica 8% in small high birefringent flakes. All intergrown, flakes 1-25μ long.

Carbonaceous matter 2-3%. In layers, defines lamination, oriented parallel in contrast to clays, which have recrystallized.

Pyrite-marcasite 1%. 0.005 mm, mixed with carbonaceous matter.

TEXTURE No fining upwards in lamellae.

P1086/73. 190.06 m. NAMBA FORMATION. Microphoto 1: 2-4.

NAME: Fine sandy mud: quartz smectite - kaolinite lutite

FRAMEWORK
Quartz 40-50%. Angular, very poorly sorted. Average size of larger grains 0.14 mm, small 0.02 mm, smaller grains partly produced by reaction between matrix and quartz. Composites 2-3%, of small individuals with zig-zag contacts.

Feldspar. Rare. 1-2 grains plagioclase, microcline.

Chert. Rare. Ferruginous microcrystalline quartz. Could be porphyry matrix.

Carbonate. Small micrite clasts, subangular.

MATRIX:
Clay 50-60%. ?Smectite and ?kaolinite. Prominent criss-cross structure, following straight boundaries of quartz grains. Much has reacted with quartz, producing embayments and disintegration.

Ferruginous oxides 5%. Hematite or goethite (orange-brown). Follows clay fabric, may cut across it. Terminates against fractures (skew planes).

TEXTURE
Grains scattered in patches through clay. Strong orientation of clay parallel to skew planes (subcutans or stress cutans). Resembles a soils, though no true cutans.

P1083/73. 131.70 m. NAMBA FORMATION. Microphoto 1: 5-7.

NAME: Muddy medium sand: immature intraclastic clay - smectite - kaolinite quartzarenite.

FRAMEWORK
Quartz 55-65%. Grain size 0.3 mm, moderately well to poorly sorted, subangular. Large grains, mostly simple with straight or slightly inclined extinction. Some composites - few individuals, with ragged zig-zag or simple contacts. A few with undulose extinction. Overgrowths moderately common, some excellent examples: follow original elongate grain shape, therefore abrasion tends to produce elongation in the C- axis direction. Marked lack of composites compared with the Namba Formation. Strong reaction with matrix has skeletonized grains and caused increase in fines 0.02 - 0.05 mm size. Also embays overgrowths.

Feldspar. Plagioclase (rare) 0.05 mm. Albite twinned, partly replaced with clay along twin planes.

Chert. Rare. Microcrystalline quartz, coarser stringers of microquartz. Slightly smaller grainsize than quartz.

Rock fragments other than chert 2%

Clay clasts - large mudflakes plus smaller angular forms. Coarse-textured ?kaolinite with 5% fine silt to sand (angular, one grain with overgrowths). Grains in clasts corroded like those of host.

Carbonate - Well rounded micrite. Rare, small.

MATRIX
Clay 35-45%. Kaolinite, smectite. Coarse criss-cross structure. Patches and crude layers are richer in one or the other clay.

TEXTURE
Grains 'float' in clay matrix. Crude lenticular banding of clay- sand and silty-clay.

WERTALOONA 1 BORE

P1269/73. 141.80 m. NAMBA FORMATION. Microphotos 5: 2-6
(MP1471/74)

NAME: Muddy fine sand. Submature cherty subarkose.

ANALYSIS - Grain size FS/PS/SFSk/ELK.

FRAMEWORK
Quartz 85-90%. 0.1 - 0.2 mm, subrounded, made angular by matrix - reaction. 50% with straight extinction. Slightly to moderately undulose extinction common, often associated with semicomposites. Simple composites with few individuals, rare types with variable grain size, zig-zag contacts. Most grains clear, some with mica and tourmaline inclusions. Some with 'rutile' needles (?sillimanite).

Feldspars 2-5%

Plagioclase 1%. Clear albite twins. Ave. size 0.1 mm, with 10 or so lamellae, or few broad diffuse lamellae.

Microline 2%. Patchy - twinned grains, some intergrown with albite. Ave. size 0.18 mm. Some have leaf-like lamellae, not extending across grains. Some may be plagioclase. Some perthitic. Irregular lamellae and sericitic alteration is common in grid-twinned grains. Same size as other feldspar.

Orthoclase 2-3%. Untwinned. Ave. size 0.15 mm, generally better rounded than other grains. Usually dusty appearance, with 'sericite' and brown stain. Sometimes intergrown with quartz.

Chert ½%. Size as for quartz. Types (1) & (2) common, others rare.
(1) Homogenous, very fine grained, 5-7 µ (rare larger grains in a ground mass of 5-7µ) some orange stained.
(2) Irregular, patchy, 1µ - 15µ.
(3) Fibrous, coarse, chalcedonic. Length fast or slow. Grains 0.28 mm long, 5-6 sets of spherules.
(4) Grouped patches - patches 0.016 mm of grains 1-2µ, extinguishing simultaneously. Brown stained. Sets of patches also extinguish simultaneously. Probably a fine quartz-rich metamorphic rock.

Rock fragments

Feldspathic. A few grains, quartz with either untwinned plagioclase or orthoclase.

Quartzite. Very fine (0.012-0.037) sized grains, coarser at margins; plus possibly, type (4) chert above.

Tourmaline Tr. Grain size as for quartz, pleochroic, greenish brown to colourless(schorl or dravite).

Staurolite Tr. Pleochroic orange brown to pale yellow.

MATRIX
Clay 5-10%. Grain size 2μ, 1st order red birefringence therefore smectite or illite.

P1252/73. 60.00 m. NAMBA FORMATION. Microphoto 1:28-34.

NAME: Burrowed mud: kaolinite - illite - RI dolomicrite.

XRD Dol & RI:CD, M:SD, K:A, Q:Tr. <2μ:RI, M, K.
Light grey parts:- Dol:D, M:SD, K:A, Q:Tr.) RI not detected
Dark grey:- M:D, Dol:SD, K:A, Q:Tr.) - unoriented.

FRAMEWORK
Quartz Tr. A few very fine silt grains, broken. Angular. Fuzzy borders, showing solution (?by carbonate-rich pore water).

Intraclasts. One large (2 mm) well rounded micrite grain, grading to matrix along the boundary. "Ghosts" of others present.

Ooliths - Pisoliths. Rare, of coarsely crystalline clay (some are probably cross-sections of canals or burrows). Large 0.5 - 0.7 mm. One oolith is cut by a canal (see below).

MATRIX 98%
Micritic carbonate 1-5μ, no obvious clay, though XRD and swelling properties suggest high palygorskite content. XRD indicates mostly RI and illite/mica. At 625x, high porosity was observed. Some pores occupied by low refractive index clay flakes.
About 40% referred to micrite is dark patches, almost isotropic, probably very fine, low birefringent clay (RI?).

TEXTURE
Burrows. Well developed, 4 mm diameterm saucer-shaped laminae (spreiten). Lamination caused by differing orientation and packing of grains, differing concentration of dark stain (C?) and alignment of minute pores (sometimes clay-filled). Some have irregular pelletal structure, large voids. Several generations of burrows are present - those preserved are the last-formed in a thoroughly bioturbated sediment. The burrows are mostly parallel to bedding. One ?burrow has a well developed clay cutans, and a central canal filled with coarse clay grains and opaque dust - suggests soil processes operative.

Canals. Numerous fine pores, 0.027 mm diameter,with a concentric zone of secondary fuzzy micrite and opaque dust (Mn oxide). Opaque material in canals is mainly sludge and grinding dust, though some may be carbonaceous filaments. Sometimes the canals are filled by clear micrite. They tend to follow boundaries of burrows and burrow laminae and are concentrated in burrowed zones.

Gastropod ??. One spiral structure 0.37 mm diameter, possibly a protoconch.

CSIRO543 54.43 m. NAMBA FORMATION. Microphoto 1:18 20-22, 27

NAME: Burrowed mud: marmorized illite, smectite intraclastic RI-kaolinite lutite.

FRAMEWORK: none.

MATRIX

Low birefringent (wh. to l.gy.) fine clay with 20-40% intraclasts, and 'ghosts' of intraclasts (papules) of coarse yellow-orange birefringent clay, rimmed on one side with orange brown to black iron oxides.

TEXTURE

In hand specimen, resembles intraclasts resulting from thixotropic behaviour, subsequently burrowed. Elongate cylindrical burrows are not laminated, and may be root holes. In this section, all gradations from 'ghost'-like to recrystallized intraclasts are observed. Some have thick, one sided, iron oxide rims (orange). Recrystallization intensifies with development of iron, extreme development resulting in spherular clay bodies with uniaxial cross under crossed polars and iron oxide rims. Textures in the fine matrix carry through into the ferruginized zone. The 'ghost' intraclasts are distinguished by differently orientated clay flakes, producing a well defined border limiting the area within (the clast). They are all rounded.

The clasts sometimes resemble mudflakes, and may have upturned rims. Iron is mainly on the upper side. Iron oxide appears to be 'sweated out' of intraclasts as they recrystallize. Iron oxides form nebulous areas in partly recrystallized matrix, without clasts. Soil students would call these papules, and relate them to soil processes. It is suggested here that ferruginization and recrystallization, resulting from incipient soil formation, have picked out original subtle bioturbation and thixotropic structures.

The recrystallization in the papules is superposed on that of the diagenetically modified flaky clay texture typical of Lake Frome Tertiary rocks in general, and observed in the matrix elsewhere and this specimen.

YALKALPO 1 BORE

P1021/73. 33.40 m. NAMBA FORMATION. Microphoto 3:24-37, 4: 1-4.
(MP4047/73)

NAME: Medium sand: submature to mature feldspar chert ?smectite quartzarenite.

ANALYSIS. Grain size FS/PS/SFSk/ELK

FRAMEWORK

Quartz 85%. Grain size 0.1 - 0.2 mm. Subrounded to well rounded. Frequently embayed as a result of reaction with matrix. Mostly simple grains, 15% undulose extinction, 2% composites. Composites usually 2-3 grains, but a number have many small grains with diffuse zig-zag contacts, may have undulose extinction cutting across grain boundaries. Some of the composites, probably metamorphic, have sets of individuals which extinguish simultaneously.

There are inclusions of bands of opaques and bubbles at varying angles to undulose extinction, though some have flamboyant structure parallel to undulose extinction. Criss-cross 'rutile' hairs in some, one has tourmaline laths.

Feldspar 2%

Orthoclase. Common (untwinned). Crystal borders or cleavage bound grains. Sericitic alteration and cleavage visible. Usually distinctive lath shape. Some originally well-rounded, but reaction with matrix produces ragged sharp edges. One Baveno twin.

Microline. Common. Grid twins: fine and coarse albite - pericline. Irregular grains partly altered to clay. Irregular embayed margins.

Plagioclase. Tr. Difficult to distinguish from microcline with coarse grid twins in small grains.

Chert 2%. Commonest type has crypto-crystalline quartz with coarser 0.02 - 0.03 mm patches, grading to very fine forms without coarse patches. Generally smaller than quartz, some well-rounded. Rarer type has radiating fibrous structure with a V-shaped arrangement of fibres within each radiae ('herring-bone' structure). A 0.64 mm irregular grain of spherular chalcedony is present - may be a void infilling, indicating incipient silicification (also observed in other Namba Formation sands).

Rock Fragments. Tr. Quartz-sericite fragments. Metaquartzite is listed under quartz.

Unknown. A few grains of high relief ($\gamma - \alpha = 0.022$) biaxial mineral.

MATRIX
Clay 10%. Smectite, as well oriented fibres or flakes.

TEXTURE
Clay flakes follow framework borders. Framework grains often in contact. Moderate porosity.

EAR 6

P1154/73. 44.00 m. NAMBA FORMATION. Microphoto 4: 24-28.
~~(MP5377/72)~~

NAME: Carbonate mud: palygorskite dolomicrite.

XRD. $< 2\mu = 70-80\%$. Dol:D, P:A-SD.

FRAMEWORK: None - rare fossil fragments (ostracode shell).

MATRIX 98%.
Finely laminated (0.055 mm), with alternating clay and micrite-rich bands. Broad patchy extinction of palygorskite superposed on micrite. Some laminae 90% clay, and clay oriented such that whole band has maximum birefringence at 45° to layers: thus fibres are parallel to bedding. Cracks are infilled by coarse clay. Strings and patches of dark iron oxides are parallel to the bedding. Micrite and clay is 0.5 - 0.25μ diameter. Branching sinusoidal texture is sometimes visible, branches 3μ wide (clotted texture) Stylolites are present.

EAR7

P1101/73. 53.24 m. NAMBA FORMATION. Microphoto 2: 8~~7~~-22.
(MP5074/73)

NAME: Calcreted oolitic pellmicrite. Described in terms of three regions, in order of succession.

(1) Lower part.

FRAMEWORK

Ooliths and pellets 50-55%. Complex coated intraclasts and pellets (ooliths), envelopes laminated. Vary from elongate rods and irregular lumps to ovoids, moderately to poorly sorted, average size 0.3 mm, ranging from 0.1 to 1.0 mm. Most oolith cores, are rounded to well-rounded, though a few are angular. Sometimes several ooliths are cemented together by a single envelope.

In the envelope, micrite layers may alternate with radial. Envelopes are 0.03 - 0.06 mm thick of layers 0.9μ thick. Some layers are darker than others. 5-10 layers commonest. Irregularities in the core are smoothed out, and may be infilled with micrite. Some have partially spalled envelopes, which are encased in new crust.

Pellets of homogenous dark micrite, identical to the matrix, and to other pellets without coatings, constitute the cores. Others are of lighter micrite with darker (ferruginous?) stain. Some have brecciated micrite cores. The pellets grade to large highly complex irregular intraclasts. Just beneath the calcrete crust (2) pellets have no envelopes, are well sorted, 0.08 mm diameter, spherical and homogenous. A complex large clast also occurs in this zone.

MATRIX

Very dark micrite with mottled diffuse pelletal structure. Grain size 1.5 - 2.5μ.

(2) Middle part - calcrete crust.

Orange coloured banded micrite, aphanocrystalline, coating solution surface developed on (1), pockmarked with solution cavities. One cavity has a micrite coat and contains ooliths orientated parallel to its sides. Another contains a clast with a one-sided laminated coating on its presumed upper side. The cavities are apparently geopetal structures.

(3) Upper Portion.

Consists of 50-60% pellets without crusts, small and spherical. These become elongate rods above the solution cavities, perhaps as a result of plastic deformation during compaction. The matrix here is of dense pale to dark grey or orange micrite with very irregular vughs and diffuse irregular micrite lumps. Some pellets are squashed envelopes, and a few have radial cracks, infilled with micrite.

One area shows several generations of micrite crust, solution surfaces, and deposition. A few well-developed ooliths are present, some truncated by a scolloped solution surface.

TEXTURE

The ooliths, scattered through a bioturbated micrite matrix, are regarded as primary features. The solution surfaces, calcrete crusts, and carbonate deposition, alternated. Some of the pellets are oriented parallel to the burrows, but normally are unoriented and scattered through the micrite.

~~WG2 BORE~~

P1103/73. 54.86 m. NAMBA FORMATION. Microphoto 2: 23-28.
(MP5074/73)

NAME: Dolo-oomicrite.

OOLITHS 55%. Ave. 0.6 mm, ranging from 0.14 to 1.1 mm, strong contrast with 1101, having small micrite cores, greater sphericity, sorting, and evenly spread through the matrix. A few intraclasts of blotchy plate-like micrite with thin coatings are present. In the envelopes unoriented micrite and microspar alternate with radial oriented crystallite layers. Centres are frequently dissolved, causing shrinkage and cracking of the core. A common feature is wavy lamination, resembling stromatolites. Between the columns, lamination is diffuse or absent. The features resemble oncolites of some workers. Radial symmetry differs from most oncolites, which are generally very one-sided.

MATRIX
Dark grey clotted micrite.

WC2 BORE

P1104/72. 75.13 m. WILLAWORTINA FORMATION. Microphoto: Film 4: 30-33.
(MP5294/72)

NAME: Extremely poorly sorted muddy medium silt: immature smectite-mica-RI-plagioclase-microcline subarkose.

XRD Q:D, KF & NaF:CD, M:SD, K:A, S:?A
$< 2\mu = 42\%$. RI:D, M:SD, S:A-SD, K:A.

FRAMEWORK
Quartz 50%. Angular and very poorly sorted

Feldspars 5-6%. Much lower percentage than indicated by XRD: much has probably partly broken from matrix.

Plagioclase. Fine and coarse albite twins. Much is very fine grained and in matrix. Alb-Oligoclase commonest. Michel-Levy method: An_{12} or 28, An_{17} or 22, An_{9} or 31, An_{9}. Fourque method: An_{15} or 25, An_{32}. One zoned grain with untwinned core.

Microcline. Fine grid twinning, coarser pericline-alb. twins. Commoner than plagioclase.

Untwinned. (Orthoclase)
Carlsbad 1 grain

Perthite. Microcline and orthoclase tupes.

Chert. Irregular coarse and fine-patch chert.

Rock fragments 1%. Microcline - quartz, plagioclase-quartz, orthoclase - quartz. Some mixed feldspars. Large grains only.

Mica 2%. Some greenish - probably biotite.

Zircon. Several grains 0.08 mm size.

Chlorite. Large detrital grains may be biotite.

MATRIX

Clays. (see XRD) 40-45%. Grain size 15μ, stained orange and speckled with minute orange translucent grains.

TEXTURE

Grains partly corroded by matrix reaction, separated by clay. Clay shows criss-cross structure.

YALKALPO 1 BORE

P1048/73. 81.43 m. EYRE FORMATION. Microphoto: Film 4: 22. (MP4047/73)

NAME: Medium sand. Mature carbonaceous and pyritic cherty quartzarenite.

ANALYSIS (1) Grain size FS/PS/SYM/VPK
(2) XRD of +240 mesh - K

FRAMEWORK

Quartz 85-90%. Ave. size 0.41 mm ranging 0.04 - 0.76 mm, subrounded to rounded, some very irregular-shaped. Composites 3-5% as for 1046, inequigranular fine-grained varieties commonest often with subparallel elongation and strain shadows. Semi-composites are as common. Some have criss-cross or radiating bands of ?ferruginous dust, often associated with fractures. Small mica crystal in one grain. A very small composite grain has clusters of small ?corundum crystals.

Feldspar. A few grains of orthoclase (untwinned).

Chert. Tr 1%. Inequigranular, fine sutured contacts, with bands of coarser microquartz. Very well rounded. One grain has a vein of fine-grained quartz along one edge, and contains spots of clay and ferruginous material.

Other rock fragments (1) Ferricrete? - one large goethite grain. Ferruginized cherty quartz (silcrete?). (2) Clay or chert? Diffuse coarse clay, heavily stained by iron oxide, rimmed by goethite or pyrite. ?Coarse kaolinite. Criss-crossed by veins of micro-quartz, largely replaced by iron oxides. Well rounded. Individuals have radiating structure in the composite grains. Some probably recrystallized volcanics *c.f.* P1048/73, P70/74 (porphyry and chert).

Gypsum. Well crystallized twinned gypsum, same size as quartz poikillitic when fine material present.

MATRIX

Opaques 8%. Intergranular black - sulphide
brownish - carbonaceous.

Clay 2-5%. Granular kaolinite, very fine and yellowish.

B240 C3 BORE

P1134/73. 111.72 m. EYRE FORMATION. Microphoto: Film 2: 31-34. (MP5377/73)

NAME: Very coarse sandy mud: muscovite quartz kaolinite lutite

XRD: K:D, Q:SD, M:A; < 2μ = K:D, M:SD

FRAMEWORK

Quartz 15%. Grain size 0.11 - 1.5 mm, coarse grains commonest. Very poorly sorted, very angular to subrounded. Some lath-like grains (crystal prisms) with intense strain phenomena and twin-like planes. Deeply penetrating grooves infilled with kaolinite are common - these do not follow strain boundaries, but are parallel to lines of ferruginous inclusions.

Mica. A few large flakes.

MATRIX

Kaolinite 85%. Remarkable banded conical structures developed on upward side of inhomogeneities in original fabric (e.g. quartz grains). The banding is produced by dark brown granules of minute size concentrated on the outside of the band. Bands have a radial fibrous effect, which often cuts across the concentric staining. Some minute illite flakes are parallel to the layers. The conical structures merge into bands parallel to the bedding. The bands often have gaps, occupied by normal-textured clay. The secondary banded structure appears to be the result of extreme soil-differentiation processes perhaps analogous to calcrete or silcrete banding, or perhaps caused by groundwater movements.

Elsewhere the fabric is granular or lattisepic.

TEXTURE

Partly skeletonized large angular quartz grains supported by kaolinite, which has been reconstituted into bands parallel to the bedding (and therefore the ground surface).

REEDY SPRINGS

P298/72. Base of section, in conglomerate. Microphoto: Film 3: 0,1.
(MP5113/72)

NAME: Sandy pebble conglomerate: calcite cemented quartzite chert rudite.

FRAMEWORK - Summary description.

Quartz 50%. Medium grained, ranging from very fine to very coarse, prismatic grains common. Includes many grains *c.f.* pebbles, described separately.

Tourmaline)
Zircon) A few grains. Tourm.-blue, zoned.

Chert. Grains of chert (as for pebble (1) below). Inequigranular with sharp boundaries between individuals. Equigranular chert with straight coarser veins. Some have oriented individuals. Spherulitic chalcedony also present.

PEBBLES (1). Brecciated chert. Matrix to breccia fragments has variable grainsize, sometimes quite coarse. Finer grained parts contain some irregular clasts with distorted internal structure.

(2). Laminated chert. Finer texture than in P297, similar to (1) above.,

(3). Quartzite, with equigranular simple individuals having euhedral contacts. Rather coarse.

(4). Quartzite. Fine grained, equigranular, with patchy undulose extinction.

Rock fragments
Volcanic grains with snowflake texture. Small, rare.

MATRIX
Mainly microspar and voids, some clay and very fine quartz.

OUTCROP

P848/71. QUIN 1/9711/1A. 'Coarse Mature Sand Unit' probably NAMBA FORMATION. Microphoto: Film: 5: 11-12.
(MP457/72) Summary Description

NAME: Fine sand: calcreted, silcreted and ferruginized quartzarenite.

FRAMEWORK
Mostly angular quartz, subangular to angular, elongate. Ave. size 0.15 - 0.17 mm. Occasional tourmaline and heavy minerals. Grains with numerous criss-crossing lines of minute inclusions or with scattered laths (tourmaline?). Strong orientation. Well sorted. Chert common and very altered. No feldspar.

MATRIX
Secondary - grains thickly coated with goethite. Intergranular voids have then been lined with micro-crystalline quartz chert, remaining space has then been filled with radiating spherular aggregates of length-fast chalcedony. Carbonate replaces the microquartz chert, but not the chalcedony, and is invariably separated from framework grain borders by a thin layer of microcrystalline quartz chert. Other specimens at this locality and elsewhere show carbonate was introduced after the fibrous chalcedony.

APPENDIX 2

PETROLOGY - TECHNIQUES

Petrological results are given in abbreviated form on the detailed logs, examples of comprehensive descriptions in this appendix. Most were described in summary form. The schemes used followed Folk (1968). No attempt was made to identify all heavy minerals or opaques present, but light minerals are described in detail. The examples chosen to represent the Namba Formation and lower part of the Willawortina Formation are from Wooltana 1 bore which contains the greatest lithological variation. The bore WC2 is used to illustrate the coarser facies of the Willawortina Formation, and PMX24a bore and Reedy Springs outcrop for the Eyre Formation.

Feldspar twin types and plagioclase compositions were recorded (Gorai 1951, Van der Plas 1966). Flat stage techniques were used to measure compositions, using mainly the Michel-Levy and Fourque methods. The Michel-Levy method is a statistical technique, therefore cannot be applied readily to sediments in which the feldspar assemblage is inhomogeneous. Each measurement gives two possible compositions for the more sodic plagioclases. In most cases the refractive index relative to quartz could not be determined because of the matrix supported texture. Even in sands, grains were separated by a film of clay, preventing the Becke line from being observed. A general idea of relative refractive index could be obtained by relief relative to quartz. It was generally low or close to quartz. Samples mounted in refractive index oils were generally less than 1.55 - i.e. at the albitic end of the spectrum. However, the difference in refractive index between the three optical axis directions varies so much that this is no more than a rough guide. Occasionally the Fourque method gave a unique determination (amounting to 10 or so grains) in nearly all cases indicating albite.

The number of determinations for a particular composition were plotted on a bar graph, producing two sets of peak-pairs, indicative two component feldspar compositions were dominant (see main text). The comments above suggest the more sodic compositions are applicable.

A similar study of feldspars in the crystalline basement rock in presumed source areas was carried out by AMDEL personnel from specimens collected by other workers, supplemented by those of the writer in the Olary and Barrier Ranges regions. These provided a basis for comparison. Few samples of Adelaide Geosyncline sediments were examined, except where they were known to have a high feldspar content and extensive outcrop. A detailed breakdown of samples used is presented, and a list of Amdel reports and authors follows. A list of basement samples within the basin (particularly on the Benagerie Ridge) is given, all of which were collected and examined by the writer in thin-section. Some of these were also reported by AMDEL (listed).

The microscope used in these studies was a Leitz laborlux pole with binocular head and 1X,4.2X,10X, 25X and 50X objectives and 12.5X occulars. A pinhole device was constructed for obtaining optical figures.

Sand grains were observed with a binocular microscope.

Authors of reports and dates are given in appendices 3 & 5 if not specified here.

CRYSTALLINE BASEMENT AND ADELAIDE GEOSYNCLINE

These rocks were described by AMDEL personnel and checked by the writer.

AUTHOR	AMDEL MP REPORT NUMBER	DATE	NUMBER OF SPECIMENS
	1244/71		14
	5377/73		4
	3169/72		1
	707/72		2
	1592/71		1
	5113/72		2
	457/72		1
Steveson, B.G.	3552/72	24.3.72	3
__________	4047/73	17.4.73	7
__________ & Brown, R.N.	2275/71	5.1.71	3
		TOTAL	38

AUTHOR	AMDEL MP REPORT NUMBER	DATE	NUMBER OF SPECIMENS
	CRETACEOUS		
	707/72		6
	5377/73		1
	4047/73		2
	3783/74		1
Williams, G. & Holland, J.	3167/68	7.5.68	2
		TOTAL	12

Approximately 20 thin sections of Cretaceous rocks from northern South Australia were also examined, provided by Dr. H. Wopfner, now of Universität Köln, KÖLN 5, W. GERMANY.

	EYRE FORMATION		
	707/72		2
	4278/72		1
	5377/73		8
	5113/72		6
	1244/71		2
	457/72		1
	4047/73		2
	1270/71	30.9.70	1
		TOTAL	23
	OLDER SILCRETE		
	2989/73		3

Approximately 10 specimens of silcretes from Lake Palankarinna were also sectioned and examined.

	NAMBA FORMATION		
	5294/72		7
	4278/72		15
	5074/73		22
	4047/73		6
	5377/73		4
	3636/72		1
	1592/71		1
	4277/72		10
	457/72		28
	1471/74		15
Davy, R.	11/71	12.8.70	2
Brewer, R.	CSIRO	1974	1
		TOTAL	110

This includes the alunite horizon specimens (7)

AUTHOR	AMDEL MP REPORT NUMBER	DATE	NUMBER OF SPECIMENS
	ETADUNNA FORMATION		
	5527/72		10

'Coarse Mature Sand' unit, of NAMBA FORMATION

	1980/75		3
Brown, R.N. & Davy, R.	457/72	14.1.72	14
		TOTAL	17

YOUNGER SILCRETE, FERRICRETE

	4277/72		1
	1244/72		3
	3636/72		1
	457/72		4
	1980/75		1
	4542/69		1
Steveson, B.G.	3783/74	10.6.74	1
	P1113/1123/72(no MP number)		8
Steveson, B.G.	1235/72	20.9.71	1
		TOTAL	21

Note: Some of these specimens are also specimens of Namba Formation.

WILLAWORTINA FORMATION

	4278/72		1
	11/71		1
	1244/71		1
	2182/70		1
	5294/72		4
	3167/68		2
	1471/74		1
	457/72		5
Whitehead, S. & Brown, R.N.	3783/74	10.6.74	8
		TOTAL	24

FELDSPAR STUDIES OF PRE-CRETACEOUS ROCKS(MAINLY CRYSTALLINE BASEMENT INLIERS)

Petrological reports supplied.

AUTHOR	AMDEL MP No.	AREA	No. SPECIMENS
Steveson, B.G.	MP 3552/72	Mt. Painter, Broken Hill, Olary	49
Cooper, R.	MP 4856/74	Olary	8
Davy, R.	MP 4415/72	Olary	14
Simpson, P.J.	339/71	Mt. Painter	3
	MP 2430/71	Olary	-
	MP 1549/72	Olary	-
			74

APPENDIX 3

CLAY MINERALOGY

In general both whole rock and < 2μ fraction of samples were xray. The unoriented whole rock samples gave information on the overall mineral content, the oriented < 2μ fraction was used to differentiate clay minerals and determine their relative abundance. Mineral percentages were estimated by calculating the ratio of peak height to width at half height, on standard diffraction traces produced by a Phillips PW1050 Diffractometer. Identifications were made by Dr. R. Brown of the Australian Mineral Development Laboratories, Frewville, S. Australia, a list of his reports is included. The writer familiarized himself with techniques and methods of identification.

The < 2μ fraction oriented samples produce well defined basal reflections. Use of this fraction restricts the sample to a mud essentially of clay minerals. It also facilitates comparison between different lithotypes by eliminating the effects of dilution by other minerals. Procedure was as follows:

(1) Disperse 10 gms in 400 mls water by use of a vitamizer (approx. 2 mins). Add 0.25ml. 1N NaOH and 2.5 mls 10% Calgon to assist dispersion.

(2) Place sample in a 5 cm diameter burette, stir with paddle for known time. The temperature was noted to permit calculation of a temperature correction, at the appropriate time for removal of the < 2μ fraction. Generally the sample was taken from 20 cms after 16 hrs of settling, using a pipette, and weighed on a plummett balance to determine < 2μ in the original.

(3) Methods and accuracy are discussed by Gibbs (1967), who recommends the smear on glass slide or suction on ceramic tile technique. The latter was used. The extracted sample (approx. 1 ml, so as to

give a constant thickness between plates) was then placed on a ceramic plate, and water removed by suction, thus orientating the clay flakes. The aggregate was washed to remove calgon and NaOH, and saturated with $MgCl_2$: $Mg^{2}+$ replaces all interlayer cations, so establishing a constant size for comparitive purposes. The plate was then xrayed in the usual manner, using CoK_{α} radiation, through 3^{o} to 30^{o} of 2θ.

(4) Some samples were subsequently treated with ethylene glycol to expand the lattice. Different degrees of expansion occur in different clays.

(5) In some cases heating to $120^{o}C$, $220^{o}C$, and $550^{o}C$ was used for further differentiation, some clays show progressive or sudden changes in peak width, height, and position at certain temperatures.

Identification methods are discussed by Warshaw & Roy (1961) and Brown (1961) and details of line spacings given by Grim (1968). Other details are given in references quoted in the main text. Some examples of interpretations are given in figs. 148-151.

Results of mineral abundance were reported by Brown using the following scheme, accurate to ± 10% for the more abundant minerals:-

D $> 50\%$
SD $> 20\%, < 50\%$
A $\sim 10\%$
Tr $\sim 5\%$

CD - two or more dominant minerals

and are so presented in the detailed logs (figs. 4-9, 17-24, 32, 33, 35).

Randomly interstratified clays were recognised by the presence of "hk" reflections in non-oriented samples, and excessively rising 'background' without well defined peaks at low 2θ, above that expected from primary beam width and scattering effects. The diffractogram frequently showed very low percentages of other minerals, in a hand specimen obviously clay, but gave no peaks diagnostic of definite clay mineral groups. These silicates have their layers stacked in a virtually non random manner. Their presence makes it difficult to estimate percentages of other clays present, since the peak heights are obscured.

A series of generalised logs (Figs. 10-14, 25-31) are also presented, alongside which the relative proportions of clay is given as a bar graph totalling 100%. Each bar is plotted at its appropriate depth. On the clay mineral fence diagram (Fig. 36) the same logs are plotted at reduced scale using a colour scheme to differentiate the clays,

Investigation of the minerals reported as illite by Brown showed both illite and mica present. The mica could be differentiated by its narrow well defined basal reflection, and presence of many additional reflections when compared with illite (Fig. 151).

In some samples carbonate was removed by the action of 1N cold HCl before xraying.

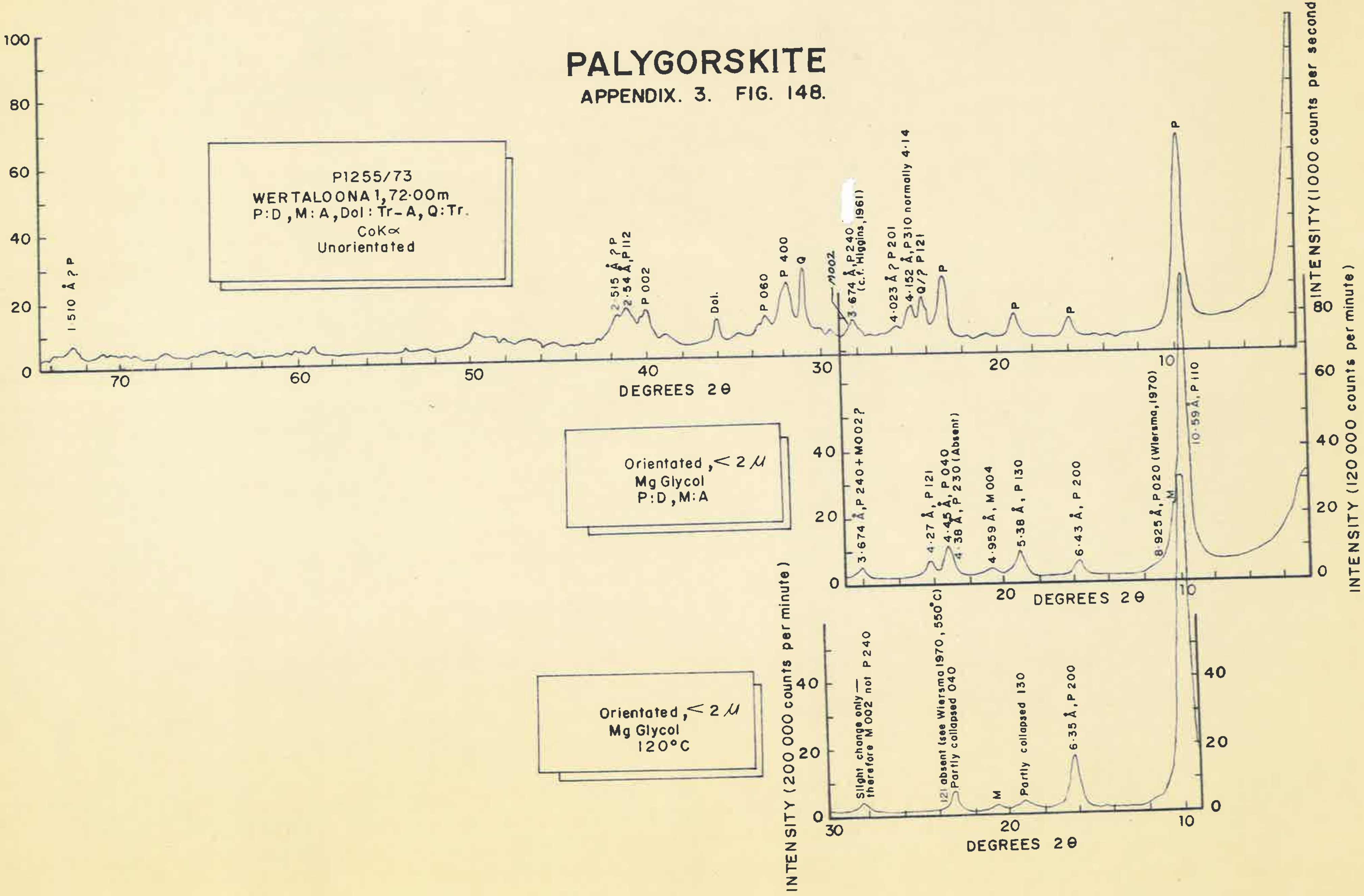
XRAY DIFFRACTION
REPORTS BY AMDEL

			Number of Samples Examined	
Author	Report No.	Date	Clay mineralogy	Whole rock or special purpose
Brown R.N.	MP 231/71	11.8.70	2	
	MP1592/71	1.10.70	8	
	MP4260/72	17.3.72		1
	MP4279/72	20.3.72		1
	MP5113/72	11.5.72		9
	MP3071/73	19.1.73		5
	MP3202/73	25.1.73	1	
	MP2856/73	3.1.73	7	9
	MP5074/73	27.6.73	9	27
	MP5377/73	31.7.73		
		11.7.73	25	11
	MP 485/74	2.8.73		3
	MP1471/74	28.11.73	23	
	MP2844/74	20.2.74	7	
	MP3784/74	16.5.74	18	
	MP3785/74	24.5.74	17	
	MP3885/74	24.5.74	13	
	MP1412/75	9.10.74		1
	MP1833/75	1.11.74	4	
		26.11.74		
	MP3950/74	18.4.75		5

			Number of Samples examined	
Author	Report No.	Date	Clay mineralogy	Whole rock or special purpose
Brown R.N. & Davy R	MP2182/70	4.1.71		7
________ & Henderson P.J.	MP1592/71	30.11.70	4	2
________ & Steveson B.G.	MP4047/73	30.5.73	26	
Collins B., Steveson B. Brown R.N. & Hill R.	MP1244/71	15.1.71		18
Davy R. & Brown R.N.	MP 457/72	14.1.72		11
	MP4277/72	26.4.72		12
	MP4278/72	26.4.72		19
	MP5527/72	18.7.72		13
Radke F. & Brown R.N.	MP3169/72	19.1.72		2
	MP3554/72	7.2.72		2
Steveson B.G.	MP2989/73	23.1.73		3
________ & Brown R.N.	MP5294/72	29.5.72		11
		TOTALS	157	175

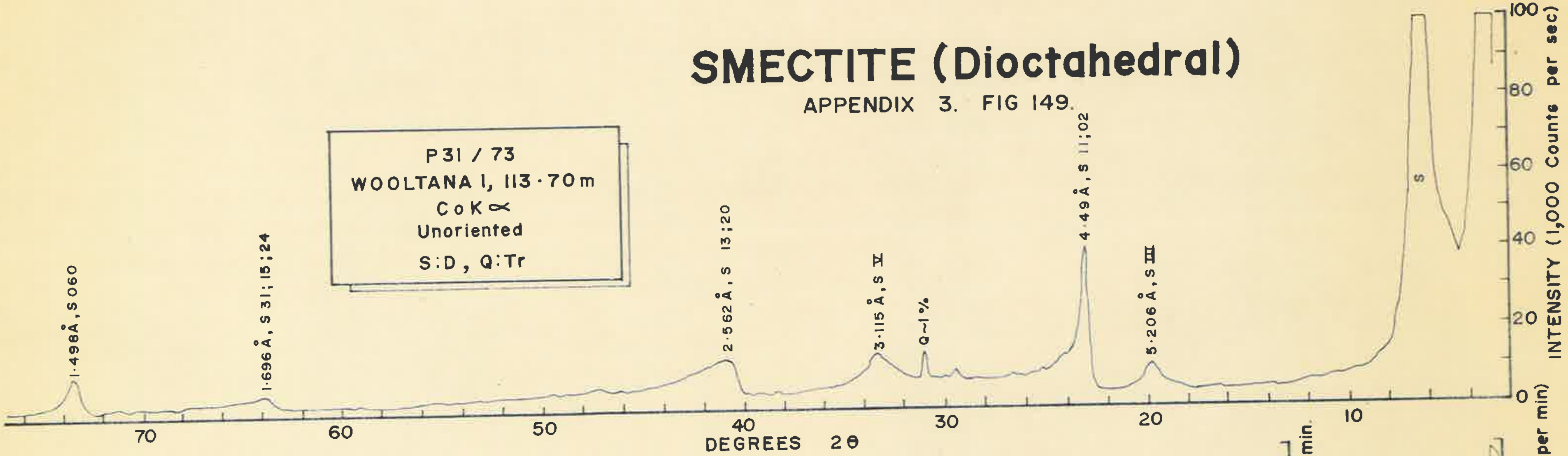
PALYGORSKITE

APPENDIX. 3. FIG. 148.

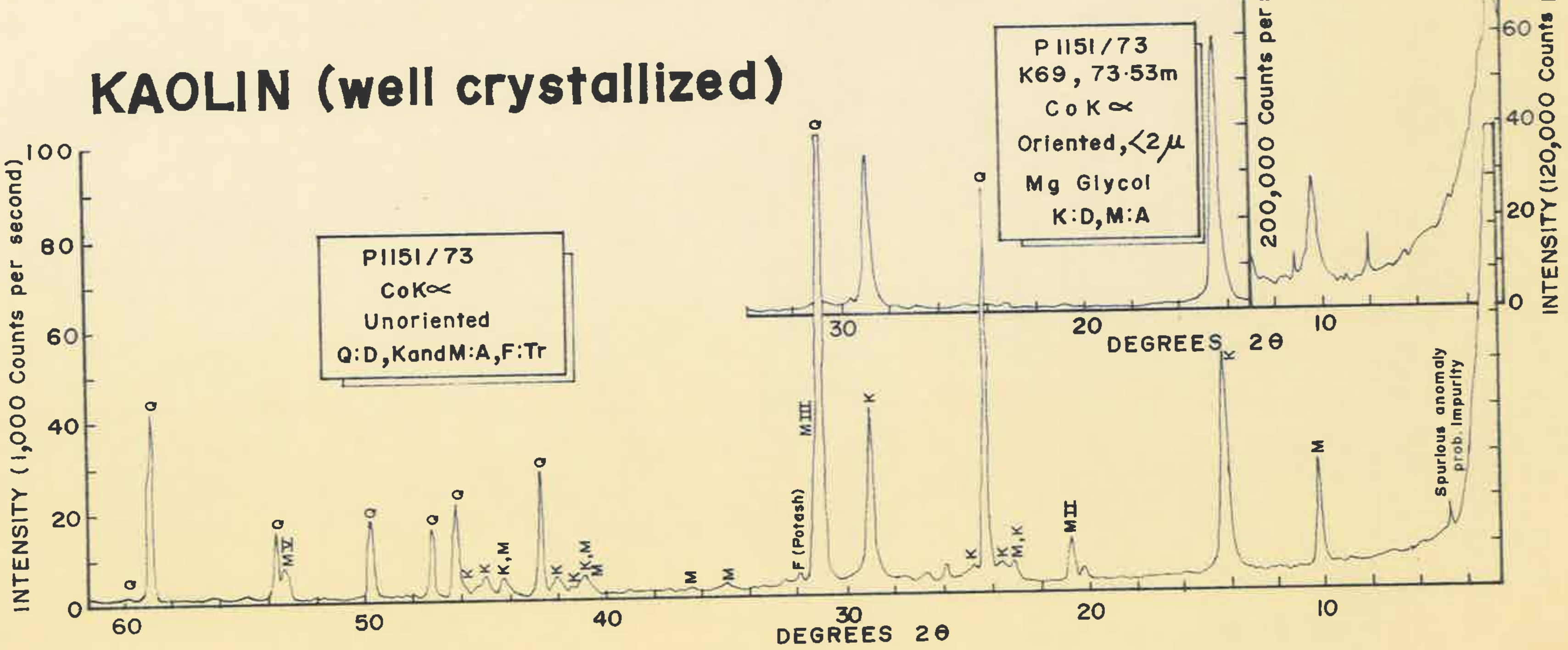


SMECTITE (Dioctahedral)

APPENDIX 3. FIG 149.

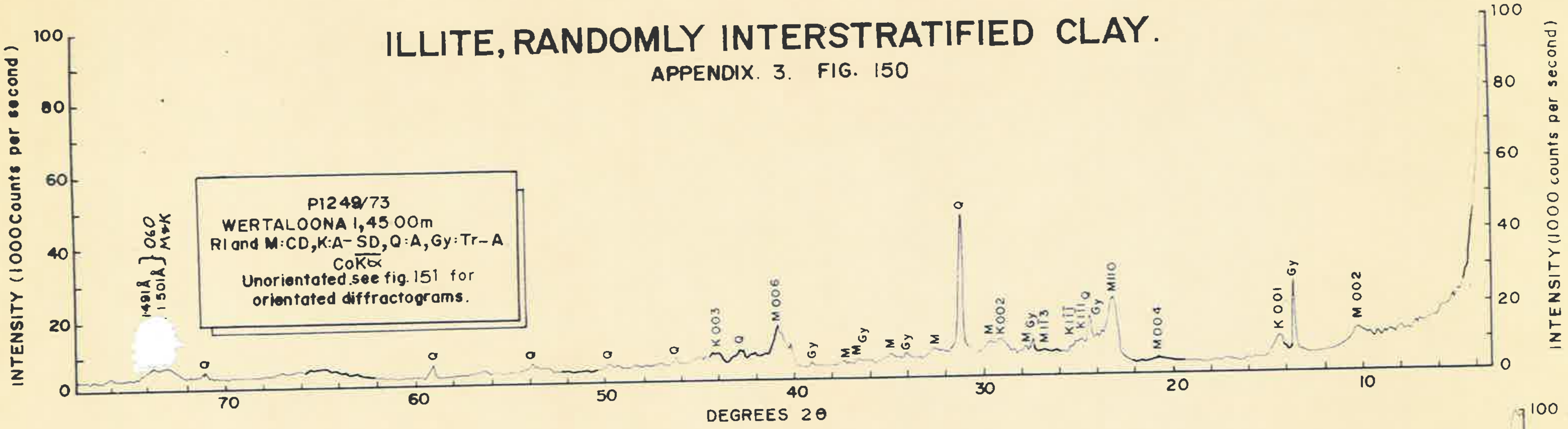


KAOLIN (well crystallized)

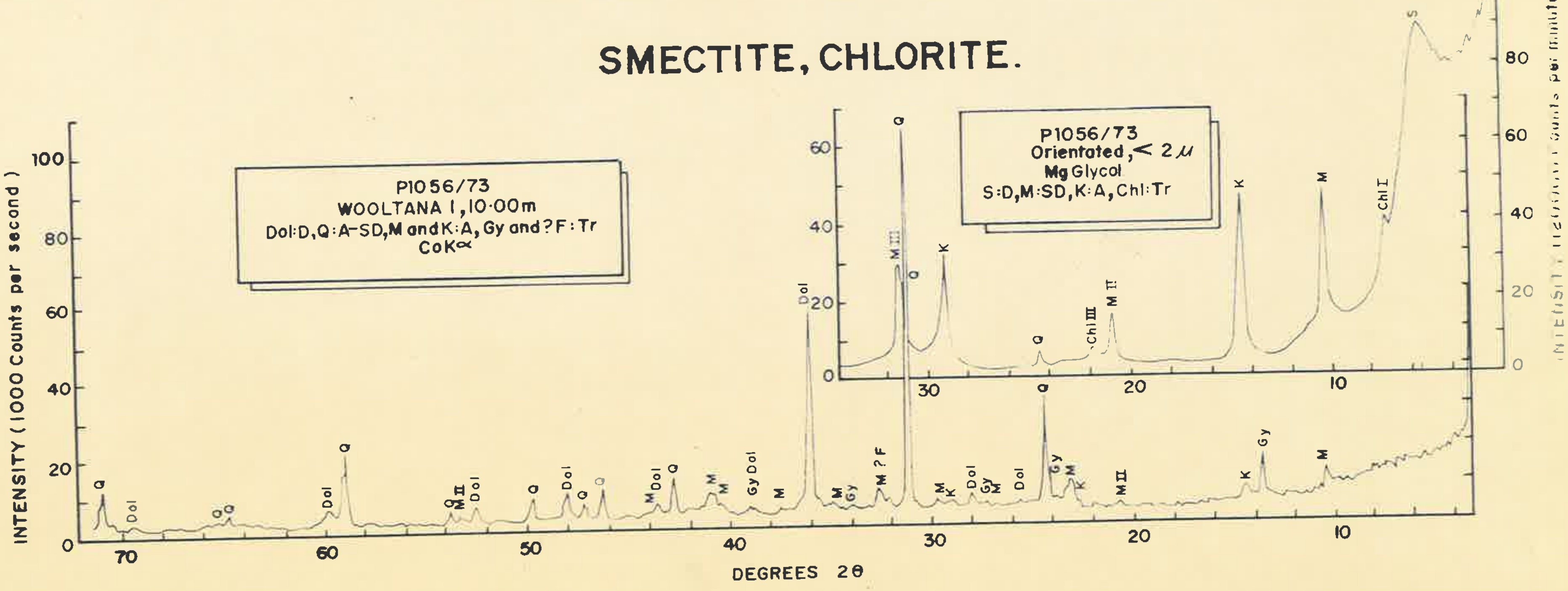


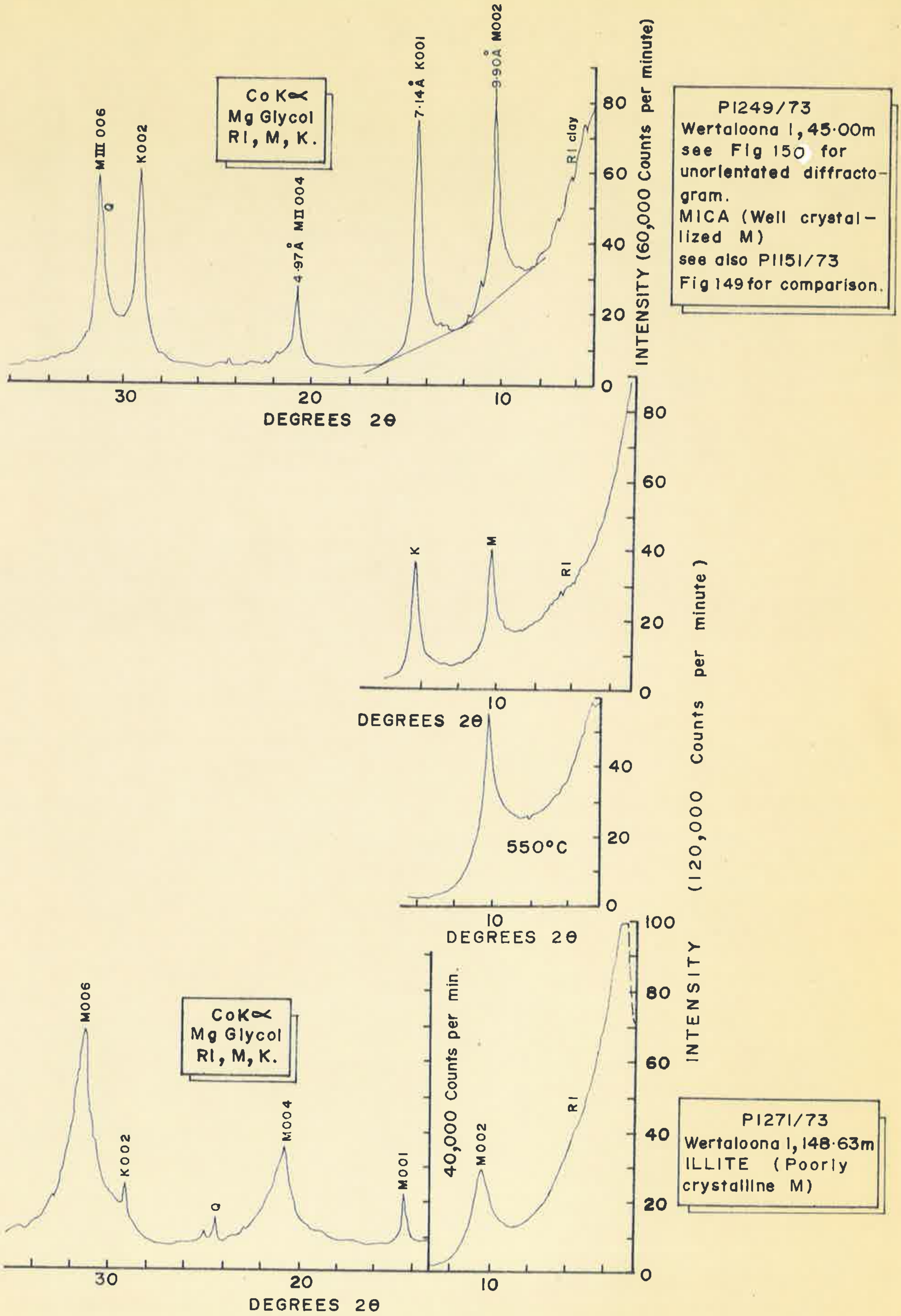
ILLITE, RANDOMLY INTERSTRATIFIED CLAY.

APPENDIX. 3. FIG. 150



SMECTITE, CHLORITE.





P1249/73
Wertaloona 1, 45·00m
see Fig 150 for
unorientated diffractogram.
MICA (Well crystallized M)
see also P1151/73
Fig 149 for comparison.

P1271/73
Wertaloona 1, 148·63m
ILLITE (Poorly
crystalline M)

COMPARISON OF ILLITE AND MICA;
RANDOMLY INTERSTRATIFIED CLAY.
ORIENTED <2μ SAMPLES

APPENDIX 3. FIG 151

APPENDIX 4

PEEL PREPARATION

1. Araldite peels

A method was required for preserving core from distintegration when dry and to reveal obscure structures clearly. A technique modified from Carver (1970, Chap. 10) was used. The core was split with guitar wire, whilst encased in a split plastic drainpipe, held at its ends by an overlapping sleeve. One half of the drainpipe was removed, holding the core, and the surface of the sediment smoothed carefully with a knife. The margins of the core, and cracks were blocked with modelling clay and a wall of clay built around the edge of the area to be peeled.

An araldite mixture (CIBA-GEIGY, Preston, Victoria) was prepared using the components resin and hardener. Two resins were used, one mobile, the other viscous. Mixed in various proportions, these gave mixtures of varying penetrative powers. Each resin required its own particular hardener, added in the appropriate proportions. For deep penetration mobile mixtures and slow hardener were used. The various proportions are given on the detailed logs.

After sufficient hardening a quick-setting mixture was poured on, and a piece of masonite, cut to size, cemented to the peel. After complete hardening, the peel was carefully removed and excess sand or clay washed off.

The relief on the peel reflects the porosity of the rock, and a portion of the sediment remains attached. Cross-stratification and burrowing was revealed in sands, where it had not previously been observed. With deep penetrating mixtures three dimensional casts of burrow systems were formed. The method was unsuccessful in burrowed clayey sediments as there was not enough porosity difference, and the clays were too dense for deep penetration.

e.g. MY752:GY250:HY830:HY850= 40:40:12:36 gms for peel 40-50 cm long
x 4-5 cm wide. Gave good results.

2. Stained Acetate peels

These were prepared from slabbed carbonates by Mr. D. Vinall of the South Australian Geological Survey (see references specified in main text). The strong reaction with acid made it unnecessary to etch the sample beforehand: the acid mixed with the stain was sufficient. The length of time left in the stain depended on the vigour of the reaction.

The reaction was stopped by immediately dousing with distilled water on completion of the reaction time. Peels were stored between glass plates, and examined with a binocular microscope, using pieces of polaroid to produce plarised light.

The peels are listed on the detailed log of Wooltana 1 bore.

APPENDIX 5

GRAIN SIZE ANALYSIS-METHODOLOGY

Samples were collected from cores for grain size analysis so as to be representative of all lithologies, and give a systematic vertical variation in selected holes. The wet sieve and pipette methods were used, following Folk (1968). Pipette work was done by Dr. B. Steveson (Australian Mineral Development Laboratories, Frewville, S. Aust.) and sieving by Mr. K. Howard of the same laboratory, Thebarton branch. Results were reported as cumulative weight percent using combined sieve and pipette results as suggested by Folk.

Sieves were checked for aggregates by binocular microscope, but none of significance was found. In general samples were readily dispersed.

Sieving was accomplished with a bank of BSS sieved at ¼ϕ intervals with a lower limit at 4ϕ, and wire squares were used for sizes > granule size. Sieve banks were shaken in a Pascal Screen Shaker for 15 mins. This process produces results identical to the older Rotap type, but is less likely to cause grain breakages. The Pascal shaker has a vertical vibration of 50-60 cycles/min rotating approximately 1/minute. Sieves were ultrasonically cleaned and optically checked at intervals in accordance with AS1152-1973 (Australian Standards Association). Initial results suggested some of the sieves were not in accordance with the standards, and optical checking revealed two were incorrect. Subsequently the appropriate sieve interval was calculated and results plotted at this interval. Later in the programme one of these sieves was replaced, and eventually a new bank of sieves were used, hence early results have variably spaced sieve interval in the coarser sizes.

The measured sieves are as follows:

BSS size	Measured Size µ
106	102
125	120
150	161
355	346 (just inside BSS standard)
1180	1250-1300 (outside BSS standard)

The corrections were used for results in Amdel Reports 4047/73, 5074/73, 5376/73 only the 1180 sieve correction was necessary in 693/74.

Pipette analyses were made using 58 mm diameter burettes. Initially stirring was done with a rotary mechanical device, but ~~leter~~ later (most of the results) a plunger of the type recommended by Folk (1968) was used. Technique was standardized so as to maintain the same degree of operator error. Checks were made on the operator using split samples, both with and without his knowledge. Results from known duplicate samples are plotted in Fig. 152 and it is observed that error is slight and consistent. Results from unknown duplicates, split approximately by hand, show that sample variability is generally greater than operator error, even in relatively homogenous rocks (Fig. 153). In general the pipetted fraction gave more closely comparable results than the sieved portion (P1279, 1280/73), as would be expected from the relatively wide sieve tolerances. Even where there was considerable difference between samples (P1285, 1288/73), the curves maintain the same shape and cross at the flexure point i.e. the component distributions have the same mean size but variable sorting.

Those samples analysed in duplicate were used to obtain an average curve, which is more representative of the total distribution than for most samples. Moment and graphic size parameters were calculated from the average in these examples. Moments were also calculated from each individual curve for duplicates, in some cases showing differences in skewness and kurtosis as follows:-

	M	σ	Sk	K
(1279	5.67	4.57	0.004	-1.33
(1280	5.50	4.61	0.08	-1.39
(1287	6.09	3.31	1.07	-0.53
(1290	6.11	3.37	0.97	-0.74
(1282	10.19	2.42	-1.04	0.52
(1284	10.27	2.40	-1.17	1.19

	M	σ	Sk	K
(1283	7.68	2.47	0.018	1.12
(1286	7.66	2.23	0.52	0.64
(1285	5.30	3.05	1.17	0.026
(1288	4.88	2.18	1.81	3.14

The last three results show considerable variation in skewness and kurtosis, suggesting moment measures of parameters be used in a generalised sense when making geological deductions. Almost the entire distribution was analysed, hence the differences are not the result of truncation, but reflect the small scale manifestation of inhomogeneity in the sediments.

Problems with gelling occurred in initial pipetting, overcome using an optimum sample size of 20-25 gms for muds. Muds were dispersed with 2.75 mls of 10% calgon solution plus 0.1N NaOH in 500 mls water.

Results were initially plotted as arithmetic cumulative curves, examples of which are shown in Figs. 152-155 here, and as cumulative curves on log probability paper (Figs. 46-50). The arithmetic plots were used to derive frequency curves (Figs. 10-14, 25, 26, 29-31) by drawing tangents (Fig. 154). There was difficulty in drawing tangents to the steep parts of curves of well-sorted sands, though similarity in shape of the resultant frequency curves suggests results are consistent. Probability plots were used to calculate graphic parameters of the distribution. All plots were made initially on McGormac graph paper, which has slight inconsistencies between sheets and pads, but these are insufficient to produce discrepancies of geologic significance. The final plots presented in this thesis were redrawn on accurately lined paper prepared for the purpose.

Some curves plotted on arithmetic paper showed plateaus at 4Ø (Fig. 155). Reruns eliminated these plateaus in most: they resulted from too much delay in taking the first sample, corrected when the operator became experienced.

LIST OF AMDEL REPORTS

Author	Report No.		Date
Steveson B.G.	693/74		9.10.73
"	5376/73		30.7.73
"	4047/73		18.5.73
"	2520,2844,2868/73		28.3.74
"	1471/73		29.10.73
"	5074/73		9.7.73
"	3253/74	moment calculations	7.3.74
"	3587/74		2.4.74
"	4545/74		14.4.75

TABLES OF BASIC DATA

Table 1 : Cumulative weight percent. 6 pp.

Table 2 : Graphic grain size statistics intercepts (from cumulative probability curves). 3 pp.

Table 3 : Graphic and moment grain size parameters. 5 pp.

Table 4 : Metric quartile deviation and median diameter. 2 pp.

APPENDIX 5, TABLE 1 - CUMULATIVE WEIGHT PERCENT

PHI	P1015	P1017	P1018	P1020	P1021	P1030	P1032	P1035	P1036	P1041	P1042	P1043	P1044	P1045	P1046	P1047
-1.75														0.21	0.03	
-1.5														0.69	0.35	0.03
-1.25														0.90	0.46	0.03
-1.00														1.77	0.91	0.15
-0.75												0.22		2.56	1.48	0.49
-0.50												0.41		3.54	2.28	1.03
-0.35												0.55		4.48	2.96	1.63
0.00												0.94		8.05	5.12	3.96
0.25												1.40		15.24	7.85	7.17
0.50					1.72					3.18		2.20	1.41	41.43	14.24	13.54
0.75					3.27				0.05	14.96	0.44	3.17	4.02	62.62	21.78	21.34
1.00					8.26				0.15	30.35	1.24	5.27	7.22	73.30	33.52	36.66
1.25					15.76				-	?44.1	1.29	7.68	10.72	75.84	44.46	54.20
1.54				1.56	34.31				1.06	68.60	3.24	15.49	16.45	79.76	65.72	74.19
1.75			1.34	4.12	42.20				2.22	76.59	3.94	20.16	21.89	81.98	73.17	77.97
2.00			4.15	23.22	57.72				6.91	82.78	5.96	31.44	42.81	85.42	83.83	83.16
2.25			6.24	43.02	63.63			1.7	11.12	84.24	10.16	40.33	61.28	86.93	87.09	86.30
2.50			9.33	63.92	69.56			2.6	15.70	85.44	20.28	50.59	76.47	88.36	89.52	88.69
2.64			11.42	74.60	74.09			3.9	19.10	86.21	30.19	57.94	82.20	89.38	91.00	90.03
3.0			18.02	85.98	82.76			5.6	26.47	88.21	49.83	73.26	90.39	91.32	93.27	92.29
3.25			22.09	88.73	86.64			7.2	29.76	89.07	55.87	83.36	93.15	92.80	94.52	93.33
3.50			26.84	90.16	88.95			9.5	34.35	90.02	62.61	90.20	96.28	94.02	95.59	94.58
3.75			30.11	90.77	90.04			11.5	37.81	90.45	66.94	93.76	97.17	94.89	96.32	95.58
4.0	0.50	2.78	34.12	91.46	91.13	21.36		11.54	42.56	90.97	73.28	97.09	97.77	95.79	97.16	96.69
4.5	4.05	13.41	37.38	91.46	91.13	30.29		15.41	43.86		?81.70				97.95	96.93
5.0	5.83	34.43	52.38	91.46	91.59	25.83	4.41	23.49	54.62		88.33				97.95	97.17
5.5	9.38	43.48	59.56	94.51	91.13	34.76	6.88	29.47	58.53		90.92				98.24	97.54
6	16.49	61.56	64.12	93.75	92.05	48.17	9.36	38.43	62.54		92.22				99.09	97.91
7	41.36	72.50	79.78	94.51	92.05	48.17	14.31	53.38	66.36		93.51					99.03
8	71.68	76.26	81.08	96.03	92.98	48.17	21.74	65.33	69.62		94.03					99.78
9	76.93	81.23	85.26	96.03	92.98	48.17	31.65	72.80	71.25		97.92					
10	83.48	84.63	87.21	94.51	94.36	57.10	41.56	77.29	76.14		99.22					
11	83.48	89.15	95.69	96.80	96.67	61.57	58.89	86.25	78.75		99.22					
12	83.48	93.67	98.96	97.56	97.14	63.81	77.46	87.75	94.72		99.22					

PHI	P1111	P1112	P1113	P1114	P1115	P1116	P1117	P1118	P1119	P1120	P1121	P1122	P1123	P1124	P1125
-3		1.86											0.19		
-2.5		5.09											0.80	2.14	
-2		9.10											4.30	10.06	
-1.75		11.2							2.9				5.8	16.3	
-1.5	1.0	13.5	1.1	0.1					5.7				8.0	23.8	
-1.25	1.2	14.5	1.3	0.2					7.5				9.7	28.1	
-1.0	1.9	17.8	1.9	0.4					15.3				14.0	39.4	
-0.75	2.9	21.4	2.8	0.9		2.9		2.0	26.4				18.3	50.2	
-0.5	4.0	24.4	3.5	1.4		5.3		8.1	35.1				21.1	57.9	
-0.35	4.7	25.9	4.0	1.8		6.8		14.0	39.4				22.5	61.4	
0.00	7.1	29.2	5.5	3.2		11.4		30.9	47.9				25.4	68.4	
0.25	9.5	31.0	6.9	4.9		15.5		41.4	53.3				27.8	73.0	
0.5	12.9	32.9	8.8	7.2		20.7		48.8	58.4				30.7	76.9	
0.75	16.1	34.6	10.7	9.4		25.8		52.8	62.5				33.7	79.7	
1.0	20.4	36.9	13.6	12.5		33.8		56.0	67.7			1.0	38.7	82.7	
1.25	23.4	38.9	16.1	15.2		41.4		57.5	71.8			2.1	44.2	84.5	
1.54	28.3	41.8	20.8	19.5		54.3		60.4	78.4	1.1		10.1	55.3	86.8	
1.75	30.4	43.2	23.0	21.4		60.0		62.4	81.0	4.0		18.0	61.1	87.7	
2.0	36.2	46.9	29.2	27.0	0.3	73.6	1.6	69.9	85.9	9.0		57.0	76.0	89.8	
2.25	39.9	49.6	33.3	30.8	2.4	80.2	3.0	75.3	87.8	18.8		75.4	82.1	91.0	
2.5	44.1	52.7	37.9	35.1	10.2	85.4	5.9	80.7	89.5	32.5		86.9	86.7	92.2	
2.64	47.0	55.0	41.3	38.0	22.7	87.7	9.0	83.8	90.4	45.0		91.2	88.9	92.9	
3.0	53.9	60.2	49.2	45.1	63.9	90.8	21.6	88.9	92.1	78.3		96.4	92.3	94.2	
3.30	57.0	62.5	52.2	48.1	77.6	91.6	29.6	90.5	92.7	89.0		97.4	93.2	94.7	
3.5	61.0	65.4	56.2	52.2	88.1	92.4	41.4	92.3	93.5	93.6		98.2	94.2	95.2	
3.75	64.0	67.4	58.6	55.1	92.5	92.8	49.3	93.1	94.0	94.3		98.4	94.6	95.5	
4.0	67.4	69.8	61.4	58.4	94.1	93.4	58.6	94.1	94.5	94.5		98.6	95.0	95.7	
4.5	70.8	71.9	64.2	61.3	94.6		67.4			94.7	32.8			96.0	0.9
5	75.0	76.6	67.3	65.5	95.6		77.7			94.75	55.9			96.4	2.5
5.5	78.6	76.9	69.3	69.0	96.4		82.7			95.0	67.6			96.7	3.8
6	81.7	79.1	70.9	71.3	96.3		85.8			95.3	74.4			97.2	7.6
7	86.3	82.9	73.7	75.5	96.9		89.1			96.1	79.8			97.7	30.5
8	89.6	85.8	76.2	79.1	97.3		90.4			96.6	81.9			98.2	51.1
9	91.5	87.5	77.6	79.1			91.7				83.2				59.0
10	93.8	89.8	81.5	82.8			92.9				89.1				63.5

PHI	P1278	P1279	P1280	P1281	P1282	P1283	P1284	P1285	P1286	P1287	P1288	P1289	P1290	P1291	P1292
-2.5	10.1	0.7	0.0												
-1.25	15.5	8.4	6.3												
-0.75	16.6	12.7	13.0			0.3	0.0								
-0.25	17.4	16.1	18.0		0.0	0.7	0.1								
0.00	17.8	17.8	20.0		0.1	0.9	0.2								
0.25	18.2	19.5	21.9		0.2	1.2	0.3		0.0	0.0			0.0		
0.5	18.7	21.9	24.3		0.3	1.7	0.4	0.0	0.0	0.0		0.0	0.0		0.0
0.75	19.1	23.8	25.9		0.3	2.0	0.6	0.0	0.1	0.1	0.1	0.1	0.1	0.0	0.0
1.0	19.4	25.2	27.1	0.0	0.4	2.2	0.7	0.0	0.3	0.1	0.3	0.3	0.2	0.0	0.1
1.25	19.8	26.4	28.2	0.0	0.4	2.4	0.7	0.0	0.5	0.1	0.5	0.8	0.2	0.0	0.1
1.50	21.1	28.5	30.7	0.1	0.6	2.8	0.8	0.2	1.0	0.2	1.0	4.3	0.2	0.1	0.1
1.75	22.5	29.8	32.3	0.1	0.7	3.1	0.9	0.7	1.4	0.3	1.8	8.2	0.3	0.1	0.1
2.0	24.2	30.9	33.6	0.2	0.7	3.3	0.9	1.9	1.7	0.6	3.1	11.4	0.5	0.1	0.3
2.25	26.2	32.1	34.8	0.3	0.8	3.5	1.0	4.6	2.0	1.2	5.1	14.3	0.9	0.1	0.8
2.50	29.5	33.7	36.6	0.5	0.9	3.7	1.1	13.4	2.4	3.0	8.4	17.7	2.0	0.2	3.2
2.75	32.8	35.5	38.4	0.7	1.0	3.9	1.2	26.3	2.7	7.8	11.7	21.0	4.4	0.3	9.2
3.0	34.2	36.2	39.1	0.9	1.1	4.1	1.2	30.4	2.9	11.9	13.0	22.3	6.1	0.4	13.2
3.25	37.2	37.9	40.9	1.3	1.2	4.3	1.3	36.8	3.1	29.7	16.2	25.0	13.9	0.5	23.5
3.50	39.5	39.4	42.4	2.1	1.3	4.5	1.4	42.3	3.4	48.0	22.2	26.8	27.2	0.6	31.9
3.75	41.5	40.6	43.5	3.1	1.4	4.7	1.4	49.2	3.6	58.0	36.0	28.5	41.9	0.8	37.9
4.0	43.4	41.7	44.6	4.2	1.6	5.0	1.5	56.5	3.8	62.9	54.2	29.5	51.1	1.1	42.1
4.5	46.9	44.4	46.5	6.5	2.5	6.1	2.7	66.7	4.4	68.5	77.1	29.5	62.2	1.5	48.2
5.0	50.3	46.6	48.7	7.0	3.4	7.1	3.2	70.7	5.4	70.4	82.7	29.2	66.9	2.6	51.3
5.5	55.5	50.1	51.5	9.8	7.7	12.2	6.7	74.3	12.0	71.9	85.1	29.7	69.1	4.7	55.1
6	60.1	54.4	55.8	12.9	10.9	42.1	10.2	76.1	46.7	73.0	86.7	30.9	71.0	8.4	58.5
7	67.8	64.9	65.5	19.8	21.1	73.6	18.4	79.3	74.3	74.8	89.3	35.3	73.7	19.5	64.7
8	73.8	74.1	74.1	29.8	31.5	77.3	27.7	82.1	78.2	76.8	91.8	39.6	75.8	27.5	69.7
9	80.2	79.4	79.8	40.6	40.9	82.5	42.9	87.7	83.8	79.0	94.8	44.0	77.9	37.0	74.6
10	84.1	82.5	83.0	48.9	54.7	87.2	52.1	92.7	89.2	82.6	97.4	47.5	83.8	51.0	79.5
11	85.7	84.6	84.2	62.9	69.3	91.5	68.8	96.4	93.1	85.1		49.4	84.6	67.0	83.2
12	88.2	87.2	86.8	72.4	80.2	94.7	79.5	97.9	95.5	88.7		51.9	88.4	77.6	87.4
13	91.5	91.1	91.2	80.7	87.6		86.8			92.4		69.1	92.2	85.3	91.3

PHI	P1048	P1049	P1050	P1051	P1053	P1054	P1091	1019A	1025A	1033A	1037A	1055A	1052A	1021A	P1248	P1258
-1.75	0.34	3.4	1.8	0.9					7.6							
-1.5	0.37	4.5	2.0	1.0		0.2			7.7							
-1.25	0.40	5.0	2.2	1.1		0.3			7.8							
-1	0.47	6.2	2.5	1.2		1.0			8.0							
-0.75	0.65	8.0	3.1	1.5		2.9			8.3							
-0.50	1.05	9.3	3.7	1.8		5.1			8.7							
-0.35	1.36	10.1	4.1	2.1		6.5			8.9							
-0.25																
0.00	2.47	12.0	5.3	3.2		10.6			9.7							
0.25	4.10	13.4	6.5	4.7		13.5			10.6							
0.5	8.72	15.0	7.8	7.1		16.7			12.2							
0.75	14.87	16.3	8.9	10.0		19.4			13.6							
1.00	26.44	18.0	10.3	14.8	0.8	22.6	1.9		15.7							
1.25	41.11	19.2	11.6	19.5	1.3	25.4	2.4		17.2							
1.50									20.0			0.2				
1.54	60.77	21.8	15.3	27.0	2.2	30.2	3.9									
1.75	64.35	23.1	17.5	30.2	2.5	32.0	5.0		21.3			0.7				
2.00	67.63	27.5	24.6	38.5	4.6	37.1	8.6		24.4		0.0	2.3	Trace	0.4		
2.25	68.81	31.1	30.3	43.3	10.9	40.9	10.3		26.1		0.1	6.1	0.1	0.8		
2.5	69.83	35.7	36.9	48.2	26.8	45.7	11.7		29.4		0.6	23.3	0.1	2.0		
2.64	70.47	39.3	41.5	51.4	43.5	49.6	12.9									
2.75									33.4		3.7	46.9	0.5	6.2		
3.00	71.72	47.6	51.6	58.1	73.7	59.3	20.0		37.5		11.5	65.3	2.3	14.8		
3.25	72.29	51.7	55.7	61.2	79.0	63.8	26.2		40.8	5.0	18.9	74.7	5.3	23.8		
3.5	72.91	57.5	60.2	64.9	82.1	69.0	37.4		45.1	5.4	32.4	81.8	10.5	37.2		
3.75	73.28	61.6	63.4	67.9	83.4	72.5	53.5		48.8	5.6	39.2	84.9	14.9	48.1		
4.00	73.62	66.2	67.1	71.4	84.4	76.9	87.0	67.67	53.0	5.7	43.8	87.1	20.3	61.1	0.2	1.7
4.5	90.96	70.9	67.2	73.6		75.8	91.8	67.9	57.3	5.7	47.6	89.4	25.3	73.8	0.7	3.5
5.0	98.84	74.0	71.6	75.3		79.1	92.2	67.8	60.2	8.8	50.1	91.2	29.4	82.8	1.2	8.6
5.5	99.35	76.6	74.6	76.8		81.6	92.3	68.9	63.5	12.1	56.8	92.6	33.3	87.4	2.5	31.2
6.0	99.60	79.9	77.9	78.5		84.2	92.3	68.9	66.1	13.7	64.8	93.6	37.1	90.0	4.7	55.1
6.5								69.3	68.1	16.7	69.7	94.5			8.4	61.5
7.00	99.85	84.4	82.8	82.4		88.1	92.5	69.6	69.6	18.0	72.0	95.4	43.3	92.1	10.9	64.0
7.5								70.0	71.0	19.9	74.0	96.0			12.3	65.0
8.0		88.1	86.6	85.8		91.4	92.8	71.2	81.8	24.4	75.5	96.7	49.8	93.0	14.0	67.5
8.5								71.8	74.7	25.0	75.8	97.0			15.6	68.8
9.0		90.4	88.6	88.6		93.0		71.1	75.3	25.9	77.4	97.6	54.5	93.4	17.2	70.3
9.5								74.9	76.7	32.8	83.7	98.2			18.9	71.8
10		92.2	90.3	91.0		95.2		83.9	82.2	47.6	84.2	98.9	61.9	95.7	21.1	72.8

PHI	P1048	P1049	P1050	P1051	P1053	P1054	P1091	1019A	1025A	1033A	1037A	1055A	1052A	1021A	P1248	P1258
10.5								81.5	84.5	47.9	83.7	98.9			30.8	75.2
11								86.9	86.7	59.2	88.3	99.1				78.1
11.5								94.3	90.3	73.2	91.4	99.4				

PHI	P1266	P1267	P1269	P1270	P1273
-1					
-0.75					
-0.50					
-0.25					
0					
0.25					
0.5		0.3	tr		0.2
0.75		0.4	tr		0.3
1		0.6	tr		0.7
1.25		0.7	tr	tr	1.4
1.5		1.3	0.1	0.6	7.2
1.75		1.8	0.6	7.0	13.2
2		4.1	15.6	70.6	34.2
2.25	0.2	7.9	57.1	84.1	49.9
2.5	1.8	12.7	75.9	86.1	62.0
2.75	15.3	19.1	79.5	87.2	72.6
3	43.6	24.4	80.9	87.9	80.0
3.25	62.9	27.3	82.0	88.5	82.6
3.5	75.9	30.3	83.7	89.4	84.4
3.75	80.2	32.3	85.0	89.9	85.1
4	82.6	35.5	86.3	90.4	85.9
4.5	84.3	41.0	87.6	90.9	86.4
5	84.8	46.6	88.4	91.5	87.0
5.5	85.6	51.2	89.2	92.0	87.5
6	86.1	54.4	89.9	92.6	88.1
6.5	86.8	56.7	90.6	93.1	88.8
7	87.2	58.4	91.4	93.6	89.3
7.5	87.9	61.0	91.9	94.2	89.9
8	88.6	62.3	92.3	94.4	90.3
8.5	89.4	64.3	92.8	94.8	90.8
9	89.7	65.9	93.2	95.1	91.3
9.5	90.3	67.5	93.5	95.5	91.9
10		69.4			
10.5		72.5			
11		75.6			

PHI	14/74	1017A	1049A	1050A	19/74	20/74	21/74	19/74	19/74	20/74	20/74	21/74	21/74
-2.5			0.0										
-1.25			8.5										
-1													
-0.75			14.4	1.9									
-0.50			0				0.01						
-0.25			18.5	2.3		0.10							
0		0.0	20.0	2.7		0.2	0.10						
0.25		0.0	21.4	3.0		0.2	0.2						
0.5		0.0	23.3	3.5		0.5	0.6						
0.75		0.1	24.6	4.0		0.7	1.1						
1	0.0	0.1	25.5	4.5	0.01	1.0	2.1						
1.25	0.0	0.1	26.4	5.1	0.10	1.3	3.8						
1.5	0.1	0.1	28.7	7.6	2.8	2.0	8.3						
1.75	0.1	0.1	30.8	10.6	4.8	2.6	12.4						
2	0.2	0.1	33.2	14.3	6.3	3.3	16.1						
2.25	0.2	0.1	36.7	18.9	7.6	4.1	19.9						
2.5	0.6	0.2	42.1	26.4	9.2	5.7	24.8						
2.75	2.7	0.3	48.5	34.4	10.8	8.6	29.6						
3	4.2	0.4	51.2	37.4	11.4	10.4	31.6						
3.25	8.0	0.9	57.2	43.9	12.8	24.0	35.6						
3.5	11.3	1.4	62.3	48.2	13.8	39.5	38.6						
3.75	14.3	1.8	66.3	51.3	14.6	45.4	40.9						
4	16.9	2.1	68.9	53.8	15.3	48.0	42.6	15.6	15.0	47.5	48.5	43.0	42.2
4.5	25.6	4.0	71.7	57.9	16.3	49.5	43.6	16.5	16.1	49.0	50.1	43.9	43.3
5	28.8	7.1	74.4	60.8	18.2	50.3	46.1	18.3	18.1	49.4	51.2	46.4	45.7
5.5	32.1	39.3	77.0	63.5	23.2	51.2	50.5	23.9	22.5	50.5	51.8	50.8	50.2
6	34.6	70.4	79.6	65.0	28.5	51.8	54.7	29.1	27.8	51.1	52.4	54.9	54.6
7	38.6	76.8	83.2	71.2	40.1	53.6	62.5	40.5	39.7	53.0	54.2	62.4	62.7
8	42.1	79.7	86.2	76.2	50.7	55.0	70.5	51.4	50.0	54.5	55.5	70.5	70.6
9	45.2	83.8	88.6	79.8	64.4	57.0	78.6	64.9	63.9	56.5	57.5	78.5	78.7
10	48.1	89.0	90.7	82.6	76.0	59.0	86.0	76.4	75.6	58.4	59.5	85.9	86.0
11	59.3	91.1	92.2	84.6	84.8	62.2	91.7	85.0	84.5	(66.2)*	62.2	91.6	91.8
12	77.6	92.6	93.8	87.1	90.9	70.4	95.7	91.0	90.8	70.0	70.9	95.6	95.7
13	81.3	92.9	95.9	90.7	92.3	91.3	96.5	92.5	92.1	91.2	91.4	96.5	96.5

TABLE 2

GRAPHIC GRAIN SIZE STATISTICS-INTERCEPTS

LAKE FROME

P. No.	Bore	Depth m	Ø5	Ø16	Ø25	Ø50	Ø75	Ø84	Ø95
1278	Wooltana 1	15.00	-3.4	-0.97	2.06	4.92	8.20	9.86	13.92
1049A		25.00	-1.46	-0.56	0.88	2.88	5.12	7.50	12.61
1279 + 1280/2		35.02	-1.92	-0.40	0.83	5.45	8.20	10.67	14.06
1050A		38.34	1.22	2.10	2.50	3.65	8.12	10.20	14.04
1281		44.00	4.14	6.52	7.58	9.94	12.29	12.69	15.60
1051		70.47	0.28	1.11	1.51	2.59	4.92	7.42	12.27
20		78.00	2.42	3.12	3.30	4.88	12.30	12.70	13.13
1282 + 1284/2		117.51	5.31	6.64	7.58	9.66	11.57	12.53	14.57
1052		124.53	3.21	3.81	4.44	8.10	12.31	14.20 to 14.60	-
1053		140.33	2.11	2.38	2.49	2.76	3.03	3.90	7.16
19		151.28	1.79	4.38	5.69	7.90	9.98	10.91	14.83
1054		156.54	-0.51	0.46	1.20	2.66	4.27	6.22	9.80
1055A		166.72	2.21	2.40	2.49	2.72	3.30	3.69	6.78
1283 + 1286/2		176.08	4.40	5.60	5.77	6.08	7.39	9.18	11.94
1285 + 1288/2		194.99	2.26	2.64	3.19	3.88	4.79	6.82	9.98
21		224.00	1.32	2.02	2.53	5.44	8.52	9.72	11.82
1091		111.60	1.69	2.83	3.23	3.69	3.90	3.99	16.18
1125	EAR 6	72.00	5.52	6.48	6.93	7.93	11.81	-	-
1025A	EAR 9	15.62	-4.30	1.04	2.05	3.80	8.78	10.42	12.65
1032		71.60	5.13	7.26	8.35	10.63	11.87	12.50	13.68
1033A		103.00	2.98	5.50	7.20	10.67	11.91	12.50	13.70
1035		115.40	3.20	4.47	5.16	6.84	9.30	11.12	14.22
1051A	Yalkalpo/1	9.04	4.75	5.92	6.34	7.25	8.61	10.19	-
1017A		16.65	4.72	5.22	5.28	5.74	6.78	9.00	13.83
1018		21.20	2.10	2.37	3.40	4.85	7.12	8.66	10.88
1019 + 1019A		30.30	2.00	2.28	2.80	2.92	9.62	10.68	11.60
1020		25.90	1.72	1.96	2.05	2.36	2.67	2.86	7.60
1021		33.40	0.81	1.21	1.41	1.85	2.68	3.09	10.10
1036		38.01	1.95	2.52	2.95	4.45	9.80	11.21	12.05
1037A		45.62	2.75	3.18	3.36	5.12	7.88	9.70 to 10.05	12.19

P. No.	Bore	Depth m	Ø5	Ø16	Ø25	Ø50	Ø75	Ø84	Ø95
1041		58.00	0.59	0.88	1.02	1.32	1.74	2.23	6.6 to 6.9
1042		59.02	1.90	2.40	2.59	3.02	4.12	4.62	8.18
1044		62.16	0.82	1.52	1.78	2.12	2.50	2.69	3.48
1043		66.05	0.98	1.61	1.87	2.45	3.03	3.30	3.85
1045		68.45	-0.26	0.20	0.32	0.60	1.14	1.99	3.76
1046		73.40	-0.02	0.70	0.81	1.16	1.87	2.02	3.38
1047		75.14	0.11	0.55	0.75	1.29	1.58	2.11	3.66
1048		81.43	0.31	0.75	0.96	1.40	4.04	4.22	4.63
1120	PMX24a	95.00	2.02	2.20	2.38	2.70	2.97	3.14	5.50
1121		102.27	2.62	3.03	3.29	3.80	4.60	5.13	9.80
1122		110.00	1.38	1.70	1.80	1.96	2.25	2.42	2.87
1123		114.90 to 115.00	-1.88	-0.87	-0.07	1.39	1.99	2.37	3.85
1124		123.13 to 124.33	-2.25	-1.75	-1.41	-0.70	0.40	1.20	3.45
1111	WC2	11.58	-0.27	0.76	1.32	2.81	5.00	6.50	10.72
1112		43.49	-2.80	-1.21	-0.38	2.28	5.12	7.45	13.30
1113		74.78	-0.80	1.22	1.78	3.07	7.54	11.00	18.40
1114		93.82	0.26	1.34	1.90	3.41	6.88	9.60	14.86
1115		123.10	2.36	2.58	2.68	2.89	3.22	3.42	4.65
1248	Wertaloona 1	40.00	6.40	8.62	10.22	-	-	-	-
1289		65.00	1.55	2.39	3.30	11.35	13.40	14.08	15.48
1258		83.13	4.65	5.20	5.40	5.89	10.41	12.20	15.96
1291		93.00	5.55	6.76	7.68	9.94	11.82	12.70	14.58
1287 + 1290/2		125.00	2.66	3.17	3.31	3.73	7.38	10.80	13.87
1266		129.50	2.63	2.80	2.88	3.07	3.46	4.40	15.75
1267		135.00	2.12	2.66	3.06	5.43	10.91	12.49	16.36
1269		141.80	1.90	2.02	2.09	2.20	2.36	3.56	11.30
1270		143.74	1.68	1.79	1.83	1.92	2.03	2.23	8.77
1273		159.00	1.40	1.72	1.88	2.31	2.86	3.46	14.25
1116	K69	68.12	-0.51	0.30	0.69	1.46	2.05	2.41	4.63
1118		74.15	-0.59	-0.29	-0.10	0.59	2.24	2.68	4.32
1117		75.03	2.41	2.88	3.10	3.74	4.82	5.70	12.10
1119		93.27	-1.53	-0.99	-0.72	0.10	1.38	1.90	4.20
1292	C15	24.83	2.62	3.10	3.32	4.76	9.15	11.22	14.31
14		52.70	3.64	4.00	4.46	10.20	11.84	13.35	16.70?

$$Mz\phi = \frac{\phi 16 + \phi 50 + \phi 84}{3}$$

$$\sigma_1 \phi = \frac{(\phi 84 - \phi 16)}{4} + \frac{(\phi 95 - \phi 5)}{6.6}$$

$$K_G = \frac{\phi 95 - \phi 5}{2.44\ (\phi 75 - \phi 25)} \qquad K_G = \frac{K_G}{1 + K_G}$$

$$SkI = \frac{(\phi 16 + \phi 84) - 2\ \phi 50}{2\ (\phi 84 - \phi 16)} + \frac{(\phi 5 + \phi 95) - 2\ \phi 50}{2\ (\phi 95 - \phi 5)} = \frac{\phi 84 - \phi 50}{\phi 84 - \phi 16} - \frac{\phi 50 - \phi 5}{\phi 95 - \phi 5}$$

APPENDIX 5

TABLE 3

GRAIN SIZE PARAMETERS

		Md	σ	Sk	K	Md	σ	Sk	K	Md	σ	Sk	K
Graph		4·60	5·34	0·076	0·54	3·27	4·15	0·37	0·58	5·24	5·19	0·010	0·47
MOMENT	1												
	2												
	3												
	4												
	A												
	B												
	C	5·44	4·66	-0·088	-1·05	3·92	3·87	0·84	-0·15	5·58	4·59	0·042	-1·36
Sample No.		1278				1049 A				1279 + 1280/2			
Graph		5·32	3·97	0·62	0·48	9·72	3·28	-0·060	0·50	3·71	3·26	0·58	0·59
MOMENT	1									4·20	3·70	1·20 (0·27)	0·33
	2												
	3												
	4												
	A									*3·99	3·23	0·92	-0·42
	B												
	C	5·67	3·92	0·55	+0·96	10·21	2·58	-1·07	0·12	4·15	3·59	1·14	0·16
Sample No.		1050 A				1281				1051			
Graph		6·90	4·02	0·59	0·33	9·61	2·87	0·018	0·49	8·7-8·8	—	—	—
MOMENT	1									*8·63	3·48	-0·26	-1·58
	2												
	3												
	4												
	A									7·88	2·73	-0·53	-1·44
	B												
	C	7·50	4·27	0·096	+1·85	8·94	2·75	-0·37	-0·24				
Sample No.		20				1282 + 1284/2				1052			
Graph		3·01	1·15	0·75	0·79	7·73	3·61	-0·0038	0·56	3·11	3·00	0·31	0·58
MOMENT	1	4·47	3·62	1·79 (0·41)	1·32					3·78	3·33	1·12 (0·26)	0·81
	2												
	3												
	4												
	A	4·06	2·72	1·75	1·25					*3·66	3·03	0·79	-0·19
	B	*3·42	1·30	1·42	0·79								
	C					8·46	3·27	-0·58	+0·71	3·75	3·25	1·05	0·57
Sample No.		1053				19				1054			
Graph		2·94	1·02	0·75	0·64	6·95	2·04	0·64	0·66	4·45	2·22	0·49	0·66
MOMENT	1	3·55	1·67	3·13 (0·72)	10·8								
	2												
	3												
	4												
	A												
	B												
	C	*3·56	1·69	3·14	10·7	6·19	1·75	0·44	1·69	4·46	2·02	1·72	1·99
Sample No.		1055 A				1283 + 1286/2				1285 + 1288/2			

Sheet 1 of 5

APPENDIX 5

TABLE 3

GRAIN SIZE PARAMETERS

		Md	σ	Sk	K	Md	σ	Sk	K	Md	σ	Sk	K
Graph		5·73	3·52	0·16	0·42	3·50	2·80	0·12 – 0·14	0·90	—	—	—	—
MOMENT	1					4·36	2·50	2·64 (0·61)	6·44	9·83	2·46	0·05	-1·45
	2												
	3												
	4												
	A					* 4·18	1·89	2·19	5·09				
	B												
	C	6·36	3·77	0·23	-1·38								
Sample No.		21				1091				1125			
Graph		5·09	5·26	0·23	0·51	10·1	2·61	-0·32	0·50	9·56	3·35	-0·46	0·44
MOMENT	1	5·32	4·33	0·31 (0·07)	-0·95					10·1	3·07	-1·10	0·04
	2												
	3												
	4												
	A	* 5·05	3·89	0·06	-1·13								
	B												
	C	5·38	4·40	0·30	-1·03					* 10·1	3·05	-1·18	0·12
Sample No.		1025 A				1032				1033 A			
Graph		7·48	3·33	0·32	0·59	3·71	3·26	0·58	0·59	6·65	2·33	0·75	0·49
MOMENT	1	8·03	2·92	0·13 (0·03)	-1·01	4·20	3·70	1·20 (0·27)	0·33				
	2												
	3												
	4												
	A	* 7·69	2·39	-0·41	-1·12	* 3·99	3·23	0·92	-0·42				
	B												
	C	8·06	2·94	0·09	-1·12	4·15	3·59	1·14	0·16	7·23	2·28	1·20	0·32
Sample No.		1035				1051				1017 A			
Graph		5·14	3·02	0·25	0·49	5·29	3·65	0·83	0·51	2·39	1·12	0·45	0·80
MOMENT	1	6·13	2·94	0·67 (0·15)	-0·54	* 5·46	3·85	0·88 (0·20)	-1·01	3·14	2·13	3·50 (0·81)	11·8
	2												
	3												
	4												
	A	* 5·97	2·63	0·39	-1·03	5·17	3·36	0·77	-1·30	* 3·07	1·81	3·13	9·00
	B												
	C	6·20	3·07	0·74	-0·46	5·53	3·95	0·86	-1·10	3·13	2·10	3·45	11·4
Sample No.		1018				1019 A + 1019				1020			
Graph		2·05	1·88	0·55	0·75	6·06	3·70	0·53	0·38	5·8 – 6·0	3·06 – 3·15	0·47 – 0·49	0·46
MOMENT	1	2·93	2·67	2·73 (0·63)	6·50	* 6·57	3·82	0·49 (0·11)	-1·34	* 6·29	3·21	0·84 (0·19)	-0·65
	2												
	3												
	4												
	A	* 2·83	2·30	2·50	5·27	6·10	3·15	0·27	-1·55	6·04	2·74	0·55	-1·25
	B												
	C	2·95	2·70	2·71	6·32	6·59	3·84	0·47	-1·38	6·30	3·21	0·82	-0·74
Sample No.		1021				1036				1037 A			

Sheet 2 of 5

APPENDIX 5 TABLE 3

GRAIN SIZE PARAMETERS

		Md	σ	Sk	K	Md	σ	Sk	K	Md	σ	Sk	K
Graph		1·48	1·24	0·55	0·77	3·35	1·51	0·54	0·63	2·11	0·69	−0·002	0·60
MOMENT	1					3·97	1·97	2·05 (0·47)	4·68				
	2	2·04	1·61	2·22 (0·51)	3·79					2·43	0·93	2·11 (0·49)	8·44
	3												
	4												
	A					3·98	1·98	1·94	3·68				
	B	*1·99	1·48	2·13	3·45					*2·41	0·88	1·72	6·43
	C					*3·97	1·97	2·04	4·47				
Sample No.		1041				1042				1044			
Graph		2·12	1·10	−0·20	0·50	0·93	1·06	0·56	0·48	1·29	0·85	0·31	0·57
MOMENT	1												
	2	2·78	1·14	1·07 (0·24)	3·06	1·31	1·48	2·26 (0·52)		*1·68	1·18	2·06 (0·47)	8·40
	3												
	4												
	A												
	B	*2·76	1·07	0·74	2·19	*1·28	1·40	2·07	4·73	1·68	1·16	1·71	5·39
	C												
Sample No.		1043				1045				1046			
Graph		1·32	0·93	0·19	0·64	2·12	1·52	0·07	0·37	2·68	0·77	0·27	0·71
MOMENT	1												
	2	*1·70	1·33	2·87 (0·66)	11·25	*2·37	1·70	0·78 (0·18)	−0·50				
	3									3·30	1·87	4·00 (0·92)	15·8
	4												
	A					2·37	1·71	0·81	−0·29	*3·23	1·53	3·66	13·5
	B	1·67	1·20	2·10	5·64								
	C												
Sample No.		1047				1048				1120			
Graph		3·99	1·62	0·47	0·69	2·03	0·40	0·25	0·58	0·96	1·68	−0·13	0·53
MOMENT	1	4·77	2·19	2·27 (0·52)	4·78								
	2												
	3									*1·75	2·92	2·50 (0·58)	7·45
	4					2·41	1·27	6·67 (1·53)	48·3				
	A	*4·67	1·88	1·88	3·04								
	B					*2·32	0·64	3·49	18·7	1·41	1·80	0·43	0·88
	C												
Sample No.		1121				1122				1123			
Graph		−0·15	1·60	0·51	0·56	3·36	3·10	0·33	0·55	2·84	4·61	0·28	0·55
MOMENT	1					4·01	3·47	1·10 (0·25)	0·57	3·40	4·47	0·83 (0·19)	−0·28
	2												
	3	0·15	2·44	3·15 (0·72)	12·4								
	4												
	A	*0·10	2·19	2·59	8·34	*3·86	3·11	0·77	−0·34	*3·15	3·97	0·54	−0·82
	B												
	C					3·97	3·38	1·03	0·36	3·34	4·35	0·77	−0·40
Sample No.		1124				1111				1112			

Sheet 3 of 5

APPENDIX 5 TABLE 3

GRAIN SIZE PARAMETERS

		Md	σ	Sk	K	Md	σ	Sk	K	Md	σ	Sk	K
Graph		5·10	5·97	0·61	0·58	4·78	4·03	0·52	0·55	2·96	0·56	0·40	0·63
MOMENT	1	5·21	4·39	0·74 (0·17)	-0·90	5·28	4·20	0·78 (0·18)	-0·78	3·54	1·70	4·62 (1·06)	21·6
	2												
	3												
	4												
	A	4·73	3·61	0·51	-1·16	4·83	3·43	0·51	-1·14	*3·47	1·32	4·14	17·7
	B												
	C	*5·11	4·22	0·70	-0·95	*5·18	4·03	0·73	-0·85				
Sample No.		1113				1114				1115			
Graph		—	—	—	—	9·27	5·03	-0·47	0·36	7·76	3·46	0·79	0·48
MOMENT	1	11·6	2·14	-1·69	1·45					8·00	2·91	0·77 (0·18)	-1·10
	2												
	3												
	4												
	A									7·46	2·05	0·46	-1·49
	B												
	C	*11·3	1·97	-1·88	2·02	8·83	4·21	-0·68	-1·29	*7·96	2·81	0·71	-1·25
Sample No.		1248				1289				1258			
Graph		9·80	2·86	-0·022	0·47	5·90	3·36	0·90	0·53	3·42	2·27	0·80	0·90
MOMENT	1									4·48	2·94	2·22 (0·51)	3·31
	2												
	3												
	4												
	A									*4·26	2·31	2·01	2·38
	B												
	C	10·4	2·24	-0·99	-0·024	5·94	3·44	1·02	-0·67				
Sample No.		1291				1287 + 1290/2				1266			
Graph		6·86	4·63	0·50	0·43	2·62	1·83	0·86	0·94	1·98	1·18	0·67	0·94
MOMENT	1	7·28	3·95	0·24 (0·05)	-1·45	3·47	2·74	2·70 (0·62)	6·02	2·94	2·44	3·31 (0·76)	9·89
	2												
	3												
	4												
	A	6·67	3·15	-0·07	-1·56	*3·32	2·24	2·43	4·49	*2·88	2·02	3·03	7·86
	B												
	C	*7·23	3·87	0·18	-1·52					2·91	2·34	3·26	9·52
Sample No.		1267				1269				1270			
Graph		2·50	2·08	0·62	0·84	1·39	1·31	0·07	0·61	1·33	1·48	0·43	0·46
MOMENT	1	3·60	3·04	2·32 (0·54)	4·04								
	2					1·87	1·63	1·54 (0·35)	2·97	1·44	1·79	1·54 (0·35)	2·12
	3												
	4												
	A	*3·41	2·48	2·09	2·94								
	B					*1·84	1·53	1·32	2·35	*1·40	1·70	1·37	1·52
	C	3·56	2·92	2·29	3·85								
Sample No.		1273				1116				1118			

APPENDIX 5

TABLE 3

GRAIN SIZE PARAMETERS

		Md	σ	Sk	K	Md	σ	Sk	K	Md	σ	Sk	K
Graph		4·11	2·18	0·56	0·70	0·34	1·59	0·34	0·53	6·36	3·80	0·62	0·45
MOMENT	1	5·00	2·65	1·90 (0·44)	2·86								
	2					0·82	1·91	1·58 (0·36)	2·65				
	3												
	4												
	A	* 4·82	2·17	1·46	1·23								
	B					* 0·79	1·83	1·42	2·04				
	C									6·89	3·50	0·43	-1·31
Sample No.		1117				1119				1292			
Graph		9·18	4·32	-0·16	0·48	—	—	—	—				
MOMENT	1					8·68	2·20	0·58 (0·13)	-0·29				
	2												
	3												
	4												
	A					* 8·45	1·59	-0·62	-0·45				
	B												
	C	9·13	3·62	-0·51	-1·47	8·63	2·09	0·40	-0·52				
Sample No.		14				1015 A							

GROUP A .... Truncated at 8 Ø; 10 Ø = 100% weight percent.

GROUP B .... Truncated at 4 Ø; 6 Ø = 100% weight percent.

GROUP C .... Truncated at 10 Ø; 12 Ø = 100% weight percent.
(in some 13 Ø used)

All extrapolated in coarse sizes as far as possible to 0·0%

GROUP 1 .... Truncated at various sizes, 9 Ø or smaller (mostly 10 Ø); 12·5 Ø = 100% wt. percent.

GROUP 2 .... Truncated at various sizes, mostly 4 Ø; 6·5 Ø = 100% wt. percent.

GROUP 3 .... Truncated at various sizes, mostly > 8 Ø; 12·0 Ø = 100% wt. percent.

GROUP 4 .... 1122/73. Truncated at 4 Ø; 6·0 Ø = 100% wt. percent.

* denotes values used in moment plots.

(0·2) Bracketed numbers in Sk column are moment values converted to graphical equivalents using Friedman's formula.

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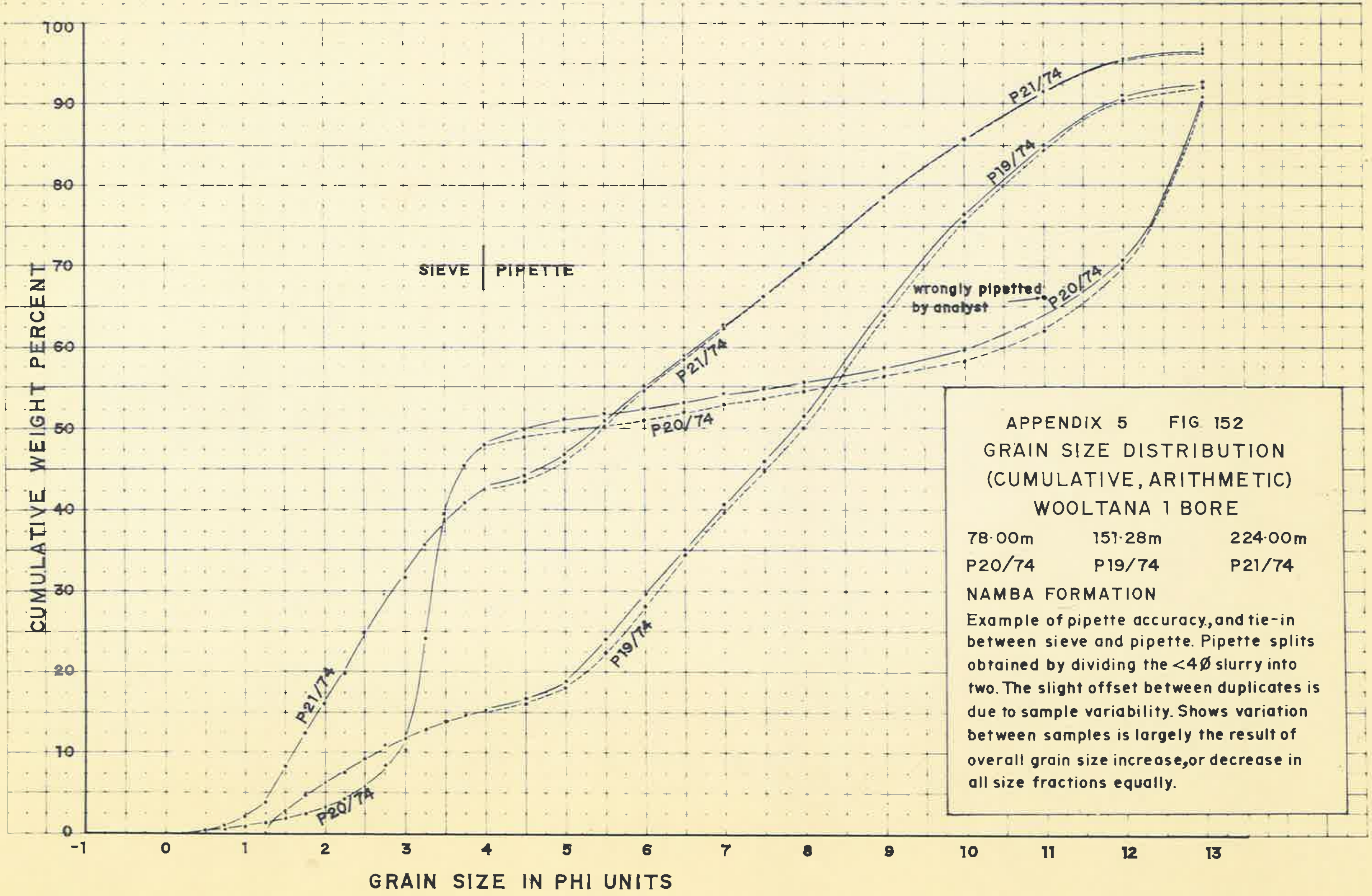
TABLE 4, APPENDIX 5

QUARTILE DEVIATION - METRIC STATISTICS

	Q_{25}	Md(Q_{50})	Q_{75}	QDa	Ska
1278	2.40 -1	3.30 -2	3.40 -3	1.18 -1	8.86 -2
1049A	5.43 -1	1.36 -1	2.88 -2	2.57 -1	1.50 -1
1279+1280 /2	5.63 -1	2.29 -2	3.40 -3	2.80 -1	2.60 -1
1050A	1.77 -1	7.97 -2	3.59 -3	8.66 -2	1.05 -2
1281	5.23 -3	1.02 -3	2.00 -4	2.51 -3	1.69 -3
1051	3.51 -1	1.66 -1	3.30 -2	1.59 -1	2.60 -2
20	1.02 -1	3.40 -2	1.98 -4	5.07 -2	1.69 -2
1282+1284/2	5.23 -3	1.24 -3	3.29 -4	2.45 -3	1.54 -3
1052	4.61 -2	3.64 -3	1.97 -4	2.29 -2	1.95 -2
1053	1.78 -1	1.48 -1	1.22 -1	2.78 -2	2.59 -3
19	1.94 -2	4.19 -3	9.90 -4	9.19 -3	5.99 -3
1054	4.35 -1	1.58 -1	5.18 -2	1.92 -1	8.53 -2
1055A	1.78 -1	1.52 -1	1.02 -1	3.82 -2	-1.20 -2
1283+1286/2	1.83 -2	1.48 -2	5.96 -3	6.18 -3	-2.64 -3
1285+1288/2	1.10 -1	6.79 -2	3.61 -2	3.67 -2	4.94 -3
21	1.73 -1	2.30 -2	2.72 -3	8.52 -2	6.49 -2
1091	1.07 -1	7.75 -2	6.70 -2	1.98 -2	9.30 -3
1125	8.20 -3	4.10 -3	2.79 -4	3.96 -3	1.39 -4
1025A	2.41 -1	7.18 -2	2.27 -3	1.20 -1	5.01 -2
1032	3.06 -3	6.31 -4	2.67 -4	1.40 -3	1.03 -3
1033A	6.80 -3	6.14 -4	2.60 -4	3.27 -3	2.92 -3
1035	2.80 -2	8.73 -3	1.59 -3	1.32 -2	6.05 -3
1015A	1.23 -2	6.57 -3	2.56 -3	4.89 -3	8.82 -4
1017A	2.57 -2	1.87 -2	9.10 -3	8.32 -3	-1.29 -3
1018	9.47 -2	3.47 -2	7.19 -3	4.38 -2	1.63 -2
1020	2.41 -1		1.57 -1	4.22 -2	4.51 -3
1019A	1.77 -1	1.32 -1	1.27 -3	8.78 -2	-4.31 -2
1021	3.76 -1	2.77 -1	1.56 -1	1.10 -1	-1.12 -2
1036	1.29 -1	4.58 -2	1.12 -3	6.41 -2	1.95 -2
1037A	9.74 -2	2.88 -2	4.25 -3	4.66 -2	2.21 -2
1041	4.93 -1	4.01 -1	2.97 -1	9.79 -2	-5.33 -3
1042	1.66 -1	1.23 -1	5.75 -2	5.43 -2	-1.15 -2
1044	2.91 -1	2.30 -1	1.77 -1	5.72 -2	3.93 -3
1043	2.74 -1	1.83 -1	1.22 -1	7.56 -2	1.50 -2
1045	8.01 -1	6.60 -1	4.54 -1	1.74 -1	-3.23 -2
1046	5.70 -1	4.48 -1	2.74 -1	1.48 -1	-2.55 -2
1047	5.95 -1	4.09 -1	3.34 -1	1.30 -1	5.56 -2
1048	5.14 -1	3.79 -1	6.08 -2	2.27 -1	-9.15 -2
1120	1.92 -1	1.54 -1	1.28 -1	3.22 -2	5.97 -3
1121	1.02 -1	7.18 -2	4.12 -2	3.05 -2	-5.75 -5
1122	2.87 -1	2.57 -1	2.10 -1	3.85 -2	-8.33 -3
1123	1.05 0	3.82 -1	2.52 -1	3.99 -1	2.69 -1
1124	2.66 0	1.62 0	7.58 -1	9.50 -1	8.31 -2
1111	4.01 -1	1.43 -1	3.13 -2	1.85 -1	7.33 -2
1112	1.30 0	2.06 -1	2.88 -2	6.36 -1	4.59 -1
1113	2.91 -1	1.19 -1	5.37 -3	1.43 -1	2.92 -2
1114	2.68 -1	9.41 -2	8.49 -3	1.30 -1	4.41 -2
1115	1.56 -1	1.35 -1	1.07 -1	2.44 -2	-3.22 -3
1248					
1289	1.02 -1	3.83 -4	9.25 -5	5.07 -2	5.04 -2
1258	2.37 -2	1.69 -2	7.35 -4	1.15 -2	-4.65 -3

	Q_{25}	Md(Q_{50})	Q_{75}	QDa	Ska
1291	4.88 -3	1.02 -3	2.77 -4	2.30 -3	1.56 -3
1287+1290/2	1.01 -1	7.54 -2	6.00 -3	4.74 -2	-2.19 -2
1266	1.36 -1	7.86 -2	9.47 -2	2.06 -2	3.67 -2
1267	1.20 -1	2.32 -2	5.20 -4	5.97 -2	3.70 -2
1269	2.35 -1	2.18 -1	1.95 -1	2.00 -2	-2.80 -3
1270	2.81 -1	2.64 -1	2.45 -1	1.82 -2	-1.19 -3
1273	2.72 -1	2.02 -1	1.38 -1	6.70 -2	3.05 -3
1116	6.20 -1	3.63 -1	2.41 -1	1.89 -1	6.72 -2
1118	1.07 0	6.64 -1	2.12 -1	4.30 -1	-2.26 -2
1117	1.17 -1	7.48 -2	3.54 -2	4.06 -2	1.17 -3
1119	1.65 0	9.33 -1	3.84 -1	6.31 -1	8.27 -2



APPENDIX 5 FIG 152

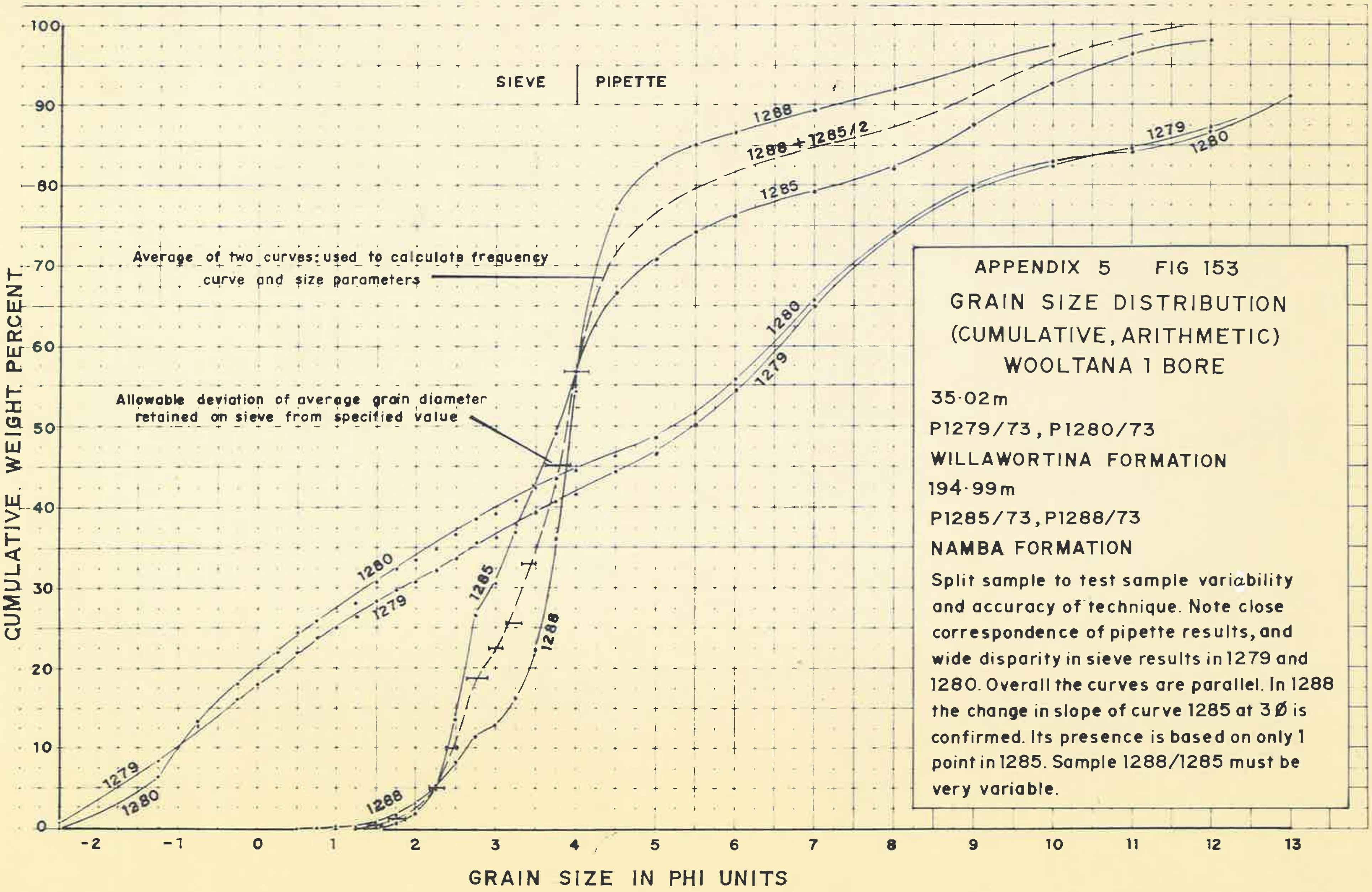
GRAIN SIZE DISTRIBUTION (CUMULATIVE, ARITHMETIC)

WOOLTANA 1 BORE

78·00m	151·28m	224·00m
P20/74	P19/74	P21/74

NAMBA FORMATION

Example of pipette accuracy., and tie-in between sieve and pipette. Pipette splits obtained by dividing the <4φ slurry into two. The slight offset between duplicates is due to sample variability. Shows variation between samples is largely the result of overall grain size increase, or decrease in all size fractions equally.



APPENDIX 5 FIG 153

GRAIN SIZE DISTRIBUTION (CUMULATIVE, ARITHMETIC)

WOOLTANA 1 BORE

35·02m

P1279/73, P1280/73

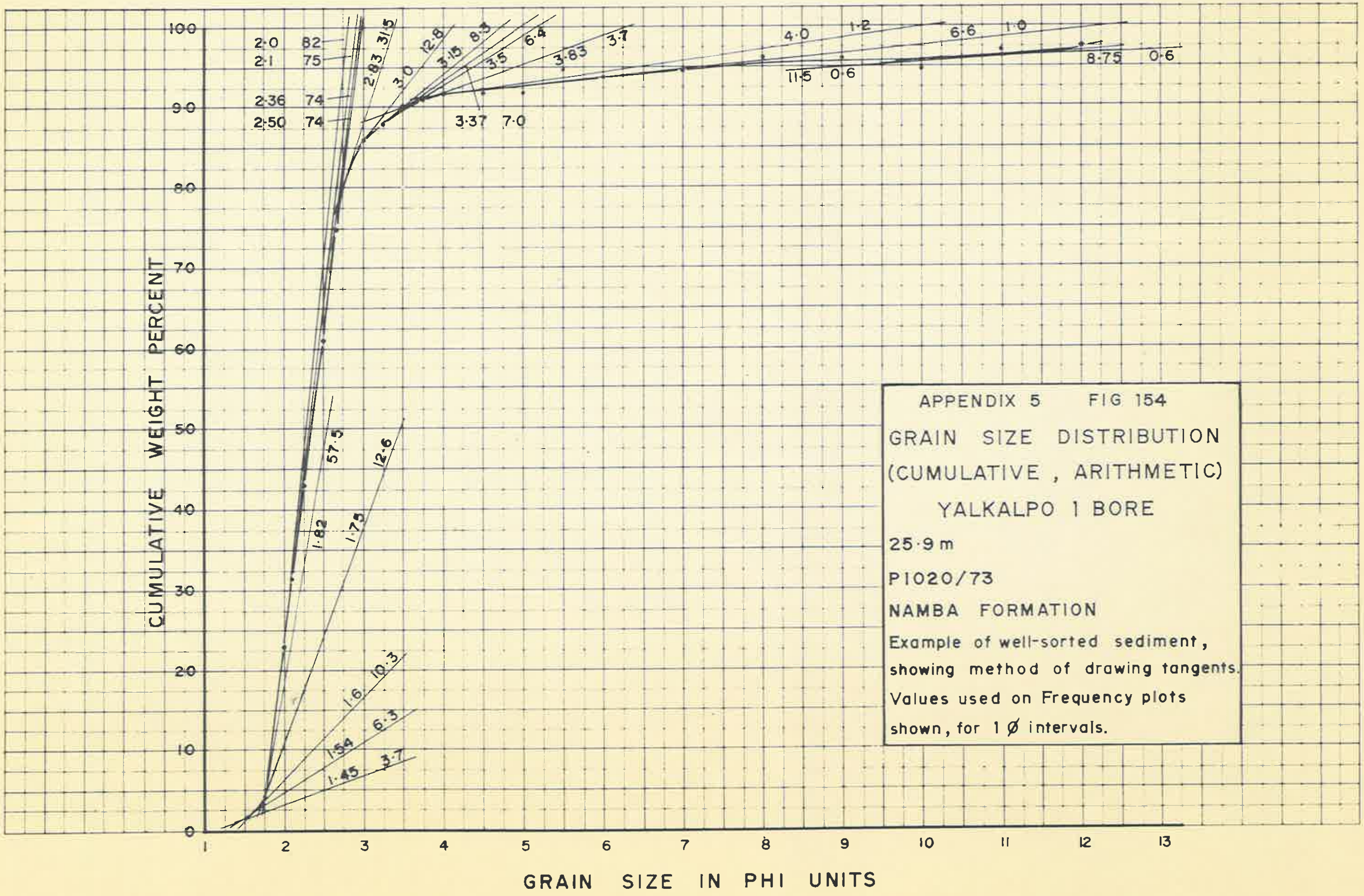
WILLAWORTINA FORMATION

194·99m

P1285/73, P1288/73

NAMBA FORMATION

Split sample to test sample variability and accuracy of technique. Note close correspondence of pipette results, and wide disparity in sieve results in 1279 and 1280. Overall the curves are parallel. In 1288 the change in slope of curve 1285 at 3 0 is confirmed. Its presence is based on only 1 point in 1285. Sample 1288/1285 must be very variable.



APPENDIX 5 FIG 154

GRAIN SIZE DISTRIBUTION

(CUMULATIVE , ARITHMETIC)

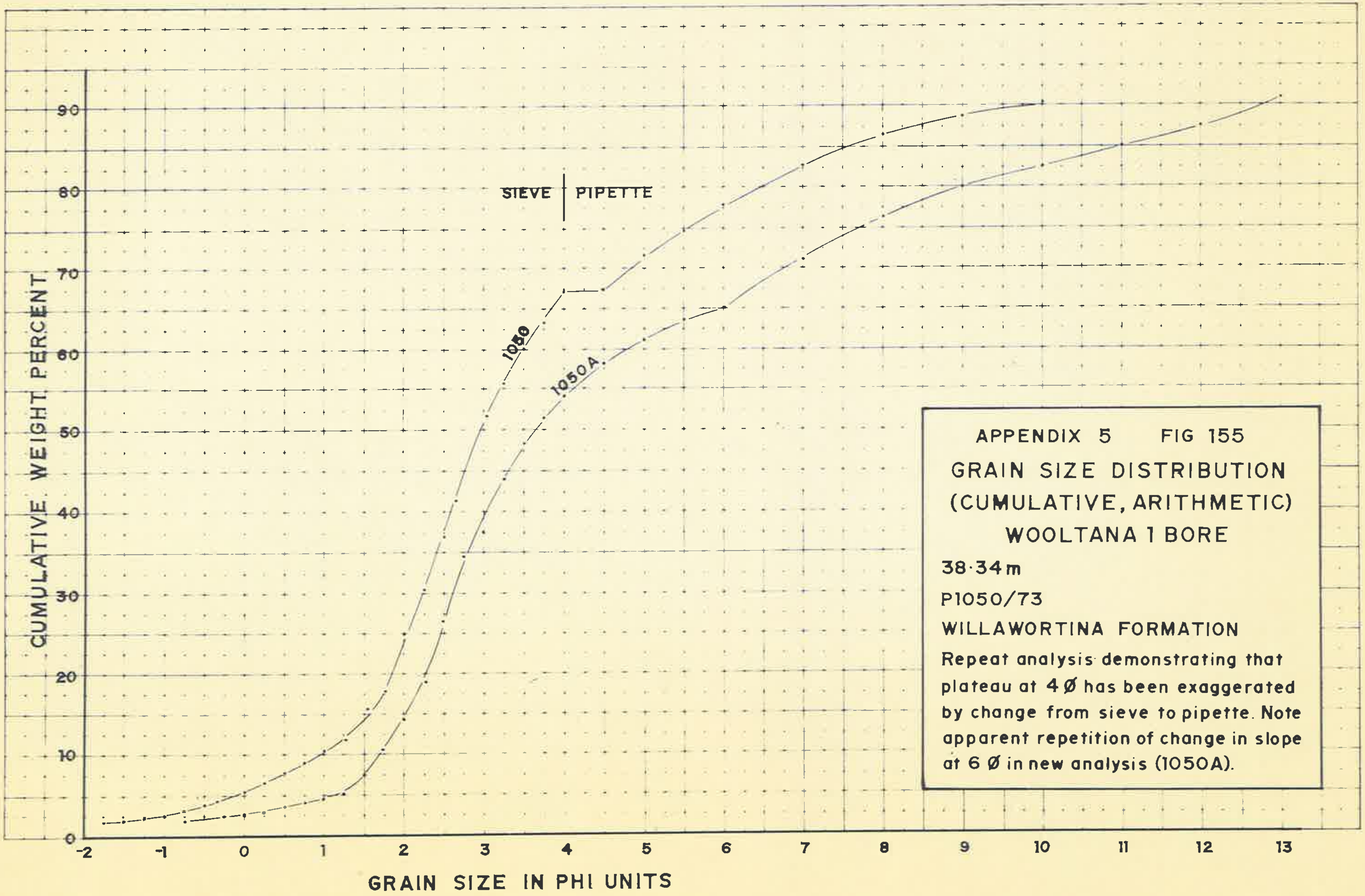
YALKALPO 1 BORE

25·9 m

P1020/73

NAMBA FORMATION

Example of well-sorted sediment, showing method of drawing tangents. Values used on Frequency plots shown, for 1 Ø intervals.



APPENDIX 5 FIG 155

GRAIN SIZE DISTRIBUTION
(CUMULATIVE, ARITHMETIC)
WOOLTANA 1 BORE

38·34 m

P1050/73

WILLAWORTINA FORMATION

Repeat analysis demonstrating that plateau at 4 Ø has been exaggerated by change from sieve to pipette. Note apparent repetition of change in slope at 6 Ø in new analysis (1050A).

APPENDIX 6

Sources of Information, Fig. 3

1. Mapping: Coats (1973) and Forbes *et al.* (1966) Dept. Mines (1970, unpub. preliminary sheet) CALLABONNA.

Private Company Drilling) Brunt (1972) (Mines Administration Pty. Ltd.
& Uranium distribution) Jarre (1972) (

Logs interpreted by the writer.

2. These trends were deduced from geomorphic features. ERTS E-1565-00000-5 photographs. Wopfner & Cornish (1967), Thomson (in Parkin 1969, Fig. 5): L. Blanche fault. Geological mapping as above.

3. Proctor *et al.* (1966). Drilling data and uranium distribution: Andrus in Bragg (1972). Western Uranium - Minoil N.L. - Petromin N.L.. Bryan (1971) Minad-Teton (Aust.) Ltd. Lineament: ERTS E-1565-00000-5 photograph.

4. Coats (1973).

5. Lineaments: ERTS as above.

6. Magnetic data - selected from Whitten (1966) Aeromagnetic Map of total intensity FROME sheet 67-113. S. Aust. Dept. Mines.

8. Fitzroy-Spencer Fracture zone - (Stewart & Mount 1972). Faulted western margin of Willyama Inlier - deduction by G. Pitt (*pers. com.*1975) S. Aust. Geol. Survey, from relationship between faults, geomorphology and earthquake activity.

Fault marked "trend uncertain"-deduced from stratigraphic relationships from the writer's logs of private company drill holes of E.A. Rudd and Associates.

Fault west of the Pasmore River, at the north-western end of the Fitzroy Spencer Fracture Zone - this is a Mesozoic-Palaeozoic feature from seismic work of United Geophysical Corpn. cited above.

9. Seismic depth data: Nelson & Galbreath (1973). Magnetic data: Whitten (1966), as above.

10. The lineament shown is deduced from a whitish streak on the ERTS E-1221-23594 - photographs 4, 5, 6 & 7 (it does not coincide with any paddock boundaries.

11. Seismic Refraction - Nelson & Galbreath (1973) cited above. Drilling and uranium distribution - Langron & Marshall (1973), Pacminex Pty. Ltd.

12. Structures defined from geomorphologic and geologic data from writer's mapping on CURNAMONA.

13. Channel trend and bore cuttings - Middleton (1973, 1974), Tricentrol (Aust.) Pty. Ltd.

14. Aeromagnetic data - cited above.

15. Data from seismic survey for Crusador Oil N.L. by United Geophysical Corpn. (Proctor *et al.* 1966). The term 'basement' here refers to pre Mesozoic rocks.

16. Early Tertiary channel from sand percentage map. Aeromagnetic data from sources as above. Channel and uranium distribution - Brunt (1974a,b) Mines Administration Pty. Ltd. with sedimentary Uranium N.L.

17. Aeromagnetic data - as above. Channel direction and basement data - Brunt (1973). Mines Administration Pty. Ltd.

18. Uranium in the Namba Formation. Data from Morgan (1973), Chevron Exploration Corp. Pty. Ltd.

19. Callen (Fig. 2, Vol. II) FROME.

20. Mound springs with waters derived from Cretaceous aquifers (Draper & Jensen *pers. com.*) are aligned as shown. Cross-sections drawn by Callen on the FROME geological sheet suggest this trend coincides with the eastern edge of the Poontana Sub Basin.

21. Feature from ERTS imagery cited above.

22. Magnetic basement trends from aeromagnetic maps cited above.

23. Lineament derived from air photo interpretation by the writer.

24. Basement uranium anomaly. Data on uranium distribution and geology: Youles (1972), Exoil N.L. and Transoil N.L.

25. Basement uranium anomalies. Zimmerman (1969) Rept. by Sampey Exploration Services for Mid-East Minerals N.L.

Other. N.S.W. Basement uranium occurrences in pre Cretaceous crystalline basement - Willis & Stevens (1974).

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PHOTOGRAPHS (All scales in mm & cms except Fig. 145)

Fig. 57. P511/71. Cootabarlow No. 2, 146.7 m. Eyre Formation-Eocene. Laminated silty mud: carbonaceous quartz kaolinite lutite. Alternating silt and clay layers, silt well sorted, clay oriented parallel to bedding. XP.

Fig. 58. CSIRO 543. Wertaloona 1, 54.43 m. Namba Formation. Silty mud: burrowed intraclastic clay lutite. 'Ghost' clast (C) with thin cutans rim in identical clay matrix. Compare Fig. 76. XP.

Fig. 59. P1089/73. Wooltana 1, 238.38 m. Namba Formation, unit 1. Laminated carbonaceous RI illite lutite. Opaque carbonaceous matter alternates with clay oriented parallel to bedding. See Fig. 125 for core.

Fig. 60. P1057/73. Wooltana 1 bore, 20 m. Willawortina Formation. Very fine sandy kaolinitic sparry dolomicrite. Arenaceous portion is a sublitharenite. Demonstrates extremely poor sorting typical of the unit, and the difference between Namba Formation and Willawortina F. carbonates (*c.f.* Figs. 103, 104, 116). Soil like texture.

Fig. 61. P1104/72. WC2 bore, 75.13 m. Willawortina Formation. See Petrological description, appendix 2. Demonstrates extremely poor sorting, matrix supported texture, criss-cross texture of clay. Mica (M) and quartz (Q). XP.

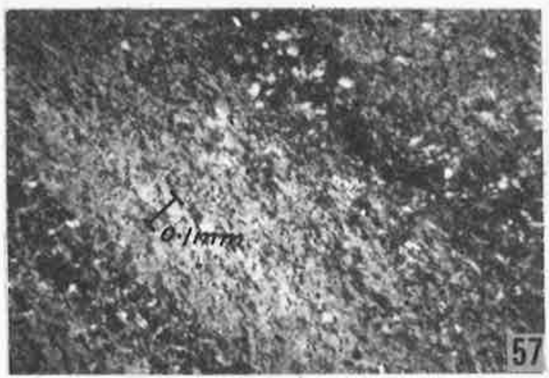
Fig. 62. As for Fig. 61. Shows detail of feldspar (microcline, F), chert (Ch), in large angular fresh grains. Quartz sand (q) and clay matrix (C). XP.

Fig. 63. P1134/73. B240/C3 bore, 111.72 m. Eyre Formation. Conical laminated texture of kaolinite (K) with ferruginous bands (Fe). Cones are built upon framework grains and merge into horizontal bands parallel to bedding. Note typical granular texture of kaolinite-illite (mica) matrix.

Fig. 64. Same as Fig. 63. Shows grooves in quartz grain (Q) infilled with kaolinite (C). Portions of grain have become islands. These grains generally hold together when removed from matrix, the clay in the cracks acting as cement. Note high angularity, emphasized by matrix reaction. XP.

Fig. 65. P1021/73. Yalkalpo 1 bore, 33.40 m. Medium sand: submature feldspar chert ?smectite quartz arenite. Namba Formation. Untwinned orthoclase (F), showing cleavage and control of shape. Also microcrystalline quartz chert (Ch) with variable grain size. XP.

Fig. 66. As for Fig. 65. Plagioclase with leaf shaped twin planes (F) - probably strained. Ragged outline caused by reaction with matrix. Fuzzy coarse chert (Ch), textures resembling fine snowflake texture of porphyry *c.f.* Fig. 82. XP.



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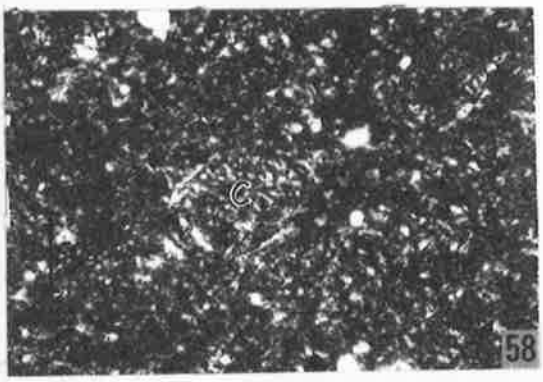

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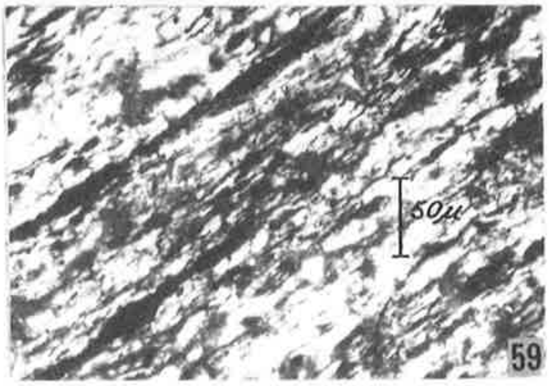

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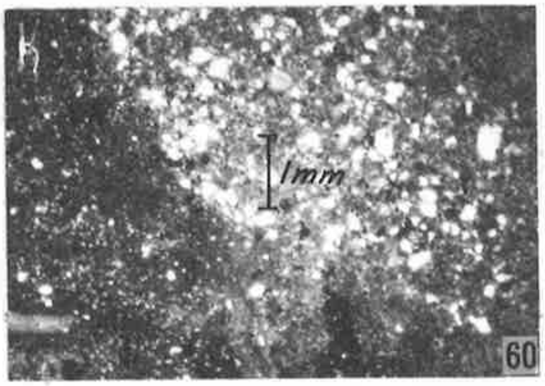

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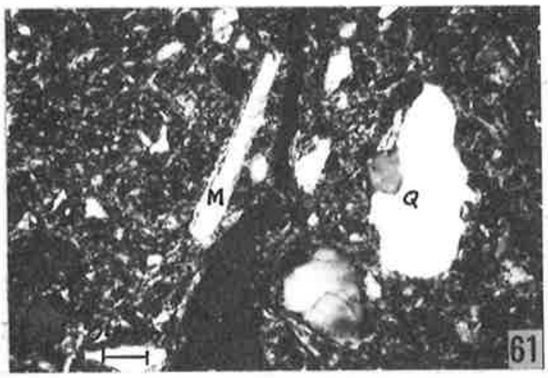

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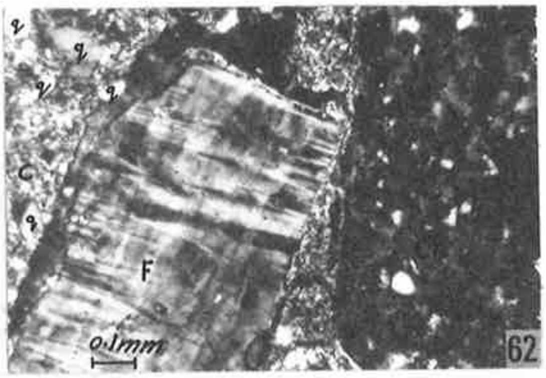

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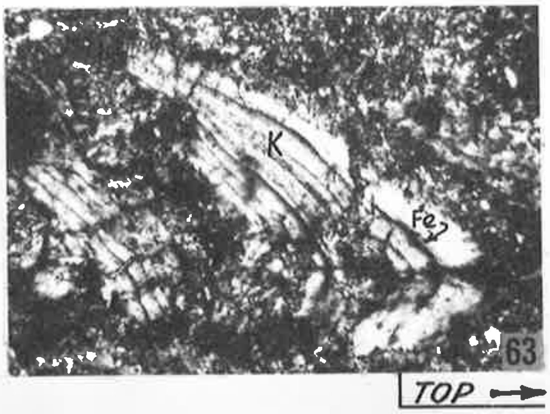

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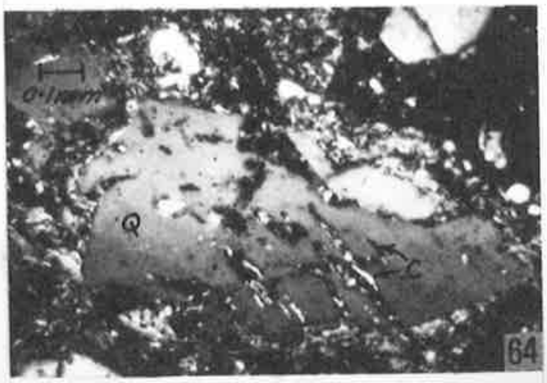

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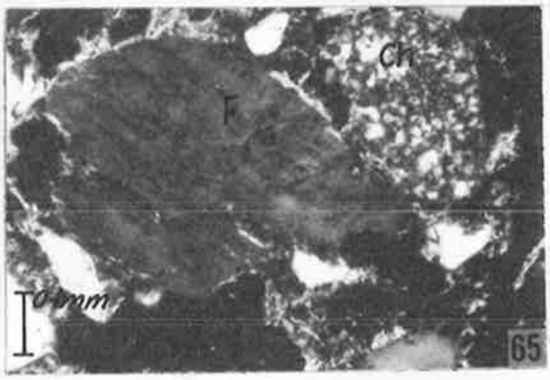

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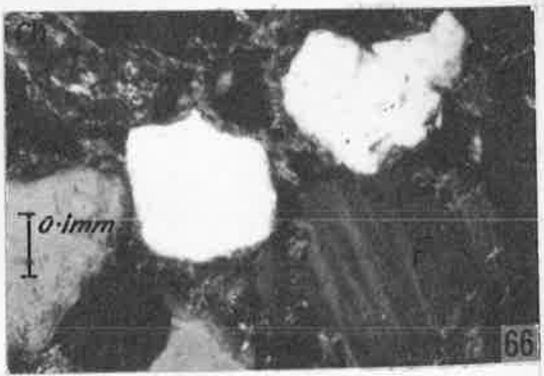

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Fig. 67. As for Fig. 66. Microcline (F) with typical grid twinning and deeply embayed margins. Simple composite quartz grain Q. XP.

Fig. 68. P235/72. EAR5 bore, 46.8 m. Namba Formation. Albite twinned plagioclase with deeply embayed margins (F). Lattisepic fabric. XP.

Fig. 69. P1269/73. Wertaloona 1 bore, 141.80 m. Namba Formation. Albite and pericline twins in feldspar (F) probably microcline. Granular clay fabric. XP.

Fig. 70. P1086/73. Wertaloona 1 bore, 190.06 m. Namba Formation. Iron mottle (Fe) opaque and dark stain. Quartz (Q). Poorly sorted.

Fig. 71. P1021/73. As for Fig. 65. Namba Formation. Fine microquartz chert (Ch) with large elongate individual. Quartz (Q) slightly undulose. XP.

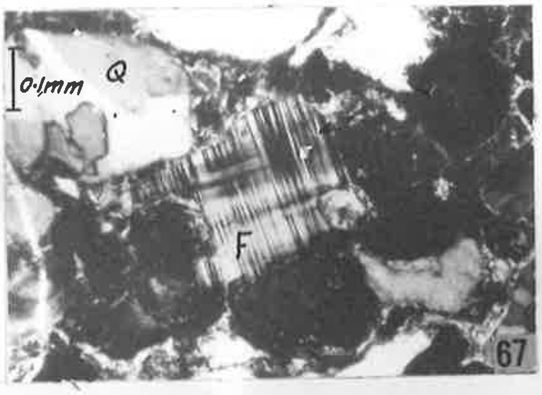
Fig. 72. P437/74. Eurinilla 1:63 360 sheet 3/4393/23A. Silcreted coarse sand ('Coarse mature sand unit') assigned to Namba Formation. Well rounded medium sand with several generations (arrowed) of quartz overgrowths. These have numerous minute orange ferruginous inclusions in different generations. XP.

Fig. 73. P1083/73. Wooltana 1 bore, 131.70 m. Namba Formation. Subangular quartz grain (Q) with overgrowth (OG), original boundary of quartz marked by iron inclusions (arrowed). Muddy medium sand-immature intraclastic clay quartzarenite.

Fig. 74. P848/71A. Quinyamble 1:63 360 sheet 1/9711/1A. Probably Namba Formation. Fine sand: calcreted silcreted ferruginized quartzarenite. Shows various generations of cementation. Iron crusts (Fe) on grains coated with microcrystalline quartz chert (Ch_1). Cavities have then been infilled by fibrous chalcedony (Ch_2). The latter has then been replaced by micrite (M).

Fig. 75. CSIRO 543. As for Fig. 58. See Fig. 126 for core. Clay clast with smaller internal clasts. Dark iron stain is concentrated on one side of clast. The banded structure so defined appears to follow bent lamellae like those of Fig. 126.

Fig. 76. P297/72. Reedy Springs type section, Unit 1, Eyre Formation. Coarse grained sand and pebbles: cherty quartzarenite with ferruginous (black) and sparry calcite cement (not visible). Large well rounded chert pebble shows wavy distorted structure.



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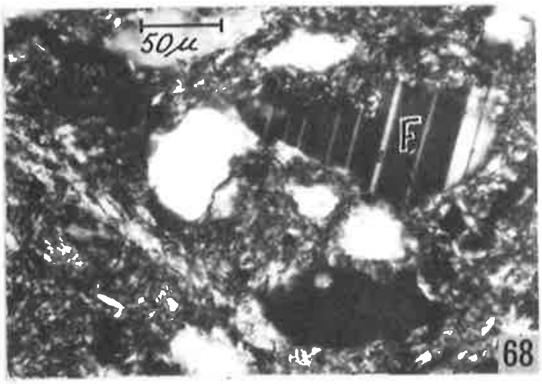

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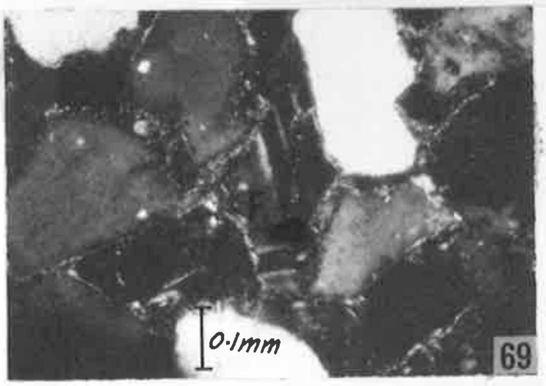

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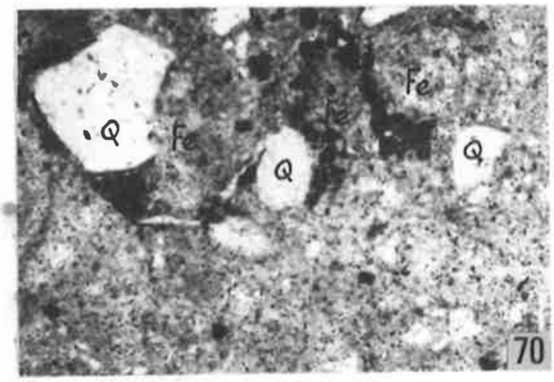

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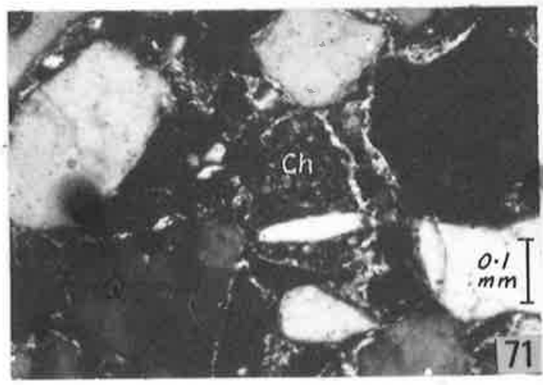

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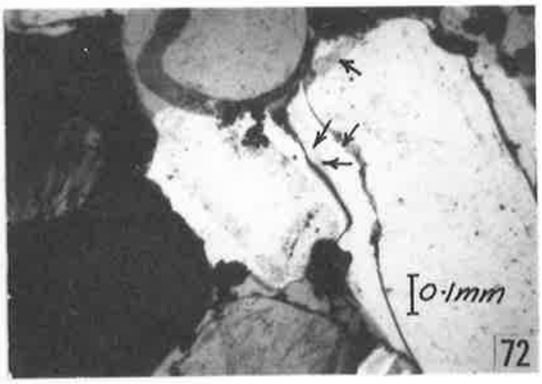

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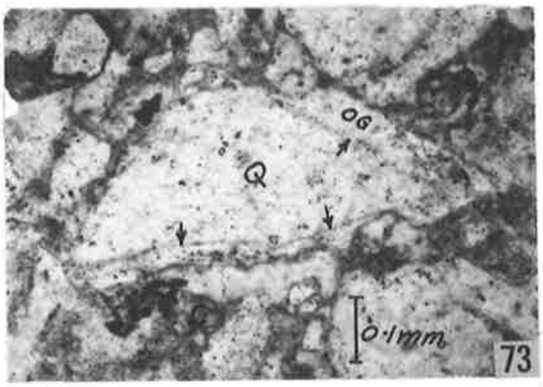

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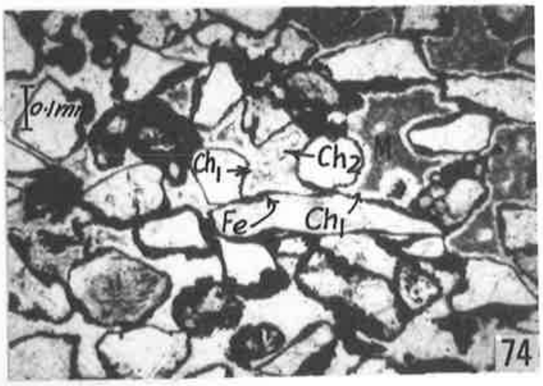

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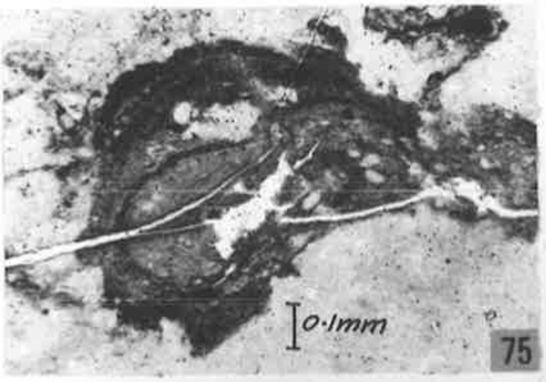

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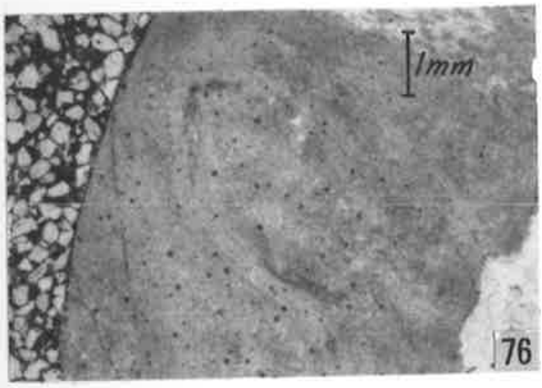

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Fig. 77. Mesozoic chert. Detrital pebble from Algebuckina Formation. Compare with other cherts, especially Fig. 78. XP.

Fig. 78. P297/72. As for Fig. 76. Inequigranular chert-detail of large pebble. Accounts for variability in small grains. XP. *c.f.* Fig. 77.

Fig. 79. As for Fig. 76. Large monocrystalline quartz pebble (bottom left) and two chert pebbles. Very fine chert at top, coarser variety with megaquartz vein. This and the other chert pebbles resemble Adelaidean cherts, most replacement of carbonates. XP.

Fig. 80. P295/72. Location as Fig. 76, but unit 3. Lithology as for P297, but no pebbles. Shows snowflake textured chert (Ch) *c.f.* Fig. 83. XP.

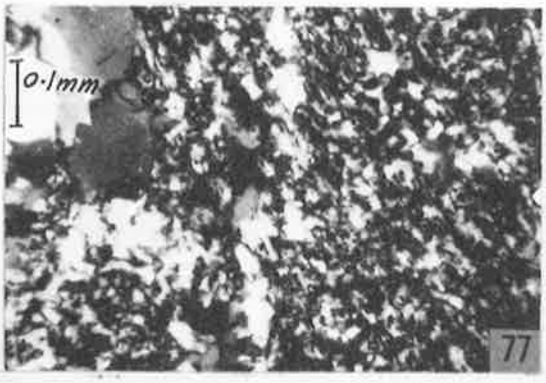
Figs. 81, 82, 83. Varieties of matrix texture in Gawler Range Porphyry, photographed F. Radke (AMDEL). Textures are similar to Benagerie Ridge Porphyry. These do not contain bands of coarser quartz such as in Fig. 87. Spec. TS30483, 29100, 30543. XP.

Fig. 84. P68/74. Eurinilla 1:63 360 sheet, 2/4435/16G. Namba Formation chert nodule, showing vughs resulting from shrinkage, partly infilled by megaquartz. These nodules are developed within silty clays and fine sands of the Namba Formation, in outcrop. For external appearance see Fig. 93. XP.

Fig. 85. P1046/73. Yalkalpo 1 bore, 73.40 m. Eyre Formation. Medium sand: carbonaceous and pyritic cherty mature quartzarenite. Black matrix of pyrite and carbonaceous matter. Shows typical sand, note roundness, grain size, and presence of chert grains. Composites very rare. XP.

Fig. 86. As for Fig. 85. Shows composite quartz grain. Ragged boundaries and strain shadows indicate derivation from mm source.

Fig. 87. As for Fig. 85. Detail of chert grain (Ch). Shows typical fine microquartz chert with coarser band crossing it. This type is common throughout the Tertiary sequence. Normal simple quartz grains with slightly inclined extinction (Q).



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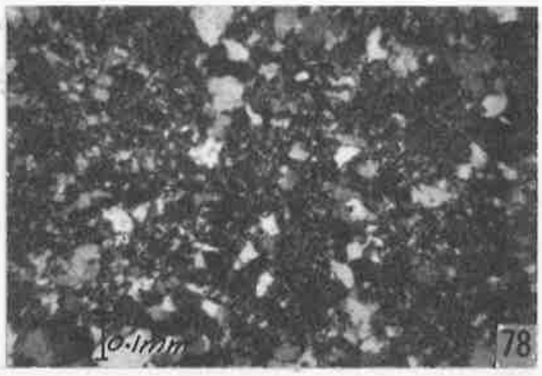

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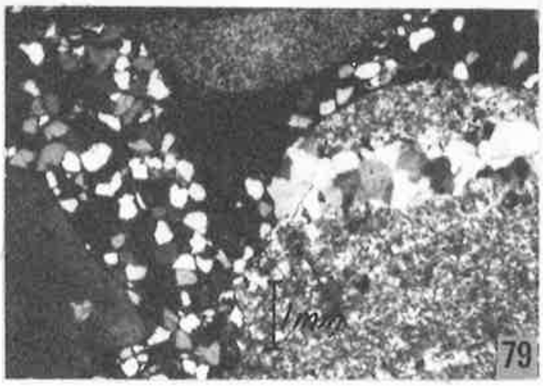

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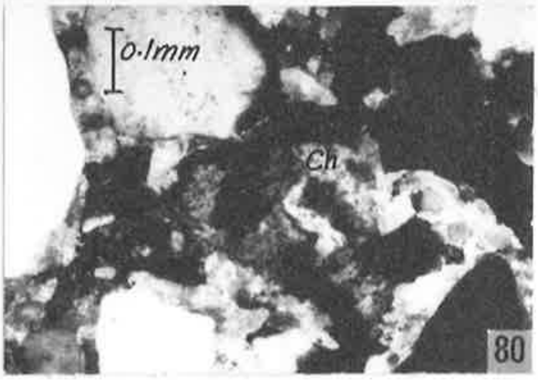

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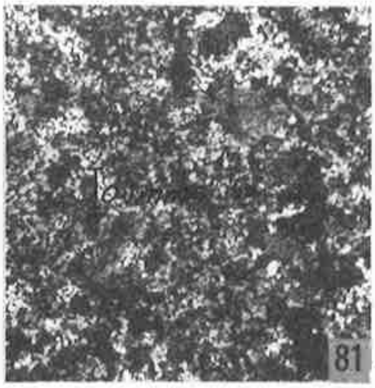

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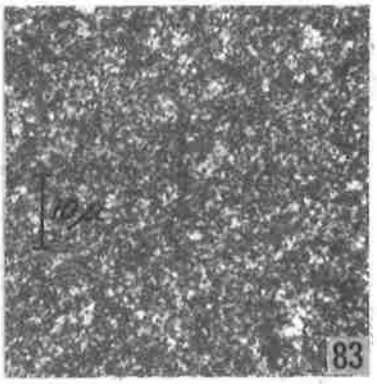

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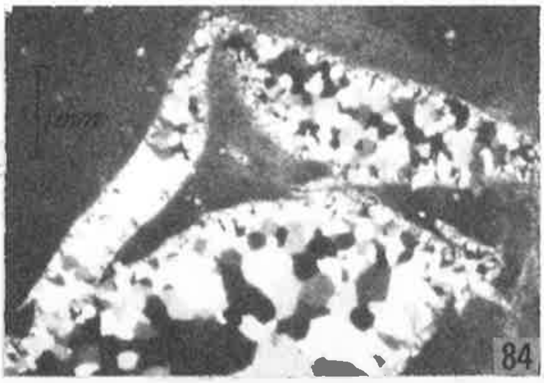

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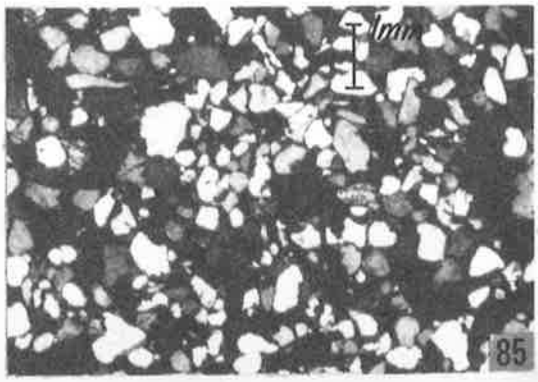

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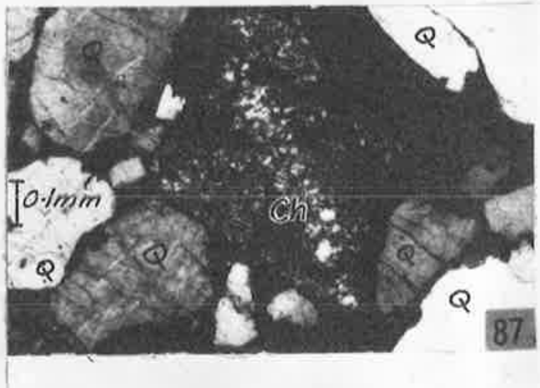

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Fig. 88. P1021/73. Yalkalpo 1 bore, 33.40 m. As for Fig. 65. Namba Formation. Coarse chert and microquartz *c.f.* Fig. 78. Recorded as composite quartz: demonstrates no clear cut boundary between chert and quartzite in small grains. Quartz (Q) with embayment (arrowed). Note clay layer adhering to grains. XP.

Fig. 89. As for Fig. 65. Large fibrous radiating chalcedonic chert grain (Ch). Irregular shape suggests it may be an infilling of a cavity, though this type of chert does occur as detrital grains. Alternatively embayments may be the result of matrix reaction. Clay film (C) and quartz (Q). XP.

Fig. 90. As for Fig. 65. Namba Formation. Typical grains of coarse chert. Subrounded. XP.

Fig. 91. Western Nuclear 589-33 bore, east end of L.Millyera. Eyre Formation, showing medium sized subrounded quartz grains - typical sample of open hole drill cuttings.

Fig. 92. P1020/73. Yalkalpo 1 bore, 25.90 m. Namba Formation. Elongate chert grain (Ch) with fine oriented texture - probably a fine grain quartz rich metasiltstone. XP.

Fig. 93. Wooltana 1 bore, 218.68 m. Namba Formation. Stained acetate peel of dolomite breccia. Shrinkage (C) cracks infilled with limestone (light grey). Note lamination in dolomite. Lime must have been mobile, and has rafted up to the cracked blocks. See Fig. 5 of Callen & Tedford for slab from which peel prepared.

Fig. 94. Wertaloona 1 bore, 161.2 m. Namba Formation 360° view of core. Very fine lamination of clay (grey) and silt (white). Cut by numerous small fractures, often diverging from a common point. The margins of the blocks defined by these fractures (A) are often downturned. The silt of A may have been buoyed up by diapiric movement of clay beneath. At C, clay has burst down through a silt layer forcing a block of silt downwards. This block has pressed into the underlying silt. At E is a thrust-like feature, indicating lateral reduction has occurred. A narrow

double crack (B) traverses part of the core. The clay in this crack has been mobilized - represents channel-way for pore water movement, perhaps an incipient dyke. At D are a number of minute clay diapirs, penetrating into the silt - these produce forms in the silt identical to reverse flame structures. Thus clay has moved both upwards and downwards.

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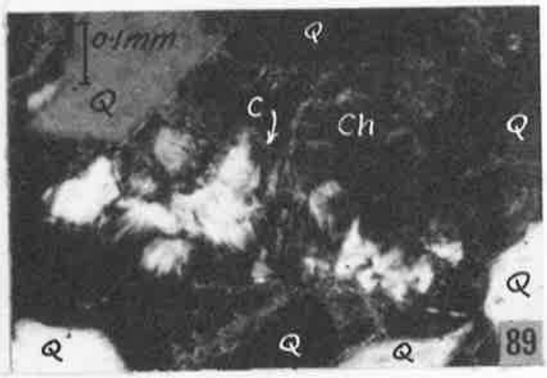

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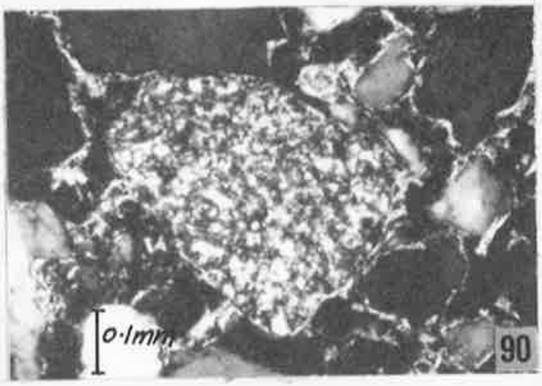

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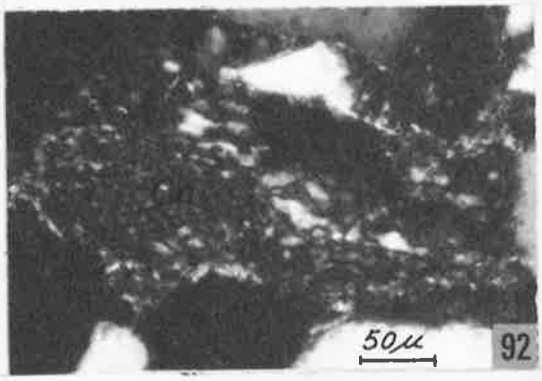

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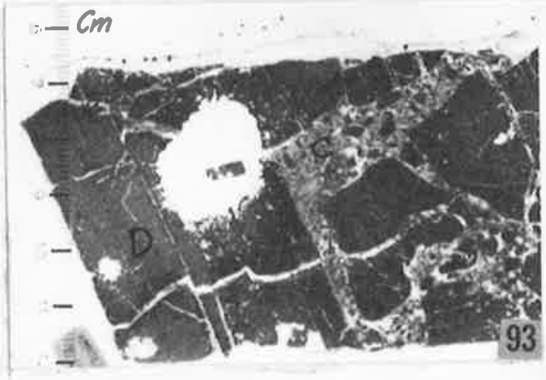

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Fig. 95. P1252/73. Wertaloona 1 bore, 60.00 m. Namba Formation. Micritic dolomite and clay, (about 50:50) showing burrowed areas (B), normal undisturbed micrite (M), quartz (Q), and ?fungal tubules (F). Peletal structure and lamination can be seen in burrows (L , arrow drawn parallel to lamination). Cross section of burrow lower left centre shows concentric lamination, and star-shaped arrangement of filaments (now voids with dark marginal stain) meeting at the centre of the burrow. Note manner in which filaments follow edges and laminae of burrows. Clay-iron pellet with concentric lamination (P) is crossed by a filament. Clays in this specimen are mainly randomly interstratified types and illite.

Fig. 96. P1154/73. EAR6 bore, 44.00 m. Namba Formation. Finely laminated palygorskite dolomicrite, clay accessory to subominant. Shows patchy broad extinction pattern of palygorskite (P), concentrated in distinct laminae.

Fig. 97. P1250/73. Wertaloona 1 bore, 50.00 m. Namba Formation. Slightly silty mud: quartz, intraclastic clay lutite. Demonstrates clay texture - broad oriented bands (S), criss-cross structure (CC) and coarse textured clay clast (Cl: probably palygorskite). Smectite and minor ?kaolinite probably constitute most of the matrix. XP.

Fig. 98. P239/72. EAR5 bore,70.8 m. Namba Formation. Mud: intraclastic illite palygorskite lutite. Complex texture with clast like structures (C) and broad oriented bands of palygorskite. The banded texture often passes through the clasts. Probably a clay which has undergone rheotropic deformation, followed by recrystallization of clay. Xray shows illite and palygorskite are intimately mixed. XP.

Fig. 99. P1086/73. Wooltana 1 bore 190.06 m. Namba Formation. Fine sandy mud: quartz kaolinite smectite lutite. Shows embedded quartz grain (Q), and well developed criss-cross texture, in which clay flakes parallel quartz grain boundaries. XP.

Fig. 100. P1081/73. Wooltana 1 bore 76.36 m. Namba Formation. Unidentified fossil fragment (F), possibly an algal or monocotyledenous plant stem. Micrite is usually coarse and well crystallized (M): hexagonal structure clearly visible.

Fig. 101. As for Fig. 100. Normal clotted texture. Unidentified fossil fragment of a small rectangular platelet.

Fig. 102. P1084/73. Wooltana 1 bore, 141.18 m. Namba Formation. Detail of clotted texture in micrite of carbonate nodule (primary). Small quartz slivers (Q) are probably remnants of grains which have reacted with matrix. Contains both calcite and dolomite.

Fig. 103. P1262/73. Wertaloona 1 bore, 107.00 m. Namba Formation. Recrystallized carbonate:unusual texture of minute spherules of prismatic dolomite crystals. Etched.

Fig. 104. As for Fig. 100. Patches of illite and kaolinite (degraded) dark area, intergrown with dolomicrite-light area. XP.

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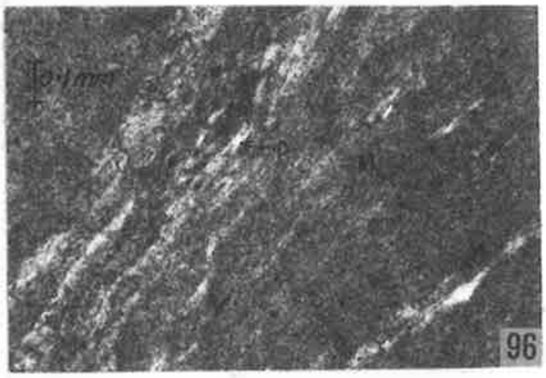

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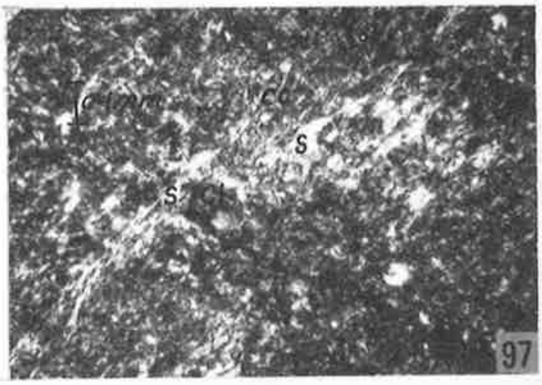

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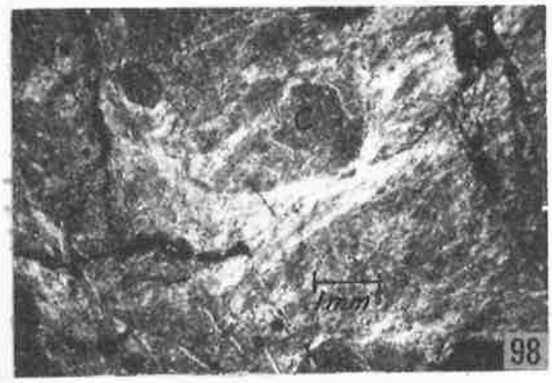

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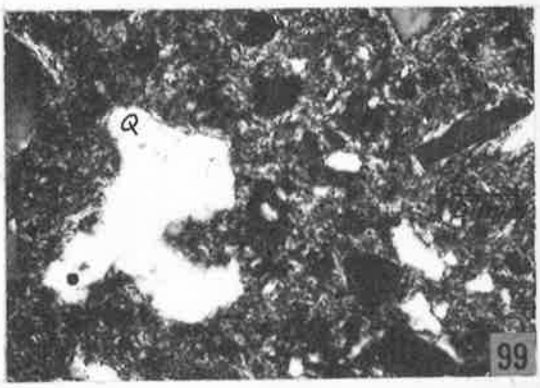

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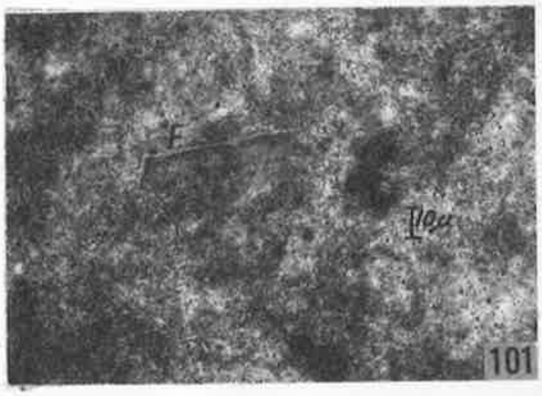

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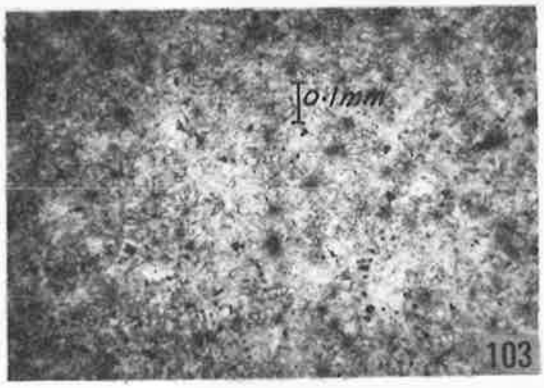

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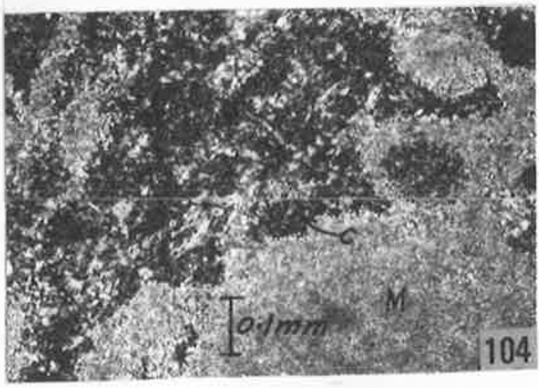

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Fig. 105. Wooltana 1 bore, 227.16 m. Namba Formation. Stained acetate peel. Algal laminite. Alternating dolomite (white or pale grey) and calcite (darker grey). Domed forms (S), curved platelets (SC), and probable animal or root trace (Tr). White spots are bubbles formed during preparation (B). See Fig. 130 for core.

Fig. 106. P1101/73. EAR7 bore 53.24 m. Namba Formation. Large intraclasts and pellets with laminated envelopes - ooliths. Uniaxial cross without crossed polars visible in O, indicating strong radial orientation of crystallites in envelope. Arrow indicates smoothed over irregularity in rod shaped intraclast. 'Pellet' is used for the smaller homogenous spherical intraclasts. Black areas are voids. XP.

Fig. 107. As for Fig. 106. Complex irregular intraclasts (I) with thin micrite envelope in matrix of dark micrite. Fitted structure (arrowed) is indicative of solution. White areas are voids.

Fig. 108. As for Fig. 106. Overall view of texture showing calcrete crust (CC) below this are irregular ooliths (O) and intraclasts (I). Ooliths may have sigmoidal shape resulting from deformation while soft, or be grouped and joined with a common envelope. Solution cavity (S) contains intraclast with a micrite coating (C_1) on its upper side. Above calcrete crust is a zone of micrite containing uncoated pellets. These pellets have been dissolved out (white voids). Represents calcreted oolitic dolomicrite.

Fig. 109. As for Fig. 106. Oolith (O) has micrite core into which the inner laminae merge, suggesting some recrystallization. The laminated coating is thick and has been partly spalled off, leaving remnant X. This has been coated with micrite and more laminae (C). Smaller oolith with well developed radial structure R.

Fig. 110. As for Fig. 106. Rod-shaped oolith with large micrite intraclast core (Oc), containing small pellet (P). Had been broken and

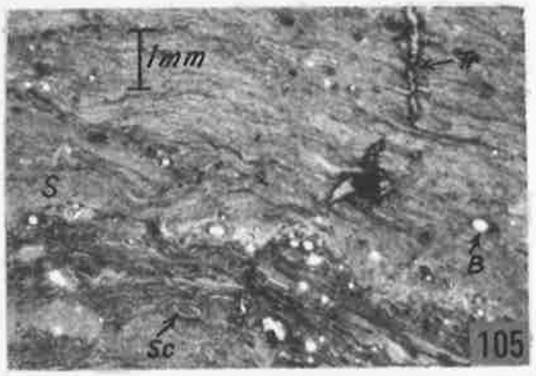
recemented (X) after coating (E) had formed, though coating seems to be partly continuous at arrow (oolith soft when fractured?).

Fig. 111. As for Fig. 106. Scolloped solution surface (white arrows) on micrite with scattered ooliths (O). Overlain by pelletal micrite.

Fig. 112. P1103/73. EAR7 bore 54.86 m. Namba Formation. Well developed oolith with small micrite pellet core, and wavy laminated envelope, grades to normal ooliths (at edges of photograph). Resembles algal oncolite. Ooliths float in dark dolomicrite.

Fig. 113. As for Fig. 112. Detail of laminated envelope showing laminae bending down (arrowed) into zones between columns, these zones being partly filled with structureless micrite (Mz).

Fig. 114. Etadunna Formation, Lake Palankarinna type section - carbonate facies. Shows typical clotted texture of dolomicrite, with rare quartz grains (Q).



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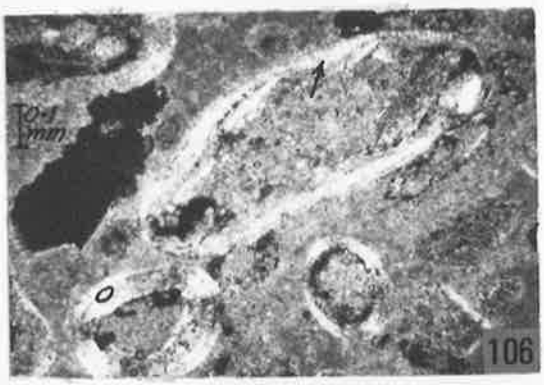

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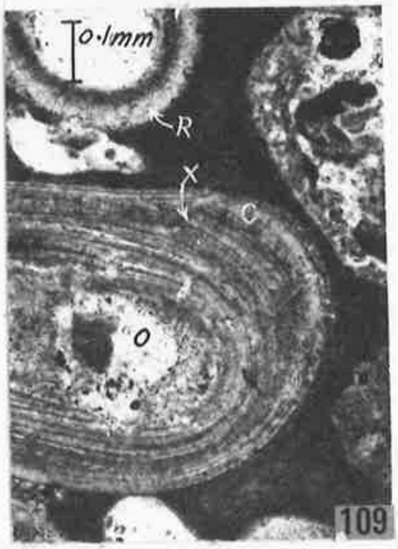

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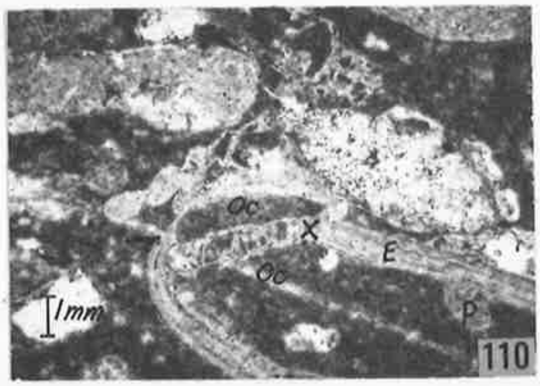

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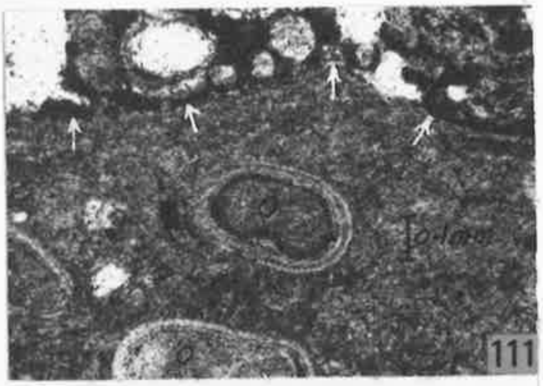

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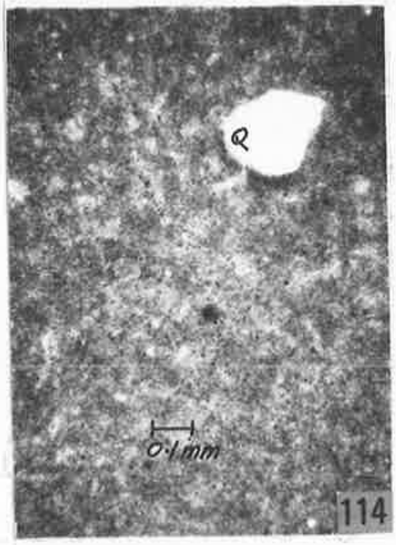

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Fig. 115. Yalkalpo bore 45.60 m. Split core contact between uppermost black clay and laminated silt. Note sharp contact, and inclined ragged clast-like forms of orange-stained clay (BC) separated by darker clay. The planes between the 'clasts' are often slickensided.

Fig. 116. Wertaloona 1 bore, 136.72 m. Split core. Example of part if cyclic sequence. Basal aphanitic white carbonate, (Carb) passing via disturbed zone of streaked out carbonate and intermixed clay into dark grey clay (BC). Clay as for Fig. 115. Light patches are oxidized zones. Relatively sharp contact at top with fine sand. Passes into laminated very fine silt sand and clay (LSC). Very fine cross-lamination at top.

Fig. 117. Yalkalpo 1 bore, 45.60 m. Split core. Transition from sand (Si) to black clay (BC) showing vertically oriented streaks. May be result of intense bioturbation or root penetration. Dipping contact at top.

Fig. 118. Wooltana 1 bore, 221.70 m. Split core. Mixed zone between black clay and dolomite breccia. Note diapiric habit of clay (BC). Indicates both clay and dolomite (Dol) were soft when mixing occurred - example of thixotropic behaviour (quick flow structure).

Fig. 119. Wertaloona 1 bore, 148.50 m. Split core. Finely laminated silt, over disturbed zone. Irregular patchy carbonate (Cal) penetrates up cracks in silt. Quick flow structure.

Fig. 120. Wertaloona 1 bore 59.45 m. Whole core, mudcake removed. Dessicated thin dolomite bed, cracks infilled by clay. Some dolomite clasts have been rafted up at top.

Fig. 121. Yalkalpo 1 bore, 22.71 m. Split core. Bioturbated zone B, between two laminated clay silt beds. Vertical burrows penetrate underlying silt. Clay layers X are produced by penetration of drilling mud. Down-curved edges produced as core enters inner tube.

Fig. 122. Wertaloona 1 bore, 112.66 m. Whole core, mudcake removed. Very finely laminated clay with minor clay-filled fractures.

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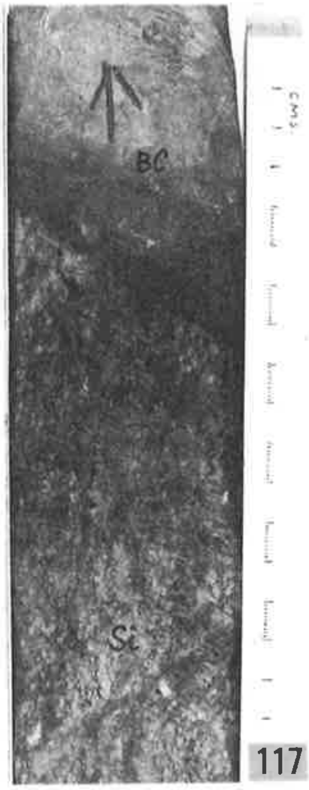

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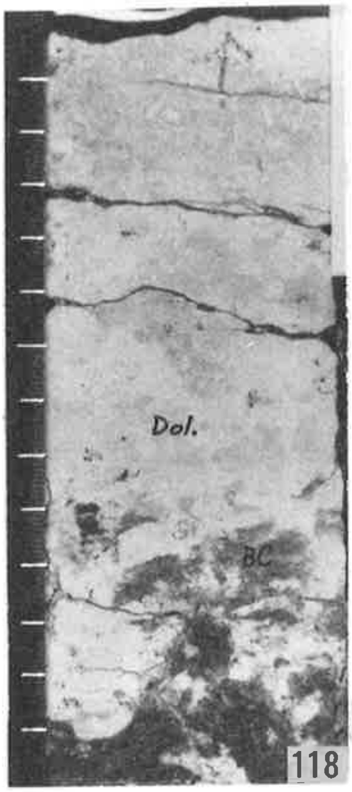

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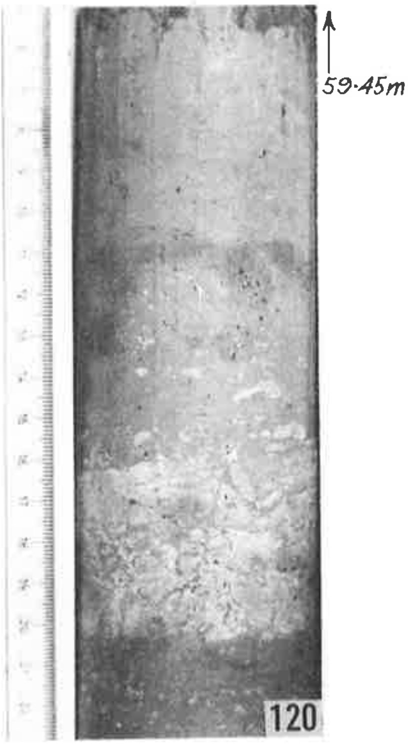

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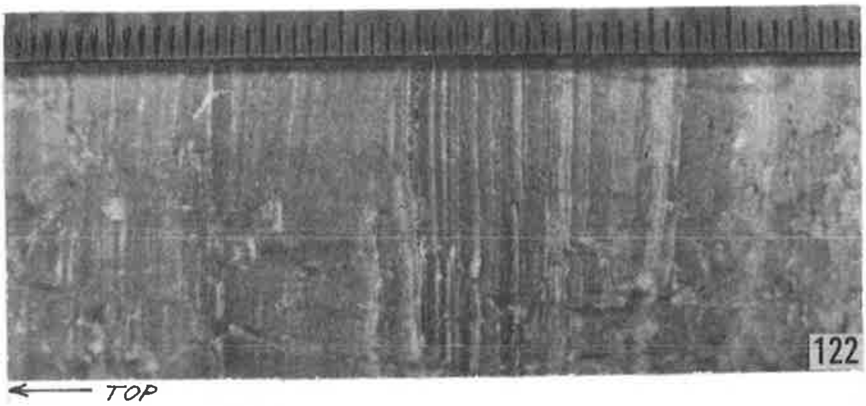

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Fig. 123. Wooltana 1 bore, 242.76 m. Namba Formation. Underside of clay layer showing clasts of ?gastropod traces, and patches of irregular depressions (feeding or resting marks?).

Fig. 124. Wertaloona 1 bore, 60.42 m. Namba Formation. Distorted clast: finely laminated clay (A) is surrounded by clay zone with flow lines and small clasts (B). Zone B represents material originally beneath the laminated clay. Typical of flow between layers of differing plasticity and specific weight. Suspended in light coloured dolomitic clay. Streaked out edge (C) and upturning of edges indicates differential movement between clast and matrix. Quick structure - example of hydroplastic behaviour.

Fig. 125. Wooltana 1 bore, 238.60 m. Unit 1 of Namba Formation: finely laminated black clay, olive clay, and thin carbonate. Upper part of fossiliferous black clay interval. See Fig. 59 for thin section.

Fig. 126. Wertaloona 1 bore, 54.43 m. Dolomitic clay (light coloured) overlying olive clay (dark zone at base). Intraclasts and burrows of olive clay scattered throughout, emphasized by ferruginous rims. Orange mottling (marmorization) increases in intensity upwards. Fig. 75 gives detail of clast with iron rim. Demonstrates interplay between burrowing, quick-flow and ferruginization.

Fig. 127. PMX24a bore, 102.58 m. Araldite peel. ?Namba Formation. Very fine grained sand, well laminated. Note mottled structure (not visible in hand specimen) probably bioturbation.

Fig. 128. Wooltana 1 bore, 122.00 m. Core. Reverse side of small-scale cross-laminated silt and clay shown in Fig. 7 of Callen & Tedford *in prep.* Shows trough structure. Resembles kappa and nu cross stratification of Allen.

Fig. 129. Wooltana 1 bore, 86.78 m. Core, mudcake removed. Dark clay ?clasts in light clay matrix. Clast-like forms are initially defined by different coloured zones within a mass of otherwise homogenous muds due to differing oxidation state of iron. Passing upwards, these secondary effects taken on the appearance of true clasts, floating in a clay carbonate matrix. Demonstrates intimate relationship between oxidation and quick flow during diagenesis.

Fig. 130. Wooltana 1 bore, 227.16 m. Split core. Namba Formation. Square shows position of Fig. 105. An acetate peel taken from this slab differentiated the carbonate as follows:

(1) 5 cms of dolomite (pale blue to colourless). The dolomite is laminated, and forms a rotated block. Single calcite (red stain) ostracode valves are present, oriented concave up or down, parallel to the bedding. The block is penetrated by cracks infilled by (2).

(2) 2-5 cm of ostracode limestone (pale to dark pink ,OL). About 25% articulated ostracode carapaces, many showing successive moult stages. The ostracodes are aligned parallel to the edges of the dolomite block (1) indicating the carbonate has flowed. The percentage of dolomite clasts in this lime bed increases upwards and passes transitionally into:

(3) 4 cm of slightly ferroan dolomite (pale blue) with many ostracode carapaces at the top. The upper surface is cracked, and the cracks (Cr) infilled with lime.

(4) 1½ cm of lime (stained pale and dark pink), passing up into well laminated ?dolomitic limestone - algal laminite.

(5) 7 cm calcite and dolomite (purple and colourless). The laminae are less than 1 mm thick, of alternating dolomite and calcite, and have a distinctive wavy texture. Algal laminite (see Fig. 105).

(6) Interlaminated palygorskite clay and dolomite grading up to pure clay.

Fig. 131. Wooltana 1 bore, 90.38 m. Laminated black clay and carbonate overlie a zone of olive clay with burrows and intraclasts, which is cut by a clay filled crack, bifurcating both upwards and downwards. Crack filled by fluidized clay, during shrinkage of dolomitic clay (light colour). Shows both sides of core, same crack. One burrow (B) passes through the crack.

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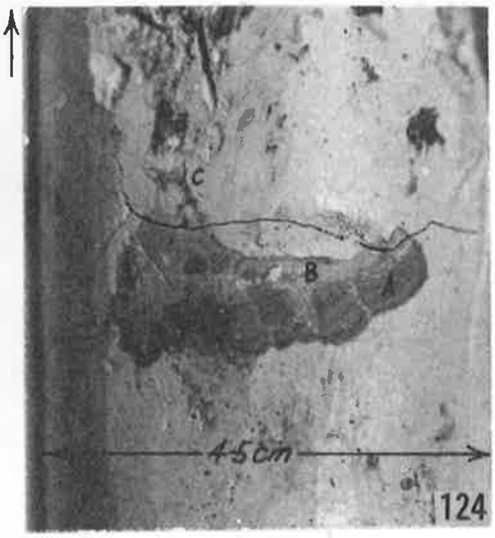

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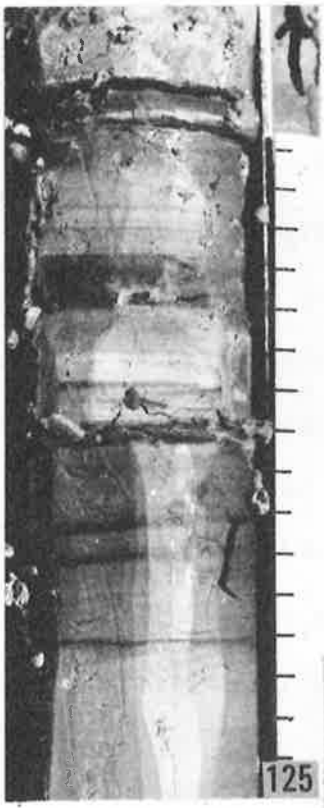

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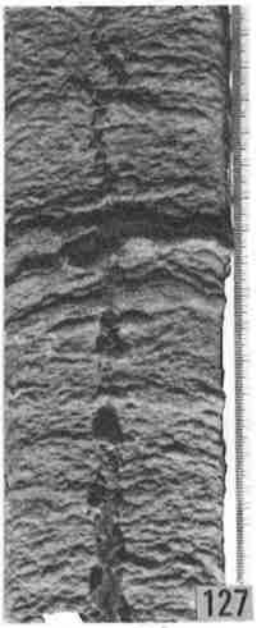

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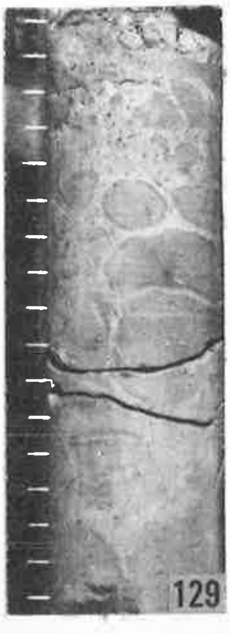

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REAR VIEW, SLIGHTLY LARGER

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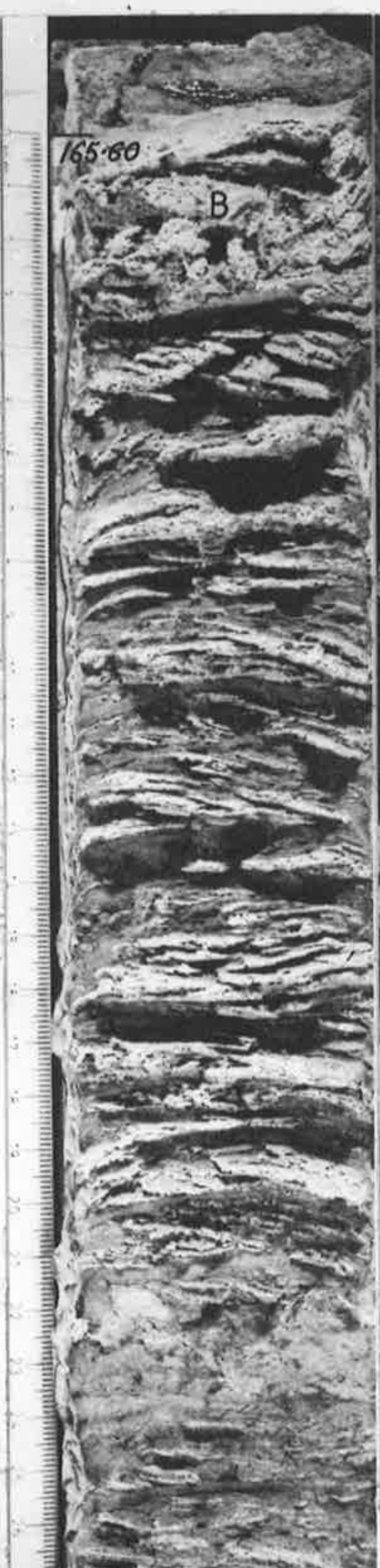

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Fig. 136. Wooltana 1 bore, 130.78 m. Namba Formation. Micaceous fine to medium sand. Three cross-beds (1-3); (1) has alternating clay and fine sand laminae; (2) dips away from observer, and is cut by a fracture (Y) probably formed during removal from core barrel. Laminae at base are distorted (X); (3) is a much thinner bed; (4) is silt bed with clay clasts at base (Cl). Lower bed suggests aqueous dune built up under conditions of alternating flow and quiet water. Lacustrine bar or delta channel deposit (though clay could have been brought as sand sized pellets).

Fig. 137. PMX24a bore, 111.80 m. Araldite peel. Eyre Formation. Very coarse grained quartz sand, very micaceous (see white flakes - M). Cross-bedded, with consecutively opposed current directions. Part of fining upwards sequence. Bar deposit of stream. Varying cross-bed direction probably partly the result of migration of dunes with curved crests.

Fig. 138. Wooltana 1 bore, 68.67 m. Araldite peel from base of tongue of Namba Formation, in zone of intertonguing with Willawortina Formation. Sandy clay (SC) overlain by clay (C) showing intensive bioturbation, with mixing at contact. Clay filled burrow, B_1 and sand filled burrow (B_2) with internal curved lamellae. Remnants of lamination (L) demonstrates much of the sequence has had the original sedimentary structure destroyed. Represents swamp or lake within a flood-plain environment.

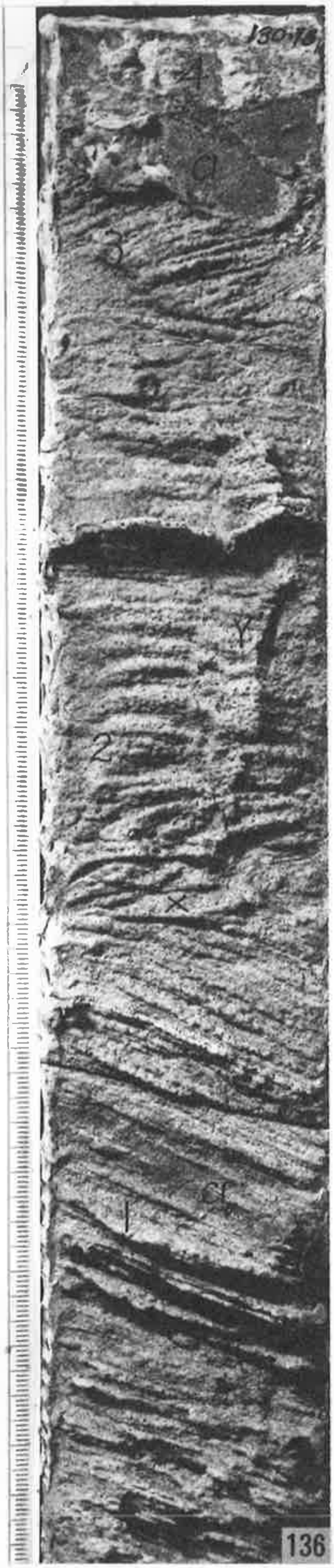

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Fig. 139. Eurinilla 1:63 360 sheet 3/4396/2, edge of Lake Namba near northern end. Namba Formation. Slumped laminated very fine sand and clay, in channel or bar. Slump is directed away from channel edge. Scale 30 cm.

Fig. 140. As for Fig. 139. Cross-bedded channel with thin sets. Current direction to WSW. Foresets and bottomsets visible. Dark clay layer marks contact with fine cross-laminated sand (Fig. 141). Omikron cross stratification of Allen. Note isolated pod of manganese stained sand (black) at corner of trench. Site of vertebrate discovery of R.H. Tedford.

Fig. 141. As for Fig. 139, higher in sequence. Small and very-small-scale cross lamination in very fine sand and clay-silt. Probably kappa and mu types. Probably represents upper part of point bar. Fig. 140 represents lower part of same point bar.

Fig. 142. Benagerie 1:63 360 sheet 1/4360/2. Namba Formation. Chert nodules weathering from fine grained sand of Namba Formation. Crusts are brown coloured. See Fig. 84 for thin section.

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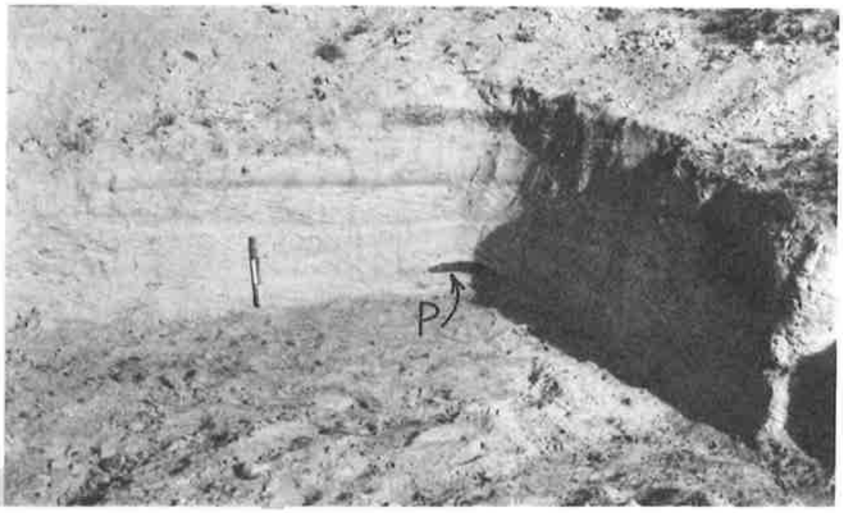

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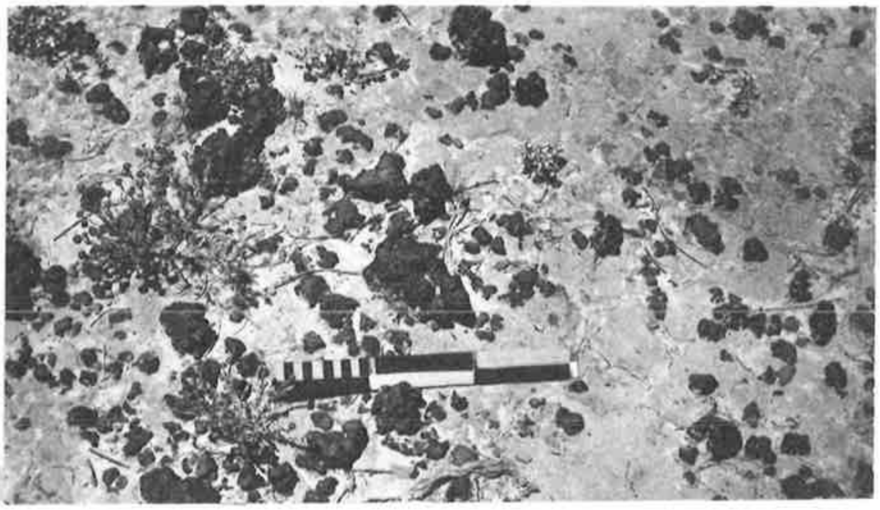

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Fig. 143. Eurinilla 1:63 360 sheet, 2/4435/16. Namba Formation. Typical outcrop of carbonate nodules.

Fig. 144. Siccus 1:63 360 sheet, 3/4383/1,2. On Pasmore River at main road ford. Coonarbine Formation (C) overlies Eurinilla Formation (B) with its basal conglomerate (prominent bench). This is cut into the sandy clays of the Willawortina Formation (A). Looking East across the valley.

Fig. 145. Elder 1:63 360 sheet, 1/0324/2. Western edge of Lake Bumbarlow. Black tough clay with irregular fractures, typical of lower member of Namba Formation. Shows large irregular pipe-like masses of alunite ramifying through the clay (white-Al). Steel tape shows 12".

Fig. 146. Siccus 1:63 360 sheet. Northern margin of Lake Millyera, showing typical outcrop of Namba Formation-thin-bedded white dolomite caps dark olive palygorskite clay. Plants are about 40 cm high.

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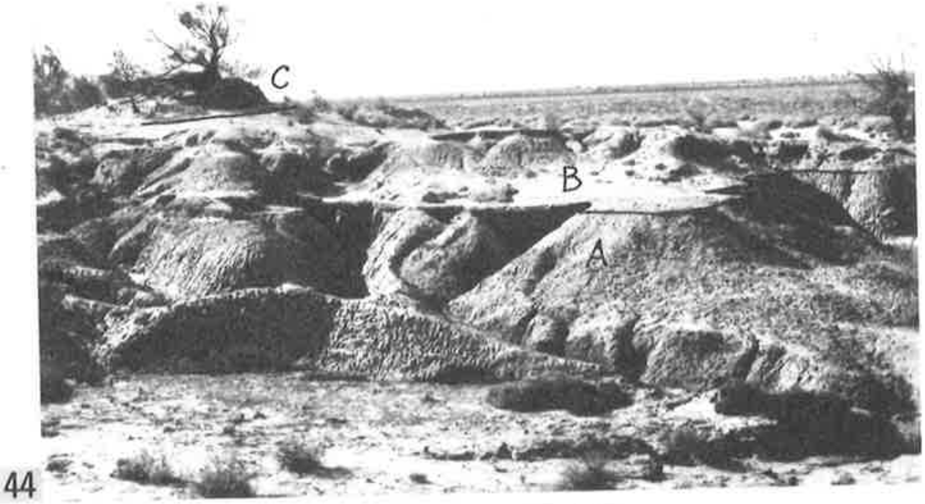

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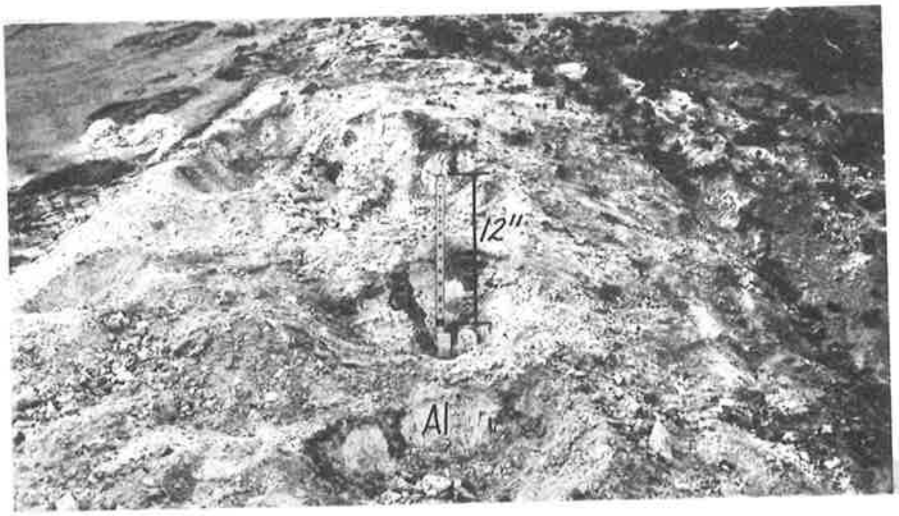

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