TERTIARY STRATIGRAPHY AND FORAMINIFERA OF THE ADELAIDE CITY AREA, ST VINCENT BASIN, SOUTH AUSTRALIA

28682

By

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Thesis submitted to the University of Adelaide in fulfilment of the requirement for the Degree of Master of Science

and proposed Bulletin of the Geological Survey of South Australia

Volume I

Stratigraphy, Figures, Plans, Appendices

South Australian Department of Mines and Energy, Adelaide, South Australia

June, 1981



Frontispiece(1)

Figure 1. Colour vertical air-photo of the Adelaide City area and surrounding suburbs; top is north; scale 1:40 000. Note apparent lack of expression of the Para Fault Zone (Dept of Lands, S.A., 4th Jan. 1979).



Frontispiece (2)

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Frontispiece (3)

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SUMMARY

The City of Adelaide, located within the Cainozoic St Vincent Basin, overlies a well-documented paralic to neritic-marine mid-Tertiary and Pliocene succession of the order of 100 m in thickness. Because they are extensively draped by Pleistocene clay and sand, the Tertiary units of the Adelaide City area (and of the adjacent Adelaide Plains Sub-Basin) are necessarily studied almost entirely from borehole material, since only the Pliocene Hallett Cove Sandstone is exposed by infrequent excavations. The year 1980 concludes a quarter-century of extensive drilling of this Tertiary sequence, and the present work summarises the stratigraphic and particularly the biostratigraphic results of more than 100 boreholes. Most of these were drilled by the South Australian Department of Mines and Energy (SADME) and mostly for engineering investigations. This report is a companion study to one on the 'Engineering Geology of the Adelaide City Area', prepared recently by J. Selby and the writer.

The City happens to be situated near several geological boundaries which have influenced Tertiary sedimentation and stratigraphy. It is only 3 km from the present eastern margin of the St Vincent Basin, where Cainozoic sediments are faulted (in the weakly seismic Eden-Burnside Fault Zone) against the Late Precambrian, Adelaidean rocks of the adjacent Mt Lofty Ranges. The Para Fault Zone (probably very weakly seismic) passes through the western parklands of the City, which also lies at the western edge of the Para

Fault Block, and at the southwestern end of the Golden Grove-Adelaide Embayment where it merges into the Adelaide Plains Sub-Basin. Sedimentation in the Adelaide City area followed the Middle Eocene opening of the St Vincent Basin as a complex rift-graben shaped by rejuvenated Delamerian tectonic trends near the passive southern margin of the Australian Plate, consequent on the initiation of drift from the Antarctic Plate in the Late Paleocene/Early Eocene.

The Tertiary succession beneath the City is similar in many respects to that exposed along the coast in the Willunga Embayment, where most of the type sections are located. However there are significant differences:

1. North Maslin Sand, the initial, Middle Eocene, braided-river, channel-sand complex in the Willunga Embayment (and parts of the Adelaide Plains Sub-Basin), is virtually absent beneath the City, but may be represented by sand deposits towards the head of the Golden Grove-Adelaide Embayment.
2. The basal unit of the Tertiary sequence beneath the City is almost always Middle Eocene Clinton Formation, featuring lignites formed in marginal coal-swamps, and including pale, sideritic, 'underclay' which rests on deeply-weathered Adelaidean bedrock.
3. The upper calcareous part of Upper Eocene Blanche Point Formation ('Blanche Point Soft Marls Member') has not been recognised beneath the City, and was presumably removed by erosion. However it occurs nearby in the Adelaide Plains Sub-Basin.

4. The Upper Eocene, regressive Chinaman Gully Formation has a thickness greater than the stratotype, but comparable to subsurface development elsewhere in the Willunga Embayment. The marginal-marine Tandanya Sand Member is a distinctive subunit described from the Adelaide City area, where it often overlies the cherty Gull Rock Member of Blanche Point Formation with erosional disconformity.

5. The younger of the two chert-bearing units, the Oligocene Ruwarung Member of Port Willunga Formation, is only preserved beneath the southern part of the City, where it is truncated by the Pliocene angular unconformity.

6. The mostly-Oligocene 'upper Janjukian unit', and younger Miocene units of Port Willunga Formation, are not found on the Para Block beneath the City proper, but are preserved subsurface in progressively more complete sequences on fault blocks of the Para Fault Zone transitional westwards to the succession in the nearby deepest part of the Adelaide Plains Sub-Basin. The 'upper Janjukian unit' and correlatives of the Longfordian Stage only occur on the Mile End Block and westwards; Batesfordian-Balcombian correlatives, with Lepidocyclina, have been found on the Thebarton Block; but Balcombian-Bairnsdalian correlatives, with advanced Praeorbulina, and Flosculinella, have not been found east of the Croydon Block.

The Munno Para Clay Member of Port Willunga Formation has not yet been intersected closer to the City than in the Croydon-2 bore; neither has the ?Lower Pliocene unit which was previously termed 'silts, Croydon', and later, 'Croydon facies', but is now named the Kooyonga Formation.

Marine influence up the Golden Grove-Adelaide Embayment declines markedly past the Adelaide City area, but lithological correlatives of Tortachilla Limestone and Blanche Point Formation are known to persist to Campbelltown and Hope Valley respectively.

For the first time locally, the planktonic and selected benthonic foraminifera which provide a basis for biostratigraphic correlation are illustrated by an extensive atlas of Scanning Electron Micrographs, with morphological and systematic notes. For some key taxa, such as Subbotina linaperta and Tenuitella aculeata, there is an emphasis on morphological variability in space, time, or population, either because this has not been done before, or to assist with the practical local problem of identifying 'poor' material from less than ideal environments.

Two new species of benthonic foraminifera are described: Massilina whitfordae sp. nov., and Planorbulinella roseannae sp. nov.

Experimentation with planktonic datum levels is preferred as being more realistic than proliferating zonal schemes. Numerous local planktonic First Appearance Datums (FADs) and Last Appearance Datums (LADs) are presented for comparison with other areas. The local homotaxial succession compares

moderately well with that in the Otway Basin; and less closely with New Zealand, although several events may have been isochronous. With the help of recent attempts at temperate-tropical correlation between southern Australia and the Indo-Pacific the local stratigraphic succession is matched tentatively with the 'standard' P. and N. Zones, epochs/series, and a recent geochronometric scale; but Australian Stages are still useful and necessary. Currently available data suggest that the Eocene/Oligocene boundary is represented within, and probably high in, the Aldinga Member of Port Willunga Formation; and that the Oligocene/Miocene boundary is represented within, and probably high in, the 'upper Janjukian unit' of the same formation.

Seven warm/transgressive episodes have left their mark on the Tertiary succession of the Adelaide City area, and can be matched to regional cycles of deposition, 'extra-tropical excursions' of warm faunal elements, and proposed global cycles of changes in sea level. One such episode was Middle to Late Eocene (Clinton Formation, South Maslin Sand); two were Late Eocene (Tortachilla Limestone/basal Blanche Point Formation, basal Port Willunga Formation); one Oligo-Miocene (Janjukian-Longfordian Port Willunga Formation); one late in the Early Miocene (Port Willunga Formation with Lepidocyclina); one early in the Middle Miocene (Port Willunga Formation with Flosculinella); and one in the Pliocene. The local, total-range zone of Hantkenina (H.) alabamensis primitiva in basal Blanche Point Formation, is better developed beneath the City than in any other known locality in the St Vincent Basin.

STATEMENT OF ORIGINALITY

This thesis contains no material which has been accepted for the award of any other degree or diploma in any University, nor to the best of my knowledge and belief, does it contain any material previously published or written by any other person except where due reference and acknowledgement is made in the text.

J.M. Lindsay

ACKNOWLEDGEMENTS

I wish to express thanks to Dr. N.H. Ludbrook, who introduced me to the Tertiary foraminiferal biostratigraphy of South Australia and the eastern St Vincent Basin, and who supervised my earliest work on the Adelaide City area for the South Australian Department of Mines.

I thank Dr. B. McGowran for his stimulating lead in foraminiferal studies, for early encouragement on this project while with the S.A. Dept. of Mines, and latterly for his help as University supervisor (jointly at first with Dr. V. Gostin).

Mr. D.H. Stapledon, now Professor Stapledon, S.A.I.T., while Supervisor of the Engineering Geology Division of SADM, gave early enthusiastic support to the idea of a joint study of the engineering geology and biostratigraphy of the Adelaide City area.

Mr. W.R.P. Boucaut, first as successor to Mr. Stapledon, and then as Chief Geologist of SADME, has played a key role in his continued assistance and encouragement to complete both this thesis and the companion volume by J. Selby and the writer. Mr. Selby, the present Departmental supervisor of engineering geology, has been a persevering and enthusiastic colleague in our inter-related work on the City area.

The writer has benefited greatly from working on, and discussing aspects of the City geology with a succession of Departmental colleagues, including (additional to those mentioned already), W.K. Harris, R.D. Steel, J.B. Firman, P.D. Allchurch, R.K. Tarvydas, S.D. Giles, M.J. Hannah, D. Armstrong, J.A. Reed and Dr. W.V. Preiss. Mr. W.K. Harris in particular, has contributed valuable palynological

information, especially in regard to the Chinaman Gully Formation. Mr. B. Finlayson, a Departmental geophysicist, capably undertook the recent detailed gravity survey of the near-City Para Fault Zone in response to the writer's request.

Mrs. T.G.M. Marcelis, Mrs. C.L. Whitford, Mrs. R. McCarthy, Mr. H. Buetefuer, Miss P. Stevenson, and Miss D. Clarke, provided much-appreciated technical assistance at various times. In particular, Cherie Whitford skilfully took and printed most of the S.E.M. photographs; and Roseanne McCarthy painstakingly made up the Plates of S.E.M. photos. Mr. W. Fairburn assisted with the proof-reading of Volume I.

The assistance of many members of the Drafting Branch is gratefully acknowledged, including B.S. Glasgow, E. Richards, B. Thomas, L.V. Wright, J. Bradford, R. Herraman, A.S. Francis together with R. Gates and E. Madden (who prepared the photo-reductions of the Plates). Latterly, careful final drafting was done by C.J. Warman, N.R. Sandercock, and especially S. Rossi.

I thank Miss D. Foreman for much high-quality draft-typing; and especially Miss F. de Angeli for the complete final-typing which has been done so well.

I am grateful to members of the Management of SADME (Mr. B.P. Webb, Mr. R.K. Johns, Dr. C.D. Branch, and Mr. W.R.P. Boucaut) for provision of all these Departmental facilities, for supporting an invaluable visit to the N.Z. Geological Survey, and for encouragement to pursue this whole undertaking to conclusion.

Dr. N. de B. Hornibrook and his colleagues at the N.Z. Geological Survey provided me with much-appreciated facilities and assistance in my examination of that Survey's type and reference collection of Tertiary planktonic foraminifera in Sept.-Nov. 1976.

I have appreciated helpful assistance from staff of the following engineering organisations in Adelaide:

- John Connell and Associates,
- Kinnaird Hill, de Rohan and Young,
- K.W.G. Smith and Associates
- and from staff of the Readymix Group (S.A.) Raw Materials Division, at the Noarlunga and Highbury East sand quarries.

Mr. N. Pledge, of the S.A. Museum, kindly facilitated access to fossil collections there.

I acknowledge with deep-felt gratitude the patient understanding, support, and encouragement of my wife Joy.

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INTRODUCTION

Aims and Scope

This is a companion work to the SADME Bulletin on 'Engineering Geology of the Adelaide City Area', prepared by J. Selby and the writer (Selby and Lindsay, in press). That study emphasises engineering geological aspects, with only a brief treatment of the stratigraphy: most of the stratigraphic input was provided by the writer. This thesis treats the stratigraphy of the Tertiary marine units in more detail, and particularly their foraminiferal biostratigraphy.

The City of Adelaide is situated only a few kilometres west of the eastern margin of the Cainozoic St Vincent Basin (Plan 1; Figs 4, 5). The Cainozoic sequence beneath the City probably attains a maximum thickness of about 140 m in the southeast Parklands (Plan 18). One aim of the present study has been to relate this sequence, and in particular the mid-Tertiary (Eocene to Miocene) marine part, to the thicker (600 m+) Cainozoic sequence beneath the Adelaide Plains to the west, and also to the coastal Tertiary stratotypes south of Adelaide (Plan 2). Further regional and interregional correlations have been pursued where expedient.

Outcrops of the marine Tertiary units in and around the City of Adelaide are very restricted, being limited to the occasional and temporary uncovering of Pliocene Hallett Cove Sandstone around the eroded and excavated scarp along the southern side of the Torrens Valley between the Adelaide Railway Station and the University of Adelaide (Figs 6-8): for the mid-Tertiary units, exposures are non-existent.



Figure 4. The City of Adelaide, near the eastern margin of the St Vincent Basin; view taken October 1980, looking N.W. from the western edge of the Mt Lofty Ranges (Eden Fault Scarp), Mt Osmond, Mountainview Place. The Adelaide Plains commence beyond the city, and stretch to Gulf St Vincent in the distance, divided by the Port Rd corridor; Torrens Island power station is in the right background.



Figure 5. Similar view of the City of Adelaide, taken October 1980, but from Seaview Rd, Mt Osmond, on the Eden Fault Scarp. Glen Osmond Road (Highway 1) extends to the South Parklands, left middle distance. The black-coloured Grenfell Centre (Ref. bores 82,83) is the highest building in the city.



Figure 6. View taken January 1980, looking S.S.W. to Central City Business District from Torrens Parade Ground, showing southern scarp of Torrens Valley, at site of old quarry in Pliocene Hallett Cove Sandstone. The northern wall of Government House Domain is visible on the left.



Figure 7. Trench, in footpath, cut in Pliocene Hallett Cove Sandstone (hard, blocky, pale grey, part mottled pale brown; with scattered moulds of bivalve molluscs); view taken May 16th, 1973, looking south up King William Rd, from near N.W. corner of Govt House Domain; scale is 2 m high.



Figure 8. Excavated exposure of Pliocene Hallett Cove Sandstone, south scarp of Torrens Valley, immediately west of Parliament House, south of Festival Theatre Plaza retaining wall, and east of Adelaide Railway Station. View taken July 1979, looking east from Station Rd ramp; site of Ref. bore 94 is off picture, to right, behind Constitutional Museum.

Therefore a study such as this is dependent on penetration subsurface, and for a century (Tate, 1882) the stratigraphic servicing of local drillholes and occasional excavations, sunk for engineering groundwater or drainage projects, has provided the immediate geological challenge and the main source of data for a developing geological synthesis.

In Appendix A are listed 107 stratigraphic reference bores situated within or near the City of Adelaide, which have been utilised in the present synthesis. Their locations are shown in Plan 5, in relation to 10 geological cross-sections (Plans 6-15). This study and its companion volume, between them, have sought to document and harmonise drilling results by means of stratigraphic summaries, geological cross-sections, structure-contour plans, and composite logs; thus achieving a considerable degree of predictability for future subsurface investigations.

All determinations in the 'Stratigraphic summaries of reference bores' (Appendix B) are the work and responsibility of the writer. A similar Table is included in the companion volume on engineering geology. These intersections are the basis for the geological cross-sections, most of which are included also in the companion volume. The writer (since 1969), and latterly J. Selby, both developed the cross-sections, but all have been finally checked, corrected, and integrated by the writer, who takes responsibility for them in their present form. All the structure-contour and distribution plans (Plans 18-25) are entirely the work of the writer, except Plan 25 ('contoured base of Quaternary deposits') which was drawn from the stratigraphic data-base initially by J. Selby

and N. Gerges, but was emended substantially by the writer to its present form. These plans are also included in the companion volume on engineering geology.

The composite and foraminiferal logs (Plans 27-29) are entirely the writer's responsibility in their present form. M.J. Hannah, during vacation employment under the writer's supervision, did an initial foraminiferal pick of the SADME South Parklands and West End Brewery bores, and made a first draft of their columnar sections and foraminiferal logs. These were much emended and redrawn by the writer for inclusion in a Departmental report (Selby and Lindsay, 1978), and were further adapted by the writer for this thesis. Bio-stratigraphic correlation and borehole summaries (Plans 30-34) are the writer's work except that Plan 34 is emended after McGowran (1973a, fig. 3).

The text discusses some of the issues raised by the Plans and Plates, and is an explanatory extension of them.

'The stratigraphic usefulness of foraminiferal microfossils lies in their general abundance in marine sediments, their preservation in cable-tool sludges and rotary cuttings, and in the rapid and well-documented advance of foraminiferal studies in recent years. As their stratigraphic ranges have become better known, many species can now be used for correlation with more confidence' (Lindsay, 1969, p.8). Foraminiferal bio-stratigraphy has proved to be a powerful tool to correlate and date the subsurface marine mid-Tertiary rocks of Adelaide City and the adjacent Adelaide Plains, as well as the coastal stratotypes at Maslin Bay and Port Willunga. The present study has presented a need and an opportunity to describe many South Australian Tertiary foraminifera as they occur in and near

Adelaide, at least to the level of systematic notes. The systematic treatment is inevitably uneven, but will be followed by ongoing, more detailed studies. Since the acquisition by SADME, in 1976, of a Scanning Electron Microscope (I.S.I. Model SMS-2, 'Super Mini-SEM'), it has been the author's aim to compile an atlas of SEM photographs of South Australian foraminifera, particularly those which are of stratigraphic importance and/or intrinsic interest. With this in view, the 61 described Plates in Volume 2 of this thesis, illustrate most of the planktonic foraminifera of the Tertiary rocks beneath Adelaide, and many of the more significant benthonic species. Numerous examples are given of intraspecific variation and of test microstructure, both being important for identification; the microstructure being particularly important in the search for a more 'natural' classification of the planktonic foraminifera. In several cases, comparative material from interstate or overseas has been photographed in order to elucidate a locally occurring species.

The area treated in detail by this thesis consists primarily of the City of Adelaide (including North Adelaide) and its surrounding North, South, East and West Parklands. Because of the stratigraphic and structural importance of the Para Fault Zone, which traverses the western and northwestern edge of the City, the base plans have been extended a little to the west to include this zone and some important boreholes in it (Plans 18-25). The plan showing the locations of stratigraphic reference bores and geological cross-sections (Plan 5) has been extended further west again to include the historic E. & W.S. Croydon-2 water bore, which is a reference standard for the 'thick' Adelaide Plains Cainozoic succession

as compared with the thinner sequence beneath the City, and features as such in the two longest cross-sections, T-U (Plan 16) and V-W (Plan 17). Following earlier work on the Croydon-2 bore by the writer (Lindsay, 1968a, c; 1969) he has checked, revised, and updated its biostratigraphy and stratigraphic nomenclature for this thesis (Plan 29). Figures 9 and 10 are views from the Croydon area down the Port Road towards the City of Adelaide, the tiered Mt Lofty Ranges, and Mt Lofty itself.

It is important to record that a stratigraphic/observation bore was rotary-drilled to bedrock by SADME during late 1979-early 1980, immediately east of Allenby Gardens Reserve, only 375 m west-southwest of the old Croydon-2 bore-site (Plan 5). This Allenby Gardens-1 bore was intended to be a virtual redrill of the old (1892) Croydon-2 bore, and indeed from preliminary samples and logs it appears that the Cainozoic section which it penetrated is closely comparable with that in Croydon-2. Unfortunately there has been no opportunity during 1980 to study the biostratigraphy of this important new reference bore. Notes on the bedrock intersection are included later, under 'BEDROCK'.

Enlarging the frame of reference, Plan 4 is a locality plan with borehole summaries by the writer, showing the City of Adelaide in relation to the southern part of the Adelaide Plains Sub-Basin on the west and northwest; and in relation to the Golden Grove-Adelaide Embayment on the east and northeast. This plan was adapted from an early draft of the



Figure 9. View along Port Road, Croydon, taken January 1980, from near the Rosetta St traffic lights, about 400 m N.W. of the site of the old Croydon-2 bore, looking S.E. towards the City of Adelaide, behind which rise the Belair Fault Block, and the Mt Lofty Block, with Mt Lofty at left.



Figure 10. View similar to above, but from about 1½ km nearer the city, immediately S.E. of the Rose St intersection, and near the site of the old Hindmarsh bore (see Cross-section T-U, Plan 16).

recently issued Adelaide 1:50 000 Preliminary Geological Map (Forbes, 1980) for which the writer supplied stratigraphic summaries of bores, and other data.

Plan 2, again with the aid of borehole summaries, shows the geological setting of Adelaide in relation to the eastern St Vincent Basin and associated structures. Plan 1 locates Adelaide with respect to the whole of the St Vincent Basin, to surrounding Cainozoic basins, and to major structural features.

Plan 3 relates the Tertiary stratigraphic sequence in the Adelaide City area to other Tertiary sequences in the St Vincent Basin, to Australian Stages, to standard 'P' and 'N' Zones, to Epochs/Series, and to a geochronometric scale.

It is a truism that large-scale geological events have had an impact on particular localities. Thus a particular Tertiary succession such as that developed in the vicinity of Adelaide may be related to a broad synthesis, and indeed is a necessary local test of its validity. As the writer has previously commented, 'the ideal locality for studying a history of transgression and regression is one sufficiently exposed to open-marine conditions to yield sequences of dateable marine faunas, but on the other hand near enough to the basin-margin to provide a sensitive sedimentary record of waxing and waning marine influence' (Lindsay and Bonnett, 1973, p. 10). In Plan 35, the marine Tertiary record of the eastern St Vincent Basin is put in a regional setting of Tertiary marine palaeotemperatures and transgressive/regressive episodes. In fact, analyses of such South Australian events and sequences have contributed fundamentally to a growing understanding of

large-scale processes in the southeastern Indian Ocean region; inter-related processes which included sea-floor spreading, tectono-(glacio-) eustasy, climatic fluctuations, sedimentary cycles, and 'extra-tropical excursions' of warm-water foraminifera (McGowran and Lindsay, 1969; Lindsay and McGowran, 1971; Lindsay, 1970c, 1976; McGowran, 1971, 1973b, 1977, 1978a, b, d; 1979b; R.J.F. Jenkins 1974; Twidale, Lindsay and Bourne, 1978; and Ludbrook, 1980).

Preamble: Some Themes from the Sixties

Since 1963, the writer's work at the South Australian Department of Mines and Energy has from time to time included the stratigraphic interpretation and correlation of many boreholes drilled in the eastern St Vincent Basin. Data on most of the Adelaide Plains holes were summarised by Lindsay (1969), and that publication is a cornerstone of this thesis. Data from subsequent studies of boreholes drilled in and around the City of Adelaide, are summarised herein (Appendices A and B) and in a companion volume treating the engineering geology for which most of the stratigraphic input was provided by the writer (Selby and Lindsay, in press).

The year 1963 was a crucial one in which to commence this study. As outlined by Berggren (1963), biostratigraphers were at that time still digesting the important book by Eames et al. (1962), especially the implications of one of their themes, namely that the Oligocene Series was in fact missing in many areas such as the Caribbean and Tethyan regions, where it had previously been determined or presumed.

Dr N.H. Ludbrook (1963a) in her Presidential Address to the Royal Society of South Australia, was strongly influenced by these authors when, contrary to previous local estimates of age and correlation (Glaessner and Wade, 1958; Glaessner, 1959) she all but excluded Oligocene rocks from the St Vincent Basin, and put the Port Willunga 'Beds' (Formation; Cooper, 1977b) entirely in the Lower Miocene. This was done because of a perceived lack of the (tropical) diagnostic 'Oligocene' faunas described and discussed by Eames and his colleagues. However at the same time, Ludbrook (1963a) nevertheless maintained the Oligocene age of almost all the Ettrick Formation in the Murray Basin and of the lower Gambier Limestone in the 'Gambier Sunklands' (Gambier Embayment of the Otway Basin; Ludbrook, 1967).

After a preliminary study of several borehole sections in the Adelaide Plains Sub-Basin, it became apparent to the writer that between the Miocene upper part of the Port Willunga Formation, and the Eocene Blanche Point 'Marls' (Formation; Cooper, 1977b) there was interposed a significant sequence with foraminifera characteristic of the Janjukian Ettrick Formation and the lower Gambier Limestone. This sequence therefore, should be probably Oligocene, by Ludbrook's own correlations. To identify it in terms of the units described by Reynolds (1953) it thus became necessary for the writer to examine the stratigraphy of the exposed type section of Port Willunga Formation at Port Willunga (Plan 2; Figs 11, 12), particularly in terms of its foraminiferal biostratigraphy with a view to correlation locally and further afield.



Figure 11. General view of northern part of stratotype Port Willunga Formation, taken Dec. 1979, looking N.E. towards Port Willunga. Note the gap in the section eroded by Aldinga Creek; and the low-angle unconformity between the uppermost Eocene-Oligocene Port Willunga Formation (dipping gently south) and the paler, raggy, Upper Pliocene Hallett Cove Sst. & Lower Pleistocene Burnham Lst. (dipping only slightly south).



Figure 12. View as above, but continued to right (east), showing Oligocene Ruwarung Member of Port Willunga Formation with hard, cherty, nodular bands, overlain by banded to raggy paler Hallett Cove Sst., and white earthy Burnham Lst., beneath slope-forming Pleistocene clay. Caves cut in cliff behind piles of old Port Willunga jetty, mark top of Aldinga Member of Port Willunga Formation.

By mid-1966 the surprising result was emerging that, far from being Lower Miocene, there was foraminiferal evidence of Eocene to Lower Oligocene age in the lower part of the type section; while the uppermost part was basal Janjukian and almost certainly still Oligocene.

These preliminary findings, with their basis of foraminiferal biostratigraphy, were announced by the writer at a meeting of the Geological Society of Australia (S.A. Division) on 15th July, 1966. The first published record was in a Note by Ludbrook and Lindsay (1966), and the new stratigraphic correlations were included in a paper at the Eleventh Pacific Science Congress, Tokyo, August, 1966, (Ludbrook, 1967).

Several factors had converged to enable such an advance at that time; and they remain as important themes in the present work.

1. Hornibrook (1965) and Jenkins (1966a) had described recently from New Zealand, species of planktonic foraminifera which had preference for temperate rather than tropical water-masses, in contradistinction to many of the species featured by Blow and Banner (1962). Among those which could be recognised in the local, latitudinally equivalent, temperate facies were Subbotina angiporoides (Hornibrook, 1965), Tenuitella aculeata (Jenkins, 1966a) and 'Globigerina' labiacrassata (Jenkins, 1966a). Subbotina linaperta (Finlay, 1939b) had been described much earlier, also from New Zealand, but with S. angiporoides was now seen to comprise a complex within which top S. linaperta had potential as a top Eocene datum level. The relative stratigraphic ranges recorded for such species by Jenkins in the more open-marine and more inter-regionally

correlatable planktonic facies of New Zealand, were tested locally, but were accepted as prima facie evidence for the time being.

By this means, New Zealand Eocene and Oligocene rocks could now be correlated more confidently with local successions. For example, the successive disappearances of T. aculeata and S. linaperta within the lower part of stratotype Port Willunga Formation were taken to be Upper Eocene and top Eocene events respectively, as in New Zealand. These range-tops were found to be more useful biostratigraphically at this level than the 'Faunal Units' 2 and 3 of Carter (1958a,b; 1959) or the similar zones of Carter (1964) and Wade (1964), because of the rarity of Globigerinatheka index (Finlay) in basal Port Willunga Formation, and because of earlier lumping of the S. linaperta/S. angiporoides complex. The successive final appearances of T. aculeata and S. linaperta would be adopted later as criteria for local zones bearing these names (Lindsay, 1967b, 1969; Ludbrook and Lindsay, 1969).

2. The writer was impressed by the practical comments of Beckmann (1957, pp. 87, 88) regarding the value of Chiloguembelina species in the Palaeogene of Trinidad B.W.I., and in the Gulf Coast of the United States. Beckmann had found that these distinctive Heterohelicidae persisted both in rich, open-marine, Globigerina/Globorotalia marls, and also, importantly, in more restricted-marine facies with a low planktonic/benthonic

ratio. Since the latter facies is usual in the marine Tertiary of the St Vincent Basin, Beckmann's conclusion seemed to be of local importance: that 'Chiloguembelina is then often the most accurate means of correlating these faunas with planktonic assemblages from other localities'.

In several borehole sections in the Adelaide Plains (Lindsay, 1965a) the writer had been finding a consistent mid-Tertiary homotaxial succession involving the consecutive final appearances of the heterohelicids Chiloguembelina and Guembelitria. This succession had been recognised also by Wade (1964, p. 274). The range-top of Chiloguembelina (as Gümbelina) had been noted by Carter as a subsidiary event occurring within his Faunal Unit 4, regarded as Oligocene. The event was recorded by him (Carter, 1958a, 1964) as a feature of the basal stratotype Janjukian, west of Bell's Headland, in the Torquay Basin of Western Victoria (Abele et al., 1976). The writer sampled the stratotype Janjukian in mid-1966, with the kind assistance of T.A. Darragh (National Museum of Victoria) and C. Abele (Geological Survey of Victoria). Micropalaeontological examination confirmed the presence of Chiloguembelina and also the hitherto unreported Guembelitria in at least the basal 4 m (up to bed 107 of Raggatt and Crespin, 1955). Guembelitria continued approximately 10 m higher (up to bed 100 of Raggatt and Crespin), proving the same homotaxial succession as in the St Vincent Basin. By this time the final appearance of Chiloguembelina in the presence of continuing Guembelitria had also been

determined near the top of stratotype Port Willunga Formation (Lindsay, 1967b), leading the writer to correlate this part of the stratotype with the basal Janjukian Stage.

At this time also, Jenkins (1966c) confirmed the correlative value of the Chiloguembelina cubensis (Palmer) extinction event, by selecting it as one of 29 planktonic foraminiferal datum planes for the Tertiary of the tropical-to-temperate circum-Pacific and Trinidad regions. Although emphasizing at that stage the homotaxial and not necessarily isochronous nature of the datum planes, Jenkins positioned the Chiloguembelina event within the upper part of the Oligocene. This provided a usefully strengthened local datum for the Upper Oligocene, which he had already related to the stratigraphic ranges of many other planktonic foraminifera in the temperate open-marine facies of New Zealand (Jenkins, 1966a).

By a slight extension upwards it was considered that the heterohelicid Guembelitria which commenced in the Early Cretaceous, was a 'Palaeogene element' (Ludbrook, 1963a, p. 11), and that its successional range-top was also within the Upper Oligocene, although it was not reported from the Tertiary of New Zealand until 12 years later (Jenkins, 1978a). The successive final appearances of Chiloguembelina cubensis and Guembelitria stavensis (now G. samwelli) were adopted later as criteria for local zones bearing these names (Lindsay, 1967b, 1969; Ludbrook and Lindsay, 1969).

3. Wade (1964) and Jenkins (1965b) had commented on the correlation problems which arise from the climatically-controlled broadly latitudinal zonation of planktonic foraminifera today and probably, to some extent at least, in the mid-Tertiary. However it was apparent, especially in New Zealand (Jenkins, 1966a) that some of the planktonic foraminifera described from 'tropical' deposits such as Trinidad (B.W.I.) and Venezuela were more environmentally tolerant than others, and could be recognized in southern temperate deposits also, even though perhaps sparsely and poorly developed. These more cosmopolitan forms provided important but tentative links with the 'tropical standard' zonations proposed, for example, by Bolli (1957a,b,c) and Blow and Banner (1962).
Only a few such species could be identified in the Port Willunga Formation stratotype (Lindsay, 1967b). Turborotalia increbescens (Bandy) and T. ampliapertura (Bolli) were found rarely in the lower part; while occasional specimens approaching Globigerina ciperoensis Bolli were found towards the top. When compared with stratigraphic ranges recorded by Blow and Banner (1962) and Jenkins (1966a) the first two species suggested Eocene to Oligocene age, while the initial appearance of G. ciperoensis was agreed to be an Oligocene event.

4. Benthonic foraminifera Halkyardia, Linderina, Crespinina, Maslinella, and Gen. nov. cf. Bolivinella, were identified as rare faunal elements of basal stratotype Port Willunga Formation (Lindsay, 1967b). Crespinina had been recorded earlier from the basal bryozoal sand of Port Willunga

Formation (Ludbrook, 1956), but these benthonics had otherwise only been found previously in South Australia in undoubted Eocene strata such as Buccleuch Beds 'A' and 'B' (Ludbrook, 1961, 1963a), unnamed beds at Kingscote on Kangaroo Island (Wade, 1955; Ludbrook, 1963a), Tortachilla Limestone and basal Blanche Point Formation (Wade, 1955; Glaessner and Wade, 1959; Ludbrook, 1963a). Their presence in basal Port Willunga Formation now supported the Eocene age determined from planktonic foraminifera, but also emphasised the disjunct distribution of the benthonics, with a significant stratigraphic gap between basal Port Willunga Formation and their previously-known occurrence in Tortachilla Limestone and basal Blanche Point Formation.

With the lead on microfaunal/climatic interpretation given from New Zealand (Hornibrook, 1967, 1968a; Jenkins, 1968) and with the publication of new sets of oxygen-isotope temperature measurements on Australian and New Zealand Cainozoic fossils (Dorman, 1966, 1968; Devereux, 1967, 1968) the time was ripe to recognise that there was a palaeoclimatic pattern in the local sporadic and disjunct distribution of the above benthonics and some other foraminifera (e.g. Hantkenina, Lepidocyclina, Amphistegina) representing warmer climate/watermass, and possibly transgression. The realisation gathered momentum through the collaborative work of McGowran and Lindsay (1969; Lindsay, 1970c; and Lindsay and McGowran, 1971). McGowran (1971) set down local foraminiferal evidence of Eocene warm-marine episodes (expansion of 'tropical' elements) in a regional framework of stratigraphic correlation, Australia-Antarctica separation/sea-floor

spreading, and associated tectono-eustatic transgression. This was followed up by R.J.F. Jenkins (1974), in summary form by Lindsay (1976), and in a wide-ranging synthesis by McGowran (1977; 1978a,b,d; 1979b).

5. In 1966, the writer recognised an interval of chert nodules and bands within stratotype Port Willunga Formation as a distinct unit of that formation (Figs 13, 14). Reynolds (1953) had noted the presence of nodular bands, but not that they are cherty. The writer (in Ludbrook and Lindsay, 1966) indicated the coincidence between the incoming of 'hard bands with siliceous nodules' halfway up the stratotype, and the disappearance of Subbotina linaperta taken to be an indicator of top Eocene. This lithological and biostratigraphic boundary was made the top of the redefined Aldingan Stage, the bottom being defined as the base of the Tortachilla Limestone. The 'interval with cherty nodules' in stratotype Port Willunga Formation was described the following year in its foraminiferal biostratigraphic setting (Lindsay, 1967b).

Previously, workers including the writer (Lindsay, 1965a) had taken the presence of siliceous nodules and bands in Adelaide Plains borehole sections as characteristic of Blanche Point Formation, and in particular the 'Blanche Point Banded Marls' of Reynolds (1953). However this approach had led to increasingly anomalous correlations and biostratigraphy. It became clear (Lindsay, 1965a) that there were two separate cherty intervals, and that the upper interval contained the distinctive Janjukian benthonic foraminifer Massilina torquayensis (Chapman).



Figure 13. View of part of stratotype Ruwarung Member of Port Willunga Formation, taken Dec. 1979, showing irregular bands of hard cherty nodules in muddy calcarenitic limestone. The head of the hammer is aligned with one such band of chert nodules.



Figure 14. As above, but closer view showing several bands of irregular purple/brown nodules of hard fossiliferous chert.

That this upper interval correlated with the nodular chert unit of Port Willunga Formation, became apparent as soon as the stratotype was examined. The same unit was later found to be well developed in the Noarlunga Embayment at the mouth of the Onkaparinga River (Lindsay, 1970a). It proved to be a very useful stratigraphic marker unit in the Adelaide Plains Sub-Basin (Lindsay, 1969) and its suspected presence beneath the South Parklands of Adelaide City (Selby and Lindsay, 1973, fig. 1) was confirmed by the SADME South Parklands bore in 1976 (Plan 27). Cooper (1977b) named this nodular cherty unit of Port Willunga Formation the Ruwarung Member; and the banded cherty unit of Blanche Point Formation, the Gull Rock Member.

METHODS

Of the 107 stratigraphic reference bores listed in Appendix A, 80 were drilled by SADME, 66 of these for engineering foundation investigations, 11 for water supply or drainage, and 3 as stratigraphic or observation holes. Of the 27 drilled by private contractor or other Government Department, 22 were for water or drainage, and 5 for foundation engineering. In most of the foundation-test holes, continuous or intermittent cores were taken. In the SADME holes these were usually drive-tube cores in the form of cylinders 100 mm diameter and up to 400 mm long, which provided ideal, more or less undisturbed samples for micropalaeontological examination. Many tube-cores were taken also in two important SADME stratigraphic bores which were drilled to bedrock (Reference bores 10, 41; Plans 28, 27). At several sites, diamond-drill cores were taken in hard Hallett Cove Sandstone (Pliocene) and Blanche Point Formation-Tortachilla Limestone (Upper Eocene). At four sites drilled by K.W.G. Smith and Associates (Reference bores 34, 35, 100, 101) portions of continuous 'hollow spiral auger' core were kindly made available for study. A number of water bores are represented only by sludge or cuttings samples (Reference bores 27, 32, 58, 68, 69, 93, 105, 106). In most cases, the bore materials have been examined personally by the writer for lithology, foraminifera, and stratigraphic interpretation. However, for 32 of the bores, only various logs have been available for analysis, but no samples: as elsewhere, the writer is responsible for the interpretations shown.

Unwashed bore sludges, cuttings, and cores, are stored in the SADME Core Library at Glenside. All washed residues, palaeontological record cards, microfaunal preparations, foraminiferal species slides, and in particular, all illustrated specimens of foraminifera, are deposited in the palaeontological collections of the Geological Survey of South Australia, Biostratigraphy Section. All available information on each bore, including lithological logs, is stored on microfiche in the geological records of SADME, in order of Bore Unit Number.

The numbers used for the Reference bores (1 to 107) are ad hoc for convenient reference in the text and elsewhere; but in Appendix A the Reference bores are identified also with their fundamental SADME Bore Unit Numbers. This 14-digit numbering system is now being used to number uniquely each bore in the State. The first 4 digits provide the standard reference number of the 1:100 000 metric map sheet, the next 3 digits refer to the number of the 1:2 500 map sheet subdivision, the following 2 digits code the type of borehole, and the final 5 digits give the accession number of the bore in order of plotting on the 1:100 000 sheet. When an area is all within the one 1:100 000 sheet, only the final digits are necessary to identify a borehole (e.g. the City of Adelaide and the Golden Grove-Adelaide Embayment, Sheet Adelaide 6628; Plan 4). At times it is expedient to identify some Departmental observation bores by their SADME Observation Bore Number, which codes first the hundred (e.g. PTG for Hundred of Port Gawler) and then the order of plotting within that Hundred (e.g. PTG-13). These numbers are kept in the SADME Register of Observation Bores, where they are cross-referenced also to their Bore Unit Numbers.

All elevations of bore-heads, surface contours, and structure contours, are expressed in metres with reference to Australian Height Datum, which is 0.256 m above Mean Sea Level, Port Adelaide. Mean Sea Level equalled 105.68 feet (32.21 m) with reference to the old datum: 'Low Water Ordinary Spring Tide, minus 100 feet', which was used in calculations prior to 1971 (including Lindsay, 1969, p.55).

Standard techniques were used to disaggregate samples for micropalaeontological examination. Care was taken first to cut away the outer, contaminated 'rind' of cores. About 250 grams of sample were soaked in a bowl for a preliminary period, often overnight, in an initially hot aqueous solution of sodium bicarbonate (about one dessert-spoonful to a litre of water) with a drop or two of detergent. The mixture was then boiled briskly for about 20 minutes, stirring frequently, and the mud content was removed subsequently by repeated decantation and washing with a water spray through a fine sieve (200 to 300 B.S.S. mesh), all the successive 'plus' fractions being retained, and the whole residue dried in a vented laboratory oven at about 140°C. For most unlithified sediments this technique resulted in satisfactory disaggregation and clean foraminifera. In the case of grey to black sediments with significant carbonaceous matter, a good cleaning effect was achieved by treating the sample, before or after the above washing process, with a hydrogen peroxide solution ('100-volume' strength, diluted to '25-volume', 3:1 with water) for not more than 4 hours.

More resistant mudstone or shale could be disaggregated effectively sometimes by means of a technique using heating oil (e.g. 'Mobilheat'), in which a heated and dried sample in a bowl is removed from the heat-source, and in a fume-cupboard is immersed in the oil until saturation, the excess oil being decanted off through a filter (and retained for re-use) following which the sample is immediately boiled briskly in a strong detergent solution (to expel and counteract the interstitial oil), and is then thoroughly sieve-washed as above, with hot water.

Heavy-liquid flotations were made frequently from the washed residues, in order to concentrate the stratigraphically-significant planktonic foraminifera. The process was carried out in a fume-cupboard, using bromoform diluted with dehydrated alcohol or a high-quality Industrial Methylated Spirit to a Specific Gravity of 1.8 (Gibson and Walker, 1967).

Washed residues were sieved to coarse, medium, and fine size-grades, each fraction being picked using a stereo-binocular microscope, with sufficient thoroughness to establish the foraminiferal microfauna present in the total sample, and in particular the presence or absence of stratigraphically significant forms. Relative abundance of species is indicated in the text by the following convention:

v (very rare, 1-2 specimens recovered)

r (rare, 3-5)

f (frequent, 6-10)

c (common, 11-25)

a (abundant, 25+)

The Scanning Electron Microscope photographs comprising Plates 1 to 61, were taken on the SADME I.S.I. 'Super Mini-SEM' with an attached 35 mm camera. 'Pan-F' film and 'Ilfospeed' paper were used.

Originals of all drafted Plans are retained by SADME.

PREVIOUS WORK

Thomas Burr, while Deputy Surveyor-General of the Province, included in his 'Remarks on the geology and mineralogy of South Australia', the first known description of the geology of Adelaide City (Burr, 1846). He recorded that water wells had met with beds of well-preserved oyster shells 'forty feet below the surface' (12 m), 'or from seventy to ninety feet above the present surface of the sea' (21 to 27 m above M.S.L. or A.H.D.). Inspection of Plan 24 shows that Burr was referring probably to the prominent shelly bed near the base of the Pliocene Hallett Cove Sandstone as developed in the northern part of the central city area, and adjacent to the Torrens Valley. Burr described in the same context, horizontal beds of white to cream fossiliferous sandy limestone and calcareous sandstone, some indurated and good for building stone. In part, perhaps mostly, these also suggest Hallett Cove Sandstone; but some of the 'lower', poorly fossiliferous, indurated beds referred to, may be the bleached and weathered Blanche Point Formation which is encountered at shallow depths beneath parts of North Adelaide (Plan 20). Burr correctly considered all these fossiliferous strata to belong to the Tertiary Period. In contrast, he recognised the much greater age of the 'unfossiliferous' basement rocks, which form the adjacent Mt Lofty Ranges, and which he compared with Sedgwick's 'Cambrian' and 'Skiddaw slates'.

Professor Ralph Tate (1882) summarised the stratigraphy of a contemporary diamond-drill hole sunk to bedrock as a demonstration bore in the Kent Town Waterworks Yard (Ref. bore 31). He determined 109.7 m of Tertiary strata, resting on a

15.5 m intersection of bedrock which he described as 'underlying fundamental rocks'; 'pre-Silurian'.

As in several other City boreholes drilled since, there is at this locality a clay/clay contact between pale-coloured Tertiary sedimentary clay (now included in Clinton Formation) and a thick, clayey, weathered bedrock profile the upper part of which is also pale-coloured (see discussion of 'BEDROCK' below). After examining samples still available from this old borehole, the writer shifted the depth of bedrock contact upwards, and re-interpreted the succession as 93.0 m of Cainozoic beds on a 32.3 m intersection of completely to highly-weathered bedrock, probably Precambrian (Lindsay, 1969). However it was this bore drilled a century ago that gave the first indication of the order of thickness of the Tertiary and Pleistocene sedimentary basin underlying the Adelaide City plateau.

With the drilling of the E. & W.S. Dept. Croydon No. 1 bore into Tertiary strata down to 244 m in 1890, Tate (1890) was able to extend his cross-section of 1882 westwards from the city, demonstrating the much greater thickness of sediments below the near Adelaide Plains. This was confirmed dramatically when in 1893 (Tate, 1898) the E. & W.S. Dept. Croydon No. 2 bore was drilled adjacent to the No. 1 bore, enlarging the known thickness of sedimentary cover to 690 m (compare Cross-section V-W, Plan 17).

David and Howchin (1896, fig. 1) were the first to explain this disparity in depth to bedrock between Kent Town and Croydon, by a major north-south fault with maximum throw 600 m down to the west at the western edge of the Adelaide

City plateau. Tate (1898) considered that the difference was better explained by contrasting depositional thickness either side of a submarine erosional scarp, rather than by a fault. Fenner (1927) on the other hand, describing the geomorphology of Adelaide in percipient detail, emphasised the role of block-faulting and named the Para Fault, the Para Fault Scarp, and the Para Fault Block.

The relationships between the Tertiary strata either side of the Para Fault were long and keenly debated. Ludbrook (1937) was the first to correlate the fossiliferous Pliocene 'Adelaidean' sands (Dry Creek Sand; Glaessner, 1951)which occur more than 100 m below sea level beneath the Adelaide Plains, with the fossiliferous sandstone (Hallett Cove Sandstone; Crespin, 1954) which is found some 20 to 30 m above sea level under the City.

L.K. Ward (1946) was only able to record two boreholes in which the Tertiary strata had been penetrated to bedrock beneath the city area: the Kent Town bore (1882), and the West End Brewery bore, drilled in 1915 (Ref. bore 9). Miles (1952) could only add two more, both of them in North Adelaide (Ref. bores 27, 50), but provided summary logs and hydrological data on these and 11 other water bores in the city and parklands. Miles (1952) and Ludbrook (1954) contain references to most of the significant papers on the geology and palaeontology of the Adelaide Plains Sub-Basin for the period 1879-1951.

W.G. Fenner and C. Kerr-Grant (Kerr-Grant, 1952) made the first gravity surveys of the City area and Adelaide Plains in 1948-49. The Para Fault Zone through the Northwest and West Parklands was clearly revealed. Total displacement of bedrock was calculated to be of the order of 700 m, west block down; and splitting or branching of the fault west of the city was suggested as shown by Miles (1952).

Most of the Tertiary formations later to be identified subsurface in the Adelaide City area, namely: South Maslin Sand, Tortachilla Limestone, Blanche Point Formation (=Blanche Point Marls), Chinaman Gully Formation (=Chinaman's Gully Beds), and Port Willunga Formation (=Port Willunga Beds), were described and named by Reynolds (1953) in classical coastal outcrops along Maslin and Aldinga Bays south of Adelaide in the Willunga Embayment (Plan 2).

Simultaneously, Glaessner (1953a) put these named formations into a framework of time and correlation, and gave a dynamic account of the stratigraphy and geological history of the Adelaide region, including reference to the City area.

Crespin (1954) named the Hallett Cove Sandstone, a term which experience has shown is applicable to the Pliocene calcareous sandstones of the City.

A bulletin on 'The soils and geology of Adelaide and Suburbs' by Aitchison et al. (1954) was a landmark study comparable with that of Miles (1952), and was much used for soils advisory services in the Metropolitan Area until revised by Taylor et al. (1974).

During the period 1954-1956 the Department of Mines provided engineering geology assistance to foundation investigations at a number of City sites including: Savings Bank of S.A. building, Bank St (March 1954; Ref. bores 74-76); M.L.C. building, Victoria Square (July-October 1954; Ref. bore 86); R.A.H. East Wing, North Tce (April-June, 1955; Ref. bores 29-30); Grosvenor Hotel, North Tce (February-March 1956; Ref. bore 71); A.N.A. building, North Tce (September 1956); Waterman building, southern King William St (October 1956; Ref. bore 61); and Supreme Court Library building, Victoria Square (1956, Ref. bore 33). Using this accession of stratigraphic information, together with earlier records, A.R. Crawford in association with N.H. Ludbrook (Departmental palaeontologist) prepared a seven-page draft on 'The geology of the Adelaide City area' in October 1956. Although never completed as a Departmental Report, it contains their notable observation that from central North Terrace to south of Victoria Square, 'there does appear to be a fairly consistent bed of variably hard Pliocene limestone which has a very gentle southerly dip. There may also be a slight southerly thickening': this unit is essentially the Hallett Cove Sandstone. A weathered and eroded upper zone (i.e. of Burnham Limestone + Hallett Cove Sandstone) displaying 'deep solution fissures filled with the overlying clay', was observed by Crawford and Ludbrook in excavations at the narrow Bank St site and has also been recognised since as a notable karst feature beneath the Central City Area (Allchurch, 1967b). A part of the pre-Pliocene clays, sands, and silts, beneath Victoria Square, was correlated with the basal part of stratotype Port Willunga Formation.

Ludbrook (1963a) later recognised subsurface correlatives of Clinton Coal Measures (now Clinton Formation), South Maslin Sand and Tortachilla Limestone in the City area.

During a building boom in the 1960's, much foundation-test drilling was done in the City, some of it relatively deep for pier foundations and settlement studies. Departmental engineering geology reports, with associated biostratigraphic reports by the writer, were prepared for sites such as the State Administration Centre, Victoria Square (1964; Ref. bores 13, 14); Morphett St and Victoria Bridges (1964; Ref. bores 1 to 6); A.M.P. building, North Tce (1965; Ref. bore 7); P.M.G. Telephone Exchange, Waymouth St (1965-66; Ref. bore 11); proposed Festival Hall, 'Carclew', North Adelaide (1965-66; Ref. bores 24, 25); new Nurses' Home, Adelaide Children's Hospital, North Adelaide (1966, Ref. bores 22, 23); and John Martin's Car Park, North Tce (1967, Ref. bore 8).

Tertiary formations which are developed beneath Adelaide were described in the broader context of the Adelaide Plains Sub-Basin by Lindsay (1969). The stratigraphy (revised in the present work) was outlined for six key boreholes in North Adelaide and seven in the city proper.

Cox (1970) contributed a detailed study of the geo-technical properties of the Hindmarsh Clay, but also included data on other formations and on groundwater, together with two geological sketch sections, all compiled from Mines Department and private sources.

In connection with foundation investigations for a proposed P.M.G. Mail Exchange adjoining Gouger St, studies of engineering geology by Tarvydas (1970) and of associated biostratigraphy by Lindsay (1970b) clarified the nature and age of Port Willunga Formation beneath the central City area. An upper silt/clay unit and a basal sand unit were recognised for the first time, both were dated Upper Eocene by means of foraminifera, and the units were correlated confidently with the basal 7 m of stratotype Port Willunga Formation at Port Willunga. This basal sand unit of Port Willunga Formation was distinguished clearly from a stratigraphically lower sand unit, which was included until recently within Blanche Point Formation, but has been described now as the Tandanya Sand Member of Chinaman Gully Formation (Lindsay and Harris, 1979). The two sands have proved to be useful marker beds for working out the structure and succession of mid-Tertiary rocks beneath the City.

Student geologist P. Teakle (1971) compiled data from many boreholes in the Adelaide City area. He constructed 10 preliminary cross-sections, a plan showing subsurface contours of the upper surface of Hallett Cove Sandstone, and one showing contours of the general ground water table.

Later in 1971 the writer, assisted for a time by student geologist S.D. Giles, made independent stratigraphic interpretations of all available city borehole data, and constructed a different network of 11 cross-sections. Prints of these came to be used widely by engineers and engineering geologists; two formed the basis of the NW-SE cross-sections prepared by the writer for Selby and Lindsay (1973) and Daily *et al*. (1976).

Reconnaissance drilling was carried out by SADM across North Adelaide and the Torrens Parklands during May-July 1974, for the Adelaide Subway Study (Ref. bores 28, 36 to 40, 59, 60, 65). The writer assisted with stratigraphic determinations which were used in the Departmental and consultants' reports (Robertson, 1974; Woodburn, 1974). Important information derived from these holes included: The discovery of shallow South Maslin Sand beneath Quaternary alluvium in the western Torrens Parklands (Ref. bore 39); and the firm identification of Hallett Cove Sandstone at two localities beneath North Adelaide (Ref. bores 36, 59). In 1979, further drilling was carried out by SADME for a proposed tunnel along King William St. The writer contributed a number of stratigraphic determinations of bore samples for a report by Conor and Armstrong (1980). The cross-section compiled from this drilling programme confirmed the stratigraphy shown in Cross-section E-F (Plan 8). Details are included in an Appendix of the companion volume by Selby and Lindsay (in press).

During the period May to September, 1976, two stratigraphic bores were drilled by SADME in the City area. Each penetrated the Cainozoic succession and bottomed in undoubted bedrock: the first in the South Parklands (Ref. bore 41) and the second at the West End Brewery (Ref. bore 10). Many cores and other samples were taken, enhancing the stratigraphic value of the bores. Detailed biostratigraphic studies have been carried out on these materials at various times, and are summarised in Composite and Micropalaeontological Logs (Plans 27, 28) and in Cross-section T-U (Plan 16). These plots have been revised from those prepared by the writer for the well-completion report (Selby and Lindsay, 1978).

GEOLOGICAL SETTING

Introduction

From a tectonic and structural viewpoint, the City of Adelaide is located strikingly in a number of boundary situations.

1. It is very near the faulted eastern margin of the Cainozoic St Vincent Basin (Plan 1). The southeastern corner of the City Parklands is only 3 km from the Eden-Burnside Fault Zone which here marks the eastern edge of the Basin and the western edge of the Mt Lofty Ranges (Figs 2, 4, 5).
2. As shown in Plan 1, the St Vincent Basin itself straddles the southern end of the major boundary feature which has been named the 'Torrens Hinge Zone' (Thomson, 1969a,b; 1970, 1976, 1980; Thomson et al., 1976; Preiss et al., in press). This 700 km-long meridional zone divides the stable Gawler Craton on the west (cratonised by 1400 Ma B.P.: Webb, 1979), from the mobile, Upper Proterozoic-Cambrian Adelaide Geosyncline on the east. It marks profound changes in, for example, thickness of Upper Proterozoic-Cambrian sedimentary cover (great increase to the east), deformation of this cover (little to the west; folding, faulting, diapirism to the east), and effect of the Cambro-Ordovician Delamerian Orogeny (little to the west, strong to the east). On a regional scale, Adelaide is near the eastern edge of the Hinge Zone.



Figure 15. View S.S.W. from crest of Black Top Road, east of Hillbank, taken November 1980, looking down western edge of south-sloping Para Block (Para Fault Scarp) to the City of Adelaide.



Figure 16. View similar to above, showing the City of Adelaide at the western edge of the Para Block, adjacent to the Para Fault and the Adelaide Plains.

3. The Para Fault Zone (see below) cuts through the western and northwestern edges of the City of Adelaide. The site of the City was selected by Colonel Light in 1836, at the western edge of a dissected low plateau, overlooking the coastal plain. Geologically this site is at the western edge of the Para Fault Block (Plans 4, 5; Fig. 15).
4. The City lies at the southwestern end of the Golden Grove-Adelaide Embayment, adjacent to the Adelaide Plains Sub-Basin (Plans 2,4,5; Figs 2,4,5,9,10,15,16,17).

The St Vincent Basin

This basin is one of the smallest of several sedimentary basins which border the southern Australian continental margin and contain marine and paralic Tertiary deposits. Others include the Bremer and Eucla Basins; the Polda and Uley-Wanilla-Cummins Basins (Lindsay, 1974); and the Murray, Otway, and Gippsland Basins. The area of the St Vincent Basin, including a probable extension on northern Yorke Peninsula (Plan 1), is of the order of 15 000 km^2. About 60% of this area is covered by Gulf St Vincent, an arm of the sea whose only entrances to the open ocean are Backstairs Passage in the south, and the broader Investigator Strait in the west. The basin dates back to the Middle Eocene, and is thought to have had restricted marine access through much of its history (Cooper and Lindsay, 1978).

A considerable part of the basin study by W.J. Stuart (1969, Ph.D. Thesis) remains unpublished, although important sections dealing with the western margin, along the east coast of Yorke Peninsula, were published promptly to formalise an independent stratigraphic nomenclature for this area (Stuart, 1970). Ludbrook (1969b) prepared a summary account of the Tertiary stratigraphy of the basin before Stuart's dissertation was available, and so emphasised the eastern part of the basin, for which she had access to the writer's published and unpublished work on the Adelaide Plains Sub-Basin. Simultaneously, this latter work was condensed and published (Lindsay, 1969); and most of the stratigraphic summaries of Adelaide Plains bores from Dublin southwards, as shown in Plans 2 and 4, are interpreted from that data-base. The eastern part of the St Vincent Basin was also treated in a discussion of the geology of the Adelaide Region (Daily et al., 1976) for which the writer contributed the segment on Tertiary geology.

A report by Meyer (1976), describing the brown coal deposits of the northern St Vincent Basin, was used in compiling that part of Plan 2, although a recent publication by Johns (1980) has superseded Meyer's report in a number of matters such as the extent and nomenclature of the coal basins. Stratigraphic summaries of four boreholes in the SADME Barabba drilling project, shown in Plan 2, are interpreted by the writer from data in Cockshell et al. (1978). Stratigraphic summaries of SADME holes Buckland Park-1 and Korunye-1 (Plan 2), drilled for the Northern Adelaide Plains Underground Gas

Storage Project (Cockshell, 1979), are interpreted by the writer from examination of samples and logs.

The writer's stratigraphic summary of the Longyear bore in Plan 2, and reference to the bore in descriptions of various units, are based on personal logging of all the available core samples. However there has been no opportunity for detailed biostratigraphic study of the bore. An outline of the stratigraphy was included in a geological cross-section compiled by the writer (in Daily et al, 1976, p. 31) and a stratigraphic interpretation was reported recently (Lindsay, 1981).

The stratigraphic summary of the Seaford drainage bore in the Noarlunga Embayment (Plan 2) is adapted from the report by B.J. Cooper (1980) which was based on biostratigraphic work by Cooper, T. Lonergan, and the writer.

A stratigraphy of the Willunga Embayment has been published recently, based largely on drillhole data (Cooper, 1979b). The stratigraphic summary of SADME WLG-38, shown in Plan 2, is adapted from detailed studies of this bore by the writer and B.J. Cooper.

The stratigraphic summary of the 'S.A. Black Coal Syndicate bore' in the Myponga Basin (Plan 2) is interpreted by the writer from the log by Ward and Duffield (1931, Min. Rev., Adelaide, 53: 86-89).

In the Hindmarsh Tiers Basin (Plan 2) the stratigraphic summary of SADME Obs. bore ENB-2 is interpreted from the log by Furness (1975) and from samples examined by the writer.

Some discussion is necessary on the nomenclature appropriate to the various parts of the St Vincent Basin (Plans 1, 2, 4). It is considered that different subdivisional

categories are needed for the four, relatively small, horn-shaped 'embayments' (Golden Grove-Adelaide, Noarlunga, Willunga, Kingscote-Cygnet); the much more extensive 'sub-basin' of the Adelaide Plains; and the more isolated small marginal 'basins' (Myponga, Hindmarsh Tiers).

Stuart (1969) introduced the term 'embayment' for the Adelaide Plains, Adelaide, Noarlunga, and Willunga basinal areas, 'in the sense of a basin-like structural area opening near the present coast to a larger subsiding feature'. Daily et al. (1976) referred to the Willunga and Noarlunga Embayments, as did Cooper (1979b). The structural term 'embayment' is defined by the American Geological Institute's 'Glossary of Geology' as 'a geosynclinal or downwarped area containing stratified rocks either sedimentary or volcanic, or both, that extends into a terrain of other rocks .....'. Similarly the A.G.I. 'Dictionary of Geological Terms' (1976) notes that 'some embayments may be one flank of a larger subsiding feature', and uses the term in a structural sense 'to designate a re-entrant of sedimentary rocks into a crystalline massif'. It is considered that the term is applicable to the various embayments of the St Vincent Basin, although admittedly on a very small scale compared, for example, with the 'Mississippi Embayment of the Gulf Coast' quoted by the A.G.I. 'Glossary of Geology'; or the well-known southern Australian Gambier Embayment of the Otway Basin (Ludbrook, 1967; Wopfner and Douglas, 1971). As an additional reason for using the term 'embayment', Cooper (1979b, p.10) introduced the palaeo-geographic connotation that the Willunga Embayment 'is also interpreted as forming a coastal bay during much of its history'.

Transition to Tertiary sandy marginal facies, similar to that demonstrated by Cooper for the Willunga Embayment, occurs also in other embayments of the St Vincent Basin.

Notwithstanding the above, there is not yet unanimity in local basin terminology. Ludbrook (1980) continues to prefer the term 'Willunga Sub-Basin', which the writer also used at one stage (Lindsay, 1969). The Adelaide Plains Sub-Basin (Lindsay, 1969) termed 'Adelaide Plains Embayment' by Stuart(1969) is regarded by the writer as occupying the extensive plains from the Eden Fault in the south (Plan 2; Fig. 17) through the western and northern Adelaide Plains, to at least the vicinity of Port Wakefield, and eastwards to faulted margins near towns such as Gawler, Hamley Bridge, and Balaklava (Plans 1,2). This whole area appears to be a structural entity, although the Cainozoic section thickens markedly south of an east-west fault near the River Light (Lindsay, 1969, fig. 2). Various 'basins' of potable underground water may be distinguished hydrologically in the Adelaide Plains as elsewhere, but they seem to relate to recharge by ephemeral streams, and do not necessarily correspond to geological sub-basins or embayments. It is confusing to separate a 'Northern Adelaide Plains Sub-basin' from an 'Adelaide Plains Sub-basin', 'on the basis of higher salinity, in the vicinity of Grand Junction Road' (Ludbrook, 1980, p. 127). The term 'Golden Grove-Adelaide Embayment' is introduced here as being more descriptive of the area involved than 'Golden Grove-Highbury Basin' (Olliver and Weir, 1967), 'Adelaide Embayment' (Stuart, 1969) or 'Highbury-Golden Grove Embayment' (Cooper, 1979b). The Golden Grove-Adelaide Embayment is discussed in more detail below.

The structural geology and the extensive brown coal (lignite) deposits of the northernmost St Vincent Basin were discussed by Johnson (1960, 1964a), Hillwood (1961), and recently by Johns (1975, 1980) and by Meyer (1976) who used the structural terminology outlined by Johnson (1960). As shown in Plans 1 and 2, the wedge-shaped 'Nantawarra Highlands Block', a bedrock inlier, divides this part of the basin into two trough-like depressions, which merge towards the northern apex of the basin. The western zone, which is bounded on the west by the Ardrossan Fault, comprises to the south, the Clinton Trough, containing the Clinton Coalfield; and to the north of a bedrock lobe, the Bumbunga depression, from Lochiel to the Barunga coal bores near Snowtown. The broader and more continuous eastern graben, extending from Balaklava to Brinkworth, is still only poorly known, but contains at its southern end the Whitwarta Coalfield, and at its northern end the coal bores in hundred of Boucaut, on the Condowie Plains between Snowtown and Brinkworth (Johnson, 1960). South of the Nantawarra inlier, the Inkerman-Balaklava Coalfield (now Wakefield Coalfield; Johns, 1980) is situated on the Port Wakefield Platform, which is bounded by the nearly-meridional Templeton and Whitwarta Faults. Tertiary brown coals of the St Vincent Basin, and particularly those beneath the City of Adelaide, are discussed below in the chapter treating CLINTON FORMATION.

The northern extremity of the St Vincent Basin merges with the southern end of the Cainozoic Pirie-Torrens Basin across a constricted transitional zone in the vicinity of Crystal Brook (Plan 1).

Non-marine gravels and sands near the northern margin of the St Vincent Basin, extend from north of Brinkworth, to Narridy, Gladstone, and Laura (Plan 1). They were mapped by Mirams (1964) and described as the Koolunga Gravels by Alley (1973) who postulated a deltaic and lacustrine depositional environment. More elevated, meridional deposits of intramontane lacustrine gravels further east, such as those mapped south of Spalding by Johnson (1964b), were correlated tentatively with the Koolunga Gravels by Alley, but have a more distant and speculative relationship to the St Vincent Basin.

In a similar way, non-marine sediments of the Barossa Valley Basin (Plan 1) comprising Oligo-Miocene carbonaceous sand, silt, clay, and lignite, up to 130 m thick (Daily et al., 1976) and named the Rowland Flat Sands by Alley (1973), have a doubtful relationship to the St Vincent Basin through a discontinuous chain of non-marine sand deposits from Sandy Creek to Gawler, and northwards through Freeling to Stockport, east of Hamley Bridge (Olliver and Weir, 1967; Alley, 1973). Glaessner and Wade (1958) considered it desirable to include these and other peripheral 'Upland Tertiaries' (e.g. Meadows Valley deposits) within the St Vincent Basin, but Ludbrook (1969b) excluded the Barossa Valley sands from the St Vincent Basin sedimentary succession.

Eocene sand deposits on the northwestern margin of the St Vincent Basin, some in the Clinton Trough and some of the 'Upland Tertiaries' type, were described by Crawford (1965). At Correll's sand pit, about 100 m above sea level, 8 km north of Melton (Plan 1), iron-stained cross-bedded gravelly quartz sands which are exposed to a depth of at least 20 m, are comparable in lithology with stratotype North Maslin Sand.

Thin partly-calcreted bioclastic carbonates described as Melton Limestone by Crawford (1960a,b; 1965) extend discontinuously across northern Yorke Peninsula, recording several Late and Middle Miocene warm, transgressive, marine pulses of varying extent (Lindsay, 1970c). Stuart (1969, text-fig. 17J) depicted extensive marine inundation of most of 'Yorke Peninsula' in a palaeogeographic reconstruction for some part of that time. Conservatively, at least the present outcrop area of Melton Limestone may be considered as a probable temporary extension of the St Vincent Basin (Plan 1; cf. Cooper, 1979b, fig. 2). However, extending the argument still further, Mayne (1976) expanded the St Vincent Basin westwards over and around Yorke Peninsula, across Spencer Gulf to the eastern edge of Eyre Peninsula, in order to include correlatives of the transgressive uppermost phase of Melton Limestone southwest of Whyalla (Lindsay, 1970c) and at Fishery Bay, on the southern tip of Eyre Peninsula (Ludbrook, 1963a). This concept of the St Vincent Basin, which would more than double its size, has not been adopted herein, although there is a possibility that it might be confirmed by future geological discoveries in and around Spencer Gulf.

A strip across the 'instep' of Yorke Peninsula, including Peesey Swamp, is shown as a probable site of marine inundation in Plan 1. In addition to the early records of relatively recent (Quaternary) marginal-marine fossils through the 'Great Salt Marsh' joining Hardwicke Bay and Sturt Bay (Tate, 1890a; Greenway and Phillipps, 1902), many outcrops of marginal-marine, Pliocene, oyster-rich sandy limestones have been noted around the margins of this zone (Greenway and Phillipps, 1902, p. 271; Ludbrook, 1959; Crawford, 1965, p. 36; Corbett,

1976, p. 48). Oligo-Miocene bryozoal limestone (recorded as 'Eocene' by Howchin, 1900, 1901) with Victoriella, occurs at the northwestern end of the Warooka Scarp, comprising the Point Turton Limestone of Ludbrook (1963a); while the writer has examined Upper Eocene sandy bryozoal limestones at the southeastern end, near Troubridge Hill (Lindsay in Foster, 1974, p. 32). This and other localities with Eocene limestone through the area, were noted by Howchin (1900, 1901).

Cooper and Lindsay (1978) recently reviewed the known occurrences of marine Tertiary rocks (mainly Upper Eocene and Pliocene) on Kangaroo Island, at the southern end of the St Vincent Basin; and further studies are in progress (Cooper and Milnes, 1980).

Although marine geophysical surveys have been undertaken in Gulf St Vincent (Cooney, 1965; Sprigg and Stackler, 1965, Stuart and Von Sanden, 1972), the only exploration well drilled to date in gulf waters is Beach Petroleum Troubridge Shoal-1, offshore 8 km east-southeast of Edithburgh (Plan 1). In 1963, this hole penetrated 259 m of Cainozoic strata (including 232 m of Tertiary carbonates) followed by 229 m of Permian 'glacial marine' claystone, sandstone, and boulder beds, in which the hole bottomed at a depth of 488 m (Ludbrook, 1963b).

The thickest Cainozoic section known in the basin (619 m) was penetrated in the E. & W.S. Croydon-2 bore, which was drilled in 1892-93 near the eastern margin of the Adelaide Plains Sub-Basin, only 2.3 km from the Para Fault Zone and the City of Adelaide (Plans 4,5,29; Fig. 18). Six kilometres to the west (Plan 4), Beach Petroleum Grange-1 well penetrated a 571 m Cainozoic section.

Age of the St Vincent Basin

The Permian Troubridge (Infra-) Basin (Stackler and Sprigg, 1965; Sprigg and Stackler, 1965; Wopfner, 1972; R.J. Foster, 1974, fig. 1) within its general southeast-northwest trend from the Coorong to central Yorke Peninsula, underlies and surrounds the southern half of the St Vincent Basin. However, the Permian sediments 'do not form part of the essentially Tertiary St Vincent Basin, although they crop out on all but the north side of the basin' (Ludbrook, 1969a, p. 40). McGowran (1973b, pp. 759-760) suggested a west-to-east, glacio-eustatic, Lower Permian marine ingression through the southern Australian Permian infra-basins, which 'perhaps reflects, in its direction and extent, early formation of the rifted Australia/Antarctica suture', transverse to the later overall north-south trend of the Cainozoic St Vincent Basin. Permian sediments are not known to occur within the Adelaide City area, but sandy and gravelly clays with varied lithic fragments, comprising the bottom 81 m of the Croydon-2 bore, have been suggested as possibly Permian although in the absence of palaeontological evidence (Steel, 1962a; Lindsay, 1969; Plan 29 herein). Well-preserved, recycled Permian spores and pollen are encountered frequently in palynological preparations of Eocene to Miocene marine sediments from the St Vincent Basin (Harris and McGowran, 1971) including the Adelaide City area (e.g. in Ref. bore 14; Harris, 1964).

Unlike the Eucla, Polda, Duntroon, Murray, and Otway Basins of the South Australian continental margin, the St Vincent Basin has yielded no evidence of Mesozoic sedimentation beneath its Tertiary sequence.



Figure 17. View taken October 1980, looking S.W. from Mt Osmond, showing the Eden Fault Scarp curving around to the west to meet the coast of Gulf St Vincent in the left centre distance. The southern end of the Adelaide Plains merges into the southern end of the Golden Grove-Adelaide Embayment in the vicinity of the Mitcham spur (middle distance, cf. Plan 4). The Glen Osmond shale quarry (P.G.H. Ceramics; Adelaidean Glen Osmond Slate) is in the lower foreground, on the Mt Barker Road.



Figure 18. View taken January 1980, looking S.E. along Port Road plantation towards central Adelaide City, from immediately N.W. of the site of the old E. & W.S. Croydon-2 bore (Garnett St cross-over); Mt Lofty in left distance (cf. Plans 4, 5).

The oldest Tertiary unit recognised in the St Vincent Basin is the North Maslin Sand; and the oldest unit dated is the lens of carbonaceous clay in stratotype North Maslin Sand (A.B.M.-Readymix sand quarry) within the Willunga Embayment (Plan 2). This non-marine clay lens which is intercalated about 10 m above the local base of the Tertiary succession, was determined as low Middle Eocene Proteacidites confragosus Zone (McGowran et al., 1970) on the basis of palynological correlation by W.K. Harris with the marine Burrungule Member of Knight Formation ('Tartwaup Formation', Dilwyn Formation) in the Gambier Embayment. More recent palynological studies suggest that the Maslin clay lens was deposited a little later in the Middle Eocene (W.K. Harris, Western Mining Corporation Ltd., personal communication, August 1980).

Four kilometres east of the type section of North Maslin Sand and the Maslin clay lens, a sand-exploration bore intersected another band of highly carbonaceous mudstone but here only 8 m below the top of the North Maslin Sand. A core from this band underwent palynological examination by W.K. Harris, who determined (in Lindsay and Harris, 1974) early Proteacidites pachypolus Zone, Middle Eocene (Harris, 1971; McGowran et al., 1971), a zone younger than the Maslin clay lens. These data indicate that the North Maslin Sand is entirely Middle Eocene in this area.

A borehole at Yatala Vale (SADME Golden Grove-46; McCallum, 1978), near the northern extremity of the Golden Grove-Adelaide Embayment (Plan 4), intersected lignitic clay interpreted as Clinton Formation, near the local base of the Tertiary succession. Palynological examination of this

carbonaceous material by Hos (1977) yielded the only bio-stratigraphic age-data so far reported from this end of the embayment. Hos determined the sample as Proteacidites pachypolus Zonule of Harris (1971), and most probably upper Middle Eocene.

Similarly, 'carbonaceous and lignitic beds near the base of the Tertiary sequence beneath the Adelaide City area, for example in the SADME South Parklands and West End Brewery bores, have been dated palynologically as Middle Eocene (Proteacidites pachypolus zone); and in deeper sections of the Adelaide Plains Sub-Basin, for example the Port Gawler and Longyear bores, the oldest carbonaceous beds are of similar age' (W.K. Harris, SADME, personal communication, January 1980).

Sedimentation in the Pirie-Torrens Basin (Plan 1) appears to have commenced at the same time as in the St Vincent Basin, within the limits of palynological resolution. The oldest microfloras reported by Harris (1972) from boreholes in the Pirie-Torrens Basin (SADM Lake Torrens-3A, 248-270 m; Santos Wilkatana-1, 99-107 m) are P. confragosus Zone, Middle Eocene, as for the Maslin clay lens. Available evidence supports the suggestion of Harris, in that report, 'that the Pirie-Torrens Basin was not a negative feature during the earliest Tertiary'; and the same applies, apparently, to the St Vincent Basin. During the Middle and Upper Paleocene, while coarse to fine fluvio-lacustrine clastics were accumulating in the already-depressed western Murray Basin (Renmark Beds; Harris, 1966; Harris in Lindsay and Bonnett, 1973) the future St Vincent Basin and Adelaide City areas were, seemingly, still part of the adjacent meridional uplands.

Regional Tectonic Control

The idea of an extensive, generally north-south tectonic valley between the western cratonic plateau and the South Australian highland chain, was perceived by Gregory (1906), who named the 'Great Valley of South Australia', linking the Lake Torrens depression with Spencer Gulf. However, he excluded the region of Gulf St Vincent from the 'Great Valley'. Fenner (1927) developed the concept of an axial 'rifted' lowland, which he named the 'South Australian Rift Valley', commenting on its complexity. He named the northern, arcuate 'Torrens Sunkland', bounded on the west by 'The Torrens Fault', and linked by the narrow 'Port Augusta Corridor' with the southern half-moon complex depression, 'The Spencer-Vincent Sunkland', which in turn is subdivided by the 'Yorke Peninsula Horst'. The eastern marginal highlands were composed of the northern 'Flinders Horst', and the southern 'Mt Lofty Horst'. Within this tectonic framework, Fenner described the setting of the City of Adelaide in perceptive structural and geomorphological detail. Howchin (1929, p. 246) thought it 'probable that the rift valley began to sink as far back as the middle of the Cainozoic era', and that it may be still sinking as evidenced by its notable seismicity.

The palynological evidence outlined earlier suggests that at least the older parts of both the St Vincent and the Pirie-Torrens Basins rifted open for sedimentation early in the Middle Eocene. Bench-mark papers by Griffiths (1971) and McGowran (1971, 1973b) first attempted to link the sequence of sedimentation in southern Australian marginal basins with the timing of Australia-Antarctica rifting and drifting according to the then rapidly-developing plate-tectonic theory.

The oldest oceanic crust generated by seafloor spreading south of the Australian continental margin, contains Magnetic Anomaly 22 (Weissel and Hayes, 1972; Markl, 1978). The age of this anomaly has been estimated variously as Late Paleocene (Heirtzler et al., 1968, Berggren, 1972, and Watkins, 1976; all 56-57 Ma) or Early Eocene (Sclater et al., 1974, La Brecque et al., 1977, and Hardenbol and Berggren, 1978, all 53 Ma; Berggren et al., 1978, c. 50 Ma; Tarling and Mitchell, 1976, 46 Ma). However, as illustrated by Deighton et al. (1976), the uncoupling of Australia and Antarctica took place progressively from west to east. Weissel and Hayes (1972, fig. 2) recorded Anomaly 22 only from south of the Great Australian Bight; and it was apparently not until Anomaly 19, which is generally agreed to lie somewhere within the Middle Eocene, that the longitude of the St Vincent Basin was reached by oceanic crust. From this point southeastwards to beyond Tasmania, a notable series of great transform faults which are aligned N-S to NNW-SSE, progressively offset the Southeast Indian spreading ridge to a marked degree (Weissel and Hayes, 1972, 1974). One, which trends NNW towards the South Australian gulfs, was named the 'St Vincent Fracture Zone' by Weissel and Hayes (1974, fig. 1). Sykes (1978, p. 641 ff.) observed that the 138°E, 'Adelaide seismic zone' (compare the Torrens Hinge Zone, Plan 1) 'is situated along the continuation of the strike of one or more major fracture zones in the southeast Indian Ocean between 140° and 145°E'. He considered it 'likely that this major pre-existing structural boundary influenced the latest pattern of continental fragmentation, the shape of the continental margin, and the location of major fracture zones near the continental margin'. However he did not discuss at all

how this essentially longitudinal zone might be maintained through the cross-cutting, east-west, Delamerian and Cainozoic structural trends which traverse southern Fleurieu Peninsula and Kangaroo Island (Plan 1), but he did view the 'ancient zone of weakness' as a very profound feature which penetrated the lithosphere. Despite this and other problems it is apparent, as he observes, that that persistent zone of weakness was reactivated in the Tertiary, and is a locus of seismic activity today (Sutton and White, 1968; McCue and Sutton, 1979). Within the limits of magnetostratigraphic and biostratigraphic resolution, the Tertiary reactivation which initiated the St Vincent Basin in the Middle Eocene accompanied the progressive crustal rupture and injection of oceanic crust to the south.

In general, the St Vincent Basin developed transverse to the spreading axis, because the faults which framed the central and northern parts of the basin paralleled Delamerian and older structural trends of the Adelaide Geosyncline and the Torrens Hinge Zone (Plan 1).

Faults

Plans 1, 2 and 4 show in plan view the style of Cainozoic faulting in the eastern St Vincent Basin, where faults are aligned west of north at the northern end of the basin, but swing to the southwest, and finally west, at the southern end. In similar fashion to Cooper (1979b) and Ludbrook (1980), the eastern and northern faults are extended tentatively into Gulf St Vincent on the basis of a conservative acceptance of the geophysical interpretations of Stuart and Von Sanden (1972). Attention will be focussed on the vicinity of Adelaide, where

the Para Fault Zone and the Eden-Burnside Fault Zone demarcate the Para Fault Block on which the City of Adelaide is situated.

There have been few, if any, observations on the ground, of the Cainozoic faults which appear to figure so prominently around the margins of the basin, and which are seen as lineaments on air and satellite photos. In the Willunga Embayment, Mawson (1953, fig. 2) illustrated and discussed an exposure in a creek at the southern end of Sellick Beach, of what he considered might be 'the main fault line along the foot of the Willunga Scarp', that is, the Willunga Fault. However, the marginal belt of crush-breccia and the central crush-conglomerate which he described, are in Cambrian Heatherdale Shale (Abele and McGowran, 1959). In the same creek-bed, poorly exposed, gravelly bryozoal limestone (Port Willunga Formation, Oligo-Miocene) cuts out in the vicinity of this fault zone as described by Howchin (1911, p. 50) but relationships are unclear in detail. Nearby, Howchin (1911) and later, Campana et al. (1955) and Abele and McGowran (1959) recognised Port Willunga Formation transgressing with angular unconformity on to Cambrian strata, but tilted steeply to the northwest by subsequent movement on the Willunga Fault. Howchin recorded dips in the Tertiary beds of from 40° up to vertical, 'and in one instance, at least, to a distinct overfold.' He noted that the curve of the dips, steepening downwards to sea level, gave the appearance of a partly-preserved monoclinal fold (Howchin, 1911, pls 14, 15, 18). This flexure is surely the result of movement on the Willunga Fault Zone. The characteristic fault-style disrupting the Cambrian strata of the Sellick Hill area is high-angle

thrusting, southeast over northwest, as displayed by the Black Hill Fault (Abele and McGowran, 1959). These authors regarded the Willunga Fault as having originated in the same stress field, and Delamerian movement on it was no doubt also high-angle thrusting. Campana et al. (1955, pls 8-11) depicted subsequent Cainozoic movements on the fault as having occurred in the same sense, but little is known or can be observed of the style of reactivation of the fault at various times in the Cainozoic: in the Middle Eocene when the basin was first formed; in the mid-Tertiary causing rapid thickening of sediments basinwards from a transgressive edge (see above, and Cooper, 1979b); probable post-Middle Miocene/pre-Pliocene movement (epeirogeny, low-angle unconformity); and various Quaternary movements (Campana et al., 1955). As a result of a gravity survey, Pegum (1962) suggested that the asymmetrical axial trough of the embayment has a 'very sharp' margin against the Willunga Fault, near Willunga. No more recent geophysical reports on this fault zone have been prepared. Cooper (1979b, figs 35-37) showed the Willunga Fault as vertical in transverse, vertically-exaggerated (20X) cross-sections of the embayment, as had Daily et al. (1976). The net displacement is obviously southeast block up/northwest block down, but whether 'reverse' or 'normal' movements predominated in the Cainozoic, is not known. Most of the sedimentary fill of the Willunga Embayment is below present sea level, and near the southwest end of the onshore axial trough Cainozoic sediments extend 300 m below sea level (Cooper, 1979b, fig. 35), so downfaulting (presumably high-angle normal faulting) is likely to have been a significant component of the total relative displacement.

In the same way as the Willunga Embayment is a wedge-shaped asymmetric tectonic valley bounded on the southeast by the Willunga Fault Zone, so the Noarlunga Embayment with similar geometry but smaller size, is bounded in a broad sense by the Ochre Cove-Clarendon Fault Zone (Plan 2). Forbes (1980, cross-section) shows this fault also as a high-angle thrust, southeast over northwest, where it traverses Adelaidean rocks in the Mt Lofty Ranges east and southeast of Adelaide. Where the fault zone meets the coast, at the southern extremity of the onshore Noarlunga Embayment, between Moana and Ochre Point (Plan 2), Stuart (1969, map 5) mapped part of a monoclinal flexure in the Tertiary succession as revealed on a rarely-exposed wave-cut platform. Here, within a horizontal distance of 130 m (measured at right angles to the strike) dips at first decrease from 38°NW, at the local base of the section (South Maslin Sand) to a minimum of 30°NW in Gull Rock Member (Blanche Point Formation), and then increase progressively to a maximum of 80°NW at the northern end of the exposure (Port Willunga Formation). The succession is attenuated by a factor of about 10%, and significantly lacks North Maslin Sand, but otherwise is comparable with the sequence penetrated in the Seaford drainage bore, 2 km to the north (Plan 2; Cooper, 1980). As on the Willunga Fault Zone, this Tertiary succession thins both by erosion and onlap as it drapes unconformably on 'bedrock' (here Proterozoic) and is steeply flexed across the Ochre Cove-Clarendon Fault Zone (Glaessner and Wade, 1958, fig. 24). Glaessner and Wade depicted this fault plane as dipping northwest at a moderately high angle (65 to 70° after corrections for obliquity and vertical exaggeration of the cross-section).

Daily et al. (1976, fig. 19) showed it as a vertical feature in a cross-section with 10X vertical exaggeration, but as with the Willunga Fault Zone direct observational data are lacking to document change during reactivation from Delamerian high-angle, southeast-facing thrusts, to Cainozoic high-angle northwest-facing 'reverse' or 'normal' faults.

There are similar problems in interpreting the history of the Eden Fault Zone and the Para Fault Zone near Adelaide (Plans 2,4,5). The Golden Grove-Adelaide Embayment is bounded on the eastern side (in a broad sense, if not everywhere in detail) by the Eden Fault Zone, with the Burnside Fault splintering in parallel from the vicinity of Magill Road southwestwards. Both the Eden and Burnside Faults are depicted by Forbes (1980) in a natural-scale cross-section, as facing northwest at extremely high angles (87°). In cross-sections with exaggerated vertical scale, such a fault-plane appears vertical, as shown herein, and for example by Lindsay (1969), and in Daily et al. (1976). Within the Readymix quarry complex at Highbury East (Olliver and Weir, 1967, p. 30) sands mapped as North Maslin Sand by Forbes (1980) are in contact with Adelaidean Stonyfell Quartzite along the Eden Fault Zone (Figs 19, 20). A small area of the contact zone has been proposed as a 'geological monument' (Toteff and McBriar, 1979) in order to preserve an ostensible exposure of the fault (Figs 21, 22). However, more detailed study of this locality is needed and will be pursued; as the statement supporting preservation acknowledges, the Tertiary/Proterozoic contact is indeed an unconformity with a basal conglomerate (Figs 23, 24). It is doubtful whether any Tertiary/Proterozoic fault contact is visible at

this site. Faulting has undoubtedly occurred in the vicinity, to tilt or drag the Tertiary sand and the unconformity into a steep, west-facing attitude with slumped or drag-folded clay-bands (Fig. 22), but at least at the level now exposed, the faulting appears to be substantially in the Adelaidean rocks.

Nevertheless, at the scale of Plan 4, in which the line drawn to delineate the Eden Fault occupies a thickness of 50 m, it is considered a valid generalisation that this fault zone marks the eastern boundary of the embayment hereabouts; and this is also indicated by Forbes (1980).

Less than a kilometre north, at the controversial 'Gun Emplacement' (Plan 4; Fig. 25) the same Tertiary sands are capped by an almost-level to gently-sloping pedogenic, ferruginised, 'lateritic' profile, which thickens to at least 6 m at the foot of Anstey Hill, and comprises a carapace of hard, blocky, ironstone ferricrete with minor silicification, overlying a zone of vertical ferruginous mottles. Firman (in Daily et al., 1976, p. 36) identified the caprock as a Lower Pleistocene marker unit associated widely with the Karoonda Surface. According to Firman (1979), the mottled zone and caprock together comprise the Plio-Pleistocene Karoonda Soil. Behind the rising eastern end of the Gun Emplacement, the ferruginous capping appears to be displaced vertically and cut off (Fig. 26), presumably in the Eden Fault Zone, as shown by Forbes (1980).

Borehole data suggest that the Hope Valley Fault extends subsurface to the southwest, as shown herein (Plans 4, 17) in consultation with Forbes (1980). It is apparently a high-angle



Figure 19. View south, October 1980, from Eden Fault Scarp above Readymix Highbury East sand quarries (foreground), looking down the eastern margin of the Golden Grove-Adelaide Embayment; quarries in Adelaidean Stonyfell Quartzite at left, and centre distance.



Figure 20. View south, October 1980, from 'The Gun Emplacement', showing features similar to above, from a different angle.



Figure 21. View S.E., Sept. 1980, of 'Geological Monument', Readymix Highbury East sand quarry, showing Tertiary sand (pale brown; centre and right) draped steeply against Adelaidean Stonyfell Quartzite (yellow, white; left), in the vicinity of the Eden Fault Zone, eastern edge of Golden Grove-Adelaide Embayment; guard-rail posts are about 1 m high.



Figure 22. Closer view of centre part of Fig. 21, showing slump or drag-folds in bands of white clay, in steeply-dipping pale brown Tertiary quartz sand (?North Maslin Sand).



Figure 23. 'Geological Monument', Readymix Highbury East sand quarries, Sept. 1980; cross-bedded Tertiary gravelly sand (?North Maslin Sand) with basal bed containing quartz and quartzite boulders, resting unconformably (hammer-head) on weathered slaty Adelaidean bedrock.



Figure 24. View near Fig. 23, showing more prominent basal coarse quartz gravel about 1 m thick, developed at the base of the Tertiary sand, on the bedrock unconformity.



Figure 25. 'The Gun Emplacement', Highbury, Oct. 1980; view N.W. across the Golden Grove-Adelaide Embayment from the Eden Fault Scarp, showing the flat-topped mesa of ?Plio-Pleistocene ferricrete overlying pink/pale brown Tertiary sands (left foreground); Modbury Hospital and Tea Tree Plaza in left distance; Fig. 26 was taken from a point near the right edge of this photo.



Figure 26. View east, from the S.E. corner of 'The Gun Emplacement', showing gently sloping, hard composite profile 6 m or more thick, apparently repeated, and finally cut out (at the tree-line) in the Eden Fault Zone.

normal fault, facing northwest, in harmony with the regional Cainozoic style of steep antithetic faults which delimit blocks tilted gently southeast. North and south of the Hope Valley reservoir, the Hope Valley Fault also apparently acted as a growth fault, marking the eastern limit of the Hope Valley lignite deposits. It was this kind of occurrence which led Glaessner and Wade (1958, p. 116) to remark that 'the underground distribution of lignites proves that some ancient fault scarps formed the boundaries of coal swamps'.

The Para Fault Zone

Because of its proximity to the City of Adelaide, and its structural and stratigraphic significance for the present study, the Para Fault Zone will now be discussed in more detail. Fenner (1927) named the Para Fault and the Para Fault Block, recognising the position of the fault by means of the Para Fault Scarp which is strongly expressed to the north of Adelaide (Figs 27, 28) but fades out west of the City. On the basis of gravity measurements and modelling during 1948-1951, Kerr-Grant (1952) suggested that the main Para Fault splits into two arcuate branches west of the City, and it was depicted thus by Sprigg et al. (1951), Miles (1952), and subsequent authors. Recently, in response to a request by the writer, Finlayson (1978) conducted a more detailed gravity survey of this area of supposed bifurcation. He concluded that his survey had not disproved the splinter-fault model, but suggested 'that there is as much evidence for the system to comprise a series of parallel or en-echelon faults'. In fact this was his preferred model, the fault zone comprising 'one major fault with a maximum throw of 650 m, with smaller nearly parallel faults on either side', as shown herein (Plans 4, 5).



Figure 27. View E.S.E. from Port Wakefield Rd, Cavan, Nov. 1980, looking across The Levels (part of Northern Adelaide Plains) to the Para Fault Scarp (Para Hills - Ingle Farm), the south-sloping Para Fault Block, and the distant Mt Lofty Ranges.



Figure 28. View S.S.W. from Black Top Rd, east of Hillbank, Nov. 1980, looking down western edge of south-sloping Para Fault Block, showing dissected Para Fault Scarp, and the City of Adelaide.

The 'major fault' is the main Para Fault, which swings south westwards from the city area to Glenelg North ('Para Fault North' of Lindsay, 1969). There it passes between several Glenelg Golf Club bores as shown in Plan 4. Bore 6 (07852), immediately north of the fault, penetrated a notably thicker Quaternary and Pliocene sequence than did the adjacent bores 2 (07848) and 5 (07849) south of the fault (see also Lindsay, 1969, appendices 1,2). It is evident that the fault behaved as a growth fault in the Pliocene and Pleistocene, during the 'Kosciusko Uplift'. Near the city the main Para Fault divides the Thebarton Block to the west, from the Mile End Block to the east. Cross-sections L-M (Plan 11), T-U (Plan 16), and V-W (Plan 17) show the interpreted throw of the fault. Total throws to bedrock as suggested by Finlayson from his gravity modelling, seem to harmonise reasonably well with available subsurface data. All of the faults in the Para Fault Zone are assumed to be of a normal, northwest-facing, dip-slip type, with a high-angle fault-plane which is best shown as vertical in a cross-section with exaggerated vertical scale.

The East Para Fault, which divides the Mile End Block from the Para Block (Plans 4,5) has been continued northwards a kilometre further than shown by Finlayson (1978, Fig. 4A) since his gravity-based block-model (Fig. 4B) shows minor fault displacement as far north as his gravity line along Strangway Terrace, North Adelaide. However there is no geophysical or other evidence that this fault joins the main Para Fault.

The interesting intersection of South Maslin Sand at shallow depth in Reference bore 39 (Plan 5; Appendices A,B) relates this bore sequence to others in North Adelaide which are also on the Para Block, and confirms that the East Para Fault passes to the west of the bore (Cross-section L-M; Plan 11). The sequence penetrated in Reference bore 59 suggests similarly that the fault is west of this bore also. In Plans 2, 4, and 5, the revised positions of the main Para Fault and the East Para Fault, west of the City, have been connected into the southwest-trending, north and south 'splinter faults' whose positions were shown by Sprigg et al. (1951) and emended by Lindsay (1969). Forbes (1980) has drawn the revised fault lines similarly.

Detection of the 'West Para Fault' by Finlayson was an important advance. The reality of the fault, and its location, have been confirmed by stratigraphic differences among the cluster of bores drilled for Coca Cola Bottlers (Diverse Products), Thebarton (Plans 4,5). As shown in Appendix B, and Cross-section T-U (Plan 16), Reference bores 58, 68, and 106, west of the fault, penetrated a thicker Quaternary sequence than Ref. bore 105 on the eastern side, encountered a Pliocene unit which Ref. bore 105 lacks, and then entered a younger (Bairnsdalian-Balcombian) unit of Port Willunga Formation than the Balcombian-Batesfordian unit entered in Ref. bore 105. The West Para Fault, which divides the Croydon Block from the Thebarton Block, has only been shown herein and by Forbes (1980) to the extent that it was detected by Finlayson (1978). Although subordinate to the main Para Fault, the West Para Fault is certainly a significant feature immediately west of

the City of Adelaide; but at present there is insufficient information to distinguish its course further north or southwest.

Steel (1962b), on stratigraphic evidence, considered that 'splinters' of the Para Fault west of the City of Adelaide had 'probably moved at different rates through the Tertiary'. Various stratigraphic differences across the Para Fault Zone, evident in cross-sections herein, illustrate the effects of such differential and persistent but probably intermittent movement.

Across the West Para Fault (Cross-sections L-M, Plan 11; and T-U, Plan 16), differences noted above indicate removal by erosion of Upper Pliocene Hallett Cove Sandstone and the uppermost (Lower to Middle Miocene) units of Port Willunga Formation from the upthrow side, probably in the Early Pleistocene. This implies movement on the fault at this time, during the Late Cainozoic 'Kosciusko Uplift'. The cross-sections also illustrate change of facies between the Quaternary sequence immediately west of the fault (Ref. bore 106) and that east of it (Ref. bore 105). In Ref. bore 106, lateral equivalents of Hindmarsh Clay are notably gravelly and sandy, to such an extent that the name Carisbrooke Sand is appropriate in part; while east of the fault there are fewer gravel lenses. This wedge of coarse and poorly-sorted fluviatile clastics on the downthrow side of the fault is a further indication of topographic relief and activity on the fault in the Early to Middle Pleistocene. The subsurface type locality for the ?Plio-Pleistocene Carisbrooke Sand (Lindsay, 1969, p. 40) is in a similar structural setting, where a 50 m-thick wedge of

sand with gravelly intervals is developed against the Para Fault at Elizabeth Vale (Plan 4; Obs. bore MPA 92). For further discussion of Carisbrooke Sand, see under 'PLIOCENE UNITS', below.

Across the main Para Fault (Cross-sections L-M, Plan 11; and T-U, Plan 16) the thickness of Quaternary sediments decreases substantially from 90 m of mainly Hindmarsh Clay with subordinate Carisbrooke Sand facies (in Ref. bore 105), to 23 m of sand and gravel in Ref. bore 51, interpreted as alluvium of the ancestral Torrens. As with the West Para Fault, this suggests topographic relief and activity on the main Para Fault in the Pleistocene.

Cross-section R-S, aligned longitudinally down the Mile End Block (Plans 5,14), indicates the gentle southerly dip of the bedrock unconformity, with concomitant thickening of the preserved Tertiary section. An angular unconformity separates the severely-truncated Gull Rock Member of Blanche Point Formation from the Tandanya Sand Member of Chinaman Gully Formation which thickens northwards dramatically. As in the rest of the Adelaide City area, on the Para Block, upper Blanche Point Formation ('Blanche Point Soft Marls Member', of Reynolds, 1953) is missing, almost certainly by erosion, from between the Gull Rock Member and Chinaman Gully Formation. In contrast, the Tandanya Sand Member is not present in the Croydon-2 bore, where Chinaman Gully Formation is only developed in fine-grained, carbonaceous and lignitic facies (Plan 29). These relationships taken together suggest that in the Late Eocene, prior to and during deposition of the prograding Tandanya Sand Member (Lindsay and Harris, 1979), epeirogenic tilting

and erosion of the Mile End Block occurred, with associated movements elsewhere in the Para Fault Zone.

Cross-section R-S (Plan 14) like most of the other cross-sections, illustrates the angular unconformity which separates the mid-Tertiary succession from Pliocene units. In this section the youngest mid-Tertiary unit affected is earliest Miocene, and no Pliocene unit older than Hallett Cove Sandstone is present; but elsewhere, in the Adelaide Plains Sub-Basin, it is evident that this epeirogenic tilting with associated faulting and erosion postdated Bairnsdalian Port Willunga Formation and occurred prior to the deposition of Kooyonga Formation ('Croydon facies'); that is, it was post-Middle Miocene and pre-Pliocene. The same regional epeirogeny also affected the Murray Basin, after the deposition of Pata Limestone and before the deposition of the Pliocene units (see for example, the writer's table 1, in Twidale et al., 1978). From the above evidence there is little doubt that the Para Fault Zone was reactivated at this time.

Cross-section R-S depicts well the already-mentioned relationship with its tectonic implications, between Lower Pleistocene Carisbrooke Sand and an eroded remnant of Hallett Cove Sandstone. This relationship is observed at many points around 'buried mesas' of Hallett Cove Sandstone beneath the Adelaide City area (Plans 6-8, 12-14, 16), and indicates local faulting, uplift, and erosion during the Plio-Pleistocene Kosciusko epeirogeny.

Middle to Late Eocene movement in the Para Fault Zone may be inferred to have taken place subsequent to deposition of Clinton Formation and prior to deposition of South Maslin Sand, although the two units often appear to be conformable

beneath the City on the Para Block. Clinton Formation, characterised by carbonaceous and lignitic lithology, is developed extensively subsurface in the vicinity of Adelaide as discussed later, but Cross-section T-U (Plan 16) shows the unit to be absent in Ref. bore 51, on the Mile End Block, even though well-developed on the Para and Croydon Blocks. Other bores further south on the Mile End Block do not penetrate deeply enough to determine the presence or absence of the unit, but at least at the northern end of the Block, the absence of Clinton Formation suggests subsequent faulted uplift and erosion. An alternative explanation, non-deposition on a ridge separating coal swamps to the east and west, would also imply differential fault movements within the Para Fault Zone, but involving 'west block up' on the East Para Fault, a sense opposite to that which is now expressed.

In the Adelaide City area, the main Para Fault Scarp is most strongly developed on the western side of North Adelaide, where the difference in elevation between the Adelaide Plains and the North Adelaide plateau is about 30 m (Plan 5). A good view of the scarp can be obtained from Torrens Road, Renown Park (Fig. 29). Various Quaternary units are exposed nearby on the slope of the Para Fault Scarp, in an open drain which follows the boundary of the Municipal Golf Links down Mildred Road for about 360 m, crossing the main Para Fault on the way. Ripon Calcrete is exposed near both the upper and lower ends of this drain, the lower (downthrown) exposure being illustrated in Figures 30, 31. A preliminary survey by the writer has shown that the calcrete, about 3 m thick, is downthrown 5-7 m on the western side of the fault. This is the locality referred to by Firman (in

Daily et al., 1976, p. 36) when he stated that in the Adelaide Region 'the Ripon Calcrete occurs only near Dublin, North Adelaide, and at Noarlunga'; but until now no-one has reported the outcrop of the Ripon Calcrete on the upthrow side of the Para Fault here, nor the evidences of Quaternary fault-displacement. Stratigraphic relationships of this distinctive Middle Pleistocene calcrete were worked out by Firman (1967a,b; 1969b, 1973), and it was recently fitted into a provisional chronostratigraphic framework by the writer (in Twidale et al., 1978). On the basis of palaeomagnetic results from the southeast of S.A. first reported by Cook et al. (1977), and confirmed recently in more detail by Idnurm and Cook (1980), this calcrete was dated approximately 600 000 to 700 000 years B.P., contemporaneous with glacial climatic stages 16-18 (Shackleton and Opdyke, 1973) which followed the Brunhes/Matuyama magnetic reversal. Normal movement of several metres on the main Para Fault at North Adelaide can thus be demonstrated as having occurred post-Ripon Calcrete, that is within about the last half-million years.

At the same locality in North Adelaide, a wedge of river gravel three to four metres thick and 130 m in length, occurs only on the downthrow side of the fault, where it rests on Ripon Calcrete. This gravel is impregnated and capped by the Bakara Calcrete (Figs 33,34), an uppermost Middle Pleistocene soil-stratigraphic unit which is distinctly younger and less consolidated than the Ripon Calcrete (Firman, 1963, 1967b, 1969a,b; 1973, 1979; in Daily et al., 1976). The gravel, in its spatial relationships, its thickness, and its well-rounded quartz and quartzite clasts (including cobbles up



Figure 29. View S.E., Jan. 1980, showing Torrens Rd (Renown Park - Ovingham) rising up the Para Fault Scarp towards the N.N.W. corner of the City's North Parklands; topographical relief is about 30 m.



Figure 30. View N.E., Oct. 1980, looking up the slope of the Para Fault Scarp, North Adelaide, showing hard and massive Ripon Calcrete exposed on the western (downthrown) side of the fault, in a drain between Mildred Rd and the Municipal Golf Links.

to 12 cm), is thus comparable with the lower part of the Telford Gravel (Firman, 1967a,b), which has been described from outwash fans flanking the highland margins of the Flinders-Olary and Mt Lofty Ranges.

Such high-energy, erosional, outwash gravels probably resulted both from renewed uplift of highland blocks, and from glacio-eustatic lowering of the base-level of erosion. Assuming that the calcreted scarp-foot gravels at North Adelaide resulted at least in part from relative uplift of the Para Block along the main Para Fault, this episode of reactivation can be dated with reference to the age of the Bakara Calcrete. The youngest phase of the Bakara Calcrete, besides its effect on Telford Gravel and equivalents, also modified and encrusted the Glanville Formation (Firman, 1966; Ludbrook, 1976) which was deposited during the Last Interglacial High Sea Level. There is a general consensus that this latter event occurred about 120 000 years ago (e.g. Veeh, 1966; Gill, 1971; Chappell, 1974, 1976; Bowler, 1976; Von der Borch et al., 1980). Granted the accepted temporal connection between glacial maxima, distribution of loess, and formation of pedogenic calcrete, the next episode of calcrete formation was the penultimate glacial maximum, climatic stage 4, dated 64000-75000 years B.P. by Shackleton and Opdyke (1973). Hence this was suggested as the age of youngest Bakara Calcrete by the writer (in Twidale et al. 1976, table 1); and it gives a minimum age indication for faulting associated with the calcreted gravels at North Adelaide.



Figure 31. As for Fig. 30, but closer view of hard and massive Ripon Calcrete exposed in drain between Mildred Rd and Municipal Golf Links, North Adelaide.



Figure 32. View S.E., Jan. 1980, from Bonython Park, West Parklands, in the Para Fault Zone between the West Para Fault and the main Para Fault, looking across the River Torrens towards Adelaide City and Mt Lofty.



Figure 33. Calcreted gravel (Bakara Calcrete, Telford Gravel correlative), Middle Pleistocene; on downthrow side of main Para Fault, Para Fault Scarp; view southeast, Oct. 1980, in drain between Mildred Rd and Municipal Golf Links, North Adelaide; hammer is 33 cm high; note clearly marked zone of reworked calcrete pebbles, possibly representing Pooraka Formation.



Figure 34. As above, but another, closer view of the calcreted gravel profile, showing poorly-sorted, fluviatile mixture of sand, pebbles and cobbles (to 12 cm) more or less rounded and lime-coated; clasts are mostly quartz and quartzite.

There are striking similarities between the displacement of Ripon Calcrete by the Para Fault at North Adelaide, and its analogous displacement by the Morgan Fault on the opposite, eastern side of the Mt Lofty Ranges, as recorded by Firman (1973, p. 33). At the present preliminary stage of investigation of the North Adelaide locality, and largely because of inadequate exposure, it is not yet possible to determine whether Bakara Calcrete and the younger Quaternary units present (such as the uppermost Pleistocene Callabonna Clay) are displaced by the main Para Fault there, or drape over it continuously as they are reported to do over the Morgan Fault. Further study of this important site will proceed, and will be published in due course.

However, in a traverse crossing the Para Fault further north, at Ingle Farm, Firman (1969b) indicated that the Bakara Calcrete is cut off by the fault. He also observed that 'later faulting and renewed alluviation during the Upper Pleistocene is recorded by Pooraka Formation'. This suggests that the Para Fault was active a few tens of thousands of years ago (Lindsay in Twidale et al., 1976, table 1).

It is difficult to demonstrate displacement of still younger units by the Para Fault. In one approach, we start with the fact that geological cross-sections through the Adelaide City area reveal the present River Torrens to be incised within a wider and deeper ancestral valley containing alluvial deposits which, in general, fine upwards from basal gravel and sand, to silt and clay. An excavated section near Brougham Place, North Adelaide, described by Allchurch (1967a) and Firman (1979, Fig. 1), showed that at this locality the valley-fill comprises:

4. Topsoil of Recent brown silty sand;
3. Callabonna Clay, a thin (¼-½ m) marker-bed of dark red-brown clay, regarded as uppermost Pleistocene (Firman, 1970, 1973; in Daily et al., 1976);
2. The Loveday Soil (Firman, 1969, a,b; 1973; in Daily et al., 1976), lime nodules in calcareous clay; at the top of
1. Pooraka Formation, brown clay, silt, and sand.

Although detailed consideration is beyond the scope of this thesis, there are indications (for example, in the Morphett St and Victoria Bridges cross-section, Plan 15, bore 14) that the more recent cut and fill of the River Torrens truncated the Upper Pleistocene units: Pooraka Formation, Loveday Soil, and Callabonna Clay. Truncation of the first two units may have been largely the result of glacio-eustatic lowering of the base level of erosion during the last glacial maximum (Lindsay, table 1, in Twidale et al., 1978), but this is unlikely to account for incision of the Callabonna Clay, which is a post-glacial unit. If incision of the Callabonna Clay was even partly due to uplift of the Para Block, it would be evidence for activity on the Para Fault within the last 10 000 years. However this line of argument is admittedly weak and inconclusive, needing further detailed stratigraphic studies of these Upper Pleistocene units.

On geomorphological considerations, where the Torrens Valley cuts through the Para Fault Zone (Plan 5) topographic contours show that the northern valley scarp south of Strangways Terrace is truncated quite sharply by the main Para Fault Scarp, while the River Torrens makes two sudden northerly bends in the Para Fault Zone. These features support the idea

of relatively recent activity in the fault zone. However, where the River Torrens terraces cross the fault zone, displacements have not yet been recognised, and this could imply that significant Recent movement has not taken place. On the other hand, the whole area has been landscaped into parks and gardens over many years (Fig. 32), and small displacements of river terraces might have been obscured or obliterated. It is interesting to recall that forty years ago Fenner (1939) concluded that the 'dirt scarp' (that is, the East Para Fault scarp, from the corner of North and West Terraces to Keswick) 'is an undoubted fault scarp ..... the continued existence of which is clear evidence of faulting and uplift in Recent times'.

The difference in elevation (Reduced Level, Australian Height Datum) between matching horizons across the Para Fault Zone increases with age as shown in the table below. The table gives the difference in elevation between a stratigraphic horizon in Croydon-2 bore and the corresponding horizon at its highest known point on the Para Block, in North Adelaide. In the case of 'base Ruwarung Member' and 'base Chinaman Gully Formation', the elevations in North Adelaide are approximations derived from projections on Cross-section C-D (Plan 7). Time (millions of years; Ma) is after La Brecque et al. (1977), Hardenbol and Berggren (1978).

TABLE

MAXIMUM DIFFERENCE IN ELEVATION OF MATCHING HORIZONS ACROSS THE PARA FAULT ZONE, CROYDON BLOCK TO PARA BLOCK, ADELAIDE CITY AREA.

Horizon	Approx. Age (Ma)	Diff. in elevation (m)
Present topographic difference		30
Top Hallett Cove Sst./Burnham Lst. (base Pleistocene)	$1^{3}/4$	130
Pre-Pliocene unconformity (Miocene/Pliocene)	5	200
Base Ruwarung Member (P.W.F.) (Eocene/Oligocene)	37	440
Base Chinaman Gully Formation (Upper Eocene)	38	490
Base Gull Rock Mbr (B.P.F.) (Upper Eocene)	39	540
Base South Maslin Sand (top Middle Eocene)	41	585
Base Clinton Formation (high Middle Eocene)	42	615

This difference in elevation of matching horizons is caused partly by tectonic separation across the Para Fault Zone; and partly by thicker sedimentation on the Croydon Block, which in turn also implies bathymetric or topographic relief across the fault zone. Most of the Tertiary units are at least twice as thick in the Croydon bore as on the Adelaide platform of the Para Block. Exceptions are the Gull Rock Member, of comparable thickness in each setting; and the Chinaman Gully Formation, which tends to be thicker beneath Adelaide City. The Table above shows that nearly one-third of the total vertical separation was attained by the end of the Eocene, in about five million years (42 to 37 Ma). Another third of the total separation has developed since the Miocene, during approximately the last five million years. It is clear that the intervening 30 Ma (Oligocene-Miocene) averaged a much slower rate of separation. When allowance is made for undoubted epeirogenic activity in the Late Miocene, the relatively slow separation across the Para Fault Zone in the Oligocene to Middle Miocene is even more striking. However direct comparison of units deposited during this time becomes impossible, because of their removal by erosion, or their non-deposition, on the Para Block. Of all the Oligocene-Miocene units, only the oldest, the Ruwarung Member, is now present on the Para Block beneath the City, and that only beneath the southern City limits as an eroded wedge-out with a maximum observed thickness of 12 m (Plans 8,13). On the Mile End Block the Ruwarung Member is complete, and 25 m thick (Plan 14); while in Croydon-2 bore it attains a thickness of 70 m (Plan 29),

which suggests growth-fault conditions on the Para Fault Zone during the Oligocene. Above the Ruwarung Member, successively younger units of Port Willunga Formation are preserved on the Mile End and Thebarton Blocks (Plan 16) which link the Croydon sequence with that on the Para Block.

In summary, there are stratigraphic indications of movement on the Para Fault Zone west of Adelaide City in the Middle and Late Eocene, the Oligocene, the Late Miocene, the Pliocene, and the Quaternary. The component faults are good examples of normal 'growth faults', having developed during sedimentation, resulting in greater stratigraphic thicknesses on their downthrown sides.

Epicentres of several low-magnitude earthquakes (maximum Richter 3.2) appear to be associated with the Para Fault Zone (Selby and Lindsay, in press), suggesting that weak activity continues to the present.

Plan 26 shows Bouguer Anomaly contours of the Adelaide area in relation to major geological features. Bouguer Anomaly contours are from the Adelaide map sheet (1978, no. 78-968), Gravity Atlas of South Australia, 1:100 000 series, Geol. Surv. S. Aust. The steep gradient associated with the Para Fault/Para Fault Zone is the outstanding linear feature of the map. A prominent trough of negative anomaly borders the fault zone to the north and west of Adelaide City, and is considered to represent the belt of thickest post-Adelaidean sediments, as penetrated by the Croydon-2 and Allenby Gardens-1 bores (Plans 4,5).

The Golden Grove-Adelaide Embayment

Plan 4 shows the location, and the structural and geological setting of the City of Adelaide at the southwestern end of the Golden Grove-Adelaide Embayment. Several views of the City in this setting are shown in Figures 2,4,5, and 35-39. On the east, the embayment is bounded in a general sense by the arcuate Eden Fault Zone and scarp which comprises the western edge of the Mt Lofty Ranges (Figs 9,10,19,20,40,41). The eastern side of the embayment occupies a fault-angle depression (Plan 17). Detailed and somewhat problematical relationships in the vicinity of this fault zone at the Highbury East sand quarries, were discussed earlier. The northern margin of the embayment is drawn around the eroded edge of Cainozoic sediments which wedge out against the tilted Para Block. The divide of outcropping Adelaidean bedrock which separates the northern half of the Golden Grove-Adelaide Embayment from the Adelaide Plains Sub-Basin, is two to three kilometres wide and extends 11 km down the western side of the Para Block from Hillbank to Northfield (Figs 15,16,28,42,43). Over this distance, the 'peneplaned' and partly dissected surface of this divide slopes gently south from a maximum elevation of 225 m in the north, between Golden Grove and Hillbank, to a maximum of 90 m in the south, near Yatala Prison, as indicated in the terrain analysis by Sprigg (1945). Looking east from the Northern Adelaide Plains, a good view can be obtained of the south-tilted Para Block and the bordering Para Fault scarp (Figs 27,44,45).



Figure 35. View S.S.W., Oct. 1980, of Adelaide City, the eastern Golden Grove-Adelaide Embayment, the arcuate Eden-Burnside Fault Zone and scarp (western edge of Mt Lofty Ranges), Readymix Riverview quartzite quarry (Adelaidean Stonyfell Quartzite) in foreground, and River Torrens and Gorge Road behind.



Figure 36. View S.W., Oct. 1980, from the same point as Fig. 35, looking down the River Torrens valley to Adelaide City, across the Golden Grove-Adelaide Embayment.



Figure 37. View S.W., Jan. 1980, from Anstey Hill, looking down the River Torrens valley and Golden Grove-Adelaide Embayment to Adelaide City; note youthful dissection of the western edge of the Mt Lofty Ranges.



Figure 38. View S.W., Oct. 1980, from Eden Fault Scarp above Readymix Highbury East sand quarries, looking down River Torrens valley and Golden Grove-Adelaide Embayment to Adelaide City.



Figure 39. View south, Jan. 1980, from Milne Rd, Modbury North, above N.W. margin of the Golden Grove-Adelaide Embayment, looking across the embayment to Adelaide City and the distant Eden Fault Scarp.



Figure 40. View south, Jan. 1980, from Modbury Heights shopping centre, above the N.W. margin of the Golden Grove-Adelaide Embayment, looking down Ladywood Drive past Tea Tree Plaza and Modbury Hospital, across the embayment to the Eden Fault Scarp, the Mt Lofty Ranges, and Mt Lofty.



Figure 41. View from Mt Osmond, Oct. 1980, looking N.N.E. up the Golden Grove-Adelaide Embayment, which is enclosed by the complex scarp of the Eden Fault Zone in the east, and the bedrock 'high' ridge on the Para Block in the N.W. (distant left), the two meeting at the head of the embayment (distant centre).



Figure 42. View N.W., Oct. 1980, from hill above Highbury East sand quarries, showing the Golden Grove-Adelaide Embayment (topographic depression) enclosed in the foreground by the Mt Lofty Ranges, and in the background by the bedrock 'high' ridge on the Para Block which rises gently to the north; Anstey Hill, Lower N.E. Rd, and the point from which Fig. 37 was taken, are on the right, behind the tree in the foreground.

The depositional limits of sedimentation on the Para Block are not known precisely. Undoubtedly some Cainozoic deposits have been eroded from the Block, but to what extent is speculative, particularly because it is known that intermittent block-faulting and associated tilting have occurred. If the ?Eocene sands preserved beneath a Plio-Pleistocene duricrust at 'The Gun Emplacement' were to indicate an original 'minimum upper level of Eocene beds' right across the Para Block, as suggested by Twidale (1976, p. 53), then it is likely that these and other deposits would have once covered the whole Para Block as far north as Golden Grove, because the sands at 'The Gun Emplacement' attain an elevation of about 215 m (Fenner, 1939; Sprigg et al., 1951). However, this ignores the depositional dip of such piedmont sands. Fenner (1939), who had earlier considered and rejected the model revived by Twidale, attributed the elevation of the Tertiary sands to post-depositional uplift of the western blocks of the Mt Lofty Ranges, particularly during the Pleistocene. That there has been uplift on the Eden Fault Zone in the vicinity, involving the tilting of these sands, is evidenced by the exposures at the Highbury East Readymix sand quarry, discussed earlier. The argument cannot be pursued further here, but a compromise seems to be necessary. For example, Stuart (1969) in a series of sketches of Tertiary palaeogeography for the St Vincent Basin, depicted 'palaeocapes' of bedrock as persisting in recognisable form between the eastern embayments due to intermittent faulting, but affected by marine inundation to a varying extent.



Figure 43. View S.S.W. from Black Top Road, east of Hillbank, Nov. 1980, looking towards the City of Adelaide down the dissected but generally south-sloping divide at the western edge of the Para Fault Block, separating the Golden Grove-Adelaide Embayment (left, concealed) from the Adelaide Plains Sub-Basin (right distance). Yatala Prison is behind the pylon on the right; Mt Lofty Ranges extend from left to centre distance.



Figure 44. View east, Oct. 1980, from Port Wakefield Rd, by I.C.I. Salt Pans, Cavan, looking across The Levels (part of Northern Adelaide Plains) to the Para Fault Scarp (Para Hills-Ingle Farm), the south-sloping Para Fault Block, and beyond, the Mt Lofty Ranges (Anstey Hill, centre; Torrens Gorge, right of centre).



Figure 45. View E.S.E., Nov. 1980, from similar locality to Fig. 44, showing The Levels, Para Fault Scarp (Para Hills-Ingle Farm), south-sloping Para Fault Block, and Mt Lofty Ranges (Torrens Gorge at centre, Black Hill area on right).

For the purposes of his report, Miles (1952, p. 20) treated as part of the Adelaide Plains the area which is shown here as the southern half of the Golden Grove-Adelaide Embayment, south of a line joining Yatala Prison and the Hope Valley Reservoir (Fig. 46). In a similar manner, the writer formerly included the Adelaide City area within the Adelaide Plains Sub-Basin (Lindsay, 1969), but has now come to attach more importance to the different structural setting of the Para Block from Adelaide City northeastwards. Besides the obvious topographic separation caused by the Para Fault Zone as far south as Adelaide City, the writer has treated already the notable thinning of Cainozoic units on to the Para Block as compared with the Croydon Block, a thinning which is linked to the 'growth fault' history of the Para Fault Zone, and to a reduction in Tertiary marine influence up the embayment.

The term 'Adelaide Embayment' as used by Stuart (1969, map 4) comprised mainly the Para Block from the City of Adelaide southwestwards to the coast. In this area there is little if any surface expression of the Para Block, and the subsurface Tertiary sequence is comparable with that of the Adelaide Plains, though displaced by faulting (Lindsay, 1969). The writer has therefore continued to regard this area as the southernmost part of the Adelaide Plains Sub-Basin, an approximate boundary with the Golden Grove-Adelaide Embayment being drawn as shown in Plan 4. As thus defined, the embayment compares in shape with the Willunga and Noarlunga Embayments, and is intermediate in area (see Plan 2).



Figure 46. View west, Oct. 1980, from the western edge of the Mt Lofty Ranges above Readymix Highbury East sand quarries, looking across the Golden Grove-Adelaide Embayment to the distant Adelaide Plains. On the left is Hope Valley reservoir, and Modbury Hospital is at the right edge of the photo. Yatala Prison and its paddocks are distant centre, on the south-sloping divide which separates the Para Block from the Adelaide Plains, but which can only be discerned with difficulty from this angle. Beyond, in the Adelaide Plains, are the I.C.I. salt pans, Torrens Island power station (with twin smokestacks), and installations at Port Adelaide (centre horizon).

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Plan 4 includes stratigraphic summaries of representative boreholes in the Golden Grove-Adelaide Embayment. Brown coal (lignite) is apparently widespread in the embayment, and is generally identified as CLINTON FORMATION (which see for further discussion). In the Adelaide City area, and towards the eastern and western margins of the embayment, Clinton Formation overlies weathered bedrock. However the Devitt bore, Payneham South (at 63.1-67.1 m), and the E. & W.S. Springbank bore, Clapham (at 163.4-167.6 m), each penetrated lignites which overlie Blanche Point Formation and which appear to correlate with CHINAMAN GULLY FORMATION (which see). SADME Hazelwood Park-1 bore (Plan 4; see Eberhard, 1980) near the southeastern margin of the embayment, also penetrated a 4 m band of black lignitic clay (134-138 m) which is overlain by Tertiary sand, and underlain by at least a further 57 m of Tertiary sand. After palynological examination of a core of this lignitic clay, Harris (1980) has identified it tentatively as a time-equivalent of Chinaman Gully Formation. The Barnes bore, Glynde, penetrated a bed of lignite at 36.6-37.8 m overlying at least 28 m of Tertiary 'dark sands with ironstone seams' (Miles, 1952, index bore 299). This lignite is probably Chinaman Gully Formation also. Thus there are probably two main stratigraphic levels at which lignite is developed in the embayment, the lower correlated with Clinton Formation, Middle to Upper Eocene; and the upper with Chinaman Gully Formation, higher in the Upper Eocene (Lindsay and Harris, 1979). Where only one lignite is present, at or near the base of the Tertiary sequence, as in

the Hope Valley Coalfield, it is identified for the present as Clinton Formation; but it is realised that further palynological studies could demonstrate wider development of the Chinaman Gully lignite.

Fossiliferous TORTACHILLA LIMESTONE has been reported from as far up the embayment as Campbelltown, in a well at a depth of 18 m (Glaessner, 1955, p. 354). BLANCHE POINT FORMATION in sandy, marginal-marine facies, extends as far up the embayment as the Hope Valley Reservoir (Wade and Lindsay, 1969, fig. 1). Stuart (1969, p. 71) reported that the 'Banded Marls' (i.e. GULL ROCK MEMBER) 'extend north-eastwards from the city of Adelaide to just south of Hope Valley Reservoir where they overlap older Tertiary sediments onto basement'. Neither PORT WILLUNGA FORMATION, represented by its basal unit the ALDINGA MEMBER, nor SOUTH MASLIN SAND, have been identified further up the embayment than the eastern City limits, where their presence in the old Kent Town bore has been inferred. However in SADME Hazelwood Park-1 bore (Plan 4; see Eberhard, 1980) core of carbonaceous sand at 116 m has undergone palynological examination, and has been identified tentatively as a time-equivalent of the Aldinga Member (Harris, 1980). A pyritic quartz sand at 101 m containing pyritised ?Turritella (the only horizon in the bore known to contain shelly fossils) represents the edge of a marine transgression and is also considered to be a correlative of the Aldinga Member. Marine Pliocene HALLETT COVE SANDSTONE is not known from further up the embayment than the Adelaide City area, as shown in Plan 24. The distributional limits of the mid-Tertiary units and their marginal equivalents have

not been studied in detail, and are not known well enough to construct meaningful distribution maps or palaeogeographic reconstructions for the embayment.

Economically important non-marine sands which crop out in the northeastern extremity of the embayment from Athelstone and Highbury to Golden Grove (Figs 2, 19-25,38,47), have been all mapped as NORTH MASLIN SAND by Forbes (1980). Olliver and Weir (1967, p. 28) tentatively correlated these sands of the 'Golden Grove-Highbury Basin' with North Maslin Sand, but they suspected diachronism involving convergent sand facies beyond the limits of marine transgression. It remains to be seen whether palynological studies will provide proof of this. A recent drilling programme by SADME culminated in a well-documented report by McCallum (1978) on the resources of construction materials (including Tertiary non-marine sand and clay) in the Golden Grove area north of the Yatala Vale Road, at the head of the Golden Grove-Adelaide Embayment (Fig. 2, Plan 4). More than 80 of the boreholes made significant intersections of Tertiary sediments: several proved thicknesses in excess of 30 m. No samples were examined by the writer. Tertiary materials described by McCallum included: fine to coarse-grained quartz sand 20 to 30 m or more thick, containing clay lenses, and widespread throughout the basinal area; fine clayey and silty sand which is up to 20 m thick in the east, but thins to the west and north; and plastic clays which infill depressions towards the south of the area, are up to 25 m thick, and which occasionally contain lignitic layers dateable by palynology. One such lignitic clay, from bore GG-46, at 19-21 m (Fig. 4) was determined as Middle Eocene (Hos, 1977). This date supports the suggestion that the

associated sands correlate with North Maslin Sand. McCallum envisaged fluvio-lacustrine environments of deposition for the Eocene sediments. He reported that the sands coarsen towards a centrally-situated, north-south channel; and also tend to coarsen in a northerly direction, indicating movement of sediment southwards.

Proterozoic BEDROCK crops out in the valley of the River Torrens as far down the embayment as Campbelltown (Sprigg et al., 1951; Forbes, 1980). The many water-bores which were drilled in this market-gardening area, and were recorded by Miles (1952), indicate bedrock at relatively shallow depths. This is particularly so near the River Torrens because of erosion. Miles logged Cainozoic cover up to 27 m thick in Windsor Gardens (Miles index bore 279), up to 37 m thick in Klemzig (Miles bore 241), and up to 58 m thick in Campbelltown East (Miles bore 247).

The thickest Cainozoic sequences in the embayment are found near the southeastern margin, in the fault-angle depression against the Eden-Burnside Fault Zone (Plans 4, 17). Morialta High School bore penetrated 117 m of largely unfossiliferous Cainozoic clay, gravel, silt, and sand, which are difficult to correlate apart from the basal 15 m of lignitic Clinton Formation. The old M.T.T. bore, Kensington Gardens, penetrated 212 m of Cainozoic clay, gravel, and sand, which again are difficult to correlate by inspection of logs, except for the basal, lignitic, Clinton Formation. The recently-completed SADME Hazelwood Park-1 bore bottomed at 195 m, still in Tertiary pyritic quartz sands (Eberhard, 1980); while SADME Myrtle Bank-1 bore bottomed at 163 m, also in Tertiary sands.

On the Burnside Splinter Block, between the Burnside and Eden Faults, the Waite Institute bore at Urrbrae (Plan 4) proved 52 m of probable Quaternary clay and gravel before entering bedrock of Adelaidean quartzite.

In the Adelaide City area, the thickest Cainozoic sections are at the southern City limits. SADME South Parklands bore (Plans 4,27) entered weathered bedrock at 112 m, while the Victoria Park Racecourse bore (Ref. bore 49; Plan 5, Appendix B) probably bottomed in or near weathered bedrock at a depth of 141.7 m.

BEDROCK

The term 'bedrock' is used for solid rock underlying soft sedimentary strata (Rice, 1954) but is relative in its application, needing definition in a particular area. Beneath the City of Adelaide, notwithstanding hard bands in Tertiary units such as Hallett Cove Sandstone and Blanche Point Formation (Gull Rock Member), bedrock in the present study comprises the much older rocks which underlie the Tertiary sequence and are almost certainly Adelaidean, Late Precambrian. So far as is known, no rocks of intermediate age intervene beneath the City, although a thick pre-Middle Eocene, post-Delamerian profile of bleached and weathered bedrock is typically present; and 81 m of gravelly sands and clays at the bottom of Croydon-2 bore are regarded doubtfully as Permian (Steel, 1962a,b; Lindsay, 1969; see Plans 4,16,17, 29).

There are no outcrops of bedrock within the City area. The nearest are about 4 km southeast at Glen Osmond, on the Eden Block; and 4½ km northeast, in the River Torrens Valley on the Para Block at Campbelltown. Both are mapped as Adelaidean, Burra Group (Forbes, 1980), comprising siltstone and slate with quartzite and dolomite bands. These same lithologies appear to be represented in borehole intersections within the Adelaide City area.

In Plan 18, the various intersections of bedrock beneath the City are plotted and contoured with respect to Australian Height Datum. The unconformity surface slopes gently south and east from a 'high' beneath Montefiore Hill, North Adelaide, and is displaced about 50 m down to the west by the East Para Fault.

There are indications that bedrock ridges extend south and east from the Montefiore Hill 'high'. The presence of this buried bedrock 'high' beneath the present topographic 'high' of North Adelaide is noteworthy but unexplained; it appears not to result from a particularly resistant lithology, since the bedrock intersected beneath Montefiore Hill is only siltstone (Ref. bore 25, see below).

Reference bore 25 was examined in detail by Allchurch (1966), and also by the writer, who contributed a palaeontological Appendix to Allchurch's report. Continuous tube-cores were available from this engineering foundation test-hole, and fortunately so, since it was possible to distinguish Eocene sedimentary clay from underlying clay and silt representing completely weathered siltstone bedrock. The basal unit of the Tertiary sequence is a clay included here within Clinton Formation, and comprising pale grey and pale brown highly plastic clay with abundant spherulitic pellets of siderite (Scott, 1966). These siderite spherulites are discussed further under CLINTON FORMATION. Small carbonaceous and woody fragments, which are present in the clay, are brown or black in colour, and are sometimes intimately impregnated and encrusted with pyrite and/or siderite. Pyritic aggregates of spherical or framboidal habit are up to 2 mm in diameter. A small proportion of sand and grit is present. Bedding is generally indistinct, but is shown to be near-horizontal by faint colour changes and occasional sandy lenses (cf. Mason, 1967). Below a depth of 35.0 m (115 ft), Allchurch logged 'a few indistinct tight vertical joints' which seem to relate to a pattern of vertical jointing in the underlying weathered

siltstone bedrock. At 35.7-36.0 m (117-118 ft) the sand-sized fraction consists almost entirely of sideritic aggregates, and lacks carbonaceous material or pyritic grains. In downhole sequence, the first small fragments of weathered, orange, micromicaceous siltstone are present at this level. A change in colour from chocolate-brown to brighter orange-brown is noticeable between 35.7 and 37.3 m (117-122½ ft) in samples disaggregated and washed for microscopic examination. The Tertiary/bedrock contact is put at about 36.0 m (118 ft), which is a little higher than the figure of 37.7 m (123½ ft) originally logged by Allchurch. However, disaggregated and washed samples from 37.0-37.3 m (121½-122½ ft) and 38.1-38.4 m (125-126 ft), contain abundant small fragments of orange micromicaceous siltstone (together with frequent sideritic aggregates and joint-coatings) and are evidently from bedrock. Similar, completely to highly weathered siltstone was intersected to total depth at 56.4 m (185 ft), a thickness of at least 20.4 m.

Other features of this well-documented bedrock interval, logged by Allchurch, include:

-- engineering soil-properties of silt, with high plasticity; very stiff to hard; moisture content much less than the plastic limit;
-- colours of pink, yellow, and red, with pale green mottling; prominent, near-horizontal bedding, with red or yellow laminae generally 1-2 mm thick, and rare sandy lenses;
-- two sets of near-vertical joints approximately at right angles, with joint-faces often stained green or brown;

-- some joints below 52.7 m are occupied by quartz veinlets;

-- during continuous push-tube coring, the standard penetration rate slowed gradually from 6-10 blows/foot between 120-153 ft (36.6-46.6 m), to 15-23 blows/foot between 153-174 ft (46.6-53.0 m), to 23-60 blows/foot between 176-185 ft (53.6-56.4 m).

This case shows that where bedrock is a deeply and completely weathered pelite, it may have been entered in a borehole long before typically hard bedrock lithologies become obvious, the contact being demonstrable by subtle changes not easily recognised during drilling. Thus in the case of an old bore, drilled in 1912-1914 at the Adelaide Railway Station-Master's residence, for which the only log-data available consist of a recorded comment: 'into black slate at ?250 ft' (76.2 m), it is probable that this represents a maximum depth to bedrock, and that a profile of weathered bedrock was penetrated for some thickness above. This is apparent when the bedrock intersection is plotted in relation to better data (Plan 18: recorded as 'by -48').

The SADME West End Brewery bore (Ref. bore 10, Plan 28) which was drilled in 1976 and examined in detail by the writer, penetrated a bleached and weathered bedrock profile for 24 m. The main lithological and structural features are described in Plan 28. In this bore, as at Montefiore Hill, the Tertiary/bedrock unconformity is a clay/clay contact, the basal unit of the Eocene sequence being again, a pale grey 'underclay', which here occupies the bottom 7 m of the otherwise lignitic Clinton Formation. Figure 47 illustrates completely weathered bedrock core from a depth of 90 m (just



Figure 47. Completely weathered bedrock, Adelaide City area; SADME West End Brewery bore, core at 90.0-90.3 m; true colour is pale grey with minor brown iron-staining; the rock is mostly clay, but there are indications of the abundant sand-sized aggregates (glaebules) of siderite and crystallised pyrite; scale is in inches (above) and centimetres (below).

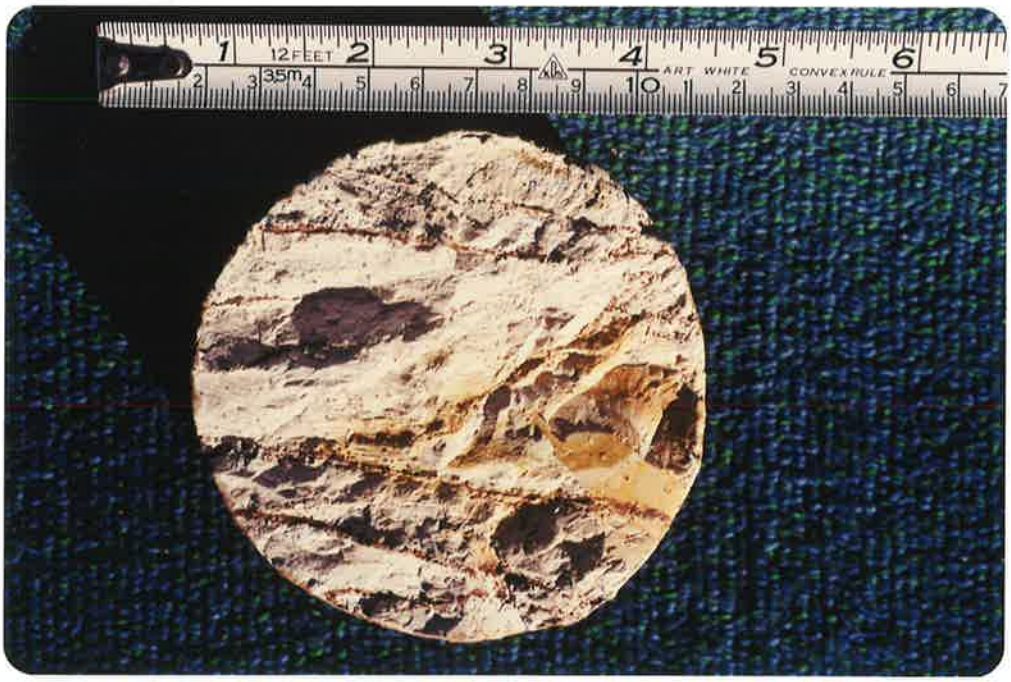


Figure 48. As above, but core at 95.0-95.3 m; true colour is pale grey with brown iron-staining; note the development of vertical jointing which is filled with partly-oxidised, granular to platy siderite, together with pyrite.



Figure 49. Bedrock, Adelaide City area; SADME West End Brewery bore, bottom-hole core at 112.0-112.3 m; true colour is pale greyish green; a tough, foliated silty shale containing a bright green phyllosilicate mineral, and finely-divided sericite flakes.

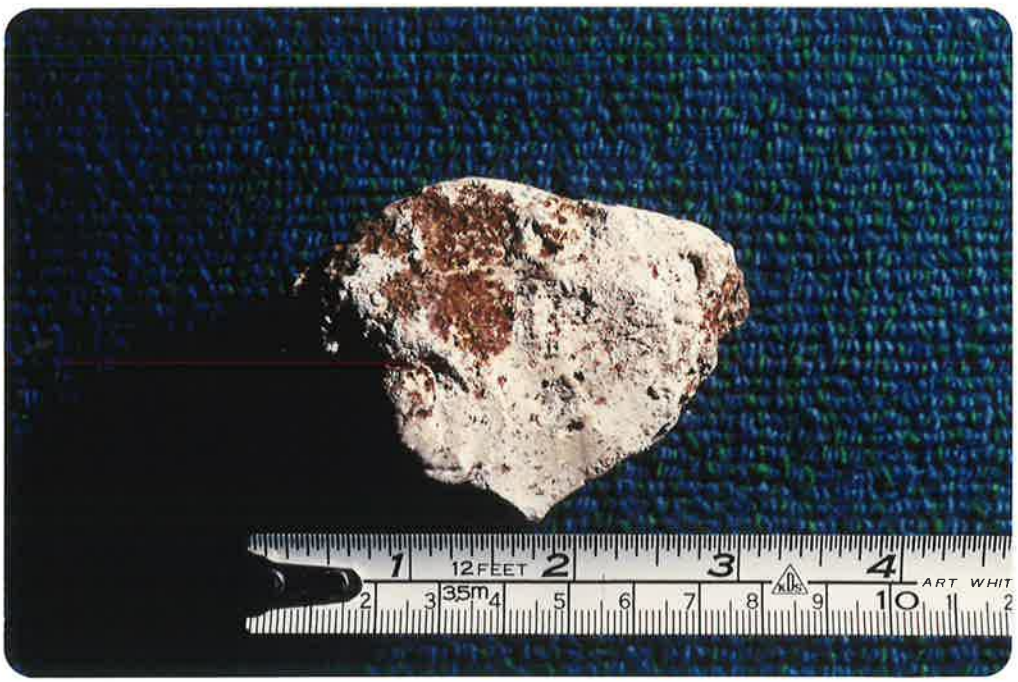


Figure 50. Completely weathered bedrock, Adelaide City area; SADME South Parklands bore, core at 115.0-115.3 m; true colour is off-white/brown; rock is mostly clay, with speckling due to sand-sized pyrite and siderite aggregates; the prominent brown patches are oxidised ferruginous material.

below the unconformity). Quartz veinlets were preserved in this clayey material. Cores also showed that siderite and pyrite as spherulites/glaebules or platy joint-fillings, continued down the weathered profile more than 10 m below the unconformity. A vertically-jointed core from 6 m below the unconformity is illustrated in Figure 48. A piece of the freshest-looking green rock from the bottom-hole core at 112 m (Fig. 49), underwent petrographic examination by Radke (1978), whose report is reproduced in Appendix C. He described the rock as a silty shale, with well-developed foliation: 'a fine-grained, argillaceous sediment which has suffered some recrystallization to produce a bright green phyllosilicate and finely divided sericite flakes'.

The SADME South Parklands bore (Ref. bore 41, Plan 27) which was also drilled in 1976 and was examined in detail by the writer, bottomed after intersecting 11 m of bleached slaty bedrock, now highly weathered to clay. The lithological succession is summarised in Plan 27. Here also, at the southern City limit, there is a clay/clay unconformity, a thin, white, underclay at the base of Clinton Formation separating weathered bedrock from Clinton lignite. A piece of completely-weathered bedrock core from 3 m below the unconformity, is illustrated in Figure 50. On disaggregation, the now-clayey rock is seen to contain frequent white to pale grey platy remnants of completely weathered slate. Abundant pyrite octahedra and frequent pyritic aggregates are present, together with abundant sideritic glaebules and aggregates, some oxidised to brown ferruginous material in prominent patches.

In the Australian Postal Institute bore, west of West Terrace (Ref. bore 32, Plans 4,5), there is also a clay/clay contact at the bedrock/Tertiary unconformity, but only sludge samples were taken. The sequence into bedrock is given below from the driller's log, and from the writer's microscopic study of the washed sludges.

91.1-96.0 m: driller - 'stiff dark grey clay'; sandy, pyritic, carbonaceous; woody fragments; Clinton Formation. 96.0-100.6 m driller - 'white pipe clay' residues contain abundant subspherical glaebules/spherulites of siderite and pyrite; these grains become larger with depth, reaching 1 mm diameter; white underclay of Clinton Formation.

..... Inferred Tertiary/bedrock unconformity.....

100.6-109.4 m: driller - 'white pipe clay'; silty clay, white, with abundant grey fragments of laminated calcareous siltstone to shale; these are more or less weathered, soft to hard; pyrite and siderite aggregates; platy sideritic joint-fillings.

109.4-110.3 m: driller - 'hard bar'; limestone, white and brown, sideritic; with clay; perhaps a calcite-siderite vein.

110.3-112.8 m (T.D.): driller - 'white and pink clay'; the washed residue contains abundant fragments of finely crystalline limestone, as above; abundant aggregates of brown siderite; occasional platy quartz fragments apparently derived from quartz veinlets.

The white and brown sideritic limestone, possibly calcite-siderite vein material, appears distinctive.

Representative samples from the lower part of the old Kent Town bore (Ref. bore 31, Plans 4,5), logged by Tate (1882), have been studied microscopically by the writer. Beneath a thin sand considered to lie at the base of the Eocene sequence (Clinton Formation, or possibly North Maslin Sand correlative) the following lithologies occur;

93.0-109.7 m: log - 'kaolin clay, mixed with sand in the upper part, and sharp quartz grit in the lower'; stiff clay, off-white to pale grey and brown, sandy, with abundant very fine mica flakes; interpreted as a bleached and completely weathered micromicaceous sandy shale; angular gritty quartz and coarse mica flakes, also present, are interpreted as being derived from a quartz-mica veinlet.

109.7-113.1 m: log - 'decomposing feldspathic quartzite'; the sample is a white clay, with fragments of bleached and completely weathered sandy shale, seamed by siderite-calcite-quartz veinlets; abundant fragments of clay-quartz-siderite rock are present.

113.1-118.0 m: log-'decomposed slaty rock, quartz vein'.

118.0-125.3 m (T.D.): log - 'feldspathose-quartzite gritstone'; 'thinly-bedded fine-grained sandstone with talcose-slate partings'; this is a white to pale grey sandy and gritty clay, with seams of brown siderite and siderite-calcite-quartz; fine-grained siderite aggregates are disseminated through the clay; a bleached and highly-weathered, jointed and veined sandy shale (?slate).

These quartz-carbonate veins are similar to those observed in the A.P.I. bore. It is noteworthy that lead-silver mineralisation in the nearby Glen Osmond area (Brown, 1908; Sprigg, 1946; Forbes, 1980) is associated also with quartz-carbonate veins in calcareous slate (Glen Osmond Slate; Burra Group, Torrensian).

Enough examples have been given to demonstrate that beneath the Cainozoic 'overmass' of the Adelaide City area, bedrock of probably Adelaidean siltstone, shale, or slate, is profoundly bleached and weathered. This zone in the Kent Town bore, outlined above, is as much as 32 m thick. Eocene sedimentation commenced on "an extremely well developed 'base surface'" (Sprigg, 1946, p. 330). The bleaching and weathering occurred pre-Middle Eocene, and 'may be as old as Mesozoic in places' (Firman in Daily et al., 1976, p. 21).

On the Mile End Block, within the study area, Reference bore 51 (Plan 5) is the only one to intersect bedrock. Samples are not available for checking, but the log quoted by Miles (1952, p. 203) records 'dark grey sand' at 83.2-87.8 m (interpreted as Clinton Formation), 'white clay (decomposed slate)' at 87.8-96.9 m, and 'grey decomposed slate' at 96.9-97.5 m (T.D.). As shown in Cross-section R-S (Plan 14), completely-weathered bedrock may have been entered at 87.8 m.

On the Croydon Block, near Adelaide City, the old Croydon-2 bore (Plans 4,5,29) was considered for many years to have reached bedrock of 'sandstone and clay slate with quartz veins' at a depth of 2 262 ft (689.5 m) (Parl. Papers,

1893, p. 20, plan 4; Tate, 1898; Howchin, 1928, 1929), before bottoming at 2 296 ft (699.8 m). Miles (1952, p. 161) considered bedrock to have been entered earlier, at 2 242 ft (683.4 m) at the top of an interval 13 ft (4 m) thick, logged also as 'sandstone and clay slate' (Parl. Papers, 1893, plan 4). The sludges of this bore were lost for many years, but were found in 1960, and were studied by Steel (1962a). Between 2 035 ft (620.3 m) and total depth, he reported gravelly clay and sand, with rock fragments of various types including shale, phyllite, slate, fine-banded sandstone, fine-grained quartzite, schist, granite, and quartz-chlorite pegmatite. Considering this polymictic association to be typical of Permian glacigenes around the St Vincent Basin, he dated the interval Permian, but without palaeontological evidence (Steel 1962a,b). The writer, after an independent examination of the samples, has continued to treat the interval as doubtfully Permian (Lindsay, 1969; in Ludbrook, 1969, fig. 93; in Daily et al., 1976; see also Forbes, 1980). If so, of course, the Croydon-2 bore did not fully penetrate to Adelaidean bedrock.

As noted earlier (INTRODUCTION), SADME Allenby Gardens-1 bore was drilled to bedrock early in 1980, only 375 m WSW of the site of Croydon-2 bore (Plan 5). Despite being situated on the axis of the same negative Bouguer gravity anomaly (Plan 26), a bottom-hole core of quartzite (hard, banded to laminated, gently-dipping, greenish-grey),

presumably Adelaidean, was cut at a subsurface depth of only 617.5-618.4 m (Figs 51a-c); and the same lithology was entered at 608.5 m, according to the driller's log. At the time of writing, the well-completion report by the well-site geologist is still being prepared, and the writer has only had time to study a few samples, but there is no doubt of the surprisingly shallow bedrock intersection, more than 70 m shallower than the shallowest estimate for the Croydon-2 bore. There appears to be no 'Permian' in the Allenby Gardens-1 bore. If there is indeed a trough of Permo-Carboniferous glacigenes which was intersected by the Croydon-2 bore, its western wall plunges at least 90 m in the distance of 375 m from the Allenby Gardens-1 bore, as shown in Cross-section V-W, Plan 17.

Other bedrock lithologies encountered in Adelaide Plains boreholes, including possibly Cambrian carbonates, are summarised elsewhere by the writer (Lindsay, 1969, pp. 28-29).



Figure 51a.



Figure 51b.



Figure 51c.

Figure 51(a-c). Bottom-hole core, SADME Allenby Gardens-1 bore, depth 617.51-618.36 m below ground level, top of core is at top left (Fig. 51a); Feb. 1980; hard, gently-dipping quartzite, presumably Adelaidean, greenish-grey, banded to laminated; mostly fine-grained, with low-angle cross-bedding (trough and planar), and coarser 'lag' horizons.

Mason (1967) described in detail the nature of the Precambrian-Tertiary contact exposed in the Golden Grove-One Tree Hill area, at the northern extremity of the Golden Grove-Adelaide Embayment. Many features are comparable with those observed in borehole samples from the Adelaide City area, as described above. 'Yellow limonite nodules' noted by Mason in the Tertiary basal white clay, are probably oxidised spherulites of siderite and/or pyrite.

CORRELATIONS, ZONES, DATUMS, AND REGIONAL EVENTS

The chapters which follow this one treat the various stratigraphic units in an orderly manner including, where appropriate, a discussion of foraminiferal (or occasionally other) biostratigraphy, age, environment of deposition, and relevant contemporaneous regional to global events. However, some preliminary general comments need to be made at this stage, in order to set the scene for what follows.

While the emphasis is on the stratigraphy of the units as they are developed in the Adelaide City area, care is taken to relate the units to their type sections which in most cases are in the Willunga Embayment. The development of a unit elsewhere in the eastern St Vincent Basin, particularly in the Adelaide Plains Sub-Basin, is treated in sufficient detail to illustrate salient features of the lithology, distribution, thickness, biostratigraphy, etc.

Plan 3 comprises a summary correlation chart which relates the Tertiary sequence in the Adelaide City area (including the Para Fault Zone) with sequences elsewhere in the St Vincent Basin, and with Australian Stages, Epochs/Series, a selected modern geochronometric scale, and tentatively with relevant P./N. Zones. This interlocking framework was begun by plotting a linear geochronometric scale (Ma = megayears = by convention, millions of years before 1950 A.D.) in relation to Epochs/ Series. From the various alternatives available, the scales of Hardenbol and Berggren (1978) for the Palaeogene, Van Couvering and Berggren (1977) for the Neogene, and La Brecque et al. (1977) for the entire Tertiary, were fitted together.

The combined scale is similar to that suggested by the Polarity Time Scale Subcommission (Watkins, 1976) apart from the dates for the Middle/Upper Eocene and Eocene/Oligocene boundaries. Except for the Eocene/Oligocene boundary, the Palaeogene part of the scale is similar to that suggested by Pomerol (1978). However, particularly in the Palaeogene, the scale differs at a number of points from those of Tarling and Mitchell (1976) and Odin (1978a,b), for example. In the present formative stage of construction of a Tertiary time scale, the above selection is not meant to imply that one scheme is 'right' and another 'wrong'; but a choice had to be made for the construction of Plan 3, and those chosen provided one consistent and reputable alternative, with a strong background of foraminiferal biostratigraphy.

Dating the Eocene/Oligocene boundary presents problems which are both radiometric and biostratigraphic. Ages younger than the 37 Ma shown in Plan 3 have been suggested, for example, by Odin et al. (1978; 33 Ma), Pomerol (1978; 34-36 Ma), Odin (1978b; 34.5-36.5 Ma), Glass and Zwart (1977; less than 35 Ma), and Tarling and Mitchell (1976; 35 Ma). In fact, some such younger date for the boundary would be convenient for our local stratigraphy : it would be more compatible with the potassium/argon glauconite dates obtained for the Upper Eocene Hantkenina zone (Lindsay and Webb, 1979; 32.1 $\pm$ 0.5 Ma to 35.0 $\pm$ 0.5 Ma), and it would ease the apparent compression of stratigraphic units in the Upper Eocene, evident in Plan 3.

Having matched the standard Epochs/Series with a geochronometric scale, relevant Middle Eocene to Middle Miocene P./N. Zones of Blow (1969, 1970) were then accommodated, after Van Couvering and Berggren (1977), Hardenbol and Berggren (1978) and McGowran (1978b, 1979b). Zone P.17 has been regarded as uppermost Eocene by most who have worked on tropical successions (e.g. Blow, 1969, 1979; Berggren, 1972; Fleisher, 1974; Quilty, 1976, 1977, 1980a; McGowran, 1978b, 1979b), but it was taken to straddle the Eocene/Oligocene boundary by Hardenbol and Berggren (1978). Some indication of this disagreement is shown in Plan 3. As discussed by Van Couvering and Berggren (1977) and by Van Couvering (1978), the base of the Aquitanian stratotype, and hence the base of the Miocene, is now known to lie within Zone N.4, and not at the base of this zone as maintained by Blow (1969, 1979). Zone N.4, which is relatively long-lasting (3 M.y.) is thus shown in Plan 3 as straddling the Oligocene/Miocene boundary. The base of Zone N.9, which is marked by the Orbulina First Appearance Datum (O. suturalis), is also taken to be the Lower Miocene/Middle Miocene boundary, at 15 Ma.

Continuing the construction of Plan 3, Australian Stages were matched tentatively to P. and N. Zones, an exercise first attempted by McGowran et al. (1971), and repeated more recently by Abele (1976a). Base Aldingan Stage, which is base Tortachilla Limestone at the stratotype (Ludbrook and Lindsay, 1966), is put low in Zone P.15 as discussed later in connection with that formation. Top Aldingan Stage is put at or near top Zone P.17, as was done by McGowran et al. (1971), not high in Zone P.18 as shown by Abele. Various aspects of the Eocene/Oligocene boundary are discussed further in the treatment of the ALDINGA

MEMBER OF PORT WILLUNGA FORMATION. The base of stratotype Janjukian Stage at Bell's Headland postdates the Subbotina angiporoides L.A.D., but is within the uppermost part of the range of Chiloguembelina cubensis. The base of the Janjukian is therefore put approximately at top Zone P.19/20, in accord with McGowran et al. (1971) and Abele (1976a), despite some continuing uncertainty as to the extinction-levels of both of the species mentioned. Thus Blow (1969) at first ranged S. angiporoides up only to within Zone P.19, then to within Zone P.19/20 (Blow, 1970); and finally to within Zone P.21 (Blow, 1979, p. 1252) with a growing awareness that 'the later extension of the range of the taxon is highly variable and probably strongly influenced by ecological conditions; the taxon persists to younger horizons in the cooler-water environments than it does in the more fully tropical environments'.

Recently, after study of the calcareous nannofossil succession of the stratotype Janjukian, Siesser (1979) has put the base of the stratotype at Bell's Headland within the span of undifferentiated nannofossil Zones NP.24-NP.25. At the lowest possible interpretation (i.e. base Zone NP.24) this would correspond to a level either high in foraminiferal Zone P.19/20 (Martini, 1971), or low in Zone P.21 (Martini, 1970; Van Couvering and Berggren, 1977; Hardenbol and Berggren, 1978). These correlations suggest that the nannofossil evidence may not be too incompatible with the placement of base stratotype Janjukian at approximately top Zone P.19/20. However both Abele (1976b, p. 234) and Siesser (1979) demonstrated a diachronously older base to the Jan Juc Formation offshore, e.g. in Nerita-1 well, where Abele recorded S. angiporoides and even

S. linaperta in the lower part of the formation, and Siesser recorded nannofossil Zone NP.22 which corresponds with foraminiferal Zones P.18-P.19 according to Hardenbol and Berggren (1978). Leaving aside the problems raised by these determinations, this downward extension of the Jan Juc Formation offshore in the Torquay Basin appears to fill most, if not all, of the gap between the Aldingan and Janjukian Stages. Whether or not this offshore section might be seen as a downward extension of the Janjukian Stage is arguable, in view of the terms of redefinition of the Stage by Raggatt and Crespin (1955), i.e. whether the scope of the Stage is or should be limited to the onshore stratotype section of Jan Juc Formation, or should be extended to include offshore downward extension of the Formation. It is significant that despite the data at his disposal Abele (1976a, table 8.1, p. 181) did not show or propose any downward extension of the Janjukian Stage to meet the Aldingan Stage. The gap is shown in Plan 3, and in the eastern St Vincent Basin it is filled by the Ruwarung Member of Port Willunga Formation.

The top of the Janjukian Stage is correlated with top Zone N.4 in Plan 3, which approximates the estimate by Abele (1976a, table 8.1), and is only slightly higher than was shown by McGowran et al. (1971, table 1). Siesser (1979) has shown recently that the top of stratotype Janjukian at Bird Rock is at or near the top of nannofossil Zone NN.1. Top Zone NN.1 correlates with a level just below the top of foraminiferal Zone N.4 according to Martini (1971), and just above the base of Zone N.5 according to Van Couvering and Berggren (1977). Thus the evidence from nannofossils supports the placement of top stratotype Janjukian approximately at top Zone N.4.

Offshore, in Nerita-1 well, the Jan Juc Formation extends up at least into nannofossil Zone NN.2, according to Siesser (1979), i.e. probably well into foraminiferal Zone N.5 (Martini, 1971; Van Couvering and Berggren, 1977). Siesser (1979, p. 169) also shows that the NP.25/NN.1 nannofossil zone boundary, which correlates approximately with the Oligocene/Miocene boundary (Van Couvering, 1978), occurs along the Torquay coast 'at the base of the hard band capping Bird Rock, approximately 2.5 m below the Jan Juc - Puebla Formation contact'. Other aspects of the Oligocene/Miocene boundary problem are discussed later in connection with the 'upper Janjukian unit' of the PORT WILLUNGA FORMATION.

As shown by McGowran et al. (1971) and Abele (1976a), the Longfordian Stage correlates with Zones N.5 to N.7, plus the lower half of Zone N.8. The base of the latter zone is marked by the successional first appearance of Globigerinoides sicanus de Stefani (= G. bisphericus Todd), a FAD which occurs in the upper Longfordian (Carter, 1964; Abele, 1976a, p. 181).

The correlation of the Batesfordian Stage was discussed recently by Abele (1976a, b), but the upper limit is shown within, and not at the top of Zone N.8, in Plan 3, for reasons which will be noted later. Singleton (1941, p. 31) defined the Batesfordian 'as the interval of time represented by the deposition of the Lepidocyclina-bearing limestones of the Batesford quarries, as well as those represented therein by non-deposition or erosion'. Abele (1976b) noted that the Batesfordian stratotype comprised the Lepidocyclina-bearing, upper 12 m of the Batesford Limestone at the Australian Cement Co. quarry, a few kilometres northwest of Geelong.

Neither Carter (1964), Wade (1964), nor Abele (1976a) recorded from the stratotype Batesfordian any morphotypes of the Orbulina bioseries more advanced than Globigerinoides sicanus (= G. bisphericus). However the latter two authors, in range charts, both depicted the first appearance of Praeorbulina glomerosa within the southern Australian range-zone of Lepidocyclina. The writer (in Lindsay and Giles, 1973) showed that in the western Murray Basin, the Lepidocyclina range-zone contains the Orbulina bioseries mostly indeed in the form of Globigerinoides sicanus (as recorded earlier by Ludbrook, 1961, and Wade, 1964), but also rarely in forms as advanced as Praeorbulina glomerosa curva and Praeorbulina transitoria, thus at least middle Zone N.8 (Blow, 1969, 1979). The writer also found that at Morgan, a thin band of foraminiferal marl, rich in planktonics and only 2.2 m conformably above the Lepidocyclina range-zone, contains frequent and well-developed Praeorbulina glomerosa curva together with common Praeorbulina transitoria, but with no higher morphotypes of the Orbulina bioseries (Lindsay and Giles, 1973, p. 5). This supports and strengthens the bio-stratigraphic significance of the rare indications of these forms within the Lepidocyclina range-zone.

In the Para Fault Zone, on the Thebarton Block immediately west of the City of Adelaide (Ref. bore 105, Plan 5), and despite poorer planktonic faunas, the presence with rare Lepidocyclina (Pl. 47, Figs 4-6) of occasional advanced Globigerinoides sicanus trending to Praeorbulina glomerosa curva (Pl. 32, Figs 9,11) hints at a similar level within the homotaxial succession; and by extension, a similar age for the Lepidocyclina range-zone.

From studies by Carter (1964) and Gostin (1966) of the stratotype Balcombian Stage (as defined by Singleton, 1941) and its nearby correlatives around eastern Port Phillip Bay, it is apparent that the lower Balcombian lacks Orbulina suturalis but contains Praeorbulina glomerosa subspp., and P. transitoria. The upper Balcombian contains O. suturalis, but not at the stratotype, where the upper beds are badly leached (Carter, 1964; Gostin, 1966). Thus the initial appearance of Orbulina, which marks the base of Zone N.9 (Blow, 1969) occurs within the Balcombian, as shown in Plan 3, and not at the base of the Balcombian as shown by Abele (1976a, p.181).

Bairnsdalian to Kalimnan Stages are plotted in Plan 3 in general accord with Abele (1976a). The Upper Pliocene Yatalan Stage is inserted after Ludbrook (1973). The uppermost Pliocene/Lower Pleistocene Werrikooian Stage, which was discussed recently by Singleton et al. (1976), and by Abele et al. (1976, pp. 218-219), is not shown in Plan 3. However according to the radiometric and biostratigraphic age-data announced by Singleton et al. (1976), the basal Werrikooian stratotype, dated at about 2 Ma, may overlap the Yatalan Stage slightly.

Having established a chronological, zonal, and stadial framework for Plan 3, the various local stratigraphic units were fitted in according to criteria which are outlined separately for each formation in the following chapters. Sources are credited at the top of each column in Plan 3, but the final arrangement is the author's responsibility. For recent unpublished palynological information on the North Maslin Sand and Clinton Formation, the writer is indebted to W.K. Harris.

Although an attempt is made in Plan 3 to indicate (often on the basis of tenuous and indirect data) the relationship of the local succession to 'standard' P. and N. Zones; and although the writer has, in the past, been associated with the adaptation, erection, and usage of planktonic foraminiferal zonal schemes (Lindsay, 1967b, 1969; Ludbrook and Lindsay, 1969; McGowran, Lindsay and Harris, 1971), he has inclined increasingly to the use of 'datum-levels' in more recent years. Despite the arguments marshalled by Blow (1970) against the use of the 'datum-plane' or 'datum-level', especially those based on 'extinction-horizons', this approach has been considered by many workers to be a practical way of attempting to order global, regional, or local biostratigraphic events, especially where the order of events is still being sorted out, or in temperate latitudes (typified by southern Australia-New Zealand) where it has been difficult to apply the tropical 'standard' zonations (Jenkins, 1966c; Hornibrook and Edwards, 1971).

While Jenkins (1966c) emphasised that his proposed 29 datum planes (all FADs or LADs) were homotaxial rather than isochronous, the same limitation applies really to the interpretation of all biostratigraphic successions. The leap from homotaxy to isochroneity (taken implicitly by Jenkins himself in the very paper quoted above!) is basic to any exercise in correlation, and can only be tested finally by the application of some physical scale such as radiochronology or magnetochronology.

The use of datum levels need not be to the exclusion of zonal schemes; the two can proceed in tandem. Thus Jenkins (1966c) proposed his series of datum planes at the same time that he was zoning the New Zealand Tertiary planktonic foraminiferal succession (Jenkins, 1966a, 1967, 1971); and Berggren (1969b)

related his proposed datum planes to Blow's P./N. zones.

In view of the confusing proliferation of Tertiary foraminiferal zonal schemes for the southern Australia - New Zealand extra-tropical region (e.g. Glaessner, 1951, 1959; Carter, 1958, a,b; 1964; Wade, 1964; Jenkins, 1966a, 1967, 1971, 1974a; Taylor, 1966, 1971, and in Abele, 1976a; Lindsay, 1967b, 1969; Ludbrook and Lindsay, 1969; McGowran, 1973a) the writer is in sympathy with the view expressed recently by McGowran (1978b, p.91) 'that zonal nomenclature really is of rather little and decreasing practical significance. What count are events in the fossil record, be they demonstrably widespread initial appearances or disappearances, or temporary immigrations and ephemeral occupations, or the fossil evidence of stratigraphically isolated marine ingressions, (i.e. ephemeral transgressions). It would seem better to concentrate on the further recognition and clarification of the various types of events, on their stratigraphic and historical meaning, and on the attempt to relate them to the standard P-Zones'. This is the basis of the approach now taken by the writer (Plans 27 to 37).

Plans 30-34, modelled on the style of McGowran (1973a, Fig. 3), were prepared originally for handouts to the 45th ANZAAS Congress, Perth (Lindsay, 1973) and have been revised subsequently. Plan 32, depicting a succession in the Murray Basin, and Plans 33 and 34, representing two successions with more open-marine planktonic facies in the Gambier Embayment of the Otway Basin, are included for comparison with the St Vincent Basin in respect to a number of species and datums. Plan 35 was prepared independently by the writer, and essentially in its present form, for presentation to the 25th I.G.C., Sydney, (Lindsay, 1976).

A similar philosophy to that of McGowran (quoted above) was being advocated more than a decade earlier by Hornibrook (1967), and was developed by Hornibrook and Edwards (1971) into a framework of 108 integrated planktonic foraminiferal and calcareous nannoplankton datum levels for the New Zealand Cainozoic. Since these authors had found that, in the New Zealand Cainozoic, 'many of the tropical zonal species ..... are so rare as to be useless' (op. cit., p. 655), they outlined a New Zealand, temperate scheme, with the plea that before any zonation or datum levels are considered 'standards', there should be similar documentation from many regions, for evaluation and cross-correlation.

Foraminiferal range-charts for the Adelaide City area and eastern St Vincent Basin are presented in Plans 36 (planktonics) and 37 (benthonics). In neither case, and especially not for the planktonic datums, is there any pretension that this is more than an attempt at local documentation for a temperate coastal basin with rather restricted marine access. The successive FADs and LADs are not proposed as 'standards', but in a spirit of experimentation. Some at least, are undoubtedly facies-controlled; others appear to have validity both regionally and beyond. The various datums and their significance, are discussed in connection with the biostratigraphy of each formation.

In Plan 35, and in the discussion of the various formations, the Tertiary sedimentary record of the Adelaide City area and the eastern St Vincent Basin is related to regional events and influences such as:

a) depositional 'sequences' or 'synthems' (McGowran, 1971, 1977, 1978a,b, 1979b; cf. Bock and Glenie, 1965; Quilty, 1977);

b) warm climatic/watermass events recognised by 'extra-tropical excursions of foraminifera' (e.g. Glaessner, 1959; McGowran, 1971, 1978b, 1979b; Lindsay, 1973, 1976, and in Twidale et al., 1976; Lindsay and Bonnett, 1973; R.J.F. Jenkins, 1974).

c) an oxygen-isotope palaeotemperature record for the Paleocene to Middle Miocene, from two DSDP sites south of New Zealand; replotted from Shackleton and Kennett (1975).

In addition, the stratigraphic record is related to regional plate-tectonics, and to the global eustatic sea-level cycles proposed by Vail et al. (1977) and Vail and Mitchum (1978).

NORTH MASLIN SAND

Introduction

It is not at all certain that North Maslin Sand occurs in the Adelaide City area, since the thin, basal, non-marine quartz sand beds which have been penetrated in a few bores, could also be accommodated in the overlying Clinton Formation. However North Maslin Sand may be widespread in the northern and eastern marginal areas of the Golden Grove-Adelaide Embayment (Forbes, 1980), and is also known from the Adelaide Plains Sub-Basin (Lindsay, 1969). Hence the unit will be treated, but comment will be confined to salient features, or to more recent advances in knowledge.

Nomenclature

Cooper (1977b, 1979b) has recently discussed the unit as it is developed in the Willunga Embayment, where the type section is exposed (Plan 2). Contrary to Cooper's proposal, the writer prefers to maintain the distinction originally made by Reynolds (1953) between the North Maslin Sand and the South Maslin Sand as formations, rather than as members of a composite formation: 'Maslin Sands'.

Type Section

As nominated by Reynolds, the type section comprises exposures in the A.B.M.-Readymix sand quarry, and in a gully immediately to the south, called 'The Canyon', both at the northern end of Maslin Beach. In the sand quarry, exposures are changing constantly. Extraction has ceased at the southern end, and the faces where Reynolds described the contact between the two sand formations are now landscaped and grassed over. At the active northern end of the quarry, a contact zone was clearly revealed on February 17th, 1976, as shown by the



Figure 52. A.B.M.-Readymix sand quarry, Maslin Beach, Feb. 1976; view looking north, showing in the foreground the multicoloured, ferruginised contact zone between North Maslin Sand (below) and South Maslin Sand (above the clay marker bed which is between the two hammers); greenish South Maslin Sand is exposed in the lower few metres of the cutting behind the group of onlookers.



Figure 53. As above, but closer view of the metre-thick, bioturbated, clay marker bed (top North Maslin Sand) whose lower half is multicoloured and ferruginised; quartzose North Maslin Sand in foreground.

accompanying photographs (Figs 52,53). The top of the North Maslin Sand is taken to be the top of the prominent, multicoloured and weathered clay band, which is less than a metre thick. This ferruginous profile is of interest in view of the buried 'lateritic' soil profile which was observed by Glaessner (1953a,b) near the top of the formation at Witton Bluff in the adjacent Noarlunga Embayment. In a cutting near the point from which Figures 52 and 53 were taken, the silty sandy clay marker bed is bioturbated, glauconitic, and poorly fossiliferous (rare bryozoal and mollusc fragments, sponge spicules, and occasional nondescript foraminifera), as evidence of the first marginal-marine influence in the succession, perhaps representing a lagoonal environment. Pale green and brown South Maslin Sand, bioturbated in places, is well exposed at the base of the northern quarry face (Fig. 52). Similarly, in drillholes exploring sand resources three to four kilometres to the east, the boundary between South Maslin Sand and North Maslin Sand was taken to be the first downhole intersection of pale grey clay bands (Lindsay and Harris, 1974; Olliver and Reed, 1976) with marine influence disappearing at about that level.

Lithology

In the stratotype sand quarry, these cross-bedded quartz sands vary from fine-grained to coarse and pebbly, from poorly-sorted to sets of graded beds, and from white to shades of ferruginous yellow, brown, and red in colour. White clay galls are common in places, thin bands of white clay are present (in addition to the multicoloured band at the top), and a partly-oxidised lens of black, brown and white clay (the 'Maslin clay lens') with well-preserved plant and other non-marine fossils, has great biostratigraphic, palaeobotanical, and palaeoclimatic

significance (Lindsay, 1969; McGowran et al., 1970; Lange, 1970; Christophel and Blackburn, 1978). By 1974, after seven years of exposure, this carbonaceous lens had been mostly removed and stockpiled to enable the surrounding sand to be quarried. The lens, probably representing a billabong swamp deposit, may have been as much as 100 m long, 45 m wide, and up to 3 m thick (Lindsay, 1969; Christophel and Blackburn, 1978), but other intercalations of clay found in the stratotype have been much thinner, and it is estimated that beds of clay would comprise less than 10% of the type section, overall. A drilling programme around the stratotype quarry showed bulk samples of North Maslin Sand to contain from 3.0% to 9.6% clay, with an average of 6.1% by weight (Olliver and Weir, 1967, p.9). Therefore, in keeping with stratotype lithology, the name North Maslin Sand is reserved for quartz sands, largely non-marine, with only minor clay intercalations which may or may not be carbonaceous. Notably lignitic units, together with carbonaceous clays and pale 'underclays', are treated as CLINTON FORMATION (which see), and should not be included in North Maslin Sand as was done recently by Cooper (1980).

A bed of sand only 2.7 m thick, which might be regarded as a lithological correlative of North Maslin Sand, was penetrated in Reference bore 50, North Adelaide. Samples are not available, but a log by Miles (1952, p. 170; and unpublished data) recorded:

111-156 ft (33.8-47.5 m): 'lignite and lignitic clays' (Clinton Formation);

156-165 ft (47.5-50.3 m): 'brown and white clay' (Clinton Formation 'underclay');

165-174 ft (50.3-53.0 m): 'clean sharp white sand with fragments of lignite' (Clinton Formation, or possibly North Maslin Sand);

174-187 ft (T.D.) (53.0-57.0 m): 'purplish and brown clay, sandy clay and sand bars (decomposed slate?)' (completely-weathered bedrock).

Groundwater was cut at 50.3 m, and the sand yielded the best quality water encountered in the bore (2 009 ppm T.D.S.).

The old Kent Town bore, Reference bore 31, cut an even thinner basal sand with the same stratigraphic relationships. There are minor disparities in the depths given in logs by Tate (1882) and Miles (1952, p. 192), but taking Tate's measurements, a fine-grained, water-bearing, quartz sand at 302-305 ft (92.0-93.0 m) underlies lignitic clay and white underclay of Clinton Formation, and overlies 'white, sandy and gritty clay' representing decomposed bedrock. The sand yielded 'a fair supply of water' (1 676 ppm), which was the best quality obtained from the bore.

Descriptions of the economically-important fine to coarse-grained non-marine sands (?North Maslin Sand) of the Highbury to Golden Grove area (Figs 2, 19-25, 38,46) were given by Olliver and Weir (1967). McCallum (1978) has recorded detailed logs of many bores which have recently outlined the sand deposits of the Golden Grove area.

In the Northern Adelaide Plains, SADME Observation bore PTG-13, at Port Gawler (Plan 2) penetrated a typical and well-defined interval of North Maslin Sand at the base of the Tertiary sequence. The lithology is pale grey, pebbly, poorly-sorted quartz sand, slightly clayey, pyritic, and with a thin

intercalation of grey carbonaceous clay (Lindsay, 1965a, 1969). The formation occurs very similarly in Beach Petroleum Grange-1 well (Plan 4; Steel, 1962c; Lindsay, 1968c, 1969), but not, apparently, in Croydon-2 bore, where the interval between South Maslin Sand and the base of the Tertiary succession is predominantly clay (Plan 29).

Distribution

Beneath the City of Adelaide, North Maslin Sand if present at all, is thin and patchy. In most bores the white underclay of Clinton Formation rests directly on weathered bedrock. However sands which may correlate with the formation are developed extensively through the northeastern end of the Golden Grove-Adelaide Embayment, at least as far south as Athelstone (Forbes, 1980). Outliers of similar sand continue several kilometres north of One Tree Hill (Campana, 1953; Olliver and Weir, 1967). Only 3½ km further northeast, across the South Para River, apparently similar 'Tertiary basal sands' occur in the Cockatoo Valley-Sandy Creek-Lyndoch area (Campana, 1953; Olliver and Weir, 1967) and have also been correlated with North Maslin Sand (Glaessner *in* Campana, 1955; Glaessner and Wade, 1958). However, marginal-marine and non-marine sand deposits at Gawler and immediately east, were estimated from fossil molluscs and foraminifera, to be Upper Oligocene-Lower Miocene (Glaessner *in* Campana, 1955; Glaessner and Wade, 1958) while Harris (*in* Daily *et al*., 1976) has palynologically determined a similar age for sands and other carbonaceous non-marine sediments of the Barossa Valley. Scout drilling and mapping link these, showing that sand deposits extend discontinuously eastwards from Gawler to Sandy Creek, while the Barossa Valley sands can be traced westwards from Rowland Flat to Lyndoch and Sandy Creek.

If the sands at Golden Grove are indeed Eocene as suggested by a single palynological date of the immediately underlying lignitic clay (Hos, 1977) there appears to be a conflict of ages by extrapolating northwards to the Oligo-Miocene sands between Gawler and the Barossa Valley. Either these various sand deposits are diachronic from Eocene to Oligo-Miocene, or more likely, it will be necessary to recognise a depositional and age-barrier somewhere between the two areas, restricting approximate time-correlatives of North Maslin Sand to the Golden Grove-Adelaide Embayment. The problem will be difficult to solve without further palynological evidence.

Caution is also needed in assigning to North Maslin Sand apparently unfossiliferous sands intersected in bores near the eastern margin of the Golden Grove-Adelaide Embayment. This has been brought out very recently in the case of the SADME Hazelwood Park-1 bore (Eberhard, 1980). In a thick and poorly fossiliferous sand sequence from 85 m to total depth of 195 m, Harris (1980a) has been able to date palynologically a black, lignitic clay intercalation at 137 m as a tentative time-correlative of Chinaman Gully Formation; and a carbonaceous silty sand at 116 m as a tentative time-correlative of the Aldinga Member of Port Willunga Formation. The sands between 85 m and 137 m might be regarded therefore as correlatives of the Pirramimma Sand Member of Port Willunga Formation (Cooper, 1977b); and those below the lignitic clay as correlatives perhaps, of Rogue Formation (Stuart, 1970; cf. Cooper, 1977a).

North Maslin Sand has not yet been proved on the Mile End Block, or the Thebarton Block, west of the City of Adelaide. Subsurface in the Adelaide Plains, as noted earlier, the formation is absent from Croydon-2 bore; but is developed

typically in SADME Observation bore PTG-13 at Port Gawler, and is thickest in Beach Petroleum Grange-1 well. It is present also at the bottom of the Tertiary sequence in SADME Observation bore MPA-65, Virginia (Plan 2). It should not be assumed that North Maslin Sand is developed continuously between these points. In fact, recent drilling by SADME to explore the distribution of the formation for possible underground storage of natural gas east of Port Gawler (Cockshell, 1979) suggests on the contrary that the sand there is a localised channel deposit.

In contrast, the formation is widespread in the Willunga Embayment, being distributed almost throughout the embayment (Cooper, 1979b, p.65). It is more restricted in the Noarlunga Embayment, although it was quarried once at Christies Beach (Olliver and Weir, 1967, p.27), and was intersected in a bore at Seaford (Cooper, 1980; only the so-called 'lower unit' is properly North Maslin Sand).

Crawford (1965, pp.32-33) described various deposits of non-marine 'basal coarse cross-bedded quartz sands', which occur subsurface along the northwestern margin of the St Vincent Basin from north of Melton to south of Ardrossan (Plan 1). Similar fluviatile sands and gravels are known from the base of the Tertiary sequence in Beach Petroleum Black Point-1 well, but are not known to extend further south (Stuart, 1969). At present there is no reason to doubt that these are all correlatives of North Maslin Sand, although care must be taken to distinguish them from the quartz-sand facies of marginal-marine Rogue Formation (Stuart, 1969, 1970).

Thickness

Beneath the City of Adelaide, doubtful correlatives of North Maslin Sand do not exceed 2.7 m in thickness (see above). Near the head of the Golden Grove-Adelaide Embayment, sands correlated tentatively with North Maslin Sand are, in places, more than 30 m thick (Plan 4, e.g. SADME bore GG-91, Yatala Vale; see McCallum, 1978; Olliver and Weir, 1967). The Highbury East sand deposits, again tentatively correlated with North Maslin Sand, attain thicknesses in excess of 20 m (Olliver and Weir, 1967, p.33). In the Adelaide Plains Sub-Basin, thicknesses penetrated in deep bores vary from 11 m at Virginia (SADME MPA-65) to 19 m at Port Gawler (SADME PTG-13), to a maximum of at least 31 m in Beach Petroleum Grange-1 (Plans 2,4; Lindsay, 1969). Although Reynolds (1953) originally estimated a thickness of 19.5 m in the stratotype quarry, Olliver and Weir (1967) recorded a maximum thickness of 28.3 m from subsequent exploratory drilling in the vicinity.

Relationships and Boundary Criteria

The stratotype, in the ABM-Readymix sand quarry at Maslin Beach, rests on Permian glacigene rocks which include ?varved sandy claystone with occasional drop-stones, and diamictite with pebbles, cobbles, and soled and striated boulders. Elsewhere in the Willunga Embayment, North Maslin Sand is known to rest on white Permian sands, probably fluvioglacial, in two of the bores described by Cooper (1979b; bores WLG-40, WLG-43). However Cooper reported that through most of the embayment, North Maslin Sand 'unconformably overlies an undulating surface of weathered Precambrian-Cambrian basement'.

Beneath the City of Adelaide, doubtful correlatives of North Maslin Sand rest on weathered bedrock, probably Adelaidean. In the Adelaide Plains Sub-Basin this is also the case, except in SADME Observation bore PTG-13 at Port Gawler, where, with a clean contact, North Maslin Sand overlies unweathered ?Cambrian massive, grey, pyritic dolomite and dolomitic limestone (Townend, 1964; Lindsay, 1965a, 1968c, 1969). In more southerly parts of the Golden Grove area, sands correlated with North Maslin Sand rest conformably on Tertiary plastic clays which are up to 25 m thick (McCallum, 1978). Several bores intersected lignitic intercalations within these clays, which are therefore regarded doubtfully as Clinton Formation.

In more complete sections, North Maslin Sand is usually overlain either by South Maslin Sand (as in the type section) or by Clinton Formation; but may be overlain by much younger units towards the margins of the St Vincent Basin and its embayments. The upper contact in the stratotype quarry has been mentioned already. There is undoubtedly a transgressive change upwards from non-marine to marginal-marine environments, marked by the gradual incoming of 'marine'-type fossils, and glauconite, while the quartz grains tend to become more rounded. It seems however, that these facies-changes do not necessarily take place just at the boundary of North and South Maslin Sands, although in broad terms such features do distinguish the two units. Bioturbation, glauconite, and marine-type fossils, were noted earlier in a clay bed at the top of stratotype North Maslin Sand, while at Christies Beach, the first brackish-water, marginal-marine influence occurs also near the top of North Maslin Sand, in

laminated sands with arenaceous foraminifera and sponge spicules (Glaessner, 1953b; Ludbrook, 1962, 1969a). In drill-hole sections a few kilometres east of the stratotype quarry, the writer (in Lindsay and Harris, 1974) commented as follows on the fading of marine influence downhole in relation to the stratigraphic boundary problem. 'Because of contamination by downhole caving, it is difficult to fix a lower limit to these features, but distinct change is noticeable and marine influence has probably disappeared by the depth at which bands of grey clay are encountered in both bores, and this is taken to be the boundary between South Maslin Sand and North Maslin Sand'.

In the Adelaide Plains Sub-Basin, in SADME Observation bore MPA-65, Virginia (Plan 2), the passage from South to North Maslin Sand which was observed by the writer (Lindsay, 1969, bore '26B') is marked by the downhole loss of glauconite, faecal pellets (some cemented into tube-fillings), sparse mollusc fragments, and occasional small foraminifera. North Maslin Sand is white (rather than grey-brown), angular, quartzose, and less muddy.

Because of the differences indicated above, and despite some lack of precision in correlation, the writer prefers to maintain the original formational status of North and South Maslin Sands, rather than treating them as members of 'Maslin Sands', as has been proposed by Cooper (1977b, 1979b). Also, since North Maslin Sand in some localities is followed by Clinton Formation and not by South Maslin Sand, it is considered better for each unit to stand independently as a formation.

Beneath the City of Adelaide, the basal non-marine sand (North Maslin Sand) where present, is overlain by the pale-coloured underclay at the base of lignitic Clinton Formation. This is also the case in SADME Observation bore PTG-13 at Port Gawler (Lindsay, 1965a, 1968c, 1969), where pale grey pyritic silty clay (basal Clinton Formation; formerly and incorrectly identified as 'Muloowurtie Clays') is underlain with a sharp contact at 330.7 m, by pale grey, pyritic, fine to coarse-grained, silty sand (top North Maslin Sand) which contains high-pressure, high-salinity groundwater. In the E. & W.S. Seaford drainage bore, Noarlunga Embayment (Plan 2), pressure-water was also cut as North Maslin Sand was entered at about 158 m, beneath a thin grey sandy clay at the base of lignitic Clinton Formation. This is a different stratigraphic interpretation from that shown by Cooper (1980).

Biostratigraphy and Age

The now-famous North Maslin Sand carbonaceous clay lens was dated early Middle Eocene by palynological correlation with the Burrungule Member of Knight Formation in the Gambier Embayment; *Proteacidites confragosus* Zone (Harris *in* Lindsay, 1969; McGowran, Lindsay and Harris, 1970). However palynological studies now in progress suggest that the clay lens was deposited a little later in the Middle Eocene (W.K. Harris, W.M.C., personal communication, August 1980). As noted earlier, a band of carbonaceous mudstone from only 8 m below the top of North Maslin Sand, in a bore four kilometres east of the stratotype, was determined as also Middle Eocene, but early *Proteacidites pachypolus* Zone, a zone younger than the Maslin clay lens (Harris, *in* Lindsay and Harris, 1974). In the Port Gawler bore, and beneath the City of Adelaide, correlatives and

possible correlatives of North Maslin Sand underlie carbonaceous beds which are also P. pachypolus Zone (W.K. Harris, personal communication, January 1980). As discussed previously, a borehole at Yatala Vale penetrated sands which are correlated tentatively with North Maslin Sand, and which overlie ?conformably a lignitic clay determined similarly as P. pachypolus Zone, and most probably upper Middle Eocene (Hos, 1977).

Environment of Deposition, and Regional Events

The North Maslin Sand was at first considered to be deltaic in origin, particularly towards the top where marginal-marine (Glaessner, 1953b; Reynolds, 1953). However Stuart (1969, 1970) regarded the unit as mostly fluviatile, and traced channels directed towards the present axis of the St Vincent Basin from surrounding highlands. He distinguished various kinds of cross-bedding, including tabular-planar, trough, and wedge; recognising basal channel-lag, point-bar deposits, and fining-upwards sequences (Selley, 1978). As reported by Christophel and Blackburn (1978), the latter author took Stuart's analysis a stage further and diagnosed deposition by a braided stream system (Blackburn, 1973). The carbonaceous 'Maslin clay lens' represents a swampy abandoned channel, ox-bow lake, or billabong. Extensive, coalescing braided-stream deposits accumulated in the Willunga Embayment. In contrast, limited drilling and seismic evidence has indicated a laterally-restricted, deeply-buried shoestring channel extending 5 to 10 km northeast from Port Gawler, and approximately 1 800 m wide (Cockshell, 1979). Beneath the City of Adelaide, the thin and patchy basal sands appear to be fluvio-lacustrine in origin.

Lange (1970), and Christophel and Blackburn (1978) report several lines of palaeobotanical evidence which indicate the presence of subtropical to tropical rainforest in the Maslin Bay area during deposition of the North Maslin Sand carbonaceous clay lens.

Kemp (1978) has recently discussed the climate of that time, and includes a palaeogeographic map of the Australia-Antarctica region for the Middle Eocene at 45 Ma, corresponding to the time of deposition of North Maslin Sand. She comments (as did Frakes and Kemp, 1972) on the warm, moist climate resulting from the anticlockwise circulation of Indian Ocean water (warm from long tropical travel-time across the equatorial Pacific, north of Australia, and around the Indian Ocean) into and around the expanding, 1 000 km-wide Australia-Antarctica gulf from the open western end. Annual precipitation in coastal South Australia is thought to have been of the order of 1 000-1 500 mm, and humidity was high, associated with summer storms of monsoonal type. The braided-river deposits represented by North Maslin Sand, were compared by Christophel and Blackburn (1978) with a regime such as that of the Ramu River valley of Papua New Guinea.

However in a wider perspective, Middle Eocene ocean temperatures for the S.W. Pacific had fallen appreciably from their high levels in the Paleocene-Early Eocene (Plan 35). Correlating the local sequence (Plan 3) with the global cycle model of Vail et al. (1977, fig. 3); it appears that sea levels during deposition of North Maslin Sand were higher than today, and generally rising during Cycle TE2.

There is no evidence for the deposition of neritic carbonates at this time across the areas now occupied by Spencer Gulf and Kangaroo Island, as was shown in a reconstruction of depositional environments by Deighton et al. (1976, p.33). However according to recent palynological estimates by W.K, Harris (pers. comm. noted earlier), North Maslin Sand was deposited later in the Middle Eocene than the 'early Middle Eocene' reported by McGowran et al. (1970); and considerably later than the late Early Eocene shown recently by McGowran (1978a, fig. 5; 1978b, fig. 2). In Plan 3, the formation is fitted roughly against Zones P.11-P.13, thus straddling the beginnings of McGowran's 'Sequence 2' (e.g. McGowran, 1978a) as indicated in Plan 35, and approximately contemporaneous with carbonate transgression in the Eucla Basin (Wilson Bluff Limestone).

CLINTON FORMATION

Introduction

An association of lignite (brown coal), pale underclay, and minor sand, rests on weathered bedrock beneath the City of Adelaide, and underlies the mid-Tertiary marine sequence. The name Clinton Formation is used herein for this typically carbonaceous association, in the same sense in which it has been used by the writer previously (Lindsay in Selby and Lindsay, 1973; Lindsay in Daily et al., 1976). The unit is widespread in the Golden Grove-Adelaide Embayment (Plan 4) and includes a relatively small brown coal deposit in the Hope Valley Coalfield. In the northern part of the St Vincent Basin, the formation contains large reserves of brown coal in several coalfields (Plan 2). Clinton Formation is therefore a significant stratigraphic unit, and merits treatment in this thesis. However it shows little evidence of marine influence, has yielded no foraminiferal faunas, and is the subject of continuing palynological studies by W.K. Harris (Western Mining Co.), so comment will be confined to important features, to stratigraphic problems, and to more recent advances in knowledge.

Nomenclature and Type Section

The name 'Clinton Coal measures' was used informally and without comment, by Ludbrook (1963a, fig. 1), for the subsurface brown coal deposits of northeastern Yorke Peninsula at the head of Gulf St Vincent, in the Hundred of Clinton (Ward, 1921b, 1922a,b; 1923). Ludbrook (1963a) also noted other Tertiary coals and lignites in the St Vincent Basin, such as the Inkerman-Balaklava deposit, and those at Golden Grove, Hope Valley, North Adelaide, 'on the upthrow side of the Para Fault in the Adelaide area', and at Noarlunga. Apart from the

'Clinton Coal measures', and the 'Inkerman-Balaklava coal sequence', these were all included in North Maslin Sands.

Harris (1966) formally described and named the Clinton Coal Measures. He included brown and black lignites, carbonaceous silts, quartz sands, and clays, which 'extend from the west near Clinton, eastwards to Balaklava and Whitwarta, and north to Snowtown'. The subsurface type section nominated by him was the interval from 150 ft (45.7 m) to total depth of 318 ft (96.9 m) in Department of Mines bore C23/C23A (the bore having been redrilled as C23A from 69.2 m), 4.2 km southwest of South Hummocks railway station, at the head of Gulf St Vincent (Johnson, 1964a). The type section comprises a total of about 55% lignite and carbonaceous clay, and 45% carbonaceous fine sand and silt.

The combined bores C23 and C23A did not penetrate the full thickness of the formation. However in bore C20, only 0.9 km to the west, Johnson (1964a) reported that the main lignitic series is underlain, to total depth of 91.7 m, by 4.9 m of 'grey fine micaceous clay' which contains a thin lignitic intercalation at 87.5 m. The interval 57.9-91.7 m was selected as an 'additional type section' by Harris (1970). Similarly, in bore C22 which is 1.6 km northwest of C23/C23A, the main lignitic sequence is underlain by 6.1 m(91.4-97.5 m) of grey clay, with 'some lignite fragments which may be cavings'. This grey clay in turn overlies deeply-weathered shaly bedrock. There are many similar instances elsewhere in the St Vincent Basin, in which pale grey clay underlies lignite, probably as 'underclay'. Both the lignite and the associated pale-coloured sedimentary clay are included here in Clinton Formation as was done by Meyer (1976) and Cooper (1977a).

The name 'Muloowurtie Clays' was used by the writer (Lindsay, 1969) for the Eocene carbonaceous clays, lignites, and pale clays, which underlie the deposits of the Late Eocene marine transgressions in the Adelaide Plains Sub-Basin and beneath the City of Adelaide. The name was used only tentatively, in doubtful identification with the Muloowurtie Clays of eastern Yorke Peninsula (Tepper, 1879; Glaessner and Wade, 1958; Crawford, 1965). Subsequently, Stuart (1969, 1970) subdivided Tepper's unit into the marine Muloowurtie Formation, below ('biogenic calcarenites, quartz sands, calcareous and glauconitic quartz sands and sandstones and minor thin conglomerates') and the lagoonal Throoka Silts, above. It is clear that the largely non-marine Eocene lignites and associated clays of the eastern St Vincent Basin should not be termed Muloowurtie Formation. The name Clinton Formation is applicable, and it is not considered necessary to erect a new name for such deposits in the Adelaide area.

However there is a nomenclatural problem where, as in the area of the Golden Grove sand deposits, associated plastic sedimentary clays with little carbonaceous content may attain thicknesses as great as 25 m (McCallum, 1978). The writer considers this too thick to be accommodated in North Maslin Sand, as discussed earlier; but on the other hand, some of the clays have so little carbonaceous matter that the name Clinton Formation is hardly appropriate. The latter name is however used, if only tentatively, because a) some lignitic intercalations do occur, b) it is probable that others were present originally but have since been oxidised and bleached, and c) basal pale clays are a distinctive feature of the Clinton Formation.



Figure 54. Electricity Trust of S.A. trial pit, 2 km southwest of Bowmans (Plan 2), near the eastern margin of the Wakefield (Inkerman-Balaklava) Coalfield, northern St Vincent Basin; photo by D. Armstrong, SADME, Nov. 3rd, 1980. Dull and woody brown coal (lignite) of the Clinton Formation, being excavated for a 1 000-tonne trial sample, is exposed from 60 m below ground level down to total depth of 70 m. The sequence overlying the Clinton Formation consists mainly of mid-Tertiary sands which are unfossiliferous apart from sporadic bioturbation. These non-marine to very marginal-marine sands are capped by brown Pleistocene clay. One of the many dewatering bore pumps is in the foreground.

The name Clinton Formation seems preferable to Clinton Coal Measures (or Clinton Lignite, of Ludbrook, 1969b, fig. 84) in view of the associated beds which are not coal or lignite. There is a further objection to the term 'Coal Measures' on the grounds that it should be restricted 'to those strata of the Carboniferous system which contain coal' (Rice, 1954). The International Stratigraphic Guide (Hedberg, 1976) recognises 'The Coal Measures', in that sense, as a particular historic usage; and apparently does not approve of 'Coal Measures' as a general and formal unit-term. Nevertheless, the Australian Code of Stratigraphic Nomenclature (Geol. Soc. Aust., 1964) allowed use of this unit-term, without restriction as to age.

Lithology and Distribution

Detailed logs of Clinton coal bores were recorded by Johnson (1964a); while Meyer (1976) has documented recent drilling by SADME in the Wakefield (Johns, 1980) or Inkerman-Balaklava Coalfield, and the Clinton Coalfield. Johns (1975, 1980) has given useful summaries of these, and of the Whitwarta Coalfield.

Low-grade, dull and woody brown coal (lignite) of the Clinton Formation was exposed recently in a 70 m-deep trial pit near Bowmans, close to the eastern margin of the Wakefield (Inkerman-Balaklava) Coalfield (Plan 2, Fig. 54).

SADME Observation bore PTG-13, at Port Gawler (Plan 2) penetrated an instructive section of Clinton Formation at a locality which links the northern coalfields with lignitic developments in the Adelaide region. The section comprises (Lindsay, 1965a):

309.4-324.3 m (1 015-1 064 ft) - lignite, carbonaceous mudstone, and carbonaceous clay; dark brown to grey; 324.3-330.7 m (1 064-1 085 ft) - pale grey pyritic clay.

The writer compared the upper interval with Clinton Formation (Lindsay, 1969, p. 30), but now both are so identified. The lower unit is underlain by typical North Maslin Sand, as discussed earlier.

Seams of dull brown coal appear to underlie much of the City of Adelaide, but taken as a whole, Clinton Formation here is mostly clay, silt and sand, variously carbonaceous and lignitic, with colour ranging from black, dark grey, or dark brown, to white, depending on the content of carbonaceous matter. As elsewhere, the darker part is almost always underlain by a pale coloured unit which is often an 'underclay' (Fig. 55). A quartz sand which occurs beneath the pale clay in two or three bores, may be either included within Clinton Formation or regarded as a correlative of North Maslin Sand. Two sections have been recorded in detail, in composite logs of SADME West End Brewery bore (Plan 28), and SADME South Parklands bore (Plan 27). Only a few tube-cores were taken in the formation, but there are indications of several relatively-thin coal seams. Analyses of four core samples are given in the Table below (after Rowley, 1977). Samples A481/76 and A482/76 were from the South Parklands bore at 110.0-110.3 m and 105.0-105.3 m respectively (Figs 56,57). Samples A483/76 and A484/76 were from the West End Brewery bore at 66.0-66.3 m and 75.0-75.3 m respectively (Figs 58,59).



Figure 55. Clinton Formation, Adelaide City area; SADME West End Brewery bore (Ref. bore 10, Plan 5), part of tube-core from 85.0-85.3 m; underclay or 'seat-earth'; pale grey stiff clay with black carbonaceous and pyritic rootlets, and abundant disseminated pyrite; Middle Eocene (cf. Plan 28).

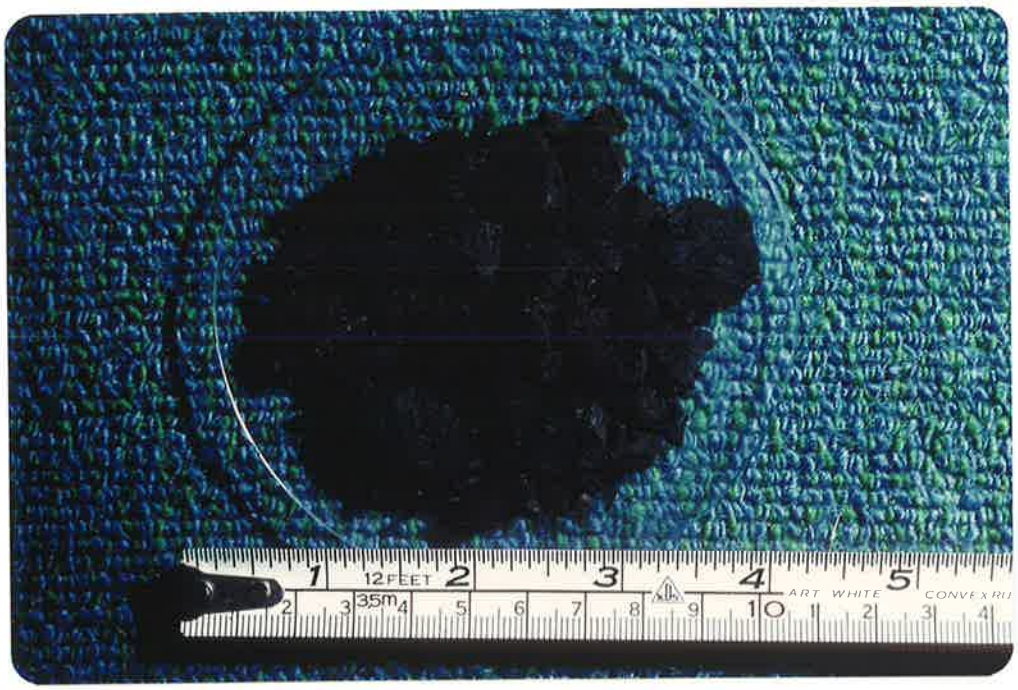


Figure 56. Clinton Formation, Adelaide City area; SADME South Parklands bore (Ref. bore 41) from tube-core at 110.0-110.3 m; brown coal (lignite); cf. sample A481/76, calorific value 20500 Joules/g (12% moisture basis); upper Middle Eocene.

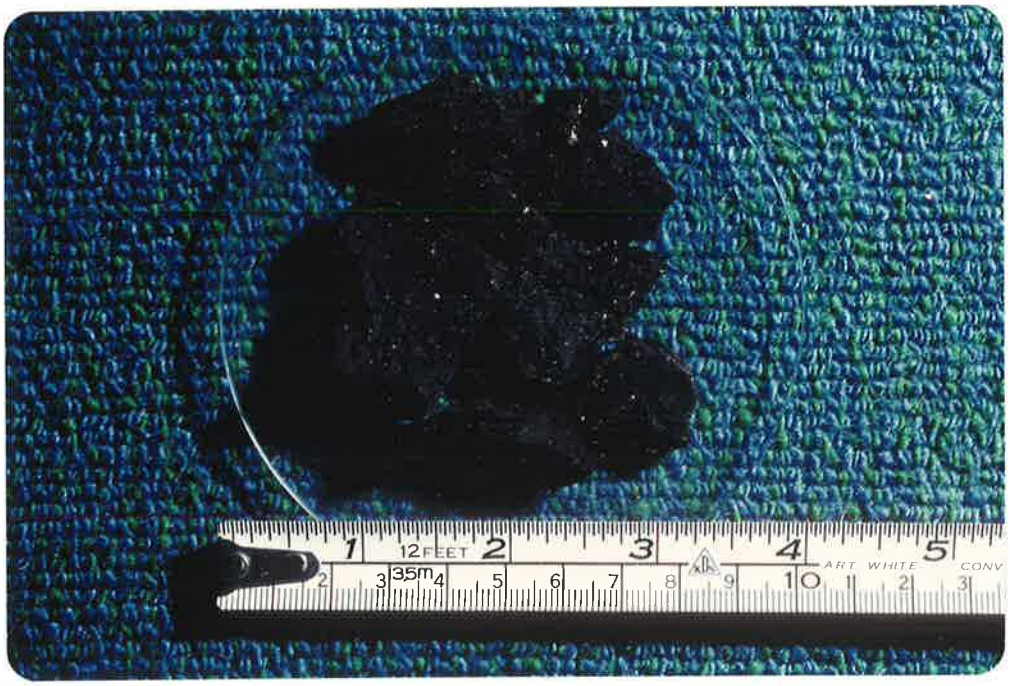


Figure 57. As above, but from tube-core at 105.0-105.3 m; brown coal (lignite) noticeably more pyritic than at 110 m; cf. sample A482/76, calorific value 18900 Joules/g (12% moisture basis).

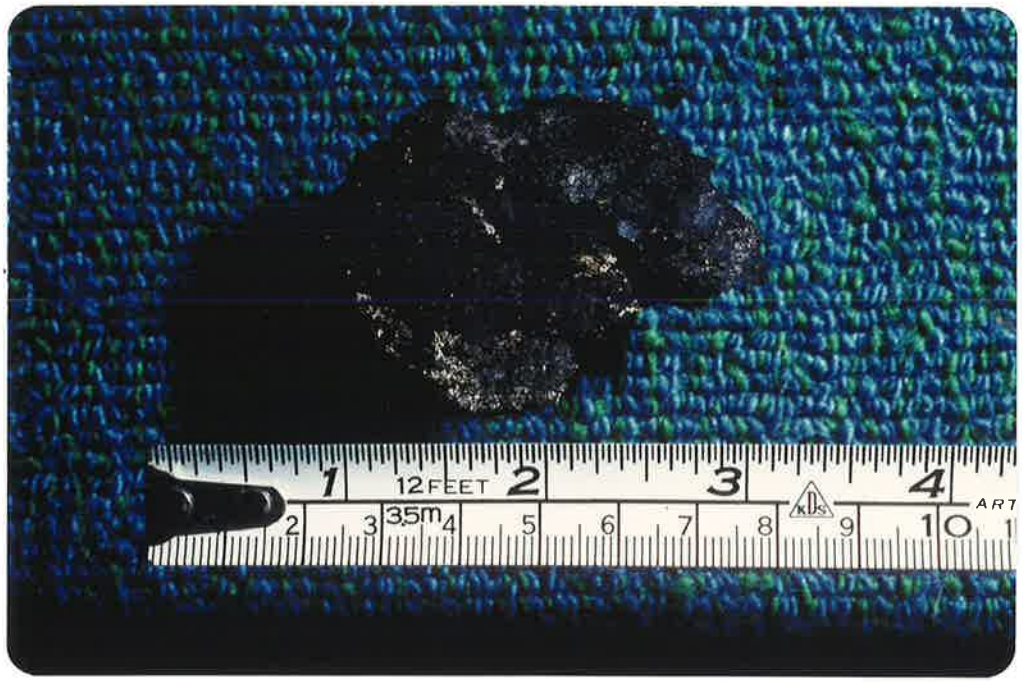


Figure 58. Clinton Formation, Adelaide City area; SADME West End Brewery bore, from tube-core at 66.0-66.3 m; pyritic brown coal (lignite); cf. sample A483/76, calorific value 18700 Joules/g, and sulphur content 6.5% (12% moisture basis); upper Middle Eocene.

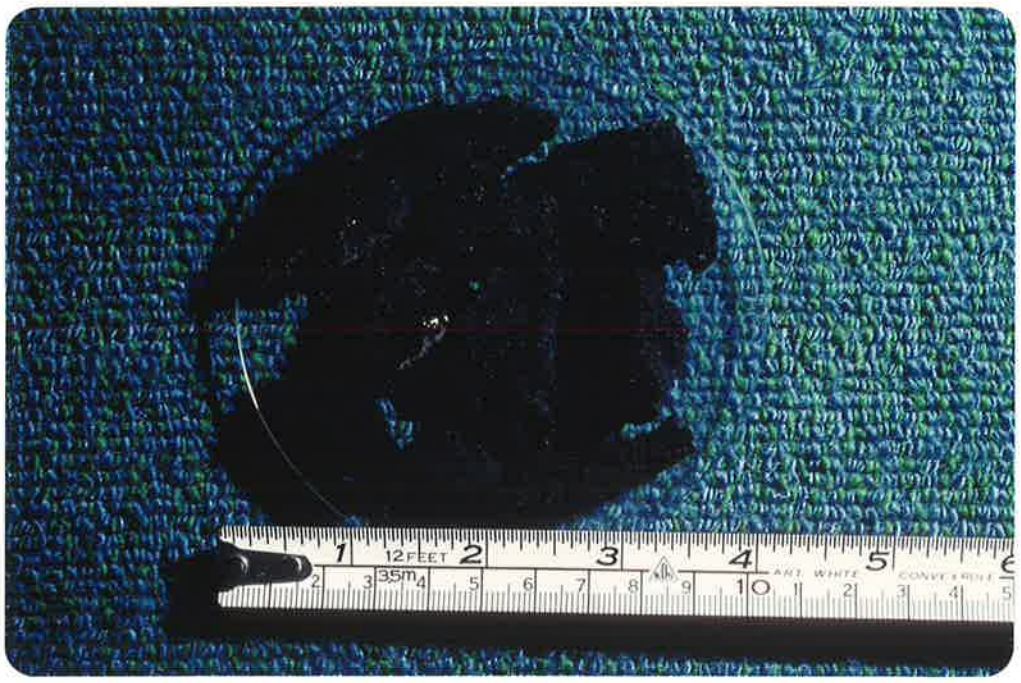


Figure 59. As above, but from tube-core at 75.0-75.3 m; less pyritic; cf. sample A484/76, calorific value 19900 Joules/g (12% moisture basis).

TABLE

Analysis, %. As received basis.

Sample Mark	(105-110°C) Moisture	Volatile	Ash	Fixed Carbon	Sulphur S	Sodium Na	Calorific Value Joules/g
A481/76	56.9	23.2	4.4	15.5	0.98	0.14	10 140
A482/76	52.7	21.0	8.8	17.5	2.25	0.15	10 180
A483/76	59.3	28.2	6.8	5.7	3.00	0.13	8 770
A484/76	59.7	30.1	5.0	5.2	1.86	0.14	9 390

Analysis, %. 12% moisture basis.

(Calculated from above)

Sample Mark	Moisture	Volatile	Ash	Fixed Carbon	Sulphur S	Sodium Na	Calorific Value Joules/g
A481/76	12.0	47.4	9.0	31.6	2.00	0.28	20 500
A482/76	12.0	39.1	16.4	32.5	4.20	0.27	18 900
A483/76	12.0	61.0	14.7	12.3	6.50	0.28	18 700
A484/76	12.0	65.7	10.9	11.4	4.05	0.31	19 900

Note: Sodium as determined is by ISO proposal TC 27/SC2, Jan. 1969, and is acid-soluble sodium.

The following comparisons can be made between these analyses and those from coal seams at the northern end of the St Vincent Basin (Meyer, 1976, table 3):

1. Moisture content is similar.
2. Volatiles in A481, 483 and 484, are higher than in the northern areas, where the figure is within the range 38-43%. The two samples from the West End Brewery bore are particularly rich in volatiles.
3. Ash content is comparable; if anything, a little lower than in the northern areas.
4. Fixed carbon content is comparable, or a little lower, in the samples from the South Parklands bore; and is relatively very low in the samples from the West End Brewery bore (only one-third of northern values).
5. Sulphur content is average in A482, 483, 484; but low in A481, which has a value less than half of all but one northern sample.
6. Sodium-ash ratios are 0.02 for the upper sample in each bore (A482, 483) and 0.03 for the lower samples. These ratios are within the acceptable limit of 0.04, and are much better than northern values, which vary from 0.08 to 0.22 and average 0.13.
7. Calorific values are only 80-90% of values for the Clinton and Inkerman-Balaklava Coalfields (20800-24900 Joules/g) but are better than the average for the Whitwarta Coalfield (18300 Joules/g).
8. Meyer (1976, p. 14) observed that in both the Inkerman-Balaklava and the Clinton Coalfields, 'the upper seam or seam-series ..... has higher average ash contents, lower average calorific values, and higher average sulphur contents than the lower seam or seam-series .....

The higher ash contents in the upper seam or seam-series reflect lower sodium-ash ratios than in the lower seams'. It is remarkable that each of these comments is also valid when applied to the upper and lower samples from the two bores in Adelaide City. Such a correspondence across a distance of 100 km suggests the possibility of broad, regional correlation between the upper seams or seam-series, and between the lower seams or seam-series.

If the four samples analysed are representative of Clinton Formation brown coal in the Adelaide area, it has a number of interesting and favourable properties, not the least of which, in the contemporary scene, is the high volatile content with its potential for distillation of petroleum products. Shaw (1923) recorded in considerable detail the hydrocarbon products obtained by the distillation of coal samples from Noarlunga and Moorlands in South Australia, and from Morwell and Yallourn in Victoria. The chemical analyses of the Adelaide samples are comparable with those of coals from Noarlunga (Ward, 1923, 1924) and Hope Valley (Ward, 1921a,b; 1924; Mining Review, 1922). Ward (1921a) commented that 'the general character of the lignite at Hope Valley is comparable with that occurring at Noarlunga, Moorlands, and Bower, as far as appearance and general chemical composition are concerned'.

The deposits at Adelaide City (see Appendix B), Hope Valley, and Noarlunga have all been referred to Clinton Formation by the writer (in Daily et al., 1976; see also Plans 2-4 etc. herein). In the E. & W.S. Seaford bore, an important reference section for the Noarlunga Embayment (Plan 2), the writer prefers to regard the clayey, carbonaceous and lignitic interval from

about 136 m to 158 m as Clinton Formation, rather than North Maslin Sand as shown by Cooper (1980). As indicated earlier, when discussing the Golden Grove-Adelaide Embayment, not all lignites in and around the embayment are identified as Clinton Formation. Some thin bands well up in the Tertiary sequence correlate with Chinaman Gully Formation, in bores (shown in Plan 4) such as SADME Hazelwood Park-1; Devitt bore, Payneham South; Barnes bore, Glynde; E. & W.S. Springbank bore; S.A. Farmers Union bore, Mile End; and the Croydon-2 bore. However where there is only the one lignitic formation, at the base of the Tertiary sequence, it is identified as Clinton Formation.

Thickness

Through the eastern St Vincent Basin, the thickness of Clinton Formation varies as shown in stratigraphic summaries of representative bores in Plans 2 and 4. Appendix B gives the thickness of the formation in nine reference bores in the City of Adelaide, where it is generally 12 to 20 m. However as depicted in Cross-section C-D (Plan 7), the unit thickens where it fills a broad bedrock depression between the South Parklands and Montefiore Hill, while it thins markedly where draped across the Montefiore Hill basement 'high'. Thus in the vicinity of the West End Brewery, Clinton Formation has a thickness of 27 m (Ref. bore 10) to more than 30 m (Miles, 1952, Index bore 215); while on Montefiore Hill the thickness is only about 6 m (Ref. bore 25; 'Carclew' bore 4, Allchurch, 1966). The formation similarly fills bedrock depressions across the Hope Valley Coalfield (Reed, in prep.) and in the Yatala Vale area (McCallum, 1978).

At most localities, the thickness of brown coal or lignite is much less than the total thickness of Clinton Formation. However in the SADME West End Brewery bore (Plan 28) most of the interval 66-76 m could be coal, judging from the driller's log, and from the analysed cores at 66 m and 75 m, although downhole cavings obscure the true lithology in the intervening sludge samples. A water bore drilled nearby within the West End Brewery in 1915 gave the first indication of a substantial seam of coal in this vicinity. The driller recorded 'brown shale or coal seam, lignite' between 50.3 and 85.3 m, a thickness of 35 m; but Miles (1952, p.191, Index bore 215) much later logged this interval as 'brown carbonaceous clay and sand'. By comparison with the SADME West End Brewery bore it does seem, however, that coal was penetrated through part of the interval.

Little more than a kilometre north, where Clinton Formation thins over the Montefiore Hill bedrock high, Reference bore 25 (Plan 5; 'Carclew' CH-2) penetrated a band of lignite less than 50 mm thick. It is disconformably overlain by South Maslin Sand, and is underlain by a pale grey to pale brown underclay or 'seat-earth' which contains rootlets that have been impregnated and encrusted with pyrite and siderite (cf. Fig. 55).

Further north again, near the western edge of the Para Block, much of Prospect appears to be underlain by coal-bearing Clinton Formation. A water bore drilled recently by SADME for Blackfriars' Primary School, Prospect South (Plan 4) penetrated black, carbonaceous, and lignitic clay between 34 and 40 m, a tube-core of coal being taken at 37.0-37.3 m. Beneath a carbonaceous, sandy interval, a further tube-core of coal was recovered from 45.0-45.3 m. A similar sequence was encountered by a drainage bore which was drilled in 1955 on

the southwestern corner of Main North Road and Regency Road, Prospect North (Plan 4) and was reported by the driller to have penetrated 'brown coal' between 32.0 and 42.7 m. However records of the subsequent examination of samples by SADM personnel (unpublished data, February, 1955) suggest that at least part of this interval was a fine-grained carbonaceous sand.

Johns (1975) summarised the distribution, seam-thickness, and reserves of brown coal in the Clinton, Inkerman-Balaklava, Whitwarta, Hope Valley, and Noarlunga fields; and has updated this information recently (Johns, 1980). In the Hope Valley field, the maximum thickness of coal was found in bore 7 (Plan 4) which penetrated an upper seam of 3.8 m, and a lower of 5.8 m, a total thickness of 9.6 m coal, separated by a 4.2 m bed of lignitic clay (Ward, 1921a).

One of the thickest seams of coal in the Golden Grove-Adelaide Embayment was penetrated by the Paradise Coal Mining Co. bore, immediately south of the intersection of Lyons Road and Lower North East Road, Highbury (Plan 4). Here, a low-grade brown coal was entered at a depth of 45.7 m and continued for a thickness of 13.1 m (Mining Review, 1911; Duffield, 1914; Ward, 1914).

In the Candy bore, Hectorville (Plan 4) sands and clays with thin coaly seams occur at depths of from 62.8 to 85.3 m, only a few metres above bedrock; while in the M.T.T. bore, Kensington Gardens, also near the eastern margin of the embayment, a bed logged as 'stiff black clay' was penetrated at 193.5-203.3 m in a similar stratigraphic position (Miles, 1952, p. 192, Index bore 217).

Relationships and Boundary Criteria

Beneath the City of Adelaide, Clinton Formation is generally the basal unit of the Tertiary succession, resting unconformably on weathered bedrock (often with an indistinct clay/clay contact), and at times filling broad depressions in it. The only exception to this would be if the thin basal sand, which occurs in two or three localities, were regarded not as Clinton Formation but (less likely) as a North Maslin Sand correlative, as discussed previously. Marginal-marine South Maslin Sand overlies Clinton Formation in the City area, either conformably, or as at Montefiore Hill, with apparent erosional disconformity. Several cross-sections suggest a conformable and interfingering relationship with more or less carbonaceous quartz sands (South Maslin Sand) which display increasing marine influence upwards (glauconite, shelly fossils).

Elsewhere in the Golden Grove-Adelaide Embayment, Clinton Formation also, as a rule, overlies weathered bedrock (Plan 4). However, because of diachronous deposition, the sands which generally overlie Clinton Formation are not always time-correlatives of South Maslin Sand. For example, in the Hope Valley area, preliminary results of a recent drilling programme (Reed, in prep.) suggest that Clinton Formation is overlain by sands which are lateral equivalents of poorly-fossiliferous marginal Blanche Point Formation.

In the Adelaide Plains Sub-Basin, Clinton Formation may have various relationships, as summarised in Plans 2 and 4. For example, at Port Gawler, in SADME Observation bore PTG-13, Clinton Formation is underlain by typical North Maslin Sand,

with a sharp contact; and is overlain, probably conformably and gradationally, by South Maslin Sand. SADME Observation bore MUW-11 at Gawler South, on a fault-block at the eastern edge of the St Vincent Basin, revealed that Clinton Formation there rests on bedrock and is overlain by a thick wedge of unfossiliferous Plio-Pleistocene Carisbrooke Sand. North of Mallala, towards Port Wakefield and Balaklava, Clinton Formation is overlain by marginal-marine sands and clays which have been correlated with Rogue Formation (Cooper, 1977a; Cockshell et al., 1978).

Biostratigraphy and Age

Beneath the City of Adelaide, Clinton Formation has yielded no undoubted records of 'marine'-type shelly fossils, or glauconite. No cores contain such elements, although a core from high in Clinton Formation in the SADME West End Brewery bore contains faecal pellets, some pyritised. Sludge samples tend to be contaminated by downhole cavings from the overlying marginal-marine South Maslin Sand, so that it becomes difficult to decide what is in situ. However in view of the indications that Clinton Formation at some localities has a conformable and interfingering contact with South Maslin Sand, some weak marine influence might be expected in the upper part.

Elsewhere in the St Vincent Basin, the situation is much the same, with only poor and doubtful evidence of any shelly fossils or glauconite in Clinton Formation. However studies in progress by W.K. Harris indicate that 'marine-type dinoflagellates occur sporadically throughout the unit, and indicate some degree of marine influence' (W.K. Harris, W.M.C., personal communication, October, 1980). This might imply that glauconite, and shelly fossils, such as foraminifera, were

originally present but have been leached out of the unit by groundwater acidised perhaps by the breakdown of pyrite. However there is no evidence that this occurred - for example the presence of moulds of fossils. Neither is it thought likely that glauconite pellets could be so removed without trace. The author considers rather that the anomaly indicates a greater sensitivity to faint marine influence on the part of 'marine'-type dinoflagellates, than that which operates for glauconite and 'marine'-type shelly fossils. This is a current topic of study by W.K. Harris, and will not be pursued further here. It does appear though, that early effects of the Eocene marine transgression into the St Vincent Basin were manifested in Clinton Formation prior to deposition of South Maslin Sand. Similarly, marine influence becomes apparent near the top of North Maslin Sand, at the stratotype and at Christies Beach, as discussed earlier.

When describing Clinton Coal Measures, Harris (1966) indicated that 'in the Clinton and Snowtown areas the unit is divisible into an Eocene (middle-upper) and a mid-Tertiary phase on palynological evidence. Elsewhere the unit is of middle-upper Eocene age'. However subsequently Harris (1970) identified in stratotype Clinton Formation both the Triorites magnificus Zonule (Middle to Upper Eocene) and the Aglaoreida barungensis Zonule (Upper Eocene to ?Oligocene), hence the correlation of the stratotype in Plan 3 - high Middle Eocene to basal Oligocene. He also indicated elsewhere, on the basis of unpublished palynological information (Harris in Ludbrook, 1967, fig. 3) that Clinton Coal Measures were deposited in three episodes: the first through Middle Eocene into Upper Eocene; the second, Upper Eocene; and the third, Oligocene to

basal Miocene. In the SADME Barunga-4 bore, near Snowtown, he reported (Harris, 1970, p.60) that at 74.4-75.9 m the Clinton Formation yields the Triorites magnificus Zonule (Middle to Upper Eocene; Harris, 1971; McGowran et al., 1971), while the upper phase, sampled at 65.5 m, is ?Lower Miocene. This upper phase contains Sparganiaceaepollenites barungensis (Harris, 1972). It is evident that these phases of Clinton Formation are time-correlatives and coaly facies of several units, such as North Maslin Sand, South Maslin Sand, Chinaman Gully Formation, and Port Willunga Formation (in part).

However, in the Wakefield (Inkerman-Balaklava) Coalfield the whole carbonaceous sequence of Clinton Formation in SADME bore 32 (Hillwood, 1961) was shown to contain the Triorites magnificus Zonule by Harris (1970, p. 60). Further south, at Port Gawler, Clinton Formation is older, samples from SADME Observation bore PTG-13 being determined as Proteacidites pachypolus Zonule, Middle Eocene (Harris, 1970, p. 56). Beneath the Adelaide City area, for example in the SADME South Parklands and West End Brewery bores, and in the Longyear bore at the southern end of the Adelaide Plains Sub-Basin, Clinton Formation is also P. pachypolus zone, of similar age (W.K. Harris, personal communication, January 1980).

Environment of Deposition, and Regional Events

The evidence discussed above suggests a scenario of coal-forming swampy tracts around the eastern and northern marginal areas of the St Vincent Basin during deposition of Clinton Formation. At least some of the swamps occupied saucer-shaped depressions in clayey weathered bedrock; others abutted

fault-scarps in fault-angle depressions. Intermittent marine influence gave rise to salty and brackish lagoons, swamps and marshes, or chains of lakes.

Pale grey to pale brown underclays or seat-earths occur typically below the lower lignites of Clinton Formation. In places, partly-mineralised rootlets are preserved. Subspherical sideritic (and often, pyritic) spherulites or glaebules occur abundantly in the underclay, and also in the uppermost few metres of weathered bedrock. They were reported on by Scott (1966), and are similar to those described by Wilson (1965), Reading (1978), and Seiglie et al. (1979). The latter authors report such spherulites to form, a) in fresh and brackish-water environments associated with the accumulation of coals; b) in fine sediment containing abundant comminuted plant tissue; c) in environments with pH higher than 7.0; and d) at the sediment-water interface where bacterial activity is at a peak.

Oxygen-isotope palaeotemperatures (Plan 35) suggest that a warm climate prevailed during deposition of Clinton Formation in the Middle to Late Eocene. It was probably moist and sub-tropical, similar to that during deposition of the North Maslin Sand clay lens, discussed earlier.

According to Vail et al. (1977), and Vail and Mitchum (1978), global sea level at this time was substantially higher than at present, and generally on a rising eustatic cycle (TE2). Harris (1980b) has intimated recently that he has found a close relationship between such cyclic rising sea-levels and the timing of the development of Tertiary basin-margin lignites in South Australia.

The Middle and Upper Eocene phases of Clinton Formation (Plan 3) were deposited in McGowran's 'Sequence 2' (McGowran, 1978a, 1979b), as shown in Plan 35.

SOUTH MASLIN SAND

Introduction

It is important to record, first of all, that South Maslin Sand does occur as a distinctive and significant unit beneath the City of Adelaide, as it does in the Adelaide Plains Sub-Basin (Lindsay, 1969) and at the coastal stratotype at Maslin Bay (Reynolds, 1953).

Nomenclature

In view of the above, and contrary to the proposal by Cooper (1977b, 1979b) the writer prefers to maintain the formational status of South Maslin Sand as described originally by Reynolds (1953), rather than relegating it to member status within a composite formation: 'Maslin Sands'.

Type Section

The typical development of South Maslin Sand at Maslin Bay is at least 30 m thick (Reynolds, 1953), and is thus comparable in thickness with the type sections of Blanche Point Formation and Port Willunga Formation. The writer commented on the South Maslin Sand stratotype (Lindsay, 1969, p.31) that it consists 'of poorly fossiliferous sands which in their exposed and oxidised state are coloured brown, purple, and green, with many ferruginous grains and coatings, some at least being oxidised glauconite. Some weak calcareous and ferruginous cementation is developed. Animal remains include rare foraminifera, echinoid spines, sponge spicules, Bryozoa, and a small fauna of Upper Eocene molluscs (Ludbrook, 1963a, 1969b)'. The formation therefore contrasts both with the underlying North Maslin Sand (almost all non-marine, non-glauconitic, and lacking in animal remains) and with the overlying richly fossiliferous Tortachilla Limestone.

Boundary relationships with North Maslin Sand at the A.B.M.-Readymix sand quarry, Maslin Beach, were discussed earlier under NORTH MASLIN SAND.

Lithology

The writer first identified a subsurface expression of the formation in the Willunga bore WB-1, 5 km inland from Maslin Bay; and then as a widespread subsurface unit in the Adelaide Plains Sub-Basin (Lindsay, 1969). In these largely unoxidised facies, South Maslin Sand comprises dark silty quartz sand, carbonaceous and pyritic, displaying an up-section increase in both glauconite and marine microfauna. Where the formation occurs relatively close to the surface beneath the City of Adelaide, and has been exposed to oxidising conditions, for example at Montefiore Hill (Ref. bore 25, Plan 5) or Wellington Square (Ref. bore 60), it displays red, brown, or yellow coloration. However elsewhere it is mostly dark grey-brown or black, in a reduced state.

The formation was penetrated by continuous tube-coring in 'Carclew' CH-2, Montefiore Hill (Ref. bore 25). The bores were logged by P.D. Allchurch (1966) in an engineering geology investigation, and samples were also examined by the writer.

The following sequence is present:

TOP

Silt, very fossiliferous and glauconitic, with a few limestone bands (Tortachilla Limestone equivalent).

South Maslin Sand

26.4-29.7 m: silty quartz sand, compact, mostly well-sorted, very fine to fine-grained; less well sorted in the lower part, with coarse and gritty grains more prominent; colours, yellow-brown in the lower part, mottled red-brown/pale greenish grey in the upper part; increasingly glauconitic up-section; slightly ferruginous, non-calcareous, finely micaceous; bedding well shown as varicoloured laminae 1-3 mm thick, with some cross-bedding apparent; a few small, poorly-preserved foraminifera and an ostracode valve were found at 26.8-27.1 m, but no animal remains at 28.3-28.7 m.

Thin lignite at top of Clinton Formation

BOTTOM

Adelaide Subway CH-8, Wellington Square, North Adelaide (Ref. bore 60) yielded a continuously-cored section of South Maslin Sand showing a marked change in colour downhole through an oxidation/reduction boundary. As logged by Robertson (1974) and also observed by the writer, mottled orange, maroon, and grey clayey sand occurs from 27.3 to 29.0 m, groundwater being cut at 27.7 m. Grey-green, fine, less clayey sand was intersected from 29.0 to 30.3 m; dark grey fine sand from 30.3 to 32.5 m; and black fine sand from 32.5 m to total depth of 34.8 m.



Figure 60. Clinton Formation/South Maslin Sand transition (see Plan 27), Adelaide City area; SADME South Parklands bore (Ref. bore 41), from tube-core at 100.0-100.3 m; dark greyish-brown, compact, clayey and silty, fine-grained quartz sand, carbonaceous, pyritic, very sparsely glauconitic; no shelly fossils, non-calcareous.



Figure 61. As above, but portion of disaggregated and washed residue, comprising mostly angular/subangular fine-grained quartz sand, together with fine-grained mica flakes, pyrite (including pyritised plant fragments, and a few cemented pyrite-quartz aggregates), and rare glauconite grains.

Several fully-cored foundation test bores for the Morphett St and Victoria Bridges bottomed in South Maslin Sand as shown in Plan 15 (after Lindsay, 1964b; Robson, 1964). A core-sample from 25.0-25.3 m, 3½ m below the top of South Maslin Sand, comprises dark grey-brown carbonaceous quartz sand, poorly-sorted, clayey, silty, gritty and pebbly (rounded quartz pebbles up to 20 mm diameter). The sand is notably pyritic (pyrite-quartz-glauconite-shell aggregates up to 25 mm, and fine-grained pyrite octohedra), part shelly and part non-calcareous, friable to compact, and with scattered hard pyrite-cemented lumps.

Summary lithological descriptions are given of the formation as penetrated in SADME South Parklands bore (Plan 27), SADME West End Brewery bore (Plan 28), and the Croydon-2 bore (Plan 29).

Colour photographs (Figs 60,61) compare the appearance of raw and washed core from the gradational boundary, at depth 100 m, between South Maslin Sand and underlying Clinton Formation in SADME South Parklands bore (Plan 27).

The historic Kent Town Waterworks bore (Ref. bore 31) penetrated 14 m of South Maslin Sand, beneath Tortachilla equivalents and above lignitic Clinton Formation. The interval was logged by Tate (1882) as:

218-252 ft (66.4-76.3 m), unit 25 - 'very fine grey sand',

252-264 ft (76.3-80.5 m), unit 26 - 'very fine grey sand with carbonaceous debris, containing water-worn pebbles and rolled fragments of shell of species occurring in no. 24'.

Two samples representing core from these intervals, were examined by the writer. The upper one (unit 25) comprises grey-brown quartz sand, mostly fine-grained, some up to very coarse, with a few angular to rounded quartz pebbles to 15 mm diameter; silty, slightly clayey; micaceous, sparsely glauconitic and pyritic; carbonaceous, and with wood fragments; rare mollusc fragments, occasional small benthonic foraminifera, a few ovoid faecal pellets. The lower sample (unit 26) comprises brownish-grey and black quartz sand, very fine to coarse-grained, rather poorly-sorted but much is fine-grained; a few quartz and quartzite pebbles up to 6 mm diameter; silty, somewhat clayey; carbonaceous, and with abundant dark brown and black carbonised wood and lignite fragments up to 10 mm; sparse glauconite and pyrite; very rare fragments of molluscs and foraminifera; occasional ovoid faecal pellets.

The writer previously (Lindsay, 1969, p. 32) summarised the South Maslin Sand section penetrated by SADME Observation bore A2 (MPA 64, 65) near Virginia in the Northern Adelaide Plains (Plan 2).

In the Longyear bore, southern Adelaide Plains (Plan 2), South Maslin Sand separates typical Tortachilla Limestone above, from lignitic Clinton Formation, below. The section comprises:

213.4-213.5 m: pale to dark brown muddy quartz sand, glauconitic and ferruginous.

213.5-221.9 m: dark brown glauconitic quartz sand with occasional shelly fossils.

221.9-223.6 m: dark brownish-grey silty quartz sand; glauconitic, micaceous.

Cooper (1979b, Appendix 1, pp. 78-79) included petrographic descriptions (from AMDEL reports) of three outcrop samples of stratotype South Maslin Sand which were collected by himself and the writer.

Distribution

The distribution of South Maslin Sand in the Adelaide City area, and structure contours of its base, are plotted in Plan 19. Cross-section L-M (Plan 11) illustrates the interesting occurrence of the formation at a shallow depth beneath Quaternary alluvium, in Reference bore 39, War Memorial Drive, near the Municipal Golf Links.

The formation is developed through the Adelaide Plains Sub-Basin (Plan 2) from the Longyear bore at the southern extremity to at least as far north as Dublin (Lindsay, 1969, Appendix 2, p. 55, ref. bore 2). However it is not known from further up the Golden Grove-Adelaide Embayment than the Kent Town bore (Ref. bore 31). As in the Noarlunga Embayment, it may be partly replaced by time-correlative Clinton Formation. Cooper (1979b, p.65) has indicated the wide distribution of South Maslin Sand in the Willunga Embayment.

Thickness

Thicknesses of the formation in various boreholes in the Adelaide City area are tabulated in Appendix B. Complete penetrations range from a minimum of 3.3 m to a maximum of 18.3 m, and Cross-section L-M (Plan 11) which includes these two extremes, displays the greatest variability in thickness of the formation. Most of the other cross-sections (Plans 6-9, 12-14) portray a more even thickness of the order of 10 m.

However Cross-section J-K (Plan 10), drawn along the eastern City margin, suggests that South Maslin Sand may attain a thickness of 20 m or more in the southeast of the City area.

At the southern end of the Adelaide Plains, South Maslin Sand in the Longyear bore (Plan 2) has a thickness of 10.2 m, similar to that in the City area. In the Northern Adelaide Plains, thicknesses in the SADME Port Gawler, Buckland Park, and Virginia bores are comparable with that of the Maslin Bay type section, i.e. of the order of 30 m. The formation attains a maximum thickness of 42 m in Croydon-2 bore (Plan 29).

Stratigraphic Relationships

Beneath Adelaide City, South Maslin Sand is underlain by Clinton Formation with conformable or disconformable contact. In downhole succession, the boundary is marked by entry into carbonaceous clay or lignite. The SADME South Parklands bore (Plan 27, Figs 60,61) and the SADME West End Brewery bore (Plan 28), appear to have transition beds of carbonaceous muddy sand or sandy mudstone, but details are masked in the sludge samples. On the Montefiore Hill 'high', the cored contact with an underlying thin bed of lignite in Reference bore 25 is sharp and possibly erosional (see Cross-section L-M, Plan 11).

At the northern end of the Mile End Block (Cross-section R-S, Plan 14) South Maslin Sand rests with apparently sharp contact on white clay which was interpreted by Miles (1952, p. 203, bore 404) as completely weathered slaty bedrock.

In the Adelaide Plains Sub-Basin, South Maslin Sand generally overlies Clinton Formation with a sand/clay or sand/lignite contact. Continuous core in the Longyear bore (Plan 2) reveals a sharp contact at 223.6 m between dark brownish-grey glauconitic quartz sand, and black lignite. In the SADME Port Gawler bore (Plan 2), the contact is at 309.4 m where dark, carbonaceous clayey sand with minor glauconite, overlies pale brown, smooth, carbonaceous clay (Lindsay, 1965a). However in the SADME Virginia bore, South Maslin Sand is underlain by North Maslin Sand, as discussed earlier in connection with that unit.

In the Noarlunga Embayment, South Maslin Sand is replaced, in part, by carbonaceous and lignitic clay and silt of the Clinton Formation, as shown in the stratigraphic correlation chart (Plan 3). This carbonaceous facies can be observed on the south bank of the Onkaparinga River immediately south of Noarlunga township (Lindsay in Daily et al., 1976, p. 26). In the Seaford drainage bore (Plan 2), whose stratigraphy was recently outlined by Cooper (1980), the writer considers it doubtful that any South Maslin Sand is present. The questionable 4 m-interval (132-136 m) so identified by Cooper, was geologically logged as black, lignitic, sandy clay, and seems better included in Clinton Formation together with Cooper's underlying 'upper unit of North Maslin Sand Member'. Grains of glauconite present in sludge samples from 132-136 m may be downhole contaminants, or may represent marine influence in uppermost Clinton Formation.

The upper contact of South Maslin Sand with Tortachilla Limestone or its equivalents, varies from unconformable to disconformable or gradational. Cooper (1979b, p. 18) has recently discussed the contact with Tortachilla Limestone at the type section, and the writer agrees that, broadly speaking, the limestone/sand boundary, which was adopted by Reynolds (1953), is the most practical and should be maintained. However Reynolds also noted (1953, pp. 123-124) that the basal part of stratotype Tortachilla Limestone may be an unconsolidated, brown, 'polyzoal limonitic sand'. The boundary between this facies and top South Maslin Sand is less obvious, especially in bore sludges, but can be picked by a rapid downhole deterioration in diversity, abundance, and preservation of fauna.

This boundary was more or less continuously cored beneath the City of Adelaide, in three major engineering geology projects with which the writer was associated:

a) Adelaide Subway Study (Robertson, 1974), bores CH/DDH-3 (Ref. bore 38), CH/DDH-6 (Ref. bore 40), CH-7 (Ref. bore 28), and CH-8 (Ref. bore 60).

b) Proposed Festival Hall, 'Carclew', Montefiore Hill (Allchurch,1966), bores CH-1 (Ref. bore 24), CH-2 (Ref. bore 25), and CH-4.

c) Morphett St and Victoria Bridges (Robson, 1964; Lindsay, 1964b), CH-5 (Ref. bore 3), CH-11 (Ref. bore 4), CH-12 (Ref. bore 5), and CH-14 (Ref. bore 6).

Boundary depths are tabulated in Appendix B. In Ref. bores 38 and 40, dark grey-green, shelly, glauconitic calcareous clay, silt, and fine sand ('sandy glauconitic marl') overlies

black, non-shelly, non-calcareous, clayey quartz sand. In Ref. bore 28, greenish-grey, glauconitic sandy silt passes down into grey clayey fine quartz sand with occasional shelly fragments. In Ref. bore 60, pale yellow-brown glauconitic limestone and marl overlies a transitional, half-metre bed of iron-stained, maroon sandy clay, which in turn overlies varicoloured clayey sands. At the 'Carclew' site, yellow-brown and grey-green, notably fossiliferous glauconitic silt, with thin and patchy bands of glauconitic limestone, overlies yellow-brown silty fine quartz sand. Plan 15 shows the nature of the lithological change beneath the Morphett St and Victoria Bridges, especially in CH-14 (Ref. bore 6) where Robson (1964) considered that the boundary was gradational.

The nature of the South Maslin Sand/Tortachilla-equivalent boundary is also shown for the SADME South Parklands bore (Plan 27), the SADME West End Brewery bore (Plan 28), and the Croydon-2 bore (Plan 29).

In the cored Longyear bore (Plan 2), basal Tortachilla Limestone is typically developed as a glauconitic and calcarenitic shelly limestone, which is brown, green and grey in colour, and hard to soft and friable. The contact with top South Maslin Sand is put at 213.4 m, where brown, muddy, glauconitic and ferruginous quartz sand is entered.

Biostratigraphy, Age, Environment of Deposition, and Regional Events

Marine foraminiferal microfaunas occur towards the top of South Maslin Sand in a number of boreholes in the City of Adelaide and the Adelaide Plains. For instance, in Morphett St and Victoria Bridges CH-14, in core from 25.0-25.3 m, 3½ m below the top of the formation, foraminifera are moderately varied, and include:

Cibicidoides umbonifer (Parr) (f)

Bolivinopsis cubensis (Cushman and Bermudez) (r)

Anomalinoides fasciatus (Stache) (v)

Asterigerina adelaidensis (Howchin) (v)

Cibicides vortex Dorreen (v)

Glabratella crassa Dorreen (v)

Gyroidinoides octocamerata (Cushman and Hanna) (v)

Spirillina medioscabra (Carter) (v)

and the planktonic form:

Pseudohastigerina micra (Cole) (v).

This microfauna is definitely marine. However the small planktonic component, the sparse bryozoal and echinoid fragments present, and the quartzose, pebbly, carbonaceous, and pyritic lithology (described earlier), suggest relatively near-shore deposition with restricted access to open-marine influence, and a reducing environment.

A core sample of dark grey silty quartz sand, from near the bottom of the same hole, taken at 26.8-27.1 m, 5½ m below the top of the South Maslin Sand, contains pyritised wood fragments, rare mollusc fragments ('Turritella', scaphopods, bivalves), occasional bryozoal and echinoid fragments, and very sparse foraminifera (only benthonic) including:

Cibicidoides umbonifer (v)

Cibicides vortex (v)

Cyclogyra sp. (v)

Oolina hexagona (Williamson) (v)

and Trifarina bradyi (Cushman) (v).

This is a more restricted marine microfauna, although the absence of agglutinated forms is noteworthy. The sample contains abundant pyritic aggregates, much dark brown carbonaceous mud, and is moderately glauconitic (frequent very fine emerald-green grains).

According to the simple fourfold classification of Selley (1978, p. 28), such glauconitic and carbonaceous muddy sands were deposited in marine, poorly-winnowed, submarine channels or fans.

Harris (1964) studied the palynology of two samples from South Maslin Sand in the same bore. The microplankton from the lower sample, at 27.1 m, suggested 'restricted access to marine conditions', while those from 25 m and higher 'indicated increasing marine conditions'. This agrees with the evidence of the animal fossils, which point to increasing marine influence up-section with the progress of the marine transgression. It is of interest that the sample from 25 m yielded the reworked Permian spore Nuskoisporites sp.

In the SADME West End Brewery bore (Plan 28), a core sample of dark grey-brown, muddy, carbonaceous, fine quartz sand, from 55.0-55.3 m, 4 m below the top of South Maslin Sand, yielded rare small benthonic foraminifera, together with one specimen each of three planktonic species:

Chiloguembelina cubensis (Palmer)

Globigerina bulloides s.l.

Globigerina officinalis Subbotina.

These are evidently hardy forms which can persist in marginal marine conditions. The sample is sparsely glauconitic.

In the SADME South Parklands bore (Plan 27) a sludge sample from 97-99 m, 1-3 m below the top of South Maslin Sand, shows only minor evidence of downhole contamination, and yields a small foraminiferal fauna which includes the tolerant planktonics Chiloguembelina cubensis and Globigerina bulloides s.l.

As outlined by Lindsay (1965a; 1969, p. 32), apparently reliable sludge samples from the top 4½ m of South Maslin Sand in the SADME Port Gawler bore (Plan 2), yielded a benthonic microfauna which expands upwards in diversity and abundance, including:

Gen. nov. cf. Bolivinella sp. nov.
Crespinina kingscotensis Wade
Linderina sp. nov.
Maslinella chapmani Glaessner and Wade,
and Pseudopolymorphina sp. nov.

This is an assemblage with indications of deposition in warm water. It is possible (but not proven) that the assemblage here is of stratotype Tortachilla age in South Maslin Sand lithology, which would illustrate a diachronous top to the South Maslin Sand. However in Plan 35, top South Maslin Sand and Tortachilla Limestone together are shown as marking the first of the two or three South Australian Late Eocene warm transgressive episodes with 'extratropical excursions of foraminifera' which have been noted by McGowran (1971, 1979b) and Lindsay (1976).

In Plan 36, four species of planktonic foraminifera (Chiloguembelina cubensis, Globigerina bulloides (s.l.), G. officinalis, and Pseudohastigerina micra) are shown as making their local initial appearance near the top of the

South Maslin Sand. At this level, Ch. cubensis and G. bulloides (s.l.) occur in SADME South Parklands bore (Plan 27) and in SADME West End Brewery bore (Plan 28); G. officinalis in the latter bore, and Ps. micra in Morphett St and Victoria Bridges bore 14 (Ref. bore 6, Plan 15). However all these entries are facies-controlled, and so lack biostratigraphic significance for dating the formation. The same can be said for all the benthonic species appearing in South Maslin Sand (Plan 37) except for Sphaeroidina bulloides (South Parklands bore, Plan 27), which was not found lower than Upper Eocene in New Zealand by Hornibrook (1961).

Apart from Sphaeroidina bulloides, there is no direct evidence from the sparse foraminiferal faunas in South Maslin Sand which might discriminate between a Middle and a Late Eocene age. Acarinina primitiva (Finlay), which does not range above the Middle Eocene Zone P.14 (Blow, 1979) is not known from the St Vincent Basin. There are a few age constraints on Tortachilla Limestone which will be discussed later in connection with that formation, but which suggest that it is no older than Zone P.15, early in the Late Eocene. McGowran (1979b) so dates the top South Maslin Sand/Tortachilla Limestone 'extratropical excursion', on the basis of inter-regional correlations, hence at least the upper part of South Maslin Sand is probably Upper Eocene as shown in Plan 3. Ludbrook (1963a, 1969b) has continued to maintain the Upper Eocene aspect of small and poorly-preserved molluscan faunas which occur at various horizons in the upper part of stratotype South Maslin Sand (Reynolds, 1953).

On palynological considerations, the North Maslin Sand in and near the stratotype is all Middle Eocene, as discussed earlier. Some lower portion of the overlying South Maslin Sand is also likely to be Middle Eocene, depending on the extent of any hiatus between the two formations. McGowran (1978b) showed most of the South Maslin Sand to be Middle Eocene (Zone P.14).

Given the age-data suggested above, the deposition of South Maslin Sand appears not to fit neatly into the global eustatic sea-level cycles proposed by Vail et al. (1977) and Vail and Mitchum (1978). The Middle Eocene part of the formation would correspond to relatively high and rising sea levels in the upper part of Cycle TE2.2, separated by a significant drop in sea level from the Upper Eocene part of the formation at the beginning of Cycle TE3. There is a lack of local evidence for a distinctive break within South Maslin Sand at the Middle/Upper Eocene boundary. It would fit the Vail cycles more neatly if such a eustatic event and associated stratigraphic break were to correspond with the South Maslin Sand/Tortachilla Limestone boundary, or with the hiatus/hard-ground in stratotype Tortachilla Limestone reported by Buonaiuto (1977). However these alternatives are not compatible with the present indications that the upper part of the South Maslin Sand is Upper Eocene.

South Maslin Sand accumulated as a pre-carbonate phase of depositional Sequence 2 of McGowran (1971, 1978a, 1979b).

UNDIFFERENTIATED TORTACHILLA LIMESTONE AND BASAL BLANCHE POINT FORMATION

Introduction

Tortachilla Limestone and its equivalents, together with basal Blanche Point Formation (beneath the Gull Rock Member), are treated together in the Adelaide City area for reasons which were outlined previously by the writer in a study of the Adelaide Plains Sub-Basin (Lindsay, 1969, p.32), and are stated in similar terms here.

The three members which Reynolds (1953) distinguished in this interval at Maslin Bay are all notably fossiliferous, and comprise respectively, brown bryozoal ferruginous sand, hard pink white and green limestones with clayey pockets and grains of goethite and iron-stained quartz, and green and dark grey glauconitic mudstone to muddy greensand. The total thickness is less than 5 m. The combined interval, with varying proportions of these lithologies, is widely recognisable as a marker unit in the St Vincent Basin, but in the Adelaide Plains Sub-Basin and the Adelaide City area, it is generally impractical to differentiate the individual members or formations. Even in the Willunga bore WB-1, only 5 km inland from the type sections, the equivalent interval, less than 2½ m thick, has a mixture of lithologies ranging from greenish and brownish-grey glauconitic ferruginous 'sandy marl', to yellow-grey and brown sandy clayey calcarenitic limestone, and brown ferruginous pelletal sand.

The descriptions of the interval as encountered subsurface in the Adelaide Plains and Adelaide City area, quoted in part above (Lindsay, 1969) are still relevant and valid. The writer also subsequently contributed summary descriptions of these

(and other) Tertiary units as they are developed both at the coastal type sections and elsewhere through the eastern St Vincent Basin, including the Adelaide City area (Lindsay in Daily et al., 1976, pp. 21-35).

Tortachilla Limestone, Blanche Point Formation, and other Tertiary units in the Willunga Embayment, have been described recently by Cooper (1979b) from bores and outcrops, including the coastal stratotypes.

Nomenclature and Type Section

Cooper (1977b, 1979b) followed Buonaiuto (1977) in regarding the green glauconitic limestone member at the Maslin Bay stratotype, not as the top unit of the 'Tortachilla Limestones' as defined by Reynolds (1953), but as the basal part of the Blanche Point Formation. However from the point of view of mappability as a limestone unit (at least in the coastal exposures of the Willunga and Noarlunga Embayments) the writer prefers to use the obvious lithological boundary between hard greenish limestone and soft glauconitic mudstone, as defined by Reynolds, despite evidence of hardground disconformity within the limestone formation.

In his revision of stratigraphic nomenclature for the Willunga Embayment, Cooper (1977b) did not designate any formal name for the basal member of Blanche Point Formation, which had been named 'Blanche Point Transitional Marls Member', by Reynolds (1953). This part of Blanche Point Formation, which lies beneath the chert-banded Gull Rock Member and above the Tortachilla Limestone, thus remains simply as 'basal Blanche Point Formation'.

Lithology

Cooper (1979b, Appendix 1) included petrographic descriptions, by AMDEL authors, of two rock samples from stratotype Tortachilla Limestone at 'Uncle Tom's Cabin', Maslin Bay. One sample (P 37/77), from 10-20 cm above the base of the formation, is described as a sandy pelletal limestone, which contains 10-20% angular to rounded quartz grains partly coated or replaced by brown goethite-limonite (0.03-1 mm), 10-30% calcitic shell fragments, and 10-20% brown ovoid to irregular-shaped pellets and pebbles of goethite-limonite-?clay (in part altered glauconitic faecal pellets), all in a brown to off-white finely crystalline matrix of calcite (30-50%). The other sample (P 38/77), taken from 70 cm below the top of Reynolds' middle 'polyzoal limestone unit' of Tortachilla Limestone, is a pale pink/cream bioclastic limestone, containing 70-80% broken calcitic shell fragments, 3-6% brown goethite-limonite pellets (mostly oxidised glauconitic faecal pellets), and only 2-4% quartz grains (0.03-0.3 mm; in part coated or replaced by goethite-limonite) all in a mineral matrix of very finely crystalline calcite (10-20%).

A third petrographic description included by Cooper (sample P40/77) is of a limestone band within the 'Blanche Point Transitional Marls Member' of Reynolds (1953), 10-30 cm above the base of Blanche Point Formation at 'Uncle Tom's Cabin'. This sample is described as a pale cream/brown bioclastic limestone, of very similar lithology to Tortachilla Limestone sample P 38/77. Thus, even in the type section, 'Tortachilla Limestone' lithology persists up into the green/grey fossiliferous glauconitic mudstone and muddy greensand of basal Blanche Point Formation. As mentioned earlier, in the Adelaide City area this combined stratigraphic interval of Tortachilla Limestone/basal

Blanche Point Formation is expressed less in typical 'Tortachilla Limestone' lithology, and more in the glauconitic mudstone/greensand ('marl') facies.

However, 'Tortachilla' facies does occur in the Adelaide City area, and in one locality at least, is documented petrographically, namely in diamond drill core from Ref. bore 40, Brougham Place, North Adelaide. A petrographic description by Radke (1978) is included in Appendix C herein (sample P742/78). The rock is described as a pale greenish-grey fossiliferous and glauconitic limestone. Reddish-brown ferruginous pellets (mostly oxidised glauconitic faecal pellets) comprise 15% of the rock, fine-grained quartz sand a subordinate 5%, while opaline silica is present only in traces, whereas it is an important constituent of hard cherty bands in the overlying Gull Rock Member of Blanche Point Formation. Bands of fossiliferous glauconitic and ferruginous limestone, equivalent to Tortachilla Limestone, were also penetrated beneath North Adelaide at the 'Carclew' site, Montefiore Hill (Allchurch, 1966; e.g. Ref. bores 24, 25). Similarly, Ref. bore 60, Wellington Square, North Adelaide (Robertson, 1974) penetrated hard bands of yellow brown and green fossiliferous ferruginous and glauconitic limestone, representing Tortachilla Limestone. At its base, the interval 26.1-26.7 m was too hard to tube-core and had to be drilled.

A band of hard grey-green glauconitic shelly limestone at 25.6-25.8 m in Ref. bore 38, Memorial Drive (Robertson, 1974) is regarded as Tortachilla facies intercalated in dark grey-green glauconitic mudstone/greensand which is more typical of basal Blanche Point Formation. A similar intercalation of hard limestone at 33.6-34.2 m in Ref. bore 40, Brougham Place (Robertson, 1974) is also regarded as Tortachilla Limestone facies,

and is illustrated in Figure 62. The Hantkenina zone occurs immediately above, at 32.5-33.5 m (Lindsay and Webb, 1979, p. 16, sample F20/78) in soft, dark greenish-grey, muddy greensand/ glauconitic mudstone (basal Blanche Point Formation). Dark, abundantly shelly, soft mudstone, pyritic and glauconitic, underlies the limestone band, and is in turn underlain by South Maslin Sand (see Appendix B).

Where only sludge samples are available in such successions, as in Ref. bore 32, West Terrace, a mixture of lithologies is encountered through the combined interval of Tortachilla Limestone equivalents/basal Blanche Point Formation ('TL/basal BPF'). There is often evidence of both rubbly carbonate cementation, and of alternating hard and soft bands. In Ref. bore 32, between 62.5 and 72.0 m, lithologies include: greenish and brownish-grey glauconitic shelly mudstone, muddy greensand, and glauconitic ferruginous limestone, all notably fossiliferous. Glauconitised shell fragments increase in abundance downhole as this stratigraphic level is approached. There is also through the unit, a downhole increase in brown, ferruginous, coloration, and in the content of brown iron-stained quartz sand.

In Ref. bore 7, A.M.P. building, North Terrace (Lindsay, 1965b) the upper part of 'TL/basal BPF' was diagnosed from a sludge sample at 45.7-47.2 m, representing dark greenish and brownish-grey, abundantly glauconitic and fossiliferous mudstone, siltstone, and limestone, with some siliceous chalcedonic patches; Hantkenina was found in this sample. A sealed-tube core from 47.2-47.5 m comprised dark greenish and brownish-grey very glauconitic shelly mudstone or muddy greensand, with many glauconitised mollusc fragments, and abundant brownish-green

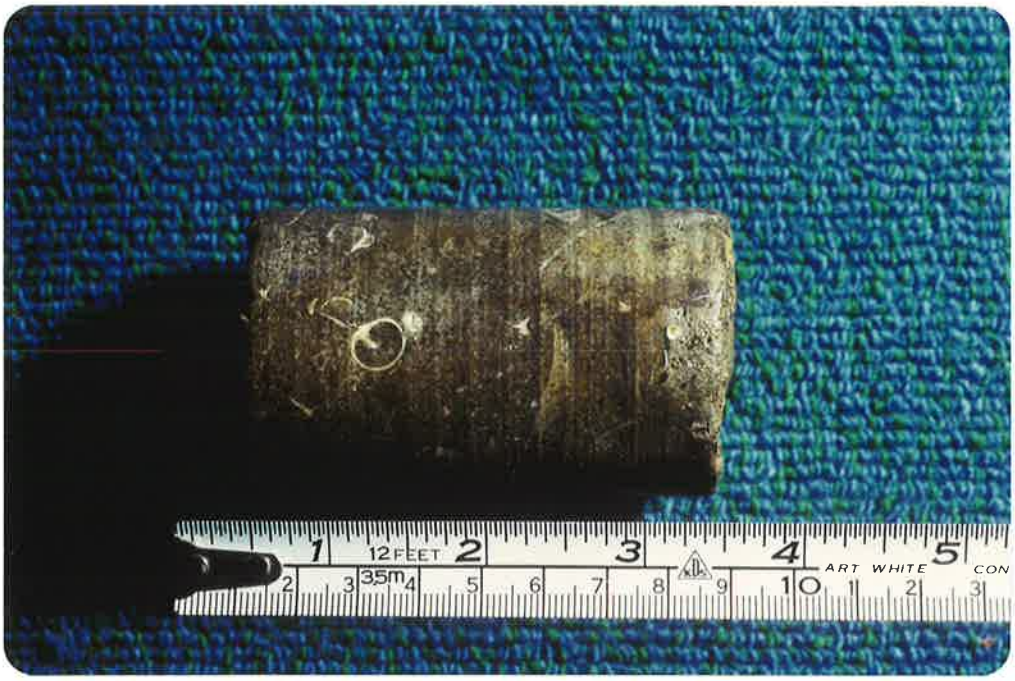


Figure 62. Tortachilla Limestone, Adelaide City area; Adelaide Subway Study, DDH-6, Brougham Place, North Adelaide (Ref. bore 40); core at 33.6-33.7 m (immediately below Hantkenina zone); hard, greenish and brownish-grey limestone, with a few darker grey pods of chert; shelly, glauconitic, ferruginous (goethite-limonite pellets, aggregates), quartz-bearing (brown to colourless, subrounded, sand-sized).



Figure 63. Tortachilla Limestone, Adelaide City area; SADME West End Brewery bore (Ref. bore 10); portion of tube-core at 50.0-50.3 m (cf. Plan 28), 4 m below Hantkenina zone; soft, pelletal, glauconitic, shelly mudstone, with minor rubbly limestone cementation.

partly oxidised glauconitic aggregates; quartz is present as mainly very fine-grained to a little coarse-grained sand. A further sealed-tube sample at 47.5-47.7 m is similar, with abundant ferruginous and glauconitic aggregates, but also contains pale brown silty limestone to calcareous siltstone, is more sandy, and is in part darker and carbonaceous. The succession suggests passage downwards from basal Blanche Point Formation to Tortachilla Limestone equivalents.

As shown in Plan 15, boreholes for the Morphett St and Victoria Bridges project (Robson, 1964; Lindsay, 1964b) penetrated the 'TL/basal BPF' interval in mainly fossiliferous mudstone/greensand facies which could all be tube-cored. The upper part, with the Hantkenina zone, contained patches and thin bands of hard spicular cherty siltstone reminiscent of the overlying Gull Rock Member of Blanche Point Formation. The lower part, equivalent to the Tortachilla level, comprised soft and friable, notably fossiliferous and glauconitic mudstone/greensand, with poorly-sorted quartz sand, much carbonaceous matter, and minor pyrite.

Included in Appendix C is a petrographic description (after Radke, 1978) of a core of non-cherty mudstone ('marl') facies from the Hantkenina zone (basal Blanche Point Formation) in Morphett St and Victoria Bridges bore 14 (Ref. bore 6). The rock is described as a 'glauconite marl', having 30% iron-stained argillaceous matrix, 15% calcite matrix (patches and veins), 25% calcarenitic shell fragments, 25% glauconite pellets and aggregates (fresh to oxidised), and 5% fine-grained detrital quartz sand.

Bores in the Adelaide Children's Hospital complex, North Adelaide (e.g. Ref. bores 20-22) penetrated the composite unit in similar mudstone/greensand facies ('greensands intersected at depths of about 60 to 70 feet at North Adelaide'; Ludbrook, 1963a, p. 8), as did the historic Kent Town bore (Ref. bore 31) at 195-218 ft (59.4-66.4 m).

A petrographic description (by Radke, 1978) of a tube-core sample of comparable facies from near the base of the 'TL/basal BPF' interval in SADME West End Brewery bore (Ref. bore 10) at 50 m, is included in Appendix C (sample P 747/78). The friable, greenish-grey and reddish-brown rock, described as a 'ferruginous marl', is grossly fossiliferous, and contains 40% iron-stained argillaceous matrix, 20% ovoid ferruginous pellets (probably oxidised glauconite), and 5% very fine to medium-grained quartz sand. A piece of this core is illustrated in Figure 63.

Various lithologies represented within this composite interval in the SADME South Parklands bore, are indicated in Plan 27. Portion of a tube-core from 95 m, and of the washed residue, are illustrated in Figures 64, 65.

On the Mile End Block, the 'TL/basal BPF' interval was penetrated in Ref. bore 93, at Mile End, between about 140 and 146 m (Plan 14). From sludge samples and logs the lithology is interpreted as greenish-grey and brown sandy marl and mudstone, with soft to hard limestone bands, all being abundantly fossiliferous and glauconitic. A hard and recrystallised band of green/brown/grey, fossiliferous, glauconitic (more or less oxidised) and sandy limestone at 143.9-145.1 m could be a Tortachilla Limestone equivalent.



Figure 64. Tortachilla Limestone, Adelaide City area; SADME South Parklands bore (Ref. bore 41), portion of tube-core at 95 m; soft, shelly mudstone, grey/green/brown, calcarenitic, glauconitic (pellets, aggregates, many part-oxidised, brownish), quartzose (brown, iron-stained quartz sand).



Figure 65. As above, but part of disaggregated and washed richly fossiliferous residue.

In the Croydon-2 bore (Plan 29) the lithological succession for this interval is quite comparable with the type section. So too is the succession at this level in the Longyear bore (Plan 2), where basal Blanche Point Formation (about 210-212.7 m) consists of green/grey very glauconitic mudstone/greensand, with thin hard bands of cherty limestone; while Tortachilla Limestone (212.7-213.4 m) comprises a thin but typical grey/green/yellow-brown, hard to friable, glauconitic ferruginous and shelly calcarenitic limestone, which becomes friable and sandy at the base. A petrographic report by Whitehead (1979) on a sample of diamond drill core from the top of this Tortachilla Limestone is included in Appendix C (sample 6627 RS 00147). The rock is a shelly glauconitic limestone, with 70-75% fine-grained calcite (matrix + recrystallised fossils), 25-30% glauconitic grains or pellets (green and unaltered, to brown highly weathered and oxidised), and 1-2% very fine-grained quartz sand.

Distribution

As shown on Plans 6-14, this composite unit occurs subsurface throughout the Adelaide City area, and on the Mile End Block. No bores have yet been drilled deeply enough on the Thebarton Block to intersect it, but it is certainly widely developed subsurface as a marker unit in the Adelaide Plains Sub-Basin (Lindsay, 1969) as it is beneath the City.

Bore-logs (Miles, 1952) indicate that transgressive greensands and glauconitic fossiliferous limestones, which probably represent the 'TL/basal BPF' unit, extend subsurface up the axis of the Golden Grove-Adelaide Embayment at least as far as Campbelltown. The writer examined a tube-core sample of

this unit, taken from a depth of 24.6 m in a foundation test bore drilled in May 1967 for the H. & L.G. Dept bridge over the River Torrens on Lower Portrush Rd, at Vale Park (Sec. 478, Hd Yatala). The sample comprised green and brown fossiliferous glauconitic mud(stone)/greensand/'marl', much of the glauconite being oxidised. There was a significant proportion of poorly-sorted quartz sand, together with lithic gravel of brown siltstone. Foraminifera included occasional Pseudopolymorphina sp. nov. (diagnostic of this stratigraphic level), frequent Asterigerina adelaidensis, rare Crespinina kingscotensis, and very rare Gen. nov. cf. Bolivinella sp. nov.

Glaessner (1966, p. 357), describing a specimen of Aturia in fossiliferous limestone at a depth of 60 feet (18.3 m) in a well at Campbelltown, commented that 'the specimen from Campbelltown is preserved in a glauconitic limestone which is the probable subsurface equivalent of the Tortachilla Limestone'. A specimen of Aturia from the 'Campbelltown Well', representing the same occurrence, was examined by the writer (S.A. Museum specimen P 5950) and is embedded in a matrix which is undoubtedly Tortachilla facies - a very fossiliferous glauconitic and ferruginous limestone, green, cream, pale brown, speckled dark brown (goethite-limonitic pellets and aggregates).

Thickness

Cross-sections A-B through R-S (Plans 6-14), and data in Appendix B, show that the average thickness of the composite unit 'TL/basal BPF' is about 5 m beneath the Adelaide City area and on the Mile End Block. This is approximately the thickness of the equivalent units at the stratotype, Maslin Bay (Reynolds, 1953; Lindsay, 1969). The maximum thickness beneath

the City is 9.5 m in Ref. bore 32, West Terrace Parklands; and the minimum is little more than 3 m in 'Carclew' CH-4, Montefiore Hill (Plan 7) where the unit thins over the Montefiore Hill 'high'.

Beneath the near-City Adelaide Plains, the unit spans a thick 18.3 m in the Croydon-2 bore (Plan 29). Elsewhere in the Adelaide Plains Sub-Basin (Lindsay, 1969) the unit thickens southwards down the coast from 2.7 m in the north, near Dublin (Plan 2) to 10 m at Port Gawler, to a maximum of 27.4 m in the Beach Petroleum Grange-1 well. At Virginia, the thickness is reduced to 5 m. Facies changes accompanying these variations were outlined by the writer previously (Lindsay, 1969, pp. 32-33). Near the southern end of the Sub-Basin, the unit has a cored thickness of 3.4 m in the Longyear bore, as noted earlier.

In the Noarlunga Embayment, the Seaford Drainage bore penetrated the composite unit through a thickness of about 4 m (Cooper, 1980).

Recent data for the Willunga Embayment (Cooper, 1979b) show that the thickness of the composite unit varies between a minimum of 3 m and a maximum of 10 m, in bores inland from the coastal stratotypes. It is worth noting that this is the same range of thickness observed in the Adelaide City area.

Stratigraphic Relationships

The contact of 'basal Blanche Point Formation' with the overlying Gull Rock Member is marked by a rapid upward increase in frequency and thickness of hard cherty bands. Thin chert and limestone bands do occur in basal Blanche Point Formation, but softer glauconitic marl/mudstone/greensand facies pre-

dominates. This is so both in outcrop at the stratotype and beneath the City of Adelaide in borehole sequences.

The nature of the contact between Tortachilla Limestone or the 'TL/basal BPF' unit, and the underlying South Maslin Sand, has been discussed earlier in connection with the latter formation.

At the bottom of the SADME Light-1 bore in the Northern Adelaide Plains (Plan 2), the 'TL/basal BPF' unit is transgressive onto, and fills fissures in, Precambrian quartzitic bedrock (Cornish, 1964; Lindsay, 1965a, 1969). From borehole logs recorded by Miles (1952), a similar transgressive relationship onto slaty bedrock is apparent in a number of localities in the Golden Grove-Adelaide Embayment, e.g. in Miles Index Bores 243, Felixstow; 239, Klemzig; 279, Windsor Gardens; 246, 266, and 267, Campbelltown.

Biostratigraphy and Age

Despite careful search, Acarinina primitiva has not been found in Tortachilla Limestone, or 'TL/basal BPF'. Having regard to the planktonic facies manifested, some of which are considered to be adequate for the presence of A. primitiva if within its stratigraphic range (comparing faunas and facies in the Gambier Embayment), the absence of the species is taken to be stratigraphically significant. Blow (1979) notes the final appearance of the species in 'Zone P.13 (?earlier part only of Zone P.14)', that is, the species does not continue to the top of the Middle Eocene. McGowran (1978b) shows a similar range to below top Middle Eocene, for southern Australia, New Zealand, and the South Campbell Plateau. Stainforth et al. (1975)

range the species only to top Orbulinoides beckmanni Zone, i.e. top Zone P.13. Hence on such negative evidence, the Tortachilla Limestone could be upper Zone P.14 or higher, i.e. uppermost Middle Eocene, or Upper Eocene. However in New Zealand, both Jenkins (1971) and Hornibrook and Edwards (1971) record A. primitiva as ranging into the basal Kaiatan (at the McCulloughs Bridge section), that is, basal Upper Eocene, although it is predominantly a Lower and Middle Eocene species. On that interpretation of the species' range, Tortachilla Limestone would be younger than earliest Late Eocene.

Contrary to the range of Tenuitella insolita suggested by Blow (1979) ('Zone P.12? - Zone P.17'), the species is only known so far from the Upper Eocene in New Zealand (upper Kaiatan to upper Runangan; Jenkins, 1971), and there is no evidence that it occurs in the Middle Eocene in southern Australia (McGowran, 1978b). Hence the presence of the species in Tortachilla Limestone (FAD, Plan 36) suggests Upper Eocene.

The presence of Tenuitella gemma in the middle part of stratotype Tortachilla Limestone, and through the 'TL/basal BPF' unit in the Adelaide City area (FAD, Plan 36) likewise suggests that these units are Upper Eocene. Although McGowran (1978b) shows a considerably earlier FAD for this species in southern Australia than that recognised in New Zealand (Jenkins, 1971, 1974a; Hornibrook and Edwards, 1971), there is no question that the FAD is Upper Eocene.

If the local top of the lower disjunct range of common and well-developed Tenuitella aculeata, which occurs in the Tortachilla Limestone (Plan 36), is synchronous with the range-top recognised in New Zealand, as suggested plausibly by McGowran (1973a, 1978b), this provides further evidence for an early Late Eocene age.

Since Cassigerinella winniana may range up from Zone P.14 (Blow, 1979, p. 1363), the presence of this species in Tortachilla Limestone (Plan 36) is at present inconclusive as to a Middle or Late Eocene age.

Of the benthonics whose ranges are plotted on Plan 37, Reussella finlayi, Halkyardia cf. bartrumi, and Sphaeroidina bulloides, which all occur in Tortachilla Limestone or 'TL/basal BPF', are not known from below the Upper Eocene in New Zealand (Hornibrook, 1961).

Taken together, the biostratigraphic evidence outlined above confirms the now long-held early Late Eocene age for Tortachilla Limestone (Ludbrook, 1963a, 1967, 1969b; Wade, 1964; Lindsay, 1969). The same age (earlier Zone P.15) has been supported recently by McGowran (1978a,b) in the context of a wide-ranging inter-regional synthesis.

In basal Blanche Point Formation, or the upper part of 'TL/basal BPF', the outstanding biostratigraphic event is the Hantkenina (H.) alabamensis primitiva range-zone, shown as the Hantkenina primitiva Datum in Plan 36. This species, and its local distribution and biostratigraphy, are discussed later in the systematic notes. The world range of the species, according to Blow (1979), is Zone P.13 - early Zone P.17, so the local thin range-zone represents but a brief 'extratropical excursion' during part of this total range, at a time of warm, transgressive and favourable conditions with less restricted access to the open ocean than usual for the St Vincent Basin (Plan 35).

On the balance of the biostratigraphic indications, and postulating the synchronism of this southern Australian Hantkenina zone with the New Zealand zone in a regional pulse of warm watermass, McGowran (1978a,b) continues to place the zone tenta-

tively in the vicinity of the Zone P.15/P.16 boundary, as was done by McGowran, Lindsay and Harris (1971). This is regarded as being 'not too inconsistent with the evidence from calcareous nannofossils (S.G. Shafik, pers. comm.)' (McGowran, 1978b, p.91).

In a recent attempt to fix a radiochronological age for the local Hantkenina zone, potassium-argon dates were obtained for eight glauconites, all from Hantkenina-bearing glauconitic mudstones, and five of them from the Adelaide City area (Lindsay and Webb, 1979). The three greatest ages obtained, presumably representing least argon leakage, were:

1. 35.0± 0.5 Ma - core, Ref. bore 40, North Adelaide;
2. 34.9 ± 0.5 Ma - auger-drilled sample, Blanche Point;
3. 34.5 ± 0.5 Ma - auger-drilled sample, N. of Witton Bluff;

giving an age in the vicinity of 35 Ma for the presumably isochronous zone. The interpretation of this result is difficult and at present inconclusive, because the calibration of the Eocene-Oligocene boundary is beset by both biostratigraphic and radiometric problems. The date of 35 Ma is about 9% 'too young' relative to an expected date of 38.5 Ma for the Zone P.15/P.16 boundary on the time-scale of Hardenbol and Berggren (1978), which has been adopted herein for the time being (Plan 3). This may reflect a systematic error, either local, or inherent in glauconite dates as suggested by Hurley et al. (1960, p. 1808). However the date of 35 Ma is not so discordant when considered relative to an alternative proposal for an Eocene-Oligocene boundary possibly as young as 33 Ma (Odin, 1978a; Odin et al., 1978).

Of interest is a recent Rb-Sr isochron age of 34.8 ± 2 Ma for a glauconite-rich band in the Castle Hayne Limestone of North Carolina (Harris et al., 1979). The authors report this formation to contain the calcareous nannofossil Zones NP.19 (Ismolithus recurvus Zone) and NP.20 of Martini (1970). Since the Hantkenina (H.) alabamensis primitiva zone in New Zealand is correlated with Martini's Zone NP.19 (compare Edwards, 1971; Hornibrook and Edwards, 1971), the date from North Carolina, given more information as to its biostratigraphic control, may eventually provide important evidence for the continuing attempt to date the local Hantkenina zone. Current first attempts to date glauconites from this zone by the Rb-Sr method have yielded anomalous results.

Pseudopolymorphina sp. nov. has not been found to range above basal Blanche Point Formation in the eastern St Vincent Basin, despite the comments of Stuart (1970) on this matter. For example, with good sample control by continuous tube-coring, the range-top of Pseudopolymorphina sp. nov. in the Morphett St and Victoria Bridges bores is related closely to the top of the Hantkenina zone. There (see Plan 15), in Ref. bores 4 and 6, top Pseudopolymorphina sp. nov. is immediately above top Hantkenina (separated by 0.5 m or less), while in Ref. bore 5, the range-tops coincide (Lindsay, 1964b). A similarly restricted upward range for Pseudopolymorphina sp. nov. was observed consistently in the Adelaide Plains Sub-Basin (Lindsay, 1969), and has been noted recently in the Willunga Embayment (Cooper, 1979b), and in the Noarlunga Embayment (Cooper, 1980).

Gyroidinoides octocamerata is not known from above 'TL/basal BPF' in the eastern St Vincent Basin (Plan 37).

Environment of Deposition, and Regional Events

The calcarenites of Tortachilla Limestone contain dispersed cirripede (barnacle) plates, detrital quartz sand up to coarse-grained size, and fine ferruginous gravel. It is considered that the formation was deposited in a relatively shallow near-shore marine shelf environment. Glaessner and Wade (1958, p.119) commented that 'the transgression of the sea into a narrow gulf and over its surrounding deltas led to a differentiation of facies. The small Eocene outcrops at Kingscote on Kangaroo Island show a more calcareous and bryozoal facies which contains, however, the same echinoids and foraminifera which occur in the Tortachilla Limestone south of Adelaide'. Transgressive Tortachilla Limestone of stratotype facies extended up the axis of the Golden Grove-Adelaide Embayment at least as far as Campbelltown.

The 'glauconitic marl' of basal Blanche Point Formation, with Hantkenina, and a higher planktonic ratio, is the result of somewhat deeper and quieter shelf sedimentation, with improved access to open-marine planktonic-bearing watermasses.

It has been considered that Tortachilla Limestone (plus top South Maslin Sand, at least at Port Gawler) with an 'extratropical excursion' of warm-water benthonics such as Halkyardia and Linderina, represents the first of three Late Eocene regional transgressive warm pulses; while the Hantkenina zone in basal Blanche Point Formation represents the second (McGowran, 1971, 1978a,b; R.J.F. Jenkins, 1974; Lindsay, 1976). The current biostratigraphic evidence does not demand much, if

any, time-separation between these local events; both are probably Zone P.15 as discussed earlier, and in the composite unit 'TL/basal BPF' they seem to merge as different facies (shallower and deeper) of the one episode, as suggested in Plan 35. This episode would correspond to the commencement of depositional Cycle 3 of Bock and Glenie (1965); to the commencement of the Late Eocene (Zone P.15 - Zone P.17) global rise of sea-level proposed as Third Order Cycle TE 3 by Vail et al. (1977) and Vail and Mitchum (1979); and to the commencement of Sedimentation Subcycle 2B (Late Eocene) proposed by Quilty (1977).

However, Buonaiuto (1977, p.33) noted within the Tortachilla Limestone 'a deeply pitted erosional surface on the topmost limestone in the Polyzoal Limestone' Member of Reynolds (1953), and regarded this as a karstic surface representing a significant lacuna (non-deposition plus subaerial dissolution) which preceded deposition of the 'Glauconitic Limestone Member'. He transferred this latter member from Tortachilla Limestone to the overlying basal Blanche Point Formation ('Blanche Point Transitional Marls'), 'to which it belongs in a new episode of sedimentation'. This might imply that the Tortachilla Limestone, as thus restricted, represents an earlier cycle, namely part of late Middle Eocene Third Order Cycle TE 2.2 (Vail et al., 1977; Vail and Mitchum, 1979) or Sedimentation Subcycle 2A (Quilty, 1977). However as discussed earlier, there is no palaeontological evidence that the Tortachilla Limestone is Middle Eocene, and the writer would prefer, with McGowran (1978a,b), to acknowledge a relatively minor hiatus within Zone P.15. The pitted surface noted by Buonaiuto can be interpreted as a local hardground. Not only could it have formed by shallow submarine

lithification (Bathurst, 1974; Marshall and Ashton, 1980), but this could have occurred very rapidly, as may be seen on the present-day southern and Western Australian littoral-neritic carbonate shelfs and reefs, which exhibit burrowing and pitting by a variety of organisms, together with chemical dissolution and redeposition of carbonate.

BLANCHE POINT FORMATION

Introduction

The emphasis in these notes will be on the distinctive, chert-banded, Gull Rock Member ('Blanche Point Banded Marls Member' of Reynolds, 1953), since basal Blanche Point Formation has been treated already, and 'upper Blanche Point Formation' (i.e. the 'Soft Marls Member') is apparently absent from the Adelaide City area, at least partly due to erosion.

Nomenclature and Type Section

In his nomenclatural revision of this formation, Cooper (1977b) moved away from the term 'marl' ('Blanche Point Marls' of Reynolds, 1953) because he considered that a significant proportion of the stratotype is of other lithology, such as fossiliferous chert; and also because of an aversion to the term 'marl', as being vague, ambiguous, and out-dated. The matter will be treated further under 'Lithology'. Cooper (1977b) did not rename either Reynolds' basal unit 'Blanche Point Transitional Marls Member', or the top unit 'Blanche Point Soft Marls Member', and the writer does not propose to do so at this stage, in view of the stratigraphy apparent in the Adelaide City area. Cooper (1979b) has recently discussed the Blanche Point Formation in the Willunga Embayment, its type area.

Lithology

Beneath Adelaide City, as at the Blanche Point stratotype, the Gull Rock Member is characterised by hard, massive to nodular bands of fossiliferous chert or cherty siltstone, a metre or (generally) less in thickness, which are separated by softer bands of spicular marl and mudstone, or muddy spongolite.



Figure 66. Gull Rock Member, Blanche Point Formation, Upper Eocene, Adelaide City area; Forensic Science Centre building, CH-1 (Ref. bore 45) D.D. core at 58.95 m; hard fossiliferous chert, dark to mid-grey, with white shell material (see petrographic description of sample P745/78, from this piece of core).



Figure 67. As above, but side view of the same piece of core, depth 58.95-59.00 m (T.D.); hard fossiliferous chert in the upper part; paler grey, softer, muddy spongolite in the lower part.

The following descriptions are adapted from those by the writer in Selby and Lindsay (1973, p. 8).

Hard bands cored in Ref. bore 45 (Forensic Science Centre building, central City, Figs 66,67) consist of a massive, tough, impure opaline or cherty siliceous rock, with a meshwork of siliceous sponge spicules. The rock is dark to mid-grey, calcarenitic and calcareous (one typical sample is 25% by weight soluble in cold dilute hydrochloric acid), glauconitic (ovoid pellets), and pyritic (spherules, aggregates). There is porosity due to some leaching of sponge spicules, leaving abundant acicular moulds. Residue released by acid treatment is spicular, muddy, micromicaceous, quartz-bearing (detrital silt to fine sand), and carbonaceous.

Soft bands in this corehole are paler grey, compact, and moderately friable. They contain abundant siliceous sponge spicules, and a calcarenitic silty matrix, so that the lithology could be described as an impure spongolite (a friable sponge-spicule rock). This soft phase is calcareous (one typical sample is 36% by weight soluble in cold dilute hydrochloric acid),quartz-bearing (detrital silt to fine sand), glauconitic, pyritic, micromicaceous, muddy and carbonaceous, as for the hard bands. The soft phase also occurs as thin seams or lenses in otherwise hard bands (Fig. 67; cf. Selby, 1972, log of CH-1).

Petrographic descriptions (by Radke, 1978) of two core samples of Gull Rock Member from the above bore, are included in Appendix C (samples P 745/78, P 746/78). Both samples are from hard bands, and are described as 'fossiliferous chert'. Sample P745/78, from a bottom-hole core at 59 m (Figs 66,67) represents a hard band at least one metre thick (58-59 m, T.D.).

The rock contains 50% siliceous matrix, mostly isotropic opaline silica which varies from clear, to dark reddish-brown and turbid (with intergrown iron-stained clay). Some micro-crystalline silica is present in minor amounts. The other major constituent, comprising 40% of the rock, is small calcite shell fragments, which are disseminated through the siliceous matrix. Siliceous sponge spicules (3%) are mostly clear opaline silica, with minor microcrystalline silica. Detrital quartz (5%) is mostly fine-grained, subangular to subrounded. Glauconite pellets (1%) are often partly oxidised, and tend to be concentrated in a millimetre-thick band. Sample P746/78, from core at 48.4 m, representing a hard band less than 0.5 m thick, is very similar in lithology to the above, but has fewer calcareous shell fragments (35%), more sponge spicules (5%) less glauconite (occasional very fine-grained pellets), and more opaque grains, probably detrital (2%).

The relatively unoxidised samples described above are medium to dark grey in colour; but in less deeply buried situations where the Gull Rock Member has at some time been weathered and oxidised, it has become off-white, yellow or brown, speckled with paler green glauconite grains. This tends to be the case up-dip beneath the Torrens Valley and North Adelaide. For instance in Morphett St and Victoria Bridges bore 5 (Ref. bore 3), the zone of weathered Gull Rock Member extends from the eroded top, at a depth of 7.3 m, to 18.6 m, a thickness of 11.3 m. At the 'Carclew' site, Montefiore Hill, North Adelaide, much of the Gull Rock Member and underlying 'TL/basal BPF' unit is weathered and oxidised. For example in Ref. bore 24 (Allchurch, 1966) the Gull Rock Member, thinned to 4 m by erosion, is dark brown and iron-stained, speckled green.

Gull Rock Member in the SADME South Parklands bore (Plan 27), and in the SADME West End Brewery bore (Plan 28) shows, in both cores and sludges, an alternation between hard fossiliferous chert and softer mudstone to spongolite. The unit becomes more glauconitic towards the base, with a downhole increase in glauconite pellets and aggregates, and in glauconitised (impregnated and replaced) shell fragments. The same succession is developed in the Morphett St and Victoria Bridges bores (Plan 15).

In the near Adelaide Plains, the Gull Rock Member in the Croydon-2 bore (Plan 29) comprises pale grey shelly glauconitic calcareous siltstone, with hard cherty bands.

A petrographic description (after Whitehead, 1979) of a core sample of hard, shelly Gull Rock Member from the Longyear bore, southern Adelaide Plains (Plan 2) is included in Appendix C. The sample (6627 RS 00146), from a depth of 200 m, is described as a glauconitic cherty marl. The dominant constituents are calcareous shell fragments and fine matrix calcite (40-45%), dispersed in a turbid, brown-stained, clay matrix (30-35%). Opal (10-15%) comprises siliceous sponge spicules (less than 5%), plus turbid opaline replacement of matrix clay in patches and bands.

Cooper (1979b, Appendix 1, sample P 41/77) included a petrographic description (by R.S. Cooper and Radke, AMDEL) of a sample of a hard band at the top of stratotype Gull Rock Member, just south of Blanche Point. This too, like the samples from Adelaide City, was described as a fossiliferous chert, the main component being a matrix of turbid brown, isotropic, opaline silica, with a minor cryptocrystalline phase. This

matrix, plus common opaline sponge spicules, makes up a high 75% of the rock. Dispersed carbonate shells and shell fragments (mostly calcitic) comprise 18%, and glauconite was not noted although clayey faecal pellets and infillings are present (5%).

Although apparently not present beneath Adelaide City, or on the Mile End Block, the 'Blanche Point Soft Marls Member' (Reynolds, 1953) is well developed in the Croydon-2 bore (Plan 29) as grey shelly soft siltstone, silt and marl, overlying Gull Rock Member and underlying Chinaman Gully Formation. This upper part of Blanche Point Formation was also discussed and recorded from elsewhere in the Adelaide Plains Sub-Basin by Lindsay (1969).

A petrographic description of a sample of stratotype 'upper Blanche Point Formation' was also included by Cooper (1979b, p.80, sample P41/76). The sample, from only 3½ m below the top of the Blanche Point Formation, proved to be a grey, fossiliferous, calcareous, siliceous claystone or siltstone.

Two petrographic descriptions (after Whitehead, 1979) of core samples of 'upper Blanche Point Formation' from the Longyear bore (Plan 2) are included in Appendix C (samples 00144, 00145). Both samples are grey, fine-grained, argillaceous limestone or marl, sample 00145 having a significant proportion of siliceous sponge spicules (10-15%).

Distribution

The distribution of the Gull Rock Member in the Adelaide City area, and structure contours of its top, are plotted in Plan 20. The member appears to have been removed by the erosive

action of an ancestral River Torrens at the western edge of the Para Fault Block, and at the northern end of the Mile End Block. No borehole on the Thebarton Block has penetrated to a sufficient depth to intersect the unit. Apart from these exceptions, the Gull Rock Member is known to be widely distributed beneath the Adelaide City area, as it is in the Adelaide Plains Sub-Basin (Lindsay, 1969), and in the Willunga Embayment (Cooper, 1979b).

The Gull Rock Member extends subsurface up the axis of the Golden Grove-Adelaide Embayment as far as Windsor Gardens, Campbelltown, Paradise, and probably Dernancourt. The Vale Park Bridge bore, mentioned earlier in connection with the 'TL/basal BPF' unit, penetrated the Gull Rock Member (eroded, weathered, and leached at the top) between 12.8 and 19.8 m. Hard bands and nodules of very dark grey spicular cherty siltstone (fossiliferous chert), which is glauconitic and pyritic, alternate with soft, dark greenish-grey, fossiliferous silty mudstone/marl, which becomes increasingly glauconitic downwards. Robertina lornensis enters (downhole) at 14.9 m, and Asterigerina adelaidensis at 15.8 m. The writer examined a sample of Gull Rock Member obtained many years ago from a depth of 11 m in a well on the property of Mr. J. Mines, Mines Rd, Campbelltown (S.A. Museum sample P 10916). The rock comprises a pale grey, light-weight mudstone/spongolite, with darker grey patches of chert, and iron-stained moulds of large 'Turritella'.

On the basis of these confident identifications, the Gull Rock Member can be recognised from the logs of many bores in the Torrens Valley, as tabulated by Miles (1952). For example,

his Index Bore 243, Felixstow, penetrated 'yellow to black fossiliferous limestone and black clay, with shells' between 24.4 and 36.6 m, overlying Precambrian slate bedrock. Most of the limestone/clay unit is probably Gull Rock Member, although the basal part of the sequence may be 'TL/basal BPF' unit. A similar sequence, transgressive on to bedrock, was penetrated in the Miles Index Bore 239, Klemzig, where the interval 15.2-27.4 m had been logged as 'glauconitic sandy clay with fossiliferous limestone', resting on decomposed slate.

The writer observed probable marginal Gull Rock Member, represented by weathered, spicular, cherty, sandy mudstone, with moulds of 'Turritella', exposed during 1969 in deep trenches at Dernancourt, south of Lyons Road.

Reed (in prep.) has recently logged spicular, glauconitic, sandy gravelly and clayey silts in two bores north of Lyons Road and adjacent to the Hope Valley Reservoir. This unit is almost certainly a marginal facies of Blanche Point Formation.

In the Northern Adelaide Plains, the Gull Rock Member (as 'Blanche Point Banded Marls Member') was not identified by Lindsay (1969) either in the Dublin Govt bore or in SADME Light-1 bore (Plan 2). It may have been intersected towards the bottom of Beach Petroleum Hallions-2 well, and was certainly penetrated in the SADME Port Gawler bore. The member (thin bands of siliceous sandstone/quartzite, identified as 'Gull Rock Member equivalent of Rogue Formation') was recorded, very doubtfully in the writer's opinion, in SADME Barabba bore 5 (Plan 2), and (less doubtfully) in SADME Barabba bore 7, near Mallala (Cockshell et al., 1978). It was not identified by these authors in SADME Barabba bores 1, 3, and 4 (Plan 2), nor in either of the other Barabba-series bores.

Typical Gull Rock Member and 'upper Blanche Point Formation' were penetrated in the Longyear bore, at the southern end of the Adelaide Plains Sub-Basin.

Thickness

Thicknesses of the Gull Rock Member in various boreholes in the Adelaide City area are tabulated in Appendix B. On the Para Fault Block, beneath Adelaide City, the maximum preserved thickness of the member is 26.5 m in the SADME South Parklands bore (Ref. bore 41). In several other bores, the thickness is between 20 and 22 m, including Morphett St and Victoria Bridges bore 5 (Ref. bore 3; 22.0 m), A.M.P. building bore 4A (Ref. bore 7; 21.2 m), and SADME West End Brewery bore (Ref. bore 10, 21.0 m). In the case of the old West End Brewery bore 2 (Ref. bore 9), samples are no longer available, and it is now impossible to separate Gull Rock Member from the 'TL/basal BPF' unit, the whole interval having been logged by the driller as 'greyish shell rock'. This combined interval is 27.4 m thick, which compares closely with the equivalent section in the nearby SADME West End Brewery bore (26.0 m). In a number of other bores tabulated in Appendix B, there is a similar problem in distinguishing Gull Rock Member from 'TL/basal BPF' and the two are combined as shown ('F + G').

In the vicinity of the Adelaide City area, Blanche Point Formation was eroded well down into the Gull Rock Member during at least four episodes, the first in the Late Eocene prior to deposition of the Chinaman Gully Formation, particularly the basal Tandanya Sand Member (see Plans 10-14); one prior to deposition of the Late Pliocene Hallett Cove Sandstone (see Plans 6,8); one early in the Pleistocene, prior to the deposition

of Carisbrooke Sand (see Plans 6,7,11); and at least one more later in the Quaternary, prior to deposition of the 'alluvium of the River Torrens' (see Plans 6-9, 11). For these reasons, the Gull Rock Member has been thinned erosionally in many City boreholes, and in some localities removed completely, as can be seen by comparing data in Appendix B, Plan 20, and the various cross-sections.

On the Mile End Block (Plan 14) there is dramatic evidence that the Gull Rock Member was truncated erosionally prior to deposition of a wedge of clastic Tandanya Sand Member from the north. The Gull Rock Member has been entirely removed from the northern end (interpretation of Ref. bore 51), while at the southern end it attains a thickness of 37.2 m.

In the Croydon-2 bore (Plan 29), evidence from old and unsatisfactory samples suggests that the Gull Rock Member may be less than 20 m thick. However in the nearby SADME Allenby Gardens bore (Plan 5) preliminary estimates put the thickness of the member at more than 30 m.

Limited bore coverage suggests that between Port Gawler and the southern end of the Adelaide Plains, the Gull Rock Member has a fairly consistent thickness of between 15 and 20 m, of the same order as that beneath the City. In the SADME Port Gawler bore, the thickness is 19 m, and in Beach Petroleum Grange-1 well it is 18 m (Lindsay, 1969). In the Longyear bore (Plan 2) the member has a thickness of 15 m. However as noted previously by the writer, the unit thickens (and develops a more marginal, sandy facies) towards the eastern and south-eastern part of the fault-blocks in the eastern St Vincent Basin (Lindsay, 1969, p.33).

The Gull Rock Member has a thickness of 21 m in the Seaford Drainage bore, Noarlunga Embayment (Cooper, 1980), comparable to that in the coastal subsurface sections of the Adelaide Plains Sub-Basin.

In the Willunga Embayment (Cooper, 1979b) the Gull Rock Member thickens to the south and southeast, towards the asymmetrically-situated depositional axis of the embayment near the Willunga Fault. The stratotype, at Blanche Point in the northwestern part of the embayment, has a thickness of only 11 m (Reynolds, 1953). However there is a southerly increase to 14 m in bore WLG-44, to 26 m in WLG-40, and to a maximum of 28 m in WLG-38 (Cooper, 1979b, p. 30 ff.).

Stratigraphic Relationships

The disconformable, erosional upper contact of Gull Rock Member with the Tandanya Sand Member of Chinaman Gully Formation in many parts of the Adelaide City area, was discussed above. The conformable, lower contact with 'basal Blanche Point Formation', or with the top of the composite unit 'TL/basal BPF', was treated earlier in connection with that unit.

Biostratigraphy and Age

The planktonic faunas of the Gull Rock Member and of 'upper Blanche Point Formation' are not notable for first or last appearances. The only datum shown for either unit on Plan 36 is the apparent FAD of Globigerina angustiumbilicata within the Gull Rock Member. Careful picking of planktonics in the SADME South Parklands bore (Ref. bore 41) did not yield this species below the middle of Gull Rock Member (Plan 27), but further detailed study of various borehole successions will be needed to check the consistency of this as a local FAD. Blow (1979) has ranged the species up only from Zone P.16.

The microfaunas in Tortachilla Limestone/basal Blanche Point Formation, underneath, and in basal Port Willunga Formation, above, seem to constrain the Gull Rock Member and 'upper Blanche Point Formation' to Zone P.16, as shown by McGowran (1978a,b).

Benthonic foraminifera typically show an upward succession of last appearances through Blanche Point Formation (Plan 37). Pseudopolymorphina sp. nov., and Gyroidinoides octocamerata do not range above 'basal Blanche Point Formation'. Gyroidinoides cf. soldanii continues upwards into basal Gull Rock Member, while the range-tops of typical Wadella hamiltonensis and Robertina lornensis occur within the same member. In what is almost a disjunct range, Maslinella chapmani virtually disappears in the Gull Rock Member, to reappear briefly and rarely in basal Port Willunga Formation. Asterigerina adelaidensis generally does not range above top Gull Rock Member, although occasional specimens, often atypical, may be found in 'upper Blanche Point Formation' (Lindsay, 1969; Cooper, 1979b). Massilina whitfordae sp. nov. is not known from above Blanche Point Formation.

An apparent, relative time-compression of Blanche Point Formation, compared with units above and below, is a notable feature of Plan 3. It seems to be an inescapable result of the presently most acceptable correlations between local formations, P-zones, and geochronometry. The whole Blanche Point Formation is constrained to deposition in about half a million years; and the Gull Rock Member in less than 200000 years, or one metre in about 10000 years, not allowing for post-depositional compaction. This rate of deposition is quite possible; it is of the same order as that of skeletal, pelletal, carbonate mud deposited in warm, productive environments either recently on

the Bahama Banks (3 m in 3800 years; Bathurst, 1971, pp. 279, 286, 292), or in Cretaceous Chalk seas (1 m in 2000 years; Bathurst, 1971, p. 405). It may be that Blanche Point Formation represents a period of productive and relatively uninterrupted deposition (biogenic carbonate-siliceous, and detrital) compared with the apparently slower and more intermittent deposition of other formations.

An alternative explanation of the apparent time-compression of Blanche Point Formation could be that the Eocene-Oligocene boundary is set 'too old' at 37 Ma, as suggested recently by some workers, and discussed earlier. For example, to put the boundary at 35 Ma (Tarling and Mitchell, 1976) or 33 Ma (Odin et al., 1978), would allow relatively much more time in the Late Eocene to accommodate local formations of that age. This would look intuitively more realistic, in relation to the relative thicknesses of these formations.

Environment of Deposition, Regional Events, and 'the Chert Problem'

According to oxygen-isotope data plotted in Plan 35 (prepared by the writer for Lindsay, 1976), and plotted independently by McGowran (1978a,b; 1979b), regional marine palaeotemperatures during deposition of the Gull Rock Member were fluctuating but moderately warm: cooler than temperatures which prevailed during the deposition of 'TL/basal BPF', but much warmer than in the Oligocene (when the cherty Ruwarung Member of Port Willunga Formation was deposited), and significantly warmer even than the Early and Middle Miocene peaks. This is in accord with much of the data summarised by Savin (1977). However according to R.J.F. Jenkins (1974), horizons with fossil penguins, e.g. the

occurrence of Pachydyptes simpsoni in the upper part of strato-type Gull Rock Member, might indicate episodes of relatively lower sea-temperature.

The muddy, dark grey, carbonaceous, and originally reduced nature of the Gull Rock Member, suggest that the marine environment of deposition was a low-energy, shelf-like gulf, with restricted access to the open ocean, and with a poorly-oxygenated bottom. The successive upward extinctions of several benthonic foraminifera, and the generally deficient planktonic microfaunas of the Gull Rock Member, also indicate an unfavourable, restricted, and possibly silled basin with less access to the open ocean than in the preceding Hantkenina zone.

From ostracode assemblages and from Victorian oxygen-isotope palaeotemperatures (Gill, 1968), McKenzie (in Cooper, 1979b, p. 92) inferred that the Blanche Point Formation in the Willunga Embayment was deposited at depths of from 50 to 100 m, on a muddy marine outer shelf with poor circulation, in warm temperate (about 15°C) waters.

There is an obvious relationship in the Gull Rock Member, between the presence of chert nodules or bands and the notable abundance of siliceous sponge spicules. Such sponge remains have long been recognised as an immediate source of diagenetic chert in carbonate rocks (Pettijohn, 1957; Pittman, 1959; Wilson, 1966; Namy, 1974). Decaying organic matter associated with anoxic bottoms reduces pH and promotes the precipitation of silica (Goldstein, 1959; Peterson and Von der Borch, 1965; Namy, 1974). The roughly rhythmic banding of chert or flint concentrations, such as is evident in the Gull Rock Member, has long been commented upon (Richardson, 1919) but is not yet explained

satisfactorily. Nor is the prevalence of chert concentrations in the Gull Rock Member, but the relative lack of such cherts in the 'upper Blanche Point Formation ' ('Soft Marls Member') which is similarly rich in sponge remains.

The ultimate origins of the silica concentrations in the Late Eocene Blanche Point Formation, and in the distinctly younger Oligocene Ruwarung Member of Port Willunga Formation, involve regional considerations far beyond the St Vincent Basin. Richly spicular and siliceous rocks which are at least partly coeval with Blanche Point Formation and the Gull Rock Member are widely distributed across the southern Australian continental margin. The Upper Eocene spongolite-bearing Pallinup Siltstone of the Plantagenet Group of southernmost Western Australia, the Princess Royal Spongolite of the Norseman area, and at least the uppermost siliceous beds of the Wilson Bluff Limestone in the Eucla Basin, are all approximate correlatives (Cockbain, 1968). At least some of the chert in the Gambier Limestone is coeval with that of the Ruwarung Member (Plans 30, 33, 34).

Silica in seawater is derived primarily from vulcanism and from continental weathering (Pettijohn, 1957, p. 439). Oceanic currents distribute this input, and may especially induce high productivity of siliceous organisms at the edges of major water masses and in areas of upwelling (Riedel, 1959). All three factors - vulcanism, continental weathering, and oceanic circulation - may well have operated to produce the cherts of the Gull Rock and Ruwarung Members, and their southern Australian correlatives.

Apart from the nearby Southeast Indian Ocean Ridge spreading-centre, which was a potentially major supplier of silica from the Early Eocene onwards, Eocene-Oligocene volcanic rocks are recorded in the Otway Basin of western Victoria (Abele et al., 1976), although not from South Australia or Western Australia. The relative input of silica from these sources into the adjacent ocean is not known but its westward distribution along the southern Australian coast could have been accomplished by an anticlockwise gyre in the arm of the southeastern Indian Ocean opening between Australia and Antarctica (Deighton et al., 1976). The link remaining across the South Tasman Rise between the continental plates, as they drifted apart, was not breached deeply until perhaps the middle Oligocene (Deighton et al., 1976), and even after that an anti-clockwise gyre could well have been maintained for some time around the arcuate configuration of the southern Australian continental margin, as an offshoot of the then-active, but constricted, Circum-Antarctic Current.

As discussed by Wopfner (1978), the Late Eocene to Oligocene was also a time of major silcrete formation associated with the 'Cordillo Surface'. Vast areas of inland Australia were affected, extending as far south as the southern coastline (northwestern Yorke Peninsula, and Spilsby Island). Wopfner regarded kaolinisation as the chemical process by which this silica was released from the parent rocks, and envisaged a depositional environment 'in low-energy flood-plains and delta-plains of humid, tropical to subtropical climatic regions, where, due to subdued relief, run-off is sluggish and drainage inadequate'. In addition to the immense quantity of silica

thus released and locked into this silcrete, it is conceivable that some at least was available in the Late Eocene and Oligocene for transport in solution to the Tertiary basins of the southern continental margin. There is widespread evidence of southerly palaeo-drainage at this time. For example Harris (in Harris et al., 1980, p. 226) notes that 'the Eocene sediments in the Port Pirie bore are fluvial and are part of the sediment fill of the Pirie-Torrens and St Vincent grabens which had an outlet to the south in the region of Port Wakefield, where indeed deltaic facies were deposited. But these sediments are related to a major north-south system whose origins were north of Lake Torrens'. The muddy nature of Blanche Point Formation, and a low but consistent proportion of detrital quartz sand, suggest that this was indeed a time of considerable discharge of river-water and sediment into the St Vincent Basin.

Some presently-unknown combination of the above factors is adequate to provide the silica-rich environment which led eventually to the deposition of the Gull Rock and Ruwarung Members in the eastern St Vincent Basin, to chert in the Rogue Formation of the western and northern St Vincent Basin (Stuart, 1969, 1970; Cooper, 1977a) and to chert deposition elsewhere in southern Australian marine Tertiary basins. Many questions remain unanswered, such as why particular stratigraphic levels should be singled-out as chert-bearing, and what are their correlations in detail; whether the formation of chert nodules and bands was rapid (syndepositional or immediately post-depositional; Harris, 1958; Namy, 1974), or slow and late diagenetic (Steinitz, 1970); the reasons for the rhythmic banding of chert beds or nodule horizons; and the possible role of early or

late-stage interaction between meteoric and interstitial marine waters on the near-shore shallow shelf (Knauth, 1979). To add to the problems, one major inter-regional consideration at least, that of climate and temperature, was seemingly not a determining factor in chert production. The Eocene cherts were deposited in relatively warm regimes, while the early and middle Oligocene cherts, at least, were formed after the oceanic cooling crisis near the Eocene-Oligocene boundary. This point was made recently by Frakes (1979, p. 198) when he commented that 'paradoxically, the abundant Eocene cherts were formed mostly during times of warmth and comparatively low rates of upwelling, while early Oligocene ones occur abundantly only in the southern hemisphere. The latter should be more widely distributed if they resulted from the cool climatic conditions which prevailed in the Oligocene'.

Further discussion of 'the chert problem' is outside the scope of this thesis.

CHINAMAN GULLY FORMATION

Introduction

It is only recently that Chinaman Gully Formation has been recognised in the Adelaide City area (Lindsay and Harris, 1979). Prior to this, the strata in question were considered to be equivalents of 'upper Blanche Point Formation' (i.e. 'Blanche Point Soft Marls Member'). The breakthrough came when W.K. Harris, in the course of his palynological studies (in progress; unpublished data) detected a distinctive dinoflagellate assemblage which is characteristic of Chinaman Gully Formation, thus enabling the unit to be identified in borehole cores from the City of Adelaide, and correlated with borehole intersections in the Willunga Embayment (the type area) and the Adelaide Plains Sub-Basin. It was also recognised that the unit, whether in sand, mud(stone), or lignitic facies, is only poorly calcareous if at all, in contrast to the significantly calcareous 'upper Blanche Point Formation' as it is developed in the stratotype and elsewhere.

Nomenclature

The Chinaman's Gully Beds, which were described by Reynolds (1953) were given modern formational status as Chinaman Gully Formation by Cooper (1977b).

Only one member has been formally distinguished, namely the Tandanya Sand Member (Lindsay and Harris, 1979).

Type Section

The stratotype of Chinaman Gully Formation extends along about 600 m of coastal section centred on Chinaman Gully, at Maslin Bay, in the Willunga Embayment (Reynolds, 1953). A half-metre bed of glauconitic and fossil-bearing green clay, put by Reynolds at the base of stratotype Port Willunga Formation, has been regarded subsequently by authors as the topmost bed of

stratotype Chinaman Gully Formation (Ludbrook in Cochrane, 1956; Lindsay, 1967b; Cooper, 1979b).

The subsurface type section of the Tandanya Sand Member is the interval between depths of 39.9 and 43.0 m (131-141 feet) in Ref. bore 14, foundation test bore 4, State Administration building, eastern Victoria Square, in the heart of the City of Adelaide. The member has also been penetrated by many other bores in the Adelaide City area (Lindsay and Harris, 1979, fig. 1).

Lithology

Although very thin (2.1 m), the type section of this formation comprises a variety of even thinner clastic beds including clays, silts, and fine to coarse sands, as tabulated by Reynolds (1953). Some of the beds are laminated sands and clays. In the coastal exposure, the formation is largely oxidised; and this, superimposed on rapidly-varying lithology, results in a distinctive multicoloured appearance in shades of yellow, white, brown, red, green, blue, and grey (for a colour photograph, see Cooper, 1979b, p. 24, pl. 11).

Five kilometres inland from the type section, in bore WB-1, Glaessner and Woodard (1956) correlated with the Chinaman Gully Formation a lignite at 125.9-126.8 m (413-416 feet) together with associated dark grey carbonaceous sands and clays, making a total interval of 118.9-134.1 m (390-440 feet). Although the appearance of this unoxidised lithology was in striking contrast to that of the coastal stratotype, correlation was confident (and was supported by Lindsay, 1966, 1969) because this upper carbonaceous interval in the bore separated units above and below which could be correlated both microfaunally and lithologically with Port Willunga Formation and Blanche Point

Formation respectively. Subsequent palynological studies by W.K. Harris, referred to by Lindsay and Harris (1979), and by Cooper (1979b, p.20) have confirmed the general correctness of this correlation. Considering in detail the succession in bore WB-1 at this level, the writer suggested that the interval of black carbonaceous sand and fine gravel immediately above 125.9 m might be basal Port Willunga Formation, while the dark grey clays with sponge spicules, encountered immediately below 131.1 m, appeared to be Blanche Point Formation (Lindsay, 1966, p. 6). Thus the interval correlated with Chinaman Gully Formation was reduced by the writer from Glaessner and Woodard's estimate of 118.9-134.1 m (15.2 m) to 125.9-131.1 m (5.2 m). Cooper (1979b), without further discussion, changed the interval in question to 121-130 m (9 m), and also reported unoxidised Chinaman Gully Formation in other bores in the Willunga Embayment, where it is similarly developed as carbonaceous silt and sand with thin seams of lignite.

The sequence identified as Chinaman Gully Formation beneath the City of Adelaide is exemplified by that penetrated in the SADME South Parklands bore (Ref. bore 41) and summarised in Plan 27. The interval comprises an upper mudstone (silt/clay) unit (Fig. 68), and a lower sand unit, the Tandanya Sand Member, which is silty and fine-grained (Fig. 69) to coarse and pebbly (Fig. 70). In this bore, both units are relatively unoxidised and carbonaceous, exhibiting dark to pale grey-brown colours. However up-dip, in the SADME West End Brewery bore (Ref. bore 10, Plan 28) the formation has an eroded top, immediately beneath the Pliocene unconformity. Weathering, leaching, and partial oxidation have taken place, so that what is left of the upper unit, here a silty clay, is pale greenish-grey mottled brown, while the Tandanya Sand (more permeable and so more susceptible



Figure 68. Upper, fine-grained, unit of Chinaman Gully Formation, Adelaide City area, uppermost Eocene. SADME South Parklands bore (Ref. bore 41), tube-core at 54.0-54.3 m; dark grey-brown carbonaceous mudstone (silt/clay), quartzose (very fine-grained sand), pyritic (common pyritised sponge spicules, internal casts, framboids), calcarenitic, foraminiferal; finely micaceous.



Figure 69. Tandanya Sand Member of Chinaman Gully Formation, Adelaide City area, uppermost Eocene. SADME South Parklands bore as above, but tube-core from base of the Member, at 64.0-64.3 m; laminated pale grey, glauconitic, silty, very fine-grained quartz sand; and darker brownish-grey, carbonaceous, sandy silty mudstone; sparsely pyritic, finely micaceous, non-calcareous.



Figure 70. Tandanya Sand Member of Chinaman Gully Formation, Adelaide City area, uppermost Eocene; SADME South Parklands bore, 60-62 m, washed residue of sludge sample; calcarenitic, fossiliferous quartz sand, pebbly (to 11 mm), pyritic, sparsely glauconitic, foraminiferal; with minor black, carbonaceous siltstone (laminae, lenses).



Figure 71. Tandanya Sand Member of Chinaman Gully Formation, Adelaide City area; SADME West End Brewery bore, bailed sludge at 27 m; pale yellow-grey gravelly quartz sand, poorly-sorted.

to oxidation) is pale yellowish-grey with minor ferruginous cementation (Fig. 71).

Similarly, a foundation test bore for John Martins Car Park, North Terrace (Ref. bore 8) intersected eroded, weathered, and partly-oxidised Chinaman Gully Formation immediately beneath the Pliocene Hallett Cove Sandstone, the bore bottoming in the Tandanya Sand Member. At this locality, the upper, fine-grained unit of Chinaman Gully Formation (depth 23.3-24.7 m) is a mottled grey and brown silt, clayey and finely sandy, leached and non-calcareous, with ferruginous casts of bryozoans and small molluscs, and rare ovoid faecal pellets. The upper part of the Tandanya Sand Member (24.7-29.0 m) is a fine to medium-grained, very silty quartz sand, which is bioturbated and contains sandy burrow-tubes and abundant faecal pellets. Being less permeable this bed has suffered less from oxidation, and is mid-grey, carbonaceous, pyritic (framboidal aggregates, pyritised sponge spicules), and glauconitic. The bore bottomed (29.0-30.0 m, T.D.) in poorly-sorted quartz sand, very fine to very coarse-grained, containing subangular to rounded quartz gravel up to 10 mm diameter. This gravelly sand is grey, mottled off-white, brown, and yellow; it is clayey and silty, glauconitic, and finely spicular.

Opportunity not available to Lindsay and Harris (1979) is taken here, to document the full sequence of Chinaman Gully Formation in Ref. bore 14, Victoria Square - the borehole section which includes the stratotype of the Tandanya Sand Member. The whole formation is preserved in tube-core samples which are stored at the S.A. Dept of Mines and Energy Core Library at Glenside. The interval in this bore which is now identified as

Chinaman Gully Formation was originally correlated by the writer (Lindsay, 1964a) with the 'Blanche Point Soft Marls Member', although the facies was recognised as being less calcareous and more sandy than that part of stratotype Blanche Point Formation.

TOP of Chinaman Gully Formation

Apparently conformable contact with overlying basal sand unit of Aldinga Member, Port Willunga Formation.

All samples are sealed-tube cores from depths shown.

34.21-34.59 m (112'3"-113'6") Silt, clayey, sandy (very fine to fine-grained) quartzose; dark grey, carbonaceous, with pale grey sandier lenses; micaceous, glauconitic, slightly calcareous; abundant pyritised sponge spicules, and frequent iridescent bluish sulphide aggregates.

34.59-34.98 m (113'6"-114'9") Generally as above, but more coherent, roughly bedded; abundant fine carbonaceous fragments and fibrous material; frequent dark grey faecal pellets; non-calcareous; common pyritised sponge spicules, and iridescent bluish-bronze framboidal sulphide aggregates.

34.98-35.36 m (114'9"-116'0") Silt, clayey and sandy, dark grey, as above; but with frequent mollusc fragments, and a few dark green glauconite pellets; common faecal pellets; abundant pyritised sponge spicules, common pyritised (burrow)tube-casts; frequent fish bones; a pyritic internal cast of a large Lenticulina sp.

35.36-35.74 m (116'0" - 117'3") As above, but semi-lithified, hard to disaggregate; mechanical analysis - 65% silt, 24% clay, 11% sand.

35.74-36.12 m (117'3" - 118'6") Silt, clayey, sandy (very fine-grained, quartzose) dark grey; with frequent small lenses of sand, pale grey, very fine to fine-grained, quartzose; the whole sample soft, plastic, muddy; pyritic, micaceous, non-calcareous; rare pale green glauconite pellets.

36.12-36.50 m (118'6" - 119'9") As above, but firm, only slightly plastic; pyritised spicules less abundant; but pyritised tube-casts, and framboidal and other pyritic aggregates are common.

36.88-37.26 m (121'0" - 122'3") Silt, clayey, with only minor and very fine-grained quartz sand; rather soft and plastic; dark grey, carbonaceous; pyritic (abundant framboidal aggregates and disseminated grains; common pyritised sponge spicules); rare dull olive-green glauconite ovoid pellets; non-calcareous; micaceous; tube-casts of pale grey coarse quartz silt.

37.26-37.64 m (122'3" - 123'6") As above, but few pyritised spicules, more frequent glauconite pellets and common dark grey faecal pellets, frequent sulphide aggregates (some framboidal), and rare pyritised tube-casts.

37.64-38.02 m (123'6" - 124'9") Very similar to the previous sample.

38.02-38.40 m (124'9" - 126'0") Silt, clayey, dark grey, carbonaceous; with minor very fine-grained quartz sand; mechanical analysis 62% silt, 26% clay, 12% sand; many (burrow)tube-casts of pale grey quartzose coarse silt and very fine-grained sand; abundant pyrite framboidal aggregates, often as tube-fillings; micaceous; non-calcareous.

38.79-39.17 m (127'3" - 128'6") Silt, clayey, sandy (mostly very fine-grained quartz, but some fine to coarse-grained); moderately coherent and plastic, moderately friable; pyrite common as pyritised sponge spicules and framboids.

39.17-39.55 m (128'6" - 129'9") Patchy dark and pale grey; the darker lenses of carbonaceous clayey silt, with very fine-grained quartz sand; the paler lenses of muddy quartz sand, mostly very fine-grained, some fine to very coarse-grained; the darker lenses have frequent iridescent framboidal sulphide aggregates; the paler lenses are only slightly pyritic with a few pyritised sponge spicules and sulphide aggregates; overall non-calcareous, micaceous, occasional small grains of glauconite.

39.55-39.93 m (129'9" - 131'0") Silt, clayey, very dark grey, carbonaceous, with very fine-grained quartz sand; small lenses, patches, and tube-casts of pale grey, quartzose, coarse silt and very fine-grained sand; frequent sub-rounded coarse quartz grains; otherwise as above.

Conformable contact with top of Tandanya Sand Member

39.93-40.31 m (131'0" - 132'3")	Dark grey, with a little patchy paler grey, as above; more or less carbonaceous, gritty, poorly-sorted sandy mud and muddy sand, with quartz from silt-size to 6 mm gravel; sand and gravel mostly sub-rounded to rounded; quite glauconitic (common dark green ovoid pellets); pyritic (frequent fine-grained disseminated; occasional pyritised sponge spicules); micaceous; non-calcareous; rare dark grey faecal pellets.
40.31-40.69 m (132'3" - 133'6")	Sand, quartzose, poorly-sorted, very fine to very coarse-grained; gravelly (quartz gravel to 7 mm diameter); clayey, silty; carbonaceous, dark grey; pyritic (aggregates and fine disseminations); frequent dark green glauconite pellets; micaceous.
40.69-41.07 m (133'6" - 134'9")	Sand, fine to coarse-grained, quartzose; dark to pale grey, carbonaceous; silty, clayey; rare, finely-broken, bivalve mollusc fragments; occasional glauconitic internal casts of small gastropods, bivalves; occasional bryozoal and echinoid fragments; frequent sponge spicules (both siliceous and pyritised); one or two small foraminifera; rare dark grey faecal pellets; rare quartz-sulphide cemented aggregates, and a few pyritised tube-casts.

41.07-41.45 m (134'9" - 136'0") Sand, dark to pale grey, carbonaceous, poorly-sorted, but much is coarse to very coarse-grained; gravelly (to 6 mm diameter); clayey and silty; pyritic (with an occasional pebble of cemented pyrite-quartz); minor glauconite.

41.45-41.83 m (136'0" - 137'3") As above, but less pyritic (rare pyritised sponge spicules and disseminated pyrite grains).

41.83-42.21 m (137'3" - 138'6") Sand, pale and dark grey, quartzose, very fine to fine-grained, rare coarse grains; silty, and with considerable dark brown carbonaceous clay; prominently micaceous; glauconitic (fine-grained pellets and grains); rare pyritised sponge spicules.

42.21-42.60 m (138'6" - 139'9") Similar to above, but with common glauconite and faecal pellets, and more fossiliferous (common sponge spicules, some pyritised, others siliceous, associated with occasional small siliceous ovoids; foraminifera are infrequent, mostly very small, and include both planktonics - ?Globigerina cf. leroyi, G. officinalis - and benthonics - Sphaeroidina bulloides, Pyrgo sp.).

42.60-42.98 m (139'9" - 141'0") Sand, similar to above, but less fossiliferous, and with abundant glauconite pellets (fine-grained dark and pale green, or brown); pyritic (rare pyritised spicules, and pyritic grains); carbonaceous (fine fragments and dark brown clay).

Bottom of Tandanya Sand Member; conformable contact with basal silt unit of Chinaman Gully Formation

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42.98-43.36 m (141'0" - 142'3") Silt, clayey, very dark grey-brown, notably carbonaceous (lignitic); irregularly laminated with sand, paler brown, quartzose (very fine-grained), silty; micaceous; minor glauconite; pyritic (fine framboidal aggregates and disseminated grains).

43.36-43.74 m (142'3" - 143'6") Laminated lignitic silt and very fine-grained sand, as above; mostly silty; finely glauconitic (mostly in the sand laminae); very finely pyritic; non-calcareous; compact, but friable; mechanical analysis 62% silt, 22% sand, 16% clay.

43.74-44.12 m (143'6" - 144'9") As above, with abundant fine-grained glauconite throughout; very carbonaceous; laminated.

44.12-44.50 m (144'9" - 146'0" As above, very carbonaceous, in part roughly laminated, but fossiliferous, calcareous; abundant bivalve mollusc fragments; abundant sponge spicules (both opaline and pyritised) and associated minute siliceous discs and ovoids; frequent foraminifera, dominated by small Cibicidoides sp.; abundant glauconite internal casts of gastropod and bivalve mollusc juvenile stages; rare echinoid spines; pyritic (pyritised spicules, framboids, coatings, fillings).

BOTTOM of Chinaman Gully Formation at about 45.7 m (150 feet); disconformable contact with cherty Gull Rock Member of Blanche Point Formation.

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There are several notable features of the above closely-sampled sequence. It is apparent that in this bore a silty and very carbonaceous (lignitic) interval several metres thick, conformably underlies the Tandanya Sand Member, and separates it from the top of the cherty Gull Rock Member. This interval is regarded as undifferentiated Chinaman Gully Formation. In many other bores the Tandanya Sand rests directly on the Gull Rock Member with an erosional disconformity. Typical 'upper Blanche Point Formation' ('Soft Marls') is absent, but the content of sponge spicules does demonstrate some faunal similarity to the Blanche Point Formation. The marginal-marine nature of the Chinaman Gully Formation is apparent.

In Ref. bore 89 (Western Courts building CH-3, Gouger St/Mill St) at the southwestern corner of Victoria Square, Chinaman Gully Formation was penetrated similarly by a well-cored foundation test bore during an engineering investigation (Rogers, 1972). The upper fine-grained unit (38.6-44.5 m) consisted of black carbonaceous silt, pyritic, finely micaceous, and non-calcareous, becoming sandy in the basal half-metre. Rogers reported a few fossils, and also the presence of steeply-dipping joints with shiny, slickensided surfaces. The Tandanya Sand Member (44.5-47.5 m) is present as a well-defined, dark grey, water-bearing quartz sand, fine to coarse-grained, with more or less rounded quartz grains. Underlying the Tandanya Sand, and, as at the type section, separating it from the cherty Gull Rock Member, a yellow, grey and black laminated silt between 47.5 and 49.1 m was noted as being calcareous, with some fossils.

In view of the stratigraphic interest of the old Kent Town bore (Ref. bore 31; Tate, 1882) it is useful to record the interval presently assigned by the writer to Chinaman Gully Formation. The upper fine-grained unit occupies the interval 29.6-37.2 m (97-122 feet). Tate logged this, his unit no. 16, as 'black clayey sand (fossiliferous)'; but it was logged by Miles (1952, index bore 216) as 'black fossiliferous sandy clay'. The unit is thus black and carbonaceous, with both clay and sand. It is not at present included in the Tandanya Sand Member, although part of it may be lithologically transitional.

The Tandanya Sand Member is taken to be the interval 37.2-38.7 m (122-127 feet). This was Tate's unit 17, which he logged as 'lighter-coloured and more sandy than No. 16, with thin bands of sharp white quartz sand, which are slightly inclined to the horizontal' (i.e. low-angle cross-bedding). This interval was also logged by Miles as 'black fossiliferous sandy clay', but is taken to be a laminated clayey sand, partly black and carbonaceous, partly white and non-carbonaceous.

Tate's unit no. 18 (127-131 feet; 38.7-39.9 m), logged by him as 'light blue calcareous clay', is at present interpreted to be the basal part of Chinaman Gully Formation, since hard (cherty) limestone of the Gull Rock Member was not reported until a depth of 39.9 m (131 feet). However Tate observed the 'light blue calcareous clay, graduating into' the 'blue argillaceous limestone', so the main boundary might just as well be put at 38.7 m (127 feet), as it was by Miles.

An interesting old sample of the Tandanya Sand Member is retained in the W. Howchin collection, at the South Australian Museum. The sample, of grey quartzose gravelly sand (the gravel up to 6 mm diameter) was obtained from total depth of 34.7 m (114 feet) in a water bore drilled in 1914 for A. Walton and Co., Grote St/West Tce (Ref. bore 87). Tandanya Sand was intersected at 33.5 m, and was water-bearing, as it often is beneath the City when not too muddy.

As noted earlier in discussion of the Golden Grove-Adelaide Embayment, several bores in the embayment beyond the Adelaide City area have penetrated thin beds of carbonaceous clay to lignite, which are correlated with Chinaman Gully Formation. A core of lignitic clay from a depth of 137 m in the SADME Hazelwood Park-1 bore (Plan 4; see Eberhard, 1980) has been identified palynologically by Harris (1980a) as a tentative time-equivalent of Chinaman Gully Formation. This lignitic clay occurs within a sequence of carbonaceous and pyritic fine to medium-grained sands, some of which may also correlate with Chinaman Gully Formation, in Tandanya Sand facies.

In the Devitt bore, Payneham South (Plan 4), a lignite at 63.1-67.1 m overlies Blanche Point Formation (with Gull Rock Member), and is correlated with Chinaman Gully Formation. It is overlain by sand, which may also correlate with Chinaman Gully Formation, in Tandanya Sand facies.

The Barnes bore, Glynde (Plan 4; Miles, 1952, index bore 299) penetrated a thin lignite at 36.6-37.8 m within a sequence of dark carbonaceous sands. The lignite, and possibly some of the sand, may correlate with Chinaman Gully Formation.

The E. & W.S. Department Springbank bore, considered to be located at the mouth of the Golden Grove-Adelaide Embayment (Plan 4), penetrated the following sequence which is correlated with Chinaman Gully Formation:

163.4 - 164.6 m	black lignitic clay,
164.6 - 166.7 m	fine brown sand,
166.7 - 167.6 m	lignite.

This sequence, 4.2 m thick, is underlain by Blanche Point Formation and equivalents, to the total depth of 231.0 m.

Further to the southwest, the Longyear bore, at the southern end of the Adelaide Plains Sub-Basin (Plan 2), penetrated Chinaman Gully Formation, Tandanya Sand facies, in the following cored sequence:

158.2-160.5 m Fine to coarse and gravelly argillaceous sand(stone), with more or less rounded quartz grains; pale to medium-grey, silty, carbonaceous; part strongly bioturbated, part slightly calcarenitic.

160.5-160.9 m No recovery.

160.9-162.3 m Grey muddy sand(stone) with bands of black carbonaceous mudstone.

162.3-165.3 m Laminated, black/grey, very carbonaceous mudstone/very fine-grained silty sand(stone).

This 7 m-thick interval is underlain by calcareous and shelly 'upper Blanche Point Formation' ('Soft Marls'), and is overlain by fossiliferous sands which correlate with the Aldinga Member of Port Willunga Formation.

As shown in Plan 29, the Croydon-2 bore penetrated an interval interpreted to be Chinaman Gully Formation between 451 and 463 m, a thickness of 12 m. At 451 m (1480 feet), the samples show a marked downhole lithological change to a very dark brown carbonaceous and lignitic silt/clay, which is pyritic and slightly glauconitic. By 454 m, the colour is nearly black. Between 460 and 463 m the lithology is mainly carbonaceous silty clay, with little residue remaining in the washed samples. There is minor quartz sand, very fine-grained, and in places cemented to argillaceous sandstone. Animal fossils continue very sparsely through the unit: a few sponge spicules, and occasional foraminifera - notably the final appearance of Tenuitella aculeata at 460.3 m. At 463 m, there is a distinct downhole lithological change to pale grey, fossiliferous, calcareous silt(stone), representing 'upper Blanche Point Formation' ('Soft Marls'). The 12 m-thick highly carbonaceous interval which was first tentatively correlated with Chinaman Gully Formation by the writer (Lindsay, 1968a), had not been distinguished as an entity prior to the work of Steel (1962a).

Distribution

Plan 21 depicts the subsurface distribution, structure contours, and thickness, of the Tandanya Sand Member beneath Adelaide City and on the Mile End Block. The member dips at little more than 1° towards the south to southeast, and has been removed up-dip by erosion along an irregular line which is mostly south of the River Torrens, as shown in various cross-sections (Plans 6-9). The upper fine-grained part of Chinaman Gully Formation is truncated similarly.

In the Golden Grove-Adelaide Embayment, as outlined earlier, beds of carbonaceous clay or lignite (possibly with associated carbonaceous sands) have been identified as Chinaman Gully Formation in bores around the southeastern margin, and up the axis of the embayment as far as Glynde.

As shown in Plan 2, the Chinaman Gully Formation has a rather widespread, if sporadic, distribution in the subsurface of the Adelaide Plains Sub-Basin. In Tandanya Sand and/or lignitic clay facies, the formation is recorded from the Longyear bore at the southern margin, from the Croydon-2 bore near the City of Adelaide; in the east from the Elizabeth Oval bore; and at least as far north as the east-west fault near SADME Korunye-3, SADME Light-1, and probably Beach Petroleum Hallions-2 well. Several of these localities are in fault-angle depressions, but in SADME Buckland Park-1 bore, the occurrence is not related to any known fault.

Cooper (1979b, p.67, fig. 43) has plotted the known distribution of Chinaman Gully Formation through part of the Willunga Embayment.

Only in the Seaford drainage bore (Plan 2; Cooper, 1980) has the formation been recorded subsurface in the Noarlunga Embayment.

Thickness

In the Willunga Embayment, Cooper (1979b, fig. 43) showed a fourfold progressive thickening of Chinaman Gully Formation southeastwards from the coastal stratotype (2.1 m) towards the Willunga Fault (more than 8 m).

Similarly in the Adelaide City area (Plan 21), the clastic wedge of the Tandanya Sand Member thickens towards the south and southeast, although the even progression of isopachs is interrupted by irregularities north of Victoria Square. Taken as a whole, including the fine-grained facies, the Chinaman Gully Formation beneath the City of Adelaide tends to thicken gradually towards the south and east, as shown by some of the cross-sections (Plans 6-8, 10, 13). The total thickness in many cases is of the order of 10 m, but approaches 17 m in the southeastern Parklands (Ref. bore 53). Thicknesses can be derived from Appendix B.

As shown in Cross-section R-S (Plan 14), the Tandanya Sand Member thickens remarkably from 7.6 m (Ref. bore 93) to more than 23 m (beyond Ref. bore 51) towards the northern end of the Mile End Block. However the overlying fine-grained unit of Chinaman Gully Formation appears to maintain a fairly constant thickness.

As shown in Plans 2 and 4, the thickness of Chinaman Gully Formation in the Adelaide Plains Sub-Basin is mostly of the same order as that beneath the Adelaide City area (about 10 m). The SADME Korunye-3 bore, in the Northern Adelaide Plains, has been only incompletely studied, but the thickness of 6.5 m indicated for 'Teg' is a minimum figure. There are indications that some of the underlying pyritic sand and mudstone shown as undifferentiated Tertiary ('T') could also be Chinaman Gully Formation, contributing to a relatively thick wedge of the unit in the fault angle. W.K. Harris (in Lindsay and Harris, 1979, p. 4) intimated from unpublished palynological work, that correlatives of Chinaman Gully Formation thicken northwards in the St Vincent Basin, in strongly prograding sequences.

Stratigraphic Relationships

In the Adelaide City area, a number of continuously-cored bores (e.g. Ref. bores 11, 14, 15, 45, 89) show a conformable and transitional relationship between Chinaman Gully Formation and the overlying Aldinga Member of Port Willunga Formation. However in Ref. bore 18, there is a distinct lithological break (although possibly still conformable) between sandy silt at the top of Chinaman Gully Formation, and rubbly sandy limestone at the base of the Aldinga Member.

The subsurface type section of the Tandanya Sand Member (Ref. bore 14) relates conformably and transitionally to the fine-grained units of Chinaman Gully Formation above and below it, as described earlier. Cross-section N-O (Plan 12) demonstrates these relationships.

Cross-sections such as C-D (Plan 7), P-Q (Plan 13), and R-S (Plan 14) illustrate an erosional disconformity between the Tandanya Sand Member and the underlying Gull Rock Member. In other Cross-sections (E-F, Plan 8; G-H, Plan 9; and J-K, Plan 10) it is a fine-grained basal unit of Chinaman Gully Formation, and not the Tandanya Sand, which rests on the disconformity surface. Still other Cross-sections (A-B, Plan 6; N-O, Plan 12) depict a combination of these disconformable relationships.

The gentle southerly or southeasterly dip of Chinaman Gully Formation leads to its truncation up-dip, in the vicinity of the Torrens Valley, by Upper Pliocene Hallett Cove Sandstone (Plan 8), Lower Pleistocene Carisbrooke Sand (Plans 6,7), or Quaternary Torrens alluvium (Plans 8,9,12).

In the Adelaide Plains Sub-Basin, both the Croydon-2 bore (Plan 29), and the Longyear bore (described earlier) show Chinaman Gully Formation to be underlain by 'upper Blanche Point Formation' ('Soft Marls') with sharp lithological change; and to be overlain by the Aldinga Member of Port Willunga Formation, also with a distinct difference in lithology.

At the stratotype, Maslin Bay (Reynolds, 1953), and in several bores in the Willunga Embayment (Cooper, 1979b), Chinaman Gully Formation similarly follows 'upper Blanche Point Formation' ('Soft Marls Member') with a sharp lithological change involving a dramatic drop in the content of carbonate and of marine fossils. Reynolds noted that concentrations of white, earthy, carbonate nodules near the top of Blanche Point Formation, beneath the contact, might indicate weathering and erosion prior to the deposition of Chinaman Gully Formation; but time-constraints within Zone P.16 suggest that any such hiatus was relatively short. At the base of the generally fossiliferous Aldinga Member of Port Willunga Formation, a thin gravelly quartz sand bearing occasional shark teeth disconformably overlies the emended topmost bed of stratotype Chinaman Gully Formation, which is green, clayey, glauconitic, and contains poorly-preserved foraminifera (see below). However in bores, the contact is marked by a down-hole decrease in marine fossils, glauconite, and carbonate content.

Biostratigraphy, Age, and Environment of Deposition

The topmost bed of stratotype Chinaman Gully Formation contains molluscan moulds (including frequent moulds and casts of '*Turritella*'), occasional bryozoal fragments, and a few

glauconitic internal casts of foraminifera (Gen. nov. cf. Bolivinella, Crespinina kingscotensis, ?Linderina sp.). The sample (F 118/66, Lindsay, 1967b) contains abundant glauconite ovoid pellets and grains, and represents a fair degree of marine influence.

Ludbrook (in Cochrane, 1956) reported on a variety of small foraminifera (mostly benthonic, but including a glauconite-infilled test of Globigerinatheka index) recovered from samples correlated with Chinaman Gully Formation in the Willunga bore WB1. Ostracode valves, sponge spicules, small molluscs, and glauconitic pellets were noted also; and, as at the stratotype, marine influence is evident. Unpublished palynological data supplied by W.K. Harris enabled Cooper (1979b, p.20) to report that 'recent recognition of marine dinoflagellate cysts with spores, pollen and acritarchs during palynological studies of this unit, suggest a marginal marine environment of deposition for the Chinaman Gully Formation'. However, faunal diversity and by inference, marineness, is notably less than for either 'upper Blanche Point Formation' or the Aldinga Member.

In the Tandanya Sand Member as developed beneath the Adelaide City area, Lindsay and Harris (1979) recorded 'sparse and sporadic foraminifera (including a few planktonic forms), sponge spicules (mostly pyritised), fragments and minute internal casts of molluscs, occasional bryozoal and echinoidal fragments. Plant fossils include spores, pollen, and organic-walled micro-plankton. Pyritised tube-casts (?burrows) also occur'. As detailed earlier, the whole of Chinaman Gully Formation in Ref. bore 14, Victoria Square, has this kind of marginal marine faunal assemblage associated with glauconitic and other faecal pellets, burrow-casts, and bioturbation.

In the Adelaide City area, the Tandanya Sand Member is typically both glauconitic and carbonaceous. According to the simple fourfold classification of Selley (1978, p. 28), the depositional environment corresponds therefore to a marine, poorly-winnowed, submarine channel or fan. Selley notes (op. cit. p. 238) that submarine channels and fans may be developed at the foot of an accretional feature (e.g. delta) or a tectonic feature (e.g. submarine fault scarp). Moderate marine transgression in the largely enclosed St Vincent Basin, over or against active fault scarps such as those associated with the Para and Eden Fault Zones, could have produced such settings on a relatively small scale, needing neither a great depth of water, nor great distance from the shore. In Cross-section N-O (Plan 12), the Tandanya Sand appears to occupy a shallow channel, 5 m deep and less than a kilometre wide, cut into the Gull Rock Member of Blanche Point Formation. In Cross-section R-S (Plan 14), the notable wedge of Tandanya Sand, here a dark, fine to coarse and gravelly sand (part poorly-sorted, part banded) with sparse marine fossils, could represent slumped and graded deposits associated with the adjacent (submarine) Para Fault Scarp. The Tandanya Sand, and the Chinaman Gully Formation as a whole, tend to be developed near the faulted eastern margins of the St Vincent Basin (including the Adelaide City area).

Detailed study of the lignitic facies of Chinaman Gully Formation (and other units) is being undertaken by W.K. Harris. He has suggested recently (Harris, 1980b) that in the St Vincent Basin the main development of these latest Eocene lignites can be ascribed to a depositional environment 'high

on the delta plain', in an ancient coastal complex, during a time of warm climate, high annual precipitation, rainforest vegetation, and eustatic high sea-level. As shown in Plan 35, this episode(3), represented by the Chinaman Gully Formation and the Aldinga Member, corresponds to the last stages of the warm Paleocene-Eocene, preceding the terminal Eocene cooling crisis.

Chinaman Gully Formation, because of its marginal-marine deposition, generally lacks distinctive foraminiferal faunas, either planktonic or benthonic. The local LAD of Pseudohastigerina micra and the local FAD of Globigerina angulifficinalis are shown in Plan 36 at the stratigraphic level of the Tandanya Sand Member, on the basis of only one or two specimens. The first appearance of the latter species was a latest Eocene event (Zone P. 17) according to Blow (1969, 1979); but the Chinaman Gully Formation is overlain by the Aldinga Member of Port Willunga Formation, and much of this member is also latest Eocene on the basis of a number of biostratigraphic indicators (Plans 36,37).

As stated by Harris (in Lindsay and Harris, 1979), the Chinaman Gully Formation lies within the spore/pollen zone of Sparganiaceaepollenites barungensis, which ranges in age from latest Eocene into the Oligocene (Harris, 1970, 1971; McGowran, et al., 1971). However more precision in correlation may be possible from the dinoflagellate biostratigraphy on which W.K. Harris is presently working.

Regional Events

The Chinaman Gully Formation is likely to have been deposited under a regime of sea-level higher than the present day, and also under the influence of a cycle of globally rising sea-level (Cycle TE3 of Vail et al., 1977; Vail and Mitchum,

1979). Under these conditions, as Vail et al. showed, regression (e.g. the Chinaman Gully Formation) rather than transgression (e.g. the Aldinga Member) can occur, if facies are displaced seawards by a sufficiently high influx of terrigenous sediment. Transgression can assert itself when the influx of terrigenous sediment declines below a critical level, enabling marine facies to migrate inland. A tectonic pulse involving the uplift of fault blocks in the Adelaide area could explain the influx of terrigenous sediment which led to the progradation of Chinaman Gully Formation, and would also explain erosional contact and angular unconformity with Blanche Point Formation (Cross-section R-S, Plan 14; and possibly Cross-section A-B, Plan 6). A higher, and rising sea-level might also have climatic effects leading to increase of regional rainfall, and hence increased erosion and movement of sediment basinwards. However this effect would be countered to some extent by the higher base-level of erosion/aggradation which results from a higher sea-level. The maintenance of marginal coal-forming environments in a basin (such as produced the lignites of Clinton Formation, and to a lesser extent Chinaman Gully Formation) depends on an equilibrium between complex interacting processes.

The deposition of Chinaman Gully Formation appears to correspond to part of the middle, regressive, episode of Depositional Cycle 3 of Bock and Glenie (1965); to a late stage of Sedimentation Cycle 2B of Quilty (1977); and to a late stage of Sequence 2 of McGowran (1978a,d; 1979b).

PORT WILLUNGA FORMATION

INTRODUCTION

Coastal exposures of bryozoal limestones, mudstones and sands, at Port Willunga-Aldinga, comprising the upper part of Tate's Lower Aldinga Series (Tate, 1878, 1879; Tate and Dennant, 1896; see Ludbrook and Lindsay, 1966) were described and named Port Willunga Beds by Reynolds (1953). In accord with the Australian Code of Stratigraphic Nomenclature, the term 'Beds' was used by Reynolds and continued by subsequent authors to imply incomplete knowledge of thickness, lithology, or stratigraphic relationships. However, increasing knowledge over recent years, latterly from hydrogeological drilling by SADME in the Willunga Embayment, led Cooper (1977b) to upgrade the Port Willunga Beds to formational status, and to formally name three members. The two oldest of these, namely the Aldinga Member (= 'Aldingan unit' of Lindsay, 1970a) and the Ruwarung Member (= 'siliceous unit' of Lindsay, 1969, 1970a) are identified beneath the City of Adelaide, as discussed below. It is likely that younger units of the Formation were deposited there also, since they occur on down-faulted blocks immediately west of the City, but if so, they were removed by erosion prior to deposition of the Hallett Cove Sandstone in the Late Pliocene.

In all, seven units of Port Willunga Formation are recognised in the vicinity of the City of Adelaide, including the western faulted blocks (Plans 3, 16). From youngest to oldest they comprise:

7. Port Willunga Formation above the Munno Para Clay Member (Balcombian and Bairnsdalian Stages, Middle Miocene);
6. Munno Para Clay Member (Balcombian, Lower to Middle Miocene)
5. Port Willunga Formation below Munno Para Clay, and of lower Balcombian and Batesfordian Stages, Lower Miocene;

4. Longfordian Stage, Lower Miocene;
3. Janjukian Stage above Ruwarung Member, i.e. the 'upper Janjukian unit' of Lindsay (1969); mostly, if not all, Upper Oligocene;
2. Ruwarung Member (Janjukian, and pre-Janjukian/post-Aldingan; Oligocene;
1. Aldinga Member, including mudstone (silt/clay) and basal sand units (uppermost Aldingan Stage; probably mostly uppermost Eocene).

Units 3,4,5, and 7, are not formal lithostratigraphic units, and it is not proposed to define them as such in the present study. Within the clastic/carbonate sandy limestones of the whole sequence above the cherty Ruwarung Member, the only markedly contrasting lithological unit is the Munno Para Clay Member. Units 5 and 7 are only distinguished biostratigraphically, or in the presence of the Munno Para Clay intercalated between them. Units 3 and 4 are also essentially biostratigraphic, recognised by palaeontological correlation with the Victorian Janjukian and Longfordian Stages respectively.

Within the area treated, as shown in Cross-section T-U (Plan 16), all seven units are only known to occur together on the Croydon Block, in Croydon-2 bore. Beneath most of Adelaide City only unit 1 is present, overlain by unit 2 in the southern part. Younger units are present on the Mile End and Thebarton fault blocks. The nature of the complete succession, 266 m thick in Croydon-2 bore, supports assignment of all seven units to the Port Willunga Formation. The upper half of this interval in Croydon-2 bore was so identified by Glaessner (1953a) as soon as Reynolds defined the Port Willunga Beds. Ironically, it is the lower half of the interval that correlates with the type section, the cherty Ruwarung Member being particularly well developed.

In the type section, only units 1, 2 and 3 are exposed (Lindsay, 1967b, 1969) although unit 4 crops out at Sellick Beach a few kilometres to the south, in the same stratigraphic succession within that embayment. Unit 5, including the Lepidocyclina zone, occurs in the same succession but only inland and subsurface (Cooper, 1979b). No younger units of Port Willunga Formation are known from the Willunga Embayment, and none younger than unit 3 are known from the Noarlunga Embayment (Cooper, 1979a, 1980). Units 2 to 7 are widespread and readily recognisable in the southern part of the Adelaide Plains Sub-Basin, but only subsurface (Lindsay, 1969). Unit 1 is well developed in the Longyear bore (Plan 2) at the southern end of the sub-basin, and beneath the City of Adelaide. It is also recognisable in Croydon-2 bore; but elsewhere, in the absence of Chinaman Gully Formation, it is difficult to separate from uppermost Blanche Point Formation.

Estimates of the age of the type section have varied between Miocene and Eocene over the past century, the section being now dated Upper Eocene and Oligocene. Tate (1879) at first suggested a Lower Miocene age for the upper part of his 'Lower Aldinga Series' (much later to comprise the type section of Port Willunga Formation) as distinct from the stratigraphically lower 'glauconitic limestones at Aldinga' (partly at least, Tortachilla Limestone) which he dated Eocene. This is strangely in conflict with the later comment of Tate and Dennant (1896, p. 119) that in the 1879 paper 'the term Eocene was applied to the Lower Aldinga Series, and that of Miocene to the Upper Series'. However it is clear that by 1896 these authors regarded the whole of the 'Lower Aldinga Series' as Eocene. Tate (1899, p. 107) finally regarded the upper part of the Series as Upper Eocene, the middle as Middle Eocene, and the lower part Lower Eocene. This would have dated the type section of Port Willunga Formation Upper to possibly Middle Eocene, depending on where he divided the 'upper' and 'middle' parts of the Series; but this

he did not detail. Since 1966 (Lindsay, in Ludbrook and Lindsay, 1966; Lindsay, 1967b) the lower part of the type section has been recognised as Upper Eocene.

Dennant and Kitson (1903) largely followed Tate's last age assignments, but soon Chapman (1914), influenced by the work of Gregory and McCoy, was putting the whole of Tate's Lower Aldinga Series in the Miocene, together with the 'Janjukian Series', which Tate had latterly distinguished as Oligocene(?). Howchin (1918, 1923, 1928) similarly correlated the whole of Tate's Lower Aldinga Series with the Janjukian Series, dating both Miocene. He photographed the middle part of the type section of Port Willunga Formation (1918, fig. 321). Singleton (1941) tentatively put all 'the lower beds at Aldinga and in Adelaide bores' low in the Barwonian System (Janjukian Stage, Upper Oligocene to Miocene). David and Browne (1950) dated and correlated the 'Lower Aldingan' exposures similarly.

Crespin (1946) listed many foraminifera recovered from five 'Lower Aldingan' samples, four of which certainly came from stratotype Port Willunga Formation (three from the Aldinga Member, one from the Ruwarung Member). She dated all five samples Middle Miocene ('Longfordian substage of the Balcombian'). Later however (Crespin, 1954) she too came to correlate the Lower Aldingan beds with the Janjukian Stage, but dated both Upper Eocene. Younger subsurface beds of the Adelaide Plains borings (her 'Oaklands Limestone') she dated Lower Miocene, Balcombian Stage.

Glaessner (1951) correlated the 'Polyzoal Beds of Aldinga Bay' (i.e. stratotype Port Willunga Formation plus exposures at Sellick Beach) mostly with the Janjukian and Longfordian Australian Stages, and with the Aquitanian of Europe, near an indefinite Oligocene-Miocene boundary. The type section was similarly dated Oligocene to Lower Miocene by Glaessner and Wade (1958) and Glaessner (1959); but was restricted to the Lower Miocene (Aquitanian) by Ludbrook (1963a). Wade (1964, text-fig. 2) recognising the greater antiquity of the strato-

type, dated it all Oligocene (Janjukian). As outlined by Lindsay (1967b), the most diagnostic planktonic foraminiferal event at present available to link the outcropping type sections of the Jan Juc Formation and the Port Willunga Formation is the final appearance of Chiloguembelina in the presence of continuing Guembelitria. This event occurs near the base of the former section, and near the top of the latter. Hence Lindsay (1967b, p. 98) 'inferred that less than 20 feet (6 m) of Port Willunga Beds, at the top of their type section, are early Janjukian. Most of the middle, siliceous, interval appears to be strictly pre-Janjukian and it is post-Aldingan as at present defined'. Such a gap between the Aldingan and Janjukian Stages was shown too by Abele (1976a, table 8.1). However Abele (1976b, pp. 234-235) also recorded older Jan Juc Formation (lower Oligocene - upper Eocene) revealed by offshore drilling in the Torquay Basin. If these strata were to be included in the Janjukian Stage (and it is possible to infer from the definition by Singleton, 1941, that they might be) then the gap between the Janjukian and Aldingan Stages would be closed.

In the following discussion of the various units of Port Willunga Formation, only those which occur beneath the City of Adelaide will be treated in detail.

ALDINGA MEMBER

Nomenclature

The locality Aldinga has been used stratigraphically in various senses for more than a century. Tate's use of 'lower Aldinga series', 'lower Aldinga beds', or 'Lower Aldingian Series' has been discussed already in connection with stratotype Port Willunga Formation. His 'upper Aldinga series' would now correspond to Hallett Cove Sandstone + Burnham Limestone (Upper Pliocene - Lower Pleistocene).

Crespin (1954) introduced the term Aldinga Limestone in a sense largely synonymous with the earlier-defined Port Willunga Beds of Reynolds (1953) whose name therefore took precedence.

The lower part of stratotype Port Willunga Formation, up to the base of the unit with chert nodules (Ruwarung Member of Cooper, 1977b) was made the uppermost unit of the Aldingan Stage by Ludbrook and Lindsay (1966), and was thus informally termed the 'Aldingan unit' of the Formation by Lindsay (1970a). This was formalised to Aldinga Member of Port Willunga Formation by Cooper (1977b).

There need be no confusion between the two usages of the name Aldinga once it is clearly understood that the term Aldingan Stage is used in a time-rock sense for the time interval required for the deposition at Maslin and Aldinga Bays of the sequence from Tortachilla Limestone through to the base of the Ruwarung Member of Port Willunga Formation, whereas the term Aldinga Member is used in a rock-stratigraphic sense, and embodies only the latest part of the Aldingan Stage. The Aldinga Member is notable as being the only part of the Port Willunga Formation included in the Eocene Aldingan Stage.

Type Section

The stratotype of Port Willunga Formation, as designated by Reynolds (1953) and further described by Lindsay (1967b), is well exposed in low coastal cliffs north and south of Port Willunga in the northern part of the Willunga Embayment, 37 km south-southwest of the City of Adelaide (Plan 2). Dips are low, of the order of one to three degrees in a general southerly direction. The Aldinga Member, the basal unit of the Formation,

is exposed along the coast for about one kilometre from Chinaman Gully southwards to the ruins of the old Port Willunga jetty, except for a 250-metre gap eroded by the present and ancestral Aldinga Creek.

Lindsay (1970a) described a comparable and also well-exposed reference section of the Aldinga Member ('Aldingan unit') near the mouth of the Onkaparinga River, Port Noarlunga South, in the adjoining Noarlunga Embayment (Plan 2). This reference section, 10 km north of the stratotype, is somewhat thinner (9 m as against 13 m) and more clayey (marly), but is still clearly bounded by the Chinaman Gully Formation below, and the cherty Ruwarung Member above.

Lithology

The stratotype is a fossiliferous sequence of variable lithology comprising bryozoal and foraminiferal sands and calcareous sandstones, muddy limestones, silts and clays (skeletal calcarenitic mudstones or 'marls'). The lower half of this interval is mostly quartzose and sandy, with a thin basal gravelly sand, while the upper half is more silty and clayey (Reynolds, 1953; Lindsay, 1967b, 1970a). Similarly, Lindsay (1970b) and Selby and Lindsay (1973) recognised, beneath the Adelaide City area, a lower sand/sandstone unit and an upper silt or silt/clay unit of basal Port Willunga Formation i.e. the Aldinga Member.

The Aldinga Member is only known in the Adelaide City area from boreholes, as it does not crop out there nor indeed anywhere in the Golden Grove - Adelaide Embayment or the Adelaide Plains Sub-Basin. A useful section of the Member was penetrated by foundation test bore G4 for the State Administration

Building, Victoria Square (Ref. bore 14, Plans 5, 8; Appendices A,B) where continuous tube-coring proved a minimum thickness of 5.5 m of the fine-grained unit, above 4.3 m of the basal sand unit. This sequence is described in the Table below.

TABLE

Section through Aldinga Member, State Administration Building, Victoria Square, Adelaide (Ref. bore 14; after Lindsay, 1964a)

Depth (m)	Description
24.08 - 24.38	Sand and sandstone, calcareous, quartzose, fossiliferous, shelly, clayey; brown, mottled dark brown.
	BASE OF HALLETT COVE SANDSTONE
----------	angular unconformity ----------
	PORT WILLUNGA FORMATION, ALDINGA MEMBER, silt/clay unit
24.38 - 24.69	Silt, stiff, clayey, calcareous, fossiliferous, sparsely shelly, glauconitic, micaceous, pale greenish-grey mottled pale and dark brown.
24.69 - 25.00	Silt as above, but pale grey-brown, mottled dark brown, and with black manganiferous dendritic deposits; sandy (sparse very fine-grained quartz, and abundant ovoid faecal pellets); mechanical analysis (E. & W.S. Dept. lab.) 62% silt, 31% clay, 7% sand; 10.2% lime (soluble in dilute hydrochloric acid).
25.00 - 25.30	Not sampled.

25.30 - 25.91 Clay and silt, stiff, compact, platy, sandy (very fine to fine-grained quartz; ovoid faecal pellets, partly glauconitised); calcareous, fossiliferous, micaceous; pale greenish-grey mottled in shades of brown, and dark brown ferruginous patches.

25.91 - 26.21 Not sampled.

26.21 - 26.52 Clay, similar to above, silty, sandy (very fine-grained quartz; abundant ovoid faecal pellets, some glauconitised) sparsely shelly; brownish-grey mottled dark brown, dark grey; mechanical analysis 44% clay, 27% silt, 19% sand; 13.5% lime.

26.52 - 27.13 Silt and clay, as above, mottled greenish-brown, grey, dark grey, dark brown; abundant ovoid faecal pellets, many glauconitised, some oxidised.

27.13 - 27.43 Silt, clayey, quartzose (fine-grained sand), only slightly calcareous; abundant ovoid pellets (glauconite and oxidised glauconite); brown-grey, speckled ferruginous brown; much siliceous sponge spicule debris, mostly fine and broken; mech. anal. 46% silt, 35% clay, 19% sand.

27.43 - 28.04 Silt, with many spots of ferruginous siltstone, non-calcareous, spicular, pelletal, glauconitic, clayey, quartzose (fine-grained sand), micaceous; mottled pale and dark grey, pale and dark brown, greenish; bioturbated, only poorly fossiliferous, apart from fine spicular debris.

28.04 - 28.35 Not sampled.

28.35 - 28.65 Similar to above; grey, with patchy dark brown ferruginous mottling; mech. anal. 64% silt, 28% clay, 8% sand.

28.65 - 28.96 Mud to mudstone, semi-lithified; mottled pale and dark grey, greenish and brownish, pelletal, glauconitic, slightly carbonaceous, minor pyrite; micaceous, quartzose (very fine-grained sand); poorly fossiliferous.

28.96 - 29.57 Mud, sandy, quartzose (very fine-grained), with more sandy laminae and lenticles; dark grey mottled pale grey, pale brown; only slightly calcareous, if at all; sparsely glauconitic, finely micaceous; carbonaceous; abundant ovoid faecal pellets.

29.57 - 29.87 Silt, friable, sandy, quartzose (very fine to fine-grained sand); clayey; grey, mottled dark grey, brown; calcareous, fossiliferous, parts shelly; glauconitic, micaceous.

----------conformable contact ----------

ALDINGA MEMBER, sand unit

29.87 - 31.39 Sand, soft, friable, quartzose, very fine-grained, clayey and silty; pale brown; glauconitic, micaceous; calcareous in parts; fossiliferous; mech. anal. at 30.48 - 31.09 m, 68% sand, 20% silt, 12% clay.

31.39 - 34.21 Sand, very fine to fine-grained, similar to above, but mottled brown and grey; darker grey and carbonaceous at base; non-calcareous; glauconitic (glauconitised ovoid faecal pellets); sparsely fossiliferous.

---------- conformable contact ----------

CHINAMAN GULLY FORMATION (upper fine-grained unit)

34.21 - 38.40 Silt, soft and plastic to semi-lithified; clayey, quartzose (very fine-grained sand); dark grey, carbonaceous, pyritic (including abundant pyritised sponge spicules, framboidal aggregates, pyritised burrow-fillings); mostly non-calcareous; sparsely glauconitic; micaceous; mech. anal. at 35.36 - 35.74 m, 65% silt, 24% clay, 11% sand; mech. anal. at 38.02 - 38.40 m, 62% silt, 26% clay, 12% sand.

At the southwestern corner of Victoria Square, foundation test drilling for the Western Courts Building, Mill Street (Rogers, 1972) penetrated both units of the Aldinga Member in Core Hole 3 (Ref. bore 89, Plan 5, Appendix B). In the upper unit (depth 24.3 - 32.8 m) the top two metres below the erosional unconformity comprise a finely sandy silt of low plasticity, containing patches which are more sandy. The interval is glauconitic, calcareous, fossiliferous, structureless, and of moderate porosity: the colour ranges from yellow-grey to grey, representing some degree of oxidation, but not as pervasive as in the sequence described above in Ref. bore 14, State Administration Building. The remaining 6.5 m of the upper unit are

greenish-grey to black, and thus less oxidised, consisting of a finely micaceous silt of low plasticity and moderate to high porosity. This interval is fossiliferous and in part shelly: it is moderately pyritic towards the base. The lower, sand unit (depth 32.8 - 38.6 m) is greenish-grey to dark grey, quartzose (fine-grained sand and silt), becoming more silty towards the base. The sand is calcareous, with shell fragments. It has high porosity, and its variable penetration rate is due to some minor cementation to calcareous sandstone.

Three core samples of the upper fine-grained unit of the Aldinga Member, taken in a closely adjacent bore, also in the Supreme Court complex, southwestern Victoria Square (Ref. bore 33, Plan 5; Crawford, 1956a) are illustrated here to indicate the gross lithology and the effects of oxidation/weathering beneath the unconformity (Figs 72-74). A petrographic description of the middle sample, from a depth of 27.4-29.0 m, is attached in Appendix C. The rock is described as a glauconitic and sandy marl. It consists of 'glauconite pellets, fine-grained quartz-rich detritus and shell fragments disseminated through a turbid matrix of intimately intergrown clay and carbonate'.

The upper and lower units of the Aldinga Member were cored continuously in foundation test drilling for a proposed P.M.G. Mail Exchange building at the western end of Gouger Street, one kilometre west of Victoria Square (Tarvydas, 1970; Lindsay, 1970b; Ref. bores 15, 18; Appendices A, B; Plans 5, 12). Here the upper unit, with maximum thickness at least 3.7 m, is a clayey silt of low to high plasticity, mottled in shades of green-grey, fawn-grey and yellow-brown, with considerable brown



Figure 72. Upper mudstone (silt/clay) unit of Aldinga Member, Port Willunga Formation, Adelaide City area; uppermost Eocene. Supreme Court Library bore PB-1 (Ref. bore 33), Victoria Square; tube-core from 25.9-27.4 m, approx. 1 m below unconformity; weathered sandy silty mudstone, pale greyish-brown, mottled orange/brown and dark grey; sparsely shelly (white, chalky preservation); glauconitic (pale brown, pale green, ovoid pellets).



Figure 73. As above but tube-core from 27.4-29.0 m, approx. 3 m below unconformity; weathered sandy silty mudstone, pale grey, mottled orange/brown; sparsely shelly (pink, moderately good preservation); glauconitic (pale to mid-green ovoid pellets).



Figure 74. As for Figs 72,73, but from tube-core at 30.2-30.5 m (T.D.), approx. 5 m below unconformity; sandy silty mudstone, mid to dark grey (minor orange/brown spots, seams, mottles); notably shelly (good preservation); glauconitic (pale to dark green ovoid pellets).



Figure 75. Basal sand unit of Aldinga Member, Port Willunga Formation, Adelaide City area; uppermost Eocene; SADME South Parklands bore (Ref. bore 41); pumped sand sample from 42-43 m (Plan 27); shelly, quartz/calcarenite sand, fine to coarse-grained, pale brownish-grey; with foraminifera, molluscs, bryozoal and echinoid fragments, corals, barnacle plates; minor cementation to calcareous sandstone.

ferruginous staining. There are a few nodular patches of white earthy limestone, adding to the evidence for erosion, weathering and oxidation. The silt contains 5 - 10% fine to coarse-grained quartz sand, together with abundant sand-sized ovoid faecal pellets (mostly ½ to 1 mm long), many of them now green glauconite. The interval is partly calcareous and partly leached, moderately fossiliferous, and in places shelly. The lower, sand unit here is mostly a soft, silty, fine-grained quartz sand and skeletal calcarenite, shelly in part, greyish-fawn to pale brown, glauconitic (pelletal) and micaceous. There is minor cementation to hard glauconitic calcareous sandstone, and one drillhole penetrated a metre-thick bed of it. Penetration rates during tube-coring were variable, but it proved necessary to drill through the cemented band.

Both units of the Aldinga Member were penetrated in SADME South Parklands bore (Ref. bore 41, Appendices A, B; Plans 5, 8,13,27). Here, the upper, fine-grained unit (depth 37-42 m) comprises mudstone and silt, brownish and greenish-grey, clayey, quartzose (very fine-grained sand), glauconitic (pelletal), carbonaceous, sparsely pyritic, finely micaceous, skeletal calcarenitic, and in parts shelly. The underlying arenaceous unit (depth 42-52 m) is a fossiliferous quartz sand, skeletal calcarenitic, coarse-grained to very fine and silty, pale brownish-grey, glauconitic (pelletal), in part shelly (Fig. 75).

The SADME Hazelwood Park-1 bore (Eberhard, 1980) near the southeastern edge of the Golden Grove-Adelaide Embayment (Plan 4), appears to have penetrated a very marginal, sandy facies of the Aldinga Member. Core of carbonaceous quartz sand from 116 m, examined palynologically by Harris (1980a), was tentatively

determined by him as a time-equivalent of the Aldinga Member. The only animal fossils recognised in the bore comprised a horizon of pyritic internal casts of ?Turritella in pyritic quartz sand at 101 m. In view of the palynological determination, this horizon is considered to be also a probable correlative of the Aldinga Member, representing the extreme edge of a marine transgressive episode. The term Pirramimma Sand Member, defined in the Willunga Embayment (Cooper, 1977b, 1979b) is also applicable to such marginal-marine, poorly fossiliferous sand facies at this stratigraphic level, as shown in Plan 3.

The cored Longyear bore, at the southern end of the Adelaide Plains Sub-Basin (Lindsay, 1981) is a useful subsurface reference section linking the Adelaide region with the southern embayments. In this bore the Aldinga Member can be recognised clearly between 118.7 and 158.2 m (39.5 m), as a rather variable succession of fossiliferous muddy and sandy strata which lie beneath the cherty Ruwarung Member and above the much less-marine Chinaman Gully Formation. Here, as at the stratotype and beneath Adelaide City, the Aldinga Member can be broadly divided into an upper fine-grained unit, mostly calcarenitic sandy mudstone (118.7-127.4 m; 8.7 m) and a lower quartz-calcarenite sand (127.4-158.2 m; 30.8 m).

The mudstones are grey to grey-brown, quartzose (fine-grained sand), glauconitic (abundant ovoid pellets), pyritic, more or less carbonaceous, micaceous, skeletal calcarenitic, and shelly in parts. A grey-green muddy greensand is inter-calated at 121.8-123.8 m within this upper sequence. It is significant that this greensand interval is comparable both lithologically and in stratigraphic position with the Port Julia

Greensand Member of Rogue Formation on eastern Yorke Peninsula (Crawford, 1965; Stuart, 1969, 1970) and in the northeastern St Vincent Basin (Cooper, 1977a). A brown iron-stained horizon at 125 m may represent a weathering surface.

The sand unit is quartzose, poorly-sorted (fine to coarse-grained), muddy, skeletal calcarenitic, and shelly in parts; it is dark grey above 133 m, then pale brown to 136 m. Between 136.2 and 136.9 m, a spectacular 'pseudo-Tortachilla' facies is developed, comprising a fossiliferous, shelly, muddy calcarenite/quartz sand, which is pale greenish-brown speckled with dark brown polished pebbles (up to 10 mm) of iron-stained quartz, and ferruginous (goethite-limonite), lithic, or oxidised glauconite material. A petrographic description of a sample from 136.63-136.68 m, representing the 'pseudo-Tortachilla' facies, is attached in Appendix C. There the rock is described as a fossiliferous, argillaceous sandstone, consisting mainly of detrital quartz (50-60%), calcareous fossils and fragments (20-25%), and iron-stained interstitial clay (20-25%). Underlying this facies, grey, pyritic, glauconitic, muddy, fossiliferous sands continue down to at least 155.5 m. Beneath an interval of no sample recovery (155.5-157.9 m), probably representing sands, a thin bed of grey, glauconitic, fossiliferous, sandy mudstone (157.9-158.2 m) is taken to mark the base of the Aldinga Member. This is underlain by a gravelly sand (158.2-160.5 m) which may represent the Tandanya Sand Member of Chinaman Gully Formation.

In contrast to the sequence in the Longyear bore, the Aldinga Member as penetrated by the Croydon-2 bore presents a rather uniform lithology of grey fossiliferous silt and siltstone (Plan 29). In this facies, and in the absence of the Chinaman

Gully Formation, it is difficult to separate the Aldinga Member lithologically, from upper Blanche Point Formation in the Adelaide Plains Sub-Basin (Lindsay, 1969).

Distribution

Plan 22 shows the distribution of the sand unit of the Aldinga Member beneath the City of Adelaide and on the down-faulted Mile End Block. Cross-sections demonstrate that the Aldinga Member is truncated up-dip to the north by the Pliocene Hallett Cove Sandstone (Plans 7,8,12), by the Lower Pleistocene Carisbrooke Sand (Plans 6,10,12), or by Quaternary 'Torrens alluvium' (Plans 10,12,14). The Member is thus mostly absent from the Torrens valley in the vicinity of Adelaide City, and is missing completely from beneath North Adelaide. It has not been recognised further up the Golden Grove-Adelaide Embayment than the City limits. However, sandy, marginal to non-marine time-correlatives have been identified tentatively near the southeastern edge of the embayment in the SADME Hazelwood Park-1 bore, as discussed earlier, and further palynological studies of such sequences may well reveal similar time-correlatives elsewhere up the embayment.

In the Adelaide Plains Sub-Basin the Aldinga Member is identified at least in the Croydon-2 and Longyear bores, as described earlier. Hence time-correlatives are probably widespread in the Sub-Basin, but in calcareous mudstone/siltstone facies they are difficult to separate lithologically from upper Blanche Point Formation if Chinaman Gully lignite or sand are not recognisable as marker beds (Lindsay, 1969, pp. 18, 34).

Cooper (1979b, fig. 45) has outlined the known extent of the Aldinga Member in the Willunga Embayment; and its presence in the Noarlunga Embayment has been recorded in coastal outcrop (Lindsay, 1970a) and subsurface in the Seaford drainage bore (Cooper, 1980).

Thickness

Apart from the effects of erosional truncation, cross-sections show that the Aldinga Member as a whole maintains a fairly constant thickness of 12 to 15 m beneath the City. This compares closely with the thickness of stratotype Aldinga Member at Port Willunga, namely about 13 m (Lindsay, 1967b). As shown in Plan 22, and in Appendix B, the sand unit beneath the central City is mostly between four and six metres thick; but is notably thin in the Kent Town bore (Ref. bore 31: less than one metre) and relatively thick across the South Parklands (e.g. 10 m in Ref. bore 41). The upper, fine-grained unit is often seven or eight metres thick, but is relatively thin in Ref. bore 41 (five metres).

On the Mile End Block, the Aldinga Member was penetrated by Ref. bores 51 and 93 (Cross-section R-S, Plan 14). These reveal a somewhat greater total thickness than beneath the City proper (Ref. bore 51, 18.2 m; Ref. bore 93, 21.0 m). As shown in Plan 22, the sand unit alone has a thickness comparable with that beneath the City proper, and thickens to the south. The upper silt/clay unit however, is thicker than anywhere beneath the City.

No bores have penetrated to the Aldinga Member on the Thebarton Block, between the Main Para Fault and the West Para Fault, but on the Croydon Block, the Aldinga Member attains a thickness of 49 m in Croydon-2 bore (Plans 16, 29).

In the Longyear bore, as noted earlier, the Aldinga Member comprises an upper mudstone unit (8.7 m) and a lower sand (30.8 m), totalling 39.5 m.

Relationships and Boundary Criteria

Beneath the City, the basal sand of the Aldinga Member is underlain, apparently conformably, by dark grey carbonaceous silt which is identified as Chinaman Gully Formation (Lindsay and Harris, 1979). In Ref. bores 14 (Lindsay, 1964a), 15 (Tarvydas, 1970), and 45 (Selby, 1972) for example, continuous tube-core samples revealed a gradational boundary between silty fine-grained sand above, and fine sandy silt below. However in Ref. bore 18 (Tarvydas, 1970; Lindsay, 1970b) a metre-thick bed of pale brown, hard, glauconitic, calcareous sandstone is the basal bed of the Aldinga Member sand unit. The contact with the underlying dark grey sub-fissile silt is apparently sharp but could still be conformable. This borehole was only 65 m south of Ref. bore 15.

On the Mile End Block, the contact (in sludge samples only) appears to be conformable and gradational. In Ref. bore 51, it is between carbonaceous gravelly fine to coarse sand (above) and carbonaceous sandy clay (below). In Ref. bore 93, the contact is between 'sloppy' sand silt and clay, above, and 'stiff' sandy silty clay, below. The passage in the Longyear bore, from Aldinga Member sand, through a thin sandy mudstone, to gravelly Tandanya Sand, was discussed earlier.

The contact between the upper silt/clay and the lower sand of the Aldinga Member, is revealed as conformable and in places gradational, by continuous tube-coring in many bore-holes.

In the City area, the contact between the Aldinga Member (silt/clay unit) and the overlying cherty Ruwarung Member, is only known from sludge and tube-core samples of Ref. bore 41, and from logs of a few old bores. In Ref. bore 41, the nodules of hard cherty mudstone typical of Ruwarung Member contrast with the inter-nodular matrix of clayey silt (mudstone) which is also the lithology of the top of the Aldinga Member. Thus the base of the Ruwarung Member is marked by the downward disappearance of cherty nodules, and this appears to be gradual. Because of the difficulty of tube-coring the hard cherty nodules there is no boundary core. Core and sludge samples from the boundary zone are as follows:

34 - 36 m sludge, abundant fragments of chert; Ruwarung Member.

35.0 - 35.3 m, core, no chert; interpreted as a soft chert-free band near the base of Ruwarung Member.

36 - 38 m sludge, only a few chert fragments; driller did not record hard 'sandstone' (i.e. chert) phase below 36 m; base Ruwarung Member/top Aldinga Member put approximately at 37 m.

38 - 40 m sludge, occasional small fragments of cherty lithology are regarded as downhole contamination; Aldinga Member, silt/clay unit.

40.0 - 40.3 m, core, no chert; Aldinga Member.

This interpretation is consistent with geophysical logs of the borehole (Selby and Lindsay, 1978) particularly the Point Resistivity curve which shows a 'spiky' record through the main zone of cherty nodules, gradually reducing to a minimum at 37 m.

Geological cross-sections cited earlier show that beneath much of the central City the Aldinga Member is truncated by a low-angle erosional unconformity, overlain either by Pliocene Hallett Cove Sandstone, by Lower Pleistocene Carisbrooke Sand, or by younger Quaternary alluvium of the Torrens.

Biostratigraphy

The sand unit of the Aldinga Member beneath the City has yielded significant foraminiferal faunas in Reference bores 16,17,18 (Gouger Street), 32 (West Parklands) and 41 (South Parklands). In each case the planktonic/benthonic ratio is very low, at the most only a few per cent, but the following more significant planktonic species are variously represented, range data being plotted on Plan 36.

Cassigerinella winniana (Howe)

Chiloguembelina cubensis (Palmer)

Globigerina officinalis Subbotina, trending to

Globigerina angulioficinalis Blow (Pl. 23, Figs 9,11; Pl. 24, Figs 6, 8-10)

?Globigerina sp. cf. ?G. brevis (Jenkins) (Pl.19, Figs 2,3)

'Globigerina' labiacrassata (Jenkins) (Pl. 20, Figs 3,5; Pl. 23, Figs 1,2,4,5)

Globigerinatheka index (Finlay) (Pl. 34, Figs 7-10; immature)

Subbotina angiporoides angiporoides (Hornibrook)

(Pl. 27, Figs 2-10)

Subbotina cf. angiporoides minima (Jenkins)

(Pl. 27, Fig. 11; Pl. 28, Figs 1,3,4,6,7)

Subbotina cf. angiporoides lindiensis Blow

(Pl. 28, Figs 2,5) -

Subbotina linaperta (Finlay) (Pl. 30, Figs 5-10;

Pl. 31, Fig.3; Pl.32, Fig.1)

Subbotina ex group linaperta - angiporoides

(Pl. 31, Figs 4-6,8,9; Pl. 32, Fig.2)

?Subbotina sp. cf. ?S. praeturritilina (Blow and Banner)

(Pl. 26, Figs 1-3)

Tenuitella aculeata (Jenkins) (Pl. 12, Figs 9-11;

Pl. 13, Fig. 11)

Tenuitella gemma (Jenkins)

Tenuitella insolita (Jenkins) (Pl. 14, Figs 10,11;

Pl. 15, Figs 1,2,4,5)

Tenuitella munda (Jenkins)

Testacarinata inconspicua (Howe) (Pl. 12, Fig. 5).

The presence of Cassigerinella winniana (= C. eocaenica) and the absence of C. chipolensis (Cushman and Ponton) together suggest Eocene age (e.g. Blow, 1969, 1979). Globigerinatheka index is represented in this lower part of the Aldinga Member both here and at the Port Willunga stratotype by only a few immature, single-apertured specimens; but is nonetheless an important Eocene indicator. As discussed in the systematic notes, the presence of even the single specimen of Testacarinata inconspicua strengthens the dating of this sand unit as Eocene. Tenuitella insolita has not been recorded elsewhere from above the Eocene. Subbotina linaperta and Tenuitella aculeata, both

described from New Zealand, are not known to range above the Eocene there. Problems concerning their upward limits elsewhere are discussed in the systematic notes. Although Subbotina angiporoides s.s. ranges from Upper Eocene through Middle Oligocene, Jenkins (1966a, 1971) has only recognised the subspecies S. angiporoides minima in the Middle to Upper Eocene of New Zealand. A convincing but unfigured specimen of S. angiporoides lindiensis has been recovered recently from the sand unit in Ref. bore 18, from core at 25.3-25.6 m (specimen Ff 1140). A doubtful specimen from the same bore and unit, at 27.1-27.4 m, is illustrated in Plate 28, Figures 2,5. The species, with its characteristic asymmetrical, recurved and twisted porticus, has a range of Zone P.15 to Zone P.16, Upper Eocene, according to Blow (1979).

The cumulative evidence of the above planktonics indicates that the sand unit of the Aldinga Member is Eocene. Other forms also suggest Upper, or uppermost, Eocene. For instance, Blow (1969) noted that forms transitional from Globigerina officinalis to G. angulofficinalis began to appear only in the latest Eocene (Zone P.17). The initial appearance of 'Globigerina' labiacrassata high in the Upper Eocene of South Australia, and thus earlier than in New Zealand, was recorded previously by Ludbrook and Lindsay (1969). Tenuitella munda, which is considered to be restricted to the Oligocene in New Zealand, also appeared earlier in southern Australia, in the Late Eocene, as discussed in the systematic notes. The absence of Guembelitria samwelli Jenkins from the sand unit in the Aldinga Member is considered to be significant, since

Chiloguembelina cubensis is present, and the two species favoured the same facies. This suggests that the sand unit is older than terminal Eocene, at which time it is estimated from other evidence that G. samwelli first appeared in South Australia. The presence of single specimens of ?Globigerina cf. brevis and ?Subbotina cf. praeturritilina is consistent with a stratigraphic position high in the Upper Eocene.

Benthonic forms in the sand unit beneath Adelaide City include occasional Gen. nov. cf. Bolivinella sp. nov., Crespinina kingscotensis Wade, Linderina sp. nov., Maslinella chapmani Glaessner and Wade, and Reussella finlayi Dorreen. A preliminary inspection of this sand unit in the Longyear bore showed the presence of Crespinina, Linderina, and Halkyardia. The same benthonic assemblage occurs in the lower, sandy part of the Aldinga Member at Port Willunga (Lindsay, 1967b) and at Port Noarlunga South (Lindsay, 1970a). All of these forms (see Plan 37) are restricted to Eocene strata in South Australia so far as is known.

The silt/clay unit of the Aldinga Member beneath the City has yielded usable microfaunas in the above-mentioned bores, and also in Ref. bores 14 and 33 (Victoria Square). Again the planktonic/benthonic ratio is very low and the foraminiferal facies is if anything, poorer than in the sand unit, but planktonics include:

Cassigerinella chipolensis (Pl. 10, Figs 3-10, 12)

Cassigerinella winniana (Pl. 10, Fig. 11; Pl. 11, Figs 1-11)

Chiloguembelina cubensis

Globigerina angulifficinalis (Pl. 17, Figs 8,10)

'Globigerina' labiacrassata (Pl. 20, Figs 7, 9; Pl. 22, Figs 2,5,6,9; Pl. 23, Figs 3,6,7)

Guembelitria samwelli (Pl. 3, Figs 1,2,6,7; Pl. 4, Figs 2-5, 6-10)

Subbotina angiporoides

Subbotina sp. (v. small, ?cf. linaperta)

Tenuitella aculeata (Pl. 12, Figs 6-8; Pl. 13, Figs 1-10; Pl. 14, Figs 1,4,5)

Tenuitella gemma (Pl. 14, Figs 8,9)

Within the Cassigerinella populations C. winniana predominates, but particularly towards the top of the unit occasional specimens of C. chipolensis are present. For example in Ref. bore 33 (Supreme Court Library, Victoria Square) in which the unit was intersected from 25 m to total depth of 30.5 m, core at 30.2 - 30.5 m contains frequent C. winniana but no C. chipolensis, while at 27.4 - 29.0 m, out of 26 specimens of Cassigerinella two are referable to C. chipolensis. In Ref. bore 41 (SADME South Parklands bore) where the unit is relatively thin (depth: 37-42 m), core from 40.0-40.3 m yielded 25 specimens of Cassigerinella, mostly C. winniana, but including three C. chipolensis and two transitional forms. A similar association of occasional C. chipolensis with C. winniana (= C. eocaenica), in the uppermost part of the Aldinga Member at Port Noarlunga South, was noted by Lindsay (1970a). Of the specimens from the

stratotype Aldinga Member identified as 'Cassigerinella cf. chipolensis' by Lindsay (1967b) (see also Ludbrook and Lindsay, 1969, fig. 2), most are C. winniana, but there are two or three transitional forms. In a more recently collected sample from the top of the Aldinga Member at Port Willunga (F24/78, 0.1-0.25 m below the basal bed of Ruwarung Member at the hewn caves) out of 14 Cassigerinella picked, 13 are C. winniana and only one is C. chipolensis.

These local studies seem to comprise the most complete record to date of the relationship between these two Cassigerinella species. Cordey (1968), while describing C. eocaenica (i.e. C. winniana) and distinguishing it morphologically from C. chipolensis, did not relate the two in any continuous stratigraphic sequence but implied that C. chipolensis commenced at the Eocene-Oligocene boundary as zoned by Blow and Banner (1962) and Bolli (1966). Blow (1969) ranged C. chipolensis 'from within the earlier part of Zone P.18', and C. eocaena (sic) 'from within Zone P. 16, to within the early part of Zone P. 19'. Several authors in recent studies (e.g. Quilty, 1976; Krasheninnikov and Pflaumann, 1978a) have ranged C. chipolensis upwards from Zone P. 18, or basal Oligocene, but without any reference to C. winniana (C. eocaenica). Stainforth et al. (1975) recorded the first appearance of C. chipolensis in the earliest Oligocene, and distinguished it carefully from C. eocaenica which however, according to them was only 'currently recorded from the Late Eocene in a single submarine core'. Jenkins and Orr (1972) recorded only C. chipolensis, without any reference to C. eocaenica, and showed its first appearance to be in the uppermost

Eocene (see Site 77B range chart, p. 70). However their oldest specimen of '*C. chipolensis*' (pl. 1, fig. 8) appears to have two or three planispiral chambers in the final whorl and is probably *C. winniana* rather than *C. chipolensis*. This specimen occurred within the range of *Subbotina linaperta*, whose final appearance was taken to mark top Eocene.

At a Colloquium on the Eocene held at Paris in 1968 under the auspices of the Comité Français de Stratigraphie (1968) it was generally agreed that at least for basins of 'the Mesogean domain' (circum-Mediterranean, Middle East, Asia) the Eocene-Oligocene boundary should be put (*inter alia*) between the planktonic foraminiferal zones of *Globigerina gortanii gortanii* and *Pseudohastigerina micra* - *Cassigerinella chipolensis* (or *Globigerina sellii* Zone). Thus the first appearance of *C. chipolensis* is a diagnostic event for the Eocene-Oligocene boundary so defined. The local record of *Cassigerinella* suggests that this homotaxial event is in fact a lineage in which *C. chipolensis* developed from *C. winniana* by progressively earlier biserial chamber arrangement; and that this event or process occurred during the deposition of the upper unit of the Aldinga Member. *Cassigerinella* is usually present in marine fine-grained rocks of the South Australian mid-Tertiary, and persists in muddy facies poor in other planktonics, making this *C. chipolensis* First Appearance Datum (Plan 36) useful for the recognition of the Eocene-Oligocene boundary in the eastern St Vincent Basin.

Guembelitria and *Chiloguembelina* are also usually present in this facies in southern Australia within their ranges. In view of the position of the *C. chipolensis* FAD discussed

above, the FAD of Guembelitria samwelli towards the top of the Aldinga Member is a close approximation to the Eocene-Oligocene boundary in the City area as at Port Willunga (Lindsay, 1967b), Port Noarlunga (Lindsay, 1970a), and in the Adelaide Plains Sub-Basin (Lindsay, 1969).

Typical 'Globigerina' labiacrassata, with thick-rimmed apertural arch, is present in the upper part of the Aldinga Member, both at the stratotype (Pl. 20, Figs 1,2,4,6) and beneath the City (Pl. 20, Figs 7,9; Pl. 22, Figs 2,5; Pl. 23, Fig. 7). McGowran (1973a), like Ludbrook and Lindsay (1969), found that in the better planktonic facies of the Gambier Embayment of the Otway Basin, the final appearance of Globigerinatheka index preceded the initial appearance of 'Globigerina' labiacrassata, as it does within the Aldinga Member. Also, in the bore studied by McGowran (1973a), overlap of the ranges of 'G.' labiacrassata and Subbotina linaperta was demonstrated by their occurrence together in core. The same overlap is observed near the top of stratotype Aldinga Member in sample F24/78, mentioned earlier.

S. linaperta is small and doubtful in the upper Aldinga Member of the City area, most if not all identifiable specimens of Subbotina being S. angiporoides. However at Port Willunga more definite S. linaperta ranges up to the base of stratotype Ruwarung Member. There is little doubt that the specimens illustrated in Plate 30, Figures 1-4, and Plate 31, Figures 2, 11, and 12, are S. linaperta, comparable with at least some of the illustrated New Zealand material, with a similar degree of 'compression'; of the final chamber, i.e. with its equatorial periphery elliptical, and bulging laterally to

overlap as far as, or further than the first and third chambers of the final whorl. Two specimens illustrated previously, by light microscopy, as S. linaperta (Lindsay, 1967b, pl. 1, Figs 23,24) are re-illustrated here, also as S. linaperta (Pl. 31, Figs 10-12). In each case, the final chamber is 'compressed' a little more than typical S. angiporoides s.s. but a little less than typical S. linaperta.

D.G. Jenkins (1974a) cast doubt on the South Australian identification of S. linaperta. His Table 3 asserted the Oligocene age of the linaperta zone at Port Willunga (Lindsay, 1967b), the part Eocene - part Oligocene age of the same zone in Ludbrook and Lindsay (1969), and the Eocene age of the same zone in McGowran et al. (1971), implying various degrees of misidentification of S. linaperta as well as possible diachronism in its final appearance. Abele (1976a, table 8.1) and Rade (1977, text fig. 2) were also influenced to date the South Australian S. linaperta zone, and the topmost Aldingan Stage, as part Late Eocene, part Early Oligocene. This is all relevant to the biostratigraphy and age of the Aldinga Member, which in the eastern St Vincent Basin contains the last S. linaperta. In the present study particular care has therefore been taken to compare local material with type and comparative specimens of S. linaperta which were studied at the New Zealand Geological Survey in 1976, and subsequently. Specimens of the species from the New Zealand Bortonian (Middle Eocene; near-topotypes) and Runangan (Upper Eocene) have been photographed to make clear its diagnostic features (Pl. 28, Figs 8-11; Pl. 29, Figs 1-6).

Contrary to previous authors, it appears to the writer that in New Zealand the species ranges higher than Globigerinatheka index, as is the case in South Australia. This became evident after picking the lower Whaingaroan sample S136/694 (basal McDonald Limestone, Kakanui River; Jenkins, 1971, Table 20) at the New Zealand Geological Survey in 1976. The sample, from the Globigerina brevis Zone, lacks Globigerinatheka index, and was said to lack S. linaperta (Jenkins, 1971, Table 20). However in the writer's opinion the sample contains several specimens of S. linaperta (e.g. Pl. 29, Figs 7-11) in a Subbotina population which is predominantly S. angiporoides. This sample was regarded by Jenkins (loc. cit.) as basal Oligocene, the Eocene-Oligocene boundary being put a little lower, still within the Whaingaroan Stage (i.e. post-Runangan) and above the range-top of S. linaperta as shown by him. S. linaperta in sample S136/694 is thus very close to the Eocene-Oligocene boundary recognised by Jenkins.

Jenkins suggested (1971, p.18) that 'the Eocene-Oligocene boundary of Blow and Banner (in Eames et al., 1962) which they placed between the Globigerina turritilina turritilina and Globigerina oligocaenica Zones, lies within the lower part of the Whaingaroan Stage in the New Zealand rocks'; and that in N.Z. the uppermost Eocene 'interval extending from the Cribrohantkenina danvillensis Zone to the Globigerina oligocaenica Zone of Blow and Banner is probably represented by the Globigerina (G.) brevis Zone, which is correlated with the lower part of the Whaingaroan Stage'. Writing several years later, he reiterated a similar view (Jenkins, 1970, p. 22).

This Eocene-Oligocene boundary as proposed by Blow and Banner (1962) is essentially the same as that used by Bolli (1966, 1972), by the 1968 'Colloquium on the Eocene', by Bolli and Krasheninnikov (1977, and references), and by Berggren (1978, and references).

Thus, providing specimens of S. linaperta can be distinguished from S. angiporoides and from the S. linaperta - S. angiporoides complex on agreed morphological criteria, the homotaxial LAD of S. linaperta (Plan 36) would still seem to be a useful approximation to top Eocene, as advocated by Lindsay (1967b, 1969), Ludbrook and Lindsay (1969), and McGowran et al. (1971). As shown in Plan 36, this LAD of S. linaperta is a) virtually at the top of the Aldinga Member, b) approximately synchronous with the LAD of Tenuitella aculeata, c) a little above the FADs of Cassigerinella chipolensis and Guembelitria samwelli; and d) significantly above the LAD of Globigerinatheka index, which was taken as a working approximation to top Eocene in southern Australia by McGowran (1973a) and Abele (1976a), for example.

Typical Tenuitella aculeata occurs in the basal part of the upper unit of the Aldinga Member beneath the City (Pl. 12, Figs 6-8; Pl. 13, Figs 1-8; Pl. 14, Figs 1,4,5). The few specimens found near the top of the Member are less spinose (Pl. 13, Figs 9,10). At the stratotype, Lindsay (1967b) recorded top T. aculeata in a green clay marker bed with white limy nodules, midway through the Member. However, as is the case beneath the City, rare finely spinose specimens which are probably T. aculeata have been found subsequently up to the top of the Member (sample F24/78; Plan 30), and similar specimens occur almost to the top of the Member in the Adelaide Plains Sub-Basin (e.g. in core, SADME Light-1 bore, Plan 2).

T. aculeata has not been recorded from above the Kaiatan Stage (lower Upper Eocene) in New Zealand. On present information it ranges upwards in southern Australia further than it does in N.Z. (Ludbrook and Lindsay, 1969; McGowran et al., 1971; McGowran, 1973a), perhaps to the top of the Eocene in the eastern St Vincent Basin, in view of the preceding discussion. Jenkins (1973) mentioned that the species 'has also been found recently in the Upper Eocene-Oligocene of France (private communication from Mr. D. Curry)'. In a more recent letter from Professor Curry to Dr. N.H. Ludbrook, dated 19/3/77, he recorded what is very probably T. aculeata from the Sables de Fontainebleau (Stampien, Lower to Middle Oligocene) of France; from the Sands of Vieux-Joncs (Sannoisian, Upper Tongrian, Lower Oligocene) in Belgium; and from the type Lattorfian (Lower Oligocene) in North Germany; besides the Upper Eocene of Britain, France and the Crimea; and the Middle and Upper Eocene of the United States. However a longer range in parts of Europe does not necessarily alter the Eocene span of the species in the Australasian region, although it reduces the value of the species for inter-regional correlation.

A group of planktonic foraminifera, mainly Turborotalia increbescens (Bandy) but including several specimens of T. ampliapertura (Bolli), occurs sparsely in the upper 11 m of stratotype Aldinga Member (see Systematic Notes; cf. Lindsay, 1967b, fig. 2). Similar but better-developed populations of this group are found in upper Lacepede Formation and basal Gambier Limestone, in the Gambier Embayment, below the FAD of S. linaperta (Plans 33,34). Blow (1969, p. 349) observed

that 'G.(T.) increbescens evolves into Globigerina ampliapertura within the earliest part of Zone P.17'. Since a few specimens of T. ampliapertura are found in this homotaxial succession in stratotype Aldinga Member as low as sample F14/67 (Lindsay, 1967b, fig. 2), it would appear that at least the upper fine-grained unit of the Aldinga Member is no lower than Zone P.17, uppermost Eocene. The T. increbescens - T. ampliapertura group has not yet been found in the Adelaide City area, probably because of poorer planktonic facies.

Benthonic foraminifera in the silt/clay unit of the Aldinga Member in the Adelaide City area include:

Massilina torquayensis (Chapman) (Pl. 49, Figs 14-16); Pl. 50, Figs 1-9)

Planorbulinella roseannae sp. nov. (Pl. 55, Figs 1-11; Pl. 56, Figs 1,4).

Massilina torquayensis also occurs at this stratigraphic level, below the Ruwarung Member, in the Adelaide Plains Sub-Basin (core samples from SADME Light-1 bore, and from the Longyear bore, Plan 2; see also Croydon-2 bore, Plan 29) and in the Noarlunga Embayment (Lindsay, 1970a; Cooper, 1980). In the Willunga Embayment, the species was found in drill cores through much of the Aldinga Member (Cooper, 1979b, figs 28,31), and its range is so indicated in Plan 37. Similarly, in the Gambier Embayment (Plan 33) the species makes its first appearance (in core) high in the Lacepede Formation, in what is regarded by the writer as uppermost Eocene, below the LAD of S. linaperta.

Planorbulinella roseannae sp. nov. usually occurs in some abundance in muddy facies in a thin zone extending from high in the Aldinga Member to basal Ruwarung Member, although the total range of the species extends above and below this (Plan 37). This marker zone is well developed beneath the Adelaide City area; and at the same stratigraphic level in the Adelaide Plains Sub-Basin (e.g. Pl. 56, Figs 2,5; Lindsay, 1969, p. 35, pl. 2, fig. 6; both from SADME Light-1 bore), the Noarlunga Embayment (Lindsay, 1970a; Cooper, 1980), and the Willunga Embayment (Cooper, 1979b).

In view of the distribution of foraminifera in the Aldinga Member as outlined above, it is apparent that there are several alternatives for placement of the Eocene-Oligocene boundary within the Member.

1. A benthonic fauna of Eocene aspect in South Australia with Crespinina, Halkyardia, Linderina, Maslinella, Gen. nov. cf. Bolivinella, and Reussella finlayi, but lacking Asterigerina adelaidensis and Pseudopolymorphina sp. nov., makes its local final appearance in the lower, sand unit of the Aldinga Member; in the uppermost part of 'the sands near the middle of the Rogue Formation' on eastern Yorke Peninsula (Stuart, 1970, pp. 171, 173); and in the upper part of Buccleuch Bed 'A' (Ludbrook, 1961) or equivalents (Lindsay and Bonnett, 1973) in the Murray Basin. This corresponds to the youngest (Zone P. 16) of the warm episodes (extra-tropical excursions of larger benthonic foraminifera) of Lindsay (1976) and McGowran (1978a,b; 1979b). Adams (1970) recorded the extinction of Linderina within the Upper Eocene, but well before the Eocene-Oligocene boundary. Therefore to put the boundary at the top of the sand unit is, on that basis, drawing it too low.

2. The final appearance of Globigerinatheka index was suggested as 'a good working horizon for the Eocene boundary in the Otway Basin' by McGowran (1973a, p.53). This criterion, also adopted by Abele (1976a) would put the boundary approximately at the top of the sand unit of the Aldinga Member as with the benthonic fauna discussed above. However there seems to be considerable variation in the upward limit of Globigerinatheka/Globigerapsis, as discussed by Bolli (1972). Many studies of 'tropical' successions demonstrate the extinction of the group well before the end of the Eocene. Bolli (1966) recognised a further Upper Eocene zone above the extinction of Globigerapsis, while Blow and Banner (1962) proposed two such zones post-Globigerapsis. Fleisher (1974) in the tropical Arabian Sea region found G. index only up to upper Zone P.14 (Middle Eocene), with other species of the group only surviving to Zone P.15 (lower Upper Eocene). In contrast, an eastern Pacific tropical succession studied by Quilty (1976) was reported to contain G. index up to Zone P.18 (Lower Oligocene); while Jenkins and Orr (1972) in the same region, recorded a specimen of Globigerapsis from their Lower Oligocene Pseudohastigerina barbadoensis Zone. Berggren (1969a, pp. 125, 126) recorded G. index in a temperate fauna from the Danish Søvind Marl, which is apparently very near to the Eocene/Oligocene boundary, but which he preferred, on the balance of evidence, to regard as uppermost Eocene, Zone P.17. Blow (1969, p. 330) on the basis of this record, ranged G. index up into Zone P.18, basal Oligocene, but has since revised the upward range doubtfully to Zone P.17 (Blow, 1979). Berggren (1978) took his G. index Zone to top Eocene (Zone P.17) in the North Atlantic region.

Ludbrook and Lindsay (1969), noting considerable inter-regional variation in extinction levels of the species, commented on its lesser environmental tolerance in South Australia as compared with Subbotina linaperta. In New Zealand, where the extinction levels of the two species have been reported to coincide (but see the discussion earlier on S. linaperta in the lower Whaingaroan), the final appearance of G. index has long been a marker for the top of the Runangan Stage (Finlay and Marwick, 1940; Hornibrook, 1958a, 1961; Srinivasan, 1968; Jenkins, 1971). This was taken to be top Eocene by Hornibrook, and by Srinivasan, but to be somewhat below top Eocene by Jenkins (1971), as discussed earlier. Jenkins (1966c, 1974a) and Hornibrook and Edwards (1971) considered the G. index LAD to be more reliable than the S. linaperta LAD, the former constituting an 'abrupt extinction' and the latter a 'gradual extinction of a taxon' (Jenkins, 1970). The writer is not convinced that this is so in southern Australia; nor that a gradual and homotaxial extinction of a taxon in a series of complex populations (S. linaperta - S. angiporoides group) is intrinsically inferior in biostratigraphic value to an abrupt extinction which was possibly temperature-controlled (Jenkins, 1970, p. 19). McGowran (1978b) recorded 'spectacular variation in abundance of Globigerinatheka index' in parts of the Browns Creek and Castle Cove sections of the Victorian Otway Basin, showing that the species was affected strongly by fluctuating environment and facies. In summary, there is general agreement that the G. index LAD is Eocene, but latitudinally dia-chronous; and there is disagreement as to whether it represents

top Eocene in southern Australia - New Zealand, the writer inclining to the view that by available correlations the datum is lower than the Eocene-Oligocene boundary.

3. The extinction of Tenuitella insolita was used by Jenkins and Orr (1972) to mark the top of their Globorotalia insolita Zone, a horizon which they regarded as a little below the Eocene-Oligocene boundary. At that time this record of T. insolita in DSDP Site 77, eastern equatorial Pacific, was the only one known to them outside New Zealand. There, the species had been described only from the Port Elizabeth section, ranging up to a final appearance below top Globigerinatheka index and the top of the Runangan Stage; and significantly below the Eocene-Oligocene boundary drawn by Jenkins (1966a, 1971). In the first Australian record of the species, McGowran (1973a) found top T. insolita less than a metre below top G. index in the Gambier Embayment; and these tops are reported to coincide in the Castle Cove section of the Victorian Otway Basin (McGowran, 1978b). It is noteworthy that in the admittedly poorer planktonic facies of the Adelaide area a similar relationship holds (Plan 36). Here, as with G. index, T. insolita occurs in the sand unit of the Aldinga Member but has not yet been found in the upper unit. On the balance of available evidence, it is considered that both species disappeared before the end of the Eocene.

4. The FAD of Cassigerinella chipolensis in the presence of C. winniana occurs in the upper part of the upper unit of the Aldinga Member (Plan 36), and has been discussed already as an inter-regional indicator of the Eocene-Oligocene boundary

appropriate to local facies. This microfaunal event appears to provide the most direct connecting link with the boundary recommended by the majority of participants at the 'Colloque sur l'Eocène', Paris, May 1968 (Comité Français de Stratigraphie, 1969).

5. The LAD of Subbotina linaperta in the presence of continuing S. angiporoides was discussed earlier, and is considered to relate closely to the Eocene-Oligocene boundary. The utility of this LAD depends on there being a) sufficient populations of the Subbotina complex, and b) agreement on the cut-off point for key morphological parameters of S. linaperta.

Environment of Deposition

The marine origin of the Aldinga Member is evidenced by its faunas of foraminifera, bryozoans, echinoids, molluscs and ostracodes, with rare brachiopods and corals. Glauconite, also a marine indicator, is present throughout as glauconitised ovoid faecal pellets and casts, but the low planktonic/benthonic ratio indicates a relatively near-shore neritic environment with restricted access to the open ocean. Barnacle plates in the sand unit suggest deposition in shallow water. At the coastal stratotype, Port Willunga, the cross-bedded basal bryozoal quartz sands of the Member represent marine transgression following the regressive interlude associated with Chinaman Gully Formation. No doubt a similar relationship holds for the City area, where Chinaman Gully Formation is developed more thickly than in the coastal exposures. These marine basal sands of the Aldinga Member are glauconitic, and only poorly carbonaceous if at all. Where well-winnowed, as at the base of the type

section, this combination of characters suggests a barrier, bar, or shoal sand (Selley, 1978, p. 28). Where muddy and poorly-winnowed, a slightly deeper or more sheltered environment is indicated. The fining-upwards progression from the sand to the fine-grained unit probably represents increasing water-depth, and a 'temperate' but relatively diverse planktonic foraminiferal microfauna is present near the top of the Member at the type section. However the carbonaceous and pyritic nature of the upper unit, where preserved from weathering and oxidation, suggest a relatively near-shore situation, restricted circulation with a tendency to anaerobic bottom conditions, and limited access to the open ocean.

Linderina and Halkyardia in the sand unit, although rare, hint at relatively warm water temperatures (Hornibrook, 1968a; McGowran, 1971, 1977, 1978b, 1979b; R.J.F. Jenkins, 1974; Lindsay, 1976). Nevertheless, as McGowran pointed out, Discocyclina, Asterocyclina, Nummulites and Pellatispira, all present in the Carnarvon Basin Eocene, are absent from the South Australian record which represents but the southeastern, distal end of the last southerly Eocene 'extra-tropical excursion' of warm faunal elements. However the planktonic foraminifera of the sand unit give no indication of warm-water influence, apart perhaps from the occasional presence of ?Subbotina cf. praeturritilina. On the contrary, the lower unit of the Aldinga Member at Port Noarlunga South contains the earliest of the Australian temnopleurid marsupiate echinoids, a group whose incoming has been associated with southern oceanic cooling late in the Late Eocene (Foster in Lindsay, 1970a; Philip and Foster, 1971; Foster, 1974). Such a temperature constraint would help

to explain the brevity and rarity of the final local appearance of Halkyardia and Linderina in the sand unit.

McGowran (1978b, p. 92) noted a time-correlation between marked cooling in the Indian Ocean in the early Middle Eocene (compare Plan 35), and the entry of Guembelitria-dominated assemblages on the Naturaliste Plateau. In the eastern St Vincent Basin, including the Adelaide City area, Guembelitria samwelli makes its first appearance only two or three metres below the top of the Aldinga Member (Lindsay, 1967b, 1969, 1970a) and very close to the Eocene-Oligocene boundary, which suggests correlation with another major cooling event shown in Plan 35 and discussed below.

Regional Events

Vail et al. (1977) and Vail and Mitchum (1978) depict a global cycle (TE3) of rising sea-level through Zones P.15 to P.17, climaxing at the Eocene-Oligocene boundary. The transgressive Aldinga Member corresponds to the final part of this cycle, to the final part of sedimentation cycle 2B of Quilty (1977), to a late or middle part of Sequence 2 of McGowran (1971, 1977, 1978a, 1979b; cf. Plan 35), and to a later part of depositional cycle 2 of Bock and Glenie (1965). Harris (1980b) stresses the importance of this latest Eocene eustatic transgression in South Australia, and the resultant deposition of lignites in the Eucla, St Vincent, and Murray Basins. During the course of this transgression, the prograding, regressive, and in part lignitic phase correlating with Chinaman Gully Formation, was followed by the transgressive and more marine correlatives of the Aldinga Member (compare the sequence of Moorlands Lignite Member-Buccleuch Beds, in the western Murray Basin).

A small regional rise in palaeotemperatures towards the Eocene-Oligocene boundary is discernible from oxygen-isotope data for benthonic foraminifera (Shackleton and Kennett, 1975; Kennett and Shackleton, 1976; McGowran, 1978a,b, 1979b; cf. Plan 35 herein). However, as discussed above, and as is evident from Plan 35, this warming effect at the time of deposition of Chinaman Gully Formation and the Aldinga Member was weak, and hardly succeeded in maintaining the level of Late Eocene palaeotemperatures evident from the deep-water oxygen-isotope data. In contrast, surface-water data depict falling regional oceanic palaeotemperatures through the Late Eocene. Nevertheless, despite the overall (but fluctuating) decline in regional temperatures through the Eocene, Harris (1980b) infers from palynological evidence a relatively high annual precipitation, 'probably in excess of 1 000 mm', with sub-tropical rainforest vegetation covering much of southern Australia.

What has been called 'the most profound climatic event of the Tertiary' (Wolfe, 1978; O'Keefe, 1980) occurred at or about the Eocene-Oligocene boundary. As first suggested by Benson (1975), on the basis of his studies of deep-sea ostracodes, the 'psychrosphere' (Bruun, 1957; Gk 'psychros' = cold) which is the lower, cold, dense layer of the world's oceans, and polar in origin, appears to have formed rapidly at that time. Shackleton and Kennett (1975; cf. Plan 35) demonstrated simultaneously a dramatic drop in the oxygen-isotope palaeotemperatures of both bottom and surface waters south of New Zealand (DSDP Site 277) at about the Eocene-Oligocene boundary. The same two authors in the following year detailed oxygen-isotope and biostratigraphic evidence for the sudden drop in bottom-water temperatures at this site (5°C in about 100 000 years), which

they dated earliest Oligocene, and attributed to the freezing of Antarctic surface waters, with the production of extensive sea-ice (but not yet Antarctic ice-sheets), this in turn resulting in the initiation of two-layer psychrosphere/thermosphere oceanic circulation (Kennett and Shackleton, 1976). The latest O-isotope measurements by Keigwin (1980) on monogeneric benthonic foram fractions of cores from Site 277 and Site 292 (Philippine Sea) suggest that at a time very close to terminal Eocene, bottom-water temperatures dropped sharply at both sites. Similar measurements on planktonic foram fractions in the same study suggest that near-surface water temperatures also dropped sharply at the high-latitude site but less markedly so at the tropical site. A rapid drop in O-isotope neritic palaeotemperatures close to the Eocene-Oligocene boundary had been reported previously for New Zealand (Devereux, 1968) and Victoria (Gill, 1968). The Late Eocene 5°C drop in low-latitude O-isotope bottom-temperatures, which was reported by Savin et al. (1975), 'must be isochronous with the sub-Antarctic event' according to Kennett and Shackleton (1976), and they attributed various discrepancies in synchronisation to diachronous usage of the Eocene-Oligocene boundary between tropical, temperate, and sub-Antarctic sequences.

There is the potential for important feed-back in relating such oxygen-isotope results to biostratigraphic datum-levels and to the Eocene-Oligocene boundary. The recent work by Keigwin (1980) on material from Site 277, when combined with earlier data from Jenkins (1975) and Kennett and Shackleton (1976), shows that the bottom-water chilling event at that site occurred in the ?G.brevis Zone, close in time to the last appearances of

Globigerinatheka index and Subbotina linaperta in Core 21.2.60. Keigwin (1980) found also that the bottom-water chilling event at the tropical Site 292 corresponded to the last appearances of Hantkenina primitiva and 'Globorotalia' cerro-azulensis, both of which range up only into the earlier part of Zone P.17, according to Blow (1979). If the two cooling events were manifestations of the same phenomenon, they provide a valuable time-line to link these temperate and tropical LADs.

The 'terminal Eocene event' appears to have had worldwide repercussions including (as summarised by Keigwin, 1980) a sudden drop in the calcite compensation depth of 1-2 km, a decrease in planktonic microfossil diversity, a change in planktonic biogeographic patterns, and increased erosion of deep-sea sediments over wide areas. Wolfe (1978), adopting a 'young' date of 34 Ma for the Eocene-Oligocene boundary, showed by studies of North American fossil leaf physiognomy that the terminal Eocene event there saw a rapid decline in mean annual temperature and in seasonal equability.

McGowran (1978a, 1979c) has supported a causal link between regional cooling and the formation of southern Australian earliest Oligocene cherts. In view of the biostratigraphic evidence outlined earlier, it is reasonable to correlate the local commencement of cherty sedimentation in the Port Willunga Formation (base Ruwarung Member, overlying the Aldinga Member) with the terminal Eocene cooling event. This also feeds back to confirm local recognition of the Eocene-Oligocene boundary at or near the top of the Aldinga Member.

At least three triggering mechanisms have been proposed for the terminal Eocene event. Kennett and Shackleton (1976) suggested that during the northward drift of Australia a critical threshold of Antarctic isolation and refrigeration was reached. Thierstein and Berger (1978) developed their hypothesis of an 'injection event', in which the tectonic opening of the Greenland Sea passage released brackish water over the world's oceans from a previously isolated Arctic Ocean, disrupting oceanic heat-exchange, and leading eventually to the refrigeration of Antarctica. Most recently, O'Keefe (1980) visualised an extension of the effects of the vast, 34 Ma tektite fall ('younger' terminal Eocene; Glass and Zwart, 1977) to include formation of a globe-encircling, equatorial, planar ring system of captured fragments, casting seasonal shadows and producing greatly increased severity of winter climates (especially at middle to high latitudes; cf. Wolfe, 1978) during the ring's anticipated lifetime of a few million years.

RUWARUNG MEMBER

Nomenclature

This Member, which had been distinguished earlier and informally as the Port Willunga Beds 'interval with cherty nodules' (Lindsay, 1967b), 'siliceous unit' (Lindsay, 1969, 1970a; Lindsay *in* Daily *et al.*, 1967), or 'cherty unit' (Lindsay *in* Selby and Lindsay, 1973), was formally named by Cooper (1977b).

Type Section

This occupies the central part of the Port Willunga Formation stratotype in continuous coastal cliff exposures in the vicinity of Port Willunga (Figs 11,12). The basal cherty bed ('hard consolidated grey marly bed' of Reynolds, 1953, fig. 2) crops out in the cliffs beneath the Pliocene angular unconformity as far north as the Port Willunga kiosk; and chert nodule beds typical of the Member may be seen in the cutting leading down from the kiosk to the caves hewn in the cliffs. The hard basal bed of the Ruwarung Member forms the roof of most of these caves (see Lindsay in Daily et al., 1976, fig. 20b; Cooper, 1979b, pl. 16). Excellent cliff exposures of Ruwarung Member extend southwest for approximately one kilometre, until the top of the Member dips below beach level about one kilometre northeast of Snapper Point (Fig. 76). An important reference section of the Member is similarly well exposed on the southern side of the mouth of the Onkaparinga River, in the Noarlunga Embayment (Lindsay, 1970a).

Lithology

At its stratotype, the Member is characterised by bands of hard nodules of fossiliferous chert (Figs 13,14). These occur within fossiliferous, impure, soft limestones, which are variously clayey silty and sandy. Recognition of this upper cherty interval (Lindsay, 1967b) stratigraphically distinct from the older cherty Gull Rock Member of Blanche Point Formation ('Banded Marls Member') was a key to the subdivision and correlation of the subsurface Tertiary of the Adelaide Plains Sub-Basin (Lindsay, 1969).



Figure 76. Coastal cliffs about 1½ km N.E. of Snapper Point, Aldinga Bay, Dec. 1979. Cainozoic sequence from beach level upwards comprises stratotype Ruwarung Member, Hallett Cove Sandstone, Burnham Limestone, Pleistocene clays, and a loess-calcrete profile. A minor normal fault just right of centre, displaces units from Oligocene Ruwarung Member to Lower Pleistocene Burnham Lst., left (N.E.) side down.



Figure 77. Ruwarung Member of Port Willunga Formation, Adelaide City area; SADME South Parklands bore (1976), core sample from 25 m, near top of Member; weathered, mottled pale grey and dull white, fossiliferous, spicular, sandy chert, with minor brown iron-staining; compare petrographic description of this specimen in Appendix C.

In SADME South Parklands bore (Ref. bore 41, Plan 27) the Ruwarung Member consists of hard irregular nodules of fossiliferous spicular chert (Fig. 77) in a matrix of fossiliferous mudstone; both are glauconitic, calcarenitic, quartzose and sandy. The uppermost few metres of the unit, beneath the Oligocene-Pliocene angular unconformity, are partly oxidised and bleached to off-white, fawn and pale grey colours. The remainder is medium to dark grey, carbonaceous and pyritic.

As described by Reynolds (1953, fig. 2) the type section is brown, yellow, green, pale grey or white, due to exposure and oxidation (Figs 13,14).

Petrographic descriptions of 11 specimens of Ruwarung Member cherts are included in Appendix C. One sample is from the South Parklands bore in the City Area (Fig. 77), one from the Port Willunga Formation stratotype, one from the Onkaparinga River mouth in the Noarlunga Embayment, one from the Longyear bore in the southern Adelaide Plains, and seven are from SADME Observation bore PTG 62, 5 km S.E. of Two Wells in the northern Adelaide Plains (Plan 2).

In these petrographically studied samples, pale brown predominantly opaline silica matrix comprises from 40 to 70% of the rock, but in some this includes local areas of re-crystallisation to microcrystalline or cryptocrystalline inter-growths. This figure also includes an appreciable proportion of a zeolite mineral in the outcrop sample from the Noarlunga Embayment and in the three deepest of the core samples from Observation bore PTG 62.

Siliceous sponge spicules (opaline to chalcedonic silica) comprise 20% of the South Parklands bore sample, but are only a minor constituent of some of the other rocks.

The rocks contain various proportions of detrital quartz grains (5-30%, mostly very fine-grained sand, but bimodal in sample P 810/68 from bore PTG 62), glauconite (0-15%, as glauconitised ovoid faecal pellets, or infillings of sponge-spicule canals and foraminifera), and calcitic shell fragments (0-35%). Up to 2% pyrite may be present in those rocks which have undergone less oxidation. Pyritised sponge spicules occur abundantly in core at 30 m in the South Parklands bore.

Distribution

As shown in Plan 23, the Ruwarung Member occurs on the Para Block only beneath the southern part of the City of Adelaide, and has not been recognised any further up the Golden Grove-Adelaide Embayment. It is present on most of the Mile End Block, and probably occurs on the Thebarton Block, but known bores there have not penetrated to sufficient depth to intersect it. On the Croydon Block near the Adelaide City area, Croydon-2 bore (Plan 29) penetrated the thickest known section of the Member; and it is well developed elsewhere beneath the Adelaide Plains (Lindsay, 1969), including the Longyear bore (Lindsay, 1981).

In the Willunga Embayment, Cooper (1979b, fig. 46) was able to show only a very restricted subsurface distribution inland from the coastal stratotype, the Ruwarung Member being still only known from bore WB-1 (cf. Lindsay, 1966, 1969), in which nodules of fossiliferous cherty siltstone and fine sandstone occur intermittently through the Ruwarung interval in distinctly marginal facies.

In the Noarlunga Embayment inland from the coastal exposures, the Ruwarung Member has only been penetrated in the Seaford drainage bore, near the coast (Plan 2; Cooper, 1980).

Thickness

The outcropping stratotype of Ruwarung Member at Port Willunga has a thickness of 15.8 m (Lindsay, 1967b), while in WB-1, the only borehole intersection in the Willunga Embayment, the thickness was 27 m (Lindsay, 1966, 1969). The exposed reference section at Port Noarlunga South is 22 m thick (Lindsay, 1970a); but in the nearby Seaford drainage bore, from the writer's own observations, the Ruwarung Member has a total thickness of about 32 m (depth 28-60 m), rather than the 30 m (depth 35-65 m) reported by Cooper (1980).

Like the other mid-Tertiary units, the Ruwarung Member is only known from borehole intersections in the Adelaide City area. Probably nowhere beneath the City, on the Para Block, is a complete thickness of Ruwarung Member preserved. Cross-sections (Plans 6-8, 10, 13, 16) show that beneath the southern part of the City the Member remains only as an eroded wedge thinning up-dip to the north beneath the Pliocene angular unconformity (Hallett Cove Sandstone), the maximum thickness penetrated being 12.2 m in the SADME South Parklands bore (Ref. bore 41; Plan 27).

On the Mile End Block, immediately west of the City, a complete section of Ruwarung Member is preserved in the S.A. Farmers' Union bore, Mile End (Ref. bore 93) between 46.3 and 70.1 m depth, a thickness of 23.8 m (Plan 14). The same cross-section shows that on the northern part of the Mile End

Block, the Police Barracks bore, Port Road (Ref. bore 107), intersected only 12.8 m of the Member, truncated by a Plio-Pleistocene angular unconformity (Carisbrooke Sand). This interval in the bore between 27.4 m and total depth of 40.2 m was logged by Miles (1952, index bore 307; and unpublished data) as 'alternating hard bars of rock (?limestone) up to two feet thick, with sandy marl, fossil oysters, Turritella etc'. The unit was identified by Miles as ?Pliocene, but although samples are no longer available there is little doubt, from the geometry of the cross-section, that the unit is Ruwarung Member and is neither Pliocene Hallett Cove Sandstone nor the other possible alternative: Gull Rock Member of Blanche Point Formation.

In the Croydon-2 bore (Plans 16, 29) the Ruwarung Member attains its maximum known thickness of 69.8 m. Other thicknesses penetrated in Adelaide Plains bores are tabulated by Lindsay (1969, unit 8). In the stratigraphically important Longyear bore, drilled subsequently in the southern Adelaide Plains (Plan 2) Ruwarung Member is at least 26.2 m thick between depths of 92.5 m (top of core) and 118.7 m, where the lowest chert nodule of this unit was recognised (Lindsay, 1981). In the SADME Korunye-3 bore, in the Northern Adelaide Plains (Plan 2), the unit is clearly developed between 94 and 117 m (thickness 23 m), comprising dark nodules and patches of spicular chert or cherty mudstone within glauconitic mudstone, limestone or sand.

Relationships and Boundary Criteria

Upper and lower boundaries of the Ruwarung Member at the stratotype and elsewhere, are defined by the limits of the cherty nodule development characteristic of the Member. No upper contact of the Member with any younger unit of Port Willunga Formation is known from beneath Adelaide east of the East Para Fault because of erosional truncation as noted above. However on the Mile End Block in Ref. bore 93 (as at the stratotype) the Member is overlain by the 'upper Janjukian unit' of Port Willunga Formation. In Ref. bore 93 only cable-tool sludge samples are available, but the boundary is put at the top of the uppermost cherty 'hard bar', 0.15 m thick. Only sludge samples are available from the Croydon-2 bore also, but examination of the interval bridging the top of the Ruwarung Member suggests that, in upward succession, cherty nodules disappear with little if any other change in the lithology, i.e. conformably.

The Ruwarung Member is everywhere underlain by softer, non-cherty Aldinga Member. At the stratotype, the basal bed of Ruwarung Member comprises the 'hard consolidated grey marly bed to be seen in the caves below Port Willunga' (Reynolds, 1953, fig. 2; cf. Cooper, 1979b, pl. 16), and there is no evidence that the contact with the Aldinga Member is other than conformable.

In the South Parklands bore (Ref. bore 41) chert nodules or patches are only very sparsely developed in the silty mud-stones near the base of the Ruwarung Member. A tube-core at

35.0-35.3 m lacks any chert; a sludge sample from 36-38 m contains only a small amount of cherty lithology; and the boundary, put somewhat arbitrarily at 37 m, is not particularly marked on geophysical logs, even with hindsight. The lower boundary of Ruwarung Member in the Mile End bore (Ref. bore 93) is put at the base of the lowest of a series of cherty 'hard bars' noted by the driller. These are underlain by sticky grey-black sandy clay identified as Aldinga Member. The same boundary in Croydon-2 bore is marked by the downhole disappearance of pale to medium grey, hard and slightly cherty spicular siltstone, and its replacement by dark grey softer and more clayey silt(stone).

The Longyear bore at the southern end of the Adelaide Plains Sub-Basin, and SADME Light-1 bore in the Northern Adelaide Plains (Plan 2) both cored the base of Ruwarung Member. In the Longyear bore, grey glauconitic mudstones contain occasional cherty nodules down to a depth of 118.7 m; while in Light-1 bore grey glauconitic siltstones similarly contain occasional hard dark grey spicular cherty nodules or patches (to 20 mm diameter) down to 141.8 m. In neither case, apart from the presence or absence of cherty nodules, is there any marked lithological change across the boundary, which is therefore regarded as conformable.

In SADME bore I41, 5½ km southeast of Port Wakefield (Plan 2), the interval with chert nodules between 31 and 40 m, above the Port Julia Greensand Member, was included in Rogue Formation by Cooper (1977a). However, as conceded by Cooper, this interval of chert nodules in clayey, sandy, glauconitic,

and calcareous matrix, correlates both lithologically and biostratigraphically with what was later named the Ruwarung Member. Lindsay (1969, ref. bores 1 and 2) had previously identified this unit in the Adelaide Plains Sub-Basin as far north as Wild Horse Plain. It is apparent that the unit continues almost to Port Wakefield, with lateral change of facies in the vicinity of the head of Gulf St Vincent to the more quartzose and sandy chert-bearing Rogue Formation described by Stuart (1969, 1970). This correlation is shown in Plan 3.

Lindsay (1969, p. 35) noted that in the eastern St Vincent Basin, increasingly marginal sandy facies at this stratigraphic level may display only minor and intermittent development of the chert phase (as in the Elizabeth Oval bore; Plan 2); or in extreme cases, chert may be lacking altogether as in the Springbank bore (Plan 4). In bores 1 and 5 of the SADME Barabba drilling project (Plan 2) marginal sandy successions with sporadic nodular chert may be named by using either the western 'Rogue' or the eastern 'Ruwarung' terminology (Cockshell *et al.*, 1978).

Biostratigraphy and Age

In the Adelaide City area, samples of the Ruwarung Member are only available from the SADME South Parklands bore (Ref. bore 41). The distribution of more significant foraminifera in this bore is shown in Plan 27. The planktonic/benthonic ratio is very low, but planktonic forms include the following:

Acarinina collactea (Pl. 16, Fig. 10; Pl. 17, Fig. 1):

- one specimen apparently *in situ* from core high in the Ruwarung interval,

Cassigerinella chipolensis,

C. winniana,

Chiloguembelina cubensis (Pl. 7, Figs 5-8),

Globigerina angulofficinalis,

G. angustiumbilicata (Pl. 18, Figs 1-5),

G. bulloides s.l. (Pl. 25, Figs 2, 8-10),

G. officinalis (Pl. 24, Figs 1, 3-5),

Guembelitria samwelli (Pl. 3, Figs 3-5, 8-10;
Pl. 4, Figs 1, 6-10; Pl. 5, Figs 1-10),

Subbotina angiporoides s.s. (Pl. 27, Fig. 1),

Tenuitella gemma,

T. munda (Pl. 15, Figs 3, 6-10; Pl. 16, Figs 1-2,
4-5).

The remarkable occurrence of Acarinina collactea high in this section of Ruwarung Member is considered to be probably in situ. The extreme local rarity of the species virtually rules out cross-contamination from some other sample. The specimen appears to be slightly abraded, but the sample contains no other anachronistic material which might have been derived, say, from Tortachilla Limestone or basal Blanche Point Formation, the only other stratigraphic level from which the species is known in the Adelaide City area. The occurrence of this stratigraphically isolated specimen is discussed further in the Systematic Notes.

Subbotina angiporoides s.s. is present immediately below the unconformity, indicating that the Ruwarung section preserved in this locality is no younger than Zone P.19/20, Middle Oligocene (Blow, 1970), or possibly Zone P.21 (Blow, 1979, p. 296). Rare but good specimens of S. angiporoides s.s.

occur up to within 3 m of the top of the Ruwarung Member in outcrop at Port Noarlunga South (Lindsay, 1970a), and occur similarly almost to the top of the Member in Croydon-2 bore (Plan 29). The specimen from the basal half-metre of the Ruwarung Member stratotype identified previously as topmost S. linaperta by Lindsay (1967b, pl. 1, fig. 24), is refigured here (Pl. 31, Figs 11,12) and is still considered to be probably S. linaperta as discussed in the Systematic Notes. The base of the Ruwarung Member is thus regarded as being closely related to the Eocene/Oligocene boundary. One immature specimen of Subbotina sp. from SADME South Parklands bore, recovered from a sludge sample at 36-38 m which bridges the boundary between the Ruwarung and Aldinga Members, is 'ex group S. linaperta - S. angiporoides', but is now compared with S. angiporoides rather than with S. linaperta as shown in Plan 27.

Cassigerinella winniana and Tenuitella gemma probably range up into Zone P.21 in the eastern St Vincent Basin (see Plans 3 and 36). Blow (1979, p. 828) ranged C. winniana only up to Zone P.19/20, but remarked that the range was 'probably not yet fully evaluated'. C. winniana (= C. eocaenica) ranges up virtually to the top of the Ruwarung Member in outcrop at Port Noarlunga South (Lindsay, 1970a), but only about halfway up the Ruwarung section in the SADME South Parklands bore (Plan 27). Blow (1979, p. 779) recorded the upward limit of T. gemma as Zone P.21, or possibly the earlier part of Zone P.22. Although rare at Port Noarlunga South this species ranges up into the 'upper Janjukian unit' there (Lindsay, 1970a), but it does not continue to the top of the Ruwarung section in the South Parklands bore (Plan 27).

Tenuitella munda, which occurs through the Ruwarung section in the South Parklands bore (Plan 27), and in the upper half of Ruwarung Member in the Croydon-2 bore (Plan 29), has not been recognised previously in the St Vincent Basin. It is a characteristic species of the Oligocene in New Zealand (Jenkins, 1966a, 1971; Hornibrook and Edwards, 1971), and of the Rupelian Stage (Lower to Middle Oligocene) in north-western Europe (Berggren, 1969a). Berggren found T. munda and S. angiporoides 'commonly together in the lower part of the Rupelian'. Ludbrook and Lindsay (1969) recorded the same association from the pre-Janjukian Oligocene of the Gambier Embayment.

In the eastern St Vincent Basin, most of the concurrent range of Chiloguembelina cubensis and Guembelitria samwelli occurs through the Ruwarung Member (Lindsay, 1967b, 1969, 1970a; Cooper, 1979b), although the association commences near the top of the Aldinga Member and concludes low in the 'upper Janjukian unit' (Plan 36).

Globigerina angulisuturalis has not been found in the Ruwarung Member in the Adelaide City area, but it occurs at the top of the Member, and in the overlying 'upper Janjukian unit', in the SADME Pelican Point bore (Plan 4; Lindsay, 1968c, plan C6). In the S.A.F.U. bore on the Mile End Block (Plan 4; Lindsay, 1969, ref. bore 76), occasional specimens transitional from G. anguliofficinalis to G. angulisuturalis are found at the top of the Ruwarung Member. However here, and generally in the Adelaide Plains Sub-Basin, the G. angulisuturalis range-zone is in the 'upper Janjukian unit', as discussed under that unit and in the Systematic Notes.

G. angulisuturalis occurs rarely in the 'upper Janjukian unit' of the Port Willunga Formation stratotype, as reported by Lindsay (1969, p. 27).

Core samples from Ruwarung Member in SADME South Parklands bore at 30 m and 35 m (Plan 27) contain rare, quadrilobate, G. angulioffícinalis with incised to grooved sutures. 'G. aff. angulioffícinalis' has been recorded from the Ruwarung Member at Port Noarlunga South (Lindsay, 1970a). In the G. angulioffícinalis - G. angulisuturalis lineage, the overlap in ranges of these morphotypes occurs in Zone P.21 and possibly only the earlier part of Zone P. 22 (Blow, 1979).

Thus, in summary, the evidence of S. angiporoides indicates that the top of the Ruwarung Member is no younger than Zone P.21, as shown in Plan 3. This agrees with the appearance of G. angulisuturalis in the G. angulioffícinalis - G. angulisuturalis lineage, at the top of the Ruwarung or immediately above it; and is in accord with the known ranges of C. winniana and T. gemma (Plan 36).

Lindsay (1970a) reported the initial appearance of specimens approaching G. ciperoensis 'forma typica', from the G. angustiumbilicata - G. ouachitaensis complex in mid-Ruwarung Member (= 'siliceous unit') at Port Noarlunga South. If this homotaxial development is assumed to have worldwide time significance, as suggested by Blow (1970), it hints that the middle part of the Ruwarung Member is Zone P.19/20. Species diagnostic of Zone P.18 are lacking from the Ruwarung Member, as noted for the Port Noarlunga South section by Lindsay (1970a). However, in view of the last appearance of S. linaperta at the very base of stratotype Ruwarung Member, and by comparison

with more diverse and abundant planktonic successions in the Gambier Embayment (Plans 33, 34), particularly the morphological trend in the S. linaperta - S. angiporoides group, it may be inferred that the lithostratigraphic succession of the Ruwarung Member commenced close to the Eocene/Oligocene boundary. This is supported if the initiation of this cherty sedimentation is correlated with the terminal Eocene cooling event, as discussed earlier.

Massilina torquayensis (Pl. 49, Figs 14-16; Pl. 50, Figs 1-10) is the most biostratigraphically diagnostic benthonic foraminifer present in the Ruwarung Member beneath the Adelaide City area and elsewhere. It is typically Janjukian and Oligocene (to earliest Miocene), but at least in South Australia, appeared in the uppermost Eocene; in the Aldinga Member, eastern St Vincent Basin (Plans 27, 29, 37; Lindsay, 1970a; Cooper, 1979b, 1980), and in the Lacepede Formation, Gambier Embayment (Plan 33).

Environment of Deposition, and Further Discussion of the Chert Problem

The faunas of the Ruwarung Member, and its glauconitic nature, indicate marine origin. However the low planktonic/benthonic ratio, the calcarenitic and at times quartzose sandy lithology, and the partly dark grey carbonaceous character (e.g. Plan 27), all suggest a neritic environment with restricted access to the open ocean.

The chert problem has been discussed already at some length, in connection with the Gull Rock Member of the Blanche Point Formation. As with the Gull Rock Member, the chert content of the Ruwarung Member which is its distinctive feature, raises interesting issues involving environment of deposition,

silica geochemistry, and diagenesis; some of which are beyond the scope of this study, and indeed are as yet unresolved. A contemporary review by Mizutani and Oehler (in press) notes 'the mechanisms of nodular chert formation in carbonate sediments' as a subject for which 'no satisfactory explanation .... has yet come to light', and which merits special attention. The Ruwarung cherts are often seen to be rich in siliceous sponge spicules, both as actual spicules and as dissolution moulds. Remains of siliceous microorganisms (diatoms, radiolarians etc.) have not been reported from the Member, but the siliceous spicules seem adequate to account for a biogenic origin for the observed matrix of micro- to cryptocrystalline opaline silica. In a petrographic examination of Ruwarung nodular chert from SADME South Parklands bore (Ref. bore 41; Plan 27; Fig. 77; Appendix C) Radke (1978) distinguished 20% siliceous spicules and 40% opaline silica matrix. The following 'silica pathway' seems consistent with the petrography:

opaline silica sponge spicules → partial dissolution reprecipitation → isotropic opaline silica →

→ partial recrystallisation → microcrystalline to cryptocrystalline chert →

→ partial recrystallisation → chalcedonic quartz.

Knauth (1979) proposed recently that 'many nodular cherts in limestone have formed in the ground water of mixed meteoric-marine coastal systems where dissolution of biogenic opal and mixing of marine and fresh waters can produce waters highly supersaturated with respect to quartz and undersaturated with respect to calcite and aragonite'. A key observation is that hydrogen- and oxygen-isotope analyses of Phanerozoic

nodular cherts indicate that the cherts 'although collected predominantly from marine carbonate sequences, appear to have formed in waters that were meteoric or at least contained a major meteoric-water component'. Such analyses are not yet available for the Ruwarung Member. Knauth suggests some depositional geometries in which meteoric waters will circulate through marine-deposited material into a submarine mixing zone, and indeed produce layers of chert nodules such as those observed in the Ruwarung. Burial by an overlying prograding shoreline sequence could result in leaching by meteoric groundwater into a succession of mixing zones, each marked by a band of nodular cherts.

However the most marginal Ruwarung environments have not yielded the most prolific cherts, for in sandy facies marginal to the eastern St Vincent Basin, the cherty phase of Ruwarung Member is developed only intermittently or sparsely. Even in the stratotype, nodules are not present to the same degree as in the thicker and deeper sections beneath the Adelaide Plains. In the S.A.H.T. Elizabeth Oval bore (Plan 2) the Ruwarung Member approaches vanishing point since chert development at this stratigraphic level is restricted to sands at 231.7 - 232.3 m which contain some cementation to spicular and silty siliceous fine-grained sandstone.

Correlations

In the Willunga Embayment (Cooper, 1977b, fig. 2), and probably elsewhere in the eastern St Vincent Basin (Plan 3), the Pirramimma Sand Member of Port Willunga Formation can be a lateral facies correlative of the Ruwarung Member.

Correlation with part of the Rogue Formation has been indicated already.

In the Murray Basin, Oligocene chert-bearing carbonates in the Ettrick Formation (Lindsay and Bonnett, 1973, p. 15; Lindsay and Williams, 1977, p. 15) are bio- and litho-stratigraphic correlatives of the Ruwarung Member.

Siliceous nodules and bands are extensively developed at two distinct stratigraphic levels, separated by a largely non-cherty interval, in the Gambier Limestone of the Gambier Embayment, Otway Basin (Lindsay, 1967a; McGowran, 1973a). The lower cherty unit is of uppermost Eocene and Oligocene age, while the upper cherty unit ranges from Upper Oligocene to at least Lower Miocene (Ludbrook and Lindsay, 1969; Ludbrook, 1971; McGowran, 1973a). At least the Oligocene parts of these chert-carbonate units are time-correlatives of the Ruwarung Member.

Regional Events

It was noted earlier, when discussing the significance of the upper boundary of the Aldinga Member, that the incoming of chert which marks the base of the Ruwarung Member appears to coincide with the critical oceanic cooling event near the beginning of the Oligocene (Kennett and Shackleton, 1976). The suggestion of McGowran (1979a) that there is a time-correlation between 'well-marked chert horizons in oceanic and neritic carbonates' and 'climatic lows', seems to be confirmed in this case. However as discussed earlier, it is doubtful whether the Gull Rock Member of Blanche Point Formation was deposited under cool conditions.

'UPPER JANJUKIAN UNIT' OF PORT WILLUNGA FORMATION

Introduction

This unit will be treated relatively briefly, since although widely developed in the eastern St Vincent Basin, it has been intersected in the Adelaide City area only by Ref. bore 93, on the Mile End Block (Plan 5).

Nomenclature and Boundary Criteria

It is convenient to retain this as an informal unit in order to assist in the practical subdivision of the Port Willunga Formation. However it is not proposed to name the unit as a formal member of the Port Willunga Formation, since so far as is known, it does not have a characteristic and mappable lithostratigraphic identity which would distinguish it from overlying Lower Miocene sandy limestones and calcarenitic sands (Longfordian and Batesfordian Stage correlatives). As indicated by Lindsay (1969, p. 36) the base of the 'upper Janjukian unit' is determined lithologically by contact with the uppermost cherty phase of the underlying Ruwarung Member (= 'siliceous unit'); but the top of the 'upper Janjukian unit' is determined biostratigraphically, at the last appearance of Victoriella conoidea (Rutten), Massilina torquayensis, Bolivinopsis cubensis (Cushman and Bermudez), or Gyroidinoides sp. cf. G. allani (Finlay), benthonic species which typically do not range above the Janjukian Stage (Plan 37).

The unit has been referred to previously, as the 'upper Janjukian member' (Lindsay, 1967c, 1968a,c), the 'upper Janjukian unit' (Lindsay, 1969, 1970a), or the 'Janjukian unit' (Lindsay in Daily et al., 1976) of Port Willunga Formation. The name arose after the writer had attempted to discover the stratigraphic relationship between the type section of Port Willunga Formation and the Janjukian stratotype, by comparing the position in each of the Chiloguembelina cubensis LAD, in the presence of continuing Guembelitria samwelli (Lindsay, 1967b, and unpublished data). From this comparison it was

estimated that the uppermost part of the Ruwarung Member (= 'interval with cherty nodules') correlates with the basal part of the Janjukian stratotype near Bell's Headland, in the Torquay area of western Victoria. The 'upper Janjukian unit' is therefore the upper of the two units of Port Willunga Formation which between them correlate with the Janjukian stratotype. The name does not imply that the unit correlates only with the upper part of the Janjukian stratotype. In fact it is known that this is not so, since the unit contains the Guembelitria samwelli LAD (Plan 36) which occurs at Bell's Headland in the lower Janjukian.

Lithology and Distribution

The Table below outlines the lithology of the 'upper Janjukian unit' in the S.A. Farmers Union bore 1, Mile End, Ref. bore 93. The lithological descriptions are a combination, by the writer, of a driller's log (W.D. Wilson), a geologist's log (P.G. Miller), and the writer's microscopic study of washed residues. All samples are cable-tool sludges.

TABLE

Depth (m; feet)	Lithology
31.4 - 34.4 m (103-113 ft)	Sandy limestone, calcareous sandstone, and clayey quartz sand; fossiliferous, calcarenitic; yellow, mottled red-brown; quartz sand content is mostly fine-grained, angular to subangular, and iron-stained; glauconitic (ovoid pellets, part-oxidised).

Conformable contact: base Longfordian Stage correlatives, top of 'upper Janjukian unit'.

- -

34.4 - 36.9 m (113 - 121 ft)	As above, but softer, more clayey, with thin hard seams of sandy limestone/ calcareous sandstone at 35.1-35.2 m, 36.3-36.6 m; yellowish-brown, ferruginous, glauconitic (ovoid pellets, part-oxidised).
36.9 - 37.5 m (121 - 123 ft)	Sandstone, calcareous, moderately hard; fossiliferous, calcarenitic; with angular to rounded quartz pebbles, sand, and clay.
37.5 - 39.3 m (123 - 129 ft)	Sandy clay (marl), fossiliferous, calcarenitic, yellow-brown; with quartz pebbles; a thin hard bar of calcareous sandstone/sandy limestone at 38.4 - 38.6 m.
39.3 - 42.4 m (129 - 139 ft)	Bedded sandy clay (marl) and sand; fossiliferous, calcarenitic, sparsely glauconitic; bands of quartz gravel; hard bars of sandy limestone/calcareous sandstone at 39.9-40.0 m, 40.5-40.6 m; yellowish-grey.
42.4 - 46.3 m (139-152 ft)	As above, but yellowish-grey speckled green, more glauconitic; less gravelly; a hard band of sandy limestone/calcareous sandstone at 43.0 - 44.5 m.

Conformable contact: base 'upper Janjukian unit', top Ruwarung Member.

- -

46.3 - 46.5 m (152 - 152.5 ft)	As above with first (downhole) hard bar or nodule of dark grey chert, spicular, glauconitic.

The variable lithology of the 'upper Janjukian unit' in the Adelaide Plains Sub-Basin and in the Port Willunga Formation stratotype was outlined previously by the writer (Lindsay, 1969, pp. 35-36). Much the same range of rock-types was encountered there as on the Mile End Block, i.e. fossiliferous sandy limestone, calcareous sandstone, sandy clay (marl), and clayey sand. This is also seen in the Croydon-2 bore (Plan 29). Only in the Dublin Govt bore (Plan 2; Lindsay, 1969, p. 36, ref. bore 2) did the unit display a distinct lithological top contact, in which bluish-green and brown fossiliferous marl was overlain by Longfordian limestone.

The writer noted previously that hard bands low in the 'upper Janjukian unit' in SADME bore PTG-62, Northern Adelaide Plains (Plan 2) had been wholly or partly dolomitised (Lindsay, 1969, p. 36; after Kelly, 1969). A relatively thick interval of sandy dolomitised limestone and dolomite, which is here identified as 'upper Janjukian unit', was encountered in SADME bore WLG-38 in the Willunga Embayment (Plan 2; B.J. Cooper, 1979b, pp. 36-38, with petrographic descriptions in appendix 1, after R.S. Cooper, 1976).

At the top of the type section of Port Willunga Formation described by Reynolds (1953), the 'upper Janjukian unit' is exposed at low tide around Snapper Point, as shown in Figure 78. A shallow synclinal structure is outlined by harder bands in the bryozoal limestones which comprise the unit. North of Snapper Point, the beds dip gently south; west of the Point the dip is east; and south of the Point the dip is north, as mapped by Thomson and Horwitz (1962). A view of this inter-tidal exposure of Oligocene 'upper Janjukian unit' at Snapper



Figure 78. Snapper Point (left middle distance), and part of the offshore Aldinga Reef Aquatic Reserve, looking south-west at low spring tide, Dec. 1979, showing wave-cut platform of 'upper Janjukian unit'. Harder bands of the bryozoal limestone (sandy, quartzose, glauconitic) indicate the gentle southerly dip north of Snapper Point, and the shallow syncline facing the Point. Guembelitria samwelli is present in the limestones, but not Chiloguembelina cubensis; the age is Late Oligocene. Outcropping Port Willunga Formation has descended here to intertidal level, and is overlain, with low-angle unconformity, by Late Pliocene Hallett Cove Sandstone (low outcrop at back of beach), which in turn is overlain by white, earthy, Burnham Limestone (Early Pleistocene), and slope-forming, Pleistocene olive clays.

Point, which was included by the writer in the Annual Report for 1972-1973 of the S.A. Director of Mines and Government Geologist (fig. 37, p. 95), shows the easterly dip of the strata west of the Point. Well-sorted, coarse bryozoal limestone between Snapper Point and Aldinga Beach contains Victoriella conoidea within the Guembelitria samwelli range-zone, at about 4½ m stratigraphically above the Ruwarung Member (Stuart, 1969, pp. 205, 223), indicating a southerly extension of the 'upper Janjukian unit' beyond Snapper Point.

In the Noarlunga Embayment, quartzose bryozoal limestones of the 'upper Janjukian unit' outcrop similarly in the uppermost part of the exposed Port Willunga Formation between Port Noarlunga South and Seaford, in low, back-beach cliffs, and inter-tidally (Lindsay, 1970a). As between Snapper Point and Aldinga Beach, Victoriella conoidea has been reported as present within the Guembelitria samwelli range-zone, at about 4½ m above the Ruwarung Member (Stuart, 1969, pp. 205, 223). From the writer's own observations, the association of V. conoidea and G. samwelli occurs no more than 3 m above the top of the Ruwarung Member in the nearby Seaford drainage bore, rather than the figure of 10 m reported by Cooper (1980). The first (downhole) chert fragments, indicating Ruwarung Member, are present in the same sludge sample (depth 25-28 m) which contains V. conoidea. Similar limestones bearing the V. conoidea horizon, were mapped by Stuart (1969, pp. 204, 223; map 5, chart 9) on a rarely-exposed wave-cut platform at the southern flank of the Noarlunga Embayment, 1½ km south of Moana (Plan 2).

In the Hindmarsh Tiers Basin, in SADME Hindmarsh Tiers Obs. bore ENB-2 (Plan 2), the earliest mid-Tertiary sediment is quartzose skeletal calcarenite/calcirudite with lithic pebbles. The presence of Guembelitria samwelli (but not Chiloguembelina cubensis) and Bolivinopsis cubensis indicate Late Oligocene age (Lindsay in Furness, 1975, appendix 1) and correlation with the 'upper Janjukian unit' of Port Willunga Formation.

In the adjacent Myponga Basin, penetrated by the S.A. Black Coal Syndicate bore (Plan 2), the earliest mid-Tertiary strata comprise yellow, apparently chert-free, bryozoal limestone (Mining Review, 1931, p. 88). The indications by Glaessner (1953b) of the age and correlation of the lower part of this limestone sequence, together with the recorded presence of Chiloguembelina cubensis (= 'Gümbellina'; Glaessner in Campana et al., 1955, p. 3), suggest that these lowermost limestones are also equivalents of the 'upper Janjukian unit', but that deposition of the unit commenced earlier in the Late Oligocene there, than in the Hindmarsh Tiers Basin (Lindsay in Daily et al., 1976, p. 28).

Thickness

In the Adelaide City area, the 'upper Janjukian unit' is 11.9 m thick in the S.A.F.U. Mile End bore (Ref. bore 93).

The unit has a thickness of 19.8 m in the Croydon-2 bore (Plan 29). Elsewhere in the Adelaide Plains Sub-Basin, as indicated previously (Lindsay, 1969, appendix 2), the thickness is a minimal 4 m in the SADME Port Gawler bore PTG-13, increases eastwards to 25 m near the Redbank Fault in SADME Obs. bore

PTG-62 (Plan 2), averages about 13 m, and is at a maximum of 31 m near the southern margin, in Flinders University bore 1, Bedford Park. There is some evidence that the unit thickens relatively towards basin margins and in fault-angle depressions.

At the top of the outcropping type section of Port Willunga Formation described by Reynolds (1953), an incomplete and approximate 3½ m thickness of 'upper Janjukian unit' was estimated by the writer (Lindsay, 1967b). As discussed above, the unit is at least 5 m thick in the vicinity of Snapper Point, as measured by Stuart (1969). Inland, in Willunga Embayment bores, the unit attains a thickness of 23 m in WB-1 (Lindsay, 1966, 1969) and 30 m in WLG-40 (Cooper, 1969b, fig. 28).

In the Noarlunga Embayment, the writer estimated a thickness of about 3.7 m in coastal exposures between Port Noarlunga South and Seaford (Lindsay, 1970a). The Seaford drainage bore nearby, encountered the probably eroded and weathered top of the unit at a depth of about 21.5 m (Cooper, 1980); but as noted above, chert of the Ruwarung Member is present downhole from at least 28 m, making the 'upper Janjukian unit' about 6½ m thick, rather than the 13½ m indicated by Cooper.

In the Hindmarsh Tiers Basin, in SADME Obs. bore ENB-2 (Plan 2), a thickness of several tens of metres is possible on the basis of the incomplete biostratigraphic information available (Lindsay in Furness, 1975, appendices 1, 2).

Biostratigraphy, Age, and the Oligocene-Miocene Boundary

As shown in Plan 36, a number of planktonic datum-levels are associated with the 'upper Janjukian unit'. Most of these are of regional importance, e.g. the Globigerina angulisuturalis FAD and LAD, and the LADs of Chiloguembelina cubensis, Cassigerinella winniana, Pseudohastigerina, Guembelitria samwelli, and 'Globigerina' labiacrassata.

Fifteen local first or last appearances of benthonic foraminifera, and part of the lower acme interval of Amphistegina, are shown as associated with the 'upper Janjukian unit' in Plan 37.

In the Mile End bore (Ref. bore 93), the top of the 'upper Janjukian unit', at 34.4 m, is recognised on the basis of the range-top of Bolivinopsis cubensis in the sludge sample from 34.4-36.9 m. This occurs immediately below the interval of abundant Amphistegina (30.2-34.4 m; central part of the lower acme of Amphistegina), which is also here the concurrent range interval of Sherbornina atkinsoni and S. cuneimarginata. Within the unit, in this bore, the range-tops of Globigerina angulisuturalis (Pl. 17, Figs 9-11), Guembelitria samwelli, Tenuitella gemma, and Cibicidoides umbonifer (Parr), (Pl. 37, Fig. 11; Pl. 38, Figs 1, 2) occur in the sludge interval 40.2-42.4 m.

The microfaunal succession through the 'upper Janjukian unit' in the Croydon-2 bore is indicated in Plans 29 and 31. The unit is thicker here than on the Mile End Block, and the faunas are more diverse. The top of the unit, at 312.4 m, is recognised on the basis of the range-top of Massilina torquayensis in the sludge sample from 312.4-313.9 m.

Gyroidinoides cf. allani which is also present in the sample, occurs as one isolated specimen 30 m higher, but that is not considered to be sufficient reason for putting the top of the 'upper Janjukian unit' so high in the face of the other bio-stratigraphic evidence. The local range-zone of Globigerina angulisuturalis is delineated by rare but admissible specimens in two out of the three sludge samples between the depth limits of 313.9 and 318.5 m. A transitional morphotype 'ex group G. angulisuturalis - G. ciperoensis' occurs as high as 266 m (Pl. 19, Figs 6, 9). A few specimens of Victoriella conoidea were found only in the sample from the bottom of the G. angulisuturalis range-zone, at 317.0-318.5 m (Pl. 61, Fig. 9). The range-top of Guembelitria samwelli is lower, in the sludge sample from 326.1-327.7 m; and that of Globigerina ouachitaensis s.s. is near the bottom of the unit, in the sample 329.2-330.7 m. The range-top of Bolivinopsis cubensis is within the sample interval 315.2-317.0 m, below which the species is consistently present through the unit.

The writer previously outlined similar foraminiferal associations and successions in the 'upper Janjukian unit' elsewhere in the Adelaide Plains Sub-Basin, and at the top of the type section of the Port Willunga Formation (Lindsay, 1969, pp. 26-27).

In addition to the above records of Victoriella conoidea in the 'upper Janjukian unit', the species has been found subsurface in the same unit in SADME Obs. bore PTG-66 (bore 'G'), Two Wells, at a depth of 82.3-85.3 m (sludge sample); and in SADME Obs. bore PTA-40, Pelican Point (Plan 4) at 210.3-213.4 m (cuttings sample). Recognisable glauconitic

steinkerns of Victoriella were recovered from sludge samples of leached intervals at the same stratigraphic level in the E. & W.S. Springbank bore (Plan 4) at 86.9-90.8 m, and the S.A.H.T. Elizabeth Oval bore (Plan 2) at 174.0-175.6 m. V. conoidea has also been found in the 'upper Janjukian unit' subsurface in the Willunga Embayment bores WLG-38 and WLG-40 (Cooper, 1979b).

In order to determine the age of the 'upper Janjukian unit' in relation to the Oligocene-Miocene boundary, it is necessary to relate the local succession to the European stratotype boundary. As Van Couvering (1978) observed recently, the beginning of the Miocene Epoch, and thus the Oligocene-Miocene boundary, is now embodied by international agreement in the base of the exposed Aquitanian stratotype (at normal water level) in the bank of the Saucats River at Moulin de Bernachon, S.W. France. This is essentially as recommended by the Tertiary Era Sub-Committee of the Geological Society of London (George, et al., 1969, pp. 157-158).

The writer, in a previous brief discussion of the Oligocene-Miocene boundary (Lindsay, 1969, pp. 26-27), recognised that the boundary was probably represented in the eastern St Vincent Basin by some horizon within the 'upper Janjukian unit'; and that Globigerina angulisuturalis could be useful in correlating the boundary. Jenkins (1964b, 1966b) found one specimen of G. angulisuturalis in a sample from about 3 m above water level at Moulin de Bernachon, thus proving that the species does range into the basal stratotype Aquitanian and Miocene, though perhaps only just.

In New Zealand there is surprisingly little record of G. angulisuturalis, compared even with the St Vincent Basin, let alone the Gambier Embayment. Jenkins (1966a, 1971) identified only two specimens with certainty, the lower from the type section of the Whaingaroan Stage, in the 'G.(G.) euapertura' Zone, and the upper from mid-Waitakian Stage in the G.(G) woodi woodi Zone. This latter zone, which was earlier regarded as Lower Miocene by Jenkins (1966a, 1971), has more recently been considered pre-Miocene by Hornibrook and Edwards (1971), Jenkins (1974a), and Van Couvering and Berggren (1977, text fig. 1, cf. p. 295). Thus the two N.Z. specimens of G. angulisuturalis span a range of middle to possibly uppermost Oligocene.

In the Gambier Embayment, Ludbrook and Lindsay (1969) recorded only a narrow range-zone of G. angulisuturalis, within their tentatively Upper Oligocene G. euapertura zone. McGowran (1973a) provisionally correlated this range-zone of 'common and typical' G. angulisuturalis with part of Zone P.21 (Upper Oligocene). This range-zone was seen to be succeeded by a newly-recognised interval (Lindsay and McGowran, 1971) marked by members of the Turborotalia kugleri s.l. group (mostly T. pseudokugleri, some T. mendacis, few if any T. kugleri s.s.) in the presence of G. ciperoensis, but lacking Globigerinoides, and thus estimated as Zone P.22 (Blow, 1969), uppermost Oligocene. These intervals and microfaunal associations are depicted in Plans 33 (adapted from McGowran, 1973a, fig. 3., with emendations) and 34. At the locality treated in Plan 33, the Gambier Limestone, fortunately, has been eroded down to a

stratigraphic level below the Globigerinoides FAD. As a result, it can be demonstrated for example, that here the Victoriella LAD and probably much of the T. kugleri group range-zone are pre-Globigerinoides. On the other hand, at the locality treated in Plan 34, downhole contamination in sludge samples makes it difficult to determine the 'Globigerinoides Datum', although a few other FAD's are estimated, e.g. those of Globoquadrina dehiscens s.s., the T. kugleri group, and Globigerina angulisuturalis.

Lindsay and McGowran (1971) interpreted these successive but slightly overlapping intervals of 'common and typical' G. angulisuturalis, and the T. kugleri group (reported earlier by McGowran et al., 1971) as representing warm ingressions of a regional character and thus of value in regional correlation, for example with New Zealand. The two episodes are distinct and successional, but condensed, in the Waikerie area of the Murray Basin (Plan 32), where only the G. angulisuturalis episode was detected previously by the writer (in Lindsay and Bonnett, 1973). The occurrence there together (in core) of top T. kugleri group and bottom Globigerinoides primordius is noteworthy, as is the location of top Victoriella at the boundary between the two planktonic episodes.

In the St Vincent Basin, the T. kugleri group has not yet been recognised, but as summarised in Plan 31, the episode with typical G. angulisuturalis persists, though through an even narrower interval than at Waikerie, reflecting still less open marine access. If this episode in the Adelaide region is indeed coeval with the angulisuturalis episode in the Gambier Embayment, rather than merely homotaxial, then the former, like the latter, is Upper Oligocene, since we are

dealing with an episodic climatic/facies 'window', rather than with the total world range of G. angulisuturalis which admittedly extends into the basal Miocene. It would then follow that most if not all of the 'upper Janjukian unit' is Upper Oligocene. However, only in one bore in the Adelaide Plains Sub-Basin (SADME Obs. bore PTA 57, bore 'M', Buckland Park) does the G. angulisuturalis LAD coincide with the top of the 'upper Janjukian unit'. In every other case, the top of the unit is higher, and is recognised by the range-tops of 'Janjukian' benthonic foraminifera. Since the uppermost part of the Janjukian stratotype is now considered to extend up slightly into the basal Miocene, on the evidence of calcareous nannofossils (Siesser, 1979), it has been deemed advisable to show the uppermost part of the 'upper Janjukian unit' as extending similarly up into the basal Miocene herein.

Globigerinoides does not occur in the 'upper Janjukian unit'. Even if it did, it would not prove a post-Oligocene age, since there has been a growing realisation that, unfortunately, the 'Globigerinoides FAD' is diachronous, perhaps climatically-controlled, and is certainly pre-Miocene particularly in relation to the base of the Aquitanian stratotype (see for example, Lamb and Stainforth, 1976; Van Couvering and Berggren, 1977; Shafik and Chaproniere, 1978; and references therein). On the western side of the St Vincent Basin, occasional specimens of Globigerinoides primordius have been found below the Guembelitria samwelli LAD (Stuart, 1969, p. 207). This association has not been observed in the eastern St Vincent Basin, or elsewhere in South Australia; it is unusual and was previously found to be

puzzling because of the consistently Palaeogene association of Guembelitria elsewhere in the Tertiary. However it is now clear that the overlap does not require a Miocene age, since, as outlined above, the initial appearance of Globigerinoides primordius which defines the base of Zone N.4, was in the Late Oligocene (e.g. Van Couvering and Berggren, 1977; Hardenbol and Berggren, 1978).

Environment of Deposition, and Regional Events

Like other units of the Port Willunga Formation, the 'upper Janjukian unit' was deposited in a neritic marine environment. The low planktonic/benthonic ratio is likewise evidence of continuing restriction of access to open-marine influence, with a probable slight improvement indicated for the G. angulisuturalis episode.

Vail et al. (1977) and Vail and Mitchum (1978) proposed that the most dramatic movement in global sea level during the entire Cainozoic took place about midway through that era, with a drop from possibly 150 m above to 200 m below present sea level, early in the Late Oligocene (about base Zone P.21, 30 Ma). In the eastern St Vincent Basin, within the present limits of biostratigraphic resolution, this approximates the close of cherty sedimentation at the top of the Ruwarung Member; but a major regional unconformity is not observed at this stratigraphic level. However, the succeeding 'upper Janjukian unit' generally has a coarser-grained quartzose detrital component (often sandy), is more winnowed, and represents deposition in a shallower, higher-energy environment. In the S.A.F.U. Mile End bore, as outlined above,

much of the unit is fossiliferous sand, calcareous sandstone, and sandy limestone. Gravelly bands with quartz pebbles, and occasional barnacle plates, suggest shallow water-depths.

In several localities around the St Vincent Basin, correlatives of the 'upper Janjukian unit' are transgressive e.g. on to Precambrian granite along the Tickera coast, northeast of Wallaroo (Plan 1; Lindsay, 1970c); and on to Permian deposits in the Myponga and Hindmarsh Tiers Basin (noted above), and at Point Turton (Plan 1; Point Turton Limestone, with Victoriella; Ludbrook, 1963a).

At the western margin of the Murray Basin, time and rock-correlatives of the 'upper Janjukian unit' similarly transgress, e.g. on to granite and metasediment in the Monarto area (Plan 1; with Victoriella, and Guembelitria samwelli; Lindsay and Williams, 1977), and on to metasediment in the River Marne valley, 15 km S.S.W. of Swan Reach (with Bolivinopsis cubensis; personal observation).

In the Gambier Embayment, the angulisuturalis and 'kugleri'-group episodes (McGowran et al., 1971) were seen as 'important incursions which reflect relatively short-lived warmer and more open-marine conditions' (Lindsay and McGowran, 1971). It is a striking coincidence that bio-stratigraphically the older episode matches a proposed global rise of sea level in cycle TO2.1, while the younger episode corresponds to a further global rise in cycle TO2.2 (Vail et al., 1977; Vail and Mitchum, 1978). These two episodes together correlate with the earlier part of transgressive sedimentation cycle 3A on the Northwest Shelf of W.A. (Quilty, 1977).

McGowran (1978d, 1979b) has recently indicated other circum-Australian events and deposits associated with this the earliest part of his third sedimentary Sequence. The Sequence is plotted in Plan 35, in relation to the 'upper Janjukian unit' and palaeotemperature indicators.

The incomplete O-isotope palaeotemperature curve in Plan 35, for sub-antarctic waters, suggests a minor warm peak at the time of deposition of the 'upper Janjukian unit'. However O-isotope data plotted by Gill (1968) for Victorian shallow-water '*Ostrea*' and '*Pecten*', show a marked rise in palaeotemperature (extending well above 20°C) towards the Oligocene-Miocene boundary. The 'lower *Amphistegina* acme' extends above the 'upper Janjukian unit' into basal Longfordian Port Willunga Formation (Plans 31, 37, cf. Plan 32). Hornibrook (1968a) concluded that the present-day '20°C mean annual isotherm roughly corresponds to the southern limit of the distribution of *Amphistegina* in the Pacific'. He noted that *Amphistegina* is abundant on the Great Barrier Reef, and occurs only as far south as Sydney Harbour. There is little doubt that the genus is tropical/subtropical, and that its lower acme represents a real and considerable warming in the St Vincent Basin, as in the Murray Basin (Lindsay and Bonnett, 1973).

MIOCENE UNITS OF PORT WILLUNGA FORMATION

Correlative of Longfordian Stage; the 'Longfordian unit'

Although widely developed in the nearby Adelaide Plains Sub-Basin (Lindsay, 1969), Longfordian correlatives occur in the Adelaide City area only on the Mile End Block, where they have been encountered in Ref. bores 57 and 93 (Plans 4,5,14).

This unit has evidently been eroded from the Para Block in the vicinity of the City, but is present on that Block to the south and southwest, beyond the Golden Grove-Adelaide Embayment (Plan 4), in the Daws Road High School bore (Lindsay, 1969, bore 85), the E. & W.S. Glenelg East Bore (Lindsay, 1969, bore 92), the E. & W.S. Paringa Park bore (Lindsay, 1969, bore 91), and the H.R. Weymouth bore (Lindsay, 1969, bore 93).

As with the 'upper Janjukian unit', the 'Longfordian unit' is distinguished in the eastern St Vincent Basin by various characteristic foraminifera, i.e. biostratigraphically, rather than by a particular lithology. Hence no formal stratigraphic name is given to the unit, although it is useful in the subdivision of the Port Willunga Formation.

The 'Longfordian unit' was intersected in two of the foundation test holes for the Hilton Bridge project, Burbridge Road, at the northern end of the Mile End Goods Yards (Johnson, 1976). Bore CH-2, plotted in Plan 5 as Ref. bore 57, bottomed in the unit at 24.1 m after intersecting a thickness of about 2.6 m. Here, the unit comprises fossiliferous calcareous quartz sandstone, sand, and sandy limestone, pale brown mottled dark brown and red-brown, ferruginous. The unit is banded or rubbly, hard and cemented, to soft clayey and friable; glauconite is common as pellets, foraminiferal infillings, and steinkerns, much being more or less oxidised. Bore CH-3, 50 m southeast of CH-2, also bottomed in the unit, at 24.0 m, after intersecting about 3 m of the unit. The lithology is similar to that in CH-2, comprising pale grey, cream and brown, fossiliferous, glauconitic, sandy limestone and clayey sand.

In each of these bores the Longfordian unit is overlain unconformably by an eroded remnant of Pliocene Hallett Cove Sandstone (see Cross-section R-S, Plan 14).

In the S.A.F.U. bore, Mile End (Ref. bore 93), the Longfordian unit was entered at 26.5 m (beneath Pleistocene Carisbrooke Sand) and a thickness of 7.9 m was penetrated. Lithologies comprise:

26.5 - 27.7 m	Clayey quartz sand, mustard-brown and pale greenish-grey, glauconitic (steinkerns), leached.
27.7 - 30.2 m	Fine quartz sand, yellow, fossiliferous, with sparse shell fragments; a thin hard bar of sandy limestone/calcareous sandstone at 29.0 m.
30.2 - 31.4 m	Fossiliferous sandy limestone/calcareous sandstone, moderately hard.
31.4 - 34.4 m	Clayey sand/sandy clay; yellow, brown, red-brown; calcarenitic, glauconitic; some cementation to calcareous sandstone/ sandy limestone.

The Longfordian interval is underlain conformably by the 'upper Janjukian unit'.

In the Croydon-2 bore (Plan 29) the 'Longfordian unit' is more than 50 m thick, comprising brownish fossiliferous glauconitic sand and sandy limestone. The writer previously outlined the similar lithology of the unit elsewhere in the Adelaide Plains Sub-Basin (Lindsay, 1969).

In the coastal exposures of the Willunga Embayment, the Longfordian unit does not form part of the type section of Port Willunga Formation described by Reynolds (1953) and Lindsay (1967b). However the unit crops out further south, as the youngest exposed part of the same stratigraphic succession, along the southern end of Sellick Beach (Plan 2). Here, in low back-beach cliffs and inter-tidal outcrops near the axis of the Embayment, the unit comprises friable to cemented brownish calcarenitic limestones. Three or four kilometres inland, Longfordian fossiliferous sandy limestones and sands 60 m thick were penetrated in SADME Obs. bore WLG 38 (Plan 2; Cooper, 1979b).

The Longfordian Stage, defined by Carter (1964), is named after the town of Longford, south of Sale, in Gippsland. The geology of the Gippsland Basin has been described recently by Hocking et al. (1976). The Longfordian Stage, which is embodied in the lowest part of the Gippsland Limestone, is recognised in the eastern St Vincent Basin by means of several of the key benthonic foraminifera nominated by Carter (1964), planktonic faunas here, at this level, being too sparse and restricted to be useful. Negatively, the Longfordian is marked by the absence of Janjukian foraminifera discussed earlier. The top of the Longfordian is characterised by the final appearance of Sherbornina cuneimarginata and typical Astrononion centroplax. As shown in Plan 37, a number of other benthonic foraminiferal events are useful local indicators of the Longfordian. The upper part, and often the main peak, of the 'lower Amphistegina acme' occurs near the base of the Longfordian unit. Also low in the unit are the first appearances of

Operculina victoriensis and Gypsina howchini, and the last appearance of Sherbornina atkinsoni. Cibicides vortex ranges to the top of the unit, while Porosorotalia crassimura extends only slightly higher. Lepidocyclina howchini does not occur in the 'Longfordian unit' of the Port Willunga Formation. In effect the unit is based on a benthonic foraminiferal biozone: a multi-taxon concurrent-range-zone, including at the base, part of an acme-zone (Hedberg, 1976).

In the Hilton Bridge bores CH-2 and CH-3, the 'lower Amphistegina acme' is prominent in the few samples of the Longfordian unit (Pl. 35, Figs 1-4). Astrononion centroplax, Cibicides vortex, Porosorotalia crassimura (Pl. 56, Figs 9,10), and Sherbornina atkinsoni (Pl. 58, Figs 7,9; Pl. 59, Fig. 2) are also present, but not S. cuneimarginata or any Janjukian indicators.

The 'lower Amphistegina acme' is also prominent in the Longfordian unit where cut by the S.A.F.U. Mile End bore. Here, Sherbornina cuneimarginata (Pl. 59, Figs 3,5) and S. atkinsoni occur together. Other species include common Planolinderina inaequilateralis (Pl. 54, Figs 10-12), frequent Pararotalia verriculata (Pl. 53, Figs 3-5), and rare Astrononion centroplax, Crespinella parri (Pl. 39, Figs 3-5) and Textularia vertebralis. The only planktonic foraminifer is a specimen of Globigerina officinalis, recovered from the base of the unit.

On the Thebarton Block, immediately west of the Adelaide City area, Coca Cola/Diverse Products bore 4A (Ref. bore 105, Plan 5) just entered the Longfordian unit, which conformably underlies a ?basal Balcombian-Batesfordian interval with Lepidocyclina (Cross-section T-U; Plan 16). The bottom sample,

from 124.0-125.5 m, comprises cream-pale brown sandy limestone with minor glauconite (part-oxidised), and contains the range-top of typical Astrononion centroplax.

In the Croydon-2 bore (Plan 29) the top of the Longfordian unit is put at the last appearance of Astrononion centroplax and Sherbornina cuneimarginata. The latter species makes its initial appearance in the 'upper Janjukian unit', as it does in the Willunga Embayment, SADME Obs. bore WLG 38, in which the species occurs in core samples with Victoriella conoidea and Massilina torquayensis (Cooper, 1979b). The upper part of the 'lower Amphistegina acme' is developed in the basal 17 m of the Longfordian unit in the Croydon-2 bore. Textularia vertebralis (Pl. 61, Figs 7,8), Crespinella parri (Pl. 39, Figs 6,9), and Porosorotalia crassimura (Pl. 56, Fig. 3), are illustrated from the unit in this bore. The planktonic/benthonic ratio is low, and Globigerinoides is extremely rare; but Globigerina angustiumbilicata, G. bulloides s.l., G. officinalis, G. woodi woodi, and G. woodi connecta occur sporadically within the unit (though not restricted to it). Isolated specimens of ?G. juvenilis (Pl. 19, Figs 8,10) and ?G. obesa (Pl. 23, Figs 8,10) are illustrated and discussed in the Systematic Notes, as are specimens of G. 'ex group angulisuturalis-ciperoensis' (Pl. 19, Figs 6,9) and G. 'ex group angustiumbilicata-ciperoensis' (Pl. 19, Fig. 7).

The 'lower Amphistegina acme' is present in the Longfordian unit of Port Willunga Formation along the southern part of Sellick Beach. In two samples (F102/73, F103/73), Amphistegina is common to abundant, as is Pararotalia verriculata. However

the stratigraphically highest sample (F1/75), collected from inter-tidal outcrop about half a kilometre north of the southern end of Sellick Beach, lacks Amphistegina and is apparently from above the 'lower Amphistegina acme'. The microfauna is dominated instead by Operculina victoriensis with less common Gypsina howchini, Pararotalia verriculata, and Planolinderina inaequilateralis; and occasional Astrononion centroplax.

The quartzose clastic/carbonate lithology of the local Longfordian unit suggests a shallow neritic depositional environment. The low content of planktonic foraminifera indicates nearshore deposition and/or restricted access to the open sea. As noted earlier, the 'lower Amphistegina acme' represents a period of warm-water deposition. In the Waikerie area of the Murray Basin the top of this acme coincides with the top of the thin interval with the T. kugleri group (Plan 32). The two may thus represent the same warm episode (Lindsay, 1976). If this is an isochronous regional event, as suggested by McGowran (1978d, 1979b), it is likely that it is expressed also in the eastern St Vincent Basin by the 'lower Amphistegina acme'. As discussed earlier, this can be linked somewhat speculatively with the Oligocene-Miocene global sea-level Cycle TO2.2 (Vail et al., 1977; Vail and Mitchum, 1978), but biostratigraphic resolution is not precise enough to exclude earliest Miocene Cycle TM1.1. McGowran (1979b, fig. 5) shows only the one 'extra-tropical excursion' of larger foraminifera in the latest Oligocene of the Murray and St Vincent Basins, characterised by both Amphistegina (the lower acme) and Operculina. However in both the Murray Basin (e.g. Lindsay,

1965c) and the eastern St Vincent Basin (e.g. Plan 29) only the top of the 'lower Amphistegina acme' overlaps with the initial range of Operculina, the two being almost successional. This contrasts with the 'upper Amphistegina acme', in which large Amphistegina and Operculina occur together (e.g. with Lepidocyclina; Plan 35). Above the 'lower Amphistegina acme', small Amphistegina and Operculina occur sparsely and intermittently in the Longfordian (Plan 35). As suggested for the Carnarvon Basin by McGowran (1979b, p. 253), this represents a degree of withdrawal of pantropical elements in the earliest Miocene.

The Longfordian unit of Port Willunga Formation corresponds to the lower and middle part of sedimentary Sequence Three of McGowran (1978d, 1979b); and to part of Cycle 3A of Quilty (1977). The hiatus between Cycles 3A and 3B on the western continental margin, shown by Quilty as centred on Zone N.6, and thus apparently Longfordian, is instead considered to lie near the Zone N.8/Zone N.9 boundary (Chaproniere, 1975, 1976; McGowran, 1979b).

Oxygen-isotope palaeotemperatures for the N.Z. sub-antarctic (Plan 35) show, for near-surface water, an initial drop in temperature in the earliest Miocene, followed by a steady rise through Longfordian time towards the time of the Batesfordian climatic optimum. The record for deep water is more fluctuating, but trends eventually in the same direction. O-isotope data plotted by Gill (1968) for Victorian shallow-water 'Ostrea' and 'Pecten', also show a conspicuous rise in temperature through the Early Miocene towards the Batesfordian peak.

Correlative of Batesfordian and ?lower Balcombian Stages

This unit, with Lepidocyclina, does not occur strictly within the Adelaide City area, but was penetrated on the Thebarton Block immediately to the west, in Coca Cola/Diverse Products bore 4A (Ref. bore 105, Plan 5). The geological setting of the unit, Tmp(5), in the Para Fault Zone, is shown in Cross-section T-U (Plan 16).

Singleton (1941), Carter (1964), and more recently, Abele (1976b, p. 238 ff.) have discussed the definition and correlation of the Batesfordian Stage, named after the town of Batesford, near Geelong. Carter (1964) regarded this Stage 'as the geochronological unit which is limited by the limiting events of Faunal Unit 9', including the range-zone of Lepidocyclina as developed in the Batesford limestone quarries. Correlatives of the Batesfordian Stage in the Port Willunga Formation of the Adelaide Plains Sub-Basin were described previously by Lindsay (1969, p. 37). The boundaries of the unit are partly biostratigraphic and partly lithostratigraphic. No formal stratigraphic nomenclature is proposed. The conformable lower boundary with the Longfordian unit is taken to be at the range-top of Sherbornina cuneimarginata and/or typical Astrononion centroplax, as indicated by Carter (1964). Where the Munno Para Clay Member of Port Willunga Formation is present, its lower boundary is also the upper boundary of the 'Batesfordian and ?lower Balcombian' unit. The local range-zone of Lepidocyclina howchini is the central feature of the unit, but may not extend upwards and downwards to its limits.

The Batesfordian Lepidocyclina howchini range-zone in the western Murray Basin was shown to be associated not only with Globigerinoides sicanus (= bisphericus), but also with Globigerinoides transitorius and Praeorbulina glomerosa curva, revealing a biostratigraphic overlap with the lower part of the Balcombian Stage (Lindsay and Giles, 1973). This anomaly has not yet been resolved satisfactorily. It is highly likely that the Batesfordian warm climatic peak, with its 'extra-tropical excursion' of Lepidocyclina, was regionally synchronous (Lindsay, 1976; McGowran, 1978d, 1979b), and that the unit with Lepidocyclina in the St Vincent Basin shares the problem of being not only Batesfordian but also lower Balcombian. This is the reason for the clumsy name of the 'Batesfordian and ?lower Balcombian' unit. Planktonic foraminifera are much less diverse and abundant at this stratigraphic level in the eastern St Vincent Basin than in the western Murray Basin. Only one specimen representing the 'Orbulina bioseries' was found in the Lepidocyclina range-zone in Ref. bore 105. Significantly, the specimen (illustrated in Pl. 32, Figs 9,11) is of Globigerinoides sicanus transitional to Praeorbulina glomerosa curva (cf. Blow, 1956).

Lepidocyclina howchini occurs rarely in Ref. bore 105, between depths of 102 and 108 m. Two specimens from this interval are illustrated (Pl. 47, Figs 4-6). An additional specimen at 118-120 m may represent downhole contamination in rotary drill-cuttings. Other foraminifera from the unit include:

Range-top 92 m -

Marginopora vertebralis,

Operculina victoriensis,

Amphistegina lessoni,

Parrellina craticulatiformis (Pl. 53, Figs 6,9),

Parrellina howchini.

Range-top 94 m -

Austrotrillina howchini,

Sigmomorphina subregularis.

Range-top 98 m -

Gypsina howchini.

Range-top 100 m -

Crespinella parri.

Range-top 104 m -

Globigerina woodi woodi (Pl. 26, Figs 4,5,7),

G. woodi connecta (Pl. 26, Figs 6,8),

Planolinderina inaequilateralis,

P. plana.

Range-top 120 m -

Astrononion cf. centroplax,

Pararotalia verriculata (Pl. 53, Fig. 2).

The lithology of the unit in this bore is sandy limestone, quartzose, calcarenitic, off-white/pale grey/cream/brown, sparsely glauconitic; much is hard and recrystallised, but softer intervals of calcarenitic clay (marl) and clayey limestone were probably penetrated. Although the driller noted much 'sandy clay' between 96 m and 109.5 m, the whole interval 93-125 m, beneath the Pleistocene unconformity, was logged as limestone by Bowering (1978). No evidence of Munno Para Clay

Member was detected in the cuttings samples, and the entire mid-Tertiary section (i.e. below about 92 m) is considered to be stratigraphically beneath Munno Para Clay.

The 'Batesfordian - ?lower Balcombian' unit can be recognised in Croydon-2 bore (Plans 29,16) even though Lepidocyclina is apparently not present. The unit conformably overlies the Longfordian interval at 259 m (range-tops of Astrononion centroplax and Sherbornina cuneimarginata) and is in turn overlain by the Munno Para Clay Member at 231.7 m, a thickness of about 27 m. The microfauna, although lacking Lepidocyclina, is similar in many respects to that in Ref. bore 105.

The same unit of Port Willunga Formation, with Lepidocyclina and a similar associated microfauna, was encountered in SADME Obs. bore WLG 38, in the Willunga Embayment (Cooper, 1979b, fig. 29). In this bore as in Ref. bore 105, the unit is at the top of the mid-Tertiary sequence, beneath the Pleistocene unconformity. Lepidocyclina also occurs in marginal sandy facies in the Willunga Embayment, at the top of the subsurface type-section of the Pirramimma Sand Member of Port Willunga Formation, in SADME Obs. bore WLG 42 (Cooper, 1979b, pp. 23,59).

Bryozoal limestones with Lepidocyclina, no doubt representing the same depositional episode, were penetrated also in the upper part (107-128 m) of the mid-Tertiary sequence in the S.A. Black Coal Syndicate bore, Myponga Basin (Plan 2; Glaessner, 1953a, p. 144; Glaessner in Campana et al., 1955, p. 3; Wade, 1958; Glaessner and Wade, 1958, p. 121; Stuart, 1969, p. 211). Praeorbulina glomerosa has been found in the upper part of the Lepidocyclina range-zone in this bore (Wade in Stuart, 1969,

p. 211), confirming that at least the upper part of the interval is lower Balcombian by planktonic correlation besides being also presumably Batesfordian.

Thus the correlations made by the writer (in Lindsay and Giles, 1973) for the Lepidocyclina howchini range-zone in the western Murray Basin, are applicable also to the range-zone in the St Vincent Basin. The episode corresponds to the first-order Globigerinoides glomerosus Datum level 85 of Hornibrook and Edwards (1971), and is within the upper part of Zone N.8 (Blow, 1969, 1979). In general, this and other closely-spaced biostratigraphic datum levels which mark the rapid development of the Orbulina bioseries, provide one of the most useful intervals for worldwide homotaxial/chronostratigraphic correlation in the entire Tertiary.

The principal of temporary extra-tropical immigration of Lepidocyclina to southern Australia during a brief interval of warm-water influence has long been recognised (Glaessner, 1959, p. 63). Authors generally, including Carter (1964) and Abele et al. (1976) in Victoria, have regarded this as one episode, the 'Batesfordian'. However McGowran (1978d, 1979b) has recently depicted three distinct episodes with Lepidocyclina in the Gippsland Basin, and possibly two in the Port Phillip Basin, the uppermost episode being correlated with the Flosculinella warm-water event of the St Vincent and Eucla Basins (cf. Plan 35). In South Australia, only the one, 'Batesfordian', extra-tropical excursion of Lepidocyclina has been known, and Lepidocyclina had never been found with Flosculinella (McGowran, 1979b, p. 254). However the writer

has now found the two together, closely associated in the same boulder of Melton Limestone (sample F58/74), 4 km north of the Melton sinkhole, and less than one kilometre southeast of Correll's sand pit on northernmost Yorke Peninsula (Plan 1). The rock, of uppermost Melton Limestone facies (Lindsay, 1970c), is a cream, fine-grained fossiliferous limestone, hard and recrystallised, algal, and with scattered quartz sand grains. One good natural section of Flosculinella is associated with several of Lepidocyclina. From these initial results, it is not certain whether these are Lepidocyclina associated with the upper, Flosculinella event; whether the Flosculinella is associated with the lower, 'Batesfordian' Lepidocyclina event; or whether the two episodes converge in this marginal situation.

The local Batesfordian - lower Balcombian unit with Lepidocyclina correlates with the rising global sea-level of Cycle TM2.1 (Vail et al., 1977; Vail and Mitchum, 1978); with part of upper Sequence 3 of McGowran (1978d, 1979b); and with the latest part of sedimentation Cycle 3B of Quilty (1977) below the mid-Miocene regression/hiatus, as discussed by McGowran (1979b, p. 242).

The Batesfordian-lower Balcombian warm peak is shown clearly in O-isotope palaeotemperature curves (Plan 35; Gill, 1968; McGowran, 1979b, fig. 6).

Chaproniere (1975) discussed the depositional environment of Lepidocyclina and associated foraminifera. The Lepidocyclina howchini benthonic assemblage of the eastern St Vincent Basin is considered to have lived in warm, shallow waters (possibly less than 12 m deep) with oceanic salinity, and on a variety of substrates (hard bottom, or sea-grasses).

The Munno Para Clay Member

This unit of Port Willunga Formation does not occur in the Adelaide City area on the Para Block, nor apparently on the Mile End or Thebarton Blocks. It was penetrated in the Croydon-2 bore (Plans 16, 29); and probably occurs on the Croydon Block west of the West Para Fault (Plan 5), although none of the available bores (Ref. bores 58,68,69,106) were deep enough to intersect the unit.

Little need be added to previous descriptions of the Munno Para Clay by Lindsay and Shepherd (1966), and Lindsay (1969), except in connection with its age, depositional environment and regional significance. Recent wide-ranging syntheses by McGowran (1978d, 1979b) argue persuasively that the unit, rather than representing a transgressive event as suggested previously by the writer, is a local expression of a widespread, regressive, cooler episode between two warm climatic peaks (the Batesfordian/lower Balcombian Lepidocyclina interval, mostly below, and the upper Balcombian Flosculinella interval, mostly above). The planktonic species Cassigerinella chipolensis, typically abundant in the Munno Para Clay, is seen now as an opportunistic coloniser in a restricted but still marine environment, rather than as evidence for improved marine access. The dark grey, carbonaceous, and sometimes finely pyritic lithology, indicates reducing bottom conditions; but the variety of well-preserved (and often pyrite-lined) benthonic foraminifera suggest that this environment was by no means uninhabitable. The two or three limestone bands often encountered within the Munno Para Clay testify to a fluctuating regime. The planktonic microfauna of the Clay (Lindsay, 1969,

fig. 6) particularly of the upper part, is for the eastern St Vincent Basin, fairly diverse; although admittedly specimens are recovered more readily than from limestones. Several species of Globigerinoides, and the three morphotypes of Praeorbulina glomerosa, are represented; but, apart from Cassigerinella chipolensis, abundances are low. The Basin had marine access, but perhaps only across a silled rim.

From all available evidence, McGowran (1978d, 1979b) has dated the regional event which is correlated with the Munno Para Clay, as about Early/Middle Miocene boundary (Zone N.8/ Zone N.9 boundary; Blow, 1969, 1979). Orbulina suturalis, whose initial appearance marks base Zone N.9, has been found in Port Willunga Formation above the Clay, but not yet in the Clay: however it is excessively rare in the eastern St Vincent Basin anyway (Lindsay, 1969, p. 21). The Flosculinella extra-tropical excursion, dated Zone N.9 (and possibly higher) by Chaproniere (1975) at North West Cape, is represented by a range-zone which is above the Munno Para Clay in all but one of 8 bores in the Adelaide Plains Sub-Basin. The exception is SADME Obs. bore MPA 63, 4½ km east of Virginia (Plan 2). In this bore, Flosculinella was found only in the upper part of the Munno Para Clay. Thus the local evidence appears to be not inconsistent with the regional age assigned by McGowran.

As noted earlier, the depositional hiatus between Cycles 3A and 3B of Quilty (1977), shown by him as centred on Zone N.6, is instead correlated by McGowran (1979b) with the Zone N.8/ Zone N.9 event. The event fits high in McGowran's Sequence 3, but surprisingly, is not apparent in the global sea-level curves of Vail et al. (1977) and Vail and Mitchum (1978).

Correlatives of Upper Balcombian and Bairnsdalian Stages

As discussed previously by Lindsay (1969, p. 38), this unit comprises that topmost part of the Port Willunga Formation which overlies the Munno Para Clay Member. The unit is not known to occur east of the West Para Fault (Plan 5). It was intersected at the top of the mid-Tertiary succession in Ref. bores 68, 69 and 106; and in the Croydon-2 bore (Plans 16,29).

The Flosculinella bontangensis range-zone discussed in the previous section, is an important feature of the unit. Three specimens of Flosculinella recovered recently from sediment pumped out of the Coca Cola/Diverse Products No. 2 water bore (Ref. bore 68) are evidently from the unit, in which the bore bottomed.

The old Nathan Brewery (now Southwark Brewery) water bore (Ref. bore 69) also bottomed in the unit, as shown in Plan 16. A sludge sample of white/cream, hard/soft, calcarenitic sandy limestone, from near the bottom of the bore, yielded a moderately well-preserved and fairly diverse (but almost entirely benthonic) microfauna including:

Praeorbulina glomerosa circularis (Pl. 32, Figs 4-8,10)

Crespinella umbonifera (Pl. 38, Figs 3-10; Pl. 39, Figs 1,2)

Discorbis cycloclypeus (Pl. 40, Figs 2,3)

Elphidium adelaidense (Pl. 41, Figs 1,4)

Epistomaroides polystomelloides (Pl. 42, Figs 5-12)

Gypsina howchini (Pl. 44, Figs 8-10)

Marginopora vertebralis

Operculina victoriensis (Pl. 52, Figs 7-11)

Pavonina triformis (Pl. 54, Figs 1-7)

Sigmomorphina subregularis

Sphaerogypsina globula (Pl. 59, Figs 6-9).

Only the one illustrated specimen from the Orbulina bioseries was recovered. Epistomaroides polystomelloides is only known from above the Munno Para Clay (Lindsay, 1969, fig. 6; Plan 37). Other ranges are shown in Plan 37.

A natural section of Austrotrillina howchini in limestone from the same unit (Ref. bore 68, 144.8-146.3 m) is illustrated (Pl. 36, Fig. 7).

Chaproniere (1975) considered that the Flosculinella-Austrotrillina association (which in South Australia is found in Nullarbor Limestone, uppermost Melton Limestone, and uppermost Port Willunga Formation) indicates a warm-water environment of fairly high energy, metahaline salinity (somewhat higher than oceanic), and depth less than 30 m, perhaps much less since modern alveolids are most abundant at depths of less than 6 m. Marginopora, which is often present also, is likely to have been derived from adjacent sea-grass communities.

As shown in Plan 35, this last depositional episode of Port Willunga Formation corresponds to an O-isotope palaeotemperature peak of the same order as that preceding the Munno Para Clay.

Port Willunga Formation, at its youngest, is early Middle Miocene, Zone N.9. The uppermost unit, with Flosculinella and Austrotrillina, is no younger than that. Adams (in McGowran, 1979b, p. 242) 'knows of no evidence that Flosculinella and Austrotrillina occur in beds above Zone N.9'. On the other hand, even the solitary specimen of Orbulina suturalis obtained from core in the uppermost unit (Lindsay, 1969, p. 21) is sufficient to prove that some if not all of the unit is above the Orbulina FAD, and is thus at least Zone N.9. As Lindsay

(1969, p. 38) reported, 'this is supported by the finding of single specimens of Heterolepa victoriensis (Chapman, Parr and Collins) in the upper part of the unit in bores 64 and 83. This benthonic species was not found below the Bairnsdalian Orbulina universa Zone by Ludbrook (1961), Carter (1964), or Reed (1965)'.

Mid-Tertiary carbonate sedimentation similarly ceased in Zone N.9 in the Murray Basin (Pata Limestone; Ludbrook, 1961; Austrotrillina and Orbulina, but not Flosculinella), and probably also in the Eucla Basin (upper Nullarbor Limestone; Crespin, 1956; Ludbrook, 1958; Flosculinella and Austrotrillina, but few planktonics and no Orbulina). McGowran (1978d, 1979b) traces this 'intra-Miocene unconformity' westwards into the Perth and Carnarvon Basins (for the latter, see Chaproniere, 1975), and links it chronologically with various circum-Australian tectonic events. These include, along the northern active margin of the Indian-Australian Plate: Himalayan collision, and at least part of the orogenic and thermal events involving the New Guinea Mobile Belt. On the southern, passive margin of the Plate, an episode of canyon-cutting in the Gippsland Basin is also correlated with the Zone N.9 unconformity; and widespread uplift of the southern continental margin at this time has long been recognised.

Thus the tectonic component of the 'intra-Miocene unconformity' appears to be well established. However it is difficult to correlate a eustatic component. No eustatic drop of sea-level is depicted in the 'Vail Cycles' at a time corresponding to Zone N.9. The Vail curves show a two-stage

eustatic drop from the Middle Miocene high sea-level, the first in the late Middle Miocene (Zone N.13), and the second at the beginning of the Late Miocene (top Zone N.15). As shown in Plan 35 (after Shackleton and Kennett, 1975), both surface and bottom sub-antarctic oceanic temperatures began to drop immediately after the early Middle Miocene peak. There followed a rapid build-up of the Antarctic ice-cap during the Middle Miocene (see Frakes, 1979, for a recent summary). The resulting eustatic drop in global sea-level was seen previously by the writer as a contributing cause of the Middle Miocene cessation of marine sedimentation in South Australian coastal Tertiary basins (Lindsay in Daily et al., 1976, p. 30), but at present the connection cannot be maintained in detail if the Vail curves are correctly correlated.

The Eocene to early Middle Miocene sequence of the eastern St Vincent Basin was gently folded, tilted, and eroded, prior to the deposition of Pliocene units, resulting in a low-angle unconformity which can be seen in coastal exposures (e.g. Figs 11,12), and is evident in cross-sections (Plans 6-8, 12,14,16). Minor faulting of the mid-Tertiary sequence can also be seen in coastal outcrops. Some faults affect only the mid-Tertiary succession, while others displace Pliocene and Pleistocene units also (e.g. Fig. 76).

PLIOCENE UNITS

KOOYONGA FORMATION

This is a new stratigraphic name which has been reserved with the Central Registry of Stratigraphic Names, Canberra, and will be formally validated in a forthcoming Quarterly Note of the Geological Survey of South Australia. The name is given to the unit known previously as 'Croydon Silts' (Rao, 1955), 'Pliocene silts' (Steel, 1962b), 'silts, Croydon' (Ludbrook, 1963a; Lindsay, 1968a), and 'Croydon facies' (Lindsay, 1969), comprising approximately the lowest 30 m of the Pliocene succession in the Croydon-2 bore (Plans 16, 29). Steel (1962b) also recognised the unit in Kooyonga Golf Club bore 6, 4½ km to the south-southwest (Plan 4). Rao's earlier usage was never published and validated. Since the geographic name 'Croydon' is preoccupied for stratigraphic purposes, the name 'Kooyonga' (Kooyonga Golf Links, Lockleys) has been selected, as the other locality designated and published by Steel. In the vicinity of the City of Adelaide, the Kooyonga Formation is not known east of the West Para Fault (Plan 5), but it does occur immediately west of this fault, e.g. in Ref. bore 58 (see below).

The type section of the Kooyonga Formation is as penetrated in the Croydon-2 bore, lithologies and depths being shown in Plan 29. The top appears to intergrade or intertongue with Dry Creek Sand, and Stuart (1969) considered the unit as merely part of that formation, but further study may result in a firmer upper boundary. The nearby SADME Allenby Gardens-1 bore (Plan 5), when examined, will provide a valuable reference section for the unit, and a check on the

old Croydon-2 bore samples. Kooyonga Golf Club bore 6 (Lindsay, 1969, p. 40, bore 78) is also nominated as a reference bore, as is Coca Cola/Diverse Products bore 1, Thebarton (Ref. bore 58, Plan 5; see below). Seven other borehole sections through the unit in the Adelaide Plains Sub-Basin, were recorded by the writer previously (loc. cit.).

In addition to grey silt ('a very fine grey silt with a poor fauna'; Steel, 1962b) and muddy, very fine-grained quartz sand, a characteristic lithology is a soft to moderately hard calcareous quartz sandstone or siltstone to sandy and silty limestone, which is brownish-grey, saccharoidal, calcarenitic, and muddy (silty, clayey). All phases contain some proportion of mollusc fragments or shells, but are generally less shelly than the typical shell beds of the Dry Creek Sand. Unlike the latter, the Kooyonga Formation is appreciably, often abundantly bryozoal (recognised as 'coral' by drillers); and it is noticeably glauconitic. Many of the brown, ferruginous grains and pellets which are present, also probably represent oxidised glauconite. Parts of the unit are sparsely and finely pyritic. Mollusc fragments, foraminifera (all benthonic), and bryozoans are major faunal constituents; also present in varying but lesser abundance are echinoid fragments, ostracode valves, Ditrupa tubes, fish remains, brachiopod fragments, and elongate algal oncolites.

The known distribution of Kooyonga Formation remains essentially as described previously by the writer, that is, only subsurface in the Adelaide Plains Sub-Basin, 'within about 4 miles (6½ km) of the present coast, and from Glenelg to Port Gawler' (Lindsay, 1969, p. 40). Within this area

Kooyonga Formation is the basal unit of the Pliocene succession, resting unconformably on early Middle Miocene Port Willunga Formation (Plans 3, 16, 29).

The nearest clear-cut section of Kooyonga Formation to the City of Adelaide is that intersected in Ref. bore 58, Thebarton. As indicated in Plan 11, the unit was encountered in this bore in the lower part of the Pliocene succession, from 124.1 m to total depth of 137.8 m, a thickness of 13.7 m. Here, the unit comprises grey, calcarenitic, silty and clayey, mostly fine-grained quartz sand, with variable cementation to muddy, calcareous fine-grained sandstone/sandy limestone. Molluscan fragments (including Ostrea, Chlamys, Spondylus), foraminifera, and bryozoans, are prominent. Green glauconite is scarce, but brownish ferruginous grains and pellets are common; many probably represent oxidised glauconite; they are not phosphatic. Fine-grained pyrite occurs sparsely.

Benthonic foraminifera include well-developed and typical Elphidium adelaidense (Pl. 40, Figs 10-12), together with Ammonia beccarii, Epistomaroides polystomelloides, Notorotalia clathrata, Elphidium crassatum (Pl. 41, Fig. 6), and Discorbis cycloclypeus (Pl. 40, Figs 6,7). However as shown in Plan 37 these all range up from Port Willunga Formation at least to the Dry Creek Sand.

More significantly, it is now clear that Crespinella umbonifera ranges up into the Kooyonga Formation (Plan 37). In the Kooyonga Golf Club bore 6, small specimens occur frequently up to a range-top at 178 m, that is through the basal 7 m of the unit. They do not appear to be reworked, and are

noticeably smaller than specimens in the Middle Miocene Port Willunga Formation, below the unconformity. In the SADME Port Gawler bore (Plan 2) a specimen of Crespinella umbonifera was found at the top of Kooyonga Formation, at a depth of 86 m. In the Murray Basin this species is not known to occur above the Lower Pliocene Loxton Sand (Ludbrook, 1961, p. 87). The writer (in Cook et al., 1977, pp. 83, 85) recorded C. umbonifera in subsurface Loxton Sand time/rock correlatives west of Naracoorte in association with the Kalimnan benthonic Fabularia howchini (Schlumberger); and with rare examples of the planktonics Globorotalia (Truncorotalia) puncticulata (Deshayes) and 'Globigerina' foliata (Bolli), which together would suggest an Early Pliocene age (Zone N.18-Zone N.19) according to ranges given by Blow (1969). Hence the last appearance of C. umbonifera in the Kooyonga Formation is considered to support the Early Pliocene age for this unit which was suggested by both Rao (1955) and Ludbrook (1963a). However the evidence does not exclude a latest Miocene age.

Sigmomorphina subregularis Howchin and Parr does not range above Kooyonga Formation in Coca Cola/Diverse Products bore 1 (Ref. bore 58; range-top at 128 m), in the Croydon-2 bore (Plan 29), or in Kooyonga Golf Club bore 6 (range-top at 160 m).

A small specimen of Operculina victoriensis was recovered from Kooyonga Formation in the Kooyonga Golf Club bore 6 at 160-163 m. The specimen may be reworked, but shows no obvious evidence of such. Larger O. victoriensis range to the top of Middle Miocene Port Willunga Formation below the unconformity.

The Kooyonga Formation appears to record, in the eastern St Vincent Basin, the Early Pliocene global rise of sea-level shown by Vail et al. (1977), and Vail and Mitchum (1978). In this, the unit is the western analogue of the Loxton Sand (and possibly Bookpurnong Beds) of the Murray Basin. The quartzose, shallow-neritic, marginal-marine Kooyonga Formation did not transgress as extensively into the St Vincent Basin as the Early Pliocene units did into the Murray Basin. This transgression, (episode 8 of Lindsay, 1976), correlates with early parts of Cycle 4 of Quilty (1977) and Sequence 4 of McGowran (1978d, 1979b). The presence of Marginopora throughout the Kooyonga Formation (Plan 29) implies at least a moderately warm-water environment.

DRY CREEK SAND

Shelly sands intersected between 320 and 410 feet (97.5-125.0 m) in the Australian Smelting Company's bore at Dry Creek, 1889, were recognised as of Pliocene age by Tate (1890b), and were named the Dry Creek Sands by Glaessner (1951).

The writer outlined previously the relationship of Dry Creek Sand to the other Pliocene units of the Adelaide Plains Sub-Basin (Lindsay, 1969, p. 39), noting that in some localities at least, Dry Creek Sand intertongues with or is gradational to the generally underlying Kooyonga Formation (= 'Croydon facies') and the generally overlying Hallett Cove Sandstone. As indicated in Plan 29, Dry Creek Sand in the Croydon-2 bore has a gradational contact with Kooyonga Formation; but Hallett Cove Sandstone is not present. The interval between 106.7 and 120.4 m is not the typical shelly sand facies of Dry Creek

Sand, but is included tentatively at the top of that formation. With its intercalation of mottled clay at 116.4-120.4 m, the interval is lithologically transitional to the overlying Hindmarsh Clay. It might also be considered transitional to Carisbrooke Sand, but unlike the typical and usual development of that formation, is fossiliferous, with a modest foraminiferal microfauna as indicated. Six kilometres north, SADME Obs. bore PTA-65, drilled recently adjacent to the Wingfield Railway Station (Plan 4), entered shelly sands (Dry Creek Sand) at 92 m. Above this, a 6 m-thick interval of unfossiliferous, poorly-sorted sand with water-polished quartz grains, is identified as Carisbrooke Sand, and is overlain by Hindmarsh Clay. The subsurface type section of Dry Creek Sand, only 3 km due east of the Wingfield bore, is thought to bear a similar relationship to Carisbrooke Sand (Lindsay, 1969, p. 39).

In Ref. bore 58, Thebarton (Plan 11), Dry Creek Sand, comprising abundantly shelly sand between 118 and 124 m, is clearly intercalated between Hallett Cove Sandstone and Kooyonga Formation. However in Kooyonga Golf Club bore 6, as indicated previously (Lindsay, 1969, p. 40, bore 78), the main development of Kooyonga Formation at the base of the Pliocene sequence (156-?184 m) is overlain by a 15 m-thick tongue of shelly Dry Creek Sand, and this again by a further 8 m of Kooyonga facies (133-141 m); Dry Creek Sand and Hallett Cove Sandstone then extend to the top of the Pliocene succession at 113 m.

Beneath the City of Adelaide, 'a brown shelly sand of Dry Creek Sands facies typically occurs at the base' of the Hallett Cove Sandstone (Lindsay, 1969, p. 39). For example, a tube-core from the base of the Pliocene unit in Victoria

Square (Ref. bore 14; 24.1-24.4 m), comprised 'brown, mottled darker brown, clayey, shelly, calcareous sand and sandstone, mostly fine-grained. Foraminifera are common, dominated by frequent large Elphidium adelaidense and Ammonia beccarii. Mollusc fragments are frequent, a few large' (Lindsay, 1964a, p. 16). This basal shelly sand constitutes 'Zone D' in the engineering subdivision of Hallett Cove Sandstone/Burnham Limestone in the Adelaide City area (Selby in Selby and Lindsay, in press). In recent foundation-test drilling along King William Road/Street for a proposed Adelaide Subway, Conor and Armstrong (1980) found Zone D to be 0-1.5 m thick, comprising brown to orange shelly sand, sometimes with weak to strong cementation to calcareous sandstone. The calcarenitic quartz sands are generally fine-grained; large oyster shells are common, gastropod and scallop shells less common.

The writer also noted 'interbedding with loose sands' within the Hallett Cove Sandstone of the Adelaide City area (Lindsay, 1969, p. 39). Above the basal shelly sand/sandstone, and at times difficult to separate from it, Selby (in Selby and Lindsay, in press) recognises 'Zone C', comprising more finely fossiliferous brown/orange quartz sands with cementation to calcareous sandstone in bands and rubbly patches. This zone was found to be 0.5-2.5 m thick by Conor and Armstrong (1980).

Hence, although for convenience the Pliocene unit beneath the City of Adelaide is identified as Hallett Cove Sandstone, it is apparent that some, especially in the lower few metres, could be regarded as of Dry Creek Sand facies. On the other hand, typical Dry Creek Sand of the Adelaide Plains Sub-Basin

contains cemented bands and patches of fossiliferous calcareous sandstone; so there is lithological overlap between the two facies.

The Pliocene sequence exposed in coastal outcrops near Port Willunga is similar in lithology and thickness to that developed beneath the City of Adelaide. Reynolds (1953, p. 132) noted the 'basal beds of highly fossiliferous yellow sands'. These, reminiscent of Dry Creek Sand, contain a variety of mollusc shells, particularly oysters and scallops. At Blanche Point, this basal shelly sand is 0.7 m thick. Interbedded sands and flaggy calcareous sandstones (Hallett Cove Sandstone) more or less fossiliferous, comprise the remainder of the unit, the whole totalling 4 to 5 m in thickness.

The relationship of 'sands at Lockleys' (Ludbrook, 1963a; Calabrian Stage, Lower Pleistocene) to the Dry Creek Sand (Upper Pliocene; Ludbrook, 1963a) is still unclear. The writer did not encounter the younger unit in Adelaide Plains bores examined subsequently (Lindsay, 1969, p. 41), and it has not been recorded or described since (e.g. Ludbrook, 1973). In describing the Roe Calcarenite, and noting correlative Lower Pleistocene units in South Australia, Ludbrook (1978) omitted reference to 'sands at Lockleys' (which might have been considered a prime correlative), implicitly included the unit in Dry Creek Sand, and extended the latter up into the basal Pleistocene. However more recently, Ludbrook (1980, pp. 46, 86) has again regarded the Dry Creek Sand as of Late Pliocene age. Singleton et al. (1976) have used biostratigraphic (planktonic foraminiferal) data and radiometric dating of associated basalts, to show that the Werrikoo Limestone of westernmost

Victoria straddles the Pliocene-Pleistocene boundary. Further stratigraphic and palaeontological study of possible correlatives may elucidate the position of the boundary in South Australia.

Discorbis cycloclypeus (Pl. 40, Figs 4, 5), Elphidium rotatum (Pl. 42, Figs 2-4), and Peneroplis pertusus (Pl. 54, Figs 8,9), are illustrated from the Dry Creek Sand in Ref. bore 58, Thebarton. The foraminifera recorded from the Dry Creek Sand in Croydon-2 bore (Plan 29) indicate the nature of the benthonic assemblages found in the formation. The lack of restricted Kalimnan (Lower Pliocene) species, and of Crespinella umbonifera, is negative evidence for a post-Early Pliocene age; but the Late Pliocene dating is based mainly on the Yatalan fauna of molluscs (Ludbrook, 1963a, 1973). This fauna 'is characterised by a considerable warm water element' (Ludbrook, 1941, 1954, 1963a, 1973); and warm conditions are also suggested by the presence of Marginopora.

The Dry Creek Sand was deposited in relatively sheltered, shallow neritic to littoral, sandy marine bays (Ludbrook, 1954). The absence of planktonic foraminifera also indicates a shallow environment with very restricted marine access. The unit extends subsurface through the Adelaide Plains Sub-Basin as far north as the River Light, but excluding a north-eastern sector north of Virginia, Angle Vale, and Gawler (Shepherd, 1968; cf. Plan 2). The Sand is thus more widespread than the Kooyonga Formation, but did not transgress as far as Hallett Cove Sandstone (see below). It did not extend across the Para Fault Zone into the Adelaide City area except as a thin basal facies of the Sandstone.

The Dry Creek Sand represents a phase of warm transgressive Episode 9 of Lindsay (1976), part of Cycle 4 of Quilty (1977), and part of Sequence 4 of McGowran (1978d, 1979b; cf. Plan 35). However this is apparently at variance with the proposed Vail global cycles of sea level (Vail et al., 1977; Vail and Mitchum, 1978), according to which the Early and Middle Pliocene were times of sea level highstand, but the Late Pliocene was one of lowstand. This is probably an oversimplification, in view of the mounting evidence for several major climatic oscillations of 'Pleistocene' type (glacial/interglacial) at least as far back as the Late Pliocene (e.g. Kennett et al., 1971; Shackleton and Opdyke, 1977; Berggren, 1978). From their O-isotope studies, Shackleton and Opdyke suggested that after 3Ma 'marine highstands in the remaining Pliocene, like those of the Pleistocene, were probably brief'. The detailed relationship between the several such Late Pliocene-earliest Pleistocene global eustatic highstands and the local sequence of Dry Creek Sand - Hallett Cove Sandstone - Burnham Limestone, has yet to be worked out.

HALLETT COVE SANDSTONE (and BURNHAM LIMESTONE)

Introduction

These two units are treated together, because for various reasons they are difficult to separate accurately in the Adelaide City area; and are therefore combined in cross-sections, isopachs (Plan 24), and stratigraphic tables (Appendix B).

Nomenclature and Type Sections

The thin hard band of fossiliferous calcareous gravelly sandstone long known in the vicinity of Hallett Cove, considered at first Miocene (e.g. Tate et al., 1896) and then Pliocene (e.g. Howchin, 1923, 1924; Sprigg, 1942), was eventually named the Hallett Cove Sandstone by Crespin (1954). The type section, about one metre thick, is now near the northwestern corner of the Sandison Reserve, in the Hallett Cove Conservation Park (Plan 2). From this point, the subhorizontal formation crops out intermittently southwards through the Conservation Park, at an elevation of about 30 m above sea level (Sprigg, 1942). The rock is pale grey/pale brown, coarsely quartzose, and richly fossiliferous, with moulds of bivalve and gastropod molluscs together with scattered corals, echinoids, algal nodules, and large Marginopora (up to 25 mm diameter). The unit contains pebble to occasionally boulder-sized lithic clasts, and Sprigg noted that reworked glacial erratics are, in places, concentrated at the base. Hallett Cove Sandstone, at its type locality, is evidently a near-shore, warm-water, marine deposit. It is underlain unconformably by the Permo-Carboniferous glacigenes, and overlain disconformably by Pleistocene mottled clays (Crespin, 1954).

Three kilometres to the north-northeast, and 350 m west of the Marino railway station (Plan 2), is the type section of the reputedly basal Pleistocene Burnham Limestone (Firman, 1976). This is part of a small exposure, noted by Howchin (1923) and Sprigg (1942) as forming the lip of a minor waterfall 10 m above sea level. However neither of these earlier authors distinguished the Pliocene unit here from the younger unit now

named Burnham Limestone. At this locality the Hallett Cove Sandstone is only about 0.5 m thick, comprising orange-brown sparsely fossiliferous calcareous quartz sandstone, bearing pebbly clasts of the underlying steeply-dipping Adelaidean rocks. The Burnham Limestone, which overlies and penetrates the Hallett Cove Sandstone, contains clasts of the latter, and consists of about 0.5 m of pale grey, apparently unfossiliferous micritic limestone. This occurrence was chosen by Firman as representative of Burnham Limestone on the Eden Block.

A supplementary section of Burnham Limestone, to represent a basinal development, was nominated by Firman (1976) in the cutting immediately south of the Port Willunga kiosk, behind the remains of the old Port Willunga jetty (Figs 11,12). Hereabouts, Firman recognised approximately one metre of off-white micritic limestone (Burnham Limestone) overlying 4 m of Hallett Cove Sandstone and underlying 8 m of Pleistocene olive/pale brown clay (cf. Figs 76, 78). The Burnham Limestone comprises 'irregular and platy nodular masses set in a sparse sandy clay matrix', and exhibits a more or less irregular, disconformable lower contact with Hallett Cove Sandstone, infilling solution-holes up to 2 m across, and containing reworked masses of Hallett Cove Sandstone. Crespin (1954, p. 14) had referred to this section when she noted that 'in the road cutting leading down to the Port Willunga Jetty, the Hallett Cove Sandstone is approximately 20 feet thick' (i.e. about 6 m of now-differentiated Hallett Cove Sandstone and Burnham Limestone). Howchin (1923, pp. 305, 306) had long previously described the same section in some detail, dis-

tinguishing the upper 'white marly limestone' as a possibly travertinous deposit formed on the lower fossiliferous sands and sandstone. Reynolds (1953, p. 132) described and measured the section, recording (measurements converted to metric): 1.52 m of 'white fossiliferous arenaceous limestone' (i.e. Burnham Limestone), over a total of 3.95 m of fossiliferous beds comprising sands interbedded with six hard bands of calcareous sandstone or sandy limestone (i.e. Hallett Cove Sandstone).

High on the north side of Blanche Point, 150 m east of Gull Rock, a similar succession which was examined by the writer is capped by about 2½ m of Burnham Limestone, comprising white, rubbly, clayey and earthy (marly) limestone with a soft base and harder top, the latter forming a broad flat platform beneath the Pleistocene clays. Burnham Limestone is underlain by about 4½ m of banded, off-white/pale brown Hallett Cove Sandstone. Because of the low-angle unconformity which separates the mid-Tertiary succession from Hallett Cove Sandstone, the latter rests on upper Blanche Point Formation at Blanche Point, but on the Ruwarung Member of Port Willunga Formation at the old Port Willunga jetty.

Firman (1976, p. 4) distinguished the Burnham Limestone from the Seaford Formation of Ward (1965, 1966).

Lithology

Authors have for many years recognised that the 'Pliocene' strata beneath the City of Adelaide are lithologically and stratigraphically similar to those exposed in the coastal sections. For instance Howchin (1923, p. 283) noted that 'the fossiliferous Lower Pliocene beds ..... that occupied the area of the present Gulf and its margins ..... are now found only in isolated patches; one of the largest of these comprises

the flat knoll on which Adelaide is built. Formerly, they were exposed on the banks of the Torrens ..... and also in quarries that were worked behind Government House'. The quarries north of Government House, and at the site of the Torrens Parade Ground, have long since been covered and landscaped (Fig. 79), but a sample of shelly Hallett Cove Sandstone from one of the quarries is illustrated (Fig. 80).

In particular, the City 'Pliocene' compares with the exposures at Port Willunga, discussed above; but the lithology and stratigraphy beneath Adelaide are complicated by the superimposed effects of karst weathering (Allchurch, 1967b) which has affected both Hallett Cove Sandstone and Burnham Limestone, masking the distinction between them (Fig. 81). Exposures of the sequence in the City are now rare and ephemeral. Even in exposed faces, such as near Parliament House (Figs 81-84) it is sometimes difficult to determine whether we are looking at highly weathered Hallett Cove Sandstone, or at Burnham Limestone; the problem is compounded when only borehole samples are available. In practice, foundation-test drilling in the City area has shown a downhole transition from mottled clay with limy patches and nodules (basal Hindmarsh Clay), through rubbly earthy and sandy limestone, clay, silt, and sand (probably part Burnham Limestone, and part weathered Hallett Cove Sandstone), to banded calcareous quartz sandstone/sandy limestone and sand (Hallett Cove Sandstone). The irregular rubbly zone which may be several metres thick, sometimes contains harder karst pinnacles, and solution pipes, sinkholes or cavities, filled with clay silt or sand. It has been termed the 'transitional unit' (e.g. Selby and Lindsay, 1973, fig. 1) or 'Zone A' of



Figure 79. City of Adelaide, Jan. 1980, view from immediately east of King William Rd, looking south towards the now landscaped site of the old quarries in Hallett Cove Sandstone. Government House is hidden behind trees in the middle distance. Hallett Cove Sandstone is present just below the footpath on right (cf. Fig. 7). Torrens Parade Ground is immediately east (cf. Fig. 6).



Figure 80. Hallett Cove Sandstone, Upper Pliocene, Adelaide City area; Uni. of Adelaide sample 7032, from old quarry north of Government House. Yellow-brown shelly calcareous sandstone, with mostly fine-grained quartz. Oyster shells prominent; scallop shell on right.



Figure 81. Clay-filled solution pipe in karst-weathered Hallett Cove Sandstone, Adelaide City area; exposed face (July, 1979) in excavation immediately west of the rear of Parliament House, adjoining Adelaide Railway Station and southern end of Festival Theatre Plaza (cf. Fig. 82). Note iron-stained vertical jointing and alteration to 'Burnham Limestone facies' in the vicinity of the solution pipe, transverse to the rough rubbly bedding of less altered Hallett Cove Sandstone at extreme left. The measuring tape is extended one metre.



Figure 82. Hallett Cove Sandstone (?and Burnham Limestone), exposed face just west of northern end of Parliament House, City of Adelaide; view looking east, July 1979; jackhammer at foot of excavation is about one metre high. At the base of the section, one metre of Hallett Cove Sandstone is hard, dense, and recrystallised, massive to flaggy, medium grey/brown. Above this are about 3 m of weathered Hallett Cove Sandstone and possibly Burnham Limestone, which are rubbly, platy, roughly bedded, earthy, white, pale greenish-grey, pale pink-brown. Figure 81 was taken at the extreme right, Figure 82 right of centre, and Figure 83 at left, by the jackhammer. Ref. bore 94 was drilled from the top level to the right of the area shown, in the car park behind the Constitutional Museum of S.A.



Figure 83. Old exposure of weathered roughly-banded Hallett Cove Sandstone/?Burnham Limestone, just west of northern end of Parliament House, City of Adelaide; view looking south (cf. Fig. 82); measuring tape is extended one metre.



Figure 84. Fresh excavation in Hallett Cove Sandstone, near Parliament House, City of Adelaide (cf. Fig. 82). The measuring tape is extended almost one metre; the rock is hard, blocky, massive to roughly banded.



Figure 85. Hallett Cove Sandstone, City of Adelaide, A.N.A. building site (Crawford, 1956b), cnr North Tce/Bank St; diamond-drill core, DDH-4, 12.0-12.7 m; see petrographic description (sample P741/78, Appendix C); tan, shelly, calcarenitic, dolomitic quartz sandstone.



Figure 86. Hallett Cove Sandstone, locality as above, but DDH-3, 12.1-13.3 m; see petrographic description (sample P740/78, Appendix C); pale buff, fossiliferous, quartzose, calcarenitic limestone; partially leached, showing mollusc moulds.



Figure 87. Hallett Cove Sandstone, City of Adelaide, from foundation trench one metre deep, north side of Horace Lamb Complex, University of Adelaide, Oct. 1974; hard, calcareous sandstone/sandy limestone, fine-grained quartzose, calcarenitic; white, pale grey, pale yellow-brown, speckled black with dendritic manganese mineral.

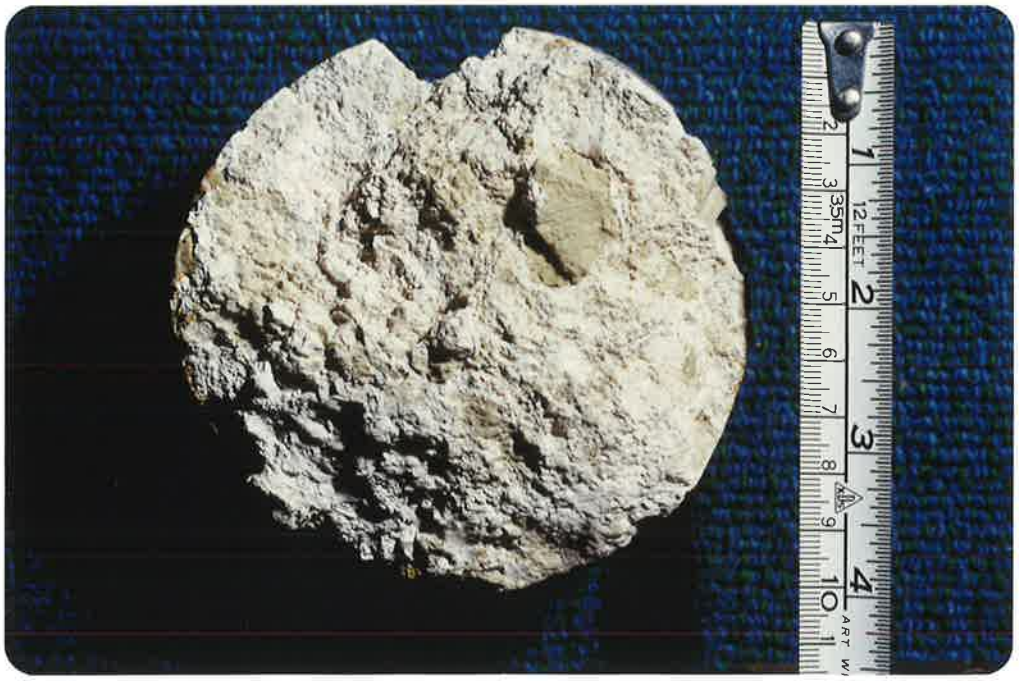


Figure 88. ?Burnham Limestone, City of Adelaide, Supreme Court Library building, Gouger St (Crawford, 1956a), foundation test bore PB-1 (Ref. bore 33), tube-core, 15.2-16.5 m; white, friable, very fine-grained micritic limestone, partly fragmental-textured, with minor quartz sand and patches of grey/green clay; sparsely fossiliferous (rare, small, recrystallised foraminifera).

engineering geology practice (Selby and Lindsay, in press). The zone may, in places, include Burnham Limestone, but is not synonymous with that formation. For these reasons it has been considered prudent, for the present, to group the two formations together in the City area, as Hallett Cove Sandstone/Burnham Limestone ('HCS/BL').

Four lithologies are illustrated in Figures 85-88. Three of these rocks are also described petrographically (Appendix C). The dolomitisation of the core illustrated in Figure 85 is noteworthy. However no dolomite is reported in the core illustrated in Figure 86, from a similar depth in a borehole on the same site, the two bores being only 20 m apart. This suggests that the dolomitisation is patchy or localised. The sample illustrated in Figure 88 is from only 0.6 m below the top of the 'transitional unit', and represents the lithology considered nearest to Burnham Limestone in the City area.

Plans 28 and 27 contain summary descriptions of the 'Pliocene' unit in the SADME West End Brewery bore and the SADME South Parklands bore respectively. The former penetrated only a thin erosional remnant of Hallett Cove Sandstone; the latter may have a capping of Burnham Limestone on Hallett Cove Sandstone, but the two are difficult to separate in the available sludge samples.

Distribution and Thickness

Plan 24 indicates the known distribution and thickness of 'HCS/BL' in the City area. Borehole intersections and thicknesses are tabulated in Appendix B. The maximum thickness of 12.2 m was penetrated in Ref. bore 91, off Sturt St, in the

southern part of the City. Erosion has removed the unit from much of North Adelaide and the Torrens Valley, and from around the elongate 'buried mesa' underlying the central and western City.

At various times the unit has been exposed by excavations on the scarp separating the upper and lower levels of the University of Adelaide; but landscaped gardens, retaining walls, buildings, etc. have almost entirely obscured these outcrops. If on some future occasion the unit is extensively uncovered by further excavations within the University grounds, it would be highly desirable to preserve a reference section as a geological monument.

At least one erosional remnant has been detected on the Mile End Block (Ref. bore 57; Plan 14); but the unit has been eroded from the section penetrated by Ref. bore 105, on the Thebarton Block (Plan 16).

The writer indicated previously that the name Hallett Cove Sandstone 'fits relatively thin developments of typically-hard fossiliferous sandstone-limestone facies either in high-level situations or in the upper part of the subsurface Pliocene of the Adelaide Plains' (Lindsay, 1969, p. 39). For example, the top 5 m of the Pliocene succession in the SADME Light-1 bore (Plan 2) are of this facies; in the SADME Pelican Point bore (Plan 4), the top 6 m; and in Beach Petroleum Grange-1 well, most of the top 12 m.

Despite coastal exposures of 'HCS/BL' up to 7 m thick in the Willunga Embayment, as discussed above, the unit was not intersected in any of the boreholes studied by Cooper (1979b). This suggests that the unit wedges out there within 2 km of the present coast.

Stratigraphic Relationships

Various cross-sections (Plans 6-8, 12-14, 16) illustrate the stratigraphic relationships of 'HCS/BL' to surrounding units in the City area. A low-angle unconformity separates the younger sequence from the mid-Tertiary succession (units of Blanche Point Formation, Chinaman Gully Formation, or Port Willunga Formation). The karstic, irregular upper contact with Hindmarsh Clay was mentioned earlier. 'HCS/BL' suffered erosion prior to the deposition of Carisbrooke Sand, and clasts of it were recycled into that unit. Carisbrooke Sand (here Lower Pleistocene; cf. Lindsay, 1969, pp. 40, 41) abuts and drapes the 'buried mesa' of 'HCS/BL' beneath the City Central Business District. Quaternary alluvium of the ancestral Torrens valley abuts 'HCS/BL' in places.

In the Adelaide Plains Sub-Basin, Hallett Cove Sandstone may intertongue and intergrade with Dry Creek Sand (Lindsay, 1969, p. 39).

Biostratigraphy and Age

Hallett Cove Sandstone contains sparse to abundant marine fossils, mostly molluscs and foraminifera. The latter increase in abundance and diversity downwards towards the iron-stained sandy and shelly basal bed. Foraminifera are shallow-marine benthonic forms, of generally late Cainozoic aspect, but not precisely diagnostic of age. The distributions of a number of species are plotted in Plans 27, 28 and 37. Several species are illustrated:

Cribrobulimina mixta (Pl. 40, Fig. 1)

Elphidium sp. (Pl. 41, Figs 2,3,5)

Elphidium crispum (Pl. 41, Figs 7-10)

Elphidium macellum (Pl. 42, Fig. 1)

Notorotalia clathrata (Pl. 52, Figs 3-6).

Ludbrook (1954, p. 49) reported that 'the sandy limestones underlying the City of Adelaide carry Dry Creek molluscs - mainly in the form of moulds ..... Where they are better preserved as in the unleached block removed in the excavations for the foundations of the Bank of New South Wales building the determinable fauna is similar to that of the calcareous sandstones exposed at Hallett Cove and Aldinga Bay'. The Yatalan fauna of Dry Creek Sand molluscs was dated Late Pliocene by Ludbrook (1963a, 1973). The Hallett Cove Sandstone, which is in places interbedded with the upper part of the Dry Creek Sand, is also regarded as Late Pliocene (Ludbrook, 1963a, 1969b, 1980).

The Early Pleistocene age of Burnham Limestone (Firman, 1976) hangs largely on a determination by Ludbrook (1966: unpublished SADM Palaeo. report, sample F103/66). This sample of mollusc-bearing sandy limestone was collected at Blanche Point, Maslin Bay, from what would be described later as Burnham Limestone. Of the four mollusc species identified, two appear to be of particular biostratigraphic significance. Placamen placidum (Philippi), and Diala (D.) lauta Adams, are now recorded elsewhere only from the Early Pleistocene (Roe Calcarenite of the Eucla Basin) to the present (Ludbrook, 1978), and not from the Yatalan Late Pliocene faunas. This strengthens the original Pleistocene dating of the fauna and of the Burnham Limestone. The associated benthonic foraminifera Ammonia beccarii and Epistomaroides polystomelloides, are longer-ranging (Plan 37).

Beneath the City of Adelaide, possible correlatives of Burnham Limestone such as the rock illustrated in Figure 88, contain rare, small, recrystallised, benthonic foraminifera, such as Elphidium spp., Nonion sp., Discorbis spp., Quinqueloculina sp., and Ammonia beccarii. A specimen of Discorbis dimidiatus is illustrated (Pl. 40, Figs 8,9).

Environment of Deposition

Hallett Cove Sandstone and Burnham Limestone display a general upward decrease in abundance, diversity, and size of foraminiferal and molluscan faunas, representing decrease in marine influence, and possibly cooler conditions, with time. The thin iron-stained shelly sand which is commonly encountered at the base of the Pliocene sequence beneath the City of Adelaide, and at Maslin and Aldinga Bays, is comparable in facies with the Dry Creek Sand of the Adelaide Plains Sub-Basin, and suggests deposition in warm-water in shallow neritic to littoral sheltered sandy bays (Ludbrook, 1954, p. 49). Ludbrook also noted in the same place that in the Adelaide City area 'east of the Para Fault the limestones are more characteristic of the littoral environment and littoral species .... are more common'.

Marginopora vertebralis occurs frequently, and up to 25 mm diameter, in stratotype Hallett Cove Sandstone; and elsewhere in the lower part of the unit. Wright and Murray (1972) showed that the present world-distribution of Marginopora is in shallow water, normal marine or hypersaline conditions, and subtropical or tropical temperatures, within the 25°C summer isotherm for surface waters.

Associations of smaller benthonic foraminifera in Hallett Cove Sandstone are dominated by Ammonia beccarii and Elphidium spp., together with miliolid and discorbid forms. These suggest marginal-marine sheltered bay to estuarine or lagoonal environments of deposition (Murray, 1973).

Ludbrook, in the unpublished report cited above, inferred an estuarine or lagoonal environment for the small assemblage of molluscs from Burnham Limestone at Blanche Point. Possible correlatives beneath the City of Adelaide contain small foraminifera, as indicated above. The faunal content as well as the lithology suggest that the unit is more than a secondary travertine mantle on the Hallett Cove Sandstone, as was proposed by Howchin (1923, p. 289). Burnham Limestone represents a distinct episode of marginal-marine deposition, but after retreat of the sea, and uplift, may well have been modified by carbonate pedogenesis, including formation of a calcrete crust. In the City area it was karst-weathered.

Regional Events

The transgressive nature of Hallett Cove Sandstone in the St Vincent Basin, and of correlative Norwest Bend Formation in the Murray Basin, were recognised by Ludbrook (1959). However the other records of Pliocene around Spencer Gulf, southwest of Whyalla and along the Wallaroo-Tickera coast, are of Miocene Melton Limestone, with Austrotrillina howchini (Lindsay, 1970c). Both Pliocene and Miocene units are probably represented at the southern end of Eyre Peninsula (Fishery Bay; Ludbrook, 1963a).

Hallett Cove Sandstone represents a late phase of warm transgressive Episode 9 of Lindsay (1976), part of Cycle 4 of Quilty (1977), and part of Sequence 4 of McGowran (1978d, 1979b; cf. Plan 35).

As discussed earlier, O-isotope palaeoclimatic studies now suggest that a number of glacial/interglacial eustatic cycles of 'Pleistocene' type occurred in the Late Pliocene and earliest Pleistocene. These provide an embarrassment of alternatives for the deposition and karst-weathering of the Hallett Cove Sandstone, followed by the deposition of Burnham Limestone and subsequent karst-weathering of both units as in the City of Adelaide. However, due no doubt to the effects of Kosciuskan uplift, there is no record of any later marine ingression into the City area.

For the purposes of Plan 25 ('Contoured base of Quaternary deposits'), Hallett Cove Sandstone/Burnham Limestone are included together as part of the Tertiary 'undermass', because of the intimate and complex relationship between the two units beneath the City.

QUATERNARY UNITS

The various non-marine units which together blanket the marine succession in the Adelaide City area are described by Selby and Lindsay (in press) and will not be treated here. The spatial relationships of some of the units are shown in the cross-sections (Plans 6-16), while lithological summaries are included in Plans 15, 27-29. In Appendix B are tabulated the total thicknesses in reference bores, of Quaternary units other than Burnham Limestone (included with Hallett Cove Sandstone) and Carisbrooke Sand (shown separately). Volumetrically, the most important units are the Carisbrooke Sand (Lindsay,

1969), the Hindmarsh Clay (Firman, 1966, 1967b), and the composite 'Torrens alluvium'. Most of the Quaternary units which are developed in the Adelaide Region were treated by Firman (in Daily et al., 1976). Earlier, in discussing the Para Fault Zone, the writer described the important exposures of Ripon Calcrete and Telford Gravel correlatives at North Adelaide.

APPENDIX A

STRATIGRAPHIC REFERENCE BORES

APPENDIX A

STRATIGRAPHIC REFERENCE BORES

Reference Bore No.	Name of bore	SADME Bore Unit No.	Town Acre etc.
1.	Morphett St and Victoria Bridges, foundation CH-4.	662841eEW00455	Adj. T.A. 8
2.	do. CH-2.	662841eEW00454	do.
3.	do. CH-5.	662841eEW00442	Railway Reserve
4.	do. CH-11.	662841eEW00445	do.
5.	do. CH-12.	662841eEW00446	do.
6.	do. CH-14.	662841eEW00403	Torrens Parklands Reserve
7.	A.M.P. Building, foundation bore 4A.	662841eEW00479	T.A. 16
8.	John Martin's Car Park, foundation bore B(3).	662842hEW00071	T.A. 23

9.	West End Brewery, water well 2 (1915).	662841mWW00225	T.A. 64
10.	SADME West End Brewery stratigraphic CH-2(1976).	662841mSW00368	T.A. 119
11.	P.M.G. Telephone Exchange, Waymouth St., foundation CH-1.	662841mEW00249	T.A. 199
12.	Reserve Bank Building, foundation CH-R4.	662841mEW00271	T.A. 270
13.	State Administration Building, Victoria Square, foundation CH-2.	662841mEW00274	T.A. 270
14.	do. CH-4.	662841mEW00276	T.A. 270
15.	P.M.G. Mail Exchange, Gouger Street, foundation CH-5.	662841mEW00288	T.A. 322
16.	do. CH-1.	662841mEW00303	T.A. 391
17.	do. CH-2.	662841mEW00304	T.A. 391
18.	do. CH-4.	662841mEW00306	T.A. 391

19.	Adelaide Central Market, Gouger Street, foundation CH-3.	662841mEW00301	T.A. 380
20.	Adelaide Children's Hospital, Rieger Building, foundation CH-1.	662841eEW00423	T.A. 717
21.	do. CH-2.	662841eEW00424	T.A. 717
22.	Adelaide Children's Hospital, Nurses' Home, Brougham Place, foundation CH-2.	662841eEW00428	T.A. 731
23.	do. CH-3.	662841dEW00686	T.A. 731
24.	Proposed Festival Hall, 'Carclew', foundation CH-1.	662841eEW00432	Adj. T.A. 749
25.	do. CH-2.	662841eEW00433	T.A. 749
26.	E.F. Marshall & Sons, drainage bore, 168 Ward St., Nth Adelaide.	662841dDW00690	T.A. 772
27.	Lion Brewing & Malting Co. Ltd. water bore 5, Jerningham St (1934).	662842aWW00166	T.A. 987

28.	Adelaide Subway Study, foundation CH-7.	662842aEW00168	T.A. 1031
29.	Royal Adelaide Hospital, East Wing, Radiotherapy Block, foundation CH-3.	662842hEW00013	Hospital Reserve 557
30.	do. CH-10.	662842hEW00020	do.
31.	Engineer-in-Chief's Dept, Kent Town bore (1881).	662842hWW00005	Waterworks Yard Reserve, East Parklands
32.	Australian Postal Institute, water bore.	662841mWW00201	West Park-lands Reserve
33.	Public Buildings Dept, Supreme Court Library, Gouger Street, foundation bore PB-1 (1956).	662841mEW00312	T.A. 408
34.	Adelaide Festival Theatre Plaza, foundation CH-3.	662841eEW00536	Houses of Parliament Reserve
35.	do. CH-4.	662841eEW00535	Adelaide Railway Stn Reserve

36.	Adelaide Subway Study, foundation GH-1.	662841dEW00683	North Parklands
37.	do. CH-2, Botanic Park.	662842hEW00087	Parklands 574
38.	do. CH-3/DDH-3.	662842hEW00001	Torrens Parklands
39.	do. CH-4, Memorial Drive.	662841eEW00401	Municipal Golf Links Parklands
40.	Adelaide Subway Study, foundation CH-6/DDH-6, Brougham Place.	662841dEW00681	Parkland Reserve
41.	SADME South Parklands stratigraphic hole CH-1, CH-1A.	662841nWW00732	South Parklands Reserve
42.	A.W. Sandford & Co. Ltd. water bore.	662842jWW00609	T.A. 144
43.	Adelaide Electric Supply Co. Ltd, water bore.	662842jWW00610	T.A. 155

44.	Govt Forensic Science Building, Divett Place, foundation CH-2.	662842jWW00630	T.A. 300
45.	do. CH-1.	662842jWW00631	T.A. 300
46.	Graphic House Ltd, Queen St, drainage bore.	662842jDW00640	T.A. 490
47.	S.A. Housing Trust, East Terrace flats, foundation CH-1.	662842jEW00644	T.A. 583
48.	University of Adelaide, Law Building, foundation CH-2.	662842hEW00125	University Reserve
49.	Victoria Park Racecourse, water bore.	662842rWW00551	East Park-lands
50.	S. Wilcox, 187 Brougham Place, North Adelaide, water bore.	662841dWW00693	T.A. 995
51.	S.A. Dept of Mines, Trainee Drillers School bore, Torrens bank.	662841eWW00407	West Park-lands
52.	Adelaide Teachers College oval, water bore 1.	662842aWW00162	Torrens Parklands

53.	Govt water bore, near reservoir South Terrace/Beaumont Road (1914).	662842jWW00604	South Park-lands
54.	I.M.V.S., Frome Road, new wing (1964), foundation CH-4.	662842hEW00035	Hospital Reserve
55.	Collegiate School of St Peter, water bore (1914).	662842hWW00104	Section 256, Hd Adelaide
56.	J.S. Chamings, South Terrace, drainage bore.	662841nDW00705	T.A. 700
57.	Hilton Bridge, Burbridge Road, foundation CH-2 (1975).	662841mEW00365	Railway Reserve
58.	Coca Cola (Diverse Products) water bore 1 (1964), Thebarton.	662841eWW00516	Allot. 49, Pt Section 1, Hd Adelaide
59.	Adelaide Subway Study, foundation CH-5, Strangways Tce, North Adelaide.	662841eEW00422	Municipal Golf Links Reserve
60.	Adelaide Subway Study, foundation CH-8, Wellington Square.	662841dEW00682	Reserve

61.	Waterman's Building, King William/ Gillies Streets, foundation bore 1.	662841mEW00348	T.A. 639
62.	Police Headquarters Building, Angas St, Victoria Square, foundation bore 5.		T.A. 409
63.	State Library, foundation pier J1.		Library Reserve
64.	University of Adelaide Chemistry Lab. extensions (1961), foundation CH-1.	662842hEW00091	University Reserve
65.	Adelaide Subway Study, foundation CH-1, Stanley St/ Mann Tce.	662842aEW00161	Parklands
66.	Modern Plate Engraving Co., drainage bore 1.	662841mDW00248	T.A. 244
67.	LeCornu Furniture Centre, foundation bore 1.	662841dEW00696	T.A. 832

68.	Coca Cola (Diverse Products), water bore 2 (1969), Thebarton.	662841 WW07724	Allot. 11, Pt Section 1, Hd Adelaide
69.	Nathan Brewery, Southwark, water bore (1946).	662841 WW07561	Pt Section 1, Hd Adelaide
70.	News Building, foundation bore S1.	662841eEW00457	T.A. 12
71.	Grosvenor Hotel extensions, foundation and drainage bore PB-1.	662841eEW00464	T.A. 13
72.	British and Foreign Bible Society proposed building, foundation and drainage bore PD-2.	662841eEW00468	T.A. 14
73.	Donaldson Andrews (now Myers) drainage bore.	662841eDW00494	T.A. 46
74.	Savings Bank of S.A., Bank St, foundation bore PB-1.	662841eEW00507	T.A. 49
75.	Savings Bank of S.A., Bank St, foundation bore PB-2.	662841eEW00500	T.A. 49

76.	do. foundation bore PB-3.	662841eEW00511	T.A. 49
77.	A.N.Z. Bank building site, King William St, foundation bore 1.	662841mEW00231	T.A. 78
78.	I.M.F.C. House, King William St/ Hindley St, foundation bore 1.	662841eEW00496	T.A. 47
79.	23-25 Leigh St, foundation bore 1.	662841mEW00358	T.A. 111
80.	G. Wilcox & Co., Currie St, water bore (1914).	662841mWW00235	T.A. 136
81.	City of Adelaide drainage bore 7, King William St/Grenfell St.	662841mDW00236	T.A. 141
82.	Grenfell Centre, foundation bore CH-2.	662841mEW00238	T.A. 142
83.	do. foundation bore CH-1.	662841mEW00239	T.A. 142
84.	Parsons & Robertsons', Pulteney St, drainage bore.	662842jDW00614	T.A. 210

85.	Cooperative Insurance Co, proposed building, Franklin St, foundation bore DDU-1.	662841mEW00256	T.A. 266
86.	M.L.C. building, Victoria Square, foundation CH-1.	662841mEW00264	T.A. 267
87.	A. Walton & Co., Grote St/West Tce, water bore (1914).	662841mWW00287	T.A. 321
88.	Proposed Govt office building, Victoria Square west, foundation CH-1.	662841mEW00291	T.A. 335
89.	Western Courts building, Gouger St, foundation CH-3.	662841mEW00309	T.A. 407
90.	Commonwealth Law Courts building, Pinkmoor St, foundation bore 1.	662841mEW00351	T.A. 453
91.	W.H. Burford & Sons Pty Ltd, Sturt St, water bore (1914).	662841mWW00346	T.A. 556
92.	Dept of the Army, Keswick Barracks, Anzac Hwy, drainage bore (1947).	662841nDW00723	Pt Sect. 6, Hd Adelaide

93.	S.A. Farmers' Union, Mile End, water bore 1 (1961-2).	662841nWW00719	Pt. Sect. 5, Hd Adelaide
94.	Adelaide Constitutional Museum, Parliament House, DDH-2.		Govt Reserve
95.	Adelaide Teachers' College, Kintore Ave, foundation corehole PB-6 (1957).	662842hEW00055	Govt Reserve
96.	Govt Forensic Lab., proposed Chemistry building, Kintore Ave, foundation CH-2.	662842hEW00096	Govt Reserve
97.	City of Adelaide drainage bore 4, Hindmarsh Square.		T.A. 150
98.	City of Adelaide drainage bore 5, Hindmarsh Square.		Reserve (T.A. 149)
99.	City of Adelaide drainage bore 6, Grenfell St/Commercial Place.		T.A. 143
100.	Rundle St Car Park, foundation CH-1, York St.		T.A. 87
101.	do. CH-2.		T.A. 87

102.	Motor Vehicles Dept building, Wakefield St, foundation CH-3.		T.A. 301
103.	Brunkhorsts, Rundle St/Charles St, water bore (1915).	662842hWW00082	T.A. 41
104.	Royal Adelaide Hospital, East Wing, foundation CH-1.	662842hEW00011	Hospital Reserve 557
105.	Coca Cola (Diverse Products) water bore 4A (1977), southeast cnr Chapel St/Admella St, Thebarton.	662841eWW04576	Pt Sect. 1, Hd Adelaide
106.	Coca Cola (Diverse Products) water bore 4 (1977), cnr Smith St/Cawthorne St, Thebarton.	662841eWW01435	Pt Sect. 1, Hd Adelaide
107.	Police Barracks, Port Rd, water bore 1 (1930).	662841eWW00410	Reserve, West Parklands

APPENDIX B

STRATIGRAPHIC SUMMARIES OF REFERENCE BORES

Key to Stratigraphic units:

A-Quaternary alluvium, Callabonna Clay, Pooraka Formation, Hindmarsh Clay, (+surficial soil, fill)
B-Carisbrooke Sand
C-Hallett Cove Sandstone/Burnham Limestone
D-Sand unit of Aldinga Member of Port Willunga Formation
E-Tandanya Sand Member of Chinaman Gully Formation
F-Gull Rock Member of Blanche Point Formation
G-Undifferentiated basal Blanche Point Formation and Tortachilla Limestone.
H-South Maslin Sand
J-Clinton Formation
K-Precambrian bedrock.

Note: Depth to top of stratigraphic unit, followed by thickness of the unit (metres).

Bore No.	Elevation (metres above A.H.D.)	A	B	C	D	E	F	G	H	J	K	Total Depth (m)
1	31.1	(9.8)	-	-	-	-	9.8(5.4+)	-	-	-	-	15.2
2	32.4	(12.2)	-	-	-	-	12.2(4.9+)	-	-	-	-	17.1
3	29.7	(7.3)	-	-	-	-	7.3(22.0)	29.3(5.8)	35.1(3.0+)	-	-	38.1
4	28.3	(20.1)	-	-	-	-	20.1(4.9)	25.0(4.6)	29.6(5.8+)	-	-	35.4
5	26.2	(16.2)	-	-	-	-	16.2(3.9)	20.1(4.6)	24.7(2.7+)	-	-	27.4
6	24.8	(15.2)	-	-	-	-	15.2(1.9)	17.1(4.5)	21.6(5.8+)	-	-	27.4
7	40.0	(7.8)	-	7.8(9.3)	-	20.6(3.9)	24.5(21.2)	45.7(5.1)	50.8(10.0+)	-	-	60.8
8	44	(8.5)	8.5(7.7)	16.2(7.1)	-	24.7(5.3+)	-	-	-	-	-	30.0
9	40.4	(6.1)	6.1(13.7)	19.8(1.5)	-	21.3(3.1)	24.4 F + G	(27.4)	51.8(0.6+)	-	-	52.4
10	40.3	(8)	8 (9)	17.0(1)	-	20.5(4.5)	25.0(21.0)	46.0(5.0)	51.0(11.0)	62.0(27.0)	89.0(24.0+)	113.0
11	44.1	(13.1)	-	13.1(11.3)	25.0(2.7)	35.2(5.6)	40.8(4.9+)	-	-	-	-	45.7
12	45.0	(14.8)	-	14.8(10.2)	29.4(4.4)	-	-	-	-	-	-	36.6
13	45.0	(17.4)	-	17.4(7.7)	30.0(4.9)	-	-	-	-	-	-	39.6
14	45.0	(16.8)	-	16.8(7.6)	29.9(4.3)	39.9(3.1)	45.7(15.3+)	-	-	-	-	61.0
15	40.8	(14.9)	14.9(8.9)	-	25.9(4.3)	35.7(2.4)	38.1(7.6+)	-	-	-	-	45.7
16	40.3	(12.5)	12.5(9.8)	-	25.3(2.4+)	-	-	-	-	-	-	27.7
17	40.7	(17.1)	17.1(6.1)	-	26.2(1.5+)	-	-	-	-	-	-	27.7
18	40.6	(12.8)	12.8(8.8)	-	25.3(4.3)	35.1(2.6)	39.3(6.4+)	-	-	-	-	45.7
19	43.1	(13.6)		13.6(9.0)	-	-	-	-	-	-	-	27.5
20	29.1	(16.8)	-	-	-	-	16.8(3.9)	20.7(3.7)	24.4(6.1)	30.5(6.1+)	-	36.6

21	30.5	(18.3)	-	-	-	-	18.3(2.7)	21.0(3.4+)	-	-	-	24.4
22	32.7	(8.5)	8.5(6.9)	-	-	-	15.4(6.2)	21.6(5.7)	27.3(3.3+)	-	-	30.6
23	33.7	(5.8)	5.8(0.6)	6.4(0.9)	-	-	7.3(2.8+)	-	-	-	-	10.1
24	42.0	(12.3)	12.3(4.8)	-	-	-	17.1(3.9)	21.0 (4.0)	25.0(0.9+)	-	-	25.9
25	42.4	(4.9)	4.9(12.2)	-	-	-	17.1(5.4)	22.5(3.9)	26.4(3.3)	29.7(6.3)	36.0(20.4+)	56.4
26	45.8	(19.8)	19.8(?)	present	-	-	22.4(9.0)	31.4(0.6+)	-	-	-	32.0
27	31.0	(14.9)	-	-	-	-	14.9	F + G (11.3)	26.2(18.3)	44.5(16.5)	61.0(52.7+)	113.7
28	34.0	(14.0)	-	-	-	-	14.0(3.0)	17.0(4.5)	21.5(8.5+)	-	-	30.0
29	38.6	(16.8)	-	-	-	25.1(1.7)	28 (2.5+)	-	-	-	-	30.5
30	34.0	(18.0)	-	-	-	18.0(1.7)	21.3(9.2+)	-	-	-	-	30.5
31	41.5	(21.0)	-	-	28.7(0.9)	37.2(1.5)	39.9(19.6)	59.4(7.0)	66.4(14.0)	80.5(12.4)	92.9(32.4+)	125.3
32	39.0	(13.7)	13.7(7.6)		27.4(3.1)	36.0(1.5)	42.7(19.8)	62.5(9.5)	72.0(11.9)	83.9(16.6)	100.5(12.2+)	112.7
33	44.5	(14.6)	-	14.6(10.4)	-	-	-	-	-	-	-	30.5
34	35.1	(4.6)	-	4.6(4.2+)	-	-	-	-	-	-	-	8.8
35	29.9	(4.6)	-	4.6(1.3)	-	7.9(2.8)	11.1(4.6+)	-	-	-	-	15.7
36	50	(13.9)	13.9(1.6)	15.5(8.8)	-	-	24.3(1.9+)	-	-	-	-	26.2
37	30	(11.6)	-	-	-	-	13.3(11.8+)	-	-	-	-	25.1
38	27	(12.0)	-	-	-	-	12.0(12.0)	24.0(3.5)	27.5(2.5+)	-	-	30.0
39	24	(15.4)	-	-	-	-	-	-	15.4(10.0+)	-	-	25.4
40	45.7	(6.2)	6.2(12.9)	-	-	-	19.1(12.9)	32.0(4.0)	36.0(2.0+)	-	-	38.0
41	39.5	(14.0) A+B		14.0(10.8)	42.0(10.0)	59.5(5.0)	64.5(26.5)	91.0(5.0)	96.0(4.0)	100 (12.0)	112(11+)	123.0
42	45	(13.7)	-	13.7(∿9)	∿22 (∿2½)	∿32 (4)	∿36 (∿22)	∿58 (5.7+)	-	-	-	63.7
43	43	(24.4)	-	-	28.0(4.0+)	-	-	-	-	-	-	32.0
44	45.5	(18.8)	-	18.8(7.8)	-	-	-	-	-	-	-	30.3
45	46.1	(19.5)	-	19.5(6.0)	31.8(5.3)	43.4(2.0)	47.3(11.7+)	-	-	-	-	59.0
46	45.7	(18.3)	18.3(8.2+)	-	-	-	-	-	-	-	-	26.5
47	50.0	(17.4)	17.4(12.8+)	-	-	-	-	-	-	-	-	30.2
48	38.1	(4.6)	-	4.6(4.1+)	-	-	-	-	-	-	-	8.7
49	49.6	(31.4) A+?B		-	∿45 (∿12)	∿64 (∿5)	70.1	F + G (15.5)	85.6(?)	present	?intersected	141.7
50	34	(6.1)	-	?6.1(?1.8)	-	-	7.9	F + G (19.5)	27.4(6.4)	33.8(19.2)	53(4+)	57.0

51	21.2	(22.9)	-	-	38.1(3.0)	45.7(22.9)	-	68.6(7.6)	76.2(11.6)	-	96.9(0.6+)	97.5
52	30	(16.8)	-	-	-	-	16.8 F + G	(10.6)	27.4(4.0)	31.4(19.8)	?near at 51.2	51.2
53	50	(26.5)	26.5(12.2)	-	~47(~8)	~65(~5)	71.6 F + G	(18.1)	89.7(5.4+)	-	-	95.1
54	31.7	(15.3)	-	-	-	-	15.3 F + G	(19.5)	34.8(1.9+)	-	-	36.7
55	39.7	(18.6)	-	-	-	25.0(1.5)	9.3(17.6+)	-	-	-	-	46.9
56	40	(5.5)	5.5(8.2)	13.7(10.1)	38.4(?)	-	-	-	-	-	-	38.4
57	20.3	(15.2)	15.2(1.6)	16.8(4.7)	-	-	-	-	-	-	-	24.1
58	19.2	(110.9)	-	110.9(26.9+)	-	-	-	-	-	-	-	137.8
59	37	(6.9)	6.9(5.1)	12.0(3.3)	-	-	15.3(3.2)	18.5(2.0+)	-	-	-	20.5
60	46	(10.3)	10.3(8.7)	-	-	-	19.0 F + G	(7.7)	26.7(8.1+)	-	-	34.8
61	43.2	(18.0)	-	18.0(0.3+)	-	-	-	-	-	-	-	18.3
62	45.0	(17.7)	-	17.7 (8.2)	32.9(5.4)	44.7(2.3+)	-	-	-	-	-	47.0
63	41.8	(8.8)	-	8.8(9.4+)	-	-	-	-	-	-	-	18.2
64	27.5	(8.7)	-	-	-	-	8.7(15.7)	-	-	-	-	24.4
65	35	(16.0)	-	-	-	-	16.0(4.2+)	-	-	-	-	20.2
66	43.4	(19.5)	19.5(2.4+)	-	-	-	-	-	-	-	-	21.9
67	49.0	(14.3)	-	14.3(0.9+)	-	-	-	-	-	-	-	15.2
68	19.2	(109.7)	-	109.7(35.1)	-	-	-	-	-	-	-	155.4
69	19.1	(108.8)	-	108.8(43.9)	-	-	-	-	-	-	-	169.2
70	33.3	(6.1)	6.1(3.2)	9.3(0.9)	-	14.1(0.5+)	-	-	-	-	-	14.6
71	37.4	(7.0)	-	7.0(7.2)	-	18.0(2.7+)	-	-	-	-	-	20.7
72	32.6	(1.3)	-	1.3(7.8)	-	12.5(3.7)	16.2(2.1+)	-	-	-	-	18.3
73	43.5	(9.4)	9.4(5.2)	15.5(3.0+)	-	-	-	-	-	-	-	18.5
74	37.6	(6.9)	-	6.9(8.2)	-	-	-	-	-	-	-	18.3
75	36.7	(5.3)	-	5.3(9.2)	-	18.0(0.3+)	-	-	-	-	-	18.3
76	37	(5.8)	5.8(1.4)	7.2(7.4)	-	18.3(2.0+)	-	-	-	-	-	20.3
77	42.5	(13.1)	-	13.1(7.5)	20.6(2.4+)	-	-	-	-	-	-	23.0
78	42.0	(10.7)	-	10.7(4.9+)	-	-	-	-	-	-	-	15.6
79	41.3	(11.7)	-	11.7(0.5+)	-	-	-	-	-	-	-	12.2
80	42.2	(13.7)	-	13.7(7.6)	21.3(6.1+)	-	-	-	-	-	-	27.4

81	44.5	(14.9)	-	14.9(6.0+)	-	-	-	-	-	-	-	20.9
82	41.9	(11.2)	-	11.2(7.8)	19.0(4.9)	28.4(4.9)	33.3(10.2+)	-	-	-	-	43.5
83	45.6	(15.2)	-	15.2(7.8)	23 (3.8)	33.2(4.2+)	-	-	-	-	-	37.4
84	46.5	(22.9)	-	22.9(6.1)	at 35.4	41.5(1.5)	?46 (15+)	-	-	-	-	61.0
85	44.3	(13.7)	-	13.7(10.5)	-	-	-	-	-	-	-	25.9
86	44.5	(16.3)	-	16.3(6.6+)	-	-	-	-	-	-	-	22.9
87	40.3	(11.3)	11.3(5.8)	?17.1(?5.5)	25.6(2.7)	33.5(1.3+)	-	-	-	-	-	34.8
88	43.9	(13.4)	-	13.4(10.1)	28.3(5.3)	-	-	-	-	-	-	36.4
89	44.8	(13.5)	-	13.5(10.8)	32.8(5.8)	44.5(3.0)	49.1(7.9+)	-	-	-	-	57.0
90	44.8	(16.2)	-	16.2(9.1)	-	-	-	-	-	-	-	28.0
91	43.4	(12.2)	-	12.2(12.2)	38.1(5.5+)	-	-	-	-	-	-	43.6
92	29	(17.4)	-	?17.4(0.9+)	-	-	-	-	-	-	-	18.3
93	19.2	(13.7)	13.7(12.8)	-	82.3(8.8)	95.4(7.6)	103.0(37.2)	140.2(5.5)	145.7(11.3+)	-	-	157.0
94	35.4	(4.3)	-	4.3(7.0)	-	-	-	-	-	-	-	12.0
95	35	(1.1)	-	1.1(9.3)	-	12.7(3.2)	16.5(14.0+)	-	-	-	-	30.5
96	38.9	(5.2)	-	5.2(9.9)	-	-	-	-	-	-	-	16.7
97	45.2	(16.5)	?16.5(?4.2+)	-	-	-	-	-	-	-	-	20.7
98	45.4	(13.7)	-	13.7(7.3+)	-	-	-	-	-	-	-	21.0
99	44.3	(16.2)	-	16.2(3.2+)	-	-	-	-	-	-	-	19.4
100	45	(15.3)	-	15.3(3.7+)	-	-	-	-	-	-	-	19.0
101	45	(15.0)	?15.0(?3.8+)	-	-	-	-	-	-	-	-	18.8
102	45	(17.3)	-	17.3(8.3)	-	-	-	-	-	-	-	30.4
103	44.6	(16.8)	-	16.8(9.1)	-	27.4(4.3+)	-	-	-	-	-	31.7
104	37.0	(18.7)	-	-	-	21.9(1.9)	-	-	-	-	-	24.4
105	20	(90)	A + B	-	-	-	-	-	-	-	-	125.5
106	20	(119)	-	119(22)	-	-	-	-	-	-	-	162.8
107	23.3	(15.2)	15.2(12.2)	-	-	-	-	-	-	-	-	40.2

APPENDIX C

PETROGRAPHIC DESCRIPTIONS OF SELECTED SEDIMENTARY ROCK SPECIMENS

BEDROCK

Sample: P744/78; TS40264

Location:

SADME West End Brewery CH-2 (Ref. bore 10), depth 112.0-112.3 m, core.

Rock Name:

Silty shale.

Hand Specimen:

A massive, green coloured rock.

Thin Section:

An optical estimate of the constituents gives the following:

	%
Argillaceous matrix	55
Bright green phyllosilicate	20
Quartz	15
Muscovite-sericite	5
Opaques and semi-opaques	5

This sample is comprised mainly of a phyllosilicate-rich matrix through which silt-sized, detrital quartz grains are disseminated. A well developed foliation is defined largely by translucent, reddish-brown iron oxides which tend to be concentrated along discontinuous, undulose bands with a parallel orientation. The most common phyllosilicate is a finely divided, weakly birefringent clay, but well developed flakes of a pleochroic green phyllosilicate as well as small, birefringent muscovite-sericite flakes were also noted.

The fine muscovites, in particular, exhibit a lepidoblastic foliation oriented parallel to the general foliation direction, although some muscovite flakes are oriented across this foliation. The bright green phyllosilicate flakes appear to have a vague preferred orientation approximately perpendicular to the general foliation direction. The bright green phyllosilicate requires X-ray diffraction to positively identify, although it could be a partially chloritized biotite or possibly even an unusual, bright green montmorillonite.

Minor opaques are disseminated through the rock as anhedral grains and granular aggregates below 0.05 mm in size.

This is a fine grained, argillaceous sediment which has suffered some recrystallization to produce a bright green phyllosilicate and finely divided sericite flakes.

(after Radke, 1978; AMDEL Report GS 4113/78).

TORTACHILLA LIMESTONE/basal BLANCHE POINT FORMATION

Sample: P742/78; TS 40262

Location:

Adelaide Subway Study, foundation test DDH-6, Brougham Place, North Adelaide (Ref. bore 40), diamond drill core, depth 33.6-33.7 m; Tortachilla Limestone correlative (immediately below Hantkenina zone).

Rock Name:

Fossiliferous and glauconitic limestone.

Hand Specimen:

A pale, greenish-grey coloured rock with some shell fragments.

Thin Section:

An optical estimate of the constituents gives the following:

	%
Calcite matrix	55
Shell fragments	20
Ferruginous pellets	15
Glauconite	5
Quartz	5
Opaline silica	Trace-1
Muscovite, rutile	Trace
Opaques	1

This sample is comprised mainly of a very fine-grained, almost micritic, calcite matrix through which glauconite pellets in various degrees of oxidation and shell fragments and minor detrital quartz are disseminated. The shell fragments are also comprised of calcite but

can usually be distinguished from the calcite matrix on textural grounds by either a finer grain size or a more fibrous character, as well as their shape. Still, the distinction between calcite matrix and shell fragments is not always obvious and the proportions given in the above list of minerals are somewhat tentative.

Glauconite is disseminated through the rock as pellets up to 0.5 mm in size, many of which have been completely oxidised to reddish-brown ferruginous material which is termed ferruginous pellets in the above list of minerals. The glauconite pellets show varying degrees of oxidation with a few consisting of completely unoxidised glauconite and some consisting of partially oxidised glauconite, although the completely oxidised pellets are the most abundant. The oxidation appears to come from the core of the pellet and work outwards with the partially oxidised pellets containing oxidised cores and almost completely unaltered margins. A few of the ferruginous pellets also contain narrow margins of glauconitic material. Traces of opaline silica are locally intergrown with some ferruginous pellets as narrow void or fracture fillings.

The detrital quartz grains are generally about 0.1 mm in size and exhibit somewhat modified subangular to subrounded shapes. Traces of detrital muscovite were also noted as small flakes below 0.1 mm long. Minor

disseminated rutile, also most likely of detrital origin, is also present as translucent, yellow grains. Opaques form anhedral disseminated grains up to 0.1 mm in size. A few detrital phyllosilicate flakes (possibly muscovite or biotite) show extensive replacement by translucent, reddish-brown iron oxides.

This is a fossiliferous limestone which contains a significant proportion of glauconite pellets, many of which have been extensively oxidised to translucent, reddish-brown limonitic material.

(after Radke, 1978; AMDEL Report GS 4113/78)

Sample: P747/78; TS 40267

Location:

SADME West End Brewery CH-2, Adelaide City area (Ref. bore 10), tube-core, 50.0-50.3 m; Tortachilla Limestone correlative.

Rock Name:

Ferruginous marl.

Hand Specimen:

A friable, greenish-grey rock with large pelecypod and gastropod shell fragments.

Thin Section:

An optical estimate of the constituents gives the following:

	%
Argillaceous matrix	40
Calcite (shell fragments)	35
Ferruginous pellets	20
Quartz grains	5
Siliceous spicules	1

This sample is comprised mainly of an essentially structureless, argillaceous matrix through which shell fragments, ferruginous pellets and quartz grains are disseminated. The matrix has a green, turbid colour and appears to consist mainly of very fine clay, although significant amounts of finely divided opaline silica could also be present. This matrix exhibits a varying amount of ferruginous staining and locally has a translucent, reddish-brown colour.

Most of the calcite in this rock obviously represents shell fragments. Some of these fragments are quite small and form intimate intergrowths with the argillaceous matrix. A small proportion of siliceous spicules are disseminated through the rock.

The ferruginous pellets are up to 2 mm in diameter and generally exhibit ovoid shapes. These pellets most likely represent oxidised glauconite pellets, but in none of these were any traces of glauconite noted. Detrital quartz grains generally between 0.1 and 0.5 mm in diameter are also disseminated through the rock and generally exhibit subangular to subrounded shapes with the larger grains generally having more rounded shapes.

This is an argillaceous, detrital sediment with abundant shell fragments and oxidised glauconite pellets and a minor quartz-rich detrital sand component.
(after Radke, 1978; AMDEL Report GS 4113/78)

Sample: 6627RS 00147; TS 41262

Location:

Longyear (Australia) Pty Ltd diamond drill test hole, Marion Rd, Mitchell Park, Section 82, Hundred of Noarlunga; core at 212.70-212.75 m; Tortachilla Limestone (Lindsay, 1981).

Hand Specimen:

A grey rock containing a few moderately large shelly fossils and numerous green grains about 1 mm in size in a fine-grained matrix. The green grains resemble glauconite in general appearance.

Thin Section:

A visual estimate of the constituents is as follows:

	%
Calcite	70-75
Glauconite	25-30
Quartz	1-2
Clay	undetermined (minor)
Muscovite	minute trace

The rock is composed predominantly of fine-grained calcite of varying turbidity and in this there are some poorly preserved outlines of shelly fossils of varying size. Much of the calcite has recrystallized and now has a common grain size of about 0.05 to 0.02 mm and former fossils now merge with recrystallized matrix. The turbid calcite probably contains some clay impurity but this is obscured by the optical properties of the carbonate and its amount cannot be determined by microscopic examination. Quartz grains about 0.05 mm in size are scattered sparsely through the rock.

Glauconite occurs as rounded to oval and also irregular grains or pellets which vary in size from about 0.2 to 2 mm long but are commonly between 0.5 and 1 mm. Many of these are green and appear unaltered whereas others show varying degrees of staining by brown iron oxide and a few are extensively weathered and oxidized. Some of the glauconite pellets have numerous, small cracks and in some pellets these have been filled by fine-grained calcite from the matrix of the rock.

The larger shell fragments noted in the hand specimen are better preserved than the finer-grained calcareous material in the matrix and some of these are over 1 cm long.

Conclusion:

Glauconitic limestone. It probably contains an undetermined amount of argillaceous material obscured by the calcite.

(after Whitehead, 1979; AMDEL Report GS 2673/79)

Sample: P748/78; TS 40268

Location:

Morphett St and Victoria Bridges, foundation test bore 14 (Ref. bore 6), north bank of Torrens Lake; tube-core at 17.4-17.7 m. Basal Blanche Point Formation (*Hantkenina* zone).

Rock Name:

Glauconite marl.

Hand Specimen:

A pale grey to tan coloured, argillaceous rock with a friable character. Locally reddish-brown limonitic staining is present along fracture surfaces and green glauconite pellets are disseminated through the rock.

Thin Section:

An optical estimate of the constituents gives the following:

	%
Argillaceous, iron stained matrix	30
Calcite shell fragments	25
Glauconite	25
Matrix calcite	15
Quartz grains	5

This sample is very similar to the previously described sample (P747/78; TS40267) in many respects, consisting of an argillaceous matrix through which small shell fragments and glauconite pellets in various stages of oxidation are disseminated. The argillaceous matrix generally has a reddish-brown, iron stained character and locally has a translucent red to nearly opaque character due to extensive iron staining.

The shell fragments in this rock are generally quite small (below 0.5 mm long) and consist of fibrous to finely granular calcite. Some calcite is also intergrown with the matrix as irregular patches and vein-like structures with a turbid, finely granular character.

The glauconite pellets are generally between 0.1 and 1 mm in size and generally exhibit round to ovoid shapes, although some with quite angular, irregular shapes are also present. Most of the pellets have quite a fresh character, but many show varying degrees of oxidation to produce translucent, reddish-brown pellets. The least oxidised pellets have a slightly reddish-brown core, while the most oxidised pellets have been almost completely replaced by translucent, reddish-brown iron oxides. Even the freshest glauconite pellets show some marginal replacement by iron oxides and typically have fractures emanating into the pellets along which oxidation to translucent, reddish-brown iron oxides has occurred.

Detrital quartz grains generally about 0.1 mm in size are disseminated through the rock and exhibit sub-angular to subrounded shapes.

This is a fine grained, clay-rich sediment with small shell fragments, glauconite pellets in varying stages of oxidation and detrital quartz grains.
(after Radke, 1978; AMDEL Report GS 4113/78)

BLANCHE POINT FORMATION

Sample: P745/78; TS 40265

Location:

Forensic Science Centre building, Divett Place, central City, foundation test CH-1 (Ref. bore 45), diamond drill core at 59.0 m. Gull Rock Member; a hard band.

Rock Name:

Fossiliferous chert.

Hand Specimen:

A massive, grey coloured rock with at least some disseminated shell fragments.

Thin Section:

An optical estimate of the constituents gives the following:

	%
Siliceous matrix	50
Calcite shell fragments	40
Quartz grains	5
Siliceous spicules	3
Glauconite	1
Feldspar	Trace-1
Tourmaline, zircon	Trace
Opaques and semi-opaques	1

This sample consists essentially of small, calcite shell fragments and some detrital quartz grains disseminated through a matrix rich in microcrystalline to opaline silica. The matrix generally has an isotropic character indicating it consists mainly of opaline silica, but it does show varying degrees of turbidity

ranging from almost clear opaline silica to dark reddish-brown, turbid opaline silica. This turbidity is believed to be due to finely divided, iron stained clay, but the exact proportion of this material is hard to determine optically.

The shell fragments are comprised mainly of calcite, although a few could contain some intergrown dolomite which is most likely due to incipient dolomitization. Siliceous spicules are also disseminated through the rock and generally consist of clear, opaline silica, although some consist of microcrystalline silica.

The detrital quartz grains are generally between 0.05 and 0.15 mm in size and exhibit subangular to subrounded shapes. Traces of detrital feldspar, pleochroic green tourmaline and zircon were also noted. Opaques are disseminated through the rock as anhedral grains and granular aggregates up to 0.1 mm in size, at least some of which could be of detrital origin.

Glauconite pellets up to 0.5 mm in size are also locally present. These pellets often have mottled, reddish-brown to green colours, indicating they have suffered incipient oxidation to produce some finely divided iron oxides. The glauconite pellets in particular tend to be concentrated in a band approximately 1 mm wide.

This is a highly fossiliferous rock with a siliceous matrix and is similar to sample P743/78 (TS40263), except that this sample has a much higher proportion of carbonate shell fragments and a much lower proportion of siliceous spicules.

(after Radke, 1978; AMDEL Report GS 4113/78)

Sample: P746/78: TS 40266

Location:

Forensic Science Centre building, Divett Place, central City, foundation test CH-1 (Ref. bore 45), diamond drill core at 48.4 m. Gull Rock Member; a hard band.

Rock Name:

Fossiliferous chert.

Hand Specimen:

A massive, pale grey rock.

Thin Section:

An optical estimate of the constituents gives the following:

	%
Siliceous matrix	50
Calcareous shell fragments	35
Siliceous spicules	5
Quartz grains	5
Feldspar	Trace-1
Glauconite, tourmaline	Trace
Opaques	2

This sample is very similar to sample P745/78 (TS40265), consisting essentially of a turbid siliceous matrix through which shell fragments, spicules and detrital quartz grains are disseminated. As with the previously described sample the turbid matrix probably contains moderate amounts of finely intergrown iron stained clay, but the exact proportion is hard to determine optically. This rock has a slightly higher proportion of siliceous spicules than sample P745/78 but the other components are about at the same level. The glauconite-rich band noted in sample P745/78 is also lacking in this rock, which contains only traces of glauconite as small pellets below 0.1 mm in diameter.

This is a siliceous rock very similar in mineralogy, texture and origin to sample P745/78.
(after Radke, 1978; AMDEL Report GS 4113/78)

Sample: 6627 RS 00146; TS 41261

Location:

Longyear (Australia) Pty Ltd diamond drill test hole, Marion Rd, Mitchell Park, Section 82, Hundred of Noarlunga; core at 199.9-200.0 m. Gull Rock Member.

Hand Specimen:

A predominantly fine-grained, grey rock with a few large shelly fossils up to 2 cm long. When closely examined under low magnification some oval to round,

green grains about 0.5 mm in size can be seen and these resemble glauconite in general appearance.

Thin Section:

A visual estimate of the constituents is as follows:

	%
Calcite	40-45
Clay	30-35
Opal	10-15
Quartz	2-3
Glauconite or altered glauconite	5-10
Pyrite	trace

This sediment contains calcareous shell fragments, a low proportion of siliceous spicules, some rounded glauconite or glauconite-like grains or pellets and a few small quartz grains in a matrix composed largely of clay which has locally been replaced by opal.

A large proportion of the calcareous shell fragments are small (0.05 to 0.15 mm) and well sorted but there are scattered, larger fragments which, as noted in the hand specimen vary up to 2 cm long. Siliceous spicules are similar to those in the previous sample but are present in lower concentration (less than 5%). Quartz grains are well sorted with a common grain size of about 0.05 to 0.1 mm. Elongate shell fragments and spicules show some evidence of preferred orientation parallel to the bedding but at least a few have apparently random orientation. Some zones or poorly

defined bands in the rock contain round to oval grains composed predominantly of a mineral resembling glauconite but these grains contain other fine-grained detrital material including a few very small calcareous fragments, quartz grains and spicules. These glauconitic or glauconite-like pellets are up to 1 mm long and they tend to occur in groups. Some have a zone of staining near the outer boundary and some are at least partly altered. Pyrite disseminated throughout the rock is very similar to that in other specimens and it includes both microspherular or framboidal pyrite and a few very small cubic crystals. Some pyrite occurs within calcareous fossils, traces occur within a few glauconite pellets but most of it is disseminated through the matrix.

The matrix is composed largely of turbid, brownish-stained clay containing minute particles of calcite but there are some irregular zones and poorly defined bands about 1 to 2 mm thick in which the matrix is now composed largely of rather turbid and impure opal.

Conclusion:

Cherty marl containing some glauconite. Some patches and bands of matrix clay have been replaced by opal. (after Whitehead, 1979; AMDEL Report GS 2673/79)

Sample: 6627 RS 00144; TS41259

Location:

Longyear (Australia) Pty Ltd diamond drill test hole, Marion Rd, Mitchell Park, Section 82, Hundred of Noarlunga; core at 172.16-172.21 m, 'upper Blanche Point Formation' (= 'Blanche Point Soft Marls Member' of Reynolds, 1953).

Hand Specimen:

A fine-grained, grey rock with a few moderately large calcareous fossils some several millimetres in size.

Thin Section:

A visual estimate of the constituents is as follows:

	%
Calcite	70-75
Clay	20-25
Quartz grains	2-3
Muscovite flakes	trace
Pyrite	trace
Siliceous spicules	1-2
Heavy mineral grains	trace

The sample is composed mainly of small calcareous fossil fragments and a few small quartz grains cemented by a fine-grained matrix which is mainly clay and some very fine-grained calcite.

Most of the shell fragments are small and well-sorted with a common grain size of about 0.05 to 0.2 mm but there are a few larger, generally elongate fragments up to about 5 mm long. There are some cylindrical spicules with a diameter of about 0.05 mm and length varying up

to about 0.5 mm. These are composed mainly of opaline silica and some have a central canal, some have been leached. Detrital quartz grains are well sorted with an average grain size of about 0.05 mm and there are a few small heavy mineral grains including opaque oxide, zircon and tourmaline. There are a few grains composed of a very fine-grained, green, micaceous mineral which may be glauconite or altered glauconite. Very small grains of pyrite are scattered through the sediment, some occurring within fossil fragments and some as very small aggregates in the matrix. There are some very small spheres probably of framboidal pyrite and one or two larger, cubic crystals of recrystallized pyrite.

The matrix is composed mainly of turbid, brownish-stained clay containing very small fragments and particles of calcite, a few minute grains of pyrite and rare traces of leucoxene. In the area sectioned there is no evidence to suggest silicification of this matrix.

Conclusion:

Predominantly fine-grained, argillaceous limestone or marl.

(after Whitehead, 1979; AMDEL Report GS 2673/79)

Sample: 6627 RS 00145; TS41260

Location:

Longyear (Australia) Pty Ltd diamond drill test hole, Marion Rd, Mitchell Park, Section 82, Hundred of Noarlunga; core at 178.23-178.33 m, 'upper Blanche Point Formation' (='Blanche Point Soft Marls Member' of Reynolds, 1953).

Hand Specimen:

A pale grey, soft, fine-grained rock with a relatively low specific gravity suggesting a high porosity.

Thin Section:

A visual estimate of the minerals is as follows:

	%
Calcite	55-60
Clay	25-30
Siliceous spicules	10-15
Quartz	2-3
Heavy mineral grains	trace
Glauconite?	minute trace
Pyrite	trace

This is similar to sample RS 00144 in that it contains a large proportion of well sorted, small fragments of calcareous fossils in a predominantly clay matrix but it differs from the previous specimen in that there is a higher proportion of siliceous spicules and there are few, if any, larger shell fragments. The calcareous fragments have a common grain size of about 0.05 to 0.2 mm and elongate fragments tend to be subparallel probably to the direction of bedding but there are many which are

not oriented. The spicules also show preferred orientation and vary in length up to about 1 to 1.5 mm but they have a diameter of about 0.3 to 0.5 mm generally with a very narrow, central canal. Detrital quartz grains are about 0.05 mm in size with a few up to 0.1 mm and are mainly angular to subangular. Heavy mineral grains include leucoxene and zircon. There are a few small grains of pale green glauconite? and one turbid, brownish fragment which could be phosphatic.

The matrix is mainly very fine-grained, brown-stained clay containing minute particles of calcite and small grains and aggregates of pyrite. There is some very fine-grained pyrite in a few shell fragments and also encrusting, or within a few spicules.

Conclusion:

Argillaceous limestone or marl similar to sample RS 00144 except that there are few, if any, larger shell fragments and there is a slightly higher proportion of siliceous spicules.

(after Whitehead, 1979; AMDEL Report GS 2673/79)

PORT WILLUNGA FORMATION

Sample: 6627 RS 00143; TS 41258

Location:

Longyear (Australia) Pty Ltd diamond drill test hole, Marion Rd, Mitchell Park, Section 82, Hundred Noarlunga; core at 136.63-136.68 m; Aldinga Member; lower, sand unit; 'pseudo-Tortachilla' facies (Lindsay, 1981).

Hand Specimen:

A relatively soft dull yellowish-grey to greenish-grey rock containing some quartz sand, clay and fossil fragments most of which are soft and partly leached. There may be some graded bedding in that towards one end of the sample there is a higher proportion of dark grains and fragments up to 1 mm in size and a few larger quartz grains. Some of these dark grains are highly polished.

Thin Section:

A visual estimate of the constituents is as follows:

	%
Detrital quartz	50-60
Calcareous fossils	20-25
Interstitial clay	20-25
Grains composed of clay and goethite	2-3 (varies)
Glauconite? grains	trace
Lithic grains	trace
Tourmaline	trace

The sediment contains well sorted detrital quartz grains and larger calcareous fossil fragments loosely cemented by a clay matrix.

Most of the detrital quartz grains are between 0.1 and 0.2 mm in size but there are a few scattered larger grains about 0.6 to 1 mm in size and these tend to be concentrated at one end of the sample. A few of the larger grains are partly encrusted with a thin layer of iron oxide and there is one quartz grain surrounded by concentrically banded iron oxide resulting in a grain with the general appearance of a ferruginous oolite with a large, quartz nucleus. There are a few detrital feldspar grains of similar size to the smaller quartz grains. Grains composed largely of clay and goethite are commonly 0.5 to 1 mm in size, well rounded or oval and some of these also have a thin, outer layer of iron oxide which is probably the cause of the polished appearance of some of these grains in hand specimen. Some of these grains which have not been so extensively altered contain a green, glauconite-like mineral associated with yellow to orange, iron oxide-stained clay and it is possible that at least some of these represent oxidized glauconite grains. Calcareous fossil fragments vary in size from about 0.2 mm to over 2 mm long and they also vary in shape, Some have cellular structures, some are long and curved and a few are circular. Some of the elongate fragments show preferred orientation which may be the direction of bedding.

In the coarser-grained portion of the sample there are a few lithic grains 2 to 4 mm long. Two of these are of weathered and oxidized, fine-grained ferruginous rock possibly ferruginous siltstone and one is of coarser-grained rock composed mainly of quartz with some iron oxide.

The detrital grains and fossil fragments are loosely cemented by turbid, fine-grained clay which is lightly stained by iron oxide. Some of this was lost during preparation of the thin section.

Conclusion:

Fossiliferous, argillaceous sandstone. The detrital material is bimodal in that it contains well sorted, fine-grained quartz with larger grains some of which are of oxidized, rounded and polished clay and iron oxide and a few of these could be oxidized glauconite. There are also a few well rounded and oxidized lithic grains and numerous fragments of calcareous fossils. (after Whitehead, 1979; AMDEL Report GS 2673/79)

Sample: P749/78; TS 40269

Location:

Supreme Court Library building, foundation test bore PB-1 (Ref. bore 33), S.W. Victoria Square; tube-core from 27.4-29.0 m; Aldinga Member, upper mudstone (silt/clay) unit.

Rock Name:

Glauconitic and sandy marl.

Hand Specimen:

A grey coloured rock with some green glauconite pellets and shell fragments.

Thin Section:

An optical estimate of the constituents gives the following:

Argillaceous matrix	30
Calcite	30
Glauconite	20
Quartz	15
Feldspar	2
Dolomite	2
Muscovite-sericite	Trace-1
Bright green phyllosilicates	Trace
Opaques and semi-opaques	1

This sample consists of glauconite pellets, fine grained quartz-rich detritus and shell fragments disseminated through a turbid matrix of intimately intergrown clay and carbonate. The matrix generally has a turbid character and at least locally shows moderate iron staining to produce a translucent, reddish-brown colour. The fine grained nature of the matrix makes estimation of the mineral proportions difficult, so that the above estimates, particularly the proportion of argillaceous matrix and calcite, are somewhat tentative. At least half of the calcite in this rock forms fine intergrowths with the argillaceous matrix, while the other half appears to represent broken shell fragments. The shell fragments are quite small and rarely exceed 0.05 mm in size. The calcite which is intimately intergrown with the matrix generally has a turbid, somewhat micritic character. Small amounts of unstained carbonate (probably dolomite) were also noted locally as small crystals below 0.05 mm in size, intergrown with the argillaceous matrix.

Glauconite is concentrated in round pellets up to 1 mm in diameter which show varying degrees of oxidation. Most of the pellets are quite fresh with only a few showing incipient oxidation to translucent, reddish-brown limonitic material. A few flakes of a bright green phyllosilicate similar to that described in sample P744/78 (TS40264) were also noted in this rock. A fine, sand-sized detritus (typical grain size about 0.1 mm with a few grains up to 0.5 mm) is comprised mainly of quartz, although a small proportion of feldspar is also present. These detrital grains generally exhibit angular to sub-angular shapes, although some of the larger grains exhibit subrounded shapes. The feldspar consists of polysynthetically twinned plagioclase and minor gridiron twinned microcline and generally has a very fresh character, although a few grains show incipient alteration to finely divided sericite. A few detrital muscovite flakes up to 0.5 mm long are also disseminated through the rock and generally exhibit fibrous, degraded textures.

This is a marly sediment with a significant fine, sand-sized detrital component, angular shell fragments and glauconite pellets.
(after Radke, 1978; AMDEL Report GS 4113/78)

Sample: P42/77: TS 37327

Location:

Port Willunga Formation, type section, Port Willunga, outcrop; 2-3 m above the base of the Ruwarung Member, cherty nodule.

Rock Name:

Fossiliferous chert.

Hand Specimen:

A massive pale brown to tan coloured rock with a slightly friable, granular texture.

Thin Section:

An optical estimate of the constituents gives the following:-

	%
Microcrystalline, cryptocrystalline and opaline silica	55
Carbonate shell fragments	35
Detrital quartz grains	5
Clay	5
Opaques and semi-opaques	1

This sample consists mainly of a siliceous matrix through which shell fragments are disseminated. Most of the matrix consists of pale brown opaline silica with an isotropic character but locally the silica has undergone recrystallization to produce microcrystalline to cryptocrystalline intergrowths with an interlocking, cherty texture and a maximum grain size of 0.05 mm.

The shell fragments are up to 1 mm in size and consist mainly of finely granular carbonate most of which is stained by the alizarin red-S solution indicating that it is calcite. Locally shell fragments appear to have been replaced by microcrystalline to cryptocrystalline silica with some fragments now consisting almost completely of finely granular silica. A few siliceous spicules which now consist of microcrystalline silica are also disseminated through the rock.

The detrital quartz forms disseminated grains between 0.05 and 0.3 mm in size. Minor clay is also present mainly as ovoid bodies up to 0.3 mm in size which have a translucent brownish colour (most likely due to iron staining) and could represent faecal pellets. Minor clay also occurs in the chambers of some shell fragments.

Opaques occur mainly as small, anhedral disseminated grains below 0.3 mm in size although locally there is a concentration of opaques as arcuate bodies which appear to represent shell fragments which have been completely replaced by opaque material (probably iron oxides). Small translucent reddish-brown rhombs below 0.05 mm in size are disseminated through the rock and most likely represent carbonate rhombs which have been partially replaced by translucent, reddish-brown iron oxides.

This sample is comprised of shell fragments disseminated through a siliceous matrix and is very similar in mineralogy, texture and origin to sample P41/77 although it appears that this sample has undergone slightly more recrystallization to produce a somewhat more coarsely granular siliceous matrix.
(after Cooper, Radke and Brown, 1977; AMDEL Report MP 2416/77).

Sample: P582/70; TS 25666 (F176/70 of Lindsay, 1970a)

Location:

Onkaparinga River estuary, near mouth, Port Noarlunga South, Noarlunga Embayment. Port Willunga Formation, Ruwarung Member, cherty nodule from basal bed.

Rock Name:

A siliceous rock (glauconitic, fossiliferous, spicular chert).

Hand Specimen:

A compact, massive, medium grained, yellow-buff rock, with rare indications of fossils.

Thin Section:

An optical estimate of the constituents gives the following:

	%
Quartz	15-20
Opaline silica) Zeolite)	65-70
Glauconite	15
Opaques and iron oxides	1-2

Tourmaline	Trace
?Zircon	Trace
Mica (biotite)	Trace
Rutile	Trace

The rock consists of sub-angular to sub-rounded quartz grains, ovoid pellets of glauconite and clay, fossil remains (sponge spicules and rarer foraminifera) and minor opaques, set in a dirty brown matrix of opaline silica with very minor zeolite. Quartz grains average 0.05-0.1 mm in diameter, glauconite pellets average about 0.3-0.5 mm. Zeolite forms rare well developed grains and lines the walls of a few cavities. Additional zeolite may be present with the opaline silica, but the proportions cannot be easily determined. The glauconite is partly oxidised and is greenish-brown in colour. The pellets have the appearance of coprolites. Glauconite is also found rarely in the centre of sponge spicules or as an infilling of foraminifera. Other mud pellets appear to be coprolitic. The cause of brown coloration of the matrix is not readily determinable. Little particulate matter was detected at 625X magnification. The matrix is not uniformly isotropic and signs of crystallisation are present with some development of very small biotites. Opaques consist of iron oxide, ?hematite or magnetite. Other grains which may have been pyritic are now represented by red-brown alteration products.

Diagenesis has allowed development of opaline silica, glauconite and zeolite, possibly partly at the expense of original carbonate in the rock.
(after Davy, 1970; AMDEL Report MP 1682/71)

Sample: 6627 RS 00142; TS 41257

Location:

Longyear (Australia) Pty Ltd diamond drill test hole, Marion Road, Mitchell Park, Section 82, Hundred of Noarlunga; core at 109.96-110.03 m; Ruwarung Member.

Hand Specimen:

A fine-grained, predominantly grey rock with some variations in colour which do not appear to be related to bedding. When closely examined under low magnification the outline of very small fossils can be seen.

Thin Section:

A visual estimate of the constituents is as follows:

	%
Matrix of opal and probably minor clay	50-60
Detrital quartz	15-20
Calcitic fossil fragments	10-15
Chalcedonic quartz	10-15
Glauconite	trace
Pyrite	trace
Tourmaline	minute trace

This is a fine-grained sediment containing detrital quartz grains and small fossils cemented by a turbid matrix now composed largely of opal.

The detrital quartz grains are well sorted with a common grain size of about 0.06 to 0.1 mm. Most of them are angular to subangular and many have small irregularities and embayments in the surface suggesting some corrosion. They are scattered uniformly throughout

the sediment and in general they are not touching. Calcareous fossil fragments are not as well sorted as the quartz grains and many are thin, curved elongate fragments of varying length. The sediment also contains numerous siliceous spicules with a diameter of about 0.05 mm and lengths varying up to about 0.5 mm. These are composed mainly of chalcedonic quartz and a few have a very small, central canal. In some zones in the rock these spicules have been leached leaving small, elongate cylindrical voids. There are a few grains of green glauconite generally less than 0.1 mm in size, a few iron oxide-stained grains and very few grains of tourmaline. In some zones there are a few rounded fragments of brown-stained clay.

The matrix surrounding and cementing these detrital grains and fossil fragments is composed predominantly of turbid and brownish stained opal containing minute impurities probably of clay. In a few elongate patches some of this matrix opal has been replaced by clear chalcedonic quartz.

Conclusion:

Fossiliferous, sandy chert in which the cementing silica is predominantly opal (opaline chert).
(after Whitehead, 1979; AMDEL Report GS 2673/79)

Sample: P809/68; TS 22392 (F114/68)

Location:

SADME Observation bore PTG 62 ('Bore N') 5 km southeast of Two Wells, Adelaide Plains Sub-Basin; Section 251, Hundred of Port Gawler; diamond drill core at 111.94-112.01 m; top of Ruwarung Member (Lindsay, 1969).

Rock Name:

Sandy and glauconitic, fossiliferous chert.

Hand Specimen:

A medium grey, massive, hard, fine-grained, indurated, muddy limestone with a few sporadically distributed coarse mollusc shells which form only 1-2% of the rock.

Thin Section:

An optical estimate of the constituents gives the following:

	%
Opaline silica	50
Quartz	30
Calcite	10
Glauconite	10
Microcline	1

Quartz and microcline grains and the bulk of fossil tests or fragments are of fairly uniform size (0.1-0.3 mm). Glauconite forms fresh, green bodies of oval or lobate shape and much of this has evidently been formed as fossil infillings. The carbonate of such latter fossils has been largely replaced by opaline silica or a secondary glauconite deposit.

Fossils comprise roughly 30% of the rock and account for virtually all the carbonate present.
Foraminifera and ?mollusc fragments are present in roughly equal proportions together with a minor proportion of spicular or hollow spine-like bodies, which latter are largely formed of or replaced by opaline silica. Rare calcitic forms filled by glauconite occur.
The matrix of the rock is a microcrystalline, almost isotropic mass of very pale brown, opaline silica.
The rock has undergone conspicuous diagenetic changes - the development of glauconite and silicification of the matrix.

Sample: P810/68; TS 22393 A,B (F115/68)

Location:

As above, but diamond-drill core at 112.47-112.52 m.

Rock Name:

Sandy and glauconitic fossiliferous chert.

Hand Specimen:

A fine-grained, massive, hard, medium to dark grey, indurated limestone with rare mollusc shells of 4-5 mm size.

Thin Section:

An optical estimate of the constituents gives the following:

	%
Opaline silica	50
Calcite	15
Quartz	15
Glauconite	10
Microcline	Trace
Tourmaline	Trace

Quartz is angular and bimodal in grain-size. The greater proportion of the mineral has a grain-size of 0.05 to 0.1 mm while a minor proportion (ca 5%) is of 0.2-0.3 mm size. Feldspar is of the finer grain-size. Calcite occurs almost entirely as organic derived material, mainly as foraminiferal tests or mollusc fragments. Traces of extremely fine material occur in the matrix. Glauconite occurs as pellets up to 0.5 mm across; these are after foram. fillings.

The matrix consists of micro- to cryptocrystalline, almost isotropic, opaline silica with traces of fine calcite. Fossils are abundant and comprise 30-40% of the rock. Roughly half of these fossils are of hollow, opalised spines of 40 microns diameter, commonly filled by glauconite. The remainder are mainly foraminifera with lesser mollusc fragments. Diagenetic effects include the silicification of the matrix by opaline silica formation following the earlier development of glauconite as infillings in fossil tests.

Sample: P815/68; TS 22398A,B (F120/68)

Location:

As above but diamond drill core at 112.98-113.06 m.

Rock Name:

Sandy and glauconitic chert.

Hand Specimen:

A grey and buff, massive, fine-grained, muddy rock in which coarse, irregular areas of harder, grey material are developed among more friable, buff coloured rock. This effect is evidently produced by differential silicification.

Thin Section:

An optical estimate of the constituents gives the following:

	%
Opaline silica	55
Quartz	20
Calcite	15
Glauconite	10
Microcline	1
?Pyrite	Trace

This rock is very similar to P811/68 in grain-size, mineralogy and textures.

Quartz and other detrital minerals range from 0.05 to 0.15 mm in grain-size.

Calcite occurs exclusively as bioclastic grains of similar size to the quartz grains.

Fossils comprise about 25% of the rock and consist mainly of silicified spines, spicules, calcareous foraminifera and minor amounts of ?mollusc fragments, ?echinoid plates, etc. Glauconite occurs mainly as internal casts of foraminifera or as infillings in the hollow spines referred to above. Mud pellets, 3-5 mm are common.

The matrix of the rock is composed of very pale brown microcrystalline opaline silica.

Diagenetic features of the rock include the formation of glauconite, ?pyrite and the silicification of the rock matrix.

Sample: P811/68; TS 22394A,B (F116/68)

Location:

As above but diamond drill core at 115.01-115.06 m.

Rock Name:

Sandy and glauconitic fossiliferous chert.

Hand Specimen:

A grey massive, fine-grained, indurated muddy limestone with irregular dark flecks and ?burrow infillings.

The specimen has a dense darker grey central region and a more friable outer region of paler, buff-grey colour.

Thin Section:

An optical estimate of the constituents gives the following:

	%
Opaline silica	50
Calcite	20
Quartz	20
Glauconite	7
Microcline	1
Hornblende, Tourmaline, ?Clay, Opaque	Trace

In most features this rock is essentially similar to P810/68, above.

A notable difference in fossil content is that foraminifera are much subordinate to silicified, hollow spines and spicular fossils. Fossils comprise an estimated 40-50% of the bed. Glauconite forms rounded pellets - some muddy coprolites and others with relict fossil (foram.) traces. The mineral also commonly forms a central filling material in fossil spines. Diagenetic effects include the development of glauconite and the silicification of the rock matrix. The variations in hand specimen friability are apparently due to differential silicification.

Sample: P812/68; TS 22395 (F117/68)

Location:

As above but diamond drill core at 128.02-128.09 m.

Rock Name:

Partly zeolitised, glauconitic, sandy fossiliferous chert.

Hand Specimen:

A grey-brown, massive, fine-grained muddy rock with diffuse markings suggesting reworking of the bed by burrowing organisms which have destroyed bedding laminations. Dark green flecks of glauconite are apparent. Rare traces of coarse mollusc shells are also present.

Thin Section:

An optical estimate of the constituents gives the following:

	%
Calcite	15
Quartz	15
Glauconite	5
Pyrite	1-2
Tourmaline, Microcline, ?Clay, Mica, Opaque	Trace
Matrix (opaline silica and zeolite)	65

The detrital quartz and feldspar are of 0.05 to 0.1 mm grain size. Calcite occurs as bioclastic material of similar size but also as abundant, much finer, disseminated grains throughout the matrix.

Much of the finer calcite has no distinctive organic form but this may be due to changes attending silicification. Glauconite forms pellets up to 0.5 mm; many of these are not foram. infillings but have the appearance of coprolites. Other mud pellets lacking glauconite, also appear to be of this origin. Fossils form at least 10% of the bed but are largely comminuted and tend to be obscured.

The matrix consists of pale brownish opaline silica with a notably high proportion of a well-crystallized zeolite mineral. The zeolite forms aggregates of euhedral grains each grain being about 10 microns across and the mineral was identified by x-ray diffraction as similar to heulandite. (Proportions of opal and zeolite cannot be estimated visually).

The brownish stain appears to be due to bituminous matter; pyrite is fairly abundant in some areas forming trains of microcrystalline grains which have generally formed inside fossil tests. Each individual grain is 3-4 microns in diameter. Diagenetic effects include the development of pyrite, glauconite, opaline silica and a zeolite.

Sample: P813/68; TS 22396A,B (F118/68)

Location:

As above but diamond drill core at 129.54 m.

Rock Name:

Partly zeolitised, glauconitic sandy, fossiliferous chert.

Hand Specimen:

A grey-brown, fine-grained, muddy rock with an indistinct fine bedding lamination and traces of mud pellets of about 1 mm size.

Thin Section:

An optical estimate of the constituents gives the following:

	%
Matrix (opaline silica + zeolite)	55
Quartz	20
Calcite	12
Glauconite	12
Pyrite	1
Tourmaline, Microcline, Micas	Trace

The rock texture and mineralogy are similar to those of P812/68 described above. Notable differences include the lower calcite content, higher quartz and glauconite values.

Glauconite internal casts after foraminifera are the major occurrence of the mineral.

Other, non-glauconitic pellets corresponding to those visible in hand-specimen are evidently coprolites. These have a similar composition to the material forming the bed.

Zeolite occurs as in the previous specimen but, once again, the fine grain-size makes visual estimation of the relative proportions of the matrix minerals impossible. It is, however, estimated that the mineral forms more than 5% of the rock.

Diagenetic changes include the formation of pyrite, opaline silica and zeolite.

Sample: P814/68; TS 22397 (F119/68)

Location:

As above but diamond drill core at 135.94 m.

Rock Name:

Partly zeolitised, glauconitic, sandy, fossiliferous chert.

Hand Specimen:

A grey-brown, fine-grained, massive mudstone.

Thin Section:

The rock is indistinguishable, microscopically, from specimen P813/68, above.

(after Kelly, 1969, AMDEL Report MP 2404/69)

HALLETT COVE SANDSTONE/BURNHAM LIMESTONE

Sample: P741/78; TS 40261

Location:

A.N.A. building site (Crawford, 1956b), cnr North Tce/Bank St, City of Adelaide; diamond-drill core, DDH-4, 12.0-12.7 m; Hallett Cove Sandstone.

Rock Name:

Fossiliferous, dolomite-cemented sandstone.

Hand Specimen:

A tan coloured rock with ribbed, dull white shell fragments.

Thin Section:

An optical estimate of the constituents gives the following:

	%
Quartz	50
Dolomite	30
Calcite	15
Feldspar	2
Muscovite, rutile	Trace-1
Tourmaline, zircon, garnet	Trace
Opaques and semi-opaques	2

This sample consists essentially of detrital quartz grains and calcite shell fragments cemented by granular dolomite. The detrital quartz grains have a bimodal character, most having a grain size of about 0.1 mm, although a larger set of detrital grains generally about 0.5 mm in diameter are also present. The finer-grained detritus generally exhibits a subangular shape but the coarser-grained detritus exhibits a variety of shapes from subangular to well rounded.

Other detritus consists of minor feldspar with traces of rutile, muscovite, tourmaline, zircon and garnet. The feldspar consists of both polysynthetically twinned plagioclase and untwinned orthoclase and generally has a very fresh, unaltered character, although a small proportion of the orthoclase has a somewhat turbid character due to incipient alteration. Most of the tourmaline has a pleochroic green colour although some pleochroic orange tourmaline was also noted. A few tourmaline grains with authigenic overgrowths are also present. The muscovite forms well developed flakes up to 0.1 mm in length which are almost certainly of detrital origin. Both the zircon and garnet form small detrital grains generally below 0.05 mm in size.

The shell fragments are comprised mainly of fibrous calcite and the proportion of calcite noted in the above list of minerals would represent an approximate proportion of shell fragments. The most common shell fragment is an arcuate pelecypod-appearing shell with a ribbed character, although a few round to ovoid calcite fossils were also noted. Minor calcite is also intergrown with a granular dolomite cement and appears to be remnants of an original calcite cement.

Most of the granular dolomite which comprises the matrix is considered to be a product of dolomitization of primary calcite cement rather than original dolomite. Many of the calcite shell fragments show some marginal replacement by finely granular dolomite, indicating that dolomitization has occurred.

Minor opaques are disseminated through the rock as anhedral grains below 0.1 mm in size and locally translucent reddish-brown iron oxides are intergrown with the carbonate matrix or around the margins of some calcite shell fragments. Traces of translucent, yellow rutile form angular, detrital grains up to 0.1 mm in size.

This is a detrital sediment which contains a bimodal, quartz-rich detrital component and large calcite shell fragments cemented by granular dolomite believed to have been produced by dolomitization. The shell fragments also locally show marginal dolomitization as well as localised marginal oxidation to produce translucent iron oxides.
(after Radke, 1978; AMDEL Report GS 4113/78)

Sample: P740/78; TS 40260

Location:

A.N.A.building site (Crawford, 1956b), cnr North Tce/Bank St, City of Adelaide; diamond drill core, DDH-3, 12.1-13.3 m; Hallett Cove Sandstone.

Rock Name:

Fossiliferous and sandy limestone.

Hand Specimen:

A massive, pale buff coloured rock.

Thin Section:

An optical estimate of the constituents gives the following:

	%
Calcite	40
Shell fragments	35
Quartz	25
Feldspar	1
Zircon, muscovite, epidote	Trace
Garnet, tourmaline, amphibole	Trace
Opaques and semi-opaques	Trace-1

This sample consists essentially of fossil, shell fragments and sand-sized quartz grains disseminated through a fine-grained calcite cement. The calcite cement forms a mosaic with a typical grain size of about 0.01 to 0.02 mm. Most of the shell fragments consist of very fine-grained, turbid calcite, but a few shell fragments comprised of somewhat fibrous-appearing calcite were also noted.

The detrital quartz grains generally exhibit sub-angular to subrounded shapes with a grain size between 0.05 and 0.5 mm. Minor detrital feldspar is also present as subangular grains generally about 0.1 mm in size. At least some polysynthetically twinned plagioclase was positively identified and other untwinned potash feldspar could also be present. All of the detrital feldspar has a very fresh character, showing virtually no alteration to sericite. One polycrystalline quartz grain contains intergrowths of finely-divided muscovite flakes. Traces of zircon, epidote, garnet, tourmaline and amphibole were also noted as detrital grains. The tourmaline typically has a pleochroic green colour, although at least one grain of pleochroic orange tourmaline was also noted. The epidote generally has a pleochroic yellow to clear colour. Only a single, detrital amphibole grain was noted and consisted of clear, tremolitic-appearing amphibole. Opaques are also disseminated through the rock as anhedral grains generally below 0.1 mm in size. A few translucent, yellow, semi-opaque grains were also noted and could represent detrital rutile.

This is a fossiliferous limestone with a significant detrital component comprised mainly of quartz and shell fragments.
(after Radke, 1978; AMDEL Report GS 4113/78)

Sample: P739/78; TS 40259

Location:

Supreme Court Library building, Gouger St, City of Adelaide (Crawford, 1956a), foundation test bore PB-1 (Ref. Bore 33), tube-core 15.2-16.5 m; ?Burnham Limestone.

Rock Name:

Limestone (calcrete)

Hand Specimen:

A friable, dull white rock with localised greyish-green, argillaceous patches.

Thin Section:

An optical estimate of the constituents gives the following:

	%
Calcite	85
Quartz	7
Clay	5
Feldspar	Trace-1
Tourmaline	Trace
Opaques and semi-opaques	2

This rock is comprised mainly of very fine-grained, locally micritic calcite which, at least locally, has a somewhat fragmental-appearing texture. The finest-grained, micritic calcite has a turbid character and tends to form angular, fragmental-appearing patches up to several millimetres in size separated by slightly coarser-grained (typical grain size below 0.05 mm) calcite. At least locally the slightly coarser-grained

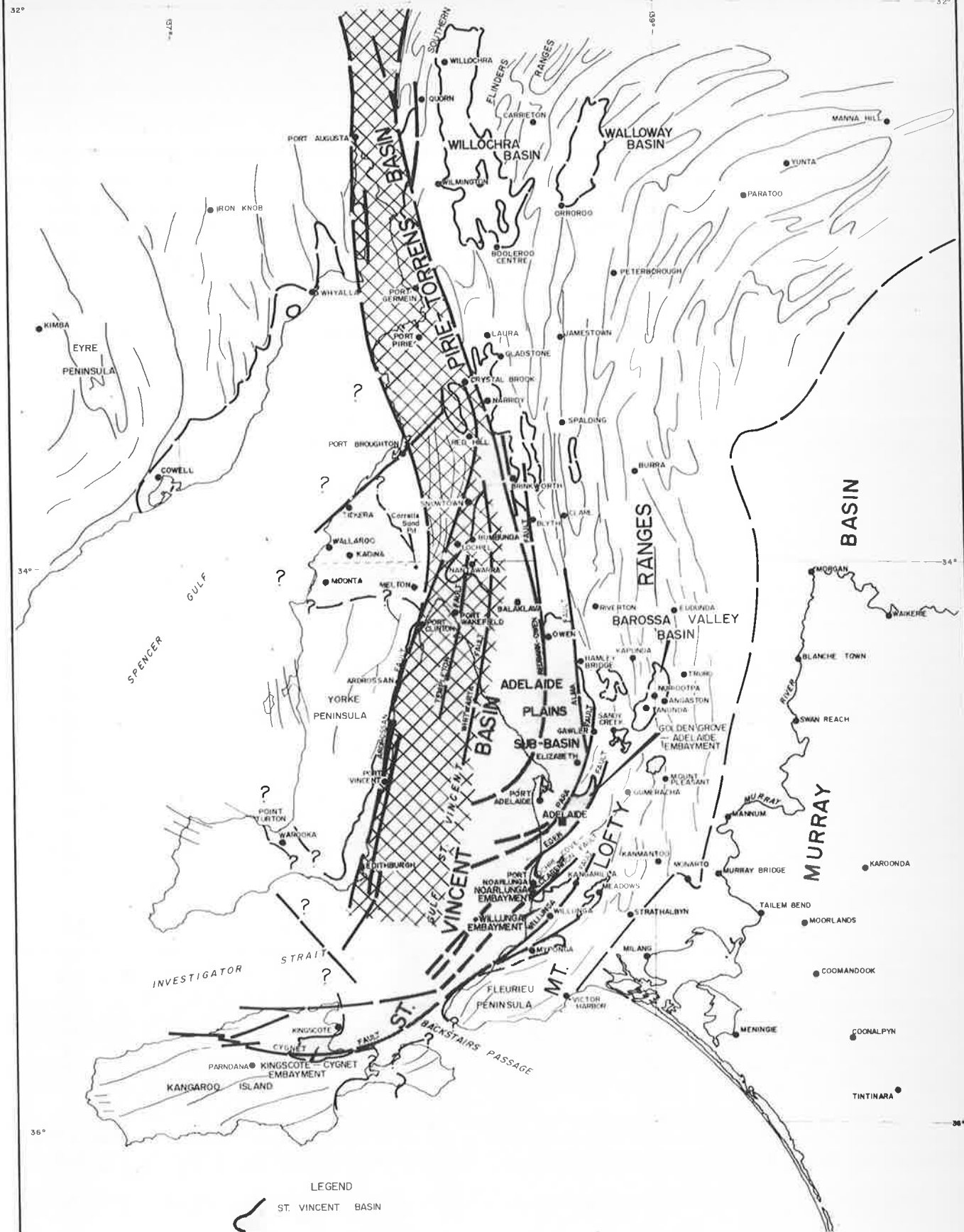
calcite tends to form vein-like structures which separate the patches of finer-grained, micritic calcite.

The clay mineral forms fibrous-appearing flakes with a reddish-brown somewhat iron-stained colour. This clay mineral also generally occurs interstitially between the finer-grained micritic calcite areas and is often intergrown with the slightly coarser-grained calcite. Minor fibrous clay also forms narrow fracture and vein fillings or irregular patches up to a few millimetres in size. Translucent, reddish-brown to opaque iron oxides are locally intergrown with the clay but also form narrow fracture fillings up to 0.1 mm wide or irregular patches up to 0.5 mm in diameter.

Detrital quartz grains, generally between 0.5 and 0.15 mm in diameter, are disseminated through the rock and exhibit subrounded to subangular, or rarely angular, shapes. A few angular, detrital feldspar grains are also disseminated through the rock. At least some of the feldspar consists of polysynthetically twinned plagioclase and it invariably has a very fresh character, showing virtually no evidence of sericitization. Traces of pleochroic, green tourmaline form detrital grains up to 0.1 mm in size. At least locally there is a concentration of detrital quartz grains in some fibrous, clay-rich patches, although most of the quartz occurs intergrown with carbonates.

This is a limestone with a fragmental-appearing texture typical of calcrete.

(after Radke, 1978; AMDEL Report GS 4113/78)



PLAN 1

DEPARTMENT OF MINES AND ENERGY – SOUTH AUSTRALIA

TERTIARY STRATIGRAPHY & FORAMINIFERA

ADELAIDE CITY AREA

STRUCTURAL SETTING OF THE ST. VINCENT BASIN AND RELATION TO SURROUNDING CAINOZOIC BASINS

	COMPILED J.M.L.	DRN SR	SCALE	PLAN NUMBER
DIRECTOR GENERAL	11/11/80	CKD	DATE AUGUST 1979	80-762

138°00'
138°30'
139°00'
34° 00'
34° 15'
34° 30'
34° 45'
35° 00'
35° 15'
35° 30'

SADME CLINTON NORTH COAL BORES C23,23A (1961)
Subsurface type section of Clinton Formation (51+m)
Cz 46
Tac 51+

SADME INKERMAN COAL BORE I41A (1975)
Q 15
Tmp 25
Taj 1
Ter 9
Tac 58
?P 3·5+

SADME BARABBA-5 BORE (1977)
Q 16
Qpc 35
Tmp-Ter-Tac 26·5
P 22·5+

SADME BARABBA-4 BORE (1977)
Q 35
Qpc 20
Tmp-Ter 11
Tac 10
?P 19+

DUBLIN GOVT. BORE (1887)
Q 39
Tmp 35·5
Teb 23
Tes 4·5
?Tac 4
?P/?€ 72+

SADME BARABBA-1 BORE (1977)
Q 38
Qpc 26
Tmp 28
Ter 17·5
Tac 59·5
?P 18+

SADME BARABBA-3 BORE (1977)
Q-Qpc 63
Tmp-Ter 43
P 23+

SADME LIGHT-1 BORE (1964)
Q 55
Tp 12
Tmp 91·5
Teg 7·5
Teb 5
P 1+

BEACH PETROLEUM (N.L.) HALLIONS-2 WELL (1963)
Q 58
Tp 6
Tmp 67
Tmp-Teg 37
Teb 16+

SADME KORUNYE-3 BORE (1978)
Q 32
Qpc 7·5
Tmp 87·5
Teg 6·5
T 40
P 24·5+

SADME BUCKLAND PARK-1 BORE (1978)
Q 65·5
Tp 22
Tmp 130·5
Teg 3
Teb 18
Tes 33
Tac 8
P 21+

SADME OBS BORE PTG 62 (1968)
Q 22 6628-0944
Qpc 17·9
Tp 0·3
Tmp 97+

SADME OBS. BORE MUW 11 (1968)
Q 8
Qpc 116
Tac 47
P 3+

SADME VIRGINIA OBS BORES MPA 64,65.A2
Subsurface type section of Munno Para Clay (7m)
Q 48
Qpc 11
Tp 7
Tmp ~139
Teb 23
Tes 37
Ten 11
?P 9+

SADME OBS. BORE PTG 13 PT GAWLER (1963-4)
Q 71
Tp 28
Tmp 116
Teb 62
Tes 32
Tac 22
Ten 19
?€ 1+

S.A. HOUSING TRUST ELIZABETH OVAL-1 BORE
Q 52
Qpc 49
Tp 12
Tmp 174
Teg 12
Teb 41
Tac 5
Tes 12+

OLD DRY CREEK BORE (1890)
Subsurface type section of Dry Creek Sand (27m)
Q-Qpc 98
To 3·9+

LONGYEAR BORE (1976)
Cz 69
Tmp 73
Teg 7
Teb 48
Tes 10·2
Tac 25·1+

E.&W.S. SEAFORD DRAINAGE BORE (1972)
Q 14
Qpc 6
Tmp 56
Teg 23
Teb 54
Tac 26
Ten 11·5+

SADME OBS. BORE WLG 38 (1974)
Q-Qpc 44
Tmp 155
Teb 46
Tes 11
Ten 53
?P/?€ intersected

S.A. BLACK COAL SYNDICATE BORE (1930)
Cz 84
Tmp 117
?P 127
P 2+

SADME HINDMARSH TIERS OBS. BORE ENB 2 (1975)
Cz 7
Tmp 119
P 30
?€k intersected

Type section of Hallett Cove Sandstone (12m)

TYPE SECTIONS
North (~20m) and South (~30m) Maslin Sands
Tortachilla Limestone (2·5m) & Blanche Pt Formation (31m)
Chinaman Gully Fm. (2m)
Port Willunga Fm. (~31m)

STRATIGRAPHIC SYMBOLS

Q .....Quaternary units: Hindmarsh Clay (mainly) and younger.
Qpc .....Carisbrooke Sand and correlatives.
Tp .....Pliocene units: Hallett Cove Sandstone, Dry Creek Sand, Croydon Formation.
Tmp .....Port Willunga Formation (latest Eocene to Middle Miocene) including Munno Para Clay Member (Miocene), Ruwarung Member (Oligocene) and Aldinga Member (latest Eocene).
Teg .....Chinaman Gully Formation (late Eocene) including Tandanya Sand Member.
Teb .....Blanche Point Formation (late Eocene) including Gull Rock Member; and Tortachilla Limestone (late Eocene).
Ter .....Rogue Formation (late Eocene and Oligocene).
Tej .....Port Julia Greensand (member of Rogue Formation) (late Eocene).
Tes .....South Maslin Sand (? Middle to Late Eocene).
Ten .....North Maslin Sand (Middle Eocene).
Tec .....Clinton Formation (Middle Eocene to Miocene).
Cz .....Undifferentiated Cainozoic units (Tertiary-Quaternary).
T .....Undifferentiated Tertiary units.
P .....Permian units (Cape Jervis Beds).
€ .....Cambrian "bedrock".
€k .....Kanmantoo Group "bedrock".
P .....Proterozoic "bedrock".

BORE UNIT NUMBER INDEX

Beach Petroleum (N.L.) Hallions-2	6528-0002
Dublin Govt. bore	6529-0083
E&W.S. Seaford Drainage bore	6527-0779
Longyear bore	6627-1691
Old Dry Creek bore	6628-4339
S.A. Black Coal Syndicate bore	6527-0420
SADME Barabba-1	6529-0023
SADME Barabba-3	6629-0670
SADME Barabba-4	6529-0015
SADME Barabba-5	6529-0008
SADME Buckland Park-1	6528-0533
SADME Clinton Nth. Coal C23	6529-0326
C23A	6529-0327
SADME Inkerman Coal I41A	6529-0325
SADME Korunye-3	6628-8599
SADME Light-1	6528-0058
SADME Obs bore ENB 2 Hindmarsh Tiers	6627-0231
SADME Obs bore MPA 64 Virginia	6628-2470
MPA 65 Virginia	6628-2471
SADME Obs bore MUW 11	6628-1618
SADME Obs bore PTG 13 Pt Gawler	6528-0243
SADME Obs bore WLG 38	6527-0552
SADME Virginia bore A2	6628-2472
SAHT Elizabeth Oval-1	6628-3095

Borehole (with name or observation number, year drilled and stratigraphic summary).
Fault (showing downthrow direction).
Approximate geological boundary.
Cainozoic embayments and small marginal marine basins.
Coalfields (after Meyer-1976).

5 0 5 10 15 20
KILOMETRES

PLAN 2

DEPARTMENT OF MINES AND ENERGY – SOUTH AUSTRALIA

TERTIARY STRATIGRAPHY & FORAMINIFERA

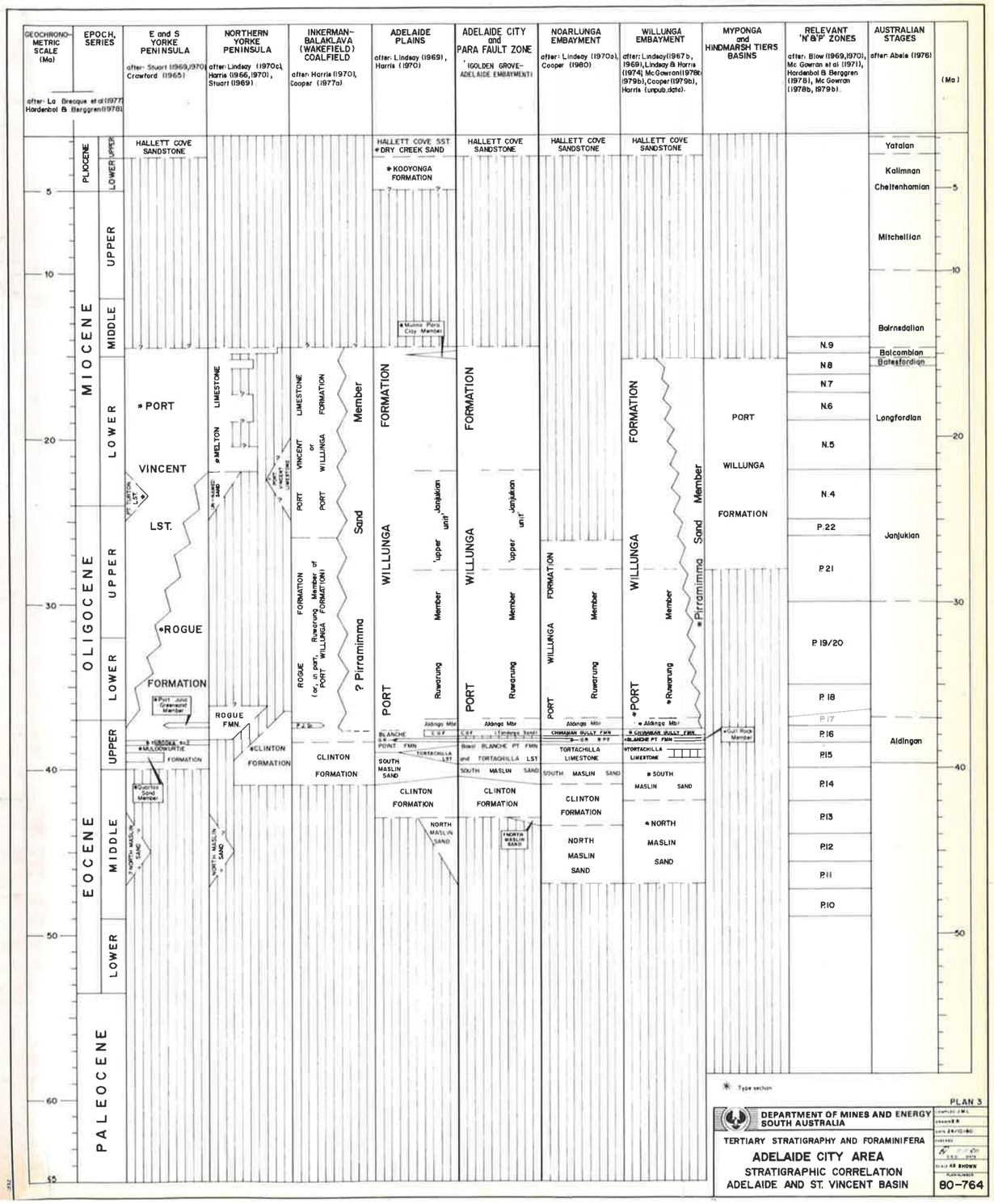
ADELAIDE CITY AREA

LOCALITY PLAN AND GEOLOGICAL SETTING

	COMPILED: J.M.L.	DRN: N.	R. S.	SCALE:
DIRECTOR GENERAL	11·11·80	CKD:		DATE: AUG. 1979

PLAN NUMBER 80-763

1532


GEOCHRONO-METRIC SCALE (Ma)
after: La Brecque et al (1977) Hardenbol & Berggren (1978)
EPOCH, SERIES
E and S YORKE PENINSULA
after: Stuart (1969,1970) Crawford (1965)
NORTHERN YORKE PENINSULA
after: Lindsay (1970c), Harris (1966,1970), Stuart (1969)
INKERMAN–BALAKLAVA (WAKEFIELD) COALFIELD
after: Harris (1970), Cooper (1977a)
ADELAIDE PLAINS
after: Lindsay (1969), Harris (1970)
ADELAIDE CITY and PARA FAULT ZONE
(GOLDEN GROVE–ADELAIDE EMBAYMENT)
NOARLUNGA EMBAYMENT
after: Lindsay (1970a), Cooper (1980)
WILLUNGA EMBAYMENT
after: Lindsay (1967b, 1969), Lindsay & Harris (1974), McGowran (1978b, 1979b), Cooper (1979b), Harris (unpub. data).
MYPONGA and HINDMARSH TIERS BASINS
RELEVANT 'N' & 'P' ZONES
after: Blow (1969,1970), Mc Gowran et al (1971), Hordenbol & Berggren (1978), Mc Gowran (1978b, 1979b).
AUSTRALIAN STAGES
after: Abele (1976)
(Ma)
PLIOCENE
MIOCENE
OLIGOCENE
EOCENE
PALEOCENE
LOWER
MIDDLE
UPPER
HALLETT COVE SANDSTONE
HALLETT COVE SST
*DRY CREEK SAND
*KOOYONGA FORMATION
*Mullins Pass Clay Member
*PORT VINCENT LST.
*ROGUE FORMATION
*Port Julia Greensand Member
*Quarries Sand Member
*MULDOWURTIE FORMATION
*NORTH MASLIN SAND
*HELTON LIMESTONE
*HARD SAND
*PORT LIMESTONE
ROGUE FMN.
*CLINTON FORMATION
LIMESTONE FORMATION
VINCENT or WILLUNGA PORT
ROGUE (or in part, PORT) Ruwarung Member of WILLUNGA FORMATION)
? Pirramimma Sand Member
CLINTON FORMATION
WILLUNGA FORMATION
PORT
Ruwarung Member
Janjukian unit
Aldinga Mbr
BLANCHE POINT FMN
SOUTH MASLIN SAND
TORTACHILLA LST
CLINTON FORMATION
NORTH MASLIN SAND
CHINAMAN GULLY FMN
TORTACHILLA LIMESTONE
*Pirramimma Sand Member
*Cut Rock Member
PORT WILLUNGA FORMATION
N.9
N.8
N.7
N.6
N.5
N.4
P.22
P.21
P.19/20
P.18
P.17
P.16
P.15
P.14
P.13
P.12
P.11
P.10
Yatalan
Kalimnan
Cheltenhamian
Mitchellian
Bairnsdalian
Balcombian
Batesfordian
Longfordian
Janjukian
Aldingan
5
10
20
30
40
50
60
* Type section
DEPARTMENT OF MINES AND ENERGY SOUTH AUSTRALIA
TERTIARY STRATIGRAPHY AND FORAMINIFERA
ADELAIDE CITY AREA
STRATIGRAPHIC CORRELATION
ADELAIDE AND ST. VINCENT BASIN
PLAN 3
80–764



LEGEND

LOCATION OF GEOLOGICAL CROSS-SECTION

BOREHOLE WHICH INTERSECTED BROWN COAL (LIGNITE)

STRATIGRAPHIC REFERENCE BORE

GOLDEN GROVE – ADELAIDE EMBAYMENT

AREA OF POSSIBLE TRANSITION AND EXTENSION AROUND EMBAYMENT

SAND PITS

NOTE – BORES ON PLAN ARE SHOWN WITH BORE UNIT NUMBERS, OBSERVATION WELL NUMBERS, NAME OF BORE, YEAR DRILLED, AND STRATIGRAPHIC SUMMARY

0 1 2 3 4 5 6 KILOMETRES

PLAN 4

DEPARTMENT OF MINES AND ENERGY – SOUTH AUSTRALIA

TERTIARY STRATIGRAPHY & FORAMINIFERA

ADELAIDE CITY AREA

LOCALITY PLAN

GOLDEN GROVE – ADELAIDE EMBAYMENT

	COMPILED J.M.L.	DRN S.R.	SCALE	PLAN NUMBER
DIRECTOR GENERAL	11/11/80	CKD	DATE SEPT. 1979	80-765

138° 36'

34° 54'

34° 57'

RENOWN PARK
RIDLEYTON
WALKERVILLE
E.&W.S. CROYDON-2
CROYDON
FITZROY
THORNGATE
MEDINDIE
JOSLIN
6628400OW1385 (YAT 66)
6628400OW1477 (YAT 67)
SADME Allenby Gardens Bore No1
PORT ROAD
BROMPTON
OVINGHAM
MAIN NORTH ROAD
ROBE TERRACE
GILBERTON
BLOCK
BOWDEN FAULT
WELLAND
WEST HINDMARSH
HINDMARSH
JEFFCOTT STREET
NORTH ADELAIDE
ST. PETERS
PARA BLOCK
CROYDON
THEBARTON
COLLEGE PARK
HACKNEY
HACKNEY ROAD
RIVER TORRENS
WEST THEBARTON FAULT
BLOCK FAULT
TORRENSVILLE
KENT TOWN
TERRACE
HENLEY BEACH ROAD
MILE END
SOUTH ROAD
NORTH TERRACE
WILLIAM STREET
EAST TERRACE
ADELAIDE
COWANDILLA
BURBRIDGE ROAD
HILTON
MAIN
MILE END SOUTH
RICHMOND
MILE END ROAD
EAST PARA FAULT
PARA BLOCK
SOUTH TERRACE
FULLARTON ROAD
WEST BEACH ROAD
KESWICK
HIGHWAY
WAYVILLE
GREENHILL ROAD
UNLEY
PARKSIDE
EASTWOOD
MARLESTON
KURRALTA PARK
ASHFORD
INDUSTRIAL

1:2500 SHEET INDEX

A — B Location of geological cross section

● 46 Stratigraphic reference bore

—— 35 —— Topographic contour in metres (A.H.D.)

62m Fault with geologically interpreted throws, after Finlayson (1978), and extended from Adelaide 1:63360 sheet

NOTE: MIDLINE OF RIVER TORRENS MARKS BOUNDARY BETWEEN ...

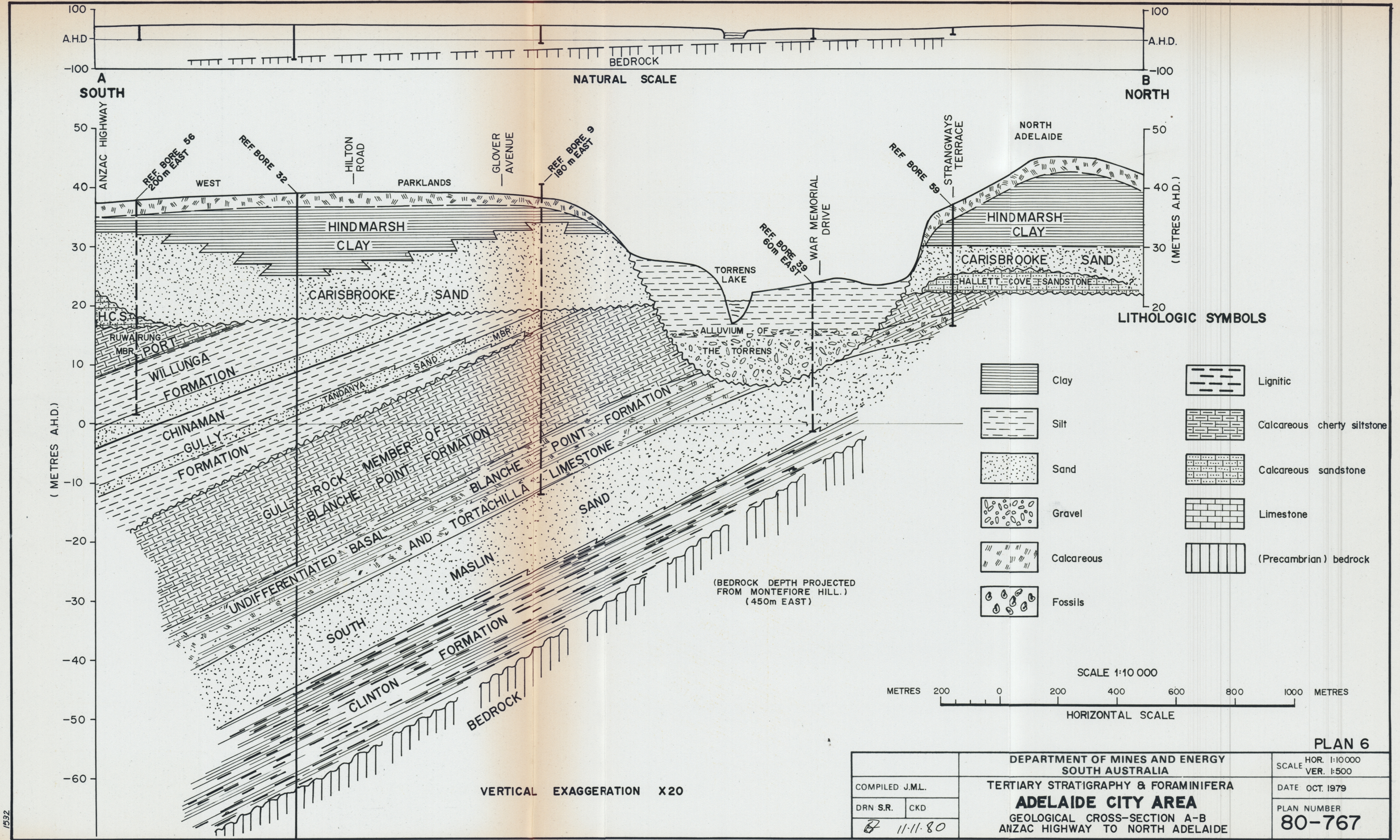
METRES 200 0 200 400 600 800 1000 METRES

PLAN 5

DEPARTMENT OF MINES AND ENERGY – SOUTH AUSTRALIA

TERTIARY STRATIGRAPHY & FORAMINIFERA
ADELAIDE CITY AREA
LOCATIONS OF STRATIGRAPHIC REFERENCE BORES AND GEOLOGICAL CROSS SECTIONS

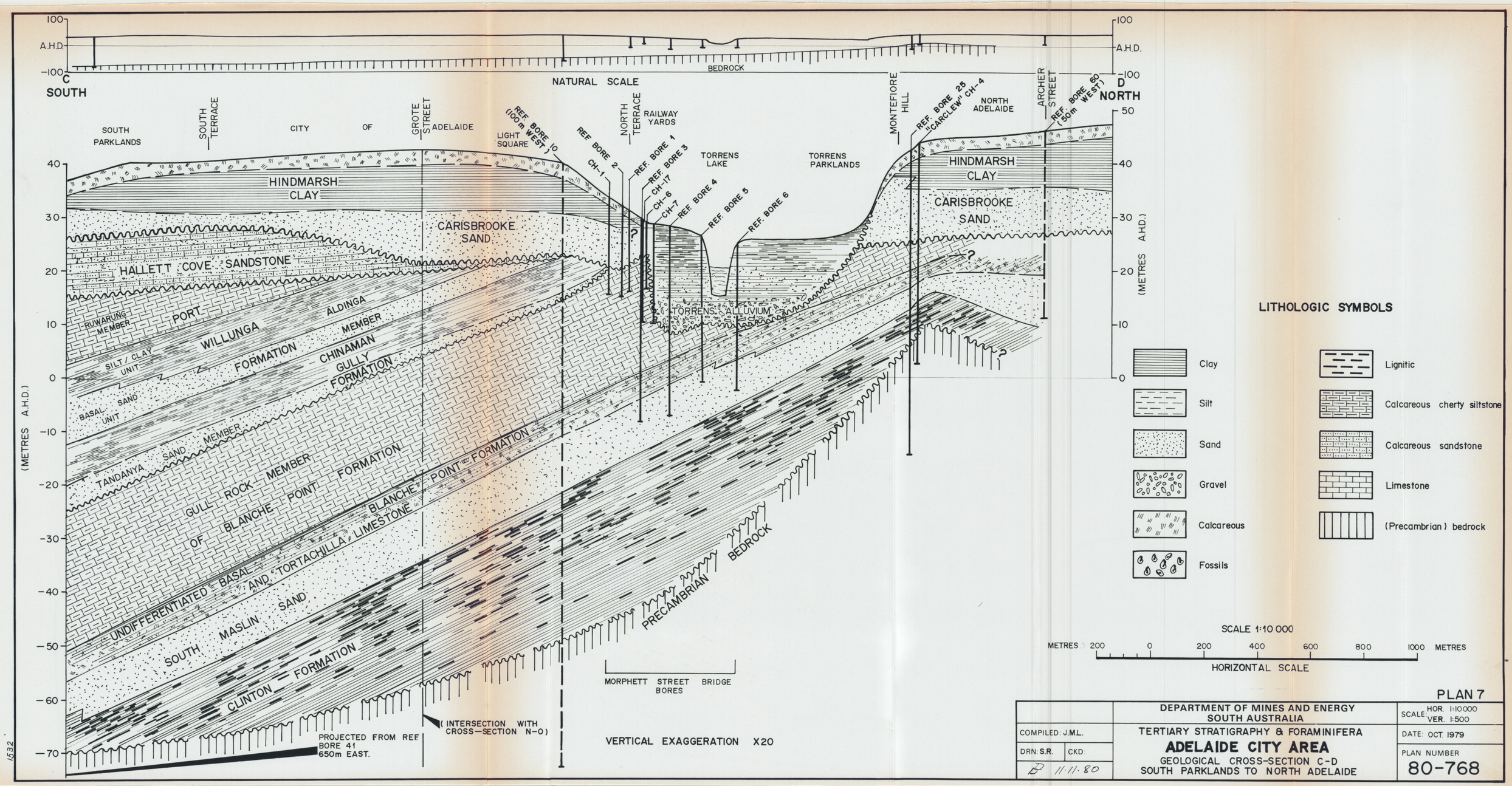
COMPILED J.M.L.	DRN N.R.S.	SCALE	PLAN NUMBER
8/11/80	CKD	DATE AUG 1979	80-766



PLAN 6

	DEPARTMENT OF MINES AND ENERGY SOUTH AUSTRALIA	SCALE HOR. 1:10 000 VER. 1:500
COMPILED J.M.L.	TERTIARY STRATIGRAPHY & FORAMINIFERA	DATE OCT. 1979
DRN S.R. CKD	**ADELAIDE CITY AREA** GEOLOGICAL CROSS-SECTION A-B ANZAC HIGHWAY TO NORTH ADELAIDE	PLAN NUMBER 80-767
11.11.80		

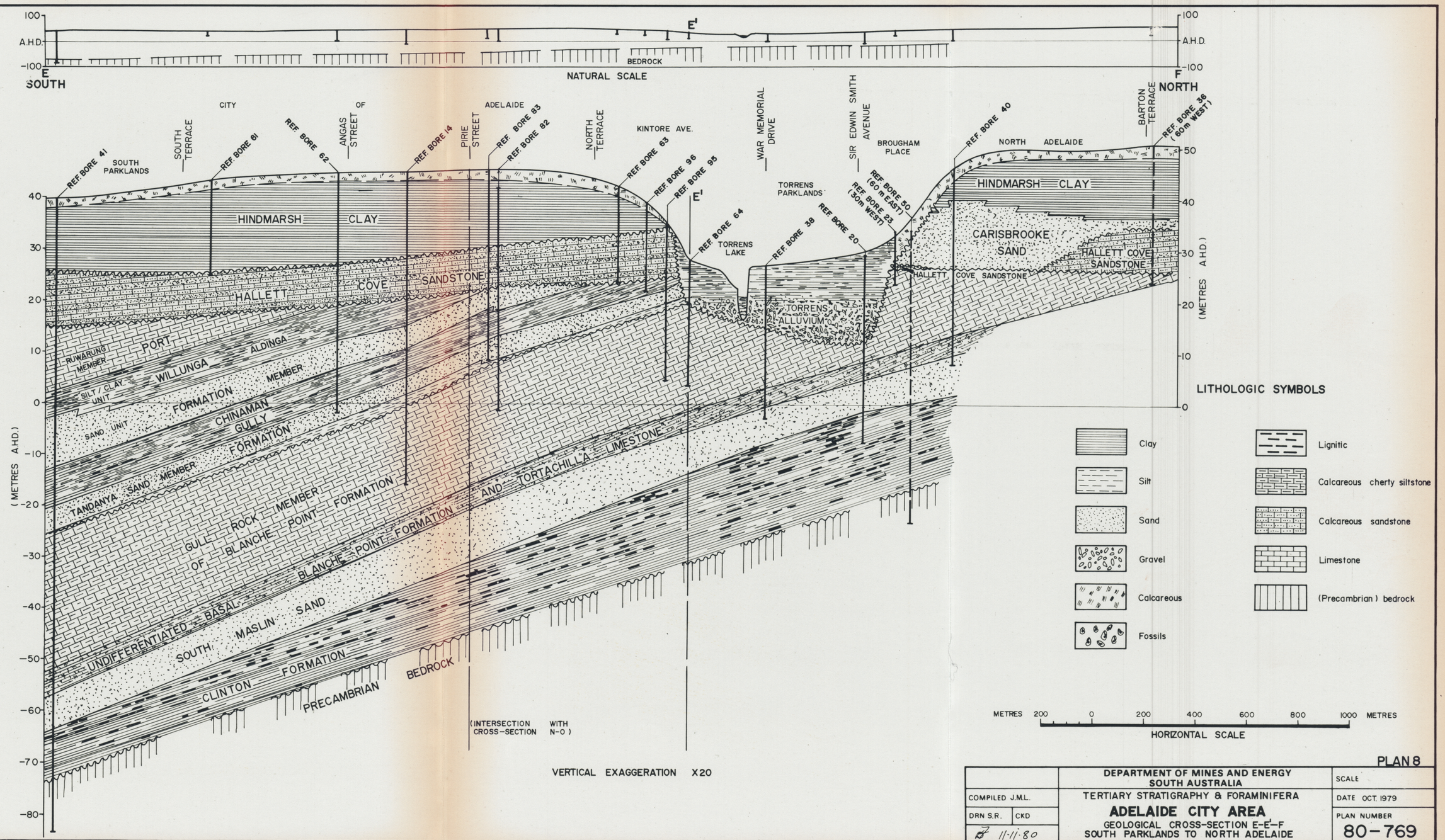
1532



PLAN 7

	DEPARTMENT OF MINES AND ENERGY SOUTH AUSTRALIA	SCALE HOR. 1:10000 VER. 1:500
COMPILED: J.M.L.	TERTIARY STRATIGRAPHY & FORAMINIFERA	DATE: OCT. 1979
DRN: S.R. CKD: B 11.11.80	**ADELAIDE CITY AREA** GEOLOGICAL CROSS-SECTION C-D SOUTH PARKLANDS TO NORTH ADELAIDE	PLAN NUMBER 80-768

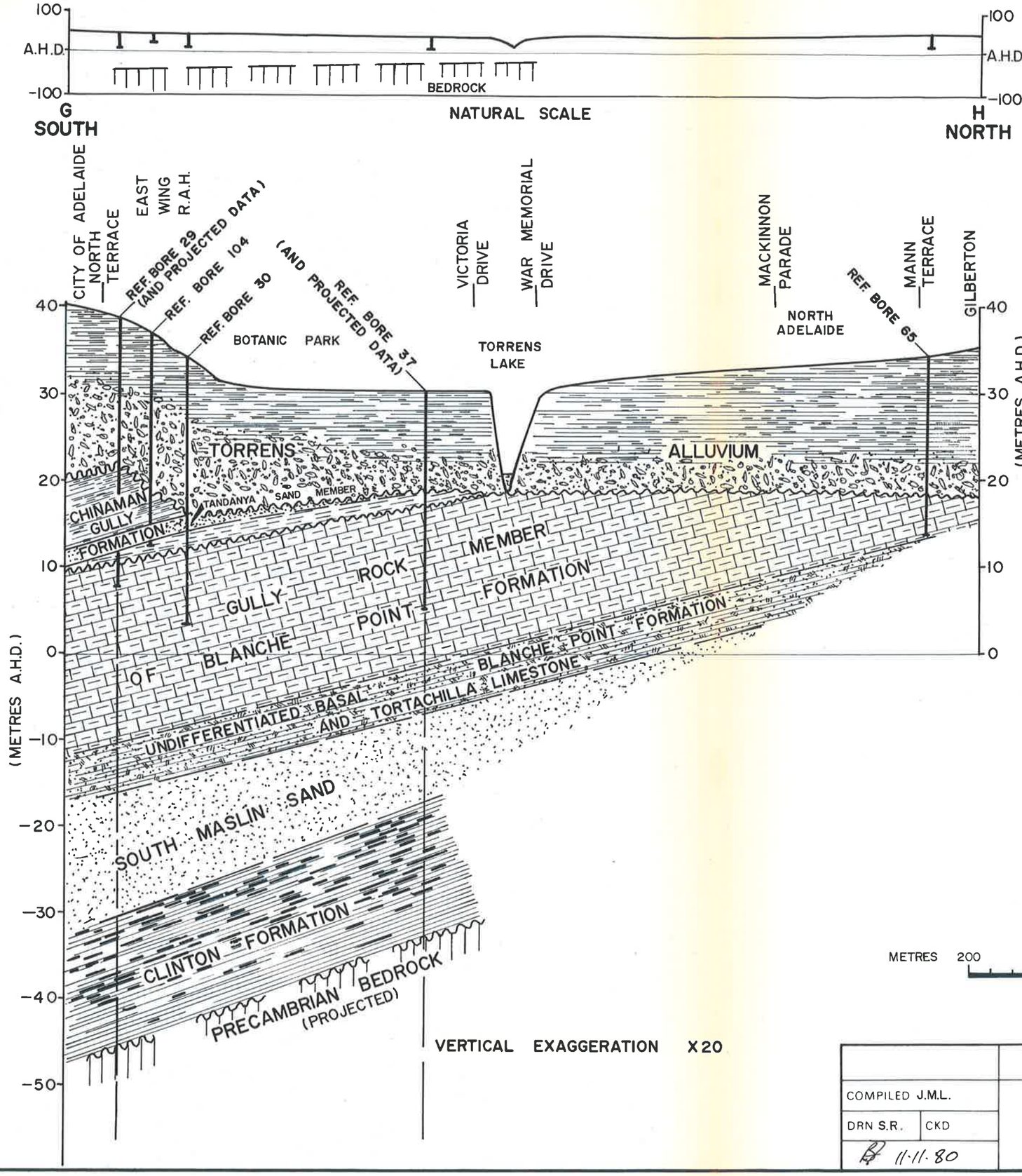
1532



PLAN 8

	DEPARTMENT OF MINES AND ENERGY SOUTH AUSTRALIA	SCALE
COMPILED J.M.L.	TERTIARY STRATIGRAPHY & FORAMINIFERA	DATE OCT. 1979
DRN S.R. CKD	**ADELAIDE CITY AREA** GEOLOGICAL CROSS-SECTION E-E'-F SOUTH PARKLANDS TO NORTH ADELAIDE	PLAN NUMBER 80-769
11-11-80		

1532



LITHOLOGIC SYMBOLS

- Clay
- Silt
- Sand
- Gravel
- Calcareous
- Fossils
- Lignitic
- Calcareous cherty siltstone
- Calcareous sandstone
- Limestone
- (Precambrian) bedrock

SCALE 1:10 000

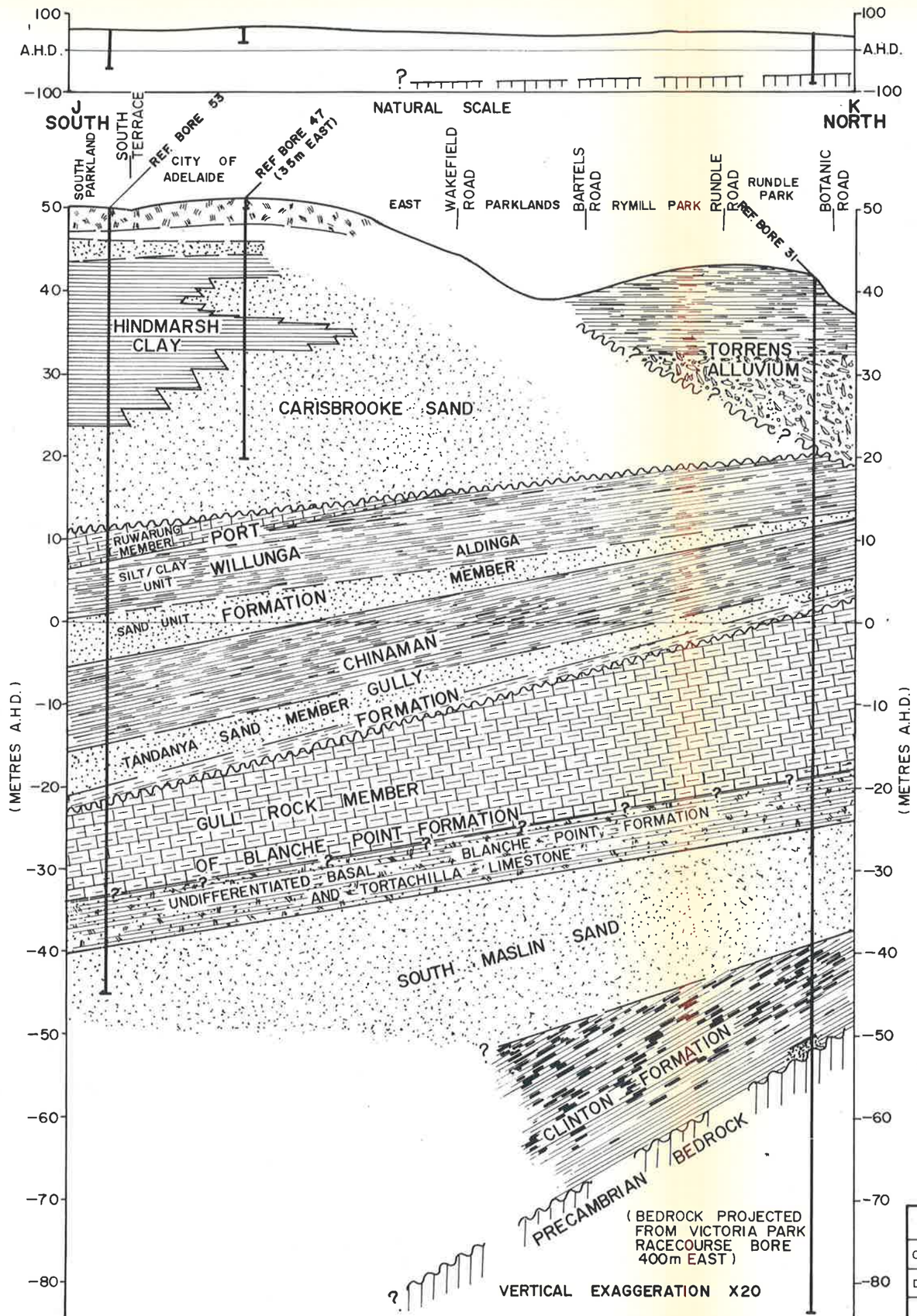
METRES 200 0 200 400 600 800 1000 METRES

HORIZONTAL SCALE

1532

PLAN 9

	DEPARTMENT OF MINES AND ENERGY SOUTH AUSTRALIA	SCALE HOR. 1:10000 VER. 1:500
COMPILED J.M.L.	TERTIARY STRATIGRAPHY & FORAMINIFERA	DATE OCT. 1979
DRN S.R. CKD	**ADELAIDE CITY AREA** GEOLOGICAL CROSS-SECTION G-H R.A.H. TO GILBERTON	PLAN NUMBER 80-770
11.11.80		



LITHOLOGIC SYMBOLS

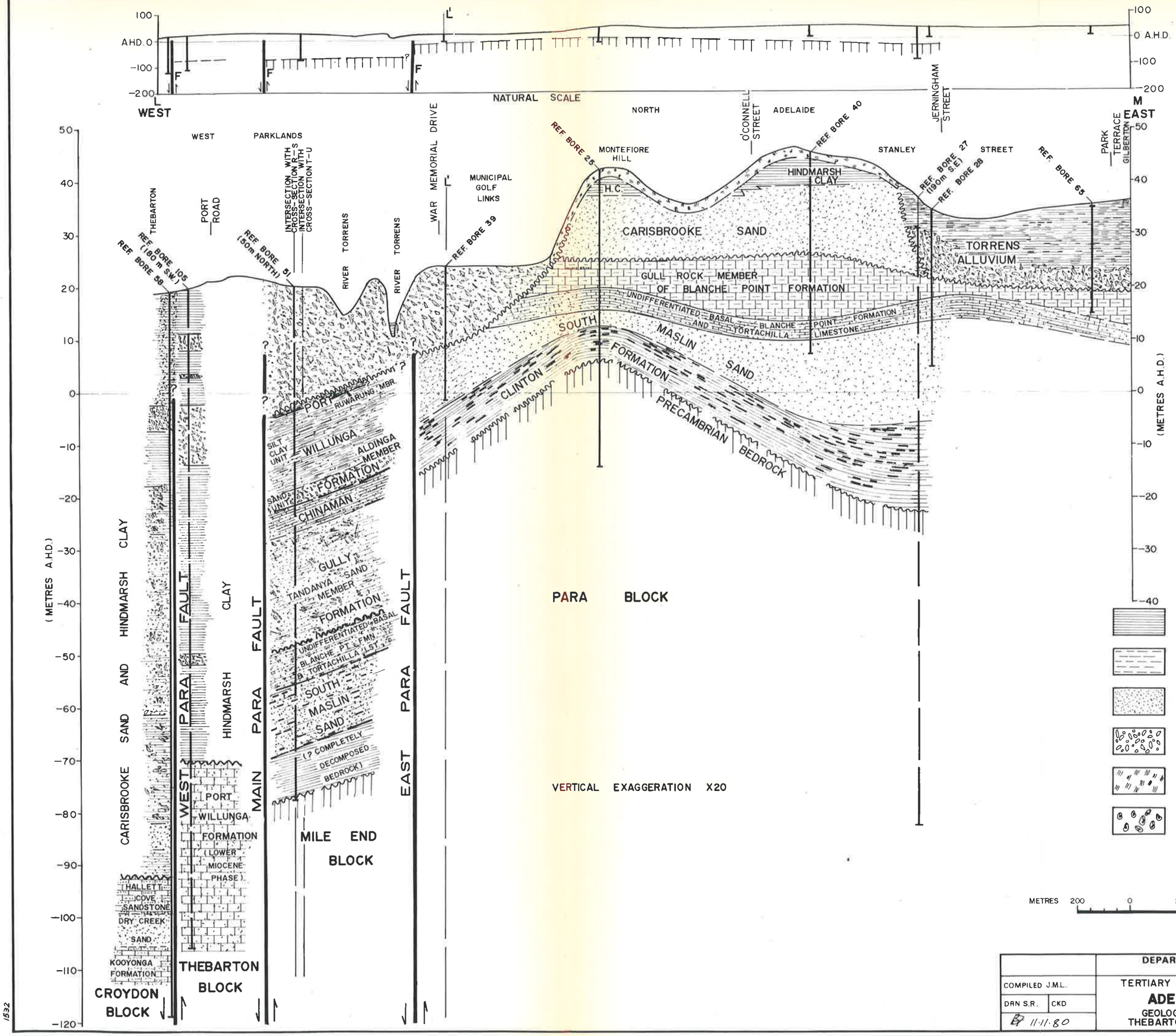
- Clay
- Lignitic
- Silt
- Calcareous cherty siltstone
- Sand
- Calcareous sandstone
- Gravel
- Limestone
- Calcareous
- (Precambrian) bedrock
- Fossils

METRES 200 0 200 400 600 800 1000 METRES

HORIZONTAL SCALE

PLAN 10

	DEPARTMENT OF MINES AND ENERGY SOUTH AUSTRALIA	SCALE
COMPILED J.M.L.	TERTIARY STRATIGRAPHY & FORAMINIFERA	DATE OCT. 1979
DRN S.R. / CKD	**ADELAIDE CITY AREA** GEOLOGICAL CROSS-SECTION J–K SOUTH PARKLANDS TO BOTANIC PARK	PLAN NUMBER 80-771
11.11.80		



PARA BLOCK

VERTICAL EXAGGERATION X20

LITHOLOGIC SYMBOLS

- Clay
- Silt
- Sand
- Gravel
- Calcareous
- Fossils
- Lignitic
- Calcareous cherty siltstone
- Calcareous sandstone
- Limestone
- (Precambrian) bedrock

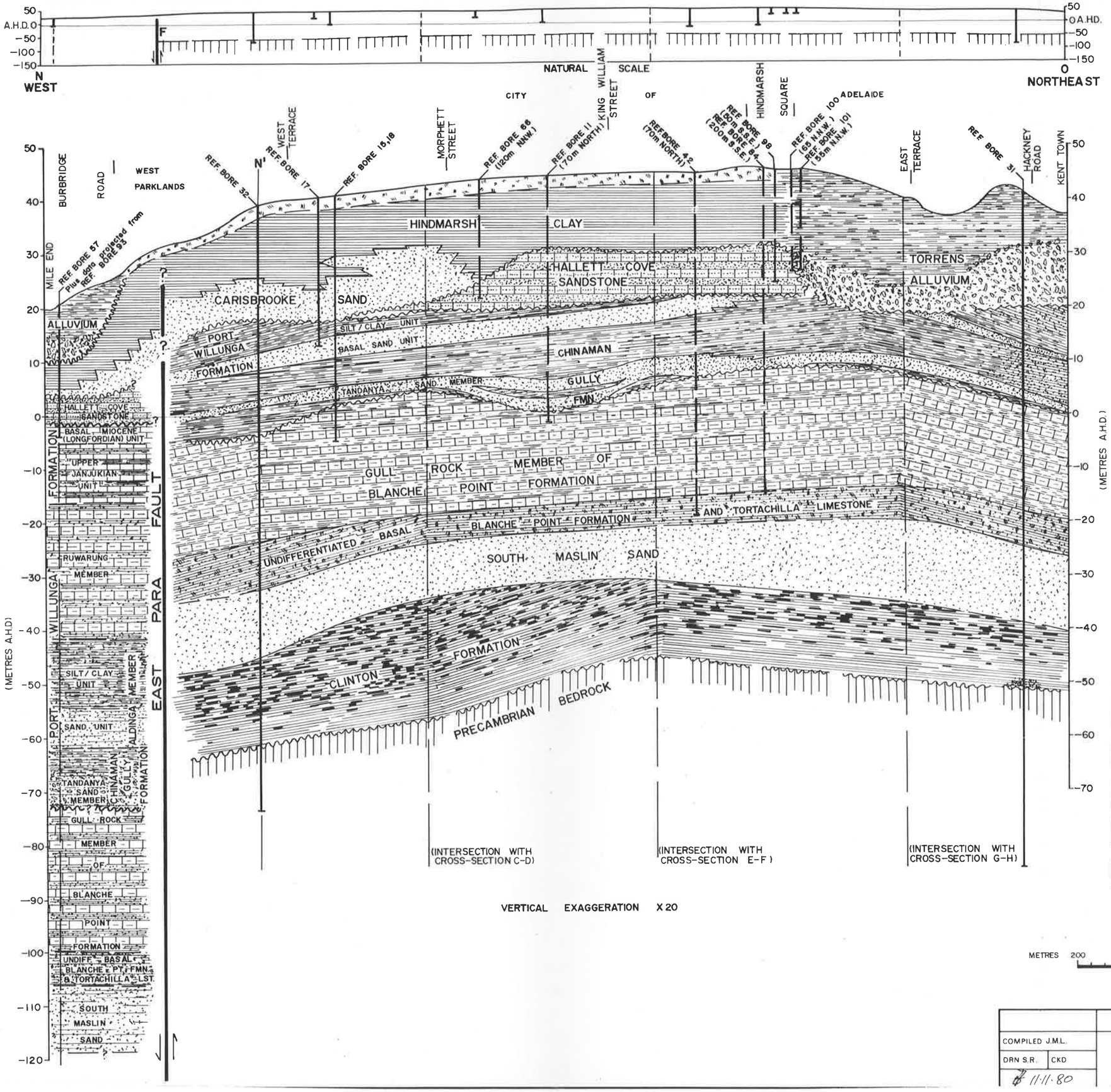
METRES 200 0 200 400 600 800 1000 METRES

HORIZONTAL SCALE

PLAN II

	DEPARTMENT OF MINES AND ENERGY SOUTH AUSTRALIA	SCALE
COMPILED J.M.L.	TERTIARY STRATIGRAPHY & FORAMINIFERA	DATE OCT. 1979
DRN S.R. CKD	**ADELAIDE CITY AREA**	PLAN NUMBER 80-772
11.11.80	GEOLOGICAL CROSS-SECTION L-L'-M THEBARTON-NORTH ADELAIDE-GILBERTON	

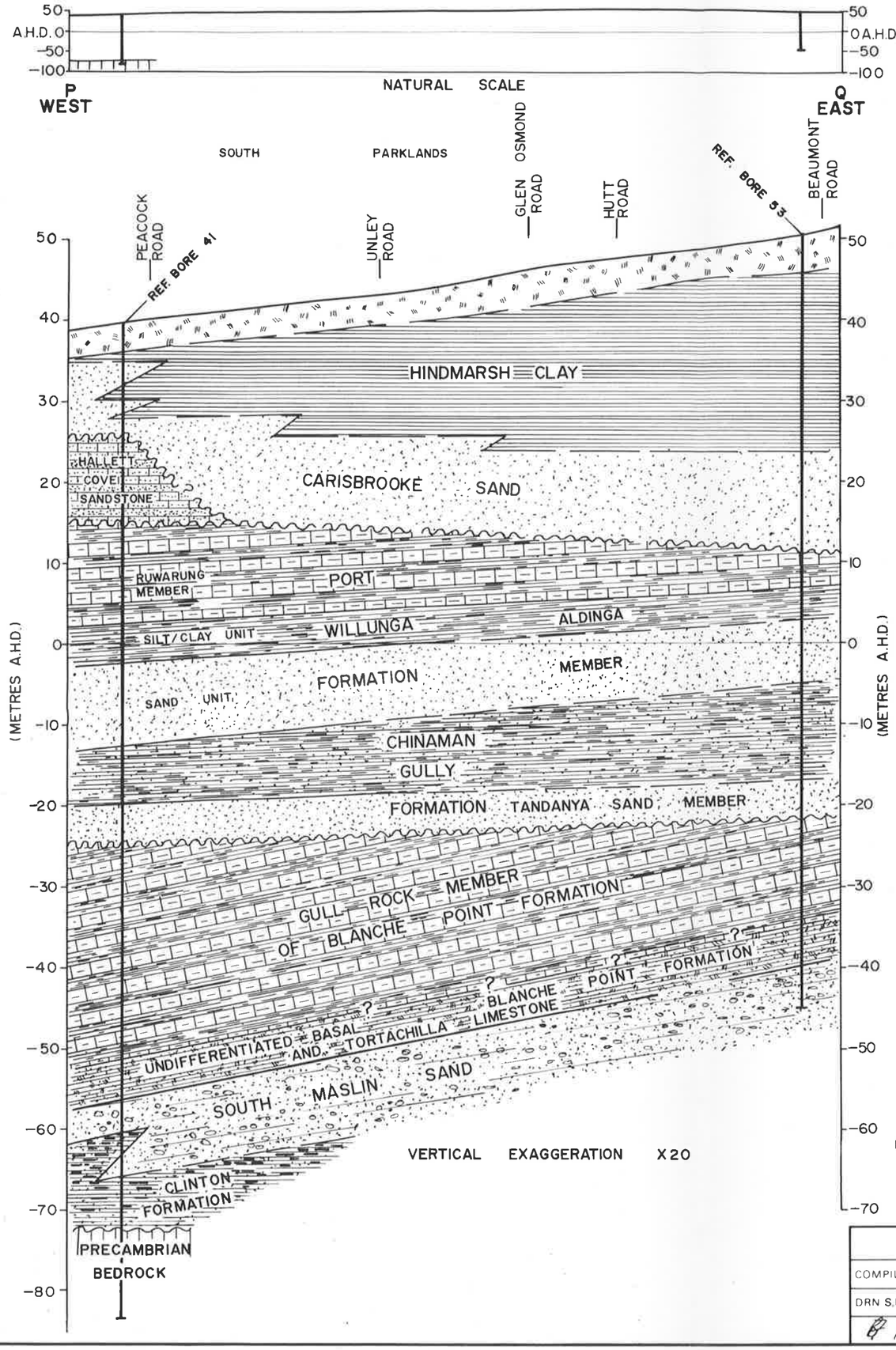
1532



PLAN 12

	DEPARTMENT OF MINES AND ENERGY SOUTH AUSTRALIA	SCALE
COMPILED J.M.L.	TERTIARY STRATIGRAPHY & FORAMINIFERA	DATE NOV. 1979
DRN S.R. CKD	**ADELAIDE CITY AREA**	PLAN NUMBER
11.11.80	GEOLOGICAL CROSS-SECTION N-N'-O MILE END TO KENT TOWN	80-773

1632



LITHOLOGIC SYMBOLS

- Clay
- Silt
- Sand
- Gravel
- Calcareous
- Fossils
- Lignitic
- Calcareous cherty siltstone
- Calcareous sandstone
- Limestone
- (Precambrian) bedrock

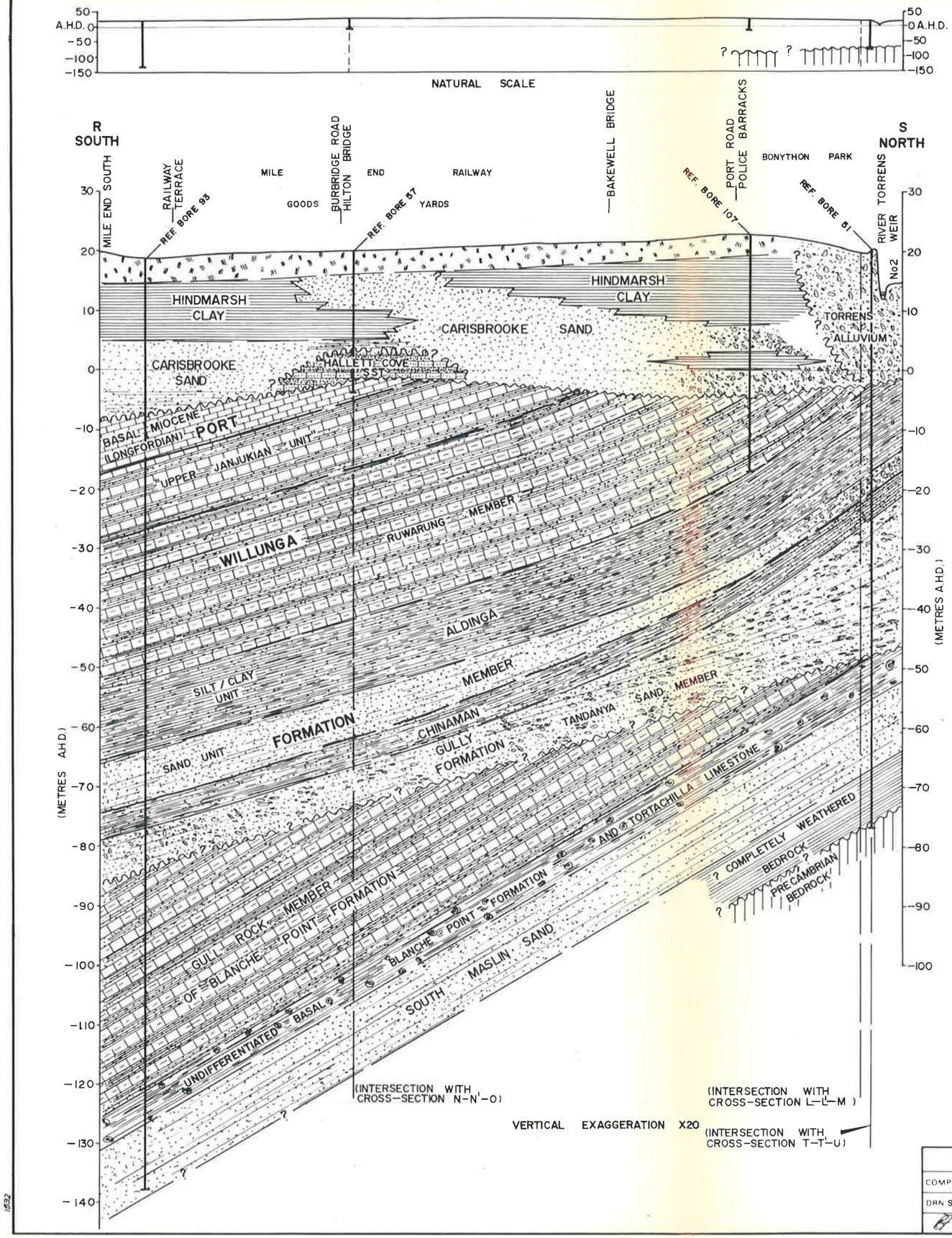
METRES 200 0 200 400 600 800 1000 METRES

HORIZONTAL SCALE

PLAN 13

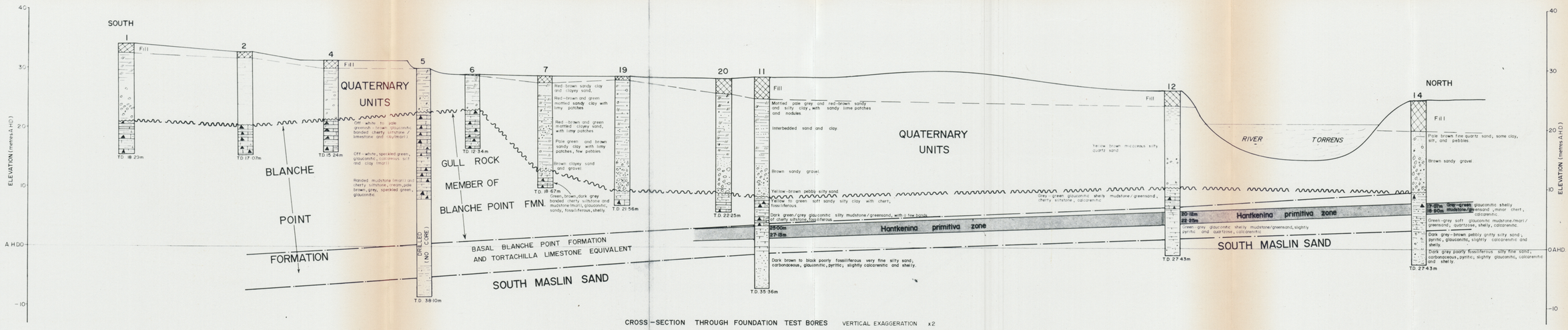
	DEPARTMENT OF MINES AND ENERGY SOUTH AUSTRALIA	SCALE
COMPILED J.M.L.	TERTIARY STRATIGRAPHY & FORAMINIFERA	DATE NOV. 1979
DRN S.R. CKD	**ADELAIDE CITY AREA** GEOLOGICAL CROSS-SECTION P-Q SOUTH PARKLANDS	PLAN NUMBER 80-774
11.11.80		

1532

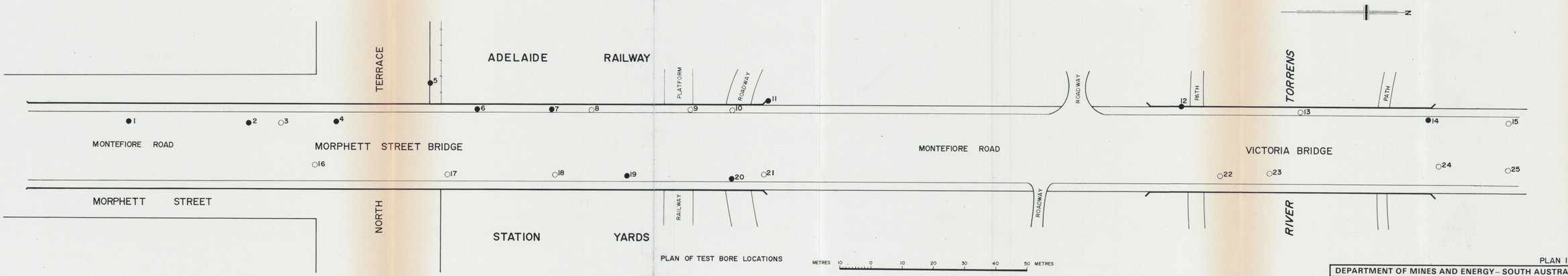


PLAN 14

	DEPARTMENT OF MINES AND ENERGY SOUTH AUSTRALIA	SCALE
COMPILED J.M.L.	TERTIARY STRATIGRAPHY & FORAMINIFERA	DATE NOV. 1979
DRN S.R. CKD	**ADELAIDE CITY AREA**	PLAN NUMBER
11.11.80	GEOLOGICAL CROSS-SECTION R–S MILE END BLOCK	80-775



CROSS-SECTION THROUGH FOUNDATION TEST BORES VERTICAL EXAGGERATION x2



PLAN OF TEST BORE LOCATIONS

METRES 10 0 10 20 30 40 50 METRES

PLAN 15

DEPARTMENT OF MINES AND ENERGY — SOUTH AUSTRALIA

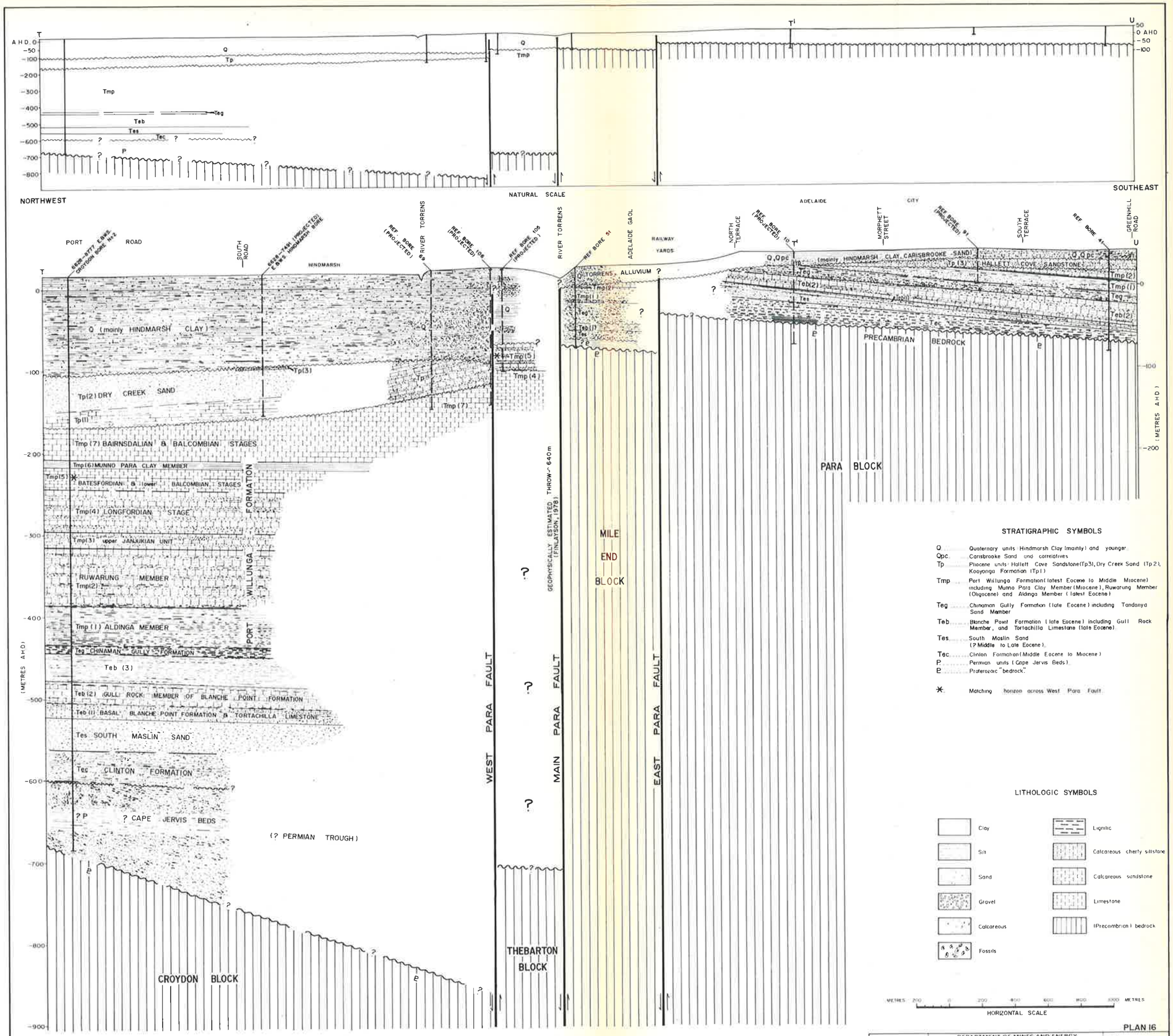
TERTIARY STRATIGRAPHY & FORAMINIFERA

ADELAIDE CITY AREA

MORPHETT ST. AND VICTORIA BRIDGES DRILLING (1964)

STRATIGRAPHIC SETTING OF HANTKENINA ZONE

	COMPILED J.M.L.	DRN S.R.	SCALE	PLAN NUMBER
DIRECTOR GENERAL	11.11.80	CKD	DATE JAN. 1980	80-776



PLAN 16

DEPARTMENT OF MINES AND ENERGY SOUTH AUSTRALIA

TERTIARY STRATIGRAPHY & FORAMINIFERA

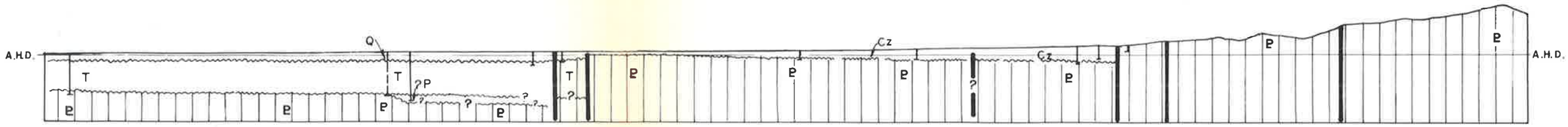
ADELAIDE CITY AREA

GEOLOGICAL CROSS-SECTION T-T'-U CROYDON TO SOUTH PARKLANDS

DRAWN JML

DATE NOV 1979

PLAN No. 80-777



NATURAL SCALE

V
WEST — NORTHWEST

W
SOUTHEAST

GOLDEN GROVE — ADELAIDE EMBAYMENT

ADELAIDE PLAINS SUB-BASIN

NORTH ADELAIDE

MT. LOFTY RANGES

08854 BEACH PETROLEUM GRANGE-1 WELL

SADME ALLENBY GARDENS-1 (projected)

08777 E.&W.S. CROYDON-2 BORE

07561 NATHAN BREWERY BORE SOUTHWARK (REF. BORE 69; PROJECTED)

04576 COCA COLA (DIVERSE PRODUCTS) BORE 4A, THEBARTON (REF. 105; PROJECTED)

SECTION A-B

SECTION C-D

SECTION E-F

RIVER TORRENS

SECTION G-H

00005 KENT TOWN BORE (REF. BORE 31)

00055I VICTORIA PARK RACECOURSE BORE (REF. BORE 49; PROJECTED)

10085 M.T.T. BORE KENSINGTON GARDENS (PROJECTED)

08992 S.A.D.M.E. MYRTLE BANK BORE (PROJECTED)

07236 W.A.I.T.E. INSTITUTE BORE (PROJECTED)

WATERFALL GULLY

WATERFALL GULLY

MT. LOFTY

A.H.D. 0
-100
-200
-300
-400
-500
-600
-700
-800

ELEVATON (metres A.H.D.)

Q
Tp
Tmp
Teb
Tes — Tec
Teg
P

WEST PARA FAULT

MAIN PARA FAULT

THEBARTON BLOCK

CROYDON BLOCK

PARA BLOCK

? HOPE VALLEY FAULT

BURNSIDE FAULT

EDEN FAULT

OCHRE COVE — CLARENDON FAULT

600
500
400
300
200
100
0 A.H.D.
-100
-200
-300
-400
-500
-600
-700

ELEVATION (metres A.H.D.)

0 1 2 3 4 5
KILOMETRES

VERTICAL EXAGGERATION x5

STRATIGRAPHIC SYMBOLS

Q ..... Quaternary units: Hindmarsh Clay (mainly) and younger.

Cz ..... Cainozoic, undifferentiated.

T ..... Tertiary, undifferentiated.

Tp ..... Pliocene units: Hallett Cove Sandstone, Dry Creek Sand, Kooyonga Formation.

Tmp ..... Port Willunga Formation (latest Eocene to Middle Miocene) including Munno Para Clay Member (Miocene), Ruwarung Member (Oligocene) and Aldinga Member (latest Eocene).

Teg ..... Chinaman Gully Formation (late Eocene) including Tandanya Sand Member.

Teb ..... Blanche Point Formation (late Eocene) including Gull Rock Member, and Tortachilla Limestone (late Eocene).

Tes ..... South Maslin Sand (? Middle to late Eocene).

Tec ..... Clinton Formation (Middle to late Eocene)

P ..... Permian units (Cape Jervis Beds).

P ..... Proterozoic "bedrock".

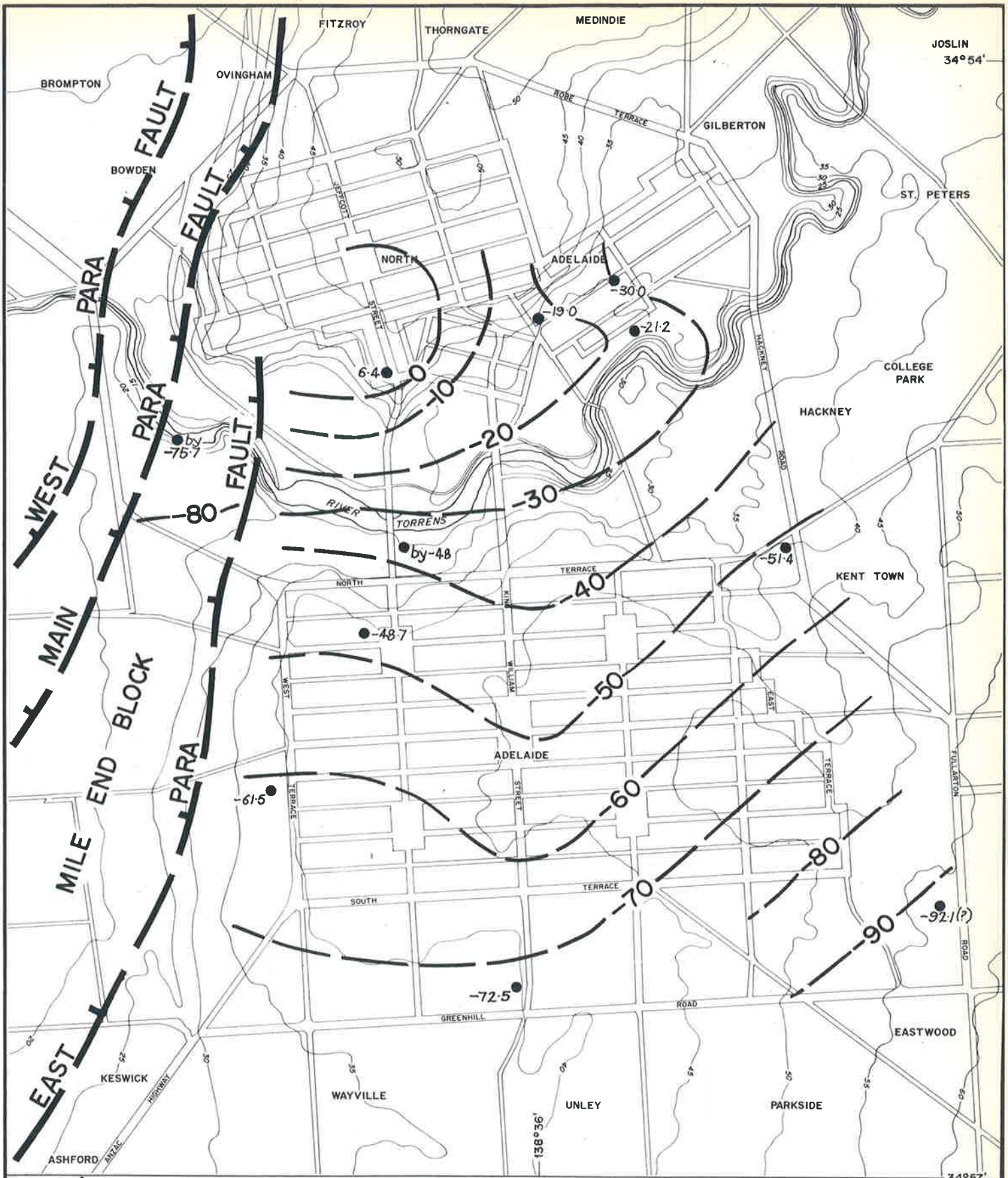
PLAN 17

DEPARTMENT OF MINES AND ENERGY — SOUTH AUSTRALIA

TERTIARY STRATIGRAPHY & FORAMINIFERA
ADELAIDE CITY AREA
GEOLOGICAL CROSS-SECTION V-W B.P GRANGE WELL TO MT. LOFTY

	COMPILED JML	DRN S.R.	SCALE	PLAN NUMBER
DIRECTOR GENERAL	11.11.80	CKD	DATE JAN 1980	80-778

1532



-50 Contours (metres A.H.D.) interpolated from data points and cross-sections.

25 Natural surface contours (metres A.H.D.).

●-92·1 Borehole location with elevation (metres A.H.D.) of borehole intersections of bedrock

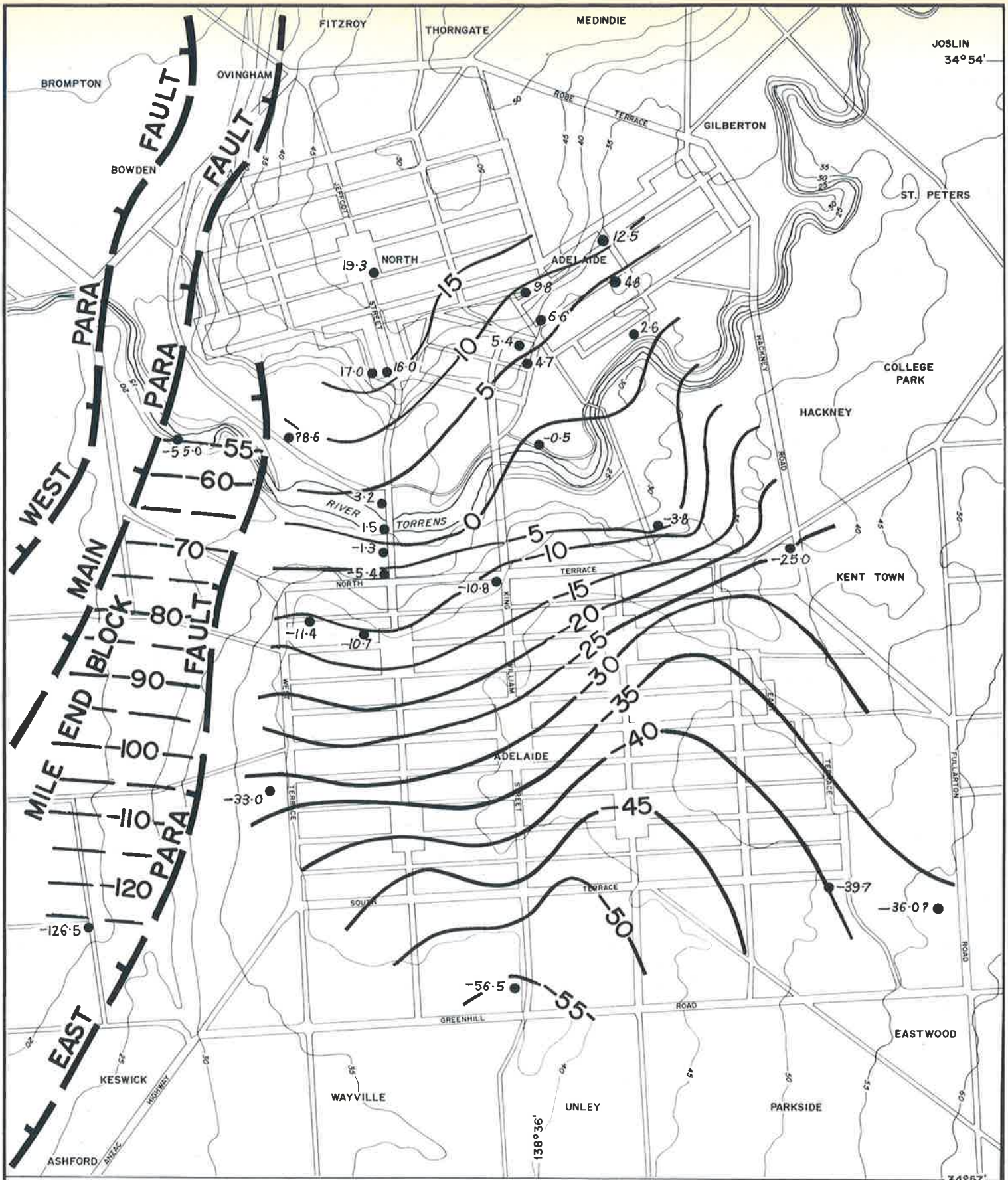
SCALE 1:25 000

200 0 200 400 600 800 1000 METRES

PLAN 18

	DEPARTMENT OF MINES AND ENERGY SOUTH AUSTRALIA	SCALE: 1:25 000
COMPILED: J. M. Lindsay	TERTIARY STRATIGRAPHY & FORAMINIFERA	DATE: OCT. 1979
DRN: S.R CKD:	ADELAIDE CITY AREA	PLAN NUMBER
BF 11·11·80	BEDROCK: CONTOURED BOREHOLE INTERSECTIONS	S15209

1532



16·0 ● Borehole location with elevation of base of unit in metres A.H.D.

—10— Structure contours of base (metres A.H.D.)

—25— Natural surface contours (metres A.H.D.)

SCALE 1:25 000

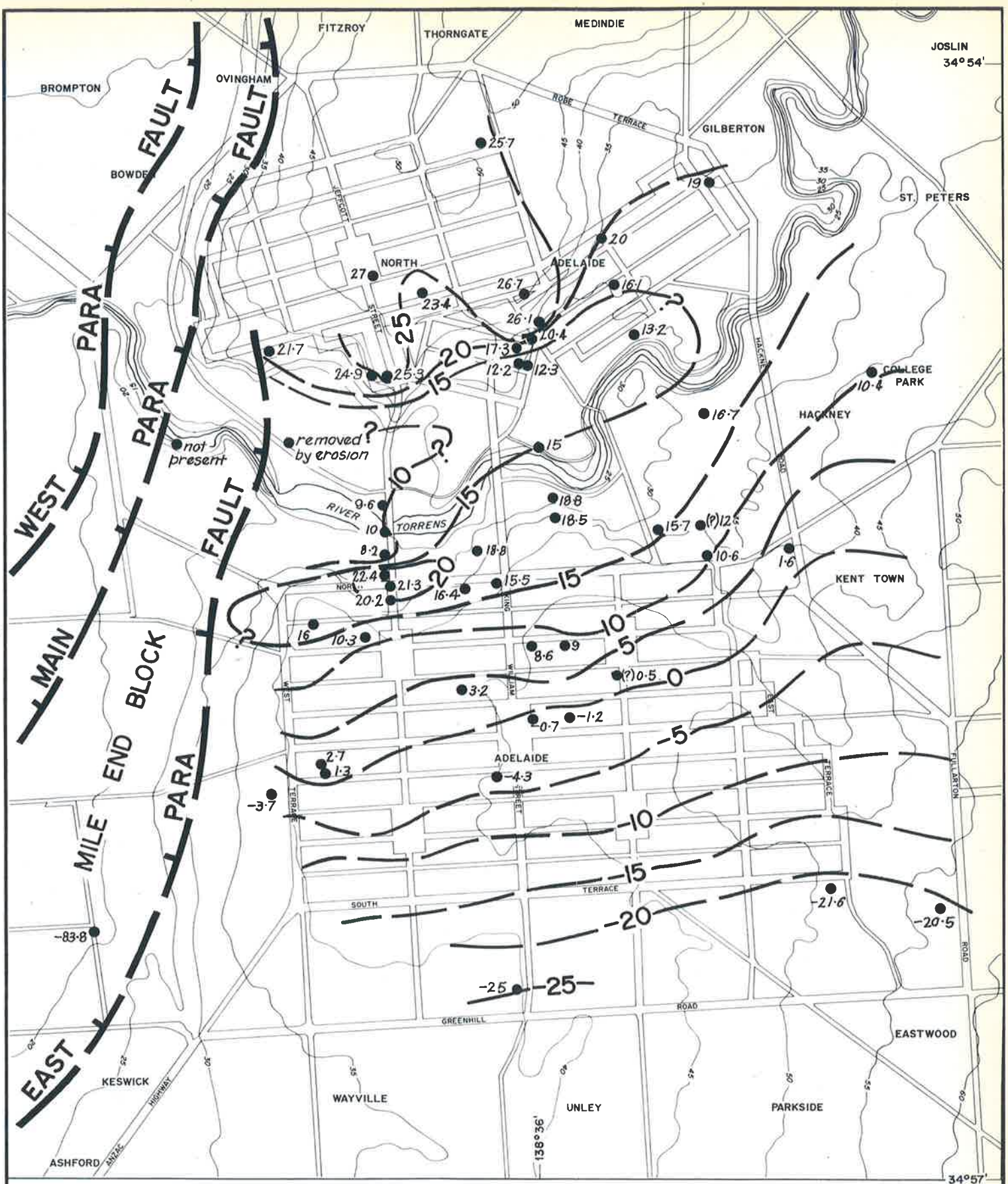
200 0 200 400 600 800 1000

METRES METRES

PLAN 19

	DEPARTMENT OF MINES AND ENERGY SOUTH AUSTRALIA	SCALE: 1:25 000
COMPILED: J. M. Lindsay	TERTIARY STRATIGRAPHY & FORAMINIFERA	DATE: OCT. 1979
DRN: S.R. CKD:	**ADELAIDE CITY AREA**	PLAN NUMBER
11·11·80	SOUTH MASLIN SAND DISTRIBUTION AND STRUCTURE CONTOURS	S 15210

1532



●9·6 Borehole location—with elevation of top of member (metres A.H.D.)

-5 Structure contours of top of member (metres A.H.D.)

25 Natural surface contours (metres A.H.D.)

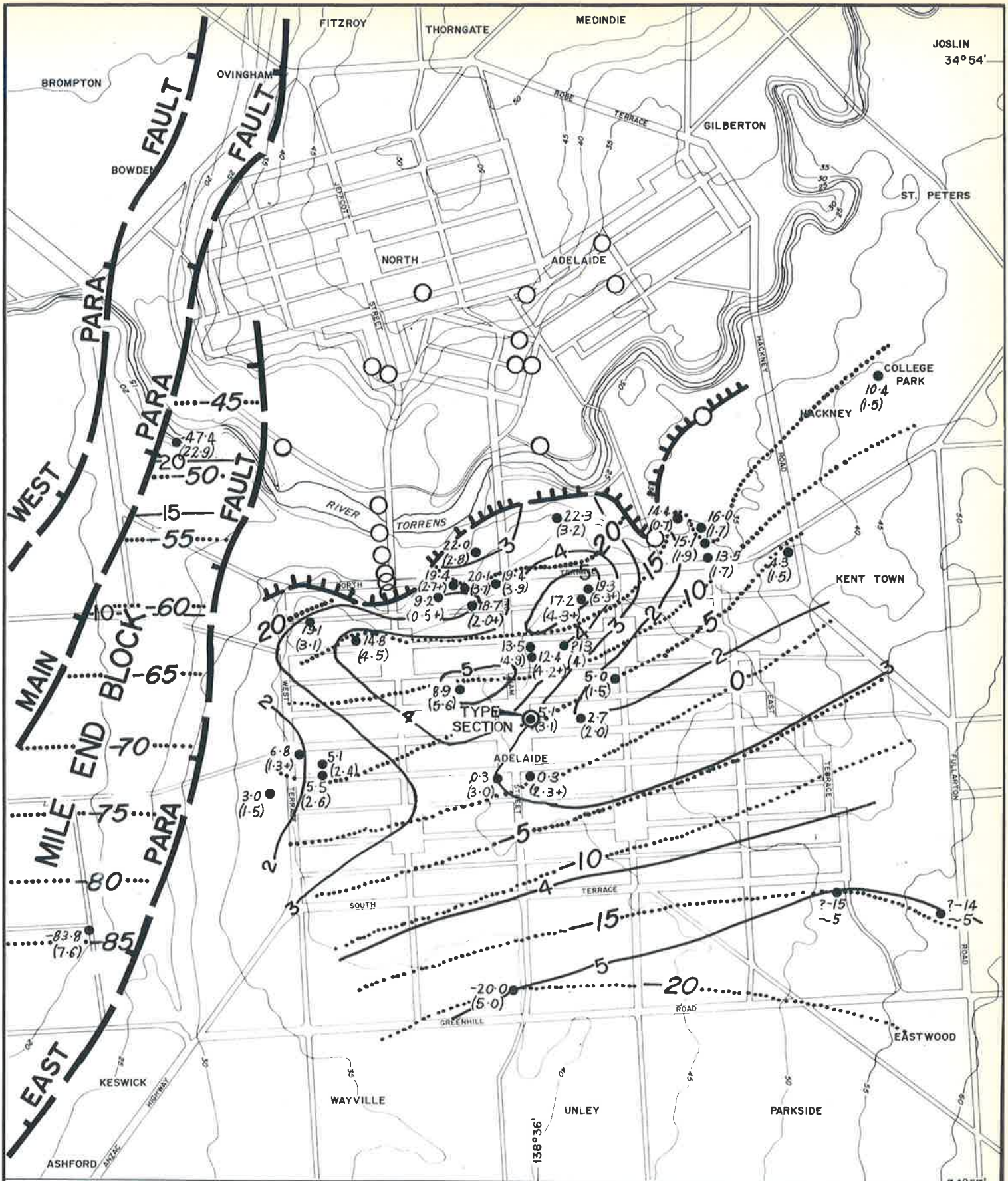
SCALE 1:25 000

200 0 200 400 600 800 1000 METRES

PLAN 20

	DEPARTMENT OF MINES AND ENERGY SOUTH AUSTRALIA	SCALE: 1:25 000
COMPILED: J. M. Lindsay	TERTIARY STRATIGRAPHY & FORAMINIFERA	DATE: OCT. 1979
DRN: S.R. CKD:	**ADELAIDE CITY AREA**	PLAN NUMBER
11·11·80	GULL ROCK MBR., BLANCHE POINT FMN. DISTRIBUTION, STRUCTURE CONTOURS	S15211

1532



25 Natural surface contours (metres A.H.D)

5 10 Isopachs (thickness in metres)

Structure contours of top (metres A.H.D.)

Unit absent in borehole due to erosion

2·7 (2·0) Borehole location—top figure is elevation of top in metres A.H.D. bottom figure is total thickness in metres

Estimated present limits of distribution of unit.

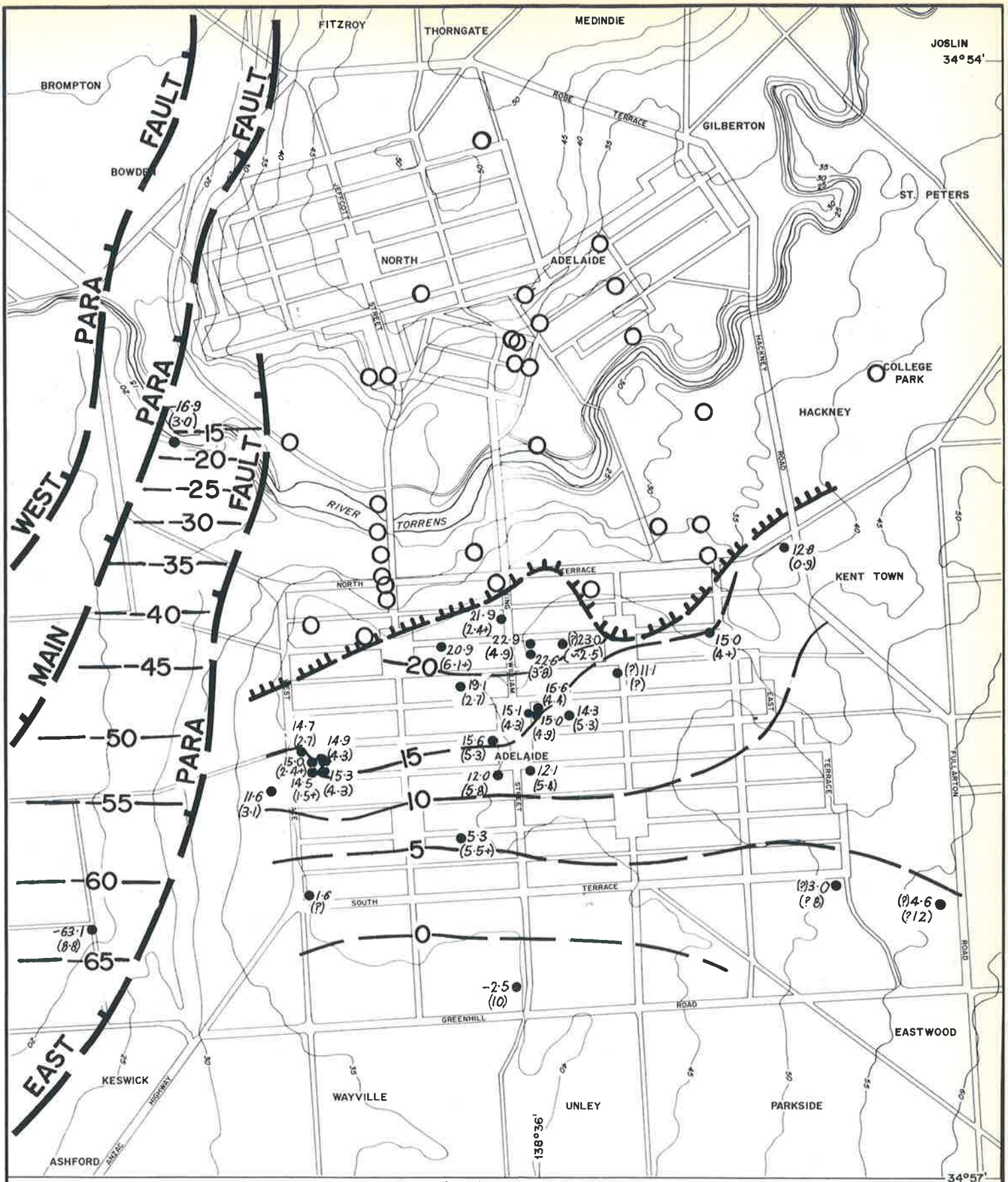
SCALE 1:25 000

200 0 200 400 600 800 1000 METRES

PLAN 21

	DEPARTMENT OF MINES AND ENERGY SOUTH AUSTRALIA	SCALE: 1:25 000
COMPILED: J. M. Lindsay	TERTIARY STRATIGRAPHY & FORAMINIFERA	DATE: OCT. 1979
DRN: S.R. CKD:	**ADELAIDE CITY AREA**	PLAN NUMBER
11-11-80	TANDANYA SAND MEMBER, CHINAMAN GULLY FM. DISTRIBUTION, STRUCTURE CONTOURS, THICKNESS	S 15212

1532



● 12·8 (3) Borehole location – top figure is elevation of top of unit (metres A.H.D.) bottom figure is total thickness (metres)

Structure contours of top of unit (metres A.H.D.)

Natural surface contours (metres A.H.D.)

○ Unit absent in borehole due to erosion

Estimated present limits of distribution of unit.

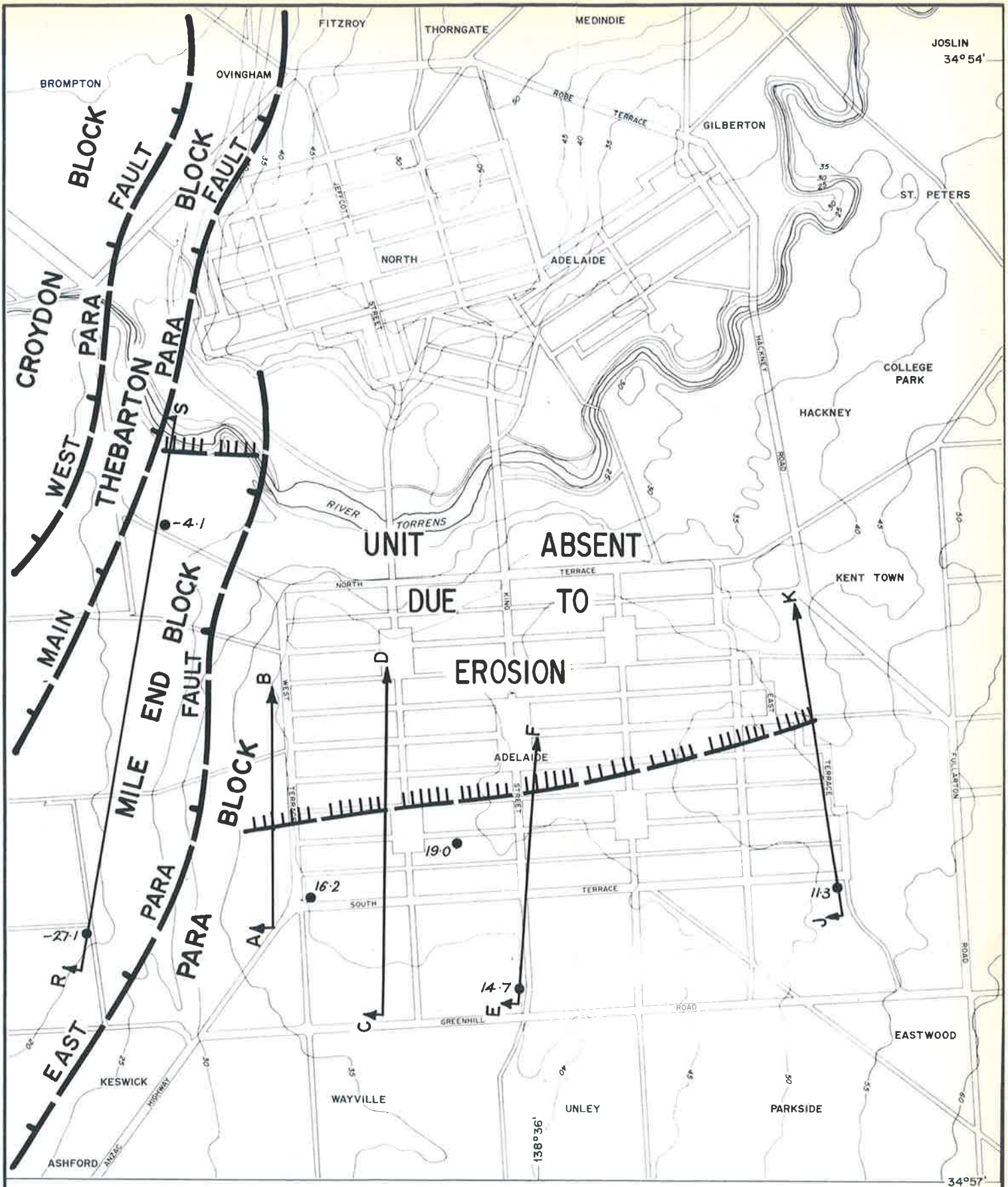
SCALE 1:25 000

METRES 200 0 200 400 600 800 1000 METRES

PLAN 22

	DEPARTMENT OF MINES AND ENERGY SOUTH AUSTRALIA	SCALE: 1:25 000
COMPILED: J. M. Lindsay	TERTIARY STRATIGRAPHY & FORAMINIFERA	DATE: OCT. 1979
DRN: S.R. CKD:	**ADELAIDE CITY AREA**	PLAN NUMBER S15213
11·11·80	BASAL SAND UNIT, ALDINGA MBR., PORT WILLUNGA FMN. DISTRIBUTION, STRUCTURE CONTOURS, THICKNESS	

1532



● 14·7 ..... Borehole location with elevation of top intersection of Ruwarung Member (metres A.H.D.)

30 ..... Natural surface contours (metres A.H.D.)

..... Estimated present limits of distribution of Ruwarung Member.

A ——— B ..... Line of cross-section

SCALE 1:25 000

200 0 200 400 600 800 1000 METRES

PLAN 23

	DEPARTMENT OF MINES AND ENERGY SOUTH AUSTRALIA	SCALE: 1:25 000
COMPILED: J. M. Lindsay	TERTIARY STRATIGRAPHY & FORAMINIFERA	DATE: JAN. 1980
DRN: S.R. CKD:	**ADELAIDE CITY AREA**	PLAN NUMBER
11-11-80	RUWARUNG MEMBER, PORT WILLUNGA FORMATION DISTRIBUTION	S 15214

1532

138° 36'

34° 54'

34° 57'

RENOWN PARK
FITZROY
THORNGATE
NORTH ROAD
MEDINDIE
WALKERVILLE
JOSLIN
BROMPTON
OVINGHAM
MAIN
ROBE TERRACE
GILBERTON
BOWDEN
JEFFCOTT STREET
NORTH ADELAIDE
ST. PETERS
COLLEGE PARK
HACKNEY
HACKNEY ROAD
KENT TOWN
RIVER TORRENS
NORTH TERRACE
KING WILLIAM STREET
EAST TERRACE
FULLARTON ROAD
ADELAIDE
SOUTH TERRACE
MILE END SOUTH
KESWICK
WAYVILLE
UNLEY
PARKSIDE
EASTWOOD
GREENHILL ROAD
HIGHWAY
ANZAC
ASHFORD

FAULT
PARA
WEST
EAST
MAIN

Pliocene units progressively downthrown and thickening to the west across the Para Fault Zone — see cross-sections.

NOTE – Depth to top, below ground = ground elevation – (elevation of base + thickness).
– "Hallett Cove Sandstone" includes Burnham Limestone ("transitional zone")
– Map prepared from interpretation of best available data.

Natural surface contours (in metres above A.H.D.)

Isopachs (thickness in metres)

Structure contours of base (metres A.H.D.)

Estimated present limits of distribution of Hallett Cove Sandstone / Burnham Limestone

Borehole location – top figure = elevation of base in metres above A.H.D. Bottom figure is total thickness.

Hallett Cove Sandstone / Burnham Limestone not present (removed by erosion)

METRES 200 0 200 400 600 800 1000 METRES

PLAN 24

DEPARTMENT OF MINES AND ENERGY – SOUTH AUSTRALIA

TERTIARY STRATIGRAPHY & FORAMINIFERA

ADELAIDE CITY AREA

"HALLETT COVE SANDSTONE":

DISTRIBUTION, STRUCTURE CONTOURS, THICKNESS

	COMPILED J.M.L.	DRN S.R.	SCALE	PLAN NUMBER
DIRECTOR GENERAL	11.11.80	CKD J.M.L.	DATE OCT. 1979	80-779

1532

138° 36'

34° 54'

34° 57'

RENOWN PARK
FITZROY
THORNGATE
NORTH ROAD
MEDINDIE
WALKERVILLE
JOSLIN
BROMPTON
OVINGHAM
FAULT
MAIN ROAD
ROSE TERRACE
GILBERTON
BOWDEN
JEFFCOTT STREET
NORTH ADELAIDE
ST. PETERS
PARA WEST FAULT
PARA FAULT
COLLEGE PARK
HACKNEY
HACKNEY ROAD
RIVER TORRENS
MAIN NORTH TERRACE
KING WILLIAM STREET
KENT TOWN
WEST TERRACE
ADELAIDE
EAST TERRACE
FULLARTON ROAD
MILE END SOUTH
SOUTH TERRACE
GREENHILL ROAD
EASTWOOD
KESWICK
WAYVILLE
UNLEY
PARKSIDE
ASHFORD
ANZAC HIGHWAY

Elevation, base of Quaternary deposits, borehole data & contours (in metres above A.H.D.)

NOTE— Thickness of deposits = ground elevation — elevation base.

Map prepared from interpretation of best available data.

Quaternary deposits include alluvium of the Torrens, Hindmarsh Clay, and Carisbrooke Sand.

Natural surface contours (in metres above A.H.D.)

METRES 200 0 200 400 600 800 1000 METRES

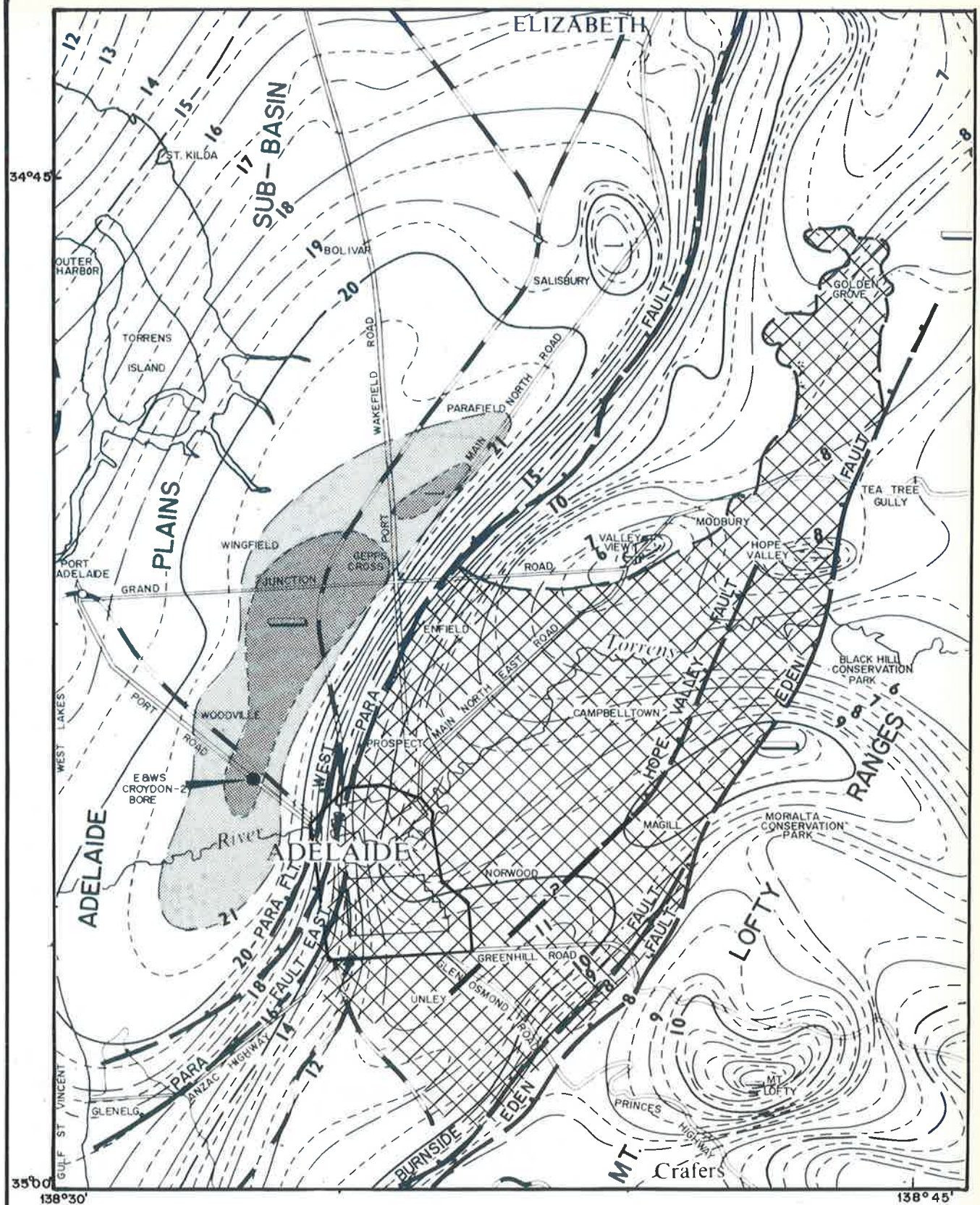
PLAN 25

DEPARTMENT OF MINES AND ENERGY — SOUTH AUSTRALIA

TERTIARY STRATIGRAPHY & FORAMINIFERA
ADELAIDE CITY AREA
CONTOURED BASE OF QUATERNARY DEPOSITS

	COMPILED J.M.L.	DRN S.R.	SCALE	PLAN NUMBER
DIRECTOR GENERAL	11/11/80	CKD J.M.L.	DATE OCT. 1979	80-780

1532



FAULT

BOUGUER ANOMALY CONTOURS (Contour interval 0·5 milligals)

GRAVITY ANOMALY – HIGH

GRAVITY ANOMALY – LOW

GOLDEN GROVE – ADELAIDE EMBAYMENT

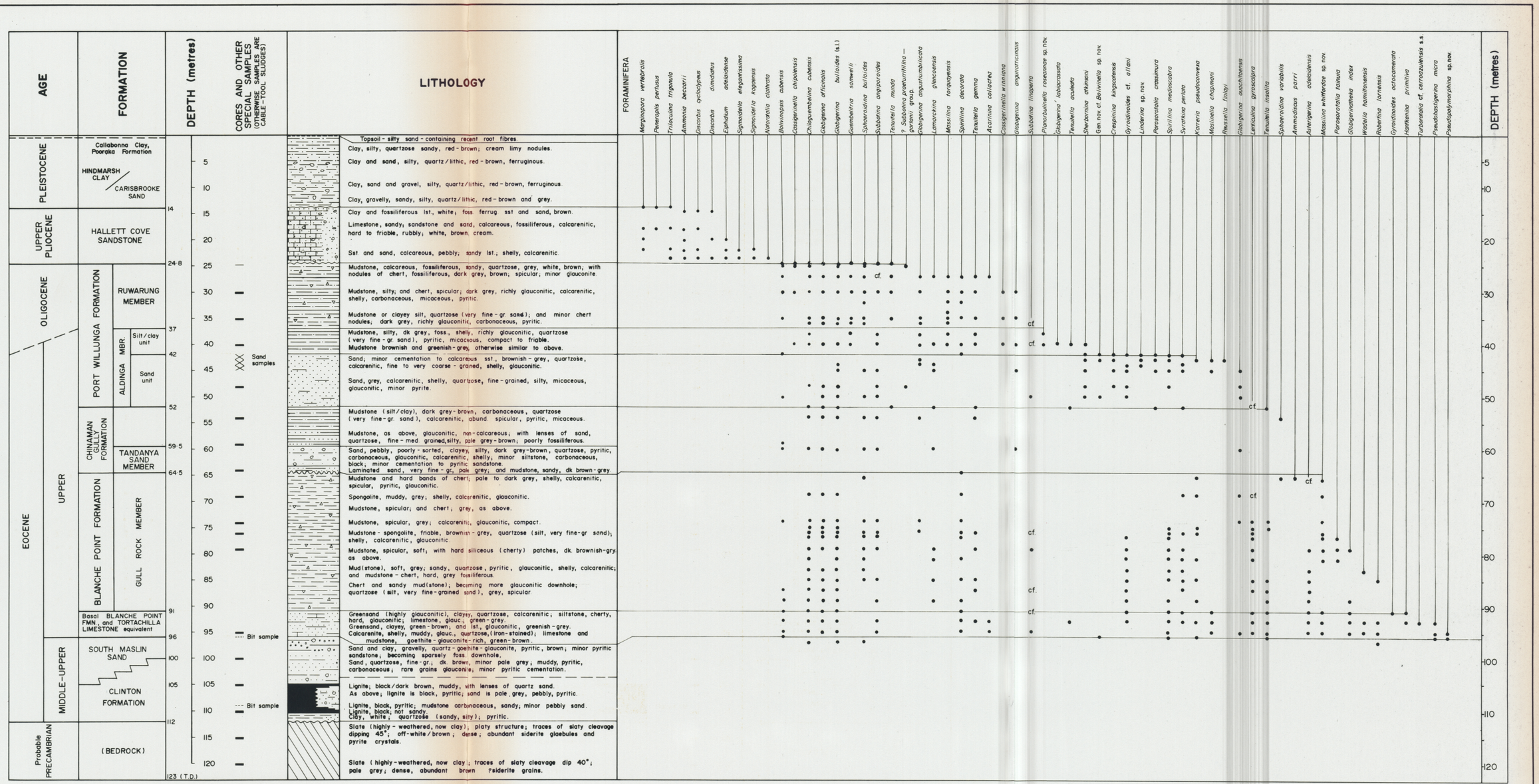
0 2 4 6 8 Kilometres

–After S.A.D.M.E. 1978

PLAN 26

	DEPARTMENT OF MINES AND ENERGY SOUTH AUSTRALIA	SCALE: 1:150 000
COMPILED: J.M.L.	**TERTIARY STRATIGRAPHY & FORAMINIFERA**	DATE: Sept. 1979
DRN: S.R. CKD:	**ADELAIDE CITY AREA**	PLAN NUMBER S15215
11·11·80	**BOUGUER ANOMALY MAP**	

1532


AGE
FORMATION
DEPTH (metres)
CORES AND OTHER SPECIAL SAMPLES (CUTTINGS SAMPLES ARE OMITTED FOR CABLE TOOL SLUDGES)
LITHOLOGY
FORAMINIFERA
PLEISTOCENE
Callabonna Clay, Poorgka Formation
HINDMARSH CLAY
CARISBROOKE SAND
UPPER PLIOCENE
HALLETT COVE SANDSTONE
OLIGOCENE
EOCENE
UPPER
PORT WILLUNGA FORMATION
RUWARUNG MEMBER
ALDINGA MBR.
Silt/clay unit
Sand unit
CHINAMAN GULLY FORMATION
TANDANYA SAND MEMBER
BLANCHE POINT FORMATION
GULL ROCK MEMBER
Basal BLANCHE POINT FMN. and TORTACHILLA LIMESTONE equivalent
MIDDLE-UPPER
SOUTH MASLIN SAND
CLINTON FORMATION
Probable PRECAMBRIAN
(BEDROCK)
14
24·8
37
42
52
59·5
64·5
91
96
112
123 (T.D.)
Topsoil - silty sand - containing recent root fibres.
Clay, silty, quartzose sandy, red-brown; cream limy nodules.
Clay and sand, silty, quartz/lithic, red-brown, ferruginous.
Clay, sand and gravel, silty, quartz/lithic, red-brown, ferruginous.
Clay, gravelly, sandy, silty, quartz/lithic, red-brown and grey.
Clay and fossiliferous lst., white; foss. ferrug. sst and sand, brown.
Limestone, sandy; sandstone and sand, calcareous, fossiliferous, calcarenitic, hard to friable, rubbly; white, brown, cream.
Sst and sand, calcareous, pebbly, sandy lst.; shelly, calcarenitic.
Mudstone, calcareous, fossiliferous, sandy, quartzose, grey, white, brown; with nodules of chert, fossiliferous, dark grey, brown, spicular, minor glauconite.
Mudstone, silty, and chert, spicular; dark grey, richly glauconitic, calcarenitic, shelly, carbonaceous, micaceous, pyritic.
Mudstone or clayey silt, quartzose (very fine-gr. sand); and minor chert nodules; dark grey, richly glauconitic, carbonaceous, pyritic.
Mudstone, silty, dk grey, foss., shelly, richly glauconitic, quartzose (very fine-gr. sand), pyritic, micaceous, compact to friable.
Mudstone brownish and greenish-grey, otherwise similar to above.
Sand, minor cementation to calcareous sst., brownish-grey, quartzose, calcarenitic, fine to very coarse-grained, shelly, glauconitic.
Sand, grey, calcarenitic, shelly, quartzose, fine-grained, silty, micaceous, glauconitic, minor pyrite.
Mudstone (silt/clay), dark grey-brown, carbonaceous, quartzose (very fine-gr. sand), calcarenitic, abund. spicular, pyritic, micaceous.
Mudstone, as above, glauconitic, non-calcareous; with lenses of sand, quartzose, fine-med. grained, silty, pale grey-brown; poorly fossiliferous.
Sand, pebbly, poorly-sorted, clayey, silty, dark grey-brown, quartzose, pyritic, carbonaceous, glauconitic, calcarenitic, shelly, minor siltstone, carbonaceous, black; minor cementation to pyritic sandstone.
Laminated sand, very fine-gr, pale grey; and mudstone, sandy, dk brown-grey.
Mudstone and hard bands of chert, pale to dark grey, shelly, calcarenitic, spicular, pyritic, glauconitic.
Spongolite, muddy, grey, shelly, calcarenitic, glauconitic.
Mudstone, spicular; and chert, grey, as above.
Mudstone, spicular, grey; calcarenitic, glauconitic, compact.
Mudstone - spongolite, friable, brownish-grey, quartzose (silt, very fine-gr sand); shelly, calcarenitic, glauconitic.
Mudstone, spicular, soft, with hard siliceous (cherty) patches, dk. brownish-grey as above.
Mud(stone), soft, grey; sandy, quartzose, pyritic, glauconitic, shelly, calcarenitic; and mudstone-chert, hard, grey fossiliferous.
Chert and sandy mud(stone); becoming more glauconitic downhole; quartzose (silt, very fine-grained sand), grey, spicular.
Greensand (highly glauconitic), clayey, quartzose, calcarenitic; siltstone, cherty, hard, glauconitic; limestone, glauc., green-grey.
Greensand, clayey, green-brown; and lst., glauconitic, greenish-grey.
Calcarenite, shelly, muddy, glauc., quartzose, (iron-stained); limestone and mudstone, goethite-glauconite-rich, green-brown.
Sand and clay, gravelly, quartz-goethite-glauconite, pyritic, brown; minor pyritic sandstone; becoming sparsely foss. downhole.
Sand, quartzose, fine-gr., dk. brown, minor pale grey; muddy, pyritic, carbonaceous; rare grains glauconite; minor pyritic cementation.
Lignite; black/dark brown, muddy, with lenses of quartz sand.
As above; lignite is black, pyritic; sand is pale grey, pebbly, pyritic.
Lignite, black, pyritic; mudstone carbonaceous, sandy; minor pebbly sand.
Lignite, black; not sandy.
Clay, white; quartzose (sandy, silty); pyritic.
Slate (highly-weathered, now clay); platy structure; traces of slaty cleavage dipping 45°; off-white/brown; dense; abundant siderite gloebules and pyrite crystals.
Slate (highly-weathered, now clay); traces of slaty cleavage dip 40°; pale grey; dense, abundant brown ?siderite grains.
Sand samples
Bit sample
Bit sample
Marginopora vertebralis
Peneroplis pertusus
Triloculina tripartula
Ammonia beccarii
Discorbis cyclocheilus
Discorbis dimidiatus
Discorbis adelaidense
Elphidium
Sigmoidella elegantissima
Sigmoidella kapiensis
Sigmoidella clathrata
Notorotalia
Bolivinopsis cubensis
Cassigerinella chipolensis
Chilogumbelina cubensis
Globigerina africinalis
Globigerina bulloides (s.l.)
Guembelitria samwelli
Sphaeroidina bulloides
Subbotina angiporoides
Tenuitella munda
? Subbotina praturritina - gortanii group
Globigerina angustiumbilicata
Globigerina glencoensis
Lamarckina
Massilina torquayensis
Spiroloculina decorata
Tenuitella gemma
Acarinina collacta
Cassigerinella wilmingtonensis
Globigerina angulisuturalis
Subbotina linaperta
Planorbulinella rosenmayr sp. nov.
Globigerina' tobacoensis
Tenuitella aculeata
Sherbornina atkinsoni
Gen. nov. cf. Bolivinella sp. nov.
Crespinina kingcotensis
Gyroidinoides cf. altani
Linderina sp. nov.
Parasorotalia crassimura
Spiroloculina mediocostra
Syrotrema perlata
Karreria pseudoconvexa
Massilinella chapmani
Reussella finlayi
Globigerina dutchitanensis
Lenticulina gyrosacopra
Tenuitella insolita
Sphaeroidina variabilis
Ammodiscus parri
Astrorhizina adelaidensis
Massilina whitfordae sp. nov.
Parasorotalia taharu
Globigerinatheka index
Wodehia hamiltonensis
Robertina tarnensis
Gyroidinoides octocameratus
Hantkenina primitiva
Turborotalia cf. cerroazulensis s.s.
Pseudohastigerina micra
Pseudopolymorphina sp. nov.
DEPTH (metres)
PLAN 27
DEPARTMENT OF MINES AND ENERGY SOUTH AUSTRALIA
TERTIARY STRATIGRAPHY & FORAMINIFERA
ADELAIDE CITY AREA
COMPOSITE AND FORAMINIFERAL LOG OF SADME SOUTH PARKLANDS BORE ADE 33
SCALE
DATE DEC. 1979
PLAN NUMBER 80-781
COMPILED J.ML.
DRN S.R. CKD
4/11/80

AGE	FORMATION	DEPTH (metres)
PLEISTOCENE	? Callabonna Clay / Pooraka Formation	1
	HINDMARSH CLAY	4
		8
	CARISBROOKE SAND	10
LATE PLIOCENE	HALLETT COVE SST.	17 / ?18
UPPER EOCENE — MIDDLE	CHINAMAN GULLY FORMATION / TANDANYA SAND MEMBER	?20
	BLANCHE POINT FORMATION / GULL ROCK MEMBER	?25
	Undifferentiated equivs. of basal BLANCHE PT. FMN. & TORTACHILLA LST.	46
	SOUTH MASLIN SAND	51
		62
	CLINTON FORMATION	65
		89
Probable PRECAMBRIAN	(BEDROCK)	113 (T.D.)

CORES AND OTHER SPECIAL SAMPLES (OTHERWISE SAMPLES ARE CABLE-TOOL SLUDGES)

- Sand sample
- Bit sample

LITHOLOGY

- Fill, bitumen and gravel.
- Clay, red-brown, sandy, silty; in part with white limy nodules.
- Clay, very stiff, pale grey mottled red-brown, sandy, silty.
- Clay, sandy, and sand, clayey, mottled red-brown, grey.
- Sand, clayey, quartzose, patches of clay, sandy; pale grey mottled orange-brown, red-brown, non-calcareous.
- Sand, clayey, quartzose, poorly-sorted, pebbly, sideritic, brown-white.
- Sandstone, clayey, hard, quartzose, pale brownish-grey.
- Sand, red-brown, clayey, quartzose, poorly-sorted.
- Sandstone, calcareous, and sand; fossiliferous, cream/brown; clay, sandy, mottled.
- Clay, silty, very fine-gr sandy, quartzose, micaceous; with abundant ovoid faecal pellets, ?glauconitic, bioturbated; pale greenish-grey mottled brown; occasional fossil casts; leached, weathered.
- Sand, gravelly, quartzose, muddy, poorly-sorted, palegrey, yellowish, sparsely glauconitic, minor argillaceous and ferruginous cementation.
- Clay, calcareous, silty; spongolite, nodules of chert, weathered, pale brownish-grey, white, mottled orange-brown; fossiliferous, spicular, glauconitic.
- Mudstone, with hard bands, nodules of chert; grey; calcarenitic, shelly, spicular; glauconitic.
- As above; becoming increasingly glauconitic downhole; dark greenish-grey.
- Mudstone to muddy greensand, v. glauconitic, dk. greenish-grey, fossiliferous, shelly, minor glauconitic limestone; slightly pyritic.
- Mudstone to limestone, green-grey/brown, shelly, v. glauc., quartzose, sandy (brown, iron-stained grains); firm, clayey, to rubbly, friable.
- Sand, quartzose, muddy, greenish-grey; pyritic, glauc., shelly, calcarenitic.
- Sand, quartzose, fine-gr., muddy, dk. grey-brown, carbonaceous, poorly foss., minor shelly fragments; sparsely glauconitic; pyritic; micaceous.
- As above, sand, fine-gr.; to mudstone, soft, sandy; shelly fossil fragments becoming very sparse; bioturbated; ovoid faecal pellets.
- Sand, quartzose, fine to v. coarse-gr.; and mudstone, sandy, very carbonaceous, both pyritic; sparse glauc. and shelly fragments (? caved).
- Lignite, friable, muddy; black-dark brown; parts quartzose, sandy; pyritic.
- Lignite, mudstone, sand, highly carbonaceous, pyritic.
- Lignite, black, friable, pyritic; minor quartz sand.
- Sand, quartzose, grey, poorly-sorted; minor lignite.
- Lignite and sand, muddy, dark brown.
- Sand, quartzose, grey; slightly muddy and carbonaceous.
- Sand, gravelly, quartzose, muddy; and minor lignite; pyritic; clay, grey.
- Clay, pale grey, stiff; black carbonaceous specks; abundant pyrite aggregates.
- Clay, pale grey, stiff, with minor fine-gr. quartz sand (= completely weathered sandy ?siltstone); occas. qtz. veinlet, jointed, glaebules and platy joint-fillings of siderite/pyrite.
- Clay, pale grey, with fine-gr. quartz sand, stiff, hard (= completely weathered sandy ?siltstone); quartz veinlets; vertically jointed, with platy siderite/pyrite along joint planes, scattered glaebules of siderite/pyrite; abundant crystals of pyrite.
- Siltstone/fine-gr. sandstone, highly weathered, clayey; pale grey, stiff, hard, solid; bedding discernable dipping ~45°; jointing steep ~80°; micaceous; siderite/pyrite along joint planes as above, and as glaebules.
- Siltstone/fine gr. sandstone, weathered, clayey, chloritic, bluish- and greenish-grey; non-calcareous; some hard fresher pieces.

FORAMINIFERA

- *Ammonia beccarii*
- *Discorbinella biconcava*
- *Elphidium advenum*
- *Elphidium maclelium*
- *Elphidium crassatum*
- *Elphidium crispum*
- *Chilogumbelina cubensis*
- *Globigerina officinalis*
- *Globigerina bulloides s.l.*
- *Karreria pseudoconvexa*
- *Lenticulina gyroscalpra*
- *Sphaeroidina bulloides*
- *Sphaeroidina variabilis*
- *Svratkina perlata*
- *Massilina whitfordae* sp. nov.
- *Spiroloculina decorata*
- *Spiroloculina mediocostata*
- *Subbotina linaperta*
- *Tenuitella insolita*
- *Astrorotalia adelaidensis*
- *Globigerinatheka index*
- *Robertina lornensis*
- *Tenuitella gemma*
- *Maslinella chapmani*
- *Subbotina angiporoides*
- *Gyroidinoides* cf. *soldanii*
- *Gyroidinoides* cf. *alloni*
- *Pseudohastigerina micra*
- *Globigerina ouachitaensis*
- *Hantkenina primitiva*
- *Gyroidinoides octocameratus*
- *Pseudopolymorphina* sp. nov.
- *Alabamina wesfalliensis*
- *Wadella hamiltonensis*
- *Lamarckina glencoensis*
- *Tenuitella aculeata*
- *Turborotalia opima nana*

DEPTH (metres): 5, 10, 20, 30, 40, 50, 60, 70, 80, 90, 100, 110

PLAN 28

DEPARTMENT OF MINES AND ENERGY — SOUTH AUSTRALIA

TERTIARY STRATIGRAPHY & FORAMINIFERA
ADELAIDE CITY AREA

COMPOSITE AND FORAMINIFERAL LOG OF
S.A.D.M.E. WEST END BREWERY BORE 6628-00368

	COMPILED J.M.L.	DRN S.R.	SCALE	PLAN NUMBER
DIRECTOR GENERAL	11-11-80	CKD	DATE DEC. 1979	80-782

1532

AGE	FORMATION	DEPTH (metres)	LITHOLOGY
PLEISTOCENE	HINDMARSH CLAY	0–117	Brown clay, sandy near surface, sandy at 6m Coarse quartzose sand and gravel Brown clay and gravel Brown clay with lime nodules Brown clay Grey clay Clay and quartz gravel, with water Yellow clay and sand with water Brown clay Brown clay and quartz gravel Brown, clayey quartz sand, at 97.5–99m Light brown sandy clay Yellow clayey quartz sand, lime cemented lumps at 115m
PLIOCENE	DRY CREEK SAND	117–152	Greenish-grey and brown clay Grey fossiliferous quartz sand, shelly, hard bar (blue-grey fossiliferous calc ss) at 126.5–129.5m Grey to grey-brown fine quartz sand with shell fragments White medium grained fossiliferous quartz sand, with shell fragments Grey fossiliferous calc ss at 145.5–147.5m Grey fossiliferous sandy limestone with hard and soft bands, abundant shell fragments, minor sst, silts, lst
	KOOYONGA FORMATION	152–197	Off white silt and fine qtz sand, with fine gravel and shell frags Grey-brown fossiliferous sand, silty lst, sst, silt, glauconitic, bryozoal shelly limestone at 184.7–185.5m Brownish-grey, very fine grained quartz sand and silt, minor limestone and sst, shelly, bryozoal, glauconitic, hard bar of shelly calc sst at 173.5–174.4m Grey fossiliferous sandy silt and silty limestone, shelly, bryozoal, rare Dictyon sp.
MIOCENE LOWER–MIDDLE	PORT WILLUNGA FORMATION MUNNO PARA CLAY MEMBER (Tatachilla phase)	197–222	Yellow-brown fossiliferous sandy limestone and hard and soft bands, abundant bryozoa and Dictyon, water at 192m
	(Tatachilla phase)	222–231	Cream to pale grey fossiliferous sandy limestone, hard to soft, bryozoal
	(Tatachilla phase)	231–244	Medium to dark brown-grey calcareous clay, silt, pyritic, fossiliferous, sandy
	(Tatachilla phase)	244–248	Pale brownish-grey with limestone, sandy, silty and clayey, fossiliferous, bryozoal, shelly glauconitic marl
	(Tatachilla phase)	248–282	Pale yellow-brown, fossiliferous sand and sandy limestone, hard and soft, clay and clayey in part, highly glauconitic and ferruginous
	(Tatachilla phase)	282–307	As above, with a clayey band at 282.9–283.6m
	(Wigunti phase)	307–320	Pale grey, pale yellow-brown fossiliferous sandy silty ls, sandy calc sst, glauconitic
	RUWARUNG MEMBER	320–392	Pale grey-brown fossiliferous silty sand and calcareous, ls, glauconitic clayey, volcanic
	RUWARUNG MEMBER	392–403	Grey clayey section, shelly and silt pyritic, glauconitic, calcareous
	ALDINGA MEMBER	403–406	Grey to dark grey siltstone/sandy clayey, fossiliferous, shelly pyritic, glauconitic, carbonaceous
	ALDINGA MEMBER	406–441	Pale grey siltstone/sandy, fossiliferous, glauconitic, pyritic
	CHINAMAN GULLY FORMATION	441–451	Dark grey–brown siltstone, carbonaceous, sandy, shelly, pyritic
	CHINAMAN GULLY FORMATION	451–461	Dark brown, black, lignitic silt and clay
EOCENE ?MIDDLE–UPPER	BLANCHE POINT FORMATION GULL ROCK MEMBER	461–504	Grey shelly soft siltstone, silt and marl
	GULL ROCK MEMBER	504–522	Pale grey shelly glauconitic calcareous siltstone, with hard shelly bands
	Basal BLANCHE POINT FORMATION and TORTACHILLA LST	522–587	As above, with dark brown–grey glauconitic sandy calcareous marl, ferruginous in part, phosphatic
		587–593	Dark, greenish-grey glauconitic clayey sand, ten band of glauconitic and carbonaceous sandy clay at top
	SOUTH MASLIN SAND	593–680	Grey glauconitic clayey sand, slightly carbonaceous and pyritic
		680–694	Off white to grey clay, sandy, silty, slightly carbonaceous, pyritic
	? CLINTON FORMATION	694–902	As above, but not carbonaceous
		902–906	Grey carbonaceous clay, very carbonaceous at 906–908m
		906–968	Sandy clay, off-white, dirty yellow/green, carbonaceous at 910–916m, dolomitic in part
		968–987	Pale brown ferruginous sandy clayey gravelly, angular fragments of milky quartz, white and red silt and loam
? CAPE JERVIS BEDS		987–1040	Pale brown gritty sandy silty clay, with angular fragments of quartz and white
? PERMIAN		1040–1095	Pale brown quartzose fine sand, very clayey, some fragments of purple shale Grey/brown, lithic fragmental/pyllite, white quartzose pegmatite, mineral with clay and sand, minor coarse clay and sand below 1083m Grey/pale-brown coarse lithic and quartz sand fragments of pyllite, sst, quartzite, pegmatite, pebbles and boulders in bottom, few fragments with well rounded quartz

FORAMINIFERA

- *Ammonia beccarii*
- *Elphidium advenum*
- *Elphidium macellum*
- *Cavarina multicameralis*
- *Discorbis apertuliformis*
- *Discorbis cyrtocystus*
- *D.scorbis dimidiatus*
- *Marginopora vertebralis*
- *Parrellina howchini*
- *Spirolina arietina*
- *Triloculina trigonula*
- *Elphidium crispum*
- *Cribroelphidium murrayi*
- *Notorotalia clathrata*
- *Gutulina regina*
- *Siphonaperta ammophila*
- *Elphidium adelaidense*
- *Elphidium crassatum*
- *Episiomorbides polystomelloides*
- *Sigmomorphina subregularis*
- *Gypsina howchini*
- *Sigmoidella elegantissima*
- *Sphaerogypsina globula*
- *Crespinella unboni-ferri*
- *Operculina victoriensis*
- *Parrellina howchini*
- *Amphistegina lessoni*
- *Cassigerinella chipolensis*
- *Globigerina angulisuturalis*
- *Notorotalia howchini*
- *Valvulineria? eximenensis*
- *Planoglobigerina planoconica*
- *Globigerina bulloides s.l.*
- *Globigerina? woodi woodi*
- *Tubulogenerina maorobbaensis*
- *Globigerina woodi connecta*
- *Parrellina cf.reticulatiformis*
- *Crespinella parri*
- *Globigerinoides kiczkus*
- *Planoglobigerina praedigitata*
- *Pararotalia verruculata*
- *Astrononion centroplus*
- *Sherbornina cuneimarginata*
- *Globigerina ouachitaensis*
- *Globigerina atlifichaels*
- *Globigerinoides quadrilobatus s.s.*
- *Globigerina operaensis s.s.*
- *Gargantiana rohlfsorina*
- *Parrellina crespinae*
- *Notorotalia sp. nov.*
- *Porosorotalia blasimuna*
- *Textularia vermebralis*
- *Globigerina juvenilis*
- *Gyroidinoides cf. altani*
- *Tenuitella munda*
- *Sherbornina atkinsoni*
- *Sigmomorphina howchini*
- *Cibicides vortex*
- *? Globigerina obesa*
- *Massilina tarquiyensis*
- *Globigerina angulisuturalis*
- *Bolivinopsis cubensis*
- *Victorella advoidea*
- *Guembelitria cenomana*
- *Cassigerinella winkleri*
- *Tenuitella gemma*
- *Subbotina angiporoides*
- *Spirillina mediocostata*
- *Pleurostomella? rosacensis sp. nov.*
- *Chiloguembelina cubensis*
- *Spirillina decorata*
- *Tenuitella aculeata*
- *Lenticulina gyroscalpra*
- *Asterigerina adelaidensis*
- *Gyroidinoides cf. soldanii*
- *Pseudoglobulimorphina sp. nov.*

NO SAMPLES

O Probably reworked

DEPTH(metres)

DEPARTMENT OF MINES AND ENERGY, SOUTH AUSTRALIA — PLAN 29

TERTIARY STRATIGRAPHY & FOREMINIFERA

ADELAIDE CITY AREA

COMPOSITE AND FORAMINIFERAL LOG OF E.M.R. CROYDON-2 BORE (1692) (6628-0877)

DRAWN	COMPILED (RK)	SCALE	PLAN NUMBER
DIRECTOR GENERAL	CHKD. B.M.	DATE JAN 1980	80-783

EAST ST. VINCENT BASIN
COASTAL SECTIONS

NORTH

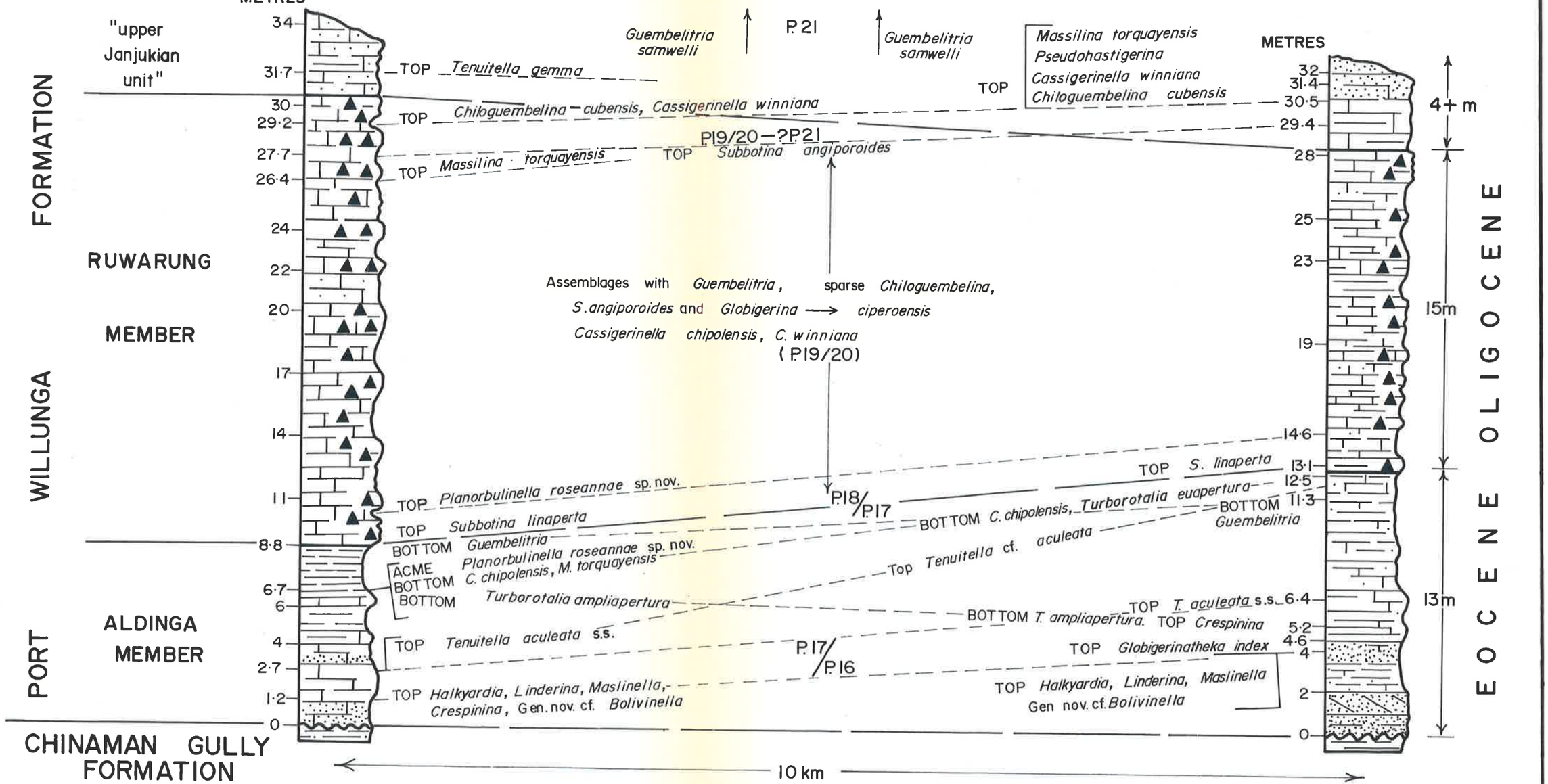
PORT NOARLUNGA SOUTH

NOARLUNGA EMBAYMENT

SOUTH

PORT WILLUNGA (TYPE SECTION)

WILLUNGA EMBAYMENT



PLAN 30

DEPARTMENT OF MINES AND ENERGY
SOUTH AUSTRALIA

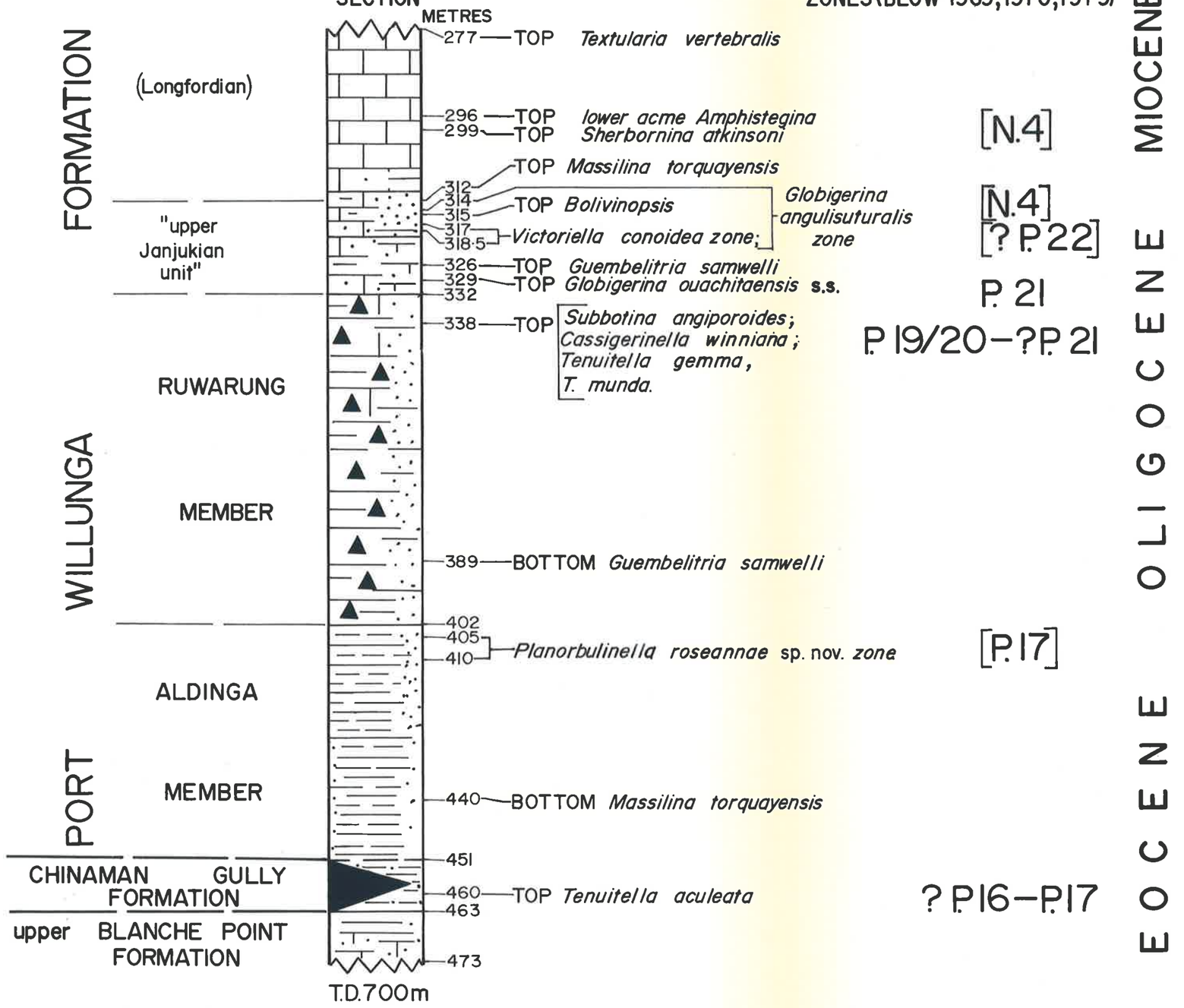
TERTIARY STRATIGRAPHY & FORAMINIFERA

ADELAIDE CITY AREA

PORT WILLUNGA FORMATION : BIOSTRATIGRAPHIC CORRELATION BETWEEN TYPE SECTION AND PORT NOARLUNGA REFERENCE SECTION

COMPILED J.M.L.	C.D.O. 11.11.80 DATE
DRAWN S.R.	SCALE
DATE 12/2/80	PLAN NUMBER 80-784
CHECKED	

1532



PLAN 31

DEPARTMENT OF MINES AND ENERGY
SOUTH AUSTRALIA

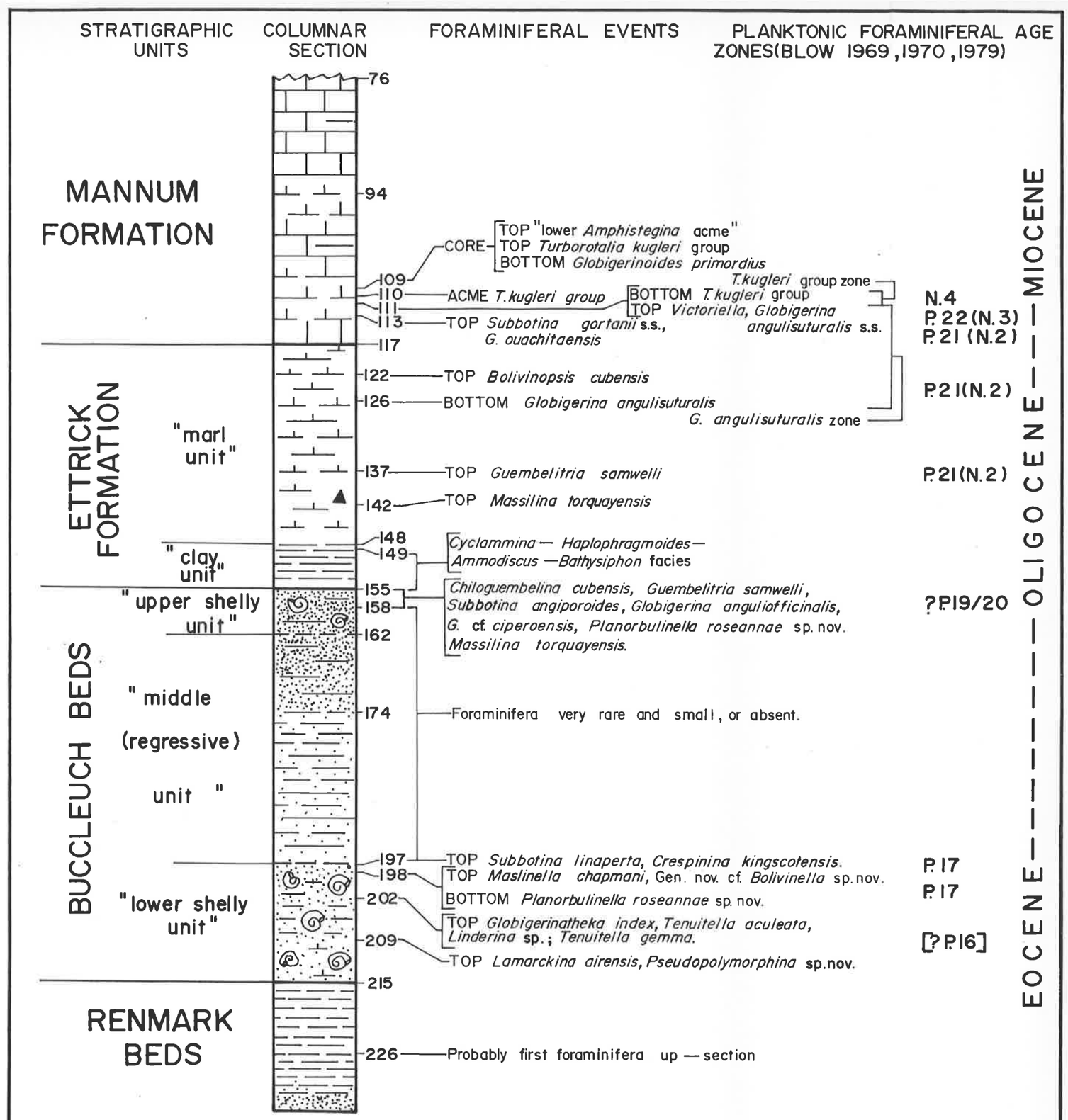
TERTIARY STRATIGRAPHY & FORAMINIFERA

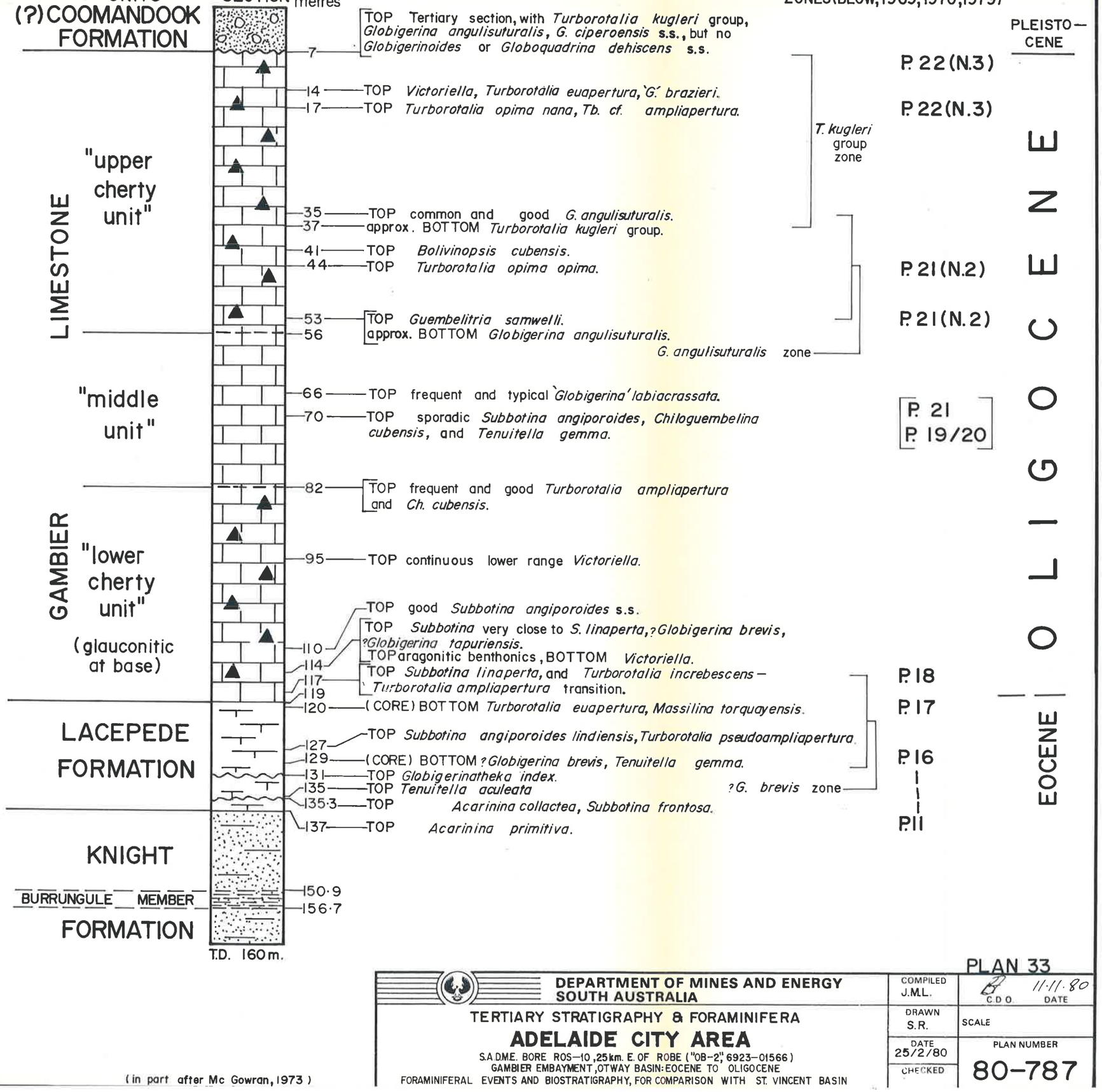
ADELAIDE CITY AREA

CROYDON — 2 BORE : UPPERMOST EOCENE TO LOWERMOST MIOCENE FORAMINIFERAL EVENTS AND BIOSTRATIGRAPHY

COMPILED J.M.L.	C.D.O. 11.11.80 DATE
DRAWN S.R.	SCALE
DATE 7/2/80	PLAN NUMBER 80-785
CHECKED	

1632


STRATIGRAPHIC UNITS
COLUMNAR SECTION
FORAMINIFERAL EVENTS
PLANKTONIC FORAMINIFERAL AGE ZONES(BLOW 1969,1970,1979)
MANNUM FORMATION
ETTRICK FORMATION
"marl unit"
"clay unit"
"upper shelly unit"
BUCCLEUCH BEDS
"middle (regressive) unit"
"lower shelly unit"
RENMARK BEDS
76
94
109
110
111
113
117
122
126
137
142
148
149
155
158
162
174
197
198
202
209
215
226
CORE — TOP "lower Amphistegina acme"
TOP Turborotalia kugleri group
BOTTOM Globigerinoides primordius
ACME T.kugleri group
T.kugleri group zone
BOTTOM T.kugleri group
TOP Victoriella, Globigerina angulisuturalis s.s.
TOP Subbotina gortanii s.s., G. ouachitaensis
G. angulisuturalis zone
TOP Bolivinopsis cubensis
BOTTOM Globigerina angulisuturalis
TOP Guembelitria samwelli
TOP Massilina torquayensis
Cyclammina — Haplophragmoides — Ammodiscus — Bathysiphon facies
Chiloguembelina cubensis, Guembelitria samwelli, Subbotina angiporoides, Globigerina angulofficinalis, G. cf. ciperoensis, Planorbulinella roseannae sp. nov. Massilina torquayensis.
Foraminifera very rare and small, or absent.
TOP Subbotina linaperta, Crespinina kingscotensis.
TOP Maslinella chapmani, Gen. nov. cf. Bolivinella sp. nov.
BOTTOM Planorbulinella roseannae sp. nov.
TOP Globigerinatheka index, Tenuitella aculeata, Linderina sp.; Tenuitella gemma.
TOP Lamarckina airensis, Pseudopolymorphina sp.nov.
Probably first foraminifera up — section
N.4
P.22(N.3)
P.21(N.2)
P.21(N.2)
P.21(N.2)
?P.19/20
P.17
P.17
[?P.16]
OLIGOCENE — MIOCENE
EOCENE
T.D. 235m
PLAN 32
DEPARTMENT OF MINES AND ENERGY SOUTH AUSTRALIA
TERTIARY STRATIGRAPHY & FORAMINIFERA
ADELAIDE CITY AREA
S.A.D.ME. WAIKERIE BORE WAK—1 ("2W",6829—00442) MURRAY BASIN:
EOCENE TO OLIGO-MIOCENE FORAMINIFERAL EVENTS AND BIOSTRATIGRAPHY, FOR COMPARISON WITH ST. VINCENT BASIN
COMPILED J.M.L.
CDO 11.11.80 DATE
DRAWN S.R.
SCALE
DATE 15-2-80
CHECKED
PLAN NUMBER 80-786
1532



(in part after Mc Gowran, 1973)

1532

PLAN 33

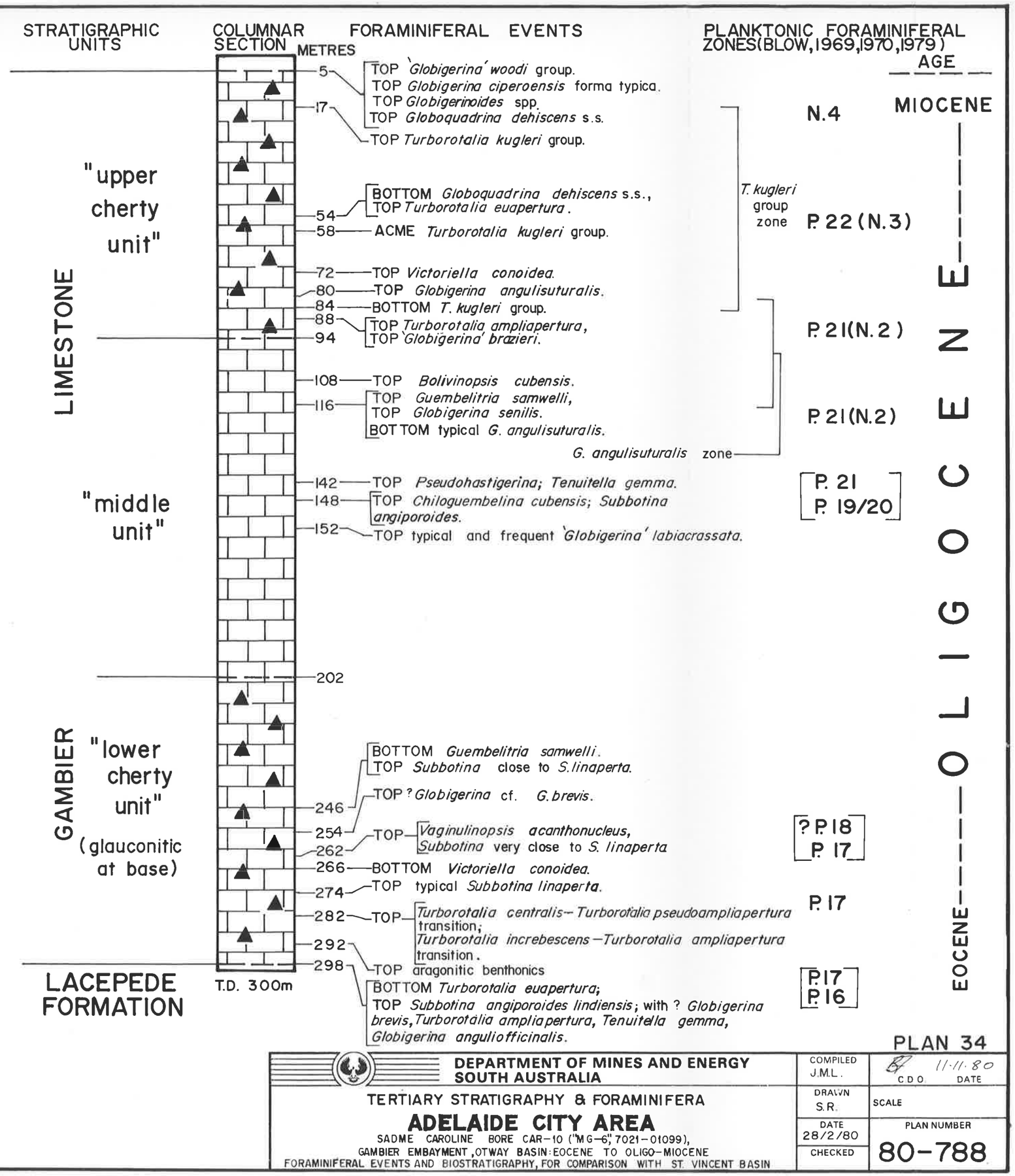
DEPARTMENT OF MINES AND ENERGY
SOUTH AUSTRALIA

TERTIARY STRATIGRAPHY & FORAMINIFERA

ADELAIDE CITY AREA

S.A.D.M.E. BORE ROS–10, 25km. E. OF ROBE ("OB–2" 6923–01566)
GAMBIER EMBAYMENT, OTWAY BASIN: EOCENE TO OLIGOCENE
FORAMINIFERAL EVENTS AND BIOSTRATIGRAPHY, FOR COMPARISON WITH ST. VINCENT BASIN

COMPILED J.M.L.	C.D.O. 11·11·80 DATE
DRAWN S.R.	SCALE
DATE 25/2/80	PLAN NUMBER 80–787
CHECKED	


STRATIGRAPHIC UNITS
COLUMNAR SECTION
METRES
FORAMINIFERAL EVENTS
PLANKTONIC FORAMINIFERAL ZONES(BLOW,1969,1970,1979)
AGE
LIMESTONE
"upper cherty unit"
"middle unit"
GAMBIER
"lower cherty unit"
(glauconitic at base)
LACEPEDE FORMATION
T.D. 300m
5 TOP 'Globigerina' woodi group.
TOP Globigerina ciperoensis forma typica.
TOP Globigerinoides spp.
TOP Globoquadrina dehiscens s.s.
17 TOP Turborotalia kugleri group.
54 BOTTOM Globoquadrina dehiscens s.s., TOP Turborotalia euapertura.
58 ACME Turborotalia kugleri group.
72 TOP Victoriella conoidea.
80 TOP Globigerina angulisuturalis.
84 BOTTOM T. kugleri group.
88 TOP Turborotalia ampliapertura,
94 TOP 'Globigerina' brazieri.
108 TOP Bolivinopsis cubensis.
116 TOP Guembelitria samwelli, TOP Globigerina senilis, BOTTOM typical G. angulisuturalis.
142 TOP Pseudohastigerina; Tenuitella gemma.
148 TOP Chiloguembelina cubensis; Subbotina angiporoides.
152 TOP typical and frequent 'Globigerina' labiacrassata.
202
246 BOTTOM Guembelitria samwelli. TOP Subbotina close to S.linaperta.
254 TOP ? Globigerina cf. G.brevis.
262 TOP Vaginulinopsis acanthonucleus, Subbotina very close to S. linaperta
266 BOTTOM Victoriella conoidea.
274 TOP typical Subbotina linaperta.
282 TOP Turborotalia centralis--Turborotalia pseudoampliapertura transition; Turborotalia increbescens--Turborotalia ampliapertura transition.
292
298 TOP aragonitic benthonics
BOTTOM Turborotalia euapertura; TOP Subbotina angiporoides lindiensis; with ? Globigerina brevis, Turborotalia ampliapertura, Tenuitella gemma, Globigerina angulofficinalis.
T. kugleri group zone
N.4
P. 22 (N.3)
P. 21(N.2)
G. angulisuturalis zone
P. 21(N.2)
P. 21
P. 19/20
? P. 18
P. 17
P. 17
P. 17
P. 16
MIOCENE
EOCENE
OLIGOCENE
PLAN 34
DEPARTMENT OF MINES AND ENERGY SOUTH AUSTRALIA
TERTIARY STRATIGRAPHY & FORAMINIFERA
ADELAIDE CITY AREA
SADME CAROLINE BORE CAR-10 ("MG-6", 7021-01099),
GAMBIER EMBAYMENT, OTWAY BASIN: EOCENE TO OLIGO-MIOCENE
FORAMINIFERAL EVENTS AND BIOSTRATIGRAPHY, FOR COMPARISON WITH ST. VINCENT BASIN
COMPILED J.M.L.
DRAWN S.R.
DATE 28/2/80
CHECKED
11.11.80 C.D.O. DATE
SCALE
PLAN NUMBER 80-788
1532

GEOCHRONOMETRIC SCALE (Ma)	EPOCH/SERIES	AUSTRALIAN STRATIGRAPHIC "SEQUENCES" (after McGowran, 1978d, 1979b)	TERTIARY SEDIMENTATION EASTERN ST. VINCENT BASIN
5	QUATERNARY	4	HALLETT COVE SST. / DRY CREEK SAND — BURNHAM LIMESTONE
	PLIOCENE		KOOYONGA FORMATION
10	MIOCENE — UPPER		(Bairnsdalian — Balcombian)
	MIOCENE — MIDDLE		MUNNO PARA CLAY MBR. (Balcombian—Batesfordian)
20	MIOCENE — LOWER	3	(Longfordian)
	OLIGOCENE — UPPER		"upper Janjukian unit"
30	OLIGOCENE — MIDDLE		RUWARUNG MEMBER
35	OLIGOCENE — LOWER		PORT WILLUNGA FORMATION (STRATOTYPE)
37	EOCENE — UPPER	2	ALDINGA MEMBER
			CHINAMAN GULLY FMN. — TANDANYA SAND MBR.
40	EOCENE — MIDDLE		GULL ROCK MEMBER — BLANCHE POINT FORMATION
45	EOCENE — LOWER		SOUTH MASLIN SAND / CLINTON FORMATION — TORTACHILLA LIMESTONE
50	PALEOCENE	1	NORTH MASLIN SAND
60			

FORAMINIFERA (ALL BUT ONE BENTHONIC) SUGGESTIVE OF WARM TEMPERATURES, EASTERN ST. VINCENT BASIN.

VARIOUS OTHER NOTABLE FEATURES.

M

M

MIDDLE TO UPPER MIOCENE HIATUS

O,A,F,M,Ⓐ
restricted—marine, regressive, organic—rich mud.

O,L,M,Ⓐ,A (upper *Amphistegina* acme)

(O,A)

V,A (lower *Amphistegina* acme)

CHERT

Rapid oceanic cooling; psychrosphere crisis

H,L,C

Regressive; minor brown coal; v. marg. marine.

CHERT

H,L,C — Ⓗ

Initiation of sedimentation; brown coal; very marginally marine in part.

LOWER TERTIARY

HIATUS

South Australian marine episodes suggesting warm water and/or transgression, Eastern St. Vincent Basin.

7
6
5
4
3
2
1

Oxygen—isotope palaeotemperatures for bottom and surface waters, DSDP sites 277 and 279A, south of New Zealand (replotted after Shackleton and Kennett 1975)

—— Benthonic foraminifera (deep water, ~ 1000m)

—•— Planktonic foraminifera (near—surface water)

°C (after Shackleton & Kennett, 1975)

0 5 10 15 20

FORAMINIFERA REFERENCE

A.....*Amphistegina*
Ⓐ.....*Austrotrillina*
C.....*Crespinina*
F.....*Flosculinella*
H.....*Halkyardia*
Ⓗ.....*Hantkenina (planktonic)*
L.....*Linderina*
L.....*Lepidocyclina*
M.....*Marginopora*
O.....*Operculina*
V.....*Victoriella*

Geochronometric scale correlated with epoch/series after La Brecque et al. (1977), Hardenbol & Berggren (1978).

PLAN 35

DEPARTMENT OF MINES AND ENERGY SOUTH AUSTRALIA

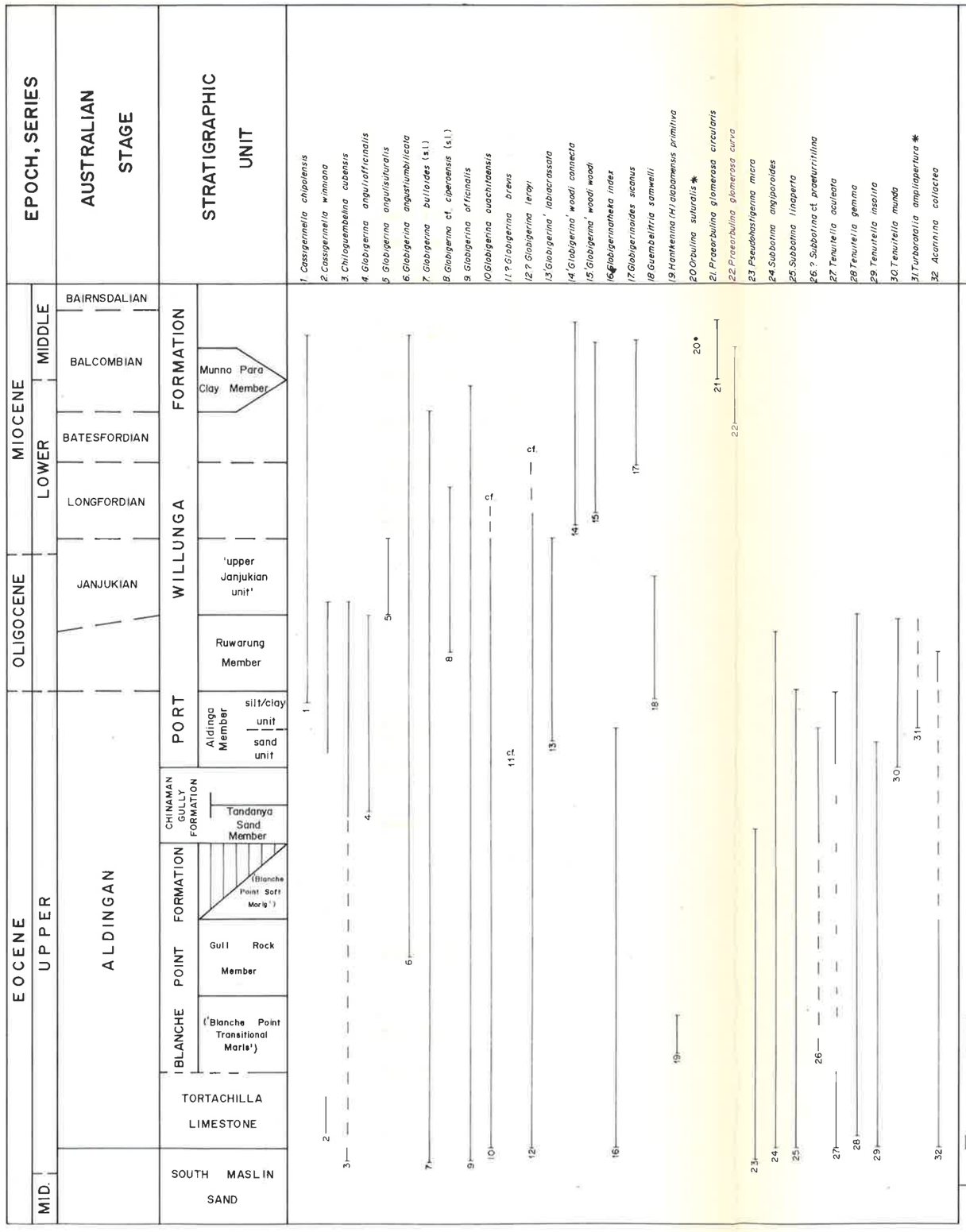
TERTIARY STRATIGRAPHY & FORAMINIFERA

ADELAIDE CITY AREA

CORRELATION OF TERTIARY SEDIMENTATION WITH PALAEOTEMPERATURE INDICATORS

COMPILED	J.M.L.
DRAWN	S.R.
DATE	FEB. 1980
CHECKED	11-11-80 C.D.O. DATE
SCALE	
PLAN NUMBER	80-789

1532



LOCAL PLANKTONIC FORAMINIFERAL DATUMS,

ADELAIDE CITY AREA

and

EASTERN ST. VINCENT BASIN

F.A.D. = First appearance datum

L.A.D. = Last appearance datum

* species not yet found in Adelaide City Area or Para Fault Zone

→ F.A.D. * *Orbulina suturalis*

→ F.A.D. *Praeorbulina glomerosa circularis*

→ F.A.D. *Praeorbulina glomerosa curva*

→ F.A.D. *Globigerinoides sicanus*

→ L.A.D. *Globigerina* cf. *ciperoensis*

→ F.A.D. *'Globigerina' woodi woodi*

→ F.A.D. *'Globigerina' woodi connecta*

→ L.A.D. *Globigerina angulisuturalis*, *'Globigerina' labiacrassata*

→ L.A.D. *Guembelitria samwelli*

→ L.A.D. *Chiloguembelina cubensis*, *Cassigerinella winniana*, *Pseudohastigerina*

→ L.A.D. *Tenuitella gemma*, *Tenuitella munda*
→ F.A.D. *Globigerina angulisuturalis*

→ L.A.D. *Subbotina angiporoides*

→ F.A.D. *Globigerina* cf. *ciperoensis*

→ L.A.D. *S. linaperta*, *T. aculeata*,
→ F.A.D. *Guembelitria samwelli*, *Cassigerinella chipolensis*

→ L.A.D. *Globigerinatheka index*, *(? Subbotina praeturritilina)*
→ F.A.D. * *Turborotalia ampliapertura* (*T. increbescens* – *T. ampliapertura* transition)
→ F.A.D. *'Globigerina' labiacrassata*; L.A.D. *Tenuitella insolita*

→ Base upper disjunct range *Tenuitella aculeata*
F.A.D. *T. munda*

→ (L.A.D. *Pseudohastigerina micra*)

→ F.A.D. *Globigerina angustiumbilicata*

Hantkenina primitiva Datum

→ Top lower disjunct range *Tenuitella aculeata*

F.A.D. *Tenuitella insolita*, *T. gemma*, *(C. winniana)*

PLAN 36

DEPARTMENT OF MINES AND ENERGY
SOUTH AUSTRALIA

TERTIARY STRATIGRAPHY AND FORAMINIFERA

ADELAIDE CITY AREA
(AND EASTERN ST. VINCENT BASIN)

MAXIMUM LOCAL PLANKTONIC FORAMINIFERAL RANGES AND DATUMS

COMPILED J.M.L.
DRAWN SR
DATE 29/10/80
CHECKED
DATE 11/11/80
SCALE AS SHOWN
PLAN NUMBER
80-790

1532

EPOCH, SERIES	AUSTRALIAN STAGE	STRATIGRAPHIC UNIT
EOCENE MID.	ALDINGAN	SOUTH MASLIN SAND
EOCENE MID.	ALDINGAN	TORTACHILLA LIMESTONE
EOCENE UPPER	ALDINGAN	BLANCHE POINT FORMATION ('Blanche Point Transitional Marls')
EOCENE UPPER	ALDINGAN	GULL ROCK MEMBER
EOCENE UPPER	ALDINGAN	BLANCHE POINT FORMATION ('Blanche Point Soft Marls')
EOCENE UPPER	ALDINGAN	CHINAMAN GULLY FORMATION
EOCENE UPPER	ALDINGAN	TANDANYA SAND MEMBER
EOCENE UPPER	ALDINGAN	PORT WILLUNGA FORMATION — Aldinga Member — sand unit
EOCENE UPPER	ALDINGAN	PORT WILLUNGA FORMATION — Aldinga Member — silt/clay unit
OLIGOCENE	JANJUKIAN	RUWARUNG MEMBER
OLIGOCENE	JANJUKIAN	'upper Janjukian unit'
MIOCENE LOWER	LONGFORDIAN	
MIOCENE LOWER	BATESFORDIAN	
MIOCENE MIDDLE	BALCOMBIAN	PORT WILLUNGA FORMATION — Munno Para Clay Member
MIOCENE MIDDLE	BAIRNSDALIAN	
PLIOCENE LOWER	KALIMNAN	KOOYONGA FMN.
PLIOCENE UPPER	YATALAN	DRY CREEK SAND
PLIOCENE UPPER	YATALAN	HALLETT COVE SST.

LOWER ACME — UPPER ACME

1. *Ammonia beccarii*
2. *Amphistegina lessoni*
3. *Asterigerina adelaidensis*
4. *Astrononion centroplax*
5. *Austrotrillina howchini*
6. Gen. nov. cf. *Bolivinella* sp. nov.
7. *Bolivinopsis cubensis*
8. *Carpenteria rotaliformis*
9. *Cibicides vortex*
10. *Cibicidoides umbonifer*
11. *Clavulina multicamerata*
12. *Crespinella umbonifera*
13. *Crespinella parri*
14. *Crespinina kingscotensis*
15. *Cribrobulimina mixta*
16. *Discorbis acervulinoides*
17. *Discorbis cycloclypeus*
18. *Discorbis dimidiatus*
19. *Elphidium adelaidense*
20. *Elphidium advenum*
21. *Elphidium crassatum*
22. *Elphidium crispum*
23. *Elphidium macellum*
24. *Elphidium rotatum*
25. *Epistomaroides polystomelloides*
26. *Flosculinella bontangensis*
27. *Gypsina howchini*
28. *Gyroidinoides* cf. *allani*
29. *Gyroidinoides octocamerata*
30. *Gyroidinoides* cf. *soldanii*
31. *Halkyardia* cf. *bartrumi*
32. *Heterolepa subhaidingeri*
33. *Heterolepa victoriensis*
34. *Karreria pseudoconvexa*
35. *Lamarckina dirensis*
36. *Lamarckina glencoensis*
37. *Lenticulina gyroscalpra*
38. *Lepidocyclina howchini*
39. *Linderina* sp. nov.
40. *Marginopora vertebralis*
41. *Maslinella chapmani*
42. *Massilina torquayensis*
43. *Massilina whitfordae* sp. nov.
44. *Notorotalia clathrata*
45. *Operculina victoriensis*
46. *Pararotalia verriculata*
47. *Parrellina craticulatiformis*
48. *Parrellina crespinae*
49. *Parrellina howchini*
50. *Pavonina triformis*
51. *Peneroplis pertusus*
52. *Planolinderina inaequilateralis*
53. *Planolinderina plana*
54. *Planorbulinella roseannae* sp. nov.
55. *Porosorotalia crassimura*
56. *Pseudopolymorphina* sp. nov.
57. *Robertina lornensis*
58. *Reussella finlayi*
59. *Sherbornina atkinsoni*
60. *Sherbornina cuneimarginata*
61. *Sigmoilopsis lapidigera*
62. *Sigmomorphina subregularis*
63. *Sigmomorphina haeusleri*
64. *Sphaerogypsina globula*
65. *Sphaeroidina bulloides*
66. *Sphaeroidina variabilis*
67. *Spirillina mediosca bra*
68. *Spirillina decorata*
69. *Svratkina perlata*
70. *Textularia vertebralis*
71. *Victoriella conoidea*
72. *Wadella hamiltonensis*

EOCENE | OLIGOCENE | MIOCENE | PLIOCENE
MID. | UPPER | LOWER | MIDDLE | LOWER | UPPER
EPOCH, SERIES

DEPARTMENT OF MINES AND ENERGY SOUTH AUSTRALIA

TERTIARY STRATIGRAPHY AND FORAMINIFERA

ADELAIDE CITY AREA

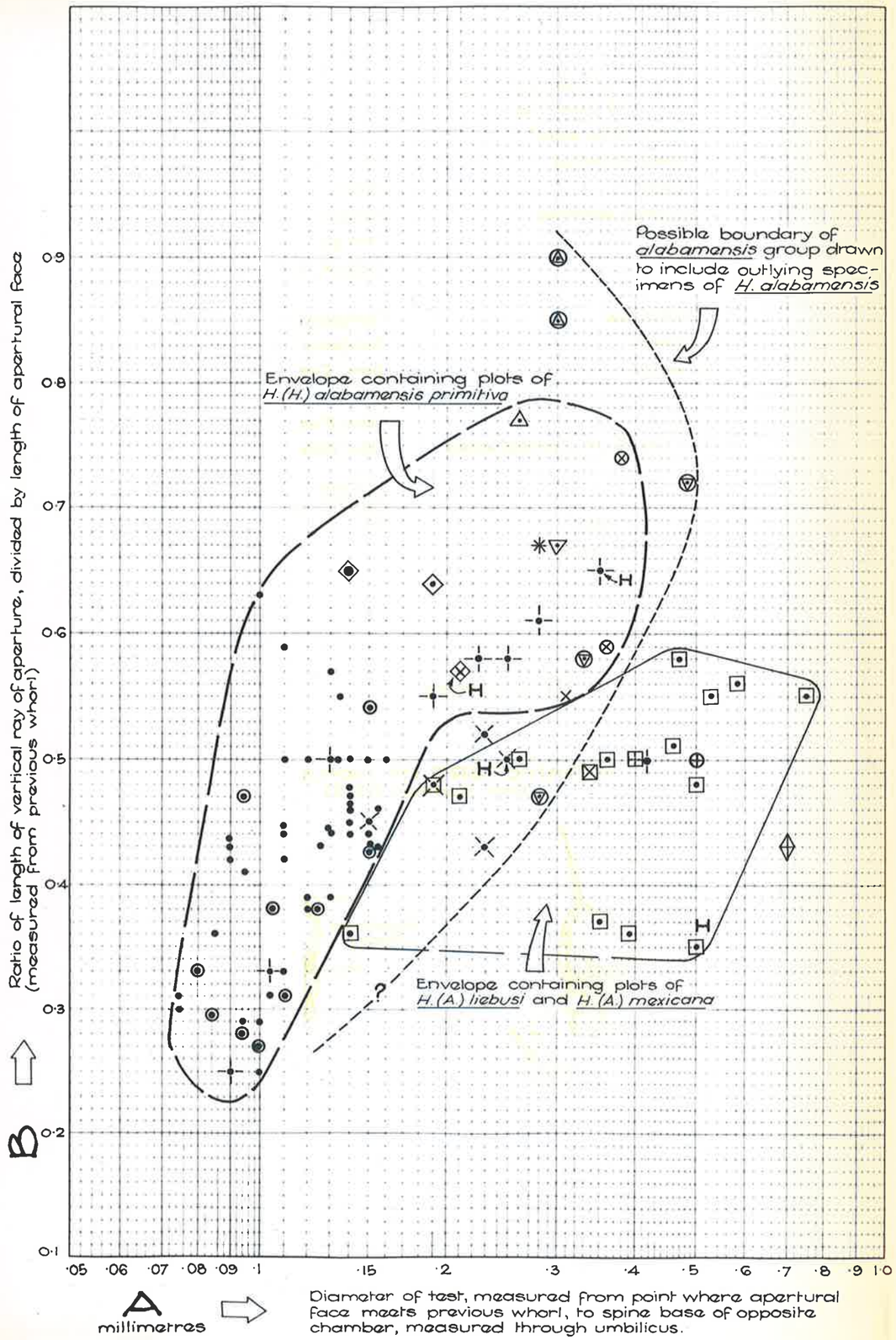
(AND EASTERN ST. VINCENT BASIN)

MAXIMUM LOCAL BENTHONIC FORAMINIFERAL RANGES

COMPILED J.M.L. | DRAWN S.R. | DATE 3/11/80 | LINE NO. | C.O.D. DATE 11/1/80 | SCALE AS SHOWN | FOAM NUMBER

PLAN 37

80—791



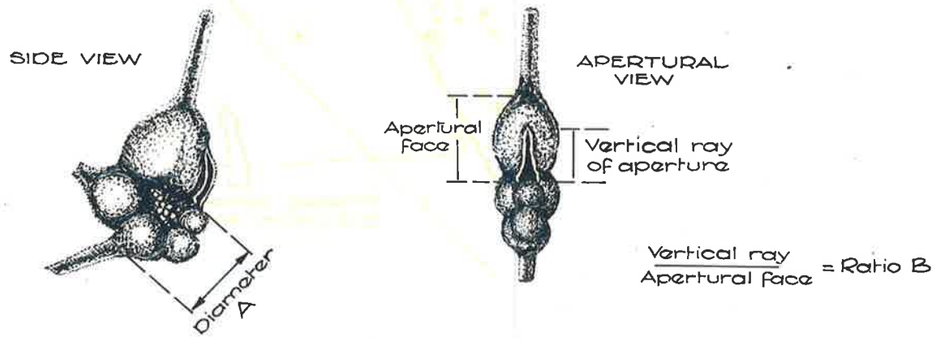
1532

LEGEND

• ..... *Hantkenina (H.) alabamensis primitiva*	Adelaide City area bores
◉ ..... *H. (H.) alabamensis primitiva*	Maslin Bay outcrop
⊹ ..... *H. 'alabamensis compressa'*	Browns Ck, Victoria: Holotype and Topotypes
◈ ..... *H. alabamensis primitiva*	Trinidad, B.W.I. Holotype (Cushman and Jarvis, 1929)
▽ ..... *H. (H.) primitiva.*	Tanganyika, Lindi (Ramsay, 1962)
△ ..... *H.(H.) alabamensis primitiva.*	Tanzania, Lindi (Blow, 1979)
× ..... *H. primitiva*	Tanganyika, Lindi, (Blow and Banner, 1962)
⊗ ..... *H. primitiva*	Italy, Castelnuovo (Dieni and Decima, 1964)
ⓐ ..... *H. (H.) alabamensis*	Tanganyika, Lindi (Ramsay, 1962)
✳ ..... *H. alabamensis*	Tanganyika, Lindi (Blow and Banner, 1962)
ⓥ ..... *H. alabamensis*	Italy, Castelnuovo (Dieni and Decima, 1964)
⊠ ..... *H. australis*	New Zealand: Holotype and Paratypes (Jenkins, 1965a)
◈ ..... *H. alabamensis*, ◈ *H. cf. alabamensis*	New Zealand: (Jenkins, 1965a)
⊡ ..... *H. liebusi*	U.S.S.R and Yugoslavia: Holotype and ? Paratypes (Shokhina, 1937)
⊞ ..... *H. (Aragonella) liebusi*	Tanganyika, Kilwa Masoko (Ramsay, 1962)
⊹ ..... *H. (Aragonella) mexicana*	Trinidad, B.W.I. (Bronnimann, 1950)
⊕ ..... *H. (A.) mexicana*	Tanganyika, Kilwa Masoko (Ramsay, 1962)
⊠ ..... *H. (A.) mexicana*	Tanzania, Kilwa Masoko (Blow, 1979)
◈ ..... *H. (A.) lehneri*	Tanganyika, Kilwa Masoko (Ramsay, 1962)

H = Holotype.

PARAMETERS OF *Hantkenina* after Ramsay (1962)



$$\frac{\text{Vertical ray}}{\text{Apertural face}} = \text{Ratio B}$$

PLAN 38

DEPARTMENT OF MINES AND ENERGY SOUTH AUSTRALIA

TERTIARY STRATIGRAPHY AND FORAMINIFERA ADELAIDE CITY AREA

BIOMETRIC PLOT OF *Hantkenina* USING THE PARAMETERS OF RAMSAY (1962)

COMPILED	J.M.L.	11·11·80	C.D.O. DATE
DRAWN	C.J.W.	SCALE	As shown
DATE	26·7·80	PLAN NUMBER	80-612
CHECKED			