GEOMORPHIC EVOLUTION OF SOUTHEASTERN FLEURIEU PENINSULA

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SUMMARY

The geomorphic features of Southeastern Fleurieu Peninsula are mapped, described and their possible origin and age considered.

As many landforms in the area are influenced by bedrock structures and as the stratigraphy of the region throws light on the sequence of historical events, detailed geological and geomorphological mapping is presented.

From field evidence the palaeogeography of the area at various points in time has been reconstructed. A Palaeozoic orogeny developed a fold belt, the base of which was intruded by a granite mass approximately 480 million years ago. Although there is inferential evidence of deposition during the Devonian, the 200 million years following the intrusion witnessed considerable erosion with the exposure of the granite occurring by the time of the Late Palaeozoic glaciation.

A Late Palaeozoic ice sheet overrode Fleurieu Peninsula from the southeast, accentuating the preglacial relief. There is no incontrovertible evidence of multiple glaciation in the area and glacigene sediments are not as extensive as previously thought. The expression of the Late Palaeozoic glaciation in the present landscape is considered.

Two major landsurfaces of erosion, the Spring Mount surface and the Green Hills surface, have been distinguished on the basis of elevation and distinctive duricrust cappings. Two main surfaces of aggradation occur in intermontane situations in the Upper Hindmarsh Valley and the Waitpinga area both of which have been dated by reference to Tertiary marine limestones. From the distribution of the limestones the roles of Tertiary tectonism and eustasy are examined.

The morphology of the present coastline reflects structure, present processes and a slight rise in relative sea level. Evidence exists for former Quaternary shorelines at elevations of 200' (60m), 100' (30m), 20' (6m), 8'-10' (2.4m-3m), -36' (-10.8m), and -66' (-19.8m), the last four of

which are considered to be the result of glacio-eustasy.

Morphometric techniques are used to analyse the development of the drainage network of Waitpinga Creek. River terraces in McKnight Creek, a tributary of Waitpinga Creek, are interpreted as climatically caused during the Late Pleistocene and Holocene. Further evidence of climatic change during the Quaternary is afforded by the relationship of fossil parabolic cliff-top dunes to the present wind régime.

This thesis is based on original research carried out in the Department of Geography, University of Adelaide. It contains no material previously submitted for a degree at any university, and to the best of my knowledge contains no material previously published or written by another author, except when due reference is made in the text of the thesis.

Signed

Robert P. Bourman

CHAPTER I

INTRODUCTION

1. LOCATION AND DESCRIPTION OF THE STUDY AREA

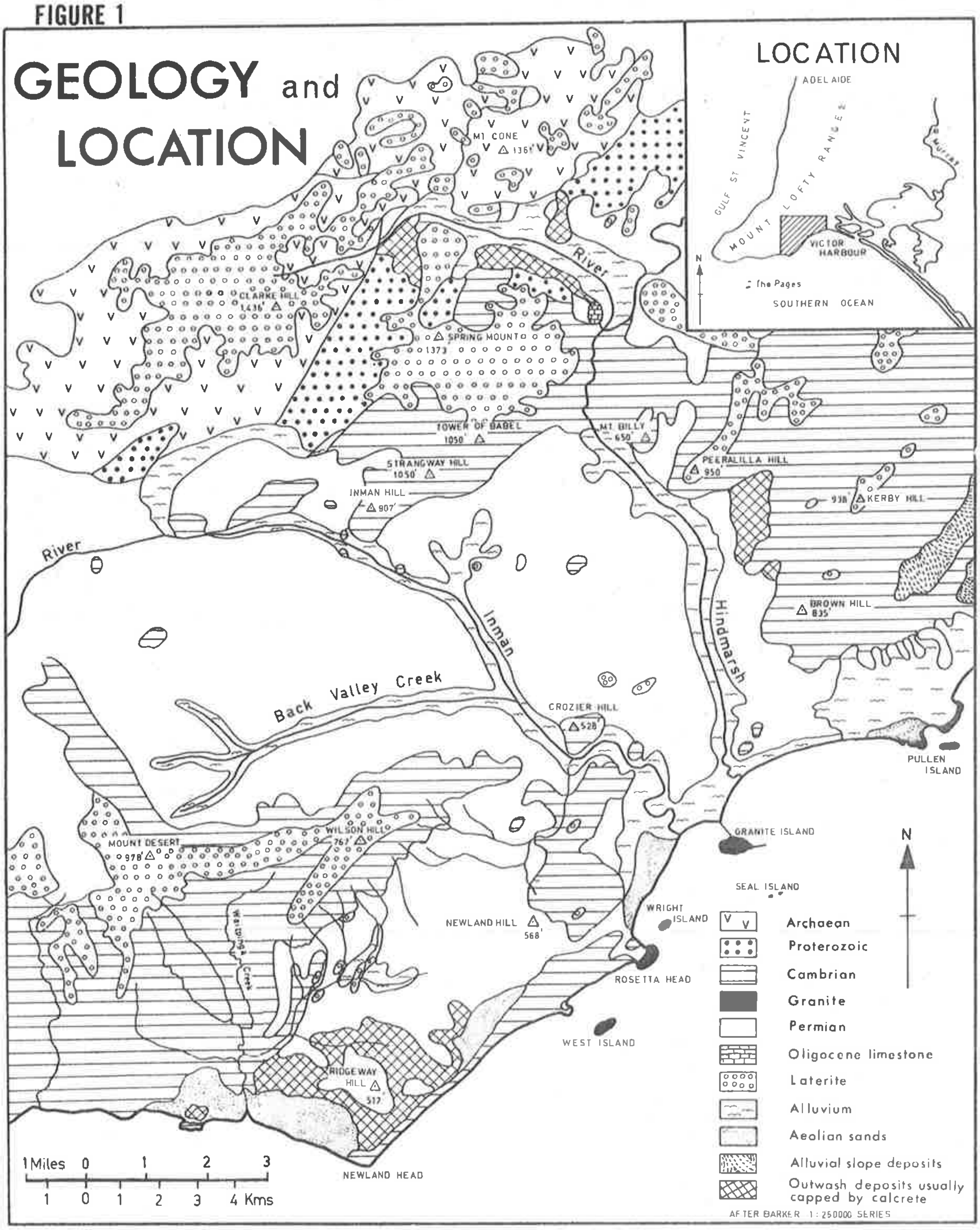
The study area is situated on southeastern Fleurieu Peninsula, South Australia (Figure 1). The southern and southeastern boundaries of the region are formed by the coastline between Parson Beach and Middleton Beach, but inland the boundaries are more diffuse, broadly coinciding with the watersheds of the Inman and Hindmarsh Rivers and Waitpinga Creek (Figure 2). Together these drain an area of some 150 miles^2 (384 km^2).

The main streams of the study area have eroded below a near level summit surface underlain by Precambrian and Cambrian bedrock and capped by laterite. It ranges in elevation between 1400' (420m) and 800' (240m). The Hindmarsh River downstream from the Hindmarsh Falls, the Inman River and its main tributary Back Valley Creek, occupy an ancient bedrock depression up to 10 miles (16km) wide, the Inman Trough, which trends in a general east-west direction across Fleurieu Peninsula. Ranges of secondary hills, up to 700' (210m) in elevation, flank the streams which drain the Inman Trough.

Intermontane basins occur in the Upper Hindmarsh Valley, upstream of the Hindmarsh Falls at approximately 800' (240m) a.s.l. and in the drainage basin of the Waitpinga Creek at about 300' (90m) a.s.l. (Figure 3). The basins occupy areas of 4.5 miles^2 (11.5km^2) and 3 miles^2 (7.7km^2) respectively.

The lower reaches of the Inman and Hindmarsh Rivers and the main left bank tributary of Waitpinga Creek are occupied by river terraces, which mark the former levels at which the streams flowed.

FIGURE 1



GEOLOGY and LOCATION
LOCATION
ADELAIDE
GULF ST VINCENT
MOUNT LOFTY RANGES
VICTOR HARBOUR
The Pages
SOUTHERN OCEAN
N
MT CONE
1361'
CLARKE HILL
1436'
SPRING MOUNT
1373'
TOWER OF BABEL
1050'
STRANGWAY HILL
1050'
INMAN HILL
907'
MT BILLY
650'
PEERALILLA HILL
950
938
KERBY HILL
BROWN HILL
835'
River
Inman
Hindmarsh
Back Valley Creek
CROZIER HILL
528
PULLEN ISLAND
GRANITE ISLAND
MOUNT DESERT
978'
WILSON HILL
767'
Waitpinga Creek
NEWLAND HILL
568'
SEAL ISLAND
WRIGHT ISLAND
ROSETTA HEAD
WEST ISLAND
RIDGEWAY HILL
517'
NEWLAND HEAD
Archaean
Proterozoic
Cambrian
Granite
Permian
Oligocene limestone
Laterite
Alluvium
Aeolian sands
Alluvial slope deposits
Outwash deposits usually capped by calcrete
1 Miles 0 1 2 3
1 0 1 2 3 4 Kms
AFTER BARKER 1:250000 SERIES

FIGURE 2

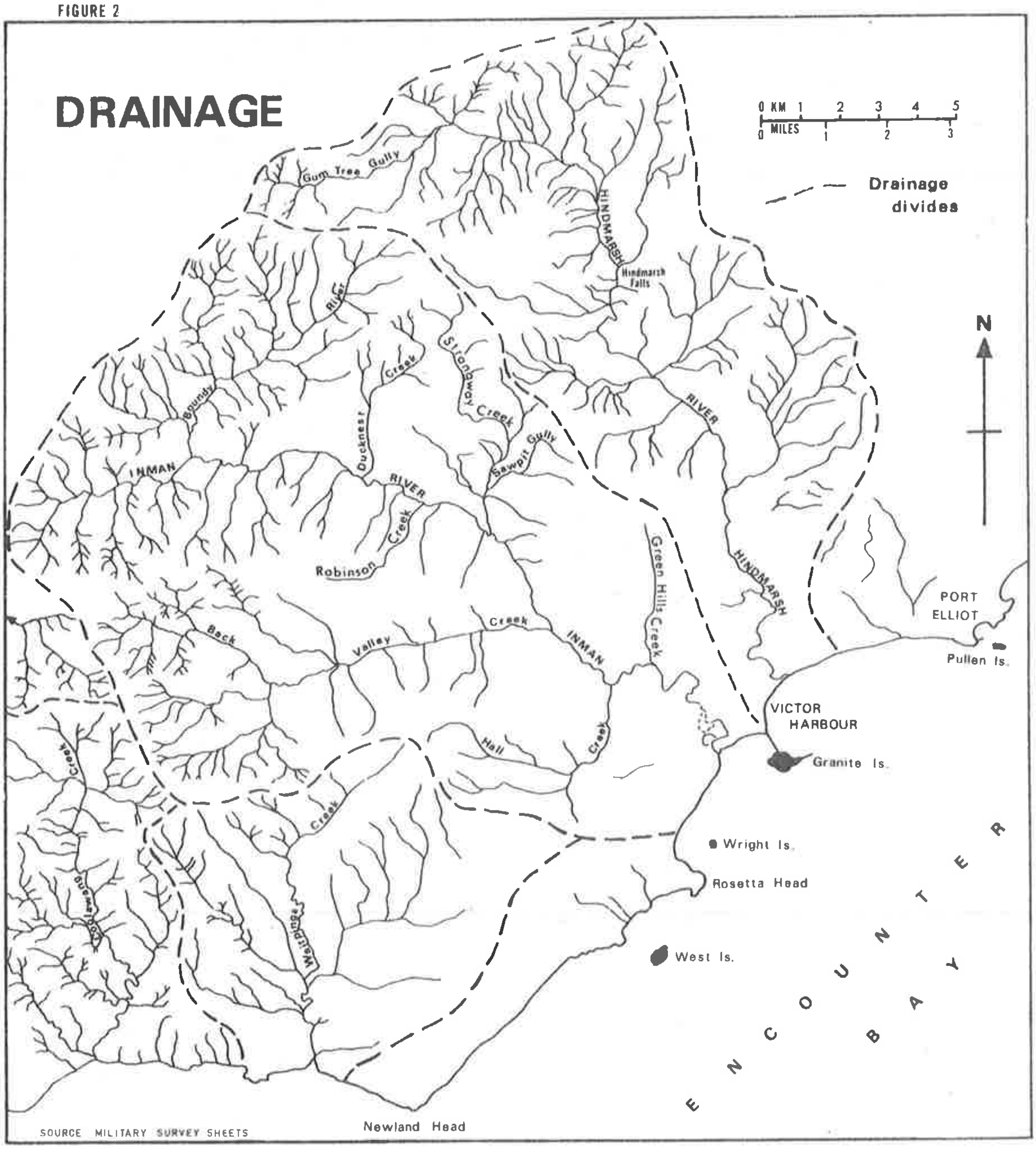
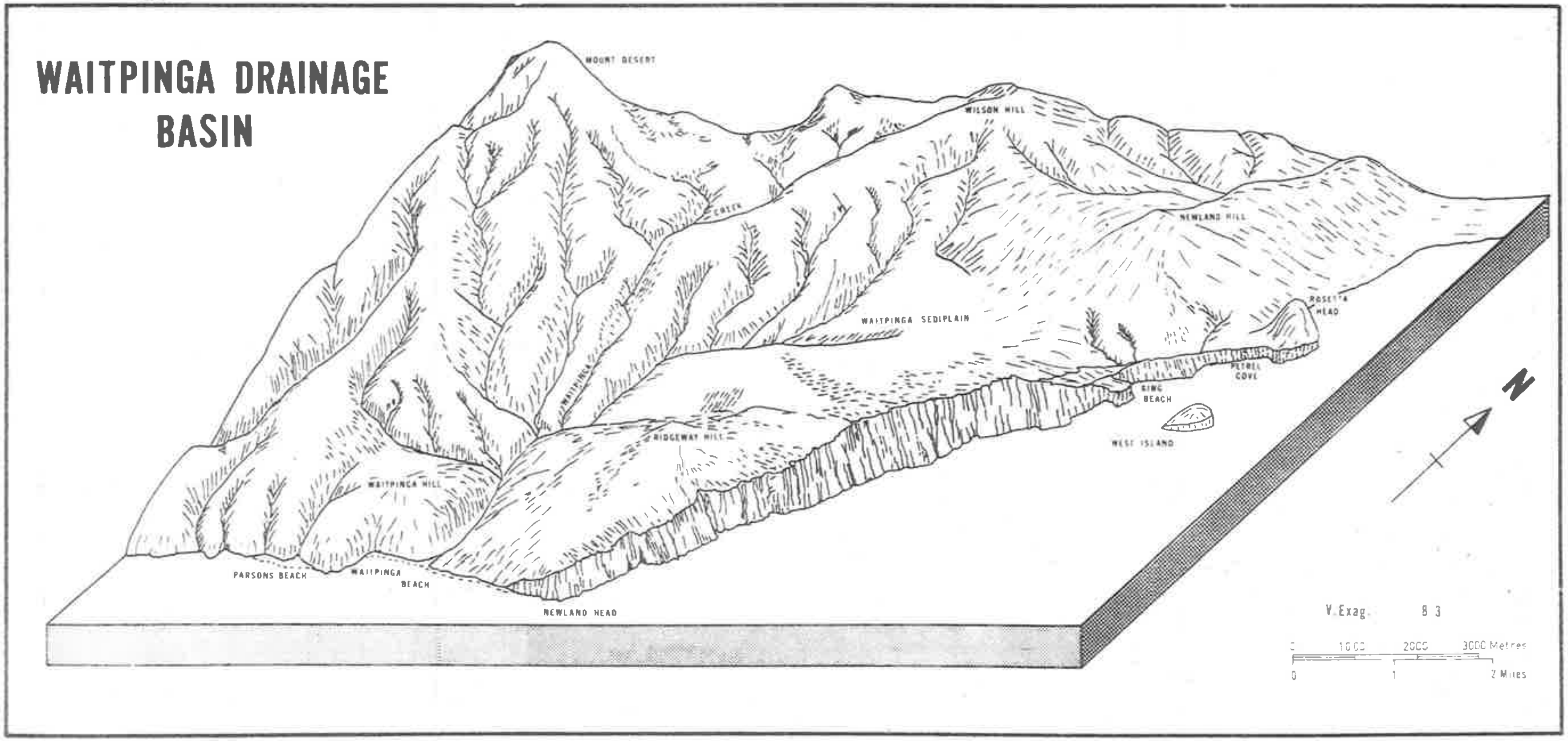

DRAINAGE
0 KM 1 2 3 4 5
0 MILES 1 2 3
Drainage divides
N
Gum Tree Gully
HINDMARSH
Hindmarsh Falls
RIVER
Strangway Creek
Creek
Duckness Creek
Boundy
INMAN
RIVER
Sawpit Gully
Robinson Creek
Back Valley Creek
INMAN
Green Hills Creek
HINDMARSH
PORT ELLIOT
Pullen Is.
VICTOR HARBOUR
Granite Is.
Hall Creek
Creek
Creek
Wright Is.
Rosetta Head
West Is.
ENCOUNTER BAY
Newland Head
SOURCE MILITARY SURVEY SHEETS

FIGURE 3


WAITPINGA DRAINAGE BASIN
MOUNT DESERT
WILSON HILL
CREEK
NEWLAND HILL
WAITPINGA SEDIPLAIN
ROSETTA HEAD
PETREL COVE
KING BEACH
WEST ISLAND
RIDGEWAY HILL
WAITPINGA HILL
PARSONS BEACH
WAITPINGA BEACH
NEWLAND HEAD
N
V. Exag. 8 3
0 1000 2000 3000 Metres
0 1 2 Miles

At the coastline sandy beaches and/or spits have developed at Horseshoe Bay, at Parson, Waitpinga and King Beaches, and in the area between Rosetta Head and Port Elliot, where the Inman Trough intersects the shore of Encounter Bay. Steep coastal cliffs are restricted to outcrops of resistant metasedimentary and granitic rocks, which also form the festoon of islands of Encounter Bay and Backstairs Passage.

2. AIMS AND METHODS OF STUDY

The main purpose of this study is to examine the distribution, age and origin of the diverse planate surfaces of southeastern Fleurieu Peninsula. These include river terraces, shore platforms, ancient, exhumed glaciated surfaces and fluvial surfaces of erosional and depositional origin.

The major aspects of the study include:

a. mapping of geomorphic units

b. an assessment of the influence of structure on landform development

c. evidence of climatic change expressed in inherited glacial landforms, palaeosols, river terraces and fossil parabolic dunes

d. the effects of lateritic weathering on land surfaces during the Cainozoic

e. the relationship of duricrusts and various planate surfaces to Cainozoic sea levels

f. the expression of the Late Palaeozoic glaciation in the present landscape.

Many features in the landscape are the result of currently operating geomorphic processes or similar processes which operated in the recent geological past. Despite the evidence of climatic change, tectonism and migrating shorelines in the study area during the Pleistocene and Holocene, these periods were ones of relative stability and uniformity when compared with earlier geological times. Thus following a discussion of the geology of the area, the more recent landforms are considered in order to describe the study area more meaningfully, and because the more ancient landforms have been considerably modified since their formation.

In the study area there is extensive evidence of two anomalous morphogenetic systems operating in the past, namely erosion surfaces capped by palaeosols, and remnants of an exhumed Late Palaeozoic glaciated landscape. In view of the widespread distribution and significance of these inherited forms in the landscape, discussions of them constitute the major section of this thesis.

During the course of this study several months were spent in the field. Field work included the mapping of morphological units on Adastra stereographic aerial photographs at a scale of 1:15840. Mapping was carried out on the basis of convex and concave breaks in slope as well as that of rock units. Cross sections were prepared from the 1:63360 map sheets of the Geological Survey of South Australia, although in some instances the geological interpretations required revision.

Elevations of river terraces, marine terraces and fossils were fixed by Dumpy levelling. Hand augering was undertaken to collect sediments from river terraces, Rosetta Head, Newland Hill and Ridgeway Hill. Six selected samples of sediments were subjected to mechanical analysis in attempts to determine their origins. In addition many more sediments were examined microscopically.

Many residents of the area were interviewed concerning the locations and logs of bores as well as evidence of geomorphic change in the landscape during historical time. Previous published work describing the area was consulted as well as much unpublished material. In addition attempts have been made to utilise theories and concepts from relevant systematic studies.

3. PREVIOUS INVESTIGATIONS

Commissioned by the South Australian Government, Victorian Government geologist A.R.C. Selwyn made the first geological study of the area during a reconnaissance survey of the country between Cape Jervis and Mount Serle (Selwyn, 1860). In the valley of the Inman River Selwyn discovered the renowned 'Selwyn Rock', a glaciated pavement which constitutes the first observed evidence of glaciation in Australia (Crawford, 1960).

In an article entitled 'The Geology of the Southeast' Hanson (1866) reported on some geological aspects of the Port Elliot and Victor Harbour areas. These aspects were commented on by Woods (1866) who criticised some of Hanson's conclusions.

A geological map of the Hundreds of Encounter Bay and Yankalilla was produced in 1892 by H.Y.L. Brown, the Government Geologist, who established a threefold classification of rocks: Primary, Shale and Sandstone Formation, and Tertiary. Furthermore, the glacial origin of the numerous exotic erratics was recognised.

David and Howchin (1897) during a search for the 'Selwyn Rock' encountered and described evidence of glacial action in the Inman Valley, while Duffield (1901) studied geological features in the Victor Harbour area.

Pride of place among the geological investigators of Fleurieu Peninsula must go to Professor Walter Howchin, who, in a series of papers between 1898 and 1931, described the geology of the region in considerable detail (for a list of the published works of Howchin see *Trans. Roy. Soc. S. Aust.* 1933, Vol.57:242-245).

Guppy (1943) continued geological research of the area when he carried out a reconnaissance investigation of parts of the Hundreds of Encounter Bay and Goolwa for a B.Sc.(Hons.) degree at Adelaide University.

Following mapping of the Yankallila and Jervis geology map sheets 1:63360 series, Campana, Wilson and Whittle (1953) extended their studies into the Encounter Bay and Milang areas, and detailed results of this work were published in 1955 (Campana and Wilson, 1955).

The Encounter and Milang geology map sheets 1:63360 series were mapped by Crawford and Thomson (1959) and Horwitz and Thomson (1960) respectively. Unpublished explanatory notes of these maps were made available to the writer by the S.A. Geological Survey and the results of the mapping of the Milang area were published by Horwitz (1960).

Features of the Late Palaeozoic glaciation of Fleurieu Peninsula were examined by Bowen (1959) as part of a doctoral thesis at the University of Melbourne, while other publications include a number on the stratigraphy and structures of the basement rocks, e.g. Forbes (1957), Daily and Milnes (1971, 1972, 1973). Several papers have appeared on the Encounter Bay Granites, a summary of which appear in Milnes (1967).

The present study area was mentioned by Brock (1964) and although he carried out no detailed work here several of his findings apply to this region. Other recent works which make mention of the study area include Crowell and Frakes (1971a, 1971b), Harris (1972), Milnes and Bourman (1972), Bourman and Lindsay (1973), and Milnes (1973).

Bourman (1969) made a preliminary investigation of the geomorphology of the Victor Harbour area as part of a B.A. (Hons.) degree in the Department of Geography at the University of Adelaide. This work included studies of some of the Late Palaeozoic glacial features and Cainozoic landsurfaces of the area. The present investigation constitutes an extension of this preliminary study.

4. ACKNOWLEDGEMENTS

Thanks are due to the many people who have assisted in the preparation of this thesis, in particular to: the local residents who were most helpful and treated me with good humour; Dr. V. Gostin of the Geology Department who instructed me in the technique of mechanical analysis of sediments; Dr. Helene Laws of the S.A. Museum who identified shells; Mr. M.R. Foale who gave expert advice on map presentation; Mr. A. Little who drafted excellent maps from rough originals; the S.A. Geological Survey which made borelog information and other unpublished material freely available; the S.A. Archives for the provision of copies of early photographs; the Bureau of Meteorology for providing wind data; Mr. A.R. Milnes and Mr. W.J.H. Slaytor for reading and commenting on the text; Mrs. H. Lomax for copying figures and plates; Mrs. M. Blaber for typing the thesis; and finally to Dr. C.R. Twidale for arranging a C14 date, and for his general assistance with the thesis.

5. A NOTE ON METRICATION

As all maps have not yet been converted to the metric system, and because there is not an exact even number conversion from feet to metres, it was decided that contour maps would be shown in imperial units. Where heights and distances are referred to in the text they are given in imperial units with the approximate metric equivalent in brackets, e.g. 1 mile (1.6km), 20' (6m). Horizontal scales on all maps are shown in both units. The map of the terraces of McKnight Creek with heights accurate to .01' is shown in both imperial and metric units, as are vertical scales on cross sections.

CHAPTER II GEOLOGY

1. INTRODUCTION

Although this study is primarily concerned with geomorphic process and evolution, detailed geological investigations have proved essential for a fuller understanding of geomorphic events. Many landforms in the study area are of structural origin, or their development has been strongly influenced by structural controls such as jointing, cleavage and lithology. The study of stratigraphical relationships and the fossil record facilitate dating of sedimentary sequences and former geomorphological events, while sedimentary structures illustrate former environments and flow directions during deposition.

A detailed knowledge of basement rock geology is invaluable in this area because of the widespread occurrence of erratics related to Late Palaeozoic glaciation. Most attempts to recognise Late Palaeozoic glacial or fluvio-glacial deposits here rest on the recognition of exotic pebbles and boulders. Moreover, as the direction of glacier movement is most reliably indicated by the provenance or origin of erratics, familiarity with basement rock source areas is vital in the assessment of the direction of glacier movement.

2. REGIONAL GEOLOGY (Figure 1)

a) *Kanmantoo Group metasedimentary rocks*

Kanmantoo Group metasedimentary rocks constitute the basement rocks of the study area and are the oldest rocks in the area where detailed work was carried out. They conformably overlie the rocks of the Adelaide Supergroup, and, on fossil evidence, have been demonstrated to be of Lower Cambrian age (Daily, 1969; Daily and Milnes, 1971, 1972, 1973).

Metasandstones, metasiltstones, laminated phyllites, and schists of the Kanmantoo Group form a largely repetitious series of rocks on the eastern side of the Mount Lofty Ranges. The rocks have been affected by several phases of folding, (Offler and Fleming, 1968), but broadly they strike northeast - southwest and dip steeply to the southeast. Schistosity is well developed in the Kanmantoo Group metasedimentary rocks and care is needed to distinguish it from bedding. Rubidium-strontium data on whole rock samples from the Kanmantoo Group metasediments has established an age of 487 ± 37 m.y. for the metamorphic event which affected these rocks and which is considered to be coincident with the emplacement of the Encounter Bay Granites (Dasch, Milnes and Nesbitt, 1971).

The resistance of the Kanmantoo Group rocks to weathering is reflected in the highest points in the topography, for Wilson Hill 767' (232m), Mount Desert 978' (293m), Crozier Hill 528' (158m), Brown Hill 835' (250m), Kerby Hill 938' (281m), Peerallilla Hill 950' (285m), Mount Billy 650' (195m), Tower of Babel 1050' (315m), Strangway Hill 1050' (315m) and Inman Hill 907' (271m) are all underlain by this group of rocks. Ridgeway Hill 517' (155m) and Newland Hill 568' (170m) are exceptions, being composed chiefly of aeolian sands.

A detailed stratigraphical study of the Kanmantoo Group metasedimentary rocks in the study area has been completed recently (Daily and Milnes, 1972, 1973). The Kanmantoo Group metasediments in the study area include the Tunkalilla and Balquidder Formations of the Brown Hill Sub-group, and the Petrel Cove Formation and Middleton Sandstone of the Wattaberri Sub-group.

b) *Encounter Bay Granites and igneous dykes*

The Encounter Bay Granites form headlands and islands in Encounter Bay from Port Elliot to West Island. These include Frenchman Rock, Commodore Point, the Sisters, Pullen (or Seagull) Island, Freeman Knob, Granite Island, Wright Island, Rosetta Head and West Island. The granite intrusion is approximately concordant with the strike of the Kanmantoo Group country rock and extends southwest to Cape Willoughby (Kangaroo Island), a distance of more than 50km. The term 'Encounter Bay Granites' (Milnes and Bourman, 1972) has been used to describe the igneous rocks of the Encounter Bay area and those at Cape Willoughby, these two outcrops being considered parts of the same intrusive mass. Recent work by Dasch, Milnes and Nesbitt (1971) established similar ages for metamorphism and intrusion and high initial Sr^{87}/Sr^{86} ratios, suggesting that the granitisation occurred through remobilisation of crustal rock, which probably occurred at great depth.

The Pages, a group of three small islands between Kangaroo Island and the mainland were mapped as granite on the Barker map sheet, 1:250000 series. However, subsequent investigations (Bourman, 1969) have demonstrated that the islands are not granite, but are formed of Kanmantoo Group rocks.

Milnes (1967) tentatively suggested a sequence of relative ages in the Encounter Bay Granites from the Port Elliot locality, these being from oldest to youngest - porphyritic granite, even grained granite, red aplite and aplite dykes and pods, fine grained granite, prophyritic microgranite, schorl-rock dykes and pods, albitisation, greisen material and quartz veins. Large megacrysts of microcline feldspar occur in the prophyritic granite, the first intrusive phase, to which phase country rock xenoliths are restricted. The xenoliths, which are generally little altered, and up to 40' (12m) in diameter, are common. Several of the largest xenoliths are possibly roof pendants as their orientation parallels the bedding of the surrounding metasediments (Milnes, 1967).

The Encounter Bay Granites have now been dated by three groups of workers, all utilising different methods. Evernden and Richards (1962), using the potassium-argon method on biotite, established an age of 457 million years B.P.; Fander (1960) arrived at an age of 415 ± 42 million years B.P. employing the uranium-lead technique on zircon concentrates; and Dasch, Milnes and Nesbitt (1971) utilising rubidium-strontium and strontium isotope data on whole rock samples derived an isochron age of 487 ± 60 million years B.P.

The granites of Encounter Bay display well developed joint patterns, the majority of which trend northeast-southwest, and southeast-northwest. Asthana (1958) suggested that some of the joints are tension joints associated with the emplacement of the granite, while others, characterised by smooth joint faces, are considered the result of later tectonic movement acting in a N.N.W. - S.S.E. direction, producing secondary shear joints.

Basic igneous dykes crop out in several localities near Rosetta Head and 4 miles (6.4km) northwest of Crozier Hill in the bed of the River Inman. No age determinations have been carried out on these dykes, but they may be dated relatively to other geological events. As they intrude the granite they are younger than the granite, and as they are folded within the Kanmantoo Group rocks they must pre-date the folding (Milnes, 1973). Consequently, dating of the amphibolite dykes could reveal relationships between orogeny and intrusion.

c) *Late Palaeozoic glacigene deposits*

The majority of recent workers, for example, Ludbrook (1957, 1965, 1967, 1969a, 1969b), Evans (1964), Freytag (1963, 1965), Paten (1969), and Harris and McGowran (1971) favour a Sakmarian (Lower Lower Permian) age for the glacigene sediments in South Australia. However, others including Crowell and Frakes (1971a, 1971b), Wanless (1960), Balme (1957), and Wopfner (1964) suggest that the deposits may extend back into the Stephanian (Upper Upper Carboniferous); and that glaciation was almost certainly initiated during the Carboniferous. For these reasons, the glaciation and the associated sediments will be referred to the Late Palaeozoic.

The Late Palaeozoic deposits are of glacial origin, consisting of glacial till and fluvioglacial (including varve) sediments. Definite glacial till is rare, and it is difficult to distinguish fluvioglacial sediments from reworked boulder clay. Lithification of the deposits is variable, some being easily broken in the hand, while others have been used, though with little success, for building stone (Howchin, 1910b). The sediments are recognised as glacigene by the presence of faceted or striated exotic pebbles of flat-iron morphology. Nevertheless, this does not preclude the possibility that they are reworked glacial or fluvioglacial sediments. As no rocks older than Eocene and younger than the Late Palaeozoic have been recognised in the area, this period of some 200 million years was one of non-deposition or erosion. Alternatively, Upper Palaeozoic and Mesozoic sediments were later removed by erosion.[1] In either case there is ample time for considerable reworking of the glacigene sediments, posing a problem only completely soluble by accurate age determinations.

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[1] Recent work by Wellman (1971) has demonstrated that the basalt flows of Kangaroo Island, formerly considered to be of Late Cainozoic age, are actually Jurassic. Triassic sediments may underlie the basalt. Although no basalts have been found on Fleurieu Peninsula, the Mesozoic on Fleurieu Peninsula may not have been an era of continuous erosion but one of deposition and erosion.

Outcrops of till occur at King Beach, east of Porters Hill (Glastonbury Hill of Howchin, 1910a), near 'Fairlands Stud', north of 'Glenayr', northwest of Adare Hill, south of Strangways Hill and in Ducknest Creek. Numerous granite boulders occur on the landward side of Rosetta Head and to the northwest along the coast. Although some of these may be due to mass movement and coastal transport of boulders from nearby granite outcrops under non-glacial conditions, the presence of exotic granites and other erratics demonstrates reworking of glacial deposits.

Possible glacial varve deposits have been described from Port Elliot (Milnes, 1967; Milnes and Bourman, 1972), and King Beach (Crowell and Frakes, 1971a). Laminated, fine grained deposits at these sites resemble glacial varves, but it should be borne in mind that non-glacial, non-seasonal rhythmites related to marine turbidity currents, to the settling of volcanic dust in lakes, or to the life cycles of organisms such as diatoms can form in non-glacial conditions (Harland, et al, 1966). Galloway and Eriksson (1971) recently reinterpreted supposed glacial varves in the Snowy Mountains as fluvial or snowmelt deposits in which banding has been accentuated by chemical precipitates.

Crawford and Thomson (1959), Thomson and Horwitz (1962) and Thomson and Amtanis (1971) indicate that part of the drainage basin of the Waitpinga Creek is underlain by Permian glacial or fluvioglacial sediments. However, Eocene fossiliferous limestone encountered in a bore sunk on the 'Glenmere'[1] property at a depth of 120' (36m) and at a height of 300' (90m) a.s.l. proves that the deposits are of Cainozoic age (Bourman and Lindsay, 1973) (Figure 4).

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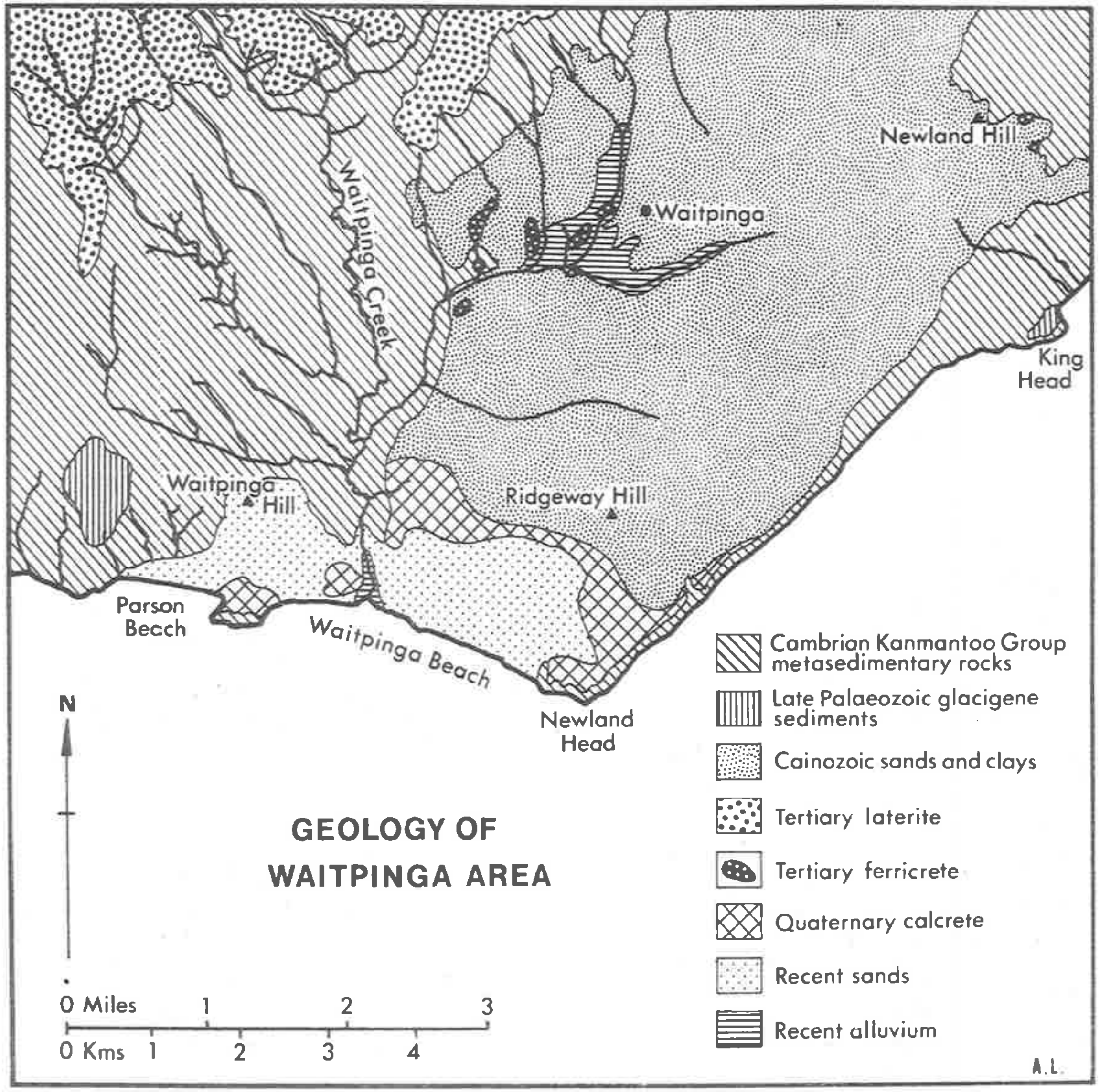
[1]Not 'Glenmen' as on Encounter map sheet 1:63,360 series

FIGURE 4


Newland Hill
Waitpinga
Waitpinga Creek
King Head
Waitpinga Hill
Ridgeway Hill
Parson Becch
Waitpinga Beach
Newland Head
N
GEOLOGY OF WAITPINGA AREA
0 Miles 1 2 3
0 Kms 1 2 3 4
Cambrian Kanmantoo Group metasedimentary rocks
Late Palaeozoic glacigene sediments
Cainozoic sands and clays
Tertiary laterite
Tertiary ferricrete
Quaternary calcrete
Recent sands
Recent alluvium
A.L.

Without a stratigraphic marker such as the Eocene limestone, glacigene and reworked glacigene sediments in the area are virtually impossible to distinguish from each other.

O'Driscoll (1954), whose mapping was followed by Glaessner and Parkin (1958), suggested that the area from Ridgeway Hill immediately north to a left bank tributary of the Waitpinga Creek is underlain by Tertiary sands and clays, but he did not state the evidence for this conclusion. However, the absence of boulders and pebbles related to the Late Palaeozoic glaciation, as well as the paucity of sediments greater than sand size in the drainage basin are highly suggestive of considerable reworking of Late Palaeozoic glacial deposits.

Two large erratics of coarse-grained Encounter Bay Granites several metres in diameter were noted in the tidal zone on the far eastern side of Waitpinga Beach. These boulders were most likely washed from Late Palaeozoic glacial deposits, long since eroded. However, they may have derived from granite outcrops seaward of their present position by storm waves, the effectiveness of waves in transporting huge rock masses being well documented.

Exotic boulders of red quartzite and microgranite were found in the small creek which flows from south of Newland Hill to the coast northeast of King Beach. The sandy clays through which it flows resemble glacigene sediments elsewhere in the area. However, the interpretation of these sediments as glacigene must be approached with caution, as the exotic pebbles may have been emplaced by aboriginal man.

Samples of pebble gravel collected from the bore site on the 'Glenmere' property, and derived from beneath the Eocene limestone, contained subrounded pebbles of quartzite, quartz and schist. Two of these pebbles displayed polishing, faceting and striations (Lindsay, 1966). Clearly this gravel may be derived from Late Palaeozoic glacial or fluvioglacial deposits.

Plate 1. Field of granite erratics 1 mile (1.6km) W.S.W. of Waitpinga Hill.

A previously unmapped area of Late Palaeozoic glacial deposits was discovered in the area southwest of Waitpinga Hill (Plate 1). At least a dozen granite erratics occur, all but one of them being of coarse grained Encounter Bay Granites, the exception resembling igneous rocks of the South East of South Australia. More erratics at shallow depth occur scattered over a fairly wide area, these being encountered during cultivation (Mr. Garnet Parsons - pers. comm.). In this area, an excellent example of a polished, soled, faceted, striated, and snub-cornered quartzite pebble was found. It meets virtually all of the criteria of von Engeln (1930) for the recognition of glacial pebbles.

Apart from this area granite erratics immediately west of the Waitpinga drainage basin are rare. Large boulders of metasandstone several metres in diameter occur in dam sites southeast of Mount Desert. Exposures of underlying basement rocks nearby are deeply weathered, thinly bedded, micaceous clayey siltstones. Thus both on size and nature the boulders may be Late Palaeozoic erratics derived from resistant metasandstones to the east.

d) *Tertiary*

(i) *Fossiliferous Eocene limestone*

Richly fossiliferous limestone was encountered during drilling operations on the 'Glenmere' property of Mr. J. Warwick in the drainage basin of the Waitpinga Creek in 1964 (Lindsay, 1966). The bore penetrated 110' (33m) of sands and clays, 8' (2.4m) of fossiliferous limestone and a thin band of pebbles, which rest on Kanmantoo Group metasedimentary basement rocks. Samples from the bore site were identified as Eocene sandy limestones, pale green and cream coloured, speckled brown with iron-stained rounded quartz grains and ferruginous pellets. Apart from echinoid and occasional molluscan fragments, the foraminiferal microfauna includes:

Crespinina kingscotensis Wade
Karreria pseudoconvexa (Parr)
Maslinella chapmani Glaessner and Wade
Gen. cf. *Bolivinella* sp.
Svratkina perlata (Andreae)
Reussella sp. aff. *R. finlayi* Dorreen
Lamarckina sp. aff. *L. airensis* Carter
Halkyardia sp.
Linderina sp.

This is an Eocene assemblage resembling that of the Tortachilla Limestone of the St. Vincent Basin and the Buccleuch 'A' limestone of the Murray Basin (Bourman and Lindsay, 1973).

(ii) *Oligocene (?) - Miocene bryozoal limestone*

Tertiary fossiliferous limestone occurs in the Upper Hindmarsh Valley and the Myponga Plain at elevations up to 800' (240m) a.s.l. Outcrops of this limestone are mapped on the Milang geology map sheet 1:63,360 series near the Hindmarsh Falls (Howchin, 1926) and near Wood Cone. Maud (1972) established that the latter occurrence is not natural, but was emplaced by man during agricultural activities. The extent of the limestone has been established by drilling, which has proved a maximum thickness of 385' (115.5m) under the Myponga Plain.

Glaessner (1953) assigned these beds to the Oligocene-Miocene, correlating them with the Port Willunga beds. Later Ludbrook (cited in Thomson and Horwitz, 1962) recognised a Batesfordian (Lower Miocene) fossil assemblage from a bore near 'Cloverdale' in the Upper Hindmarsh Valley.

An isolated fragment of Tertiary limestone from the Lower Hindmarsh Valley (Section 98, Hundred of Goolwa) was reported in Bleys (1950), but it may not have been *in situ*.

(iii) *Terrestrial Cainozoic sediments*

Considerable depth of sands and clays overlie both the Eocene limestone of the Waitpinga area and the Oligocene (?)-Miocene limestone of the Upper Hindmarsh Valley and

Myponga Plain. Clearly these sediments are of Cainozoic age so that terrestrial Miocene and Pliocene deposits almost certainly occur, although this has not been established on palaeontological evidence.

(iv) *Laterite*

The term 'laterite' is used in this thesis to describe iron-rich palaeosol profiles characterised by considerable depths of weathering. Such profiles cap many summits of the area such as Brown Hill, Kerby Hill, Peeralilla Hill, Spring Mount, Wilson Hill and Mount Desert. At lower elevations ferricrete, defined here as an iron-rich crust formed by secondary iron accumulation and not associated with deep weathering, occurs. These formations have considerable age ranges, but most of them belong to the Tertiary.

e) *Quaternary deposits*

Pleistocene and Recent deposits include river alluvia, marine deposits near the present shoreline, beach and back-shore deposits often capped by calcrete, and high level alluvial material.

The major streams of the area, the Inman and Hindmarsh Rivers and the Waitpinga Creek display river terraces formed of alluvial fills. Various types of alluvia have been distinguished and placed in the following relative age sequence from oldest to youngest (Bourman, 1969).

a. *The Ma Unga Clay* - Grey, sandy clay containing lenses of black carbonaceous material, occurring upstream from the Inman Gorge in the Inman River, and upstream from Wordles Bridge in the Hindmarsh River.

b. *Adare Clay* - reddish, yellow, sandy clay with numerous nodules of calcium carbonate. A bone fragment recovered from the Adare Clay in the lower Hindmarsh River was dated at 12,600 B.P. (Gak-2356) (Gill and Bourman, 1972).

c. *Breckan Sand* - dark grey and black clays and sands forming low terraces and flood plains.

d. Present stream channel loads, which are often formed of white sands.

High level outwash deposits cover areas of the Waitpinga drainage basin, and form screes and fans at the bases of some hills such as Brown Hill, where they merge seawards with other alluvial deposits.

Truncated remnants of consolidated Pleistocene beach and dune deposits exist at Newland Head and Port Elliot, where an extensive calcrete crust indicates their extent. Both deposits display cross-bedding, contain small shell fragments and are consolidated by calcareous cement. The beach deposits may be distinguished from the dunes by the smaller amplitude of cross-bedding and by coarser grains and shell fragments. A very complex sequence of beach deposits and calcrete crusts, resting unconformably on Kanmantoo Group metasedimentary rocks, occurs on Newland Head. The calcrete which caps these deposits is nowhere as extensive as that shown on the Encounter geology map sheet, 1:63,360 series. On this map calcrete encircles Ridgeway Hill, but apart from some small exposures along the top of the cliffs none outcrops north of Ridgeway Hill (c.f. Figures 1 and 4). Other calcrete occurs on Granite Island, Rosetta Head and the Newland Lowland. Consolidated beach deposits occur in the tidal zone and extend below sea level at Boomer Beach, Encounter Bay, Waitpinga Beach and Parson Beach. Intact micro-fossil shells found plastered to precipitous cliffs 30' (9m) a.s.l. northeast of Newland Head may be related to similar deposits.

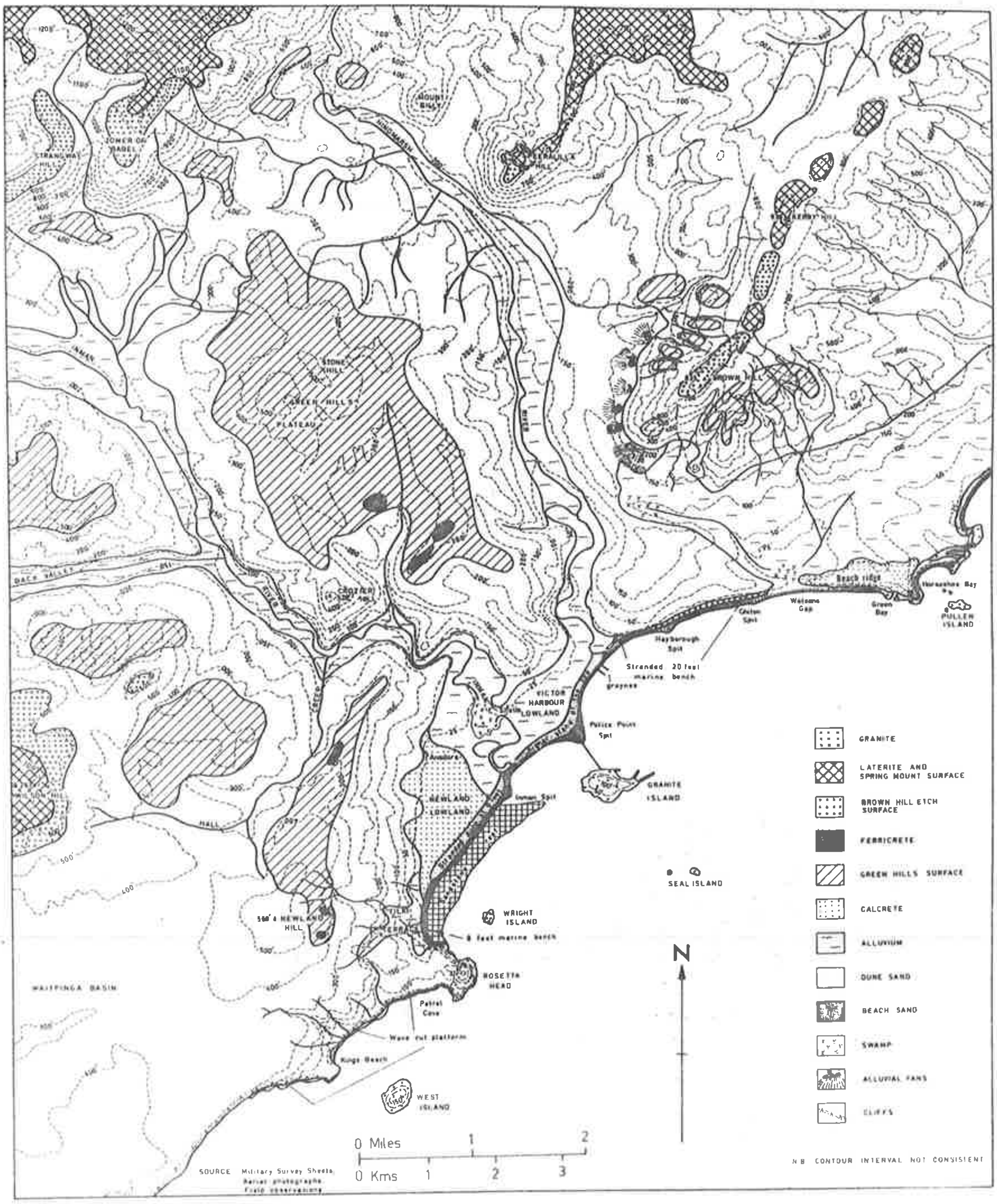
Shell beds, approximately 20' (6m) a.s.l., east of the Hindmarsh River mouth, contain the following fossils: *Ostrea sinuata*, *Anadara trapezia*, *Anapella pinguis*, *Benbicum imbricata*, *Brachyodontes hirsutus*, *Glycimeris* *striatularis, Liotia australis, Macoma deltoidalis, Mactra australis, Nassarius pauperatus, Turbo undulata, Venerupes crebrelamellata.* Both *Anadara* and *Ostrea* are very thick shelled, and as a result it has been suggested that they were living near the shoreline (Guppy, 1943). Further *Anadara* shell beds were located at the foot of a scarp backing the Newland lowland, at a similar elevation of 20' (6m). Recent shell fragments are included in beach rock about 8' (2.4m) a.s.l. at the foot of a cliff at Yilki (Bourman, 1969).

Unconsolidated sand dunes, some of them firmly fixed by vegetation, parallel considerable lengths of the present coastline. Two systems of Recent sand dunes, one vegetated and the other unvegetated overlie the calcrete capping at Newland Head, forming cliff-top dunes. These dunes almost reach the summit of Ridgeway Hill.

Estuarine deposits occur in places on the Victor Harbour and Newland lowlands. These are marly in nature and contain numerous brackish water shells of the species *Coxiella badgerensis* (Howchin, 1910a). These are of very recent age, and the marl is probably still forming (Dr. Mary Wade - pers. comm.), especially on the Newland lowland, which is covered by water for long periods in winter.

GEOMORPHOLOGY – ENCOUNTER BAY AREA

FIGURE 5



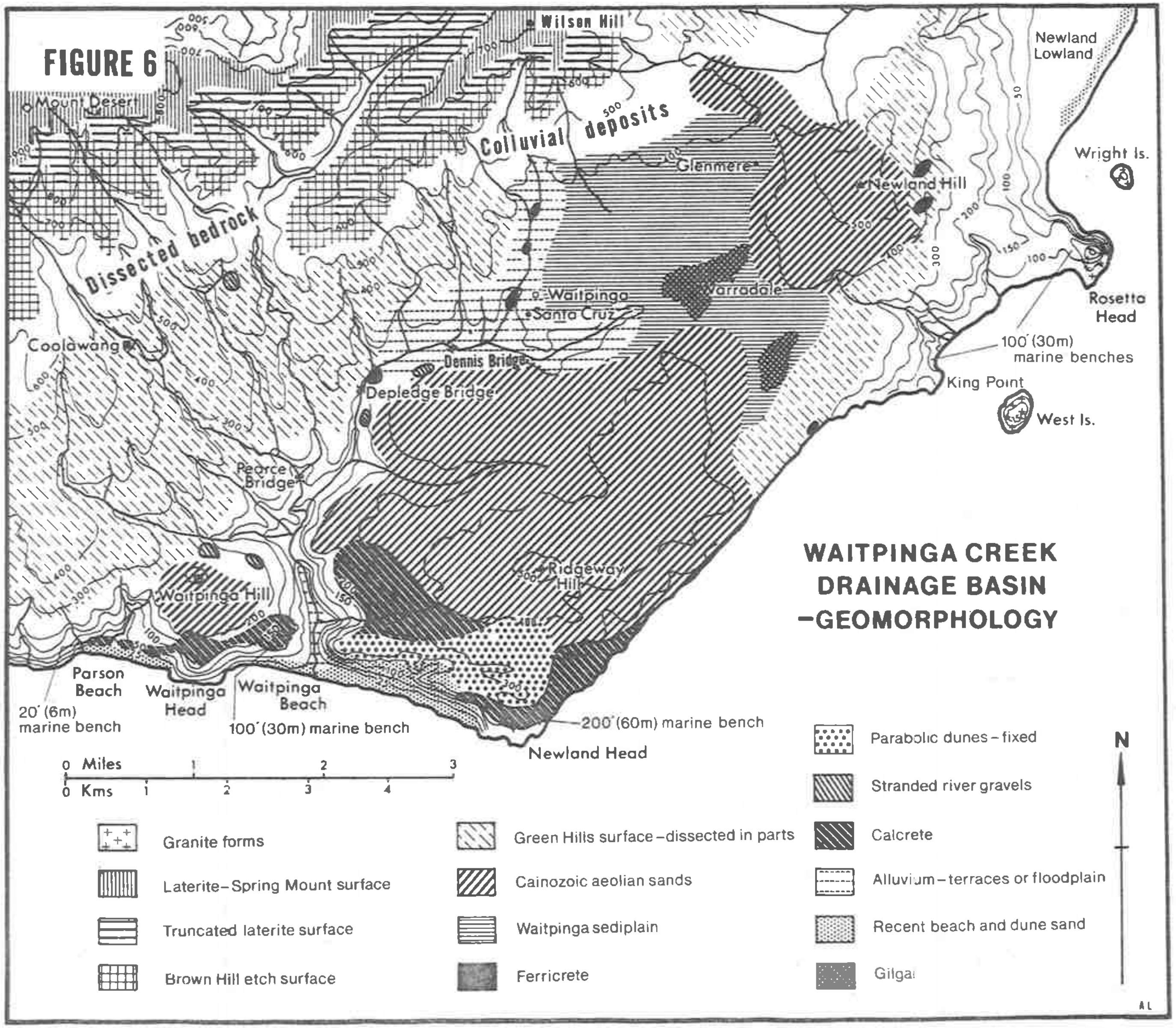


FIGURE 6
WAITPINGA CREEK DRAINAGE BASIN
–GEOMORPHOLOGY
Wilson Hill
Mount Desert
Colluvial deposits
Dissected bedrock
Glenmere
Newland Hill
Newland Lowland
Wright Is.
Rosetta Head
Warradale
Waitpinga
Santa Cruz
Dennis Bridge
Depledge Bridge
Coolawang
100´(30m) marine benches
King Point
West Is.
Pearce Bridge
Ridgeway Hill
Waitpinga Hill
Parson Beach
Waitpinga Head
Waitpinga Beach
20´(6m) marine bench
100´(30m) marine bench
200´(60m) marine bench
Newland Head
0 Miles 1 2 3
0 Kms 1 2 3 4
N
Granite forms
Laterite–Spring Mount surface
Truncated laterite surface
Brown Hill etch surface
Green Hills surface–dissected in parts
Cainozoic aeolian sands
Waitpinga sediplain
Ferricrete
Parabolic dunes–fixed
Stranded river gravels
Calcrete
Alluvium–terraces or floodplain
Recent beach and dune sand
Gilgai
AL

CHAPTER III COASTAL GEOMORPHOLOGY

1. INTRODUCTION - MORPHOLOGY OF THE COASTLINE

In the study area the configuration of the coastline reflects bedrock structure and the direction of wave attack. The coast from the mouth of Coolawang Creek to Newland Head trends approximately west-east. Two main beaches, Parson Beach and Waitpinga Beach, 1 mile (1.6km) and 2 miles (3.2km) long respectively, make up the majority of this section of the coast. Outcrops of Kanmantoo Group metasedimentary rocks separate the two beaches, and form the remainder of the coastline.

The positions of the beaches are related to fold structures in the basement rocks. Although in this area the bedrock generally dips at high angles to the southeast, folding has caused a repetition of beds (Madigan, 1925; Daily and Milnes, 1973).

Thus Parson Beach occurs within a broad-scale synclinal structure, and Waitpinga Beach within an anticlinal structure. The axes of the structures plunge to the southwest (Daily and Milnes, 1973). Various erosive processes have acted on these structures, which, at the coast, correspond with topographic depressions now filled with beach and dune sands.

The Kanmantoo Group metasedimentary rocks outcropping on this section of the coast, and from Newland Head to 0.6 miles (1 km) southwest of King Beach, are those of the Balquidder Formation of Daily and Milnes (1972, 1973). This formation supports precipitous coastal cliffs ranging up to 350' (105m) in height, northeast of Newland Head. Generally the coastline follows the strike of the thick bedded coarse grained metasandstones, which form the steep cliffs. It might be inferred that the orientation of the cliff line may originally have corresponded to a fault zone, as there is both geological and geophysical evidence for faulting on

Plate 2. Structurally controlled bays 0.6 miles (1km) southwest of King Point, the promontory on the far right of the photograph. The rocks in the foreground are those of the Balquidder Formation, thick bedded meta-sandstones, interbedded with thin intervals of meta-siltstones. The lower cliffs in the middle distance have formed on less resistant phyllites and schists (Daily and Milnes, 1973). The granite headland, Rosetta Head, is visible near the horizon.

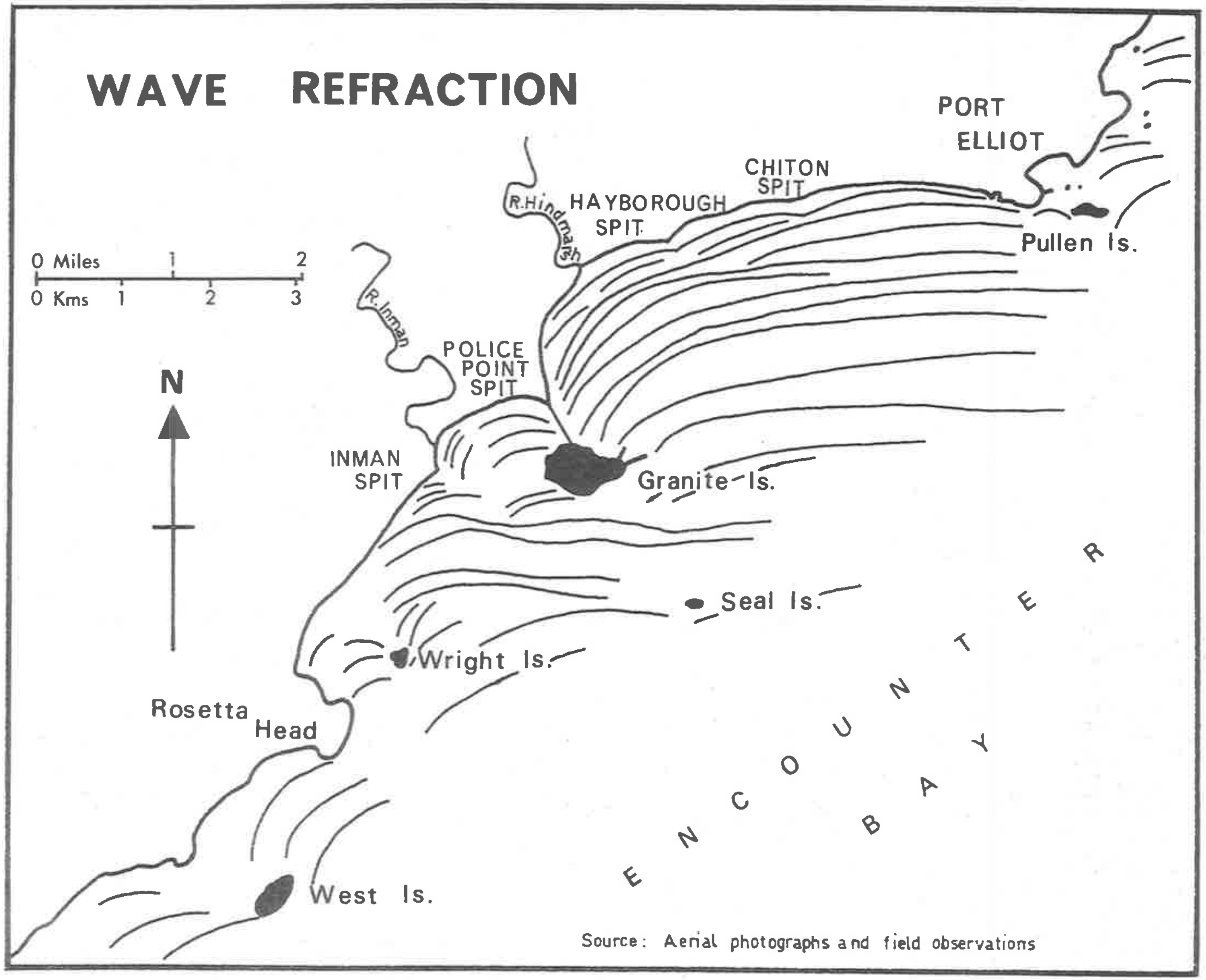
the southeastern margin of the Mount Lofty Ranges (Morony, 1971). However, the present morphology of the cliffs is explicable in terms of bedrock structures and strong wave attack from the open Southern Ocean. In detail the cliff line does not follow the strike of the basement rocks exactly, and as the Balquidder Formation includes thin intervals of easily eroded metasiltstones, small bays and inlets are common. At the southern part of Newland Head, where the strike of the bedrock trends seaward, differential erosion has developed a rugged and irregular coastline and near the northeastern section of the cliffs, where the strike nearly parallels the coast, small cuspate but structurally controlled bays have formed (Plate 2). Located along the base of the cliff line are occasional serrate shore platforms and boulder beaches.

Approximately 0.6 miles (1 km) southwest of King Beach the cliffs decrease markedly in elevation, reaching only 30' (9m) to 60' (18m) a.s.l. This topographic change coincides with a change to the less resistant phyllites and schists of the Petrel Cove Formation (Daily and Milnes, 1973).

At King Point the coastline protrudes seawards where it has been protected from the full force of waves by the resistant granite outcrop of West Island. A large part of King Point is composed of very well preserved Late Palaeozoic glacigene sediments including large granite erratics (Howchin, 1910a). Crowell and Frakes (1971a) concluded that the granite boulders at King Point were transported from West Island by wave action during a higher stand of the sea, but the presence of exotic erratics (Milnes and Bourman, 1972) favours a glacial origin. It may seem remarkable that these ancient and easily eroded deposits should form a headland, but they lie protected in the lee of a small outcrop of basement rock.

Differential erosion accounts for the plan morphology of the remainder of the coastline considered. Bays have

FIGURE 7


WAVE REFRACTION
0 Miles 1 2
0 Kms 1 2 3
N
PORT ELLIOT
CHITON SPIT
HAYBOROUGH SPIT
R. Hindmarsh
R. Inman
POLICE POINT SPIT
INMAN SPIT
Pullen Is.
Granite Is.
Seal Is.
Wright Is.
Rosetta Head
West Is.
ENCOUNTER BAY
Source: Aerial photographs and field observations

been eroded in less resistant rocks, whilst headlands are occupied by, or are protected by resistant outcrops. Small coves occur on either side of Rosetta Head, eroded in the less resistant, finely bedded metasedimentary rocks. The large bay, which extends from Rosetta Head to the granite outcrops of Port Elliot, has developed in soft glacigene, marine and alluvial deposits. Two other major bays include Horseshoe Bay and that extending from Frenchman Rock to the basement rock outcrops at Middleton.

a) *Wave refraction*

Minor variations in the orientation of the coastline are explicable in terms of wave refraction patterns imposed by:

(i) the resistant granite outcrops of West Island, Rosetta Head, Wright Island, Granite Island, Pullen Island, Freeman Knob, Commodore Point and Frenchman Rock;

(ii) by small outcrops of basement rocks and lithified glacigene sediments;

(iii) and by reefs and shore platforms eroded across marine calcareous sandstones.

As a result very complex wave refraction and diffraction patterns develop, which correspond to the configuration of the coastline (Figure 7). This is evidenced by the development of many sand spits, e.g. Police Point spit, Hayborough spit, Chiton spit, Inman spit (Bourman, 1969) and several small spits near Yilki. The thesis that some of these spits, e.g. Police Point spit in particular, may have developed as a result of the alternation of two dominant winds blowing from opposite directions, was considered (Bourman, 1969) and found inadequate. Thus the alternative hypothesis of wave refraction is favoured.

b) *Recent coastal erosion*

The coastline immediately east of Middleton is undergoing considerable erosion, and has done so since the turn of the century. Aerial photographs taken in 1949 and 1966 clearly indicate that erosion of the alluvial deposits, which form the shoreline, has caused the cliffs to retreat by several metres in the 27 year period. Hodge (1932) wrote: 'Up to about 20 years ago Middleton was famed for its wonderful beach. At low tide it was probably nearly a quarter of a mile from sandhill to sea, and so firm that vehicles could be driven for miles along its reaches in an easterly direction. But the sea encroached quite suddenly and there is now comparatively but little beach and ordinary high tides practically reach the sand hills.' Photographs taken of the beach in the late nineteenth century confirm that it was of extensive width (Plate 3). Today there are no sand dunes at all backing the beach, and at high tide (Plate 4) the sea reaches the base of the alluvial cliffs, excavating material slumped from the cliffs.

Mr. A. Neighbour of Goolwa maintains that the coast has been eroded as much as 0.25 miles (0.4 km) during his observations of the beach since 1897. He claims that the basement rock outcrops near the mouth of Middleton Creek have been exposed by coastal erosion since that time. This out-crop of rock serves as a datum from which estimates of coastal erosion may be measured on aerial photographs.

Coastal erosion is very common throughout many areas of Australia today. Glacio-eustatic rises in sea level of the order of 10cm/100 years, increased storminess and the interference of man have been cited as the causes of this problem (Thom, 1968). The rapid erosion at Middleton does not seem to be related to the effects of man as there are no records of man's interference with this section of coast. Possibly increased storminess and a slight rise in sea level may have been significant in contributing to the erosion. The tidal nature of the lower reaches of the Inman and Hindmarsh rivers supports the view of recent rises in sea level (Bourman, 1969). However, the main cause of the erosion may be related to tectonism, for the initiation of the erosion coincided with an earth tremor about 1902. The tremor was quite severe, causing cracking of some of the

Plate 3. View of Middleton Beach taken during the late 1890's, illustrating the former broad extent of the beach. The people in the photograph are those of the Basham family (Photograph by courtesy of Miss P. Basham).

Plate 4. View of Middleton Beach taken in 1972. The former sand dunes have been completely eroded, with the beach now being backed by alluvial cliffs. Basement rocks of the Kanmantoo Group form an outcrop in the swash zone. Photograph taken just after high tide.

buildings in the Goolwa area (Mr. J.S. Dodd, pers. comm.)

The Middleton Beach lies within the Murray Basin province, which could be subsiding relatively to the nearby uplands of the Mount Lofty province. Evidence from the southeast of South Australia illustrates that the Murray area has subsided relatively to the Mount Gambier region (Sprigg, 1952). Moreover, a fault line may lie buried on the eastern flank of the Mount Lofty Ranges, passing through the Port Elliot-Middleton area. Outcrops of Kanmantoo country rocks either side of the suspected fault zone display dislocated strike orientations, that on the eastern side being perpendicular to the regional strike on the west. In addition, detailed gravity contours in this area have been interpreted as indicating a 'fault-like structure, at depth, with a large density contrast, with the down-thrown side to the east' (Morony, 1971).

Thus the cause of extensive coastal erosion at Middleton Beach is probably related to subsidence of the land, especially as marked ingression has been noted to the east, but not the west of the suspected fault. This effect has been compounded by a slight rise in sea level, and has been most noticeable at Middleton Beach, where the coastline is formed on easily eroded clays.

The bays and coves of Encounter Bay are normally occupied by sandy beaches. Some of the sand is derived from streams, especially the Inman and Hindmarsh Rivers. During winter flows, sediments from these streams often extend offshore as far as Granite Island. During the past 50 years, the beach east of the Inman River mouth has extended seawards up to 50' (15m) while the coast southwest of the Hindmarsh River mouth has suffered erosion, necessitating the construction of groynes (Mr. J. Abbott - pers. comm.). The drainage basin of the Inman River and its main channel have undergone much more erosion since European occupance than the Hindmarsh River (Bourman, 1969).

Thus the different volumes of material delivered by the streams may partly account for the opposite changes at the coastline.

However, much of the beach sand is apparently derived by coastal erosion and surface wash, especially in areas backed by easily eroded sands and clays. Pocket beaches at King Beach and Petrel Cove illustrate this point admirably as they are associated with isolated outcrops of Late Palaeozoic glacigene, or reworked glacigene sediments.

c) *Longshore drift*

Some of the beach sands of Encounter Bay contain heavy mineral sands consisting essentially of magnetite, ilmenite, garnet, staurolite, green spinel, tourmaline, kyanite, rutile and zircon. These were interpreted as originating chiefly from the metamorphic aureoles formed during the intrusion of acid magma into the surrounding country rock (Thomas, 1923). If this were the case, then the distribution of these heavy mineral sands might indicate the dominant direction of longshore drift. However, the heavy minerals are derived from the metamorphic rocks as a whole, and not simply from the contact metamorphism zone (A.R. Milnes, pers. comm.). Thus they have no use as drift indicators.

The direction of longshore drift in Encounter Bay is variable, as is evidenced by the formation of the spits described above. However, the direction of drift overall is probably from the southwest and west to the east, under the influence of strong winds from the southwestern quarter (Johnston, 1917). Sand has accumulated on the southwestern sides of the groynes near the mouth of the Hindmarsh River, and the mouths of the Inman and Hindmarsh Rivers have been deflected to the east, supporting the view of west-east drift.

d) *Changes in positions of river mouths*

Some interesting changes have occurred in the positions of the mouths of the Hindmarsh and Inman Rivers and Waitpinga Creek in historical time. It was reported in

Bourman (1969) that the Hindmarsh River shortened its course by almost 0.25 miles (6.4 km) when it broke through a narrow divide of sand dunes during flooding in 1946. Some confusion surrounds this interpretation. Mr. G. Parsons of Waitpinga maintains that the river broke through to the sea of its own accord in 1943. Mr. W. Needs of Victor Harbour claims that members of the R.A.A.F., stationed at Mount Breckan in 1946, cut through the sand hills from the river to the sea, in an attempt to lower flood waters in the region following heavy rains of January 17th and 18th, 1946, when Victor Harbour experienced 7.77" (19.43cm) rain (Bureau of Meteorology).

An aerial photograph dated 24/11/45 shows that the River Hindmarsh then flowed to the sea well northeast of its present mouth. Thus it seems most probable that the course change was completed during the floods of 1946. However, the positions of the mouths of both rivers fluctuate considerably, depending on the interaction of river and coastal processes, so that the final change in the position of the mouth may have been accomplished over a period of several years.

Aerial photographs spanning the period from 1945 to 1972 reveal numerous fluctuations in the position of the mouth of the Inman River and further alterations to the mouth of the Inman River in 1927 are recorded in Cleland and Howchin (1931). The position of the mouth of the Waitpinga Creek has also changed in historical time. Normally sand bars close off the mouth of Waitpinga Creek, leading to the inundation of the alluvial flats seawards of the Waitpinga Gorge during floods (Plate 5). Riverine sediments mark the former outlet of Waitpinga Creek, which is now closed off by sand dunes. The change in position of the Waitpinga Creek mouth occurred in about 1940. (Mr. V. Dennis - pers. comm.).

Plate 5. The outlet of Waitpinga Creek (centre of photograph) is blocked by a sand bar, causing the inundation of the alluvial flats. The former outlet of the creek, now blocked by sand dunes, is in the right centre. The change in the position of the mouth occurred in about 1940. (Photograph by courtesy of S.A. Archives).

2. FORMER STANDS OF THE SEA DURING THE QUATERNARY

a) *Introduction*

Workers in regions adjoining the study area have recognised flights of terraces or benches, which have been interpreted as resulting from Pleistocene glacio-eustatic higher stands of the sea.

In southwest County Adelaide, Ward (1965, 1966) described former shorelines standing at 600' (180m), 540' (162m), 370' (110m), 105' (31.5m), 35' (10.5m), 26' (7.8m), 10' (3m), and 8' (2.4m) - 10' (3m). The area was considered to be essentially tectonically stable during the Quaternary, so that the shorelines were interpreted as glacio-eustatic features. In the Mount Compass-Milang area Maud (1972), correlated surfaces at 600' (180m), 550' (165m), 400' (120m), 200' (60m), 100' (30m), 60' (18m), 40' (12m), 26' (7.8m), 10' (3m), 7' (2.1m), 3' (0.9m) with higher Quaternary stands of the sea postulated by Ward and Jessup (1965). This was done despite the lack of evidence of diagnostic shoreline features and/or their age, especially for the seven highest surfaces. The 600' (180m) surface, which surrounds Gemmel Hill, was examined by the writer who considers it to be an etch surface because it can be traced into a weathering front underlying Gemmel Hill and some other nearby lateritic residuals.

If all glacier ice on the earth were to melt it is estimated that sea level would rise by approximately 140' (42m) to 200' (60m) (King, 1966). Therefore, this is probably the maximum elevation that Quaternary shoreline features can be expected to be located in a tectonically stable area. Despite the detailed geological mapping and investigations carried out in the Mount Lofty Ranges, no evidence of marine Pleistocene fossils have been found at the high elevations where the Pleistocene shorelines are believed to have stood (Twidale, Daily and Firman, 1966).

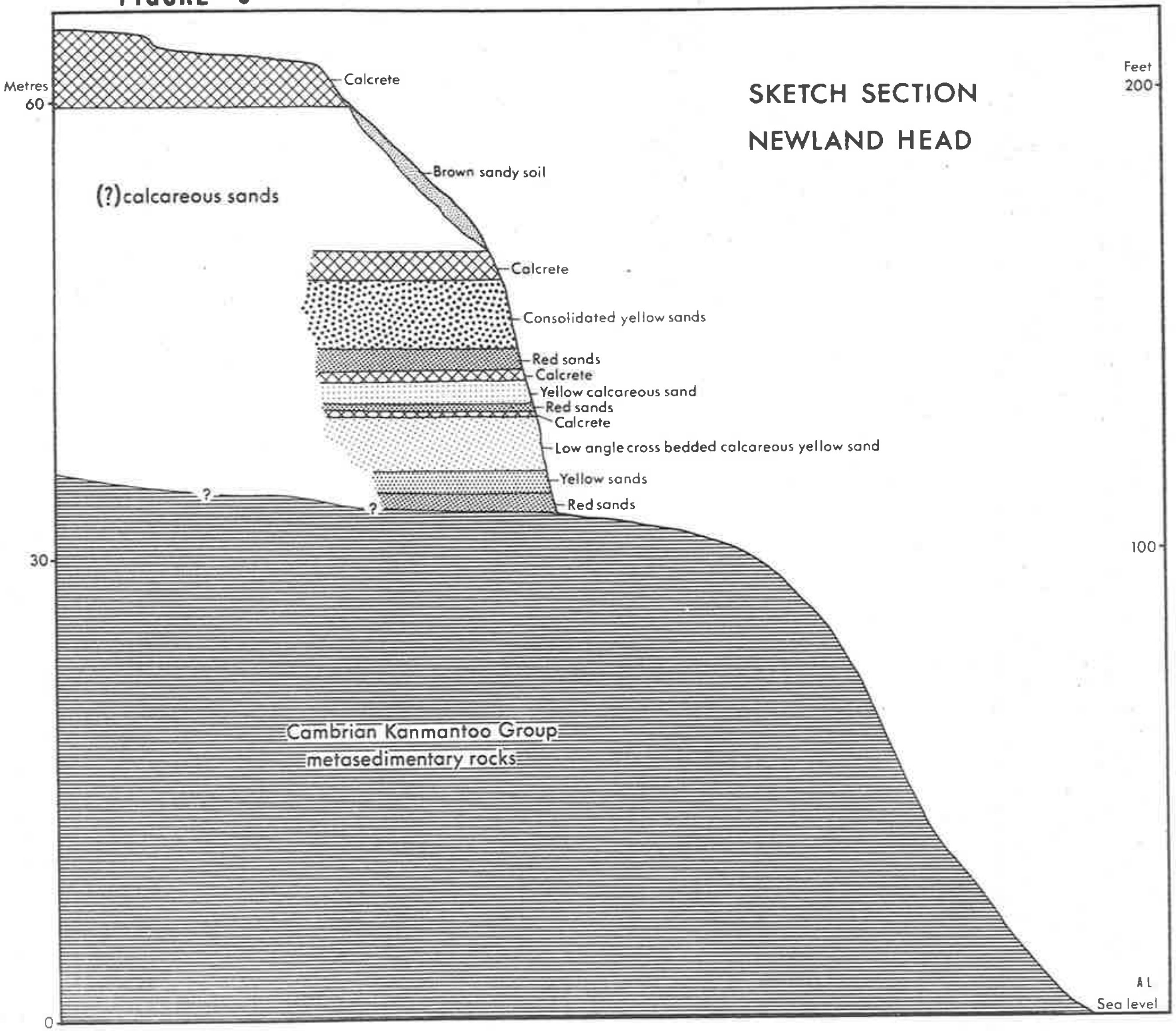
In the study area, there is no evidence of possible Pleistocene shorelines at elevations greater than 200' (60m) a.s.l. although bedrock benches occur on the western side of Brown Hill at about 600' (180m). They are not etch benches as they stand well below the level of the Brown Hill etch surface. However, projections of the slopes on the benches link up with the Green Hills erosion surface and they have been interpreted tentatively as parts of the Green Hills surface (Bourman, 1969). There is no evidence to suggest that the benches are related to a 600' (180m) Quaternary higher stand of the sea.

Morphometric evidence coupled with the identification of stranded, ferruginised river gravels suggests that the Green Hills surface developed in relation to a sea level some 200' (60m) a.s.l. (see Chapter IV). It is possible that the shoreline at 200' (60m) is of Pleistocene age, but more likely it represents a Pliocene event. This conclusion is based on the lack of ferruginisation of known Pleistocene sediments in the area. Nevertheless evidence from Newland Head and Waitpinga Hill suggests that a Pleistocene shoreline stood at approximately 200' (60m) a.s.l.

b) *200' (60m) shoreline*

At Newland Head and south of Waitpinga Hill massive calcrete crusts form gently seaward shelving benches at elevations near 200' (60m) a.s.l. (Plate 6). A complex sequence of deposits occurs on Newland Head (Figure 8). The sequence rests on a bench at about 120' (36m) a.s.l. eroded across Kanmantoo Group metasedimentary rocks. The red sands, which are interpreted as palaeosols, in two places rest directly on calcrete in which small-scale karst features have developed. Four layers of calcrete rest on calcareous sands. Bedding structures are only apparent in one of these deposits, where weathering has brought horizontal beds into relief. The contact between this

FIGURE 8



SKETCH SECTION
NEWLAND HEAD
Metres
60
30
0
Feet
200
100
Calcrete
Brown sandy soil
(?)calcareous sands
Calcrete
Consolidated yellow sands
Red sands
Calcrete
Yellow calcareous sand
Red sands
Calcrete
Low angle cross bedded calcareous yellow sand
Yellow sands
Red sands
?
?
Cambrian Kanmantoo Group
metasedimentary rocks
A L
Sea level

Plate 6. Near level calcrete capping approximately 200' (60m) a.s.l. south of Waitpinga Hill. The calcrete crust is about 3' (0.9m) thick.

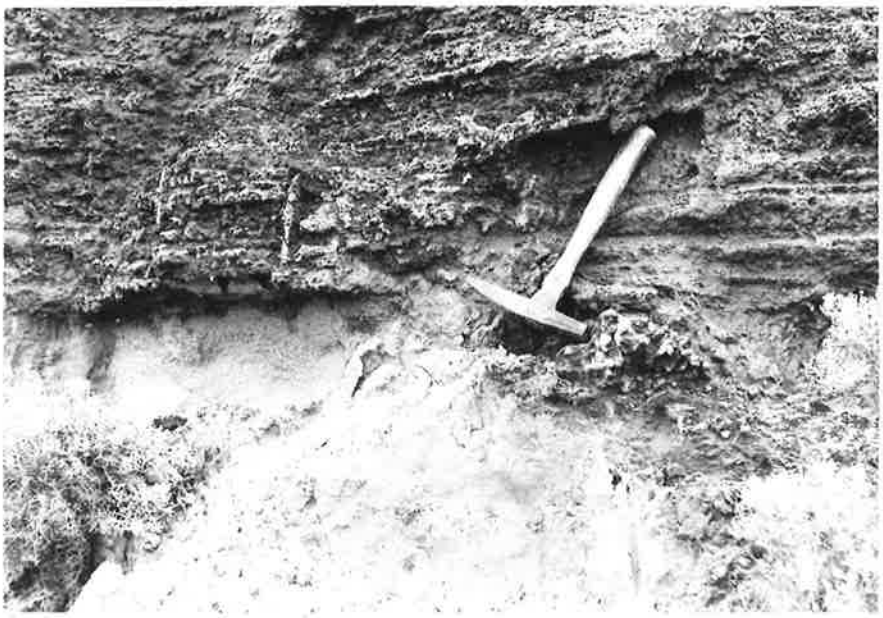


Plate 7. Contact between horizontally bedded calcareous sands, and underlying red sands on Newland Head.

deposit and the underlying red sands is pronounced and sub-horizontal (Plate 7). The coarse nature of the sand grains, the disposition of the bedding and the presence of shell fragments suggest that the calcareous sands are beach deposits rather than dune sands. At the summit, the calcrete, which is crowded with shell fragments, is about 12' (3.6m) thick.

The summit calcrete dips seaward gently and at the coast can be traced at a constant elevation over distances exceeding 350' (105m). The sequence of sediments on Newland Head has been described as aeolianite (Crawford, 1959), but it seems that on evidence presented above, many of the deposits are beach sands. Moreover, the present summit of Newland Head does not display a dune morphology. However, if the deposits are aeolian, the horizontal disposition of the calcrete layers might be the result of marine truncation of aeolian deposits.

The sequence of deposits on Newland Head represents cyclic marine and terrestrial phases, in which deposition of beach sand was followed by the formation of a palaeosol. There are four major calcrete layers in the sequence, all of which have developed on calcareous sands. They may indicate four periods of minor transgression and regression. Although the observed sequence could be accounted for in terms of a fluctuating eustatic sea level, tectonic uplift probably played a role in alternating marine and terrestrial conditions.

A similar sequence, including four horizontal calcrete layers associated with palaeosols, was described by Crocker (1946) from a cliff exposure at Scaeles Bay, Eyre Peninsula. The section is referred to as an aeolianite sequence, but the horizontality of the calcrete layers suggests a marine influence. In this instance, the deposits rest on granite, and the unconformity is situated at present sea level.

c) *100' (30m) shoreline*

There is some evidence for a Pleistocene shoreline standing approximately 100' (30m) a.s.l.

(i) A pronounced surface truncating calcareous beach and/or dune sands capped by calcrete occurs at about 100' (30m) a.s.l. on the western side of Waitpinga Creek near the coast. A similar situation had been noted at Cape Jervis by Brock (1971) where a bench at 135' (39.9m) - 150' (45m) truncates aeolianite of presumed Pleistocene age.

(ii) At King Point a horizontal surface at an elevation of 100' (30m) is developed across Late Palaeozoic glacigene sediments, where glacial erratics reworked by marine activity were first noted by Howchin (1910a). Crowell and Frakes (1971a) described Quaternary shoreline deposits in the same locality.

(iii) Calcareous deposits at a similar elevation near the summit of Granite Island and on the saddle of Rosetta Head may also be related to this higher stand of the sea, as may the gently seaward sloping surfaces between Rosetta Head and King Point.

(iv) Backing the Newland lowland, two pronounced erosional benches, truncating Late Palaeozoic glacigene deposits, occur (Bourman, 1969). They slope seaward at elevations between about 135' (39.9m) and 100' (30m) a.s.l. No diagnostic shoreline deposits have been located on these benches, but they may be related to a 100' (30m) shoreline.

d) *20' (6m) shoreline*

There is widespread geological and geomorphological evidence in the study area for a shoreline standing approximately 20' (6m) a.s.l.

(i) Marine shells have been located at 20' (6m) in a railway cutting east of the mouth of the Hindmarsh River (Duffield, 1901). The fossil assemblage of the shell bed, which can be traced for at least 40' (12m) at a constant elevation, has been listed in the geology section. The possibility that the shells were emplaced by aborigines has been considered. However, some of the shells are extremely small and would not have attracted the attention of aborigines. Moreover, the shell bed has an orientation and distribution suggestive of *in situ* deposition. It has been suggested that the pelecypod *Anadara arca trapezia*, which is not presently living in the Encounter Bay area, is a sub-fossil related to a warmer climatic phase of the Quaternary (Sprigg, 1952). However, it has also been suggested that *Anadara* is related to shallow mud flat environments, where warm conditions would prevail. Near the coast the shells were deposited in a muddy environment, but elsewhere in the study area *Anadara* shells are cemented together in a matrix of calcareous beach sands.

(ii) Other occurrences of stranded shell beds, including *Anadara*, were found to underlie both the Newland lowland and the Victor Harbour lowland (Bourman, 1969; Gill and Bourman, 1971). Although not occurring at the surface, these shell beds stand at approximately 20' (6m) a.s.l. The Newland and Victor Harbour lowlands are backed by concave breaks in slope and a pronounced but degraded cliff line, which stands as much as 1 mile (1.6km) inland from the present coastline. The degraded cliff line is interpreted as the site of the 20' (6m) shoreline. The marine origin of the lowlands is suggested by the presence of marine fossils and massive calcrete, which caps calcareous sandstones. On the Newland lowland the calcrete capping is covered by only a shallow black soil, but the calcrete of the Victor Harbour lowland has been more deeply covered by sands and clays washed from the backing higher land, and from the Inman and Hindmarsh Rivers.

Typical sections through the lowlands are as follows:

1. Newland lowland

0 - 6" (.15m)	Grey, black soil
6" (.15m) - 2.5' (.75m)	Hard, massive calcrete
2.5' (.75m) - 4' (1.2m)	Vesicular calcrete composed of siliceous sands of beach origin, cemented by calcium carbonate

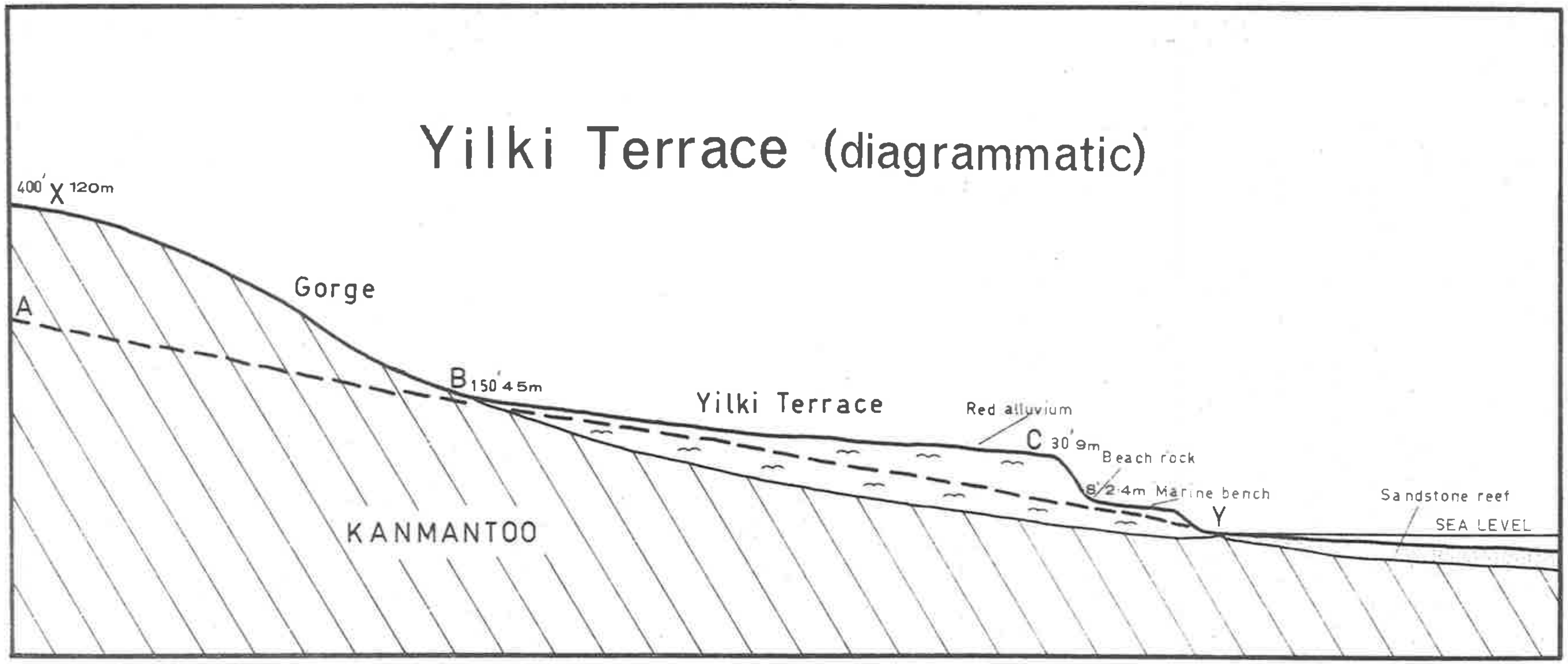
2. Victor Harbour lowland

0 - 3' (.9m)	Grey sandy soil
3' (.9m) - 5' (1.5m)	Red clay
5' (1.5m) - 9' (2.7m)	Calcrete
9' (2.7m) - 12' (3.6m)	Sand (presumably beach sand) with nodules of calcrete and small 'cockle' shaped shells at about 3m.
12' (3.6m) - 14' (4.2m)	White sand

Johnson (1944) points out that even if there are marine deposits on a terrace, that terrace need not have necessarily been formed by marine agencies. A minor marine transgression could result in the deposition of marine sediments on a surface, the broad outlines of which were due to river action. Conversely a marine platform could be subsequently covered with fluvial deposits, thereby masking its origin.

The Victor Harbour lowland is flanked by the two largest streams in the study area, and the backing escarpment is scalloped as if undercut by meandering streams. Thus the origin of the Victor Harbour lowland appears quite complex. Nevertheless, the presence of marine shells at the base of the backing escarpment suggests that this was the approximate site of the 20' (6m) shoreline.

FIGURE 9


Yilki Terrace (diagrammatic)
400' X 120m
Gorge
A
B 150' 45m
Yilki Terrace
Red alluvium
C 30' 9m
Beach rock
8' 2·4m Marine bench
Y
Sandstone reef
SEA LEVEL
KANMANTOO

(iii) Near Yilki a pronounced red alluvial fill terrace occupying a valley cut in bedrock appears related to the 20' (6m) shoreline (Figure 9). Although the top of the terrace stands about 30' (9m) a.s.l., there is evidence that the seaward side of the terrace has retreated through coastal erosion, so that the present elevation of the seaward side of the terrace does not represent the height to which the alluvial fill was originally graded (Bourman, 1969). Similar red alluvial fill deposits at comparable elevations occur in small depressions on the northern side of the saddle of Rosetta Head. The red alluvial fill of Yilki terrace has been equated with the reddish alluvial fills of the main stream terraces. The alluvial surface backing the sea cliffs at Middleton Beach may also be related to the 20' (6m) shoreline but recent coastal erosion has complicated this area. Critical evidence may have been destroyed.

(iv) East of the mouth of the Hindmarsh River the 20' (6m) shoreline is expressed as a pronounced marine bench, which extends eastward almost to Watson Gap (Bourman, 1969). The terrace is followed by the Port Elliot-Victor Harbour railway line. Although probably modified during railway construction, the terrace is a natural feature as its width is variable and far in excess of that required for the railway line. The platform, which is at least 230' (69m) in width, is backed by a steep cliff line up to 100' (30m) high, eroded in Late Palaeozoic glacigene sediments. Along this section of the coastline the 20' (6m) shoreline stood parallel to and only slightly inland from the present shore.

(v) Behind Parson Beach and Waitpinga Beach a platform has been eroded across consolidated calcareous beach and/or dune sands of Pleistocene age (Plate 8). A calcrete capping has preserved the benches from erosion.

Plate 8. Calcrete capped bench approximately 20' (6m) a.s.l. backing Parson Beach. Unconsolidated but partly vegetated reddish sand dunes rest on the calcrete surface. There is much evidence of occupance by aborigines in this area.

Plate 9. Paired river terraces near the mouth of Coolawang Creek. Stranded marine cobbles are visible in the bottom left of the photograph.

The platform is well preserved at Parson Beach where it is of uniform elevation at 20' (6m) over a distance of 350' (105m). Inland from Parson Beach a small alluvial fill terrace grades to the same elevation as the calcrete capped bench.

(vi) Westward along the coast a small beach has formed at the mouth of the Coolawang Creek. The upper part of the beach slopes at 15° and is covered with cobbles up to 8" (20cm) in diameter. This slope forms a marked contrast with the low angle slopes on the sandy part of the beach. Paired alluvial terraces at the mouth of the Coolawang stand at an elevation of 20' (6m). At this level a stranded cobble beach, similar to the present one, provides further evidence of the 20' (6m) shoreline (Plate 9).

(vii) Where the Waitpinga Creek flows from its gorge onto an alluvial flood plain about 1 mile (1.6km) from the coast there is a marked break in slope in the thalweg of the stream. (See Figure 14). The break in slope may not be the result of rejuvenation as it corresponds with a change in rock type. Nevertheless, the 20' (+6m) shoreline would have stood near this break in slope.

(viii) Intact micro-fossil shells of Quaternary age (Dr. Helene Laws - pers. comm.) were found plastered on the bedrock of the cliffs northeast of Newland Head at an elevation of about 30' (9m). However, it is difficult to determine if the shells were deposited during a higher stand of the sea, or whether they were blown there during a lower stand of the sea.

(ix) By detailed levelling it has been demonstrated that the high terrace of the Inman and Hindmarsh Rivers, the *Adare paired terrace* of filltop origin grades to a shoreline at about 20' (6m) near the coast (Bourman, 1968, 1969). The terrace has been interpreted as developing in relation to the 20' (6m) shoreline. The distal end of the femur of a large extinct marsupial (Mr. P. Aitken - pers. comm.) recovered from the Adare Clay at a depth of 16' (4.8m) was dated at 12,600 years B.P. (Gak-2356). Provided that the Adare Clay was deposited in relation to the higher sea stand at 20' (6m), the above date would approximate the time of this sea stand.

e) *8' (2.4m) - 10' (3m) shoreline*

Similar lines of evidence support a higher shoreline at 8' (2.4m) to 10' (3m) a.s.l.

(i) At Yilki the coastal road follows a stranded shore platform up to 100' (30m) wide. Here the former shoreline is indicated by a steep abandoned cliffline about 30' (9m) high, cut in the red alluvial fill of the Yilki terrace. At the base of this cliff, beach rock occurs at an elevation of about 8' (2.4m) a.s.l. It is composed of shell fragments, beach sand and small marine pebbles cemented by calcium carbonate. Although the shells are fragmented some were identified by Dr. Helene Laws of the S.A. Museum as follows:

Ninella torquata operculum
Zemitrella sp. columbellidae
Bembicium sp.
Cacozelania granaria

All of the shells are modern and indicate a Holocene age for the beach rock and for the shoreline on which they rest.

(ii) Paired alluvial filltop terrace treads formed on grey alluvium and named the *Breckan filltop terrace* in the lower reaches of the Inman and Hindmarsh Rivers, grade to 8' (2.4m) - 10' (3m) a.s.l. at the coast (Bourman, 1968, 1969).

(iii) Immediately backing the beach at Horseshoe Bay, Port Elliot, there is a marked bench at about 10' (3m) a.s.l., which is utilised as a camping ground. It may be related to the 8' (2.4m) to 10' (3m) shoreline.

(iv) Sand dunes, now well fixed with vegetation and which broadly parallel the present coast, are possibly related to the 8' (2.4m) to 10' (3m) shoreline. Such dunes occur along the coast from Yilki to the mouth of the Inman River, and northeast of Port Elliot.

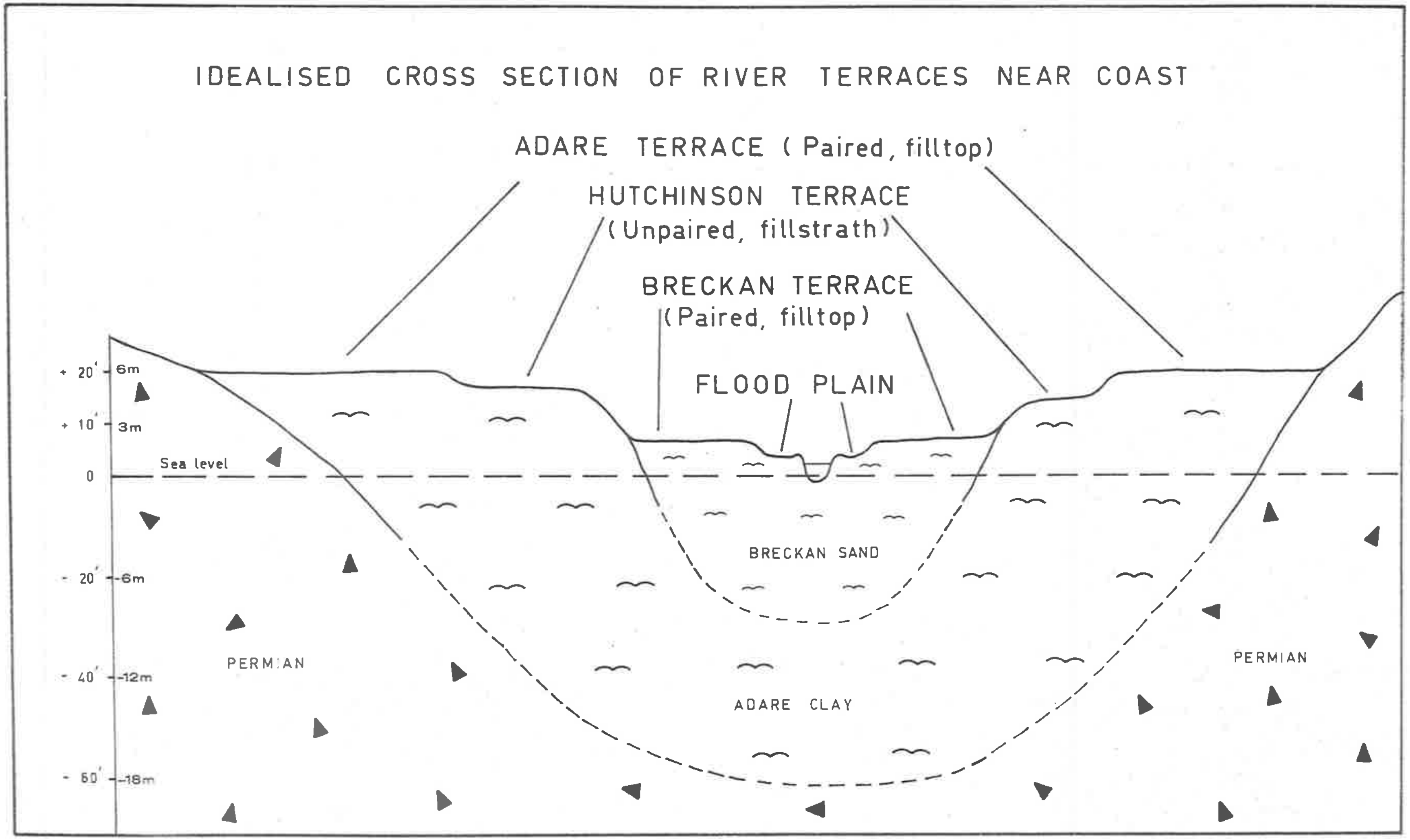
f) *Lower stands of the sea*

Evidence of strandlines formed during stands of sea level lower than at present occurs at Green Bay, along the coast of the Newland and Victor Harbour lowlands, and at Parson and Waitpinga Beaches. In these localities consolidated beach and/or dune sands extend below present sea level. Regardless of whether the deposit is dune or beach sand it must have developed in relation to a lower sea level.

Further evidence for lower stands of the sea comes from the sequences of cutting and filling postulated for the development of the terraces of the main streams (Figure 10). Low sea stands are required for the excavation of the valleys now occupied by the Adare Clay and the Breckan Sand. The absolute depth of the red Adare Clay is not known with certainty, as it is difficult to distinguish fluvial deposits from the underlying glacigene sediments. Records from a bore sited near the mouth of the Inman River suggest that the depth of the former valley could be as much as 70' (21m), a figure supported by borings in the lower reaches of the Hindmarsh River. This level corresponds with a marked break in the submarine topography between -66' (19.8m) and -72' (21.6m) seaward of West Island, Rosetta Head, Seal Island and Port Elliot (Bourman, 1969).

Bores sunk in the bottom of Encounter Bay (Johnston, 1917) have encountered cappings of 'hard limestone', which is presumably calcrete, in a maximum depth of water of 21' (6.3m). This approximate level may be related to the shoreline during the dissection of the Adare Clay, as may the gently sloping surface between -36' (-10.8m) and -66' (-19.8m) contours. Similar calcified deposits mapped in Gulf St. Vincent at a depth of -36' (-13.8m) may be related to this lower stand of the sea (Sprigg, 1952).

FIGURE 10


IDEALISED CROSS SECTION OF RIVER TERRACES NEAR COAST
ADARE TERRACE (Paired, filltop)
HUTCHINSON TERRACE
(Unpaired, fillstrath)
BRECKAN TERRACE
(Paired, filltop)
FLOOD PLAIN
+ 20' 6m
+ 10' 3m
Sea level
0
- 20' -6m
- 40' -12m
- 60' -18m
BRECKAN SAND
PERMIAN
ADARE CLAY
PERMIAN

g) *Nature of sea level changes during the Holocene*

Hails (1964) pointed out that there are two main views on sea level change during Holocene times:

(1) Sea level rose rapidly from 17,000 to 6,000 y.B.P. and then slowly to 3,000 y.B.P., without having risen above present sea level since the last interglacial.

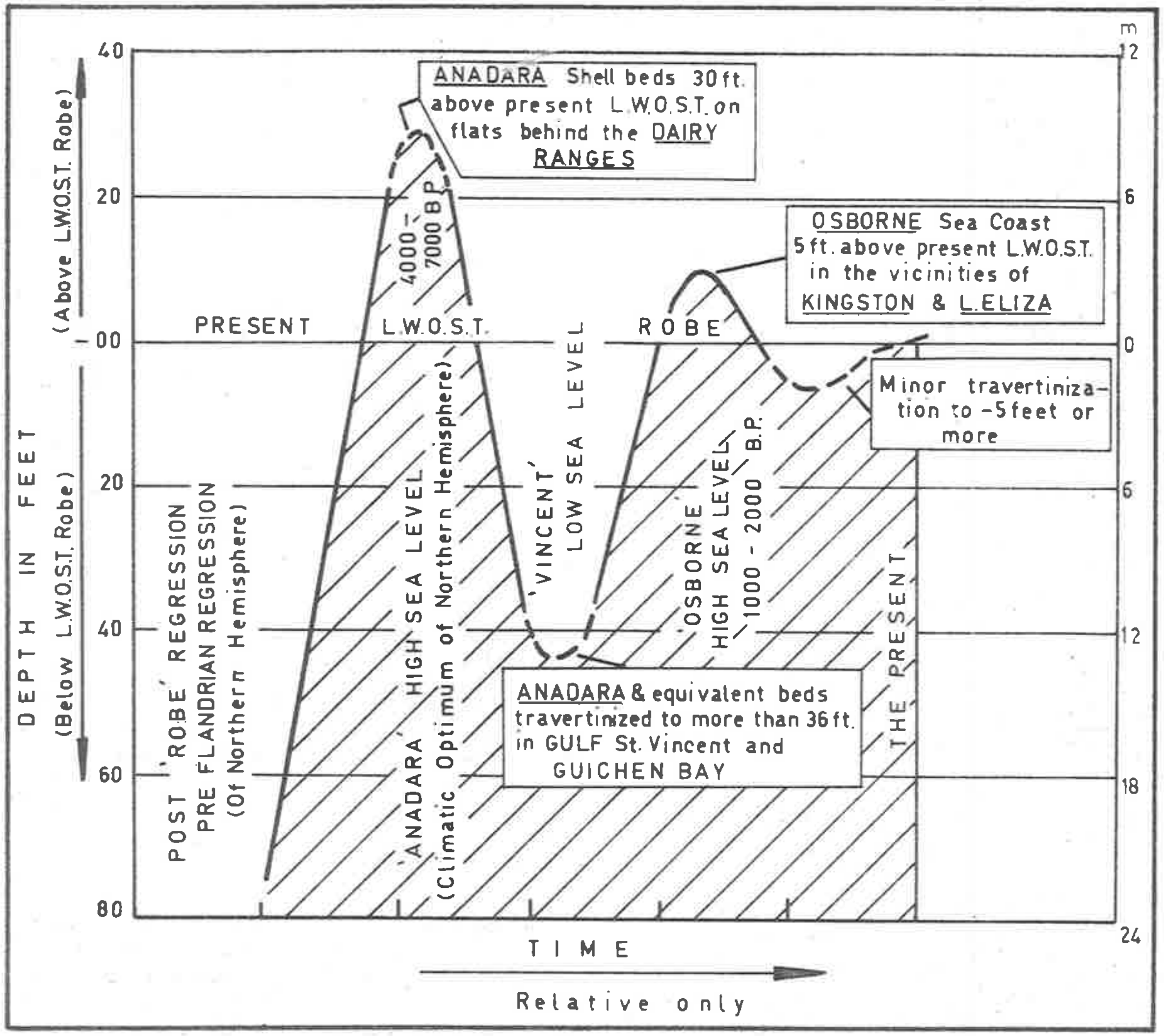
(2) Sea level, at least once, and perhaps several times during the Holocene, stood higher than at present.

After examining evidence along the east coast of Australia, Hails concluded that there was no evidence for a Late Holocene higher stand of the sea there.

As described above, there is ample evidence for a higher stand of the sea at 20' (6m) a.s.l. On the basis of a C14 date (see above) it is Late Pleistocene to Early Holocene in age. In addition there is evidence for a Holocene higher stand of the sea at 8' (2.4m) - 10' (3m). These former shorelines might be accounted for simply by tectonic uplift during the Holocene. However, associated river terraces are graded to these shorelines and have developed by alternate phases of cutting and filling. Consequently a fluctuating shoreline position above and below the present shoreline is required. This sequence of events is most reasonably accounted for by a eustatically controlled sea level. Minor tectonic uplift may have accompanied the eustatic fluctuations.

However, within the study region there is no indication of tectonic tilting or dislocation of the former shorelines over a distance of 15 miles (24km) to 20 miles (32km). Furthermore, similar sequences have been described for the Adelaide and South East regions by Aitchison et. al. (1954) and Sprigg (1952) (Figure 11). Brock (1964, 1971) described a post-Pleistocene shoreline at 26' (8m) on Fleurieu Peninsula, while the shorelines at 26' (8m) and 10' (3m) mentioned by Maud (1972) may be correlative with the 20' (8m) and 8' (2.4m) - 10' (3m) shorelines of the study area.

FIGURE 11



POSTULATED RECENT CHANGES IN RELATIVE SEA LEVEL IN ROBE-KINGSTON AND ADELAIDE DISTRICTS (After Sprigg)

Consequently, because of the widespread distribution of these former shorelines over a variety of tectonic provinces they may be ascribed essentially to eustatic sea level fluctuations. The evidence presented favours the second of the views mentioned by Hails (1964), that, during the Holocene, sea level has stood higher than at present.

h) *Sea level changes during the past 100 years*

Studies of world-wide tide gauge records have demonstrated that sea level rose at least 10cm in the past 100 years (Gill, 1972) and may be rising currently at the rate of 30cm/100 years (El-Ashry, 1971). In the study area, there is inferential evidence of a recent rise in sea level:

(i) The lower reaches of the Inman and Hindmarsh Rivers are tidal for up to 1 mile (1.6km) from the coast. The tidal range of Encounter Bay is only 2.4' (0.72m). As the scouring effect of rivers of the dimensions of the Inman and Hindmarsh Rivers would be limited to occasional flood stages, erosion below mean sea level would be minimal. The tidal nature of these streams thus appears to be related to a slight rise in relative sea level.

(ii) Recent coastal erosion near the mouth of the Hindmarsh River, and at Middleton, may be partly due to a rise in sea level.

(iii) Bourman (1969) concluded that the Police Point spit has not grown significantly towards Granite Island during the past 100 years. This conclusion might reflect the effect of the world wide rise in sea level of the past century.

i) *Summary*

Evidence has been presented for shorelines at 200' (60m), 100' (30m), 20' (6m), 8'(2.4m) - 10' (-3m), -36' (-10.8m) and -70' (-21m). In addition, evidence from the study area supports the view that sea level has risen slightly in the past 100 years.

(i) *Ages of the former shorelines*

As the shorelines at 200' (60m) and 100' (30m) truncate calcareous beach and dune sands of presumed Pleistocene age, they are ascribed to the Pleistocene, although the higher shoreline might be of Pliocene age. The -70' (-21m) shoreline is also Pleistocene in age, because during this lower stand of the sea the Inman and Hindmarsh Rivers cut deep valleys in which Late Pleistocene sediments were subsequently deposited.

The 20' (6m) shoreline relates to the deposition of the Adare Clay, which has been dated at 12,600 years B.P., a Late Pleistocene age. On the basis of the sequences of cut and fill recorded in the alluvial deposits of the area, the remaining shorelines at -36' (-10.8m) and 8' (2.4m) - 10' (3m) are younger than the 200' (6m) shoreline, and probably belong to the Early Holocene and Middle Holocene respectively.

(ii) *The roles of eustatic and tectonic effects in stranding the former shorelines*

Apart from the two highest shorelines, the remainder are interpreted as essentially the result of a fluctuating eustatic sea level, postulated from the alternate phases of incision and aggradation of the main streams of the region. This evidence of a fluctuating base level would be very difficult to account for solely in terms of tectonism since it would require successive positive and negative movements of the land relative to the sea. However, tectonism has affected the area in historic time, so that this influence cannot be entirely discounted. Small tectonic effects may have been superimposed on a dominant fluctuating eustatic sea level.

3. *Coastal dunes*

a) *Parabolic dunes*

A vegetated parabolic dune system occurs on the Newland Head area backing Waitpinga Beach (Plate 10). At Waitpinga Beach the coastal sands are exposed to strong winds primarily from the Southern Ocean. Because the area

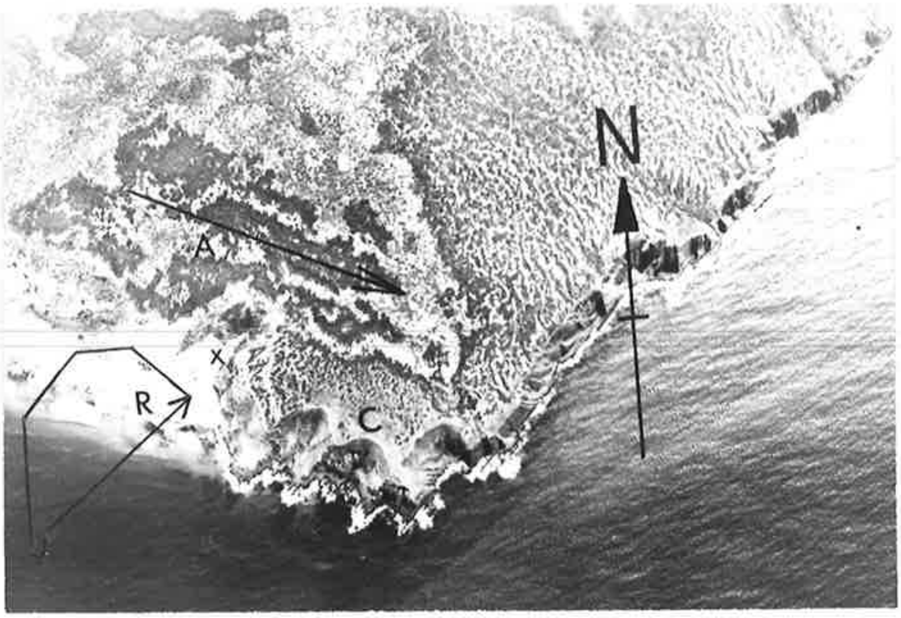


Plate 10. Vegetated, fossil parabolic dunes north of Newland Head. The dunes, the axial orientation of which is shown by the arrow (A), rest on a calcrete surface (C), which is sand free at Newland Head. The calcrete surface (C) may be related to a former shoreline 200' (60m) a.s.l. The resultant (R) of effective winds is almost normal to the axes of the fossil dunes. At (x) sand is being blown towards the top of the cliff under the influence of the present wind regime. Compare with Plate 12. (Reproduced by permission of the S.A. Lands Dept.).

is unprotected calm days are uncommon, a feature expressed in the aborigine meaning for Waitpinga, 'windy place' (Praite and Tolley, 1970).

The field of parabolic dunes is well fixed with vegetation. Not only grasses but also bushes and stunted trees[1] hold the sand, giving the impression that it is some time since the dunes were mobile. The fossil nature of the dunes was further suggested by comparison of the axial dune orientation with the present wind regime.

The wind recording station nearest to the dune field lies 8.5 miles (13.6km) to the northeast at Victor Harbour. In this distance the land rises to 567' (170m) a.s.l., which protects the wind recording station from the full force of the southerlies and southwesterlies. Higher land lies in the northwest and northeast sectors, and winds from these zones are possibly channelled along topographic depressions to some extent. However, as these are off-shore winds they may have minimal effect on dune orientation (see Jennings, 1957). Factors other than wind direction, such as vegetation, local topographic changes, presence of moisture, potential for erosion of stabilised dunes, may influence the orientation of dunes. However, Jennings (1957) concurs with Landsberg (1956) who demonstrated that the wind regime is the dominant determinant of the axial trend of parabolic dunes.

It should be noted that direction and speed of winds at Victor Harbour are not recorded instrumentally, but from a wind vane and from observations based on the rough Beaufort Chart. Furthermore, observations are usually at 30' (9m), while it is the speed and direction of the wind near the ground which is critical in initiating sand movement.

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[1]For detailed botanical description of these plants, see Cleland (in Cleland and Howchin, 1931).

The nearest active parabolic dunes to the Newland Hill area occur on Sir Richard Peninsula and Younghusband Peninsula, either side of the Murray Mouth. The dunes here extend to heights in excess of 45' (15m) a.s.l. The configuration of the contours on the Encounter map sheet, 1:63360 series reveals the axial orientation of the dunes. This orientation has been confirmed by examining aerial photos, which show parabolic dunes trending at a bearing of 233°. Parabolic dunes on the south coast of Kangaroo Island display a similar orientation.

A wind vector diagram was constructed after individual vectors b were calculated from the formula of Landsberg (1956)

$$b = s \sum_{j=3}^{12} nj\ (Vj - Vt)^3$$

where s is a scaling factor of 10^{-3}, n is the frequency of the wind in a given direction with speed v in m.p.h., Vt is the speed of 10 m.p.h., the threshold speed for sand drifting and corresponds to Beaufort number 3, and j is the Beaufort speed number.

Wind records at 1500 hours were used to construct the wind resultant, because at that time, due to drying and heating, there is maximum potential for turbulent lifting and movement of sand (discussed in Campbell, 1968). The resultant calculated for winds at 1500 hours was from 234° demonstrating the close correspondence of the axial trends of the active parabolic dunes with the wind regime.

Two other wind resultants were calculated, one for all effective winds at both 0900 hours and 1500 hours combined, and the other, following the work of Jennings (1957) for all effective *onshore* winds recorded at 0900 hours and 1500 hours. The resultants were 245° and 210° respectively. Thus in this area the wind resultant which corresponds best with the active parabolic dunes is that calculated for all effective winds at 1500 hours.

The garlands of vegetated parabolic dunes at Newland Head show a significantly different axial orientation from that of the active dunes. The former trend at 281° being orientated at 48° west of the trend of the latter. A close examination of the aerial photographs of Younghusband Peninsula revealed the presence of small, vegetated parabolic dunes, with a different orientation to the active dunes of the area, but aligned parallel to the fixed parabolic dunes of Newland Head. Many parabolic dunes of the Murray Mallee also display an orientation similar to the vegetated parabolic dunes of the Encounter Bay area.

Effective wind resultants of the current wind regime trend along 234° at Victor Harbour, 250° at Tailem Bend, 246° at Berri and 273° at Waikerie. At all of these localities the axial trend of the fixed parabolic dunes is approximately west - east. Consequently it is not unreasonable to suggest that the fixed parabolic dunes of this area of South Australia were established when the wind system was located several degrees of latitude south of its present position.

This palaeometerological reconstruction could also account for more arid conditions during the formation of the parabolic dunes, which are now well fixed with vegetation, although in a coastal situation aridity is not a prerequisite for dune building.

The parabolic dunes of Newland Head rest on calcrete of presumed (?) Pleistocene age, and they are considered to be of Holocene age. Evidence of climatic change during the Holocene is discussed elsewhere in this thesis, and the parabolic dunes of Newland Head may be correlated with an arid phase of the Quaternary.

b) *Cliff-top dunes*

The vegetated dunes of Newland Head are not only parabolic dunes, but are also cliff-top dunes. Jennings (1967) suggests four alternative hypotheses to account for cliff-top dunes:

(i) Advance of dunes from an embayment or lagoon shore onto the outer coast.

(ii) Advance of dunes up a gentle bedrock slope, followed by coastal recession resulting in cliffs topped by dunes.

(iii) Rise in sea level to the summit of a pre-existing cliff; emplacement of dunes followed by a fall in sea level isolating the cliff-top dunes.

(iv) Fall of sea level facilitating the accumulation of dunes on the coastal plain to such an extent that the dunes overtop the pre-existing cliff. A subsequent rise in sea level results in coastal erosion returning the shoreline to the original cliff thereby isolating the cliff-top dunes.

The position of the shoreline has fluctuated during the Quaternary, at elevations up to 200' (60m). The cliff-top dunes reach up to 350' (105m) a.s.l. and might, therefore, be related to the higher sea stands of the Pleistocene. However, as the cliff-top dunes are of Holocene age, and the highest Holocene shoreline for which there is evidence only reaches 20' (6m) a.s.l., hypothesis (iii) can be discounted.

The amount of coastal recession in the resistant rocks of the Kanmantoo Group required for hypothesis (ii) is probably too great to be achieved in the time available, and the position of the shoreline during the Holocene has probably not changed very much.

Sea level stood as much as 36' (10.8m) below present sea level during the Holocene so that hypothesis (iv) is a possibility, but there is no other evidence to suggest that it is acceptable.

The axial orientation of the parabolic cliff-top dunes and their distribution suggest that Waitpinga Beach provided the sand source with the dunes migrating up a sand ramp to the summit of Newland Head. Thus, in this instance, hypothesis (i) is the most acceptable, accounting for all of the observed facts.

c) *Other dunes*

Younger, unvegetated dunes back parts of Waitpinga Beach at lower elevations than the vegetated parabolic dunes. At one site immediately west of Newland Head a narrow wedge of sand is migrating towards the summit of Newland Head under the influence of the present wind regime, and is parallel to the resultant of effective winds.

CHAPTER IV - LANDSURFACES AND DURICRUSTS

1. INTRODUCTION

The study area is not only polygenetic, having developed under the influence of a variety of climatic regimes, but as it exhibits evidence of at least two major erosion surfaces, is also multicyclic (see Figures 5 and 6).

The erosional origin of the two major landsurfaces is demonstrated by their truncation of contorted bedrock of varied resistance to erosion. Evidence of the erosion surfaces exists as dissected remnants of surfaces of low relief forming a series of roughly accordant spurs and ridges at high elevations in the present topography.

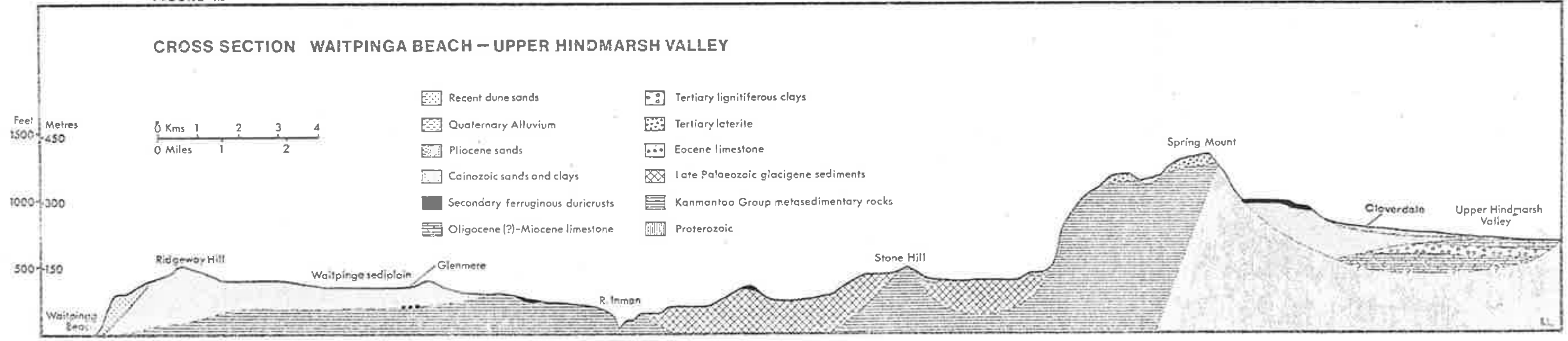
Aggradational surfaces occur in two main areas; in the Upper Hindmarsh Valley at an elevation of about 750' (225m) a.s.l., and in the Waitpinga area at an elevation of approximately 300' (90m) a.s.l. The relationships of the landsurfaces, their associated duricrusts and Tertiary limestones are shown in Figure 12.

2. THE SUMMIT SURFACE - THE SPRING MOUNT SURFACE

The name Spring Mount surface has been applied to the summit surface (Bourman, 1969) because of its extensive development in the Spring Mount area, 10 miles (16km) north-west of Victor Harbour township.As the highest, oldest and most extensive erosion surface, it is correlative with the Parawa high plain described by Brock (1964, 1971) as occurring on the spine of Fleurieu Peninsula southwest of Spring Mount.

The Spring Mount surface truncates steeply dipping Cambrian and Precambrian rocks. It characteristically occurs high in the landscape and is capped by a relict laterite profile. In the area investigated the major remnants of the surface surround Spring Mount 1373' (412m), Kerby Hill

FIGURE 12


CROSS SECTION WAITPINGA BEACH – UPPER HINDMARSH VALLEY
Recent dune sands
Quaternary Alluvium
Pliocene sands
Cainozoic sands and clays
Secondary ferruginous duricrusts
Oligocene (?)-Miocene limestone
Tertiary lignitiferous clays
Tertiary laterite
Eocene limestone
Late Palaeozoic glacigene sediments
Kanmantoo Group metasedimentary rocks
Proterozoic
0 Kms 1 2 3 4
0 Miles 1 2
Feet
Metres
1500 450
1000 300
500 150
Ridgeway Hill
Waitpinga sediplain
Glenmere
R. Inman
Stone Hill
Spring Mount
Cloverdale
Upper Hindmarsh Valley

937' (281m), Peeralilla Hill 950' (275m), Mount Desert 968' (291m), and Wilson Hill 767' (230m).

a) *Nature of the laterite on the Spring Mount surface*

The terminology and classification of weathering profiles is confused (see, for example, Paton and Williams, 1972). However, for the purposes of this study the term 'laterite' will be used to describe those weathering profiles which display a transition from an indurated iron rich zone, through a mottled weathered zone stained by iron oxides, to a weathered pallid zone, which rests on unweathered bedrock (Maignien, 1966).

The character of the indurated zone varies throughout the study area. Coarse, weakly magnetic, sub-spherical pisoliths overlie weathered zones at Wilson Hill. However, on Peeralilla Hill massive limonitic sandstone, and richly red-coloured pisoliths cemented by limonite-rich matrix form the indurated zone. Abundant cavities in the latter type give the rock a vesicular appearance (Heath, 1962). In many areas the indurated zone has been eroded and only a loose lag of limonite-rich boulders remains.

The greatest observed thickness of crust in the study area occurs on Peeralilla Hill where the indurated zone has been mined for road metal and for use as a flux. In all, some 12-14,000 tons of ore have been removed. The thickness of the indurated zone is very variable, but an open cut reveals a thickness of 8' (2.4m), shafts indicate a depth of at least 20' (6m), while estimates of the maximum thickness are as much as 30' (9m) (Heath, 1962). This approaches the thickness of crusts elsewhere in Australia, where they may exceed 40' (12m) (Dury, 1971). The iron-rich indurated capping on Peeralilla Hill, which covers an area approximately 700' (210m) by 220' (66m), is expressed topographically by a prominent rise on the summit of the hill.

Samples of the iron-rich indurated zone on Peeralilla Hill were chemically analysed when the economic significance of the deposit was being assessed (Whitten, 1962). The following is a partial analysis of the duricrust:

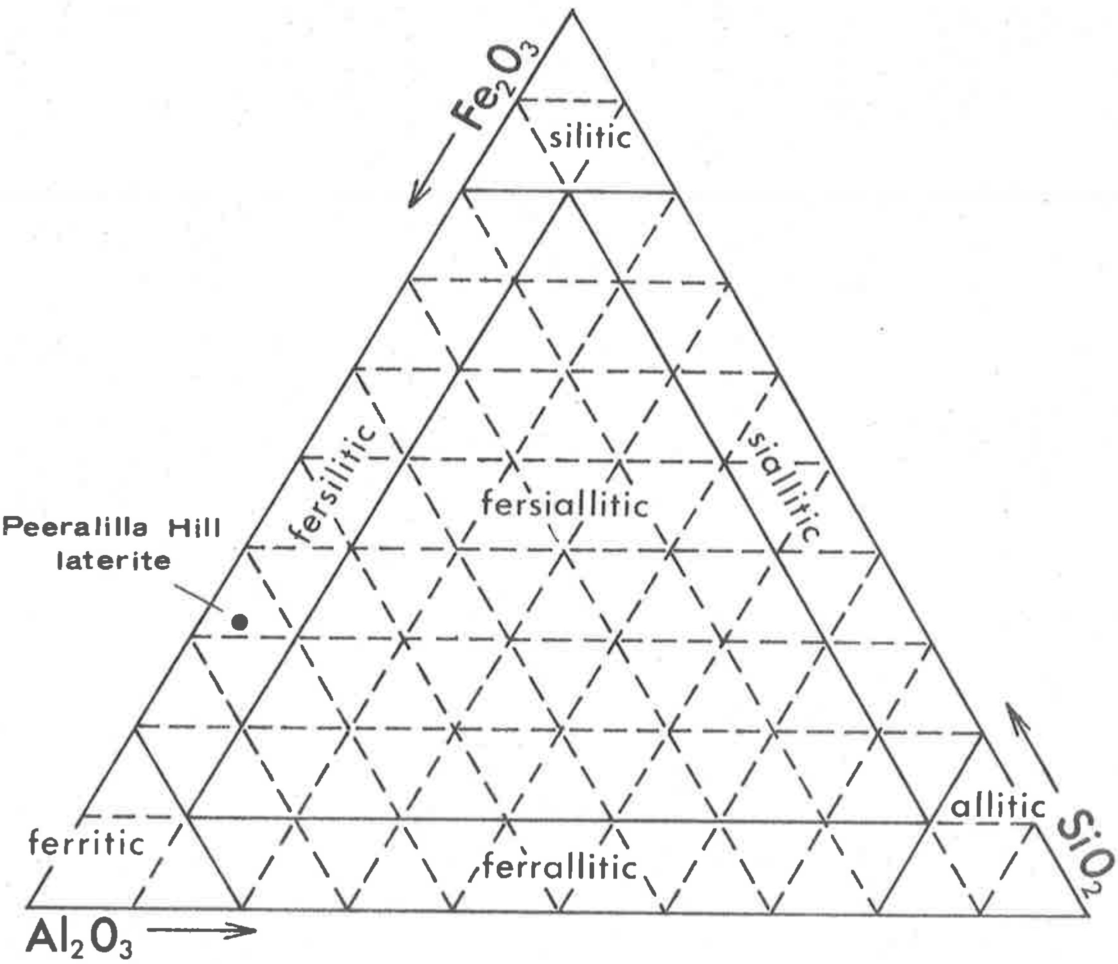
Total Fe (goethite, hematite)	39.35%
SiO_2	21.55%
Al_2O_3	2.70%

The percentages of the three major constituents of iron, silica and aluminium, normalised to 100% give values of 61.7%, 33.9% and 4.4%, respectively.

Dury (1969) derived a rational descriptive classification of 'duricrusts proper' completely free of genetic implications, by using the proportions of silica, aluminium and iron present in duricrusts. When plotted on a ternary diagram seven named types in the fersiallitic range were established. Thus on the second approximation of Dury's (1969) classification the duricrust of the Spring Mount plateau at Peeralilla Hill falls into the fersilitic crust range (Figure 13) in which the typical crystalline minerals are hematite and quartz. Although Dury's classification has the advantage of objectivity, the criteria do not take account of the mineralogical constitution of the duricrusts, as they are solely dependent on chemical composition.

The main exposures of the laterite profile occur in road cuttings on the plateau surface between Wilson Hill and Mount Desert and in a kaolin quarry north of Cut Hill at M.R. Milang (1:63,360 series) 665196. The weathered cut and fill structures near Mount Desert may be the result of the actions of the streams which eroded the original surface of low relief. These exposures display both mottled and pallid zones, and in one place (0.6 miles (1km) east of Wilson Hill) the contact between the pallid zone and the unweathered bedrock is visible. A depth of weathering of the order of 50' (15m) to 100' (30m) is

FIGURE 13



Ternary diagram of boundaries among the seven types of duricrust in the total fersiallitic range.

(Dury, 1969) A.L.

suggested by the exposures. In comparison, Brock (1964) proved a depth of deep weathering on the plateau surface in excess of 40' (12m) by augering. However, the most detailed account of the maximum known depth of lateritic weathering in the area comes from bore log information (S.A. Geol. Surv. - bore log records).

A bore collared on the plateau surface 1300' (390m) a.s.l., approximately 1.2 miles (2km) west of Spring Mount, penetrated a sequence, typical of a laterite profile (Table 1).

The profile in Table 1 appears to be an *in situ* laterite weathering profile as the bore is situated on the plateau summit and not in a valley where unconsolidated material could have accumulated. Moreover, the profile displays mottling and kaolinisation typical of laterite profiles, as well as the presence of fragments of weathered bedrock and the gradual transition from weathered to unweathered bedrock in the lower part of the bore log. Although no iron stone crust is recorded in the profile, weakly magnetic pisoliths occur at the surface.

An examination of the distribution of the deeply weathered laterite[2] profile of the study area reveals that it is restricted to the high plateau summits. The lowest observed occurrence of primary laterite is that on the McFarlane Hill - Wright Hill ridge at 400' (120m) a.s.l., but this area has probably suffered downfaulting on the margins of the Murray Basin (Thomson and Horwitz, 1962). Elsewhere the primary laterite falls within a range of approximately 670' (210m), between 1450' (435m) and 780' (234m) a.s.l.

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[2]This is the equivalent of the primary laterite developed by *in situ* weathering as described by Playford (1954) and Finkl (1971).

<u>TABLE 1</u>

0 - 6' (.15m)	Clayey brown and orange soil
6' (.15m) - 5' (1.5m)	Gritty limonitic red clay
5' (1.5m) - 15' (4.5m)	Mottled pink clay
15' (4.5m) - 45' (13.5m)	Micaceous yellowish-pink clay becoming reddish-pink
45' (13.5m) - 50' (15.0m)	Micaceous buff coloured clay
50' (15.0m) - 55' (16.5m)	Slightly gritty micaceous kaolinitic clay. Light cream to buff-coloured.
55' (16.5m) - 60' (18.0m)	Slightly gritty highly mottled red-white-yellow clay
60' (18.0m) - 65' (19.5m)	Clay with fragments of weathered ferruginised schist and crumbling quartz fragments, mottled pink
65' (19.5m) - 70' (21.0m)	Light pink coloured clay
70' (21.0m) - 75' (22.5m)	Gritty light pink coloured clay
75' (22.5m) - 90' (27.0m)	Gritty clay with mottled white-cream kaolinised patches
90' (27.0m) - 120' (36.0m)	Slightly gritty mottled cream clay
120' (36.0m) - 130' (3[illegible].0m)	Yellow gritty clay with schist fragments
130' (39.0m) - 140' (42.0m)	Medium grit quartz and yellow clay
140' (42.0m) - 170' (51.0m)	Yellow gritty kaolinised clay with schist fragments
170' (51.0m) - 175' (52.5m)	Grey gritty kaolinitic clay with schist fragments
175' (52.5m) - 195' (58.5m)	Grey clayey grit with schist and kaolinite
195' (58.5m) - 230' (69.0m)	Grey gritty clay. Schist bedrock

b) *Nature of the Spring Mount surface*

Brock (1971) suggested that the lateritic plateau remnants of Fleurieu Peninsula formerly constituted a large asymmetrical dome. The laterite remnants are not evenly distributed on either side of the central spine or drainage divide, but a greater number of them occur to the south of it. This distribution could result from the uneven dissection of the laterite surface following tilting of the surface to the southeast, with more laterite surviving on the gently sloping section of the tilt block. Another possibility is that conditions north of the drainage divide were not as suitable for lateritic weathering as conditions to the south.

Regional slopes of the reconstructed plateau surface are everywhere slight. From Spring Mount to Wilson Hill the slope is 0.8°, from Mount Desert to Wilson Hill 0.5°, and from Spring Mount to Peeralilla Hill 0.9°. Local, presumably valley side, slopes are steeper exceeding 2.5° in places, as on the flanks of Wilson Hill. Thus, despite the fact that relief amplitude of the plateau remnants exceeds 670' (210m), surface slopes are very gentle and drainage on the surface would have been extremely sluggish, providing the conditions envisaged by Woolnough (1927) for the formation of deep weathering profiles.

After considering the evolution of Fleurieu Peninsula in the light of several models of landscape development, Brock (1971) suggested that the summit surface of Fleurieu Peninsula could be regarded as a peneplain surface. Various features of old landscapes have been recognised by Mulcahy and Bettanay (1971) which might be used as criteria for the recognition of peneplain surfaces. These include:

(i) a low relief amplitude

(ii) grades of 1 foot (.3m) per mile (1.6km) of ancient river systems

(iii) lateritisation to depth of 150' (45m)

(iv) cloaking of divides by a mantle of lateritic 'sandplain' in excess of 20' (6m) thick

(v) thin alluvial and colluvial deposits less than 6.5' (2m) thick in valleys

(vi) limited present day erosional modification except in areas of instability.

The summit surface of Fleurieu Peninsula displays evidence of (i), (ii), (iii) and (vi). Much unconsolidated, highly siliceous sand occurs throughout Fleurieu Peninsula and it may have had its origin as a lateritic 'sandplain'. Thin alluvial and colluvial deposits occur in some areas, but it is difficult to determine if they are a recent phenomenon or whether they developed during the formation of the surface.

However, many of the above criteria also apply to land-surfaces which may have developed through pediplanation (Dury and Langford-Smith, 1964). Nothing in the morphology of the surface is critical in determining its genesis. As such it is probably best described simply as an erosion surface of low relief.

c) *Uplift of Spring Mount surface*

Noting that the lateritised erosion surface of the high plateau as mapped on the Milang map sheet, 1:63,360 series tilts away from the Willunga fault carrying weak dips to the east and southeast, Thomson and Horwitz (1961) suggested that the area may have behaved as a tilt block with the major movement taking place along the Willunga fault line. Here the total throw of the fault may be as much as 2000' (600m) (Thomson and Horwitz, 1961). However, the regional slopes on the remnants of the lateritic plateau are extremely slight, and thus they may reflect original drainage slopes and not tectonic tilting. Another possibility is that original drainage may have been to the north and was later reversed by tectonism, as tectonic tilting to the south and east does appear to have occurred since the Miocene. If the laterite of the Spring Mount surface is of Miocene or pre-Miocene age, which seems to be the case (see below), then unless post-Miocene tilting occurred parts of the laterite surface (e.g. Wilson Hill) would have been submerged by the Miocene seas which reached up to 800' (240m) a.s.l. As there is no evidence of the Miocene seas submerging parts of the plateau surface, the interpretation of post-Miocene tilting is favoured.

Campana, Wilson and Whittle (1953) proposed that the Tertiary orogeny was marked by 'tangential stresses acting upon a thick set of Proterozoic, Palaeozoic and Tertiary sediments' in which broad doming was followed by cracking, block faulting or thrusting according to the degree of plasticity of the formations involved.

In view of the lack of conclusive geological evidence for this theory, Brock (1964) favoured an isostatic uplift of Fleurieu Peninsula as a single tectonic unit, from the Eocene onwards. According to this interpretation, slopes on the high plateau surface would represent original drainage slopes.

d) *Age of the Spring Mount surface*

The high plateau surface is usually assigned a pre-Tertiary age because of the absence of Mesozoic sediments in the area. On Kangaroo Island Jurassic basalt apparently makesup part of the high plateau surface, indicating a post-Jurassic age for the surface. On both Fleurieu Peninsula and Kangaroo Island much erosion occurred during the Permian and in pre-Permian times. Consequently parts of the plateau surface may represent resurrected Permian erosion surfaces. In some areas glaciated bedrock surfaces and glacigene sediments occur only short distances below the high plateau surface, supporting this hypothesis.

In the Adelaide area on the Para fault block, an ancient land surface which appears to be the equivalent of the summit surface of the Mount Lofty Ranges, now dislocated by faulting, is being exhumed from beneath a cover of Early Tertiary sediments (Aitchison, et. al., 1954). If the Spring Mount surface and the exhumed surface of the Para block are correlative, then they are both of the same pre-Tertiary or Cretaceous age. A Cretaceous age for the summit surface is even more favoured in view of its possible truncation of Jurassic rocks on Kangaroo Island.

Provided that the high level erosion surface developed prior to the deposition of the Oligocene (?) - Miocene limestone in the Upper Hindmarsh Valley, then it predates the Mid-Tertiary. However, if the surface developed after the deposition of the limestone, through the process postulated by Kennedy (1962), whereby a surface of low relief might develop during uplift of the land mass, provided that denudation (total lowering of the land surface) outpaces erosion (vertical stream incision), then the surface post-dates the Middle Tertiary. This model is considered below during discussion of the age of the laterite crust which caps the surface. Although the age of a duricrust of an erosion surface does not necessarily indicate the age of the erosion surface, in the study area the distribution of duricrusts reveals something of the mode of evolution of the landsurfaces, which in turn throws light on their ages.

3. SURFACES DEVELOPED AFTER THE EROSION OF THE LATERITE WEATHERING PROFILE

The dismemberment of the laterite weathering profile resulted in the formation of minor surfaces below the level of the plateau, but high in the present relief.

Where the weathering profile has been incompletely eroded the resulting surface occurs on truncated laterite. This surface is the equivalent of part of the ridge and vale section of Brock (1964, 1971). However, Brock does not clearly distinguish between truncated laterite and etch surfaces. In this study the two are considered as separate units of the landscape. The etch surface (*Brown Hill etch surface*, Bourman, 1969) occurs where the overlying weathered lateritic profile has been completely eroded, leaving bedrock benches, which are roughly accordant with the weathering front.

Although both truncated laterite and etch surfaces are widespread throughout the study area, their relationships and positions in the landscape are best observed along spurs which extend from the Mount Desert area parallel to tributaries of the Waitpinga Creek (see Figure 6).

Both surfaces are diachronous and are still developing. Consequently neither surface is of any cyclic significance, except insofar as neither could develop until the laterite profile had formed, and was so disposed that dissection of it could occur. Certainly the development of these surfaces is not dependent upon a fixed regional base level of erosion.

The distribution of these two surfaces in the present landscape has been affected by the following:

(i) Initial irregularities in the Spring Mount surface resulting from structural influences and drainage slopes.

(ii) The depth of the lateritic weathering profile which affects the elevation of the weathering front, e.g. near Spring Mount where the weathering extends to 230' (69m) the etch surface stands approximately this distance below the summit surface, but on Brown Hill the depth of weathering is much less and there is only an elevational difference of about 40' (12m) between the summit and etch surfaces.

(iii) The degree of dissection of the laterite profile, which distinguishes the etch surface from the truncated laterite surface.

(iv) Faulting or tilting of the surfaces, e.g. the laterite surface and its associated etch surface has been offset by faulting on McFarlane Hill as mentioned above.

Consequently the etch and truncated laterite surfaces have considerable elevational ranges, although their inter-relationships and relation to the Spring Mount surface are clear. Nevertheless, recent soil cover and vegetation often obscure boundaries between the three, rendering detailed field mapping difficult.

Both surfaces are diachronous and have considerable age ranges. However, they both postdate the laterite, the age of which sets the lower age limit for the surfaces resulting from its erosion. Depending on the model of landscape development used in considering the mode of formation of the high plateau surface, the laterite could be as old as the Mesozoic or as young as the Pliocene (see below).

4. GREEN HILLS EROSION SURFACE

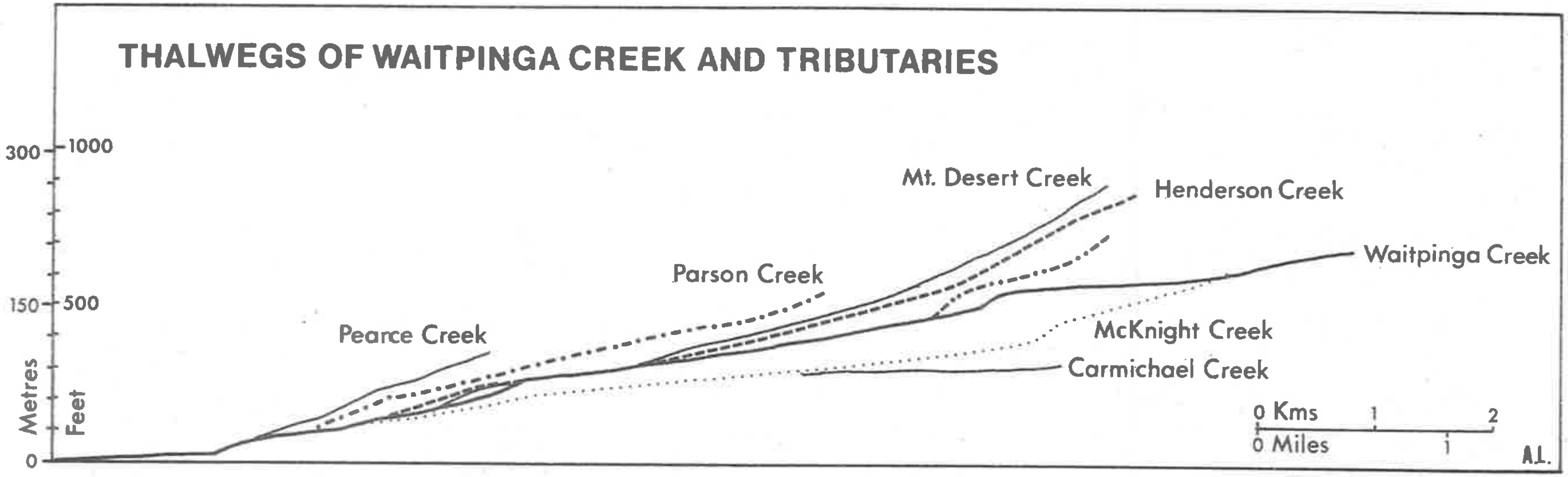
a) *Distribution*

A second extensive erosion surface occurs and is named the *Green Hills surface* (Bourman, 1969) because of its marked development near the Green Hills homestead 4 miles (6.4km) N.N.W. from Victor Harbour, where it forms the drainage divide between the Inman and Hindmarsh Rivers. Initially mapped in this area and either side of Back Valley Creek, this surface has now been recognised throughout large areas of Fleurieu Peninsula. It is best developed along the depression occupied by the Inman, Yankalilla and Bungala Rivers and their tributaries. The Green Hills surface stands below the older, Spring Mount surface and its related etch and truncated surfaces. It varies in elevation from approximately 650' (195m) inland to 200' (60m) near the coast. However, most remnants of this erosion surface stand between 300' (90m) and 500' (150m) a.s.l.

b) *Base level during the erosion of the Green Hills surface*

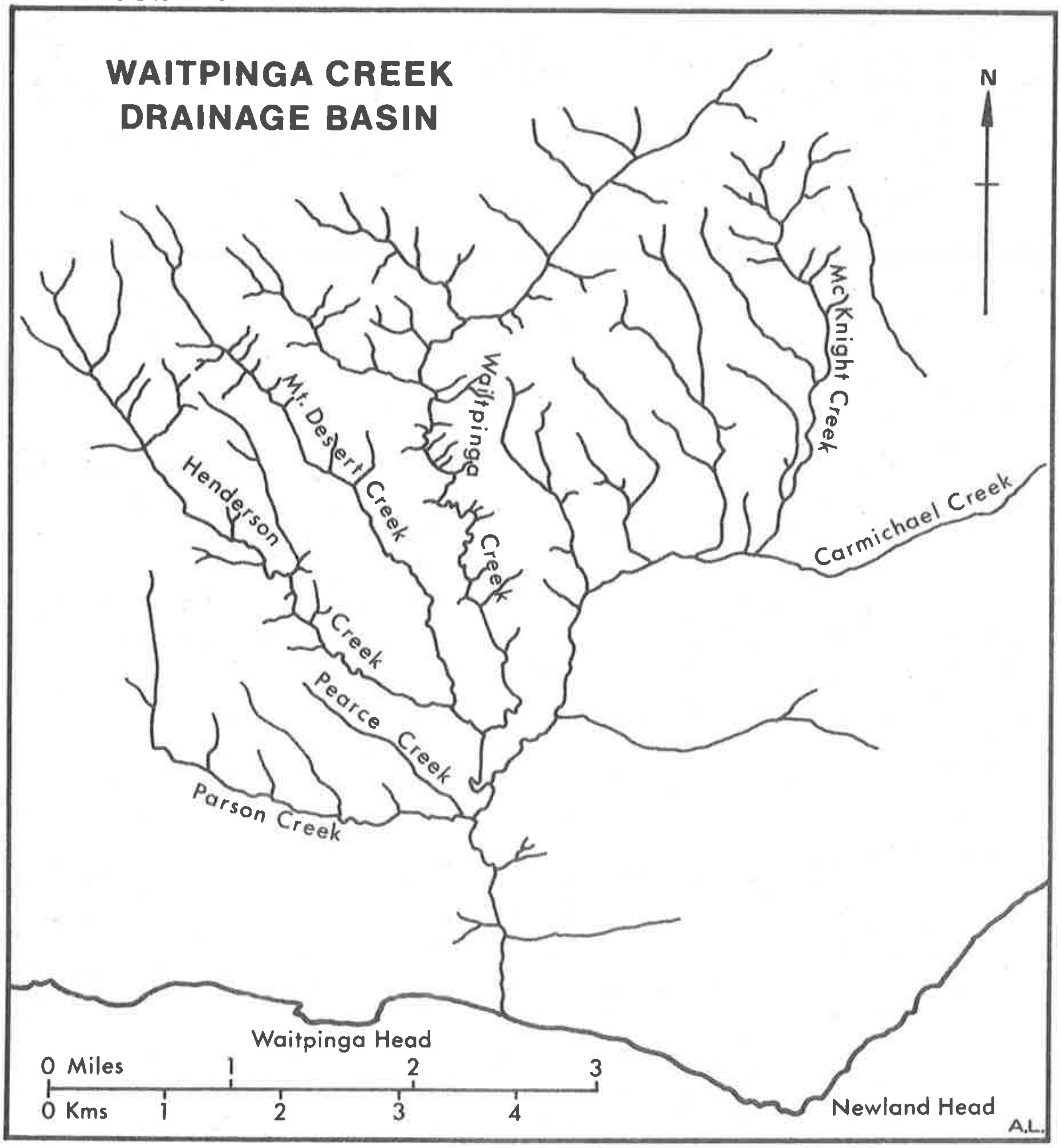
Stream thalwegs of the main channel of Waitpinga Creek and selected tributaries constructed from the 1:50000 Encounter and Torrensvale sheets at a contour interval of 50' (15m) (Figure 14) throw some light on the base level during the erosion of the Green Hills surface. To simplify the identification of the tributaries of Waitpinga Creek they have been named after the owners of the properties through which they flow (Figure 15).

FIGURE 14



THALWEGS OF WAITPINGA CREEK AND TRIBUTARIES
300
1000
150
500
0
Metres
Feet
Mt. Desert Creek
Henderson Creek
Waitpinga Creek
Parson Creek
Pearce Creek
McKnight Creek
Carmichael Creek
0 Kms
1
2
0 Miles
1
A.L.

FIGURE 15



WAITPINGA CREEK
DRAINAGE BASIN
N
Mc Knight Creek
Waitpinga Creek
Mt. Desert Creek
Henderson Creek
Carmichael Creek
Pearce Creek
Parson Creek
Waitpinga Head
Newland Head
0 Miles 1 2 3
0 Kms 1 2 3 4
A.L.

(i) *Knickpoints*[1].

Causes of convex breaks in a stream profile may include the effects of rock bars, the effects of tributary streams, intermittent shoreline erosion, tectonic or eustatic changes in base level, and changes in bedload/ discharge relationships, which would include the effects of climatic change.

A knickpoint occurs in the main channel at approximately 200' (60m) to 250' (75m) a.s.l. As the metasedimentary rocks of the Kanmantoo Group display varying resistance to erosion the knickpoint might be structural in origin. However, knickpoints occur at similar elevations in Parson, Pearce, Mount Desert and Henderson Creeks, all of which flow through rocks of the Kanmantoo Group. In view of the contorted nature of the basement rocks it would be extremely fortuitous for the accordant knickpoints in all of the channels to be of structural origin. The influence of tributary streams can be discounted as knickpoints occur in channels which have no significant tributaries and it is unlikely that similar changes in bedload/discharge relationships would occur in all channels to cause accordant knickpoints. The knickpoints are situated well inland from the coast, at about 200' (60m) a.s.l. so that the effect of steepening of gradients by coastal erosion is not possible as a cause of the knickpoints. The most likely cause appears to be rejuvenation following the uplift of the land or a falling of sea level. Further evidence for this hypothesis is considered below.

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[1]The term 'knickpoint' is used here to describe a break in a stream profile. The term 'knickpoint of rejuvenation' is used when it is possible to correlate a knickpoint with a former base level of erosion.

(ii) *Former channel deposits*

River gravel deposits at varying elevations displaying cross bedding and imbricate structures parallel the present Waitpinga Creek and its tributaries.

At Encounter 1:50000 map series M.R. 536025 river gravels stand at 240' (72m) a.s.l. and only 15' (4.5m) above the present stream channel dipping at 25° to 30° and striking at 155° (Plate 11). Downstream at Encounter M.R. 526018 gravels are situated 200' (60m) a.s.l. and almost 50' (15m) above the present channel and are similarly disposed. Other correlative river deposits at Torrensvale 1:50000 map series M.R. 461002 stand 200' (60m) a.s.l. and 175' (52.5m) above the channel of the Waitpinga Creek. Stranded river gravels also occur at Torrensvale M.R. 468007 at 150' (45m) a.s.l. At Torrensvale M.R. 465035 a prominent knoll 475' (142.5m) a.s.l. and 125' (37.5m) above the channel of Waitpinga Creek carries extensive deposits of water-rounded quartz pebbles (see Figure 6).

The widespread evidence of former river action on areas high above the present channels attests to the role played by the ancestral Waitpinga Creek and its tributaries in shaping the landsurface, below which the drainage system is now incised.

The distribution of the gravels and the presence of former broad valleys support the interpretation that the knickpoints at approximately 200' (60m) have resulted from rejuvenation following a relative fall in base level. The stranded channel deposits are at the same general elevation as the Green Hills surface and it is suggested that base level during the erosion of the Green Hills surface was some 200' (60m) a.s.l.

(iii) *Waitpinga Gorge*

Nearer the coast the former channel deposits stand progressively higher above the present stream channel, and as Waitpinga Creek nears the coast it passes through a

Plate 11. Ferruginised riverine deposits 0.3 miles (0.5km) south of Depledge Bridge, Waitpinga.

steep-sided gorge up to 200' (60m) deep. The gorge was apparently cut subsequent to the rejuvenation of the land mass, following which, knickpoints progressed headward along the main stream and tributaries.

The Inman River passes through a similar gorge about 1.5 miles (2.4km) from its mouth. The Inman Gorge was considered to be the result of superposition of drainage from soft Late Palaeozoic glacigene sediments onto underlying metasedimentary basement rocks. Various modes of origin for the gorge were considered, but superposition was favoured because of the proximity of Late Palaeozoic deposits at elevations in excess of the highest points of the gorge (Bourman, 1969). The Waitpinga Gorge might also be superposed. Late Palaeozoic glacigene deposits crop out southwest of Waitpinga Hill 1.5 miles (2.4km) from the gorge, but at a lower elevation than the gorge. The former extent of the Late Palaeozoic glacigene deposits in this area is impossible to assess.

However, the occurrence of stranded river gravels on a slightly weathered land surface truncating basement rocks suggests that the Waitpinga Gorge developed by inheritance rather than by superposition. Graded to a base level 200' (60m) a.s.l., the stream system eroded a surface into which it later incised.

(iv) *Correlation with previous work*

Brock (1964, 1971) recorded evidence of a shoreline 193' (58m) to 213' (64m) a.s.l. and attributed its present position to Tertiary tectonism. Further evidence for this former shoreline has been presented above. Later in this chapter the Green Hills surface grading to a 200' (60m) shoreline is suggested to be of Pliocene age, which further corroborates Brock's conclusion.

c) *Nature of the Green Hills surface*

In most areas the Green Hills surface truncates Late Palaeozoic glacigene sediments, which possess little resistance to erosion. Occasionally the surface is underlain by metasedimentary rocks of the Kanmantoo Group. However, the interpretation of these inliers of older, more resistant rocks as portions of the Green Hills surface must be approached with caution, for they may represent parts of a recently exhumed Late Palaeozoic glaciated landscape. This is certainly the case where the basement rocks crop out at the watershed between the Inman and Bungala Rivers, and east of the Green Hills Homestead, where striated bedrock surfaces have been noted. In some areas, basement rock outcrops (e.g. Crozier Hill) stand above the general surrounding level of the Green Hills surface. However, the basement rocks elsewhere have been bevelled forming accordant levels with nearby glacigene sediments.

The slopes on the remnants of the Green Hills surface indicate that drainage during the erosion of this surface broadly paralleled the present stream system. However, spur crest slopes and the barbed junction of Boundy River with the Inman River suggest that the Boundy River may have originally drained the surface to the west.

d) *Duricrusts of the Green Hills surface*

In addition to its distribution and relation to the other erosion surfaces, the Green Hills surface is distinguished by the sporadic occurrences of ferruginous duricrust[1], which, unlike the duricrust of the Spring Mount surface, is not underlain by a deep weathering profile.

Much of the ferricrete consists of iron-stained and cemented, variably sized, subrounded to rounded pebbles of quartz and other rocks. However, other parts of the ferricrete consist of iron-cemented, rounded quartz sands, some of which display bedding structures. The source of these cemented sands may have been the grey-white sandy

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[1]Sometimes called secondary, detrital or low level laterite. In this thesis it is called ferricrete.

eluviated A horizon, which characterises the typical laterite profile (Stephens, 1946). Unconsolidated, white, siliceous sands abound on the hills and ridges of the Green Hills surface, and where vegetation has been cleared these sands are very mobile during summer conditions. Derivation of these sands by the reworking of fluvioglacial sediments is possible, but the source favoured by the writer is from the leaching of sandy sediments under present conditions, or during Cainozoic lateritic weathering as recent or relict podsolic soils, often with associated ferriginous pisoliths, are widespread throughout the region.

The most extensive occurrences of ferricrete on the Green Hills surface are in three areas east of Crozier Hill. At these sites the ferricrete has been quarried for road metal, revealing a crustal thickness in excess of 3' (0.9m). The ferricrete here overlies pebbly glacigene sediments, indicating that it may be a lateritised deposit, especially as it contains exotic pebbles. While the pebbles may have been rounded in subglacial or englacial streams during the Late Palaeozoic, microscopic examination revealed that the sand grains of the duricrust are subrounded in contrast to the angular to subangular grains of the fluvioglacial sediments. Furthermore, the pebbles are concentrated at the surface, suggesting a channel bottom origin. Through relief inversion the pebbles now occur on ridges between present drainage lines illustrating that the former channels broadly paralleled the present streams. Other ferruginous conglomerate deposits directly overlie Kanmantoo Group bedrock on Porters Hill and in several places in the Waitpinga area, indicating an origin other than fluvioglacial.

A zone of shallow weathering occurs below some of the ferricrete remnants (e.g. Porters Hill, east of Crozier Hill and at Waitpinga near the turn-off to Waitpinga Beach). At the last mentioned place a conglomerate crust, nearly 3' (0.9m) thick overlies at least 5' (1.5m) of weathered bedrock. Parts of the Green Hills surface are not characterised by ferricrete but carry a thin scatter of pisoliths, which are underlain by up to 3' (0.9m) of red clay soil, 5' (1.5m) of weathered and mottled grey clay resting on bedrock. A prominent surface correlative with the Green Hills surface occurs on the interfluve area between Waitpinga Creek and the Coolawang Creek and is capped by the profile described above. At one section of the cliffs, which form the coast between Newland Head and King Point, weakly kaolinised bedrock associated with ferruginous pisoliths occurs at an elevation of approximately 200' (60m) a.s.l.

e) *Origin of the Green Hills surface and its associated ferricrete*

The evidence of shallow weathering on the Green Hills surface lends credence to the view that it was affected by a minor phase of lateritisation during and/or after its erosion. Invariably the secondary duricrusts occur in the bottoms of former broad valleys. Thus, they could have formed here from iron derived from the laterite of the high plateau surface, and from the higher portions of the Green Hills surface where shallow weathering took place.

On the grounds that the Green Hills surface developed essentially on easily eroded glacigene sediments, while the Spring Mount surface was eroded across resistant metamorphic rocks, it could be argued that differential erosion accounts for their differences in elevation. Thus the two surfaces would have developed contemporaneously. In parts, however, the Green Hills surface is underlain by resistant metamorphic rocks, which in turn carry remnants of ancient river gravels, similar in elevation to those on the softer sediments. Moreover, it has been demonstrated previously (Bourman, 1969) that the Green Hills surface is a distinct topographic unit, separated from the Spring Mount plateau by sharp breaks in slope, in places cut in bedrock. Consequently, the Green Hills surface is almost certainly related to a later erosional phase.

Because the Oligocene(?)- Miocene fossiliferous limestone of the Upper Hindmarsh Valley is situated well above the general level of the Green Hills surface it is not unreasonable to assume that the erosion of the surface postdates the deposition of the limestone and may therefore be ascribed to the Plio-Pleistocene.

Alternatively the erosion of the Green Hills surface may have occurred prior to the deposition of the limestone, at the time when Late Palaeozoic glacial valleys were being exhumed before the Middle Tertiary transgression. The base of the limestone lies at about 300' (150m) a.s.l. (Campana, Wilson, and Whittle, 1953, Plate X), corresponding with the general level of the Green Hills surface. However, the occurrence of more than 320' (106m) of Oligocene(?)-Miocene sediments in protected situations in the Myponga and Upper Hindmarsh Valley areas suggests a long phase of marine deposition. Because of this it may be that the present area of the Green Hills surface, in parts at least, was covered with Oligocene(?)-Miocene limestone subsequently removed by erosion. Thus parts of the Green Hills surface may be remnants of a resurrected pre-Oligocene surface.

On some of the higher parts of the Green Hills surface, erratics, associated with the underlying glacigene sediments, display conchoidal impact fractures considered by some workers (e.g. see Klein, 1963) to indicate high energy conditions on a shoreline. If the marks on the boulders are the result of marine activity, then the Green Hills surface may be partly the result of marine erosion. However, comparable surface markings have been observed on pebbles in stream beds (Conybeare and Crook, 1968, p.18), so that not too much significance should be attached to the presence of the boulders.

In conclusion, the lack of Oligocene(?)-Miocene deposits on the surface, together with the occurrence of stream deposited ferruginous gravels, which could not have survived a major marine incursion, suggest that the Green Hills surface was developed chiefly through stream activity after the Oligocene(?)-Miocene transgression. Nevertheless, as demonstrated above, its origin has probably been quite complex: Pliocene stream action may have modified a resurrected pre-Oligocene surface, which may have been partly cut by marine processes.

5. SURFACES CHIEFLY OF DEPOSITIONAL ORIGIN

While most major features of the landsurfaces of the study area can be interpreted in terms of erosion since and during the Mesozoic, this cannot apply for the Upper Hindmarsh Valley and the eastern portion of the Waitpinga drainage basin. Here sedimentation has played an important role in the evolution of the landscape.

a) *Waitpinga drainage basin*

The unconsolidated sands and clays of the eastern side of the Waitpinga drainage basin, including Newland Hill and Ridgeway Hill, were mapped by Crawford and Thomson (1959) as Permian glacigene sediments. Granted that this interpretation is correct, then logically the present morphology of the drainage basin should be considered primarily the result of continuous or intermittent erosion since the Permian.

However, it has been demonstrated that part of the Waitpinga drainage basin is underlain, at a depth of 120' (36m) and an elevation of 200' (60m) a.s.l., by Eocene fossiliferous limestone (Bourman and Lindsay, 1973). Consequently, many of the sediments forming the Waitpinga area are post-Eocene in age (see Figure 4). Thus the present morphology of the region is not simply the result of erosion since the Permian.

The thickness of the Eocene limestone intersected in a bore at 'Glenmere' was only 8' (2.4m). There is no indication of its former total thickness, and the absolute height above sea level reached by the Eocene seas. There is no record of Eocene limestone underlying the Oligocene(?)-Miocene limestone of the Upper Hindmarsh Valley, the base of which stands about 330' (99m) a.s.l. Thus the Eocene transgression was probably limited to the littoral areas and to the bedrock depression which underlies the Waitpinga drainage basin (see Figure 12).

(i) *Origin of the land-surface of the Waitpinga drainage basin*

Although it has been shown above that it would be incorrect to interpret the evolution of the Waitpinga drainage basin only in terms of erosion since the Permian, it would be equally erroneous to consider that its morphology is due to continuous deposition since the Eocene, for the Eocene marine sediments may well have been succeeded by others during the Oligocene and Miocene, which subsequently have been eroded.

Lack of detail in borelog records does not assist in the elucidation of this problem. It is possible that the two highest points in the relief (Newland Hill and Ridgeway Hill) are composed of Late Palaeozoic glacigene sediments, and stood above the level of the Eocene transgression. However, the proximity of Newland Hill to the 'Glenmere' boresite suggests that the sediments constituting Newland Hill overlie the Eocene limestone. It is highly likely that the Eocene seas entered the area via the gap in the basement rocks west of Newland Head and now occupied by Ridgeway Hill (see Figure 4). Thus these two prominent hills are almost certainly of Cainozoic age.

Two Bores sunk in 1966[1] to depths of 260' (78m) and 175' (52.5m) on the western flank of Ridgeway Hill encountered only sand, clay and limestone. The deeper bore was collared at approximately 430' (135m) a.s.l. and passed through the following sequence:

0 - 18' (5.4m)	white sand
18' (5.4m) - 100' (30.0m)	yellow sand and clay
100' (30.0m) - 198' (59.4m)	fine yellow sand
198' (59.4m) - 260' (78.0m)	limestone with pockets of sand

[1]Bore logs obtained from Mr. A. Henderson, Waitpinga.

No sediments greater than sand size were noted in the bore log, as might be expected if the sediments are glacigene. The interpretation of the limestone mentioned near the base of the bore is problematic. It might be related to the Pleistocene littoral deposits, which presently crop out near the coast, or be correlated with the Eocene limestone encountered in the 'Glenmere' bore. The limestone underlying Ridgeway Hill occurs at a comparable elevation to the Eocene limestone at 'Glenmere'. On either count the sediments forming Ridgeway Hill are neither of glacigene origin, nor of Permian age.

The second bore on Ridgeway Hill collared at about 225' (67.5m) a.s.l. intersected the following sequence:

0 - 2' (.6m)	white sand
2' (.6m) - 16' (4.8m)	sandy clay
16' (4.8m) - 60' (18.0m)	hard and soft limestone
60' (18.0m) - 105' (31.5m)	yellow sand
105' (31.5m) - 164' (49.2m)	soft grey schist with hard bands
164' (49.2m) - 175' (52.5m)	hard black to grey schist

In this case the bore is situated closer to outcrops of the littoral Quaternary calcrete, and the limestone referred to above is almost certainly related to this.

Crawford and Thomson (1959) mapped calcrete encircling Ridgeway Hill and capping duneforms northeast of it. This interpretation is incorrect. In one or two places blocky calcrete fragments lie scattered at the surface, but they are not related to *in situ* calcareous sediments as they were transported to these places for agricultural purposes (Madigan, 1925; Mr. A. Henderson, Waitpinga, pers. comm.). Calcrete only occurs on the southern and eastern sides of Ridgeway Hill. (See section on Geology and Figure 4).

The low rounded rises between Ridgeway Hill and Newland Hill are also formed of sand, for a bore in this area penetrated over 100' (30m) of white sand. However, glacigene or reworked glacigene sediments may occur at depth as an isolated boulder was struck during boring operations (Mr. V. Dennis, pers. comm.). Some of the rises display a dune-like morphology, the longitudinal trend of which is southeast-northwest (Plate 12). On the basis of the orientation of these dunes, their lack of sharp morphology, and the nature and thickness of the vegetation where uncleared, they are older than the parabolic dunes of Newland Head. Where cleared, some of the fixed dunes have become partly reactivated.

At least three pronounced depressions occur in the dune field, the deepest being approximately 50' (5m) deep and 350' (105m) in diameter. These depressions might be the result of deflation, solution, or coalescing dunes. Clays leached from the sands have accumulated in the bottoms of the depressions where dams have been located.

In the area surrounding the 'Warradale' Homestead, bores and dams have revealed that basement rocks are generally close to the surface. The micaceous clays which occur here, and which display excellent gilgai forms, have almost certainly derived from *in situ* weathering of the Kanmantoo Group metasedimentary basement rocks, and are not Late Palaeozoic glacigene sediments.

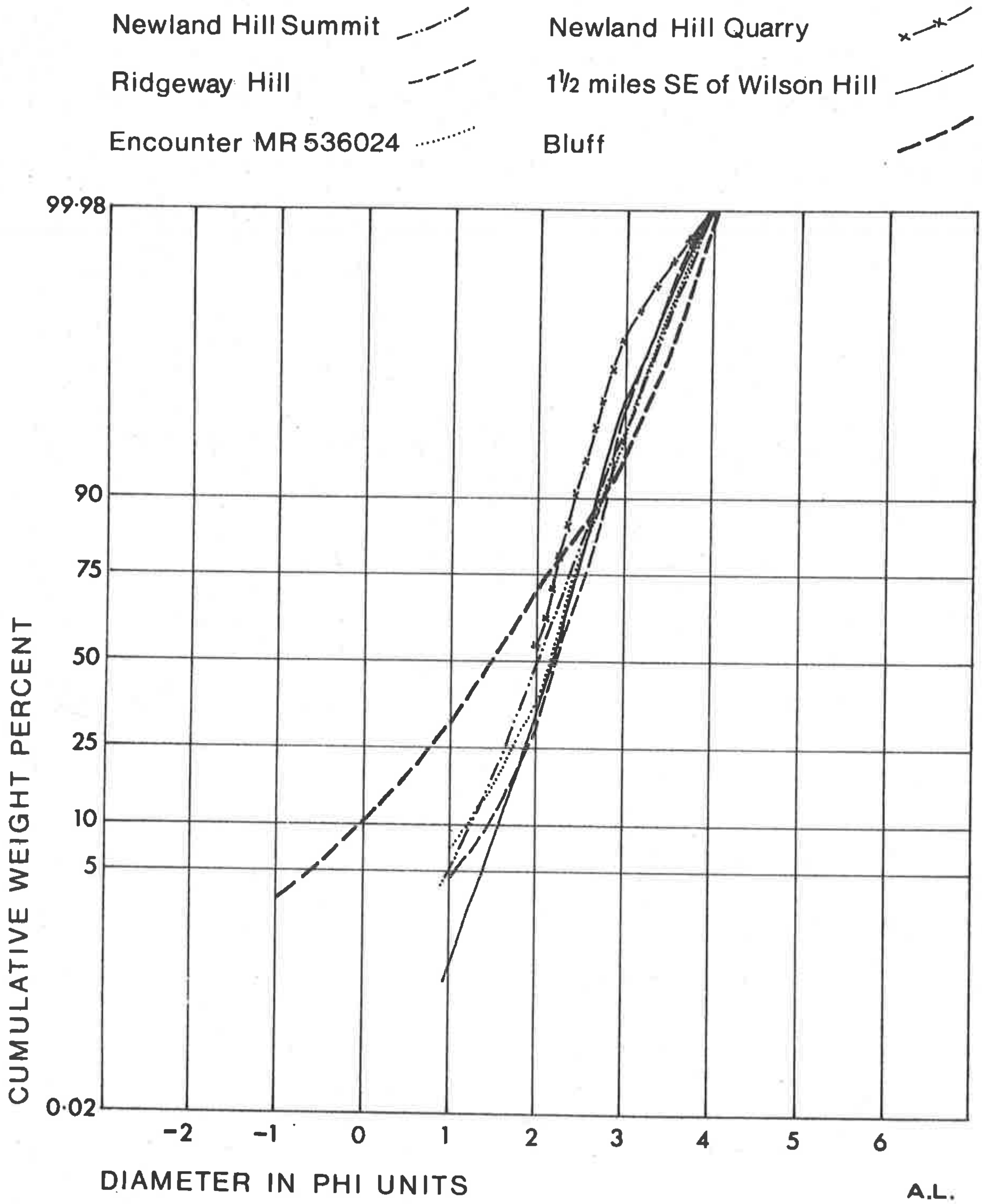
This area between Ridgeway Hill and Newland Hill was described, erroneously in part, by Madigan (1925) as "an undulating plateau covered with glacial sands and beds of travertine on the surface used for limeburning. This area is not dissected at all, but is remarkably level, an old glacial platform where sands have absorbed the precipitation and prevented the formation of streams" (p.210).

(ii) *Mechanical analysis of sediments*

However, as shown above on stratigraphic grounds the sands are of Cainozoic age, and not Late Palaeozoic as would be the case if the sands were of glacial origin. That the sands are not glacigene sediments has been strongly suggested by mechanical analysis. Samples were collected from five locations on and about Ridgeway and Newland Hills.

FIGURE 16

MECHANICAL ANALYSIS OF SELECTED SEDIMENTS



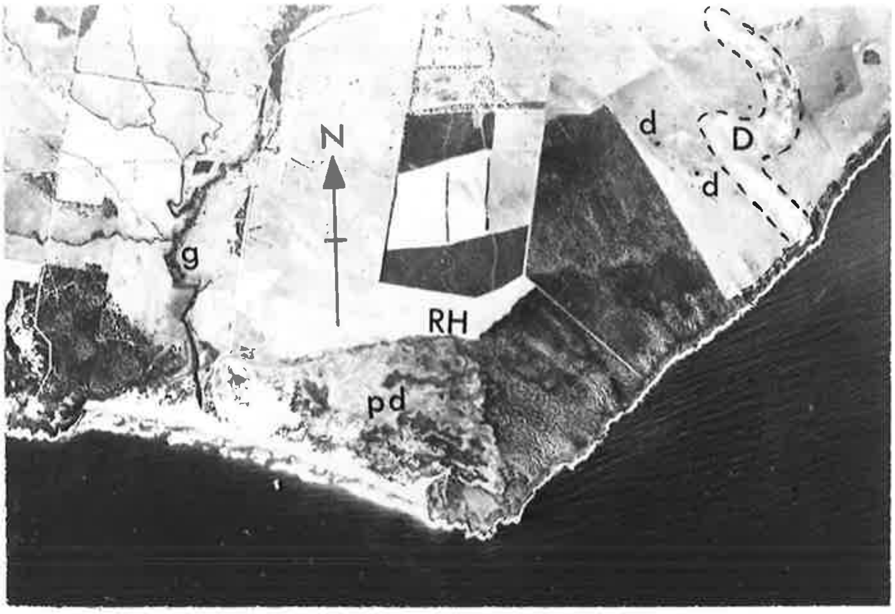


Plate 12. Field of fossil sand dunes (D) with associated depressions (d), northeast of Ridgeway Hill (RH). The area enclosed by the dashed line is mapped on the Encounter map sheet, 1:63360 series as calcrete, but it is occupied by deep, highly siliceous sands. Note the parabolic dunes (pd) south of Ridgeway Hill, and the Waitpinga Gorge (g) with ingrown meanders. (Reproduction by permission of the S.A. Lands Dept.).

Plate 13. Portion of the Waitpinga sediplain showing gilgai depressions filled with rain water. The higher ground on the horizon is formed of aeolian sands.

Approximately 50grm of each sample were analysed. Initially the clay and silt fractions were decanted during washing of the sediment, for it seemed highly likely that these fractions were the result of weathering, and therefore not relevant in considering the original nature of the sediment.

The sample was then passed through a nest of sieves of 8, 16, 30, 60, 120 and 240 British Standard Sieve sizes. Cumulative weight percents of these fractions were then calculated and plotted on graphs. From the graphs medians were noted and measures of degrees of sorting were calculated using the formula

$$\frac{(\phi\ 84 - \phi\ 16)}{2}$$

and were classified according to a verbal classification scale (Folk, 1968, p.46).

The results of the mechanical analyses are as shown in Table 2 and Figure 16.

It is considered that the sample from Rosetta Head is a fluvioglacial sediment. All other samples, except that from the Newland Hill quarry have a fine sand median, and all other samples are well sorted or moderately well sorted. Thus they contrast with suspected glacigene sediments.

Microscopically, with regard to sphericity and roundness, all samples bear similarities. Superimposed cumulative weight percent graphs of all samples, plotted against grain diameter in phi units coincide closely between 2.0 ϕ and 4.0 ϕ but at 2.3 ϕ the sample from Rosetta Head diverges markedly from the others (Figure 16). The difference is more marked than is apparent in Figure 16 as pebbles were removed prior to the analysis.

Interpretations of these results is suggested as follows: (1) The first five samples, by comparison with a fluvioglacial sediment, are not glacigene, but on the basis of their sorting and frosting appear to be aeolian sands. (2) Similarities between the first five sediments and the sixth with regard to sphericity, roundness and size ranges

Table 2

Location 1. Ridgeway Hill summit (depth 4m)

Initial silt and clay fraction of sample 39.9%

Individual percentages of remainder

0.0 ø	Very coarse sand	0%
1.0 ø	Coarse sand	4.21%
2.0 ø	Medium sand	21.51%
3.0 ø	Fine sand	71.72%
4.0 ø	Very fine sand	2.53%

Median = 2.25 ø Falls in range of fine sand

Sorting = 0.5 (well sorted)

On comparison with the visual sphericity and roundness scale listed in Folk (1968) the grains in the sample were of medium sphericity, and subangular to subrounded in shape.

Location 2. Dam at base of Ridgeway Hill

Initial silt and clay content 49.6%

Individual percentages of remainder

0.0 ø	Very coarse sand	0.0%
1.0 ø	Coarse sand	6.9%
2.0 ø	Medium sand	28.2%
3.0 ø	Fine sand	60.9%
4.0 ø	Very fine sand	3.98%

Median 2.2 ø (Fine sand)

Sorting 0.6 (moderately well sorted)

Medium sphericity. Subangular to subrounded

Location 3. Summit of Newland Hill (Depth 1.5m)

Initial silt and clay content 40.2%

Individual percentages of remainder

0.0 ø	Very coarse sand	0.0%
1.0 ø	Coarse sand	4.5%
2.0 ø	Medium sand	42.79%
3.0 ø	Fine sand	49.54%
4.0 ø	Very fine sand	3.15%

Median 2.05 ø (fine sand)

Sorting 0.55 (well sorted)

Median sphericity. Subangular to subrounded

Table 2. (continued)

Location 4. Quarry at base of Newland Hill

Initial silt and clay content 14.1%

Individual percentages of remainder

0.0 ø	Very coarse sand	0.0 %
1.0 ø	Coarse sand	0.0 %
2.0 ø	Medium sand	54.5 %
3.0 ø	Fine sand	45.02 %
4.0 ø	Very fine sand	0.47 %

Median 1.90 ø (Medium sand)

Sorting 0.35 (well sorted)

Medium sphericity. Subrounded to subangular, Includes some very well rounded grains.

Location 5. Road cutting between Newland Hill and Wilson Hill

Initial silt and clay content 36.1%

Individual percentages of remainder

0.0 ø	Very coarse sand	0.0 %
1.0 ø	Coarse sand	0.67 %
2.0 ø	Medium sand	31.54 %
3.0 ø	Fine sand	65.67 %
4.0 ø	Very fine sand	2.01 %

Median 2.2 ø (fine sand)

Sorting 0.4 (well sorted)

Medium sphericity. Subangular to subrounded.

The results from the above five samples differ considerably from that obtained from an analysis of sediments collected from the saddle of Rosetta Head at a depth of 6m. The sample contained exotic and striated pebbles which were removed from the sample, the silts and clays were decanted, and the remaining sediments were sieved.

Table 2. (continued)

Location 6. Saddle of Rosetta Head

Initial silt and clay content 9.2%

Individual percentages of remainder

-1.0 ø	Granules	3.27 %
0.0 ø	Very coarse sand	6.80 %
1.0 ø	Coarse sand	21.91 %
2.0 ø	Medium sand	42.31 %
3.0 ø	Fine sand	19.39 %
4.0 ø	Very fine sand	6.29 %

Median 1.45 (Medium sand)

Sorting 1.05 (Poorly sorted)

in the top 25% suggest that the aeolian sands may have derived from glacigene sediments. It has been demonstrated that these sands are of probable Cainozoic age. However, it is very difficult to determine whether they belong to the Tertiary or to the Quaternary. Borelog evidence suggests that either could be the case. However, in view of the ferruginisation of these sediments a Pliocene age in favoured for them. (See section below on the ages of the duricrusts).

(iii) *The Waitpinga Sediplain*

Between the 'Glenmere' and 'Santa Cruz' Homesteads in the Waitpinga Creek drainage basin, a near level surface trending northeast - southwest and here named the Waitpinga sediplain occurs. It covers an area of approximately 3 square miles (7.7 km^2). Between the two homesteads mentioned above, in a distance of 2 miles (3.2 km) the surface drops only 63' (18.9m), a slope of 0.7° to the southwest.

The sediplain is little dissected, and appears to represent an almost completely unmodified sedimentary surface. It is distinctive by virtue of its low angle slopes and calcareous surface clays, which are exposed in numerous dam excavations. The surface of the sediplain is not characterised by extensive ferruginisation, as is the great part of the drainage basin. The sediplain surface appears to postdate the phase of ferruginisation, as near the margins of the sediplain ferruginous pisoliths were found incorporated in the calcareous material of the sediplain. Borelog evidence further supports this interpretation, for in places the sediplain is underlain by thick ironstone crusts apparently related to those which crop out in the bed of McKnight Creek, where they are overlain by Quaternary alluvium. The near surface deposits of the sediplain consist of clays and sands, but between 110' (33m) and 130' (46m) fossiliferous limestone, gravels and poorly sorted angular sands and pebbles may occur. The last mentioned sediments may be glacigene, or derived from glacigene sediments.

The Waitpinga sediplain has not developed by continuous sedimentation since the Late Palaeozoic. It has undergone phases of erosion and deposition, but the present surface of this high level plain appears to be the result of sedimentation, as material has been washed from the higher surrounding country. Throughout much of the Waitpinga sediplain gilgai occur, which are particularly noticeable during winter when they fill with water (Plate 13).

Although it stands about 300' (90m) a.s.l., the sediplain is developing in relation to a local base level caused by outcrops of Kanmantoo Group metasedimentary rocks at about 250' (75m) a.s.l. This and the porous sediments underlying the higher ground probably account for the lack of dissection of the sedimentary surface.

As no fossils were found, the origin of the calcareous material of the sediplain is problematical. If the calcareous material were blown inland, it should be more widespread than at present in view of the proximity of the coast. On the other hand, the calcareous material may have been leached out of the higher land and redeposited in the depression. Alternatively the sediplain may have been formerly occupied by a lake or an arm of the sea in which the calcareous material was deposited.

(a) *Terraces of McKnight Creek*

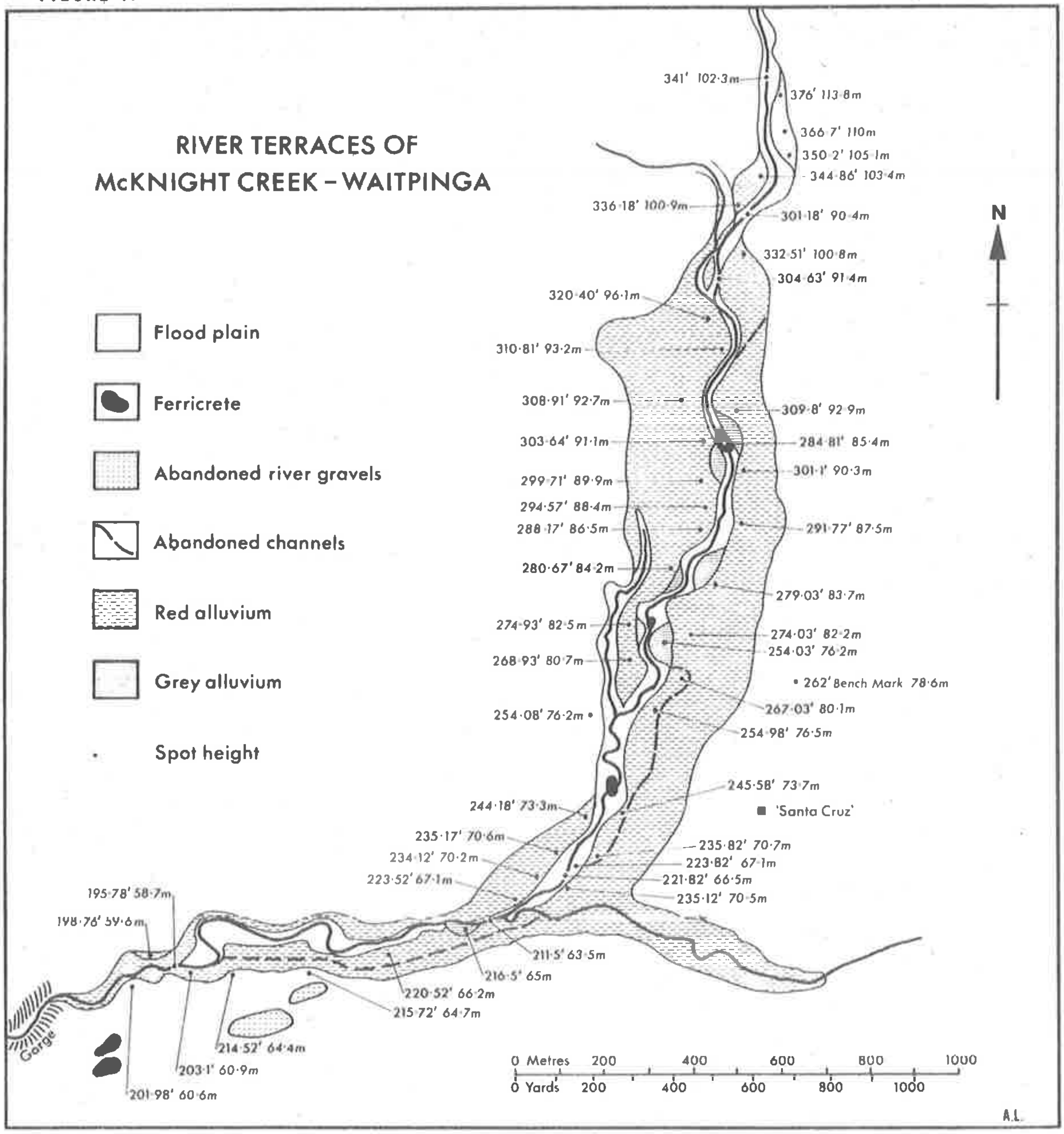
The part of the Waitpinga sediplain near McKnight Creek is comprised of river alluvium in which terraces have developed. River terraces have been defined by Leopold, et. al. (1964) as abandoned floodplains. Warner (1972) follows this definition but apparently includes as a river terrace a former floodplain abandoned by the alluviation of a stream which buries the old floodplain forming an overlapped terrace (Figure 2(c), in Warner, 1972). In this thesis a terrace is considered to be a former floodplain, developed either by alluviation or corrasion, now stranded *above* the level of flood stages by renewed downcutting of the stream.

Renewed erosion which strands former floodplains may be the result of regional uplift, eustatic emergence, local uplift accompanied by tilting or warping, alteration in the stream load/discharge ratio caused by climatic change, rapid marine erosion betrunking the stream at its mouth, or a general reduction in river loads and the consequent reduction of river gradients that accompanies the wasting of mountains during the cycle of erosion. In the last case the erosion must go on in surges and be accompanied by a succession of small appropriate climatic changes to result in alternate phases of vertical and lateral erosion (Cotton, 1940). Other factors which might cause terracing include river capture, which results in alteration of a stream's regime , anthropogenic influences such as land clearance, effects of local base levels, and the influence of increased discharge below the confluence of a tributary stream.

The terraces of McKnight Creek are unmistakably river terraces as they exhibit abandoned channels (Figure 17), natural levees, meander scars and minor depositional features which result in a micro-relief amplitude of at least 4' (1.2m).

The high red alluvial terraces are well above evidence of former flood levels, but the lower grey alluvial river flats, although standing above the floodplain, may be innundated during very high flood stages, and may be still related to the present stream regime. This problem of terrace identification is compounded by the irregular stream flow and the lack of records of flood heights and frequencies. Several floods during historical time have washed away the bridges on the Waitpinga Creek. Flood waters have reached several feet above road level (Mr. A. Jagger, Waitpinga - pers. comm.). At least during these floods the low grey alluvial river flats were innundated and in view of the uncertainty of their relation to the present

FIGURE 17


RIVER TERRACES OF
McKNIGHT CREEK – WAITPINGA
Flood plain
Ferricrete
Abandoned river gravels
Abandoned channels
Red alluvium
Grey alluvium
Spot height
N
341' 102·3m
376' 113·8m
366·7' 110m
350·2' 105·1m
344·86' 103·4m
336·18' 100·9m
301·18' 90·4m
332·51' 100·8m
304·63' 91·4m
320·40' 96·1m
310·81' 93·2m
308·91' 92·7m
309·8' 92·9m
303·64' 91·1m
284·81' 85·4m
301·1' 90·3m
299·71' 89·9m
294·57' 88·4m
288·17' 86·5m
291·77' 87·5m
280·67' 84·2m
279·03' 83·7m
274·93' 82·5m
274·03' 82·2m
254·03' 76·2m
268·93' 80·7m
262' Bench Mark 78·6m
254·08' 76·2m
267·03' 80·1m
254·98' 76·5m
245·58' 73·7m
'Santa Cruz'
244·18' 73·3m
235·17' 70·6m
234·12' 70·2m
223·52' 67·1m
235·82' 70·7m
223·82' 67·1m
221·82' 66·5m
235·12' 70·5m
195·78' 58·7m
198·76' 59·6m
211·5' 63·5m
216·5' 65m
220·52' 66·2m
215·72' 64·7m
214·52' 64·4m
203·1' 60·9m
201·98' 60·6m
Gorge
0 Metres 200 400 600 800 1000
0 Yards 200 400 600 800 1000
A.L.

stream regime, the grey alluvial flats will not be called terraces.

In several places the alluvial deposits of McKnight Creek rest on outcrops of massive ferricrete and Kanmantoo Group metasedimentary rocks, which act as local base levels and inhibit stream incision. This partly accounts for the inset nature of the alluvial river flats. The grey alluvial flats stand only 4' (1.2m) to 5' (1.5m) above the base of the present channel. The local base levels may influence the apparent relationship of the stream regime to the grey alluvial flats.

The levels of the river terraces and flats were fixed by Dumpy Levelling. The high terrace, which is underlain by red, slightly calcareous clay, including numerous pebble bands, slopes from an elevation of 376' (112.8m) to 201.98' (60.6m). At the point of maximum elevation the river channel is 35' (10.5m) deep, but downstream the channel depth is only 5.2' (1.56m). In a similar manner the height difference between the high terrace and the low grey alluvial flat changes from approximately 20' (6m) to about 3' (0.9m). Thus there is a downstream convergence of the high terrace, the low grey alluvial flat, the present stream channel and its associated floodplain. All four profiles are graded to a local base level formed by resistant Kanmantoo metasedimentary rocks where the stream enters the Waitpinga Gorge.

The levels taken demonstrate that the high red terrace is paired, being of comparable elevations on either side of the stream. Where adjacent, remnants of the low grey alluvial river flat are similarly paired. Thus it seems that both features developed by alluviation in relation to a fixed local base level, at an elevation of approximately 200' (60m) a.s.l. and more than 3 miles (4.8km) from the coast.

Because of these factors regional uplift, local uplift, eustatic emergence and rapid marine erosion must be discounted as working hypotheses to account for the terracing. There is no evidence that erosion of local base levels, river capture or increased discharge below thejunction of a tributary stream have played roles in stranding former floodplains. The distribution of the terraces and the ages of the alluvia (see below) do not favour the interpretation that terracing accompanied the erosion of the higher land during a cycle of erosion. The phases of alternate cut and fill evidenced also militate against this hypothesis.

As the gradients of present and former floodplains converge downstream, changes in base level either tectonic or eustatic in nature must be discounted. Consequently, alteration of stream regime, either by climatic change or anthropogenic influences, must be considered the most satisfactory explanation of the terracing. The relative roles played by these two factors will be considered when the ages of the alluvia have been discussed.

No datable material has been located in either the red or grey alluvial deposits. However, as the alluvia rest on ferricrete of possible Pliocene age they are possibly Quaternary in age.

Similar red and grey alluvial fills occur in the valleys of the Inman and Hindmarsh Rivers. The red alluvium (Adare Clay) is graded to a former shoreline at 20' (6m) a.s.l. A bone fragment recovered from the Adare Clay at a depth of 16' (5.4m) has been dated at 12,600 years B.P. (Gak-2356), a Late Pleistocene age. The grey alluvium of these rivers (the Breckan Sand) was deposited in relation to a sea level 8' (2.4m) to 10' (3m) a.s.l. and is associated with a marine terrace and shells all of which are modern species. Consequently the grey alluvium is of Holocene age. Because of similarities in stratigraphy and characteristics, the red and grey alluvial fills of KcKnight Creek are correlated with the Adare Clay and the Breckan Sand respectively. Correlative deposits of the Torrens River, the Klemzig Sand and the Walkerville Sand have been ascribed to the Late Pleistocene and Middle Recent respectively (Twidale, 1968, p.392).

The alternating episodes of cut and fill recorded in the terraces of the Inman and Hindmarsh Rivers (Bourman, 1969) suggest fluctuating eustatic sea levels, possibly accompanied by climatic changes. At the coast the effects of climatic change would be outweighed by a shift in base level, although the different colours of the alluvia might reflect prevailing climatic conditions during their deposition.

However, in an inland situation the influence of climatic change would dominate. Fluctuating climatic conditions could account for the alternate phases of cutting and filling of the alluvial deposits of McKnight Creek, which are identical to those of the Inman and Hindmarsh Rivers. In view of the suggested ages of the alluvial fills anthropogenic influences cannot be considered as the major cause of terracing, although land clearance since European occupance could have increased channel incision.

b) *The Upper Hindmarsh Valley*

A high level sedimentary surface similar to that in the Waitpinga area occurs in the valley of the Hindmarsh River upstream of the Hindmarsh Falls, to which level the surface is graded. The elongate Upper Hindmarsh Valley occupies an area of approximately 4.5 miles^2 (11.5km^2) and is enclosed by dissected remnants of the Spring Mount plateau surface.

A few outcrops of Late Palaeozoic glacigene sediments have been mapped between the surrounding highlands and the high level alluvial flats through which the stream flows (Thomson and Horwitz, 1960). Numerous short but deeply incised tributaries descend from the steep slopes surrounding the plateau surface. These streams have contributed to the construction of the alluvial surface flanking the trunk stream.

Early survey maps of the area indicate that streams of the Upper Hindmarsh Valley did not form an integrated drainage system nor was there a main channel. Gum Tree

Gully, now the main right bank tributary, flowed into Edinburgh swamp, which was not linked to the channels down valley. Moreover, the area about 1 mile (1.6km) upstream from the falls was also occupied by a swamp. Apparently drains have been cut to drain these swamps, as indicated by the straight channels in areas where previously no channels existed. The drainage of the swamps together with the increased runoff, resulting from land clearance, have led to the incision of stream channels and to the integration of the drainage system.

Borelog evidence demonstrates that the Upper Hindmarsh Valley and part of the Waitpinga Sediplain are underlain by Tertiary limestone. Reworked sands overlie the limestone of the Upper Hindmarsh Valley, and on this evidence, the sands are of post-Miocene age, with which the reworked sands of the Waitpinga area may tentatively be correlated.

6. SOME IMPLICATIONS OF TERTIARY MARINE SEDIMENTS IN THE STUDY AREA

The occurrence of fossiliferous Tertiary marine sediments in the study area has considerable implications for the geomorphic evolution of Fleurieu Peninsula. Dating of erosion surfaces and terrestrial deposits is facilitated, and thus tectonic and eustatic events are clarified.

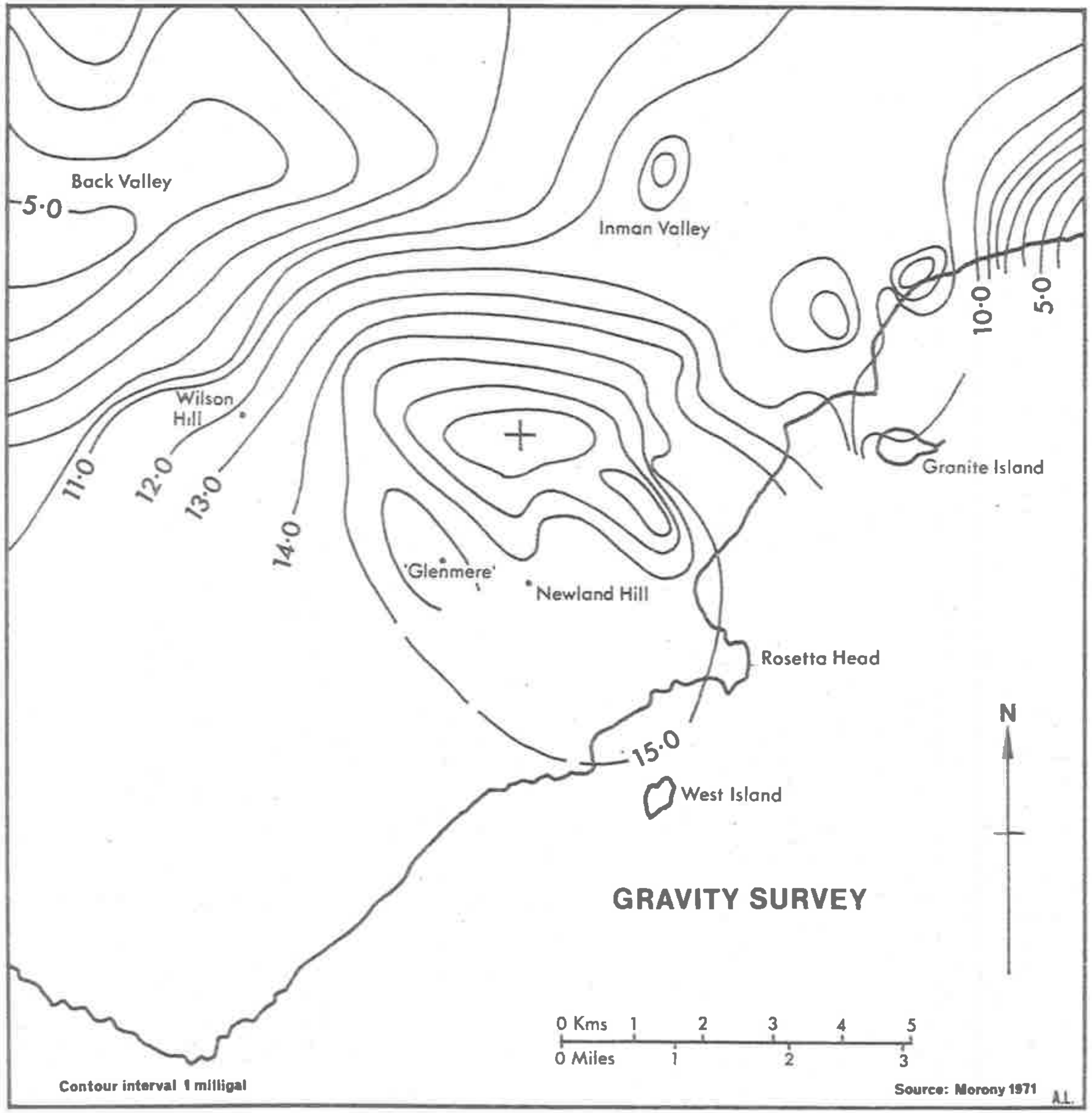
Richly fossiliferous limestone of Oligocene(?)-Miocene age underlies the Myponga Plain and the Upper Hindmarsh Valley, occurring in basins considered to be of glacial origin (Campana and Wilson, 1955; Thomson and Horwitz, 1961). These fossiliferous marine deposits indicate a major and lengthy marine transgression as they are 385' (115.5m) thick under the Myponga Plain, and occur through a similar range in the Upper Hindmarsh Valley, where they are interbedded with lignitiferous beds (Horwitz, 1960). The two basins of marine deposition are distinct, being separated by a basement rock bar (Moroney, 1971), though it has been suggested that the Tertiary seas transgressed to the Upper Hindmarsh Valley via the Myponga area (Horwitz, 1960).

Oligocene(?)-Miocene limestone outcrops in both the Myponga Plain (Madigan, 1925) and the Upper Hindmarsh Valley (Howchin, 1926) at 790' (237m) and 700' (210m) a.s.l. respectively. However, post-Miocene erosion may have reduced the level of the original deposits. Moreover, the upper level of the limestone would not represent the water level during deposition, so that the Middle Tertiary shoreline stood higher than 790' (237m) a.s.l. The several pronounced benches occurring on the scarps surrounding the Myponga Plain and the Upper Hindmarsh Valley may be related to the Middle Tertiary shoreline, but there is no evidence for this at present. Although Tertiary limestone occurs at high elevations in this area, there is no evidence that the summit surface was transgressed.

Other Tertiary marine sediments of the study area occur in the Waitpinga area. Bog logs indicate that these deposits are quite limited, and may correspond to the area covered by the higher gravity reading near 'Glenmere' (Figure 18) (G.R. Morony, pers. comm.). Here the limestone does not outcrop and is known only from one bore, where it has a thickness of only 8' (2.4m). The fossil assemblage (see section on geology) indicates an Eocene age for this limestone in contrast to the younger limestone in the Myponga and Upper Hindmarsh Valleys. As the top of the Eocene limestone stands 213' (64m) a.s.l. the Eocene shoreline would have stood in excess of this height.

All three occurrences of high level Tertiary limestone have been preserved in basins apparently excavated by Late Palaeozoic ice. Sediments interpreted as glacigene have been encountered in bores underlying the Myponga Plain (Campana and Wilson, 1955), the Waitpinga area (Lindsay, 1966) and on the periphery of the Upper Hindmarsh Valley

FIGURE 18


Back Valley
5·0
Inman Valley
10·0
5·0
Wilson Hill
11·0
12·0
13·0
14·0
Granite Island
'Glenmere'
Newland Hill
Rosetta Head
15·0
West Island
N
GRAVITY SURVEY
0 Kms 1 2 3 4 5
0 Miles 1 2 3
Contour interval 1 milligal
Source: Morony 1971
A.L.

(Horwitz, 1960). This suggests that subsequent to the glacial erosion of the depressions and their infilling with glacigene sediments, a phase of erosion occurred during the Mesozoic and/or Early Tertiary. Tertiary marine transgressions into these re-excavated valleys resulted in the deposition of considerable thicknesses of limestone. Lignitiferous sediments interbedded with the limestone (Thomson and Horwitz, 1961) indicate minor fluctuations in sea level during the Oligocene(?)-Miocene.

Based on the occurrence of the Oligocene(?)-Miocene limestone in the Myponga Plain and in the Upper Hindmarsh Valley at approximately 700' (210m) below the high plateau surface, and 700' (210+m) a.s.l., Campana and Wilson (1955) suggested several phases of tectonism:

(i) A pre-Miocene phase uplifted a pre-Tertiary erosion surface, and led to the re-excavation of the glacial basins.

(ii) An Oligocene(?)-Miocene marine transgression separated this early phase from post-Miocene tectonic phases, which resulted in the uplift of the plateau surface and the Tertiary limestones to their present positions. At least half of the total uplift of 1500' (450m) of the pre-Tertiary erosion surface was attributed to the pre-Miocene phase (Campana and Wilson, 1955).

However, this model of the Tertiary tectonic behaviour of Fleurieu Peninsula is complicated by the presence of Eocene limestone underlying the Waitpinga area and by the assumption that the summit surface is a pre-Tertiary erosion surface. The model assumes that the present plateau surface developed in relationship to a base level at or near to sea level. However, it may be possible, that under the conditions considered by Kennedy (1962), the surface developed at an elevated position (Twidale, 1968, p.329; Brock, 1971). The scheme of Campana and Wilson (1955) also presumes that the land has only moved upward during the tectonic movement. Although still largely speculative, it seems possible that the separation of Australia and Antarctica occurred in the Middle Eocene (McGowran, 1971) prior to the Oligocene(?)-Miocene transgression. A model of rifting adapted (Figure 19) from Dietz and Sproll (1969) shows initial uplift of the land followed by subsidence during the readjustment stage. Thus the simple notion of two phases of Tertiary uplift may be questionable.

This problem is compounded by the effect of rises in sea level following the production of new crustal material at the mid-oceanic ridges (McGowran, 1971), and by the recognition of phases of Tertiary glaciation and deglaciation (see, for example, Tanner, 1968).

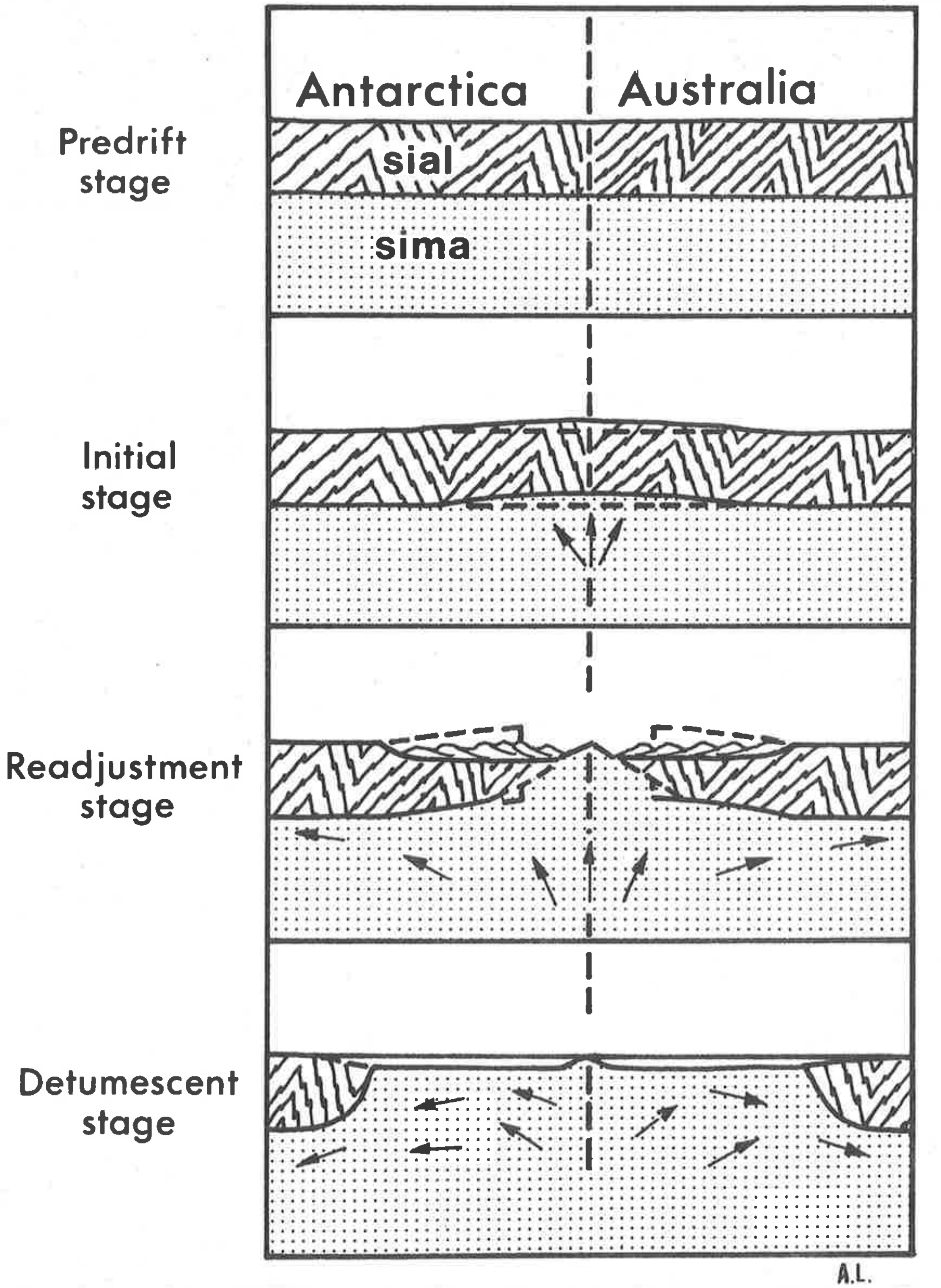
If Campana and Wilson's (1955) assumption that the summit surface developed near sea level is valid, in order to re-excavate the glaciated depression underlying the Waitpinga area, the first phase of Tertiary uplift must have been at least 1200' (345m), or the combined effects of tectonism and eustatic sea level movement must have equalled this. This assumes that there have been no major fault dislocations between the Waitpinga and Upper Hindmarsh areas during the Cainozoic. However, as discussed on page 50 there appears to have been a tilting of the plateau surface to the south and southeast of the order of 100' (30m). Moreover, a Late Palaeozoic glaciated surface in the Inman Valley displays an observable dislocation of 15" (36cm) with a downthrow to the southeast (Howchin, 1926). Unfortunately there is no indication of the total throw in this fault zone, nor is there any clue to the more precise age of the faulting.

Following the re-excavation of the glacial depressions, a marine transgression extended from about 230' (69m) a.s.l. in the Eocene, to at least 790' (237m) a.s.l. in the Oligo-Miocene, or through a height range of 560' (168m). If there has been tilting or faulting down to the south and east, then the elevational range of the Tertiary transgression would

FIGURE 19

INTERCONTINENTAL TECTONICS

DIETZ & SPROLL (1969)

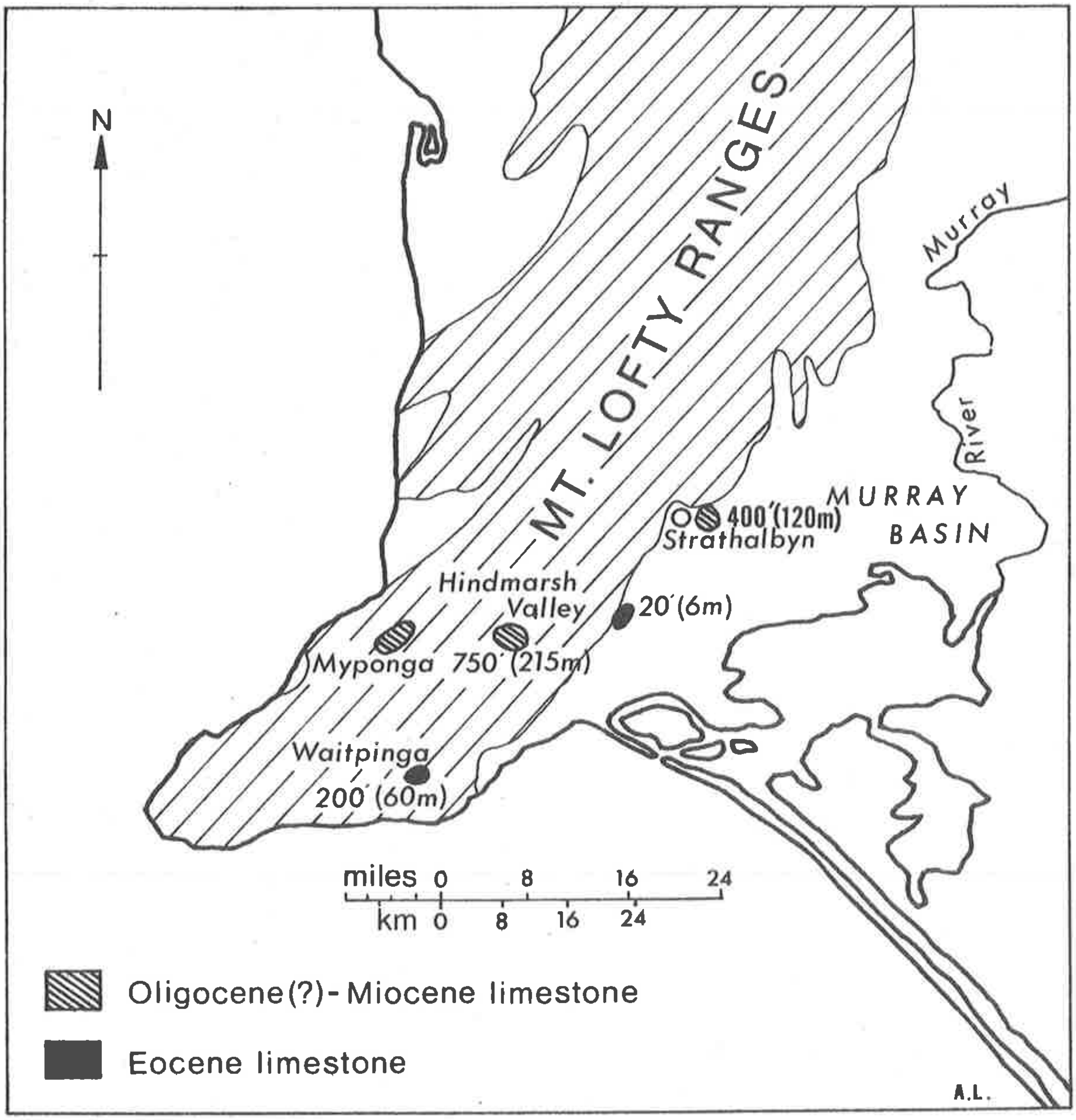


be less than the 560' (237m) calculated. An elevational difference of this order could be accommodated by eustatic movements ranging from maximum glaciation, to total deglaciation (Brown, et.al., 1969, p.341). However, other factors involved in the explanation of the present distribution of these high level Tertiary limestones include the behaviour of the continental margins during the separation of Australia and New Zealand (see Figure 19), the displacement of oceanic water due to the creation of mid-oceanic ridges, and the tectonic behaviour of Fleurieu Peninsula throughout the Cainozoic. Lignitiferous layers interbedded with the Oligo-Miocene limestones of the Upper Hindmarsh Valley suggest temporary withdrawal of the seas from the Upper Hindmarsh Valley during the Tertiary transgression.

Assuming negligible erosion of the Eocene marine deposits at Waitpinga and correlative beds surrounding the ranges at or near sea level (Howchin, 1910b; Glaessner, 1953), there appears to be a dislocation of these beds of about 220' (66m) attributable to tectonism. The elevational difference between the Eocene limestone of the Finniss River Valley and the Oligocene(?)-Miocene sandy limestones near Strathalbyn, in the Murray Basin, is of the same order as that separating the Eocene of the Waitpinga area and the Oligocene(?)-Miocene of the Upper Hindmarsh Valley, both of which lie in the Mount Lofty Ranges. If the possible tilting of the Mount Lofty Ranges to the southeast is considered, then the differences between the Early and Middle Tertiary limestones in the two tectonic provinces corresponds more closely, i.e. a difference of about 400' (120m). Consequently eustasy may be a major influence in the elevational differences between the Eocene and Oligocene(?)-Miocene limestones, while tectonism may account for the height differences between correlative beds in the different tectonic provinces (Figure 20).

FIGURE 20

RELATIONSHIPS OF SOME TERTIARY LIMESTONES IN THE MT. LOFTY RANGES & MURRAY BASIN



The Upper Hindmarsh Valley is surrounded either by outcropping bedrock or bedrock highs shallowly buried (Barker map sheet, 1:250000 series; Morony, 1971). Assuming no tectonic modifications of the plan morphology of the Upper Hindmarsh Valley depression since the glaciation, there appears to be no outlet at a sufficiently low elevation to facilitate its re-excavation following glaciation. Thus it is very possible that this basin was not filled with glacigene sediments much beyond its present extent, and many of the deposits mapped as Late Palaeozoic glacigene may be younger, reworked sediments.

7. DURICRUSTS - PREVIOUS INVESTIGATIONS

The interpretation of the ages of the duricrust cappings in the study area is controversial. Certain confusion has resulted from the apparent failure to distinguish clearly distinct duricrust cappings and the different ways in which these cappings developed. The interpretation of the origins of the duricrusts and the model of landscape evolution preferred for the development of the study area enable interpretations of the age of lateritisation to range from the Eocene to the Holocene.

Without presenting any evidence to support their hypothesis, Campana, Wilson and Whittle (1953) maintain that the laterite of Fleurieu Peninsula began to form in the Pliocene, and is still developing. Certainly under some conditions iron is mobile today as on many occasions iron-rich waters flowing from the high plateau surface have been noticed. However, there is no unequivocal evidence that deep weathering of the land surface, the critical process in laterite formation, is still proceeding. As Campana, Wilson and Whittle (1953) did not distinguish between *in situ* (or primary) laterite and ferricrete cappings (formed by reworking of the primary laterites), they may have been referring to the formation of secondary duricrusts as the process of lateritisation which is still proceeding today. Such an interpretation is acceptable.

Crawford (1959) noted the occurrence of ferruginous duricrusts over considerable relief on the Encounter Sheet (1:63360 series) and concluded that this distribution indicated 'the original irregular lateritised surface'. The time of laterisiation was attributed to the Late Tertiary. However, Crawford (1959) also classed *in situ* and derived duricrusts as one.

Thomson and Horwitz (1960) assigned the laterite of the Milang map sheet (1"63360 series) to the Pliocene. Limonite cemented gravels were traced from the high plateau surface to the Upper Hindmarsh Valley where they overlie reworked ferruginous sands resting on Oligocene(?)-Miocene limestone. The limonite-cemented gravels, in all situations, were considered to be of the same Pliocene age.

However, the contemporaneity of high level and low level duricrusts on Fleurieu Peninsula has been called into question by Brock (1964, 1971). He suggested that the lower level deposits, consisting of iron oxide cemented sands resting on low angle slopes, as 'low-slope cappings' formed after the dissection of the laterite on the high plateau.

A traverse of the ferricrete capped ridge, mentioned by Thomson and Horwitz (1961), from the Upper Hindmarsh Valley to Spring Mount revealed that the ferricrete occurring between the 900' (270m) and 1100' (330m) levels consists of sands, gravels and pebbles, chiefly subangular in shape and cemented by iron oxides. Particularly near the base of the concave break in slope, leading up to the high plateau surface, the ferricrete is composed of ferruginous breccia, which includes angular fragments of basement rock and quartz. On the steep slope separating the low level deposits from the plateau surface fragments of ferruginous material form a colluvial cover. These have been derived from the high plateau surface and are quite different from the low level cappings. In contrast they consist of weathered and ferruginised bedrock fragments, in which bedrock structures are still visible. On the Spring Mount surface the duricrust i variable in nature, being both pisolitic and vesicular, but nowhere on the high plateau surface has the duricrust been observed by the writer to consist of 'limonite-cemented gravels and sands' as claimed by Thomson and Horwitz (1961).

Superficially the two types of duricrust may seem to be related to different bedrock types; the high level type being related to metamorphic basement rocks, and the low level ferricrete to unconsolidated sands and gravels. However, in several areas near Waitpinga the ferricrete rests on Kanmantoo metasedimentary rocks. Moreover, if conditions allowed weathering to depth of 230' (69m) on the high plateau surface, and if the two duricrusts are of the same age, evidence of deep weathering underlying the low level duricrust would also be expected, as has been noted in other areas in Australia (Finkl, 1971). To date no evidence of deep weathering has been noted on the lower surface.

Thus the nature and distribution of the two duricrust cappings support the interpretation that they may have formed at different times by different processes.

Working in the Mount Compass-Milang area, Maud (1972) recognised that primary laterites on the plateau surface developed through the accumulation of iron and aluminium by the removal of silica and bases. Secondary laterites or 'orstein' soils formed by the concentration of oxides of iron and aluminium from outside sources. The latter are restricted to valley sides occupying former valley floors. Dismissing the possibility of a pre-Miocene age for lateritisation of the high plateau surface on the grounds that 'it is unlikely that such relatively minor thicknesses of ironstone could have survived from this time', Maud (1972) proposed that the lateritic ironstones of the area range in age from the Pliocene for the oldest and highest, to Holocene for the lowest and youngest. However, there is no clear evidence indicating the original thickness of the lateritic ironstones of the high plateau surface, though it should be noted that the fersilitic crust on Peeralilla Hill attains a thickness of up to 30' (9m). Moreover, as the main outside source of iron for the secondary or detrital ironstones is the high plateau surface, the present thickness does not represent the original depth.

Early Tertiary ages of lateritisation have been suggested by some workers. Reworked pisoliths have been noted in the sands and basal beds of the Tertiary Maslin Sands near Ochre Point, and have been attributed by Crespin (1954) to the Palaeocene-Eocene. Similar reworked pisoliths form a basal conglomerate underlying the Oligocene(?)-Miocene limestone outcropping near Strathalbyn (Horwitz, 1960). In both cases the reworked pisoliths were interpreted as deriving from an Early Tertiary or Mesozoic phase of lateritisation. Noting similar reworked pisoliths near Sawpit Gully (Milang map sheet, 1:63360 series) at about 235' (70.5m) a.s.l., Horwitz ascribed them, and the surface on which they rest, to the pre-Tertiary. Such an extrapolation and interpretation is questionable as this area was submerged by at least 500' (150m) during the Miocene marine transgression. Moreover, reworked pisoliths may not be all of the same age.

Iron-stained rounded quartz grains and ferruginous pellets associated with fossiliferous Eocene marine sediments intersected in a bore hole on the "Glenmere" Homestead near Waitpinga (Lindsay, 1966), may have been derived from a pre-Eocene lateritic ironstone.

Two main levels of ferruginous duricrust were recognised by Lang (1965) in the Yundi area, north of Mount Compass. He interpreted the age of the duricrust on the summit surface as Pliocene, and that in the valleys as Quaternary.

(a) *Ages and origins of duricrusts in the study area*

In the study area, the critical markers for the age(s) of lateritisation are the Eocene limestone of the Waitpinga area, and the Oligocene(?)-Miocene limestone of the Upper Hindmarsh Valley. If lateritisation occurred after the deposition of the Middle Tertiary limestones, then it would be placed in the Late Tertiary or Quaternary. But it has been shown above that the ironstone duricrust, which by extrapolation overlies the limestone of the Upper Hindmarsh Valley, is completely different in nature and origin from that of the plateau surface.

Therefore it seems most probable that the laterite of the Spring Mount surface developed before, or during the Tertiary transgression. Otherwise deep weathering profiles would surely be present within the Upper Hindmarsh Valley, which stands at a similar elevation a.s.l. to some of the remnants of the laterite surface elsewhere.

The development of primary *in situ* laterites over considerable relief and on slopes as great as 15° has been described from areas in Western Australia (Prider, 1966; Finkl, 1971) and used as evidence to demonstrate lateritisation after uplift and dissection of the plateau surface. If the interpretations of Prider (1954) and Finkl (1972) are acceptable, laterites with deep weathering profiles should occur in a variety of situations throughout Fleurieu Peninsula, especially in view of the deep weathering on the plateau surface. The absence of deep weathering profiles is not explicable entirely in terms of bedrock differences. Basement metasedimentary rocks are not affected by deep weathering at low elevations, but are so affected on the high plateau surface, thus supporting the view that the secondary ferricrete developed after the main phase of lateritisation. Ground water conditions might account for the absence of low level deep weathering, but in view of the variety of slopes and drainage conditions in the area at present, many of which have been maintained since the Late Palaeozoic, it is difficult to envisage that nowhere on the lower surfaces were conditions suitable for laterite formation.

The age of the ferricrete or detrital ferruginous crusts certainly post-dates the Miocene, evidenced by their superior position with regard to the Oligocene(?)-Miocene limestone in the Upper Hindmarsh Valley. Moreover, many areas capped by ferricrete were submerged during the Middle Tertiary marine transgression, which, considering the thickness of the associated marine deposits, was of considerable extent and duration. Consequently the secondary crusts and their associated surfaces are ascribed to post-Miocene times.

The possibility of perched relief developing in the Mount Lofty Ranges has been considered by Twidale (1968, p.329). Following the proposals of Kennedy (1962), if regional uplift exceeds the rate of downcutting by streams, which in turn outpaces the downwasting of interfluves, then theoretically, a surface of low relief could develop high in the landscape unrelated to ultimate base level, but in relation to local base levels. It is argued that this would favour the through-flow of ground waters, enhancing lateritic weathering on the high surface and accounting for the apparent absence of laterite on downfaulted blocks (Twidale, 1968).

This theory might account for the evidence observed in the Waitpinga area where deep lateritic profiles occur on the high plateau surface at 750' (225m) a.s.l., while a shallow kaolinised zone underlies a secondary ironstone duricrust at about 200' (60m) a.s.l., as under the scheme envisaged by Twidale (1968) deepest weathering would occur highest in the relief. Alternatively, the shallow weathering profile might indicate a second, less intensive phase of lateritisation, or the truncation of a deep lateritic profile followed by the deposition of an iron-cemented conglomerate. Evidence indicates that neither faulting nor tilting can be seriously considered in explaining the distribution of the profiles.

The lack of deep weathering profiles low in the relief may simply reflect poor exposures, but certainly on Fleurieu Peninsula, and possibly in the Adelaide region, transgression of the lower area by the Miocene seas would have destroyed earlier weathering profiles and prevented weathering on the submerged areas.

The Kennedy model of landscape evolution has recently been questioned and doubt cast on the development of extensive perched erosion surfaces. Crickmay (1972) suggested that the rate of active uplift exceeds the rate of stream incision which in turn always exceeds downwasting of divides. He postulates that the recurrent uplift of land masses results in the formation of only terraces or broad plains prior to rejuvenation. The writer agrees with Brock's rejection of the Kennedy model of evolution of the high plateau area of Fleurieu Peninsula for deep weathering high in the relief may require a fluctuating water table.

(b) *Palaeoclimates during the formation of the duricrust*

A humid tropical climate has long been considered a necessary requirement for the development of deep lateritic weathering. On the basis of palaeoclimatic, palaeobotanical and palaeogeomorphic evidence, Dury (1971) supports this view, and suggests that lateritisation in the middle latitudes may be related to warmer, and possibly wetter conditions during the Eocene and Middle Miocene.

Based on the records of marine planktonic microfaunas, Lindsay (pers. comm.) suggests that South Australia witnessed warmer, if not tropical, climatic phases during the Late Eocene, Middle Oligocene, Oligocene-Miocene, Early-Middle Miocene, at the Miocene-Pliocene boundary, and during the Late Pliocene. As detailed work proceeds in the palaeoclimatic field, and in the study of duricrusts in South Australia, reliable correlations of climatic phases with the formation of duricrusts may be achieved. However, much will depend on the establishment of relationships between climate and lateritic weathering, for Paton and Williams (1971) claimed that, given suitable bedrock and drainage conditions, laterite can form under virtually any climatic regime. However, they present no unequivocal evidence for this.

The possibility exists that lateritic weathering is occurring at the present time in part of the Waitpinga drainage basin, where at least 5' (1.5m) of weathered bedrock underlies a detrital ironstone crust 3' (0.9m) thick. Augering revealed that the water table occurs within the weathered zone, which is possibly still developing under the influence of a fluctuating water table. However, it is impossible to demonstrate whether the weathering is fossil or still developing. The lack of widespread evidence for present day deep weathering favours the view that the weathering is essentially fossil, and is possibly related to former higher temperatures and rainfall. If so, lateritisation could have occurred in any of the phases mentioned above by Lindsay.

(c) *Summary and conclusions concerning the age of the ferruginous duricrusts*

Several interpretations are suggested by the distribution of the ferruginous duricrusts, occurring over a height range exceeding 1000' (300m):

(i) The development of a single duricrust on a continuous and regular surface, dislocated subsequently by faulting, warping or tilting, thereby accounting for the present disposition of the duricrusts remnants. There is no evidence of sufficient dislocation of an original lateritised surface in the study area to account for the present distribution. Moreover, the lower duricrusts are completely different in nature from those of the high plateau surface, casting further doubt on this hypothesis.

(ii) The development of duricrust after the erosion of the Spring Mount surface and the Green Hills surface, and the deposition of the Tertiary marine sediments, thus placing the period of lateritisation in the Pliocene. However, the problem as to whether laterite development (apparently depending on a fluctuating water table (Maignen, 1966)), could take place on the highest points in the relief, makes this theory questionable. More importantly, if lateritisation occurred over an irregular landscape, why is there not widespread evidence of deep weathering at points low in the relief, as in other parts of Australia?

(iii) The lower duricrust is a derived deposit, not dependent on weathering for its formation; weathering and erosion could have taken place on the high plateau, with contemporaneous reworking and deposition in the lower depressions during the Pliocene. This hypothesis might assume that the high surface developed in relationship to a base level as much as 1200' (360m) below its general level. Furthermore, the Green Hills and Spring Mount surfaces do not grade into one another, but are separated by sharp concave breaks in slope, in many cases cut in basement rocks. In addition, if the Green Hills surface had been exposed to the deep weathering which occurred on the high plateau, some evidence of this should be present.

(iv) A Late Tertiary age for lateritisation would follow if the high plateau surface developed under the scheme envisaged by Kennedy (1962), while the lower Green Hills surface developed in relation to sea level. Criticisms concerning the development of perched relief viz. those of Crickmay (1972), those concerning fluctuating water tables high in the relief (Brock, 1971) and those related to the development of an extensive, planate and uniform surface in relation to a variety of local base levels, cast doubt on this theory.

(v) At least two separate phases of lateritisation, accounting for the two distinct duricrusts developed on two separate erosion surfaces. Horwitz (1960) suggested multiple phases of lateritisation, affecting the high plateau surface during the Pliocene, and the Green Hills surface during the Eocene. Both of these interpretations are considered to be incorrect, and have been discussed above.

(vi) The following sequence of events is suggested by the writer to account for the evolution of the study area:

(1) Evolution of the Spring Mount surface during the Mesozoic and Early Tertiary in relation to a base level at or close to sea level. The age of the summit surface is probably Cretaceous.

(2) Lateritisation of this surface of low relief, still close to sea level in the Eocene. This takes into account geological and palaeoclimatological evidence for lateritisation during the Eocene (Horwitz, 1960; Crespin, 1954; Lindsay, 1966; Lindsay-pers. comm.).

(3) Relative uplift of the land, followed by a marine transgression during the Oligo-Miocene. The land was not submerged, so that lateritisation of the high plateau could continue through the Oligo-Miocene under the warmer climatic conditions postulated by Lindsay. The long period of lateritisation of the high plateau surface could account for the great depth of weathering on it.

(4) Marine regression, possibly accompanied by uplift of the land. Reworking of the sands in the Upper Hindmarsh Valley and their deposition on the Oligo-Miocene limestone. Erosion of the Green Hills surface at the same time. This was not possible before the Pliocene as the area was covered by the sea, although the possibility that it is partly resurrected surface should not be overlooked.

(5) Deposition of secondary ferruginous duricrusts in broad valleys on sands which overlie the Oligocene(?)-Miocene limestone of the Upper Hindmarsh Valley, on the Green Hills surface, and in parts of the Waitpinga drainage basin during the Pliocene. The Waitpinga secondary crusts would have also been submerged during the Miocene, suggesting a Pliocene age for them. The slight degree of weathering which underlies some of the secondary duricrusts could be

accounted for by the warm Pliocene climatic phase envisaged by Lindsay. The fact that the surfaces on which the secondary duricrust occur were apparently submerged during long phases of lateritisation accounts for the absence of deep weathering profiles on them.

(6) Further relative elevation of the land, leading to dissection of the valley ferricrete, which now forms ridge tops.

The above interpretation takes into account independent evidence which suggests several phases of lateritisation. In addition it is the most satisfactory explanation of the observed facts.

CHAPTER V. LATE PALAEOZOIC GLACIATION

1. INTRODUCTION

The presence of striated bedrock surfaces and exotic erratics throughout large areas of Fleurieu Peninsula provides incontestible evidence for a severe glaciation during the Late Palaeozoic. Because of this, workers have ascribed a glacial origin to many landforms on Fleurieu Peninsula, chiefly on morphological evidence. While the shape of a landform may give a clue to its origin, landforms of similar morphology may develop under quite different sets of conditions i.e. certain landforms may be multigenetic. Consequently, evidence in addition to morphology should be sought in examining the genesis of landforms.

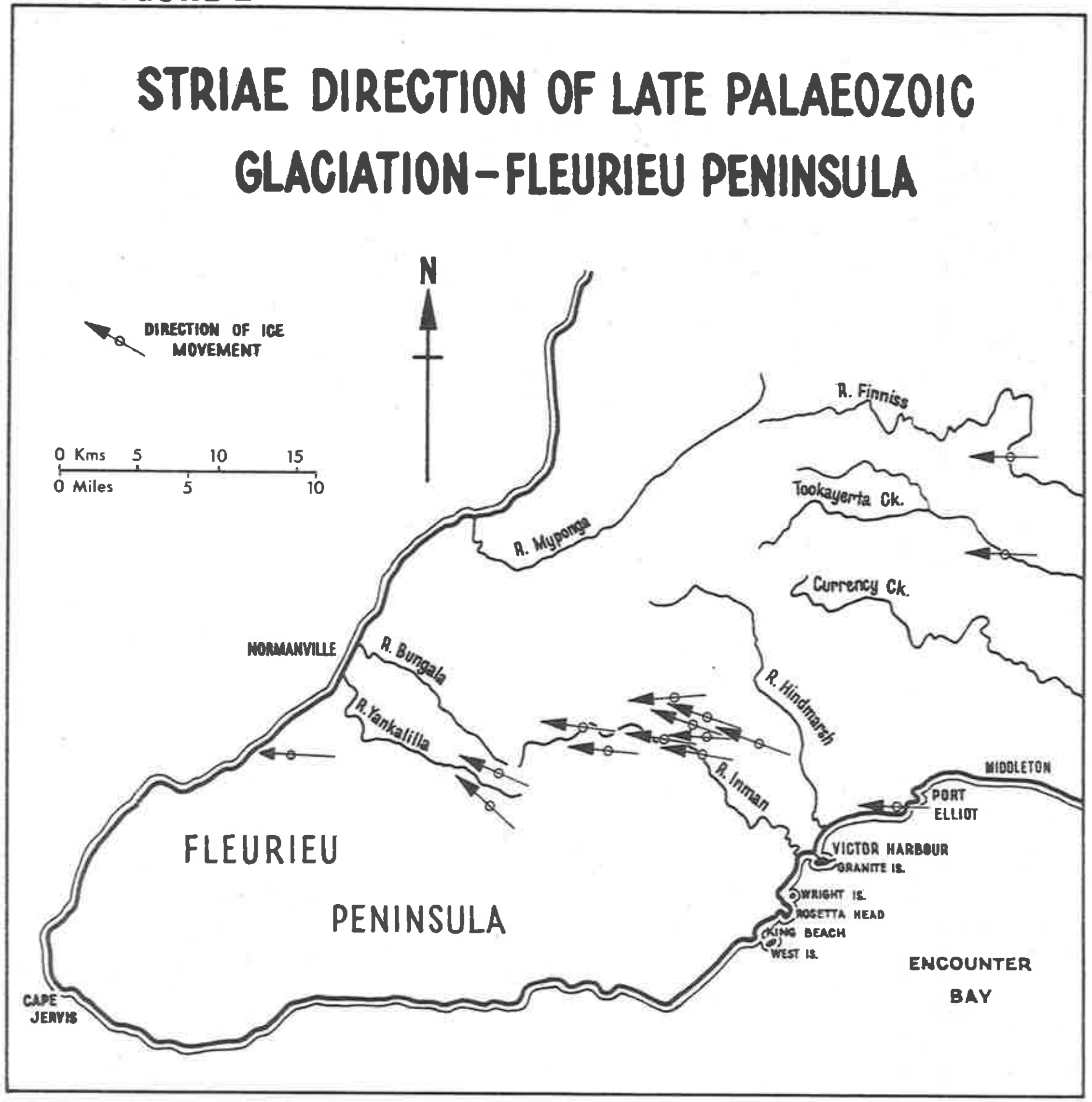
Hills interpreted as *roches moutonnées* by various workers include Crozier Hill, Rosetta Head and Stone Hill, while the granite islands of Encounter Bay and the Pages of Backstairs Passage have been similarly described. Deep basins, apparently glacially gouged, occur under Back Valley and in the area immediately north of Port Elliot. Backstairs Passage, although subject to alternative modes of formation, has long been considered to be a similar glacial depression, now drowned.

In view of the immense period of time since the Late Palaeozoic glaciation, the interpretation of these supposed glacial features will be examined critically.

2. GLACIALLY STRIATED SURFACES

Numerous striated bedrock surfaces occur on Fleurieu Peninsula, especially in the valley of the Inman River (Howchin, 1926). The distribution of striated surfaces (Figure 21) has been compiled from various sources (see Milnes and Bourman, 1972). The glaciated pavements most significant in interpreting the supposed glacial landforms include those at Port Elliot, Stone Hill, near Torrens Vale and at Christmas Cove, Kangaroo Island.

FIGURE 21


STRIAE DIRECTION OF LATE PALAEOZOIC GLACIATION—FLEURIEU PENINSULA
N
DIRECTION OF ICE MOVEMENT
0 Kms 5 10 15
0 Miles 5 10
R. Finniss
Tookayerta Ck.
R. Myponga
Currency Ck.
NORMANVILLE
R. Bungala
R. Yankalilla
R. Hindmarsh
R. Inman
MIDDLETON
PORT ELLIOT
VICTOR HARBOUR
GRANITE IS.
WRIGHT IS.
ROSETTA HEAD
KING BEACH
WEST IS.
FLEURIEU PENINSULA
ENCOUNTER BAY
CAPE JERVIS

The striated bedrock at Port Elliot is peculiar to the region in that it is the only observed pavement on granite bedrock. Striae and grooves on a highly polished rock surface of one square metre extent, indicate an east-west ice direction (Milnes and Bourman, 1972). Areas of glacially smoothed bedrock occur irregularly over a distance of 100' (30m). The possibility that the striae may be slickensides on sheeting or joint planes has been considered, and found wanting, for the pavement above, and other nearby smoothed surfaces, bear no relationship either to joints or to sheets. The discovery of this pavement on granite has numerous implications concerning the geomorphic evolution of the region.

At Stone Hill,[1] 0.6 miles (1 km) east of 'Green Hills' Homestead, finely laminated metasandstone carries numerous exposures of glacial striae, crescentic gouges and crescentic fractures (Plate 14). Evidence of glacial action on this inlier of Kanmantoo Group metasedimentary rocks was first recorded by Howchin (1926), since which time several fresh exposures have been noted. The striae direction recorded by Howchin (1926) was W 20° N.

Brock (1964) described a glaciated pavement near Torrens Vale. A series of grooves up to a yard (1m) wide and with an amplitude of 2" (5cm) to 4" (10cm) score finely laminated, cross-bedded and slumped metasandstone. Brock (1964) recorded a striae direction of W. 39° N. However, six separate readings by the writer varied between W. 28° N. and W. 31° N. Although many of the striations are on steep slopes, they fall within the range of directions noted above, apparently not significantly deviated by local topographic irregularities. This situation is common on Fleurieu Peninsula, suggesting a thick and extensive ice cover.

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[1]Local name only

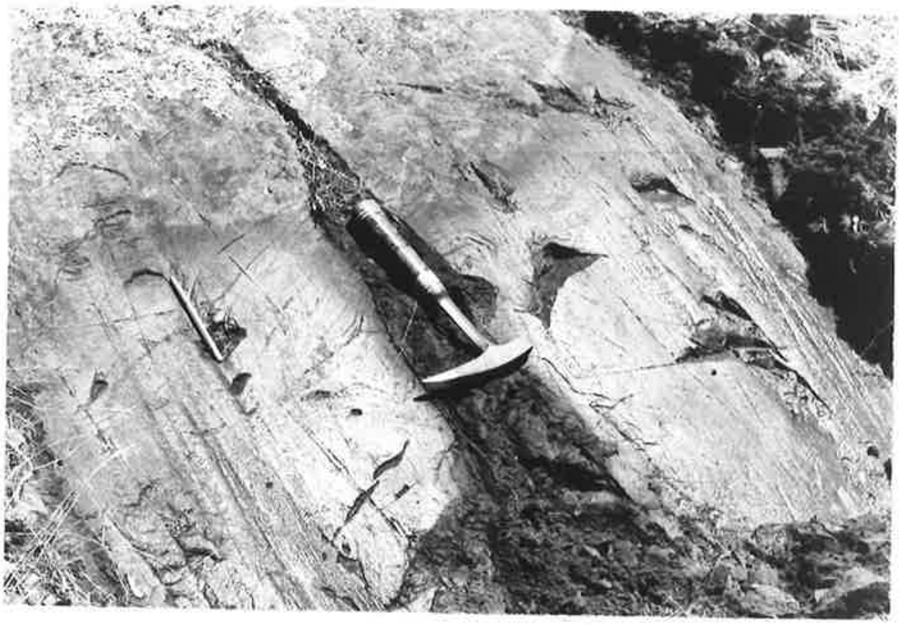


Plate 14. Glaciated bedrock surface on the southeastern section of Stone Hill, exhibiting grooves, striae, crescentic gouges and polishing. The direction of ice movement was away from the viewer. The bedrock is finely laminated metasandstone of the Backstairs Passage Formation.

Although no striae are present, Crawford (1959) claimed that glacially smoothed bedrock on the southern wall of Back Valley indicates a local ice movement of W.S.W.

A striated bedrock surface at Christmas Cove on Kangaroo Island illustrating an east-west ice movement has been described by Ward (1922, 1932). As this pavement and the pavements on Fleurieu Peninsula show ice movement from a few degrees south of west it appears certain that southeast Fleurieu Peninsula was transgressed by westerly flowing ice during the Late Palaeozoic.

3. GLACIAL ERRATICS

Erratics on southeast Fleurieu Peninsula also support this thesis. A newly discovered erratic field southwest of Waitpinga Hill includes Encounter Bay Granites as well as a boulder of granite similar to granites which underlie the Murray Basin to the east and southeast. Erratics north of Crozier Hill (Plate 15) also indicate an east-west ice movement as do erratics resting on Kanmantoo Group meta-sedimentary basement rocks N.N.E. of Newland Hill. Possible metasandstone erratics 1.2 miles (2km) southwest of Mount Desert have a potential source area to the S.S.E. Erratics of Encounter Bay Granites occur at Cape Jervis (Ludbrook, 1967), and these may have been derived from granite outcrops to the east, but the source area is not sufficiently confined to state this with certainty. Pebbles of quartz, quartzite and schist, possibly faceted and striated (Lindsay, 1966), recovered from the base of the bore hole at 'Glenmere' Homestead, support the view that Late Palaeozoic ice played a part in the excavation of the bedrock depression underlying the Waitpinga drainage basin.

4. CRITICAL EXAMINATION OF LANDFORMS INTERPRETED AS GLACIAL

a) *Stone Hill*

'Stone Hill' is the local name given to a small inlier of Cambrian Kanmantoo Group metasedimentary rocks 2.7 miles (4.5km) due north of Crozier Hill. It attains a height of almost 500' (150m) a.s.l.

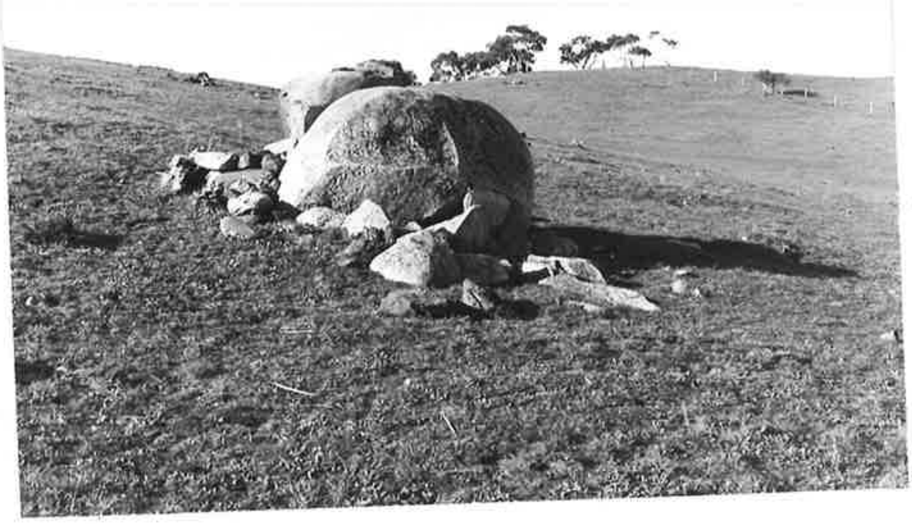


Plate 15. An erratic of Kanmantoo Group metasedimentary rock and an erratic of the Encounter Bay Granites, 0.6 miles (1km) north of Crozier Hill. Possible source areas for the erratics lie about 6 miles (9.6km) to the west near Port Elliot and Middleton.

Plate 16. Crozier Hill viewed from the west. Note the broken northwest face of the hill and the bedrock structures, which dip gently to the south.

A striated bedrock surface was discovered on the southern side of this hill by a student of Professor Howchin (Howchin, 1926). While attempting to locate this pavement, another area of striated bedrock was uncovered by the writer (Bourman, 1969). Striae on the pavement, which covers an area of 5 $feet^2$ ($2.25m^2$), vary between W. 30° N. and W. 40° N. Although the striae are crossing they are not sufficiently clear to be allotted older and younger ages. In any case, crossing striae do not necessarily indicate multiple glaciation (Flint, 1957), as has been suggested by Crowell and Frakes (1971a) for the Late Palaeozoic glaciation of South Australia.

Subsequently, during a field trip with Mr. A.R. Milnes, the original pavement of Howchin (1926), recognised from a photograph, was located, while several other exposures of striated bedrock were found including extensive areas at the extreme southeast of the outcrop. Striations extend over a distance of more than 70' (21m), while a series of crescentic gouges and fractures reflect the direction of ice movement as predicted by Harris (1943). On this exposure striae vary between W. 31° N. and W. 37° N.

In view of the numerous exposures of striated bedrock on Stone Hill and its asymmetry in cross section with regard to the known direction of ice movement it is considered to be a recently resurrected Late Palaeozoic *roche moutonnée*. Minor post-exhumation modification of the hill has occurred in some areas.

b) *Crozier Hill*

(i) *Introduction*

Crozier Hill, a distinctive and prominent feature of the lower Inman Valley, was first described by Howchin (1926), who interpreted it as a huge *roche moutonnée*, nearly 1 mile (1.6km) long, and 528' (158m) high. The evidence tendered by Howchin (1926) in support of a glacial origin for the hill was threefold; pronounced asymmetry of the hill, surrounding glacial deposits, and an erratic northwest of the hill resembling the bedrock of the hill, from which it may have been plucked.

With one exception (Twidale, 1968) Howchin's interpretation has been unquestioned. Crawford (1959) considered it a *roche moutonnée* because of its gentle southeast side (*stoss* side) and its precipitous northwest aspect, which he claimed displays glacial plucking. Campana and Wilson (1955) supported its proposed glacial origin when they described it as a glacial rock bar, while Guppy (1943) also accepted it as a *roche moutonnée*. In describing presumed glacial features in the Snowy Mountains, Browne and Vallance (1957) actually cited Crozier Hill as a classic example of a *roche moutonnée*, with which they compared similar but much smaller forms in the Australian Alps.

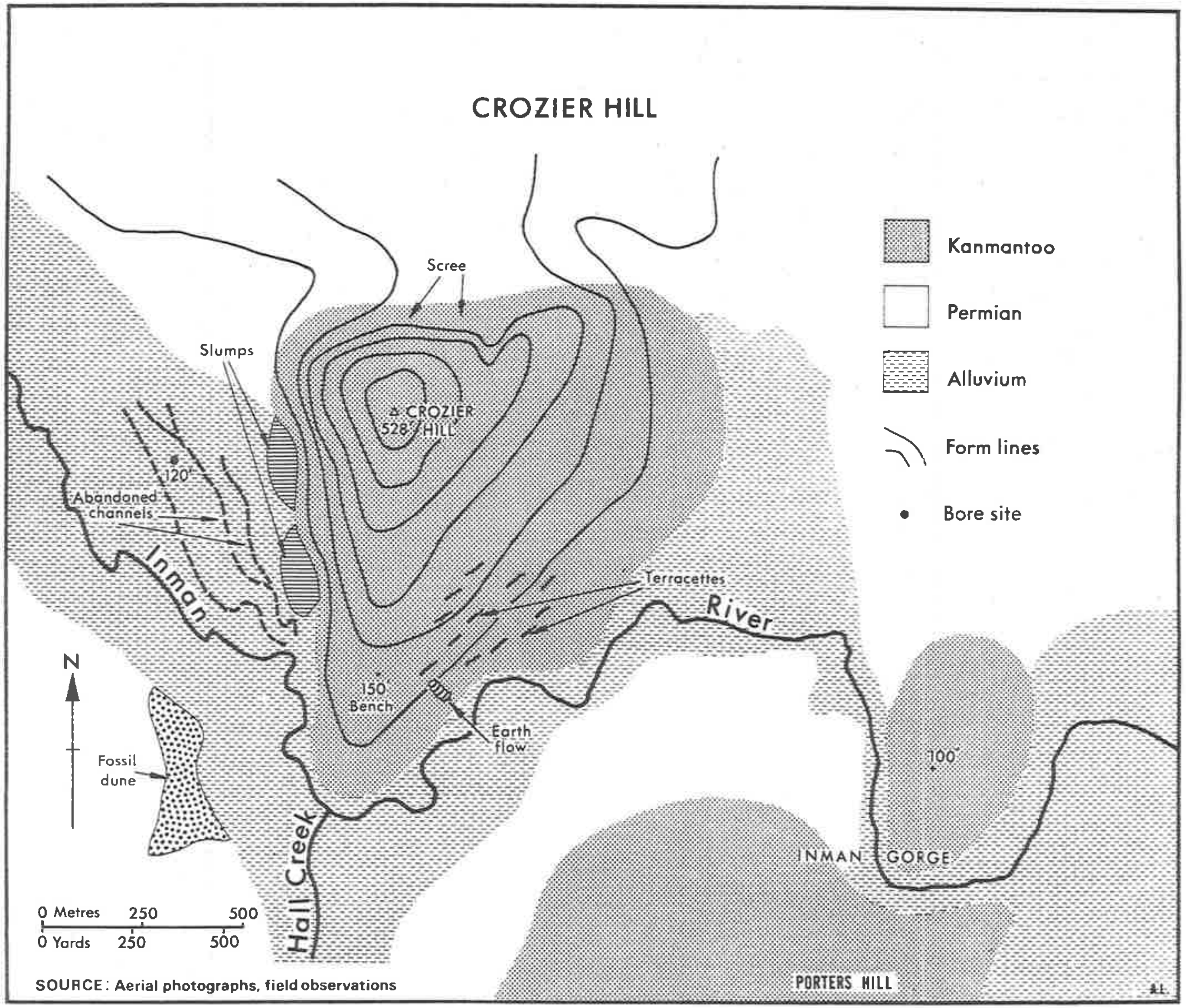
However, an alternative explanation of the morphology of the hill has been suggested by Twidale (1968), which accounts for the directly observable evidence. Structure is invoked to account for the asymmetry of Crozier Hill, with bedding dipping gently to the southeast, giving rise to a cuesta-form with a gentle southeastern slope and a broken, steeper scarp face to the northwest. The broken appearance of the northwestern slope, together with the scree which abounds on this part of the hill, are interpreted as the result of weathering under non-glacial conditions.

It was noted by Bourman (1969) that abandoned channels of the Inman River, recognisable on aerial photographs and in the field, illustrate that this stream formerly flowed at the northwestern and western base of the hill, which it may have undercut causing considerable steepening of the slope. Others account for this solely in terms of glacial action (see Figure 22).

(ii) *Discussion and new evidence*

Although the hill does exhibit a *roche moutonnée* form, and although its asymmetry, in view of the known direction of ice movement, is as expected, the morphology of the feature

FIGURE 22


CROZIER HILL
Kanmantoo
Permian
Alluvium
Form lines
Bore site
Scree
Slumps
CROZIER HILL
528'
120'
Abandoned channels
Inman
Terracettes
River
150' Bench
Earth flow
N
Fossil dune
Hall Creek
100'
INMAN GORGE
0 Metres 250 500
0 Yards 250 500
PORTERS HILL
SOURCE: Aerial photographs, field observations

alone is insufficient evidence on which to base its origin.

The bedrock underlying Crozier Hill appears to be quite variable, with some stronger metasandstone beds standing out in strong contrast to less resistant lithologies. This is reflected in the varied descriptions of it in the literature (Howchin, 1926; Campana and Wilson, 1955; Crawford and Thomson, 1959). Regardless of the precise nature of the bedrock, it is insufficiently distinctive to be used effectively as a source area for indicator erratics, as similar bedrock outcrops between Crozier Hill and Callington (Thomson, 1969). Moreover, evidence below will show that in this area local ice movement was almost due west, while a northwesterly flow would be required to explain the siliceous quartzite erratic northwest of Crozier Hill, if this were its source.

Presumed glacial and fluvioglacial sediments occur in close proximity to Crozier Hill, abutting it on the east and north. However, to the southeast, sediments previously interpreted as glacial, including those of Newland Hill and the Waitpinga drainage basin, have now been shown to be post-glacial[1] formations (Bourman and Lindsay, 1973). That other deposits in this area may be reworked glacial and fluvioglacial sediments is distinctly possible. Nevertheless, the only manner in which a Late Palaeozoic landform could be preserved in the present landscape would be by burial and subsequent recent exhumation. The possibility of Crozier Hill being a resurrected landform is considered below.

Crawford (1959) did not present incontestible evidence for plucking which he maintained is evident on Crozier Hill. Although the steeper side of the hill has a broken and craggy appearance, and fragments of bedrock litter the surface, this situation is quite common on many other bedrock outcrops of Fleurieu Peninsula. The inclination of structures in the rock, together with blocky jointing gives rise to accumulations

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[1]In this thesis 'post-glacial' refers to post-Late Palaeozoic glaciation.

of rock resembling products of freeze-thaw weathering. However, these deposits could have developed under present conditions.

According to the Encounter map sheet, 1:63360 series (Crawford and Thomson, 1959) Crozier Hill is underlain by a syncline, and four readings indicate that bedding dips to the southeast and S.S.E. at angles between 65° and 75°. Such dips might be expected to give rise to a hogback rather than to a cuesta-form as suggested by Twidale (1968). However, the dominant structural control of Crozier Hill is a secondary foliation. Intense and complex folding of the Kanmantoo Group metasediments has, in many areas, complicated the interpretation of bedding. Photolineaments in the bedrock, broadly parallel and constant for considerable distances, and clearly evident on aerial photographs and in the field, are often the result of cleavage rather than bedding. On Crozier Hill, the secondary foliation dips at a gentler angle than the bedding. The dominance of this structure is clearly evident when viewed from the southwest (Plate 16), although from the east the secondary foliation appears almost vertical. Nevertheless, it is quite possible that the morphology of Crozier Hill is due to the development of a cuesta-form, developed as a result of the attitude of the secondary foliation.

Crozier Hill was considered a glacial rock bar by Campana and Wilson (1955), closing off the Back Valley and Inman Valley glacial basins to the east. Bores in Back Valley penetrate to considerable depths and geophysical data confirms the presence of a glacial basin in this area (Crawford, 1959; Morony, 1971). No records of bores sunk in close proximity to Crozier Hill are held by the Department of Mines. However, interviews with local landowners revealed that in 1962 a bore was sunk near the Inman River, almost due west of the trig. point on Crozier Hill. The bore intersected dark loam of the river flats and blue clay and white sand, in which it was closed off at a depth of 120' (36m), still above basement rocks. A cross section drawn through the hill from east to west indicates that the steep western slope of Crozier Hill continues below the river flats.

An east-west section was chosen because this appears to have been the direction of local ice movement. First, striations on a granite glacial pavement at Port Elliot 5 miles (8km) to the east of Crozier Hill trend east-west; secondly glacially smoothed bedrock on the southern wall of Back Valley indicates a local ice movement of W.S.W. (Crawford, 1959); and thirdly erratics 1 mile (1.6km) north of Crozier Hill have possible source areas near Port Elliot and Middleton directly to the east. Howchin (1926) stated that the hill is precipitous on all sides but the southern. However, the eastern slope is quite gentle as is demonstrated by the fact that this is the only side which affords access to the summit in a conventional vehicle. Thus the east-west asymmetry of Crozier Hill is compatible with a *roche moutonnée* morphology.

As the bore was collared at an altitude of approximately 100' (30m) a.s.l., basement rocks in this area are well below sea level. It is most unlikely that the Inman River eroded the rocks to this depth during a lower stand of the sea for it makes its way to the coast via a steep-sided and narrow gorge, and there is no evidence of a buried former outlet of the river northeast of the Inman Gorge. A former outlet of the Inman River through the Waitpinga area, while flowing at a depth of at least 20' (6m) below sea level near Crozier Hill, is impossible in view of the basement rock outcrops and borelog information. There is no evidence of local faulting in the area and deflation cannot be seriously entertained as the process responsible for the steep-sided depression on the western side of Crozier Hill. Consequently, the most acceptable hypothesis for the origin of this basin is a glacial one.

Lewis (1947) points out that in the majority of instances the downslope side of *roches moutonnées* extends to a greater depth than the leading or upslope side. This appears to be the case with Crozier Hill, but detail about the subsurface form of the hill on the eastern side is lacking.

No striations on Crozier Hill have been recorded in the literature, nor were any located by the writer, despite numerous extensive searches. Surfaces of exposed or freshly exposed bedrock are markedly weathered and pitted[1], indicating the unsuitability of the rock to record and preserve striations. Often where striations have been removed by weathering, friction cracks are still present (Harris, 1943), but these too have been removed, if they were ever there. A quite remarkable correlation between bedrock and presence of striated pavements occurs on Fleurieu Peninsula. The vast majority of pavements on Kanmantoo Group metasedimentary rocks occur on rocks of the Backstairs Passage Formation of Daily and Milnes (1971), which are characteristically very resistant, homogeneous, finely laminated quartzites exhibiting slump structures. Crozier Hill is not composed of rocks of this formation, so that it is unlikely that striated pavements will be found on it. Nevertheless, striae are well preserved on soft phyllite on the wall of a quarry in the Tookayerta Creek Valley (Maud, unpub.).

In addition to striated pavements, a search for exotic boulders on Crozier Hill was undertaken, but the only loose boulders observed on the surface of the hill are those broken away from the bedrock which underlies the hill.

Despite the absence of striated pavements and exotic boulders on Crozier Hill, there is considerable evidence supporting the view that it is an exhumed landform, explaining why it may be manifested in the present landscape, despite the great passage of time since its

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[1] This would also militate against the preservation of a Late Palaeozoic landform through to the present.

possible formation. Sediments related to the glaciation juxtapose Crozier Hill to the north and northwest at elevations up to 375' (125m) and further inland they extend above the height of the hill. Moreover, the presence of small outcrops of glacial or fluvioglacial deposits up to 1000' (300m) a.s.l. (Howchin, 1910b; Guppy, 1943; Maud, unpub.), suggests that these constituted part of the pre-Tertiary or Tertiary erosion surface, in which case they would have masked Crozier Hill completely. A bench on the southern extremity of Crozier Hill at a height of 150' (45m), and a slip-off slope presumably cut by the Inman River, together with the height of the Inman Gorge, suggest that the stream during the exhumation of Crozier Hill flowed at least some 150' (45m) to 200' (60m) above the present stream course, prior to the cutting of the Inman Gorge. An undoubted resurrected *roche moutonnée* displaying numerous exposures of glaciated bedrock, Stone Hill, occurs only 3 miles (4.8km) north of Crozier Hill. Stone Hill has similar structure and asymmetry to Crozier Hill, and is at a similar elevation, but is not so completely exhumed.

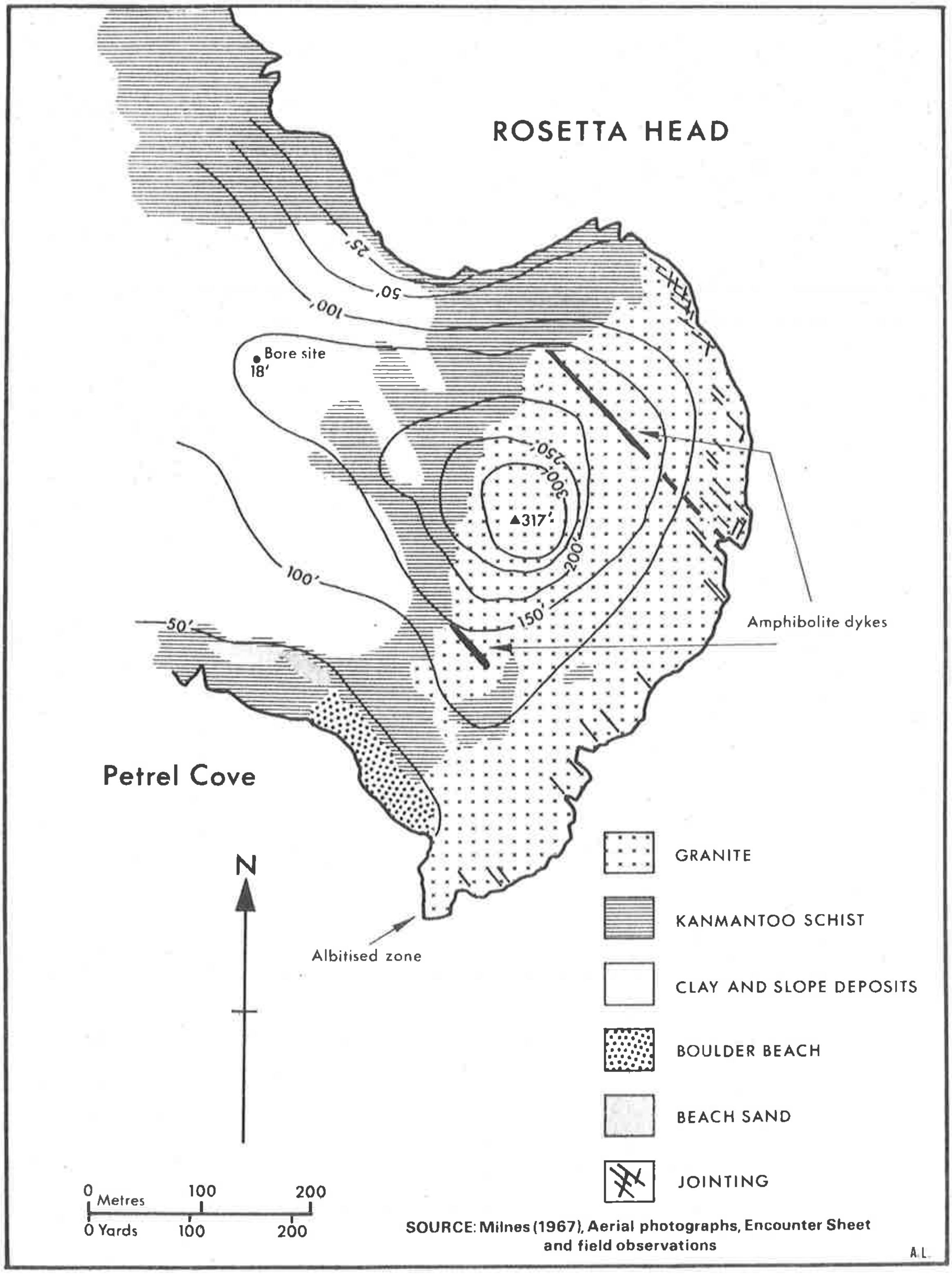
If Crozier Hill is an exhumed Late Palaeozoic *roche moutonnée* it has undergone considerable modification since being stripped of the overlying glacigene sediments. In areas where the Inman River abuts the base of the hill, mass movements have been initiated by slope steepening. Two major slumps have occurred on the western face of the hill, while on the southern side the hill face is creased with numerous terracettes. An erosional bench and a slip-off slope on the southern tip of the hill have developed as a result of post-glacial stream activity, and several small valleys are actively dissecting the hill on its southeastern side. Weathering of the hill since exposure has also caused considerable modification.

(iii) *Conclusion*

Although there is no unequivocal evidence of a glacial origin for Crozier Hill, in the form of striated pavements, exotic erratics, and undoubted plucking, nevertheless there is considerable inferential evidence suggestive of glacial activity. Overdeepening on the western side, demonstrated by borelog evidence, is perhaps the most compelling. The proximity of an undoubted exhumed *roche moutonnée*, and evidence of resurrection support the glacial hypothesis, although some of the deposits related to the glaciation may actually be younger, reworked sediments. The discovery of an erratic, similar to the bedrock of the hill, northwest of the hill is not critical as this rock type has a broad distribution. While the asymmetry of the hill may be explicable in terms of structure, this does not preclude a glacial origin as this structural situation would have proved ideal for the formation of a *roche moutonnée* (Carol, 1947; Embleton and King, 1969). While the steep northwestern and western aspect of the hill may be the result of glaciation, certainly more recent stream processes have steepened these slopes. The original outlines of the hill have suffered alteration through mass movement, weathering and gully erosion.

If no direct evidence of glacial activity on the hill is found, the best approach to further research lies in the investigation of its subsurface form. On present evidence, however, it may be concluded that originally Crozier Hill was almost certainly an ice moulded feature, but that it has suffered considerable alteration since exhumation from beneath softer sediments which protected it for millions of years. On the basis of possible ages of the Greenhills erosion surface (Chapter IV) Crozier Hill may have been buried until the Middle or Late Tertiary, with the latter age favoured. The absolute amount of modification is unknown.

FIGURE 23


ROSETTA HEAD
Petrel Cove
Bore site
18'
25'
50'
100'
150
200
250
300
▲317'
100'
50'
Amphibolite dykes
Albitised zone
N
GRANITE
KANMANTOO SCHIST
CLAY AND SLOPE DEPOSITS
BOULDER BEACH
BEACH SAND
JOINTING
0 Metres 100 200
0 Yards 100 200
SOURCE: Milnes (1967), Aerial photographs, Encounter Sheet and field observations
A.L.

c) *Rosetta Head*

Ludbrook (1969b) followed Howchin (1910a) in describing Rosetta Head as a *roche moutonnée*, while Crawford (1959) claimed that it displays a crag and tail form. Howchin based his assumption on alleged glacial deepening on the landward side of Rosetta Head, and from natural exposures on the northeastern and southwestern sides of the feature, constructed a geological cross section (Figure 24).

In a preliminary study, Bourman (1969) examined the contact between the Kanmantoo metasedimentary basement rocks and the deposits called glacial till, and concluded that these deposits consist of relatively recent slope and alluvial deposits. The colluvium is formed of angular fragments of schist, which are set in grey-brown soil and alluvium. Clearly these deposits at the surface have been derived from the schist bedrock which outcrops immediately above. One exotic pebble was found loose at the surface, but this could have been emplaced by man, and was not considered critical.

Figure 25 illustrates that there are, in fact, two small depressions on the landward side of Rosetta Head, and the most westerly of these depressions is filled with a considerable depth of red alluvium, which bears striking similarities in elevation and nature to the red alluvium of the nearby Yilki terrace (Chapter III). If it is of similar age and origin to the alluvial fill terrace of the Yilki area, it is neither of glacial origin nor of Late Palaeozoic age. An uncomformable contact between weathered basement rocks and rounded but elongated pebbles, chiefly of metasiltstone, occurs in this western depression. The morphology and inclination of the discontinuity resemble that of the modern shore platform a few metres to the northwest. Consequently, the depression may have been partly developed by marine processes.

Because of the apparent absence of deposits related to the Late Palaeozoic glaciation in the Rosetta Head vicinity, the view that it is nothing more than a structural landform was

FIGURE 24

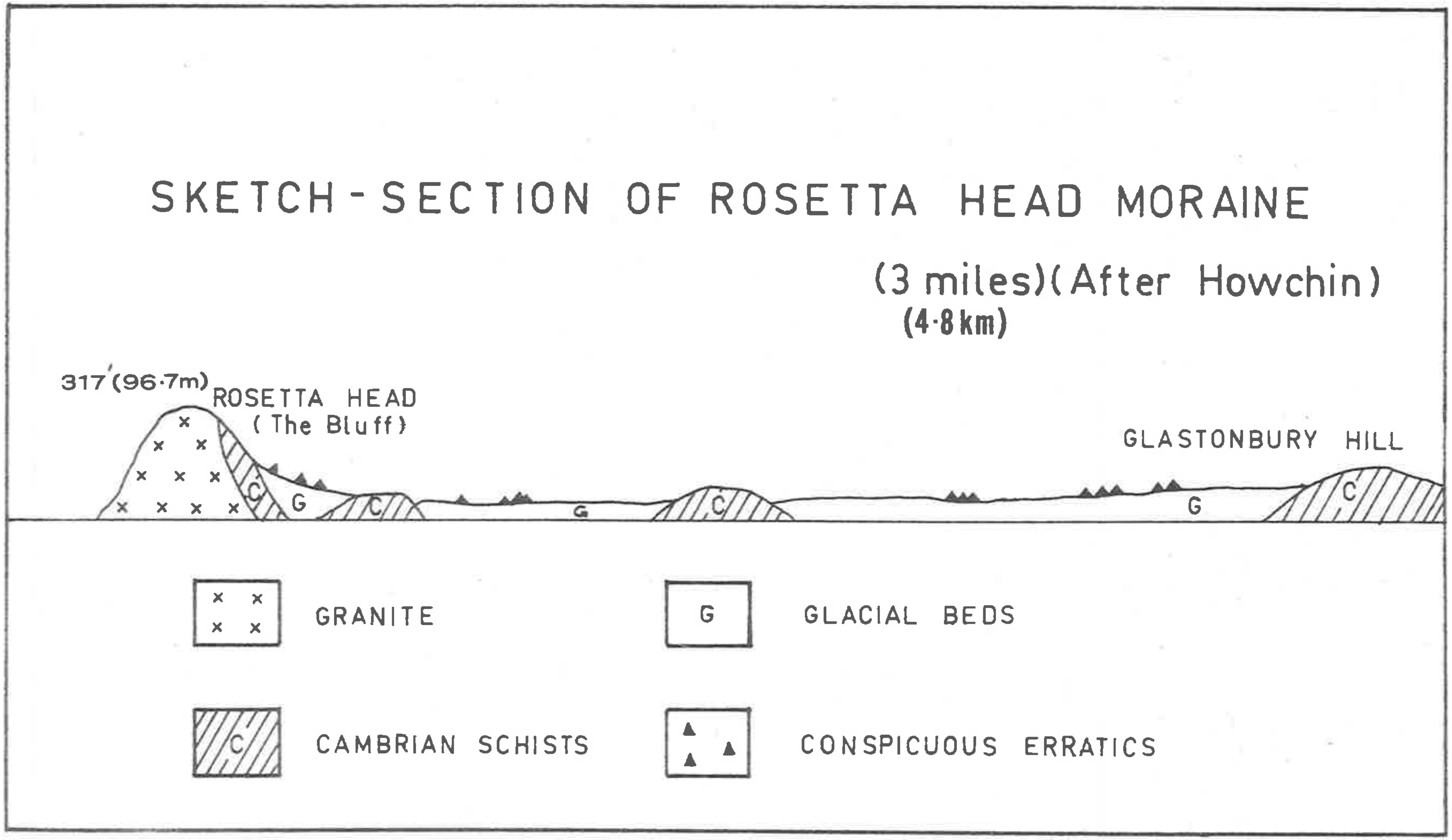
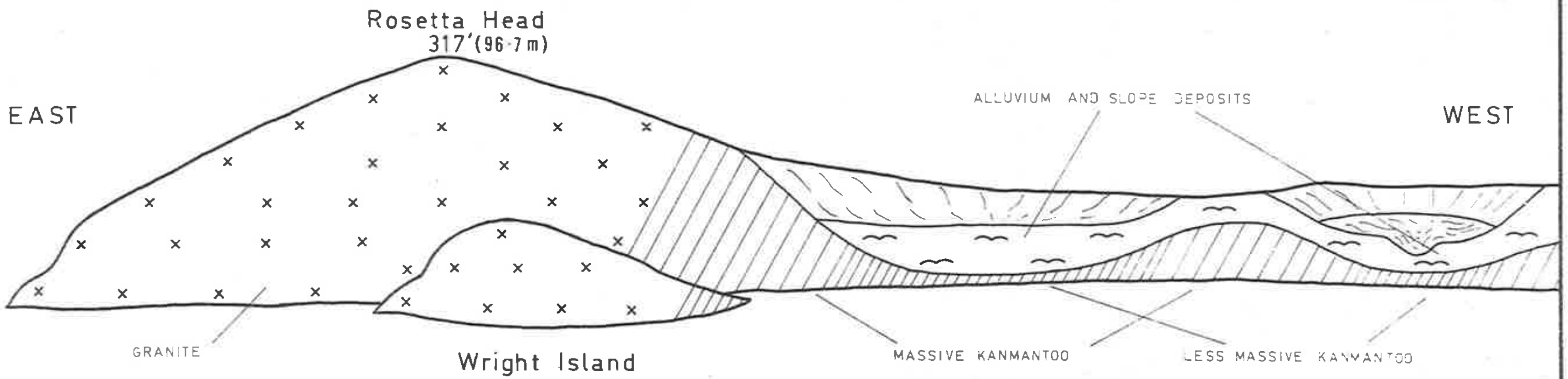

SKETCH-SECTION OF ROSETTA HEAD MORAINE
(3 miles)(After Howchin)
(4·8km)
317'(96·7m)
ROSETTA HEAD
(The Bluff)
GLASTONBURY HILL
C
G
GRANITE
GLACIAL BEDS
CAMBRIAN SCHISTS
CONSPICUOUS ERRATICS

FIGURE 25

Cross Section of Rosetta Head



considered (Bourman, 1969). The granite outcrop of Rosetta Head possesses considerable resistance, especially as it is massively jointed, and underlies the highest portion of the boulder-strewn prominence. The formation of two small bedrock depressions on the western side has been strongly influenced by structural controls, for the axes of these depressions broadly follow both the strike and cleavage of the basement rocks. Further structural control of the morphology of these depressions is in evidence, for they are underlain by finely bedded metasediments and bounded by massive and resistant outcrops on the edges. Under these structural conditions glacial activity need not be invoked to explain the present morphology of Rosetta Head, although ice would have exploited these weaknesses as effectively as non-glacial processes.

Crawford (1959) cited Rosetta Head as an example of a crag and tail because of the trail of granite boulders, interpreted by him as erratics, on the landward side of the feature. But the granite boulders, which are in various stages of progression down the landward slope of Rosetta Head are more simply explained in terms of continuing mass movement from the granite outcrops. The micaceous clays in which the boulders are sometimes set may have derived from the weathering of both the granite and the Kanmantoo Group of metasedimentary rocks.

Although a striated pavement has been located on granite at Port Elliot (Milnes and Bourman, 1972) no striations have been observed on Rosetta Head. In order further to investigate the problem of alleged glacial origin, augering was carried out, to determine if the basin forms exposed on the sides of Rosetta Head are continuous through the feature and if they are filled with glacial deposits.

Augering to depths of 14' (4.2m) and 20' (6m) penetrated deposits of sands, clays and pebbles. Samples were collected from eighteen different levels in the 20' (6m) hole and carefully examined. The long axes of the pebbles varied between about 1" (2.5cm) and 2" (5cm) and in all 282 pebbles were recovered, of which 86% were faceted, polished or striated. Flint (1957) noted that usually only about 5-10% of stones in till were clearly of glacial origin as only the more resistant managed to preserve evidence of glacial action. Some of the facets on the pebbles recovered from the auger holes on Rosetta Head may have been due to structures in the rock, explaining the inordinately high percentage of faceted pebbles in this deposit. Only a few are clearly striated, and these, using the criteria[1] of von Engeln (1930) are clearly glacial pebbles.

Among the pebbles recovered at least five exotic rock types occurred, these being porphyry, pink quartzite, light coloured quartzite, banded chert, arkose and gneiss. Thus as the area was ice covered during the Late Palaeozoic it may not seem unreasonable to suggest that Rosetta Head is indeed a glacial landform. However, this question is still not completely resolved.

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[1] 'The characteristic features of such type faceted and striated pebbles are: (1) the roughly triangular shape in plan with the facet of the largest area and that which is flattest down; (2) the pointed but scour-snubbed nose at the apex of the narrowest angle of the bottom facet; (3) an only slightly scoured or hackly back side above the base line of the bottom triangle; (4) a tendency to a hump form of the top side of the flat iron with (5) lateral facets running off towards the snubbed point; (6) chipping or nicking on the underside or at the apex of the point; (7) a tendency of the striations of the lateral facets to be directed diagonally downward toward the point; indications that variations from the norm or failure to develop one of the features in a well processed pebble are due to a particular and still obvious configuration of the original fragment or to the nature, rock structure and composition of the specimen'. (von Engeln, 1930)

Sediments from the auger holes on the saddle of Rosetta Head were subjected to mechanical analysis (discussed in Chapter IV). The results of this mechanical analysis demonstrate that the sediments are poorly sorted and are most likely of fluvial origin (Folk, 1968). As glacial pebbles were found associated with these sands, the deposits in the small depression on the landward side of Rosetta Head are fluvioglacial deposits, or reworked glacial deposits.

At King Point, 1.5 miles (2.4km) southwest of Rosetta Head, Crowell and Frakes (1971a) identified fluvioglacial deposits in a northeast-southwest trending valley, and noted that the direction of flow during deposition was from the northeast, paralleling the axes of the valleys landward of Rosetta Head. That the valleys at King Point and Rosetta Head were once continuous is quite possible, being later truncated by marine action. In any case it seems likely that the deposits landward of Rosetta Head are not of glacial till, but are fluvioglacial or reworked glacial deposits. Thus the possibility remains that the present form of Rosetta Head is not a direct reflection of Late Palaeozoic glacial action, but a consequence of structural influences and non-glacial processes.

If, however, Rosetta Head is of glacial origin, and this possibility cannot be completely discounted, then it has been considerably modified since glaciation. In view of the general movement of ice from the east and southeast, the morphology of Rosetta Head is not consistent with *roche moutonnée* asymmetry (Carol, 1947), although *roche moutonnées* with reversed asymmetry are not unknown (Demorest, 1937).

Coastal erosion involving cliff retreat by as much as 200' (60m) has steepened the seaward side of Rosetta Head since the Late Palaeozoic, while a buried bedrock depression occurs on the landward side. By taking account of these factors it is possible to reconstruct the morphology of Rosetta Head to resemble a *roche moutonnée*.

Evidence from King Point and Newland Head suggests that sea level during the Pleistocene stood at least 100' (30m) a.s.l. At this level Rosetta Head would have formed a granite island, and stood in a similar relationship to the mainland as does Granite Island today. Calcareous crusts on the saddle of Rosetta Head may be related to this higher stand of the sea and beach sand in spit or tombolo form may have formed in this area. The relatively level surface landward of Rosetta Head is probably due to marine activity at this level (see Chapter III).

Hence because of the immense period of time since its formation, if Rosetta Head had been glacially formed, so much post-glacial modification has occurred that simple interpretation of Rosetta Head as a glacial landform of Late Palaeozoic age is questionable.

d) *Backstairs Passage*

Benson (1911), noting the occurrence of glacial deposits, either side of Backstairs Passage, considered that it is a partly resurrected Late Palaeozoic glacial valley, now drowned. Although aware that faulting may have been the cause of this topographic low, he relegated it to a minor role, for he had observed no evidence of a tectonic origin for the passage. As the passage was interpreted as a glacial feature the Pages were considered to be *roches moutonnées*.

After traversing the coast of Fleurieu Peninsula from Sellicks Hill to Victor Harbour, Madigan (1925) supported the glacial origin of Backstairs Passage proposed by Benson. Again, evidence of faulting parallel to the passage was not found.

Twidale (1968,p.56)favoured a tectonic origin for the passage, suggesting that it may be related to a major fault, as the passage falls directly in line with postulated faults in the seismically active 'ankle' of Yorke Peninsula, distinct breaks in the uplands of Eyre Peninsula near Cleve and the epicentre of the Beachport earthquakes. In addition, the

Backstairs Passage area is seismically active (Twidale, 1968, p.54; Sutton and White, 1968). Working on Yorke Peninsula, Crawford (1960), found evidence of an ancient lineament trending southeast through the passage, thus supporting the structural theory. However, Campana, Wilson and Whittle (1953) in mapping the geology of Fleurieu Peninsula observed no major transverse faults, as might be expected if Backstairs Passage is a tectonic depression. Campana and Wilson (1955) considered it a submerged Permian depression.

Detailed soundings of Backstairs Passage enabled Bauer (1959) to construct an accurate map and several transverse sections of the passage. These revealed steep sides and a relatively flat bottom topography. Depths of approximately 200' (60m) occur only 550 yards (495m) from the island and are maintained to within 900 yards (810m) of the mainland. Bauer (1959) recognised that such morphology is in sympathy with either a structural or a glacial origin but suggests that the passage is not simply a drowned stream valley. He suggested that the deepest portions of the passage off Cape St. Albans 260' (78m) and Cape Jervis 230' (69m) occur where constricting sides or bosses of rock would have caused greater erosion by a northwesterly moving ice sheet. Nevertheless he points out that these depressions may be the result of subaerial erosion by streams during the lower stands of the Pleistocene seas, or by submarine tidal scour. Sprigg (1964) described significant scoured rip channels excavated in soft Permian sands and shales, offshore from Cape Jervis, to which the depressions described by Bauer may be related. Sprigg (1964) stated that in this area Backstairs Passage definitely appears to be a partly re-excavated fossil Permian valley.

The suggestion that the Pages, which are clearly visible from Ridgeway Hill, may be partly submerged, exhumed *roches moutonnées* (Benson, 1911) is an interesting one. The submarine contours of the passage do not reveal any pronounced asymmetry in the Pages which stand about 100' (30m) above the level of the floor of the passage. The North Page is roughly circular in shape with a diameter of 900 yards (810m) while the South Page is 1.2 miles (1.9km) long and 670 yards (600m) wide, trending N.N.E.-S.S.W. The Pages fall within the range of dimensions of Crozier Hill and Stone Hill, possible and proven *roches moutonnées* respectively. Nevertheless the possibility remains that the Pages represent the tops of erosional remnants formed by non-glacial processes.

Bauer (1959) claimed that corings of the Passage bottom demonstrating glacial clay covering a bedrock floor would settle the question in favour of a glacial origin. Glacial clays have been found underlying the floor of the passage down to depths of 240' (72m) (Sprigg and Stackler, 1965), and this is not surprising in view of the depth of glacigene sediments proven in bores on Fleurieu Peninsula and Kangaroo Island. However, the origin of Backstairs Passage is not resolved, as the glacigene sediments under the passage may have been carried to this depth by tectonic sinking.

Recent work by Daily and Milnes (1971, 1972, 1973) in which detailed stratigraphic mapping of the Cambrian Kanmantoo Group metasedimentary rocks of Fleurieu Peninsula and Kangaroo Island was carried out showed that the structures in the mapped rocks are continuous across the passage. For example, a regional northeasterly plunging anticline forming the core of a thrust block on Dudley Peninsula seems to be continuous with a similar anticline directly across the passage on Fleurieu Peninsula. No faults parallel to the passage were noted.

The continuity of strata across the passage rules out the possibility of transcurrent faulting in this area, but not normal or reverse faulting. The present steepness of the cliffs on either side of Backstairs Passage appears to be due to marine erosion, for spurs, apparently truncated by marine erosion, are common along the coast. Hence it is possible that the sides of an original fault trough have retreated under wave attack to their present position and that the fault zones are submerged.

Such a possibility can only be easily investigated by geophysical means. No detailed geophysical work has been carried out in the passage proper, though work here is at present under way (W. Stuart - pers. comm.). Geophysical investigations of St. Vincent Gulf reveal submarine structures trending away from Yorke Peninsula towards the passage (Stuart and von Sanden, 1972), but near the passage they fade out under an increasing cover of sediments (W. Stuart - pers. comm.). Broad scale gravity readings which cover the passage reveal that it is underlain by a gravity low, but there is insufficient detail to reveal the presence of faults.

Apparently the most compelling evidence for a structural origin for Backstairs Passage is the seismisity of the area (Twidale, 1968), for clearly earth movements of some description are occurring. But the problem is, in what direction are the movements taking place? On various lines of evidence Sprigg (1964) and Stuart and von Sanden (1972) have shown that arcuate northeast-southwest to north-south faults on the mainland join up with roughly east-west faults on Kangaroo Island. In addition to geophysical evidence for the link up, say between the Willunga Fault and the Cygnet Fault, submarine fault scarps have also been recognised. Clearly, the earth tremors of this region are more likely to be related to faults transverse to the passage than to faults parallel to it.

Thus in view of the absence of clear evidence favouring a structural origin for the passage, and the distribution of glacial sediments and features, a glacial origin is more acceptable. However, the structures trending towards the passage from Yorke Peninsula may have guided and been exploited by north-westerly moving ice. Subsequent to exhumation and drowning the walls of the passage have been modified by marine processes while parts of the floor have received sediments, and other parts have been scoured by tides.

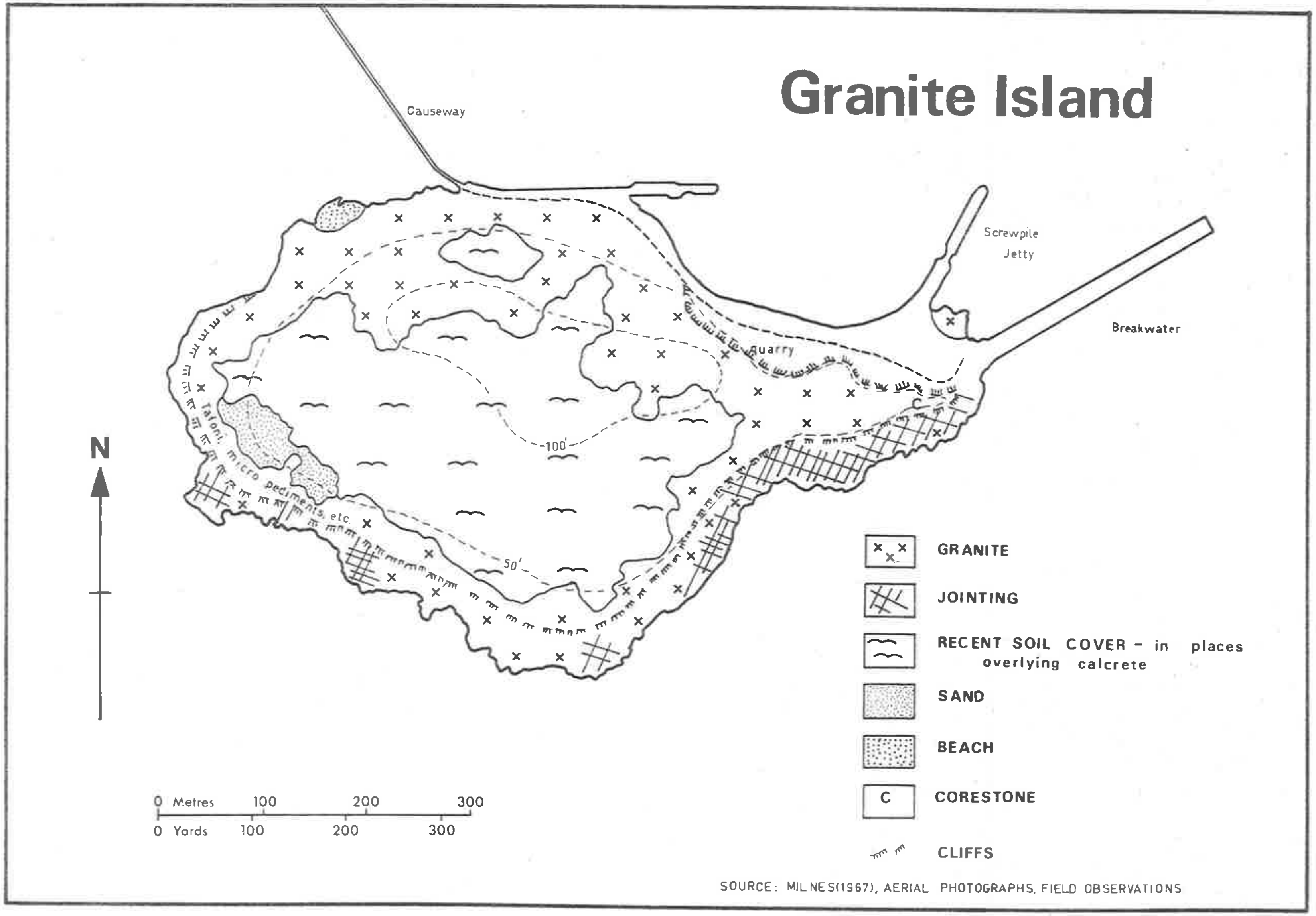
e). *Granite Islands*

The granite islands of Encounter Bay have been described as ice smoothed and abraded (Howchin, 1926; Howchin and Cleland, 1931; Guppy, 1943; Crawford, 1959). However, to date, no direct evidence of glacial activity on any of the islands has been observed. Although the present distribution of granite outcrops in the Encounter Bay area may have been broadly determined during the Late Palaeozoic (Milnes and Bourman, 1972), post-glacial processes have obliterated traces of glacial action on the islands.

The largest of the islands is *Granite Island*, which is linked to the mainland by a causeway. Soil and sand extend over a large area of the flattish summit of the island, in many areas overlying calcrete. No sedimentary structures were observed in the sand deposits, but their fineness and well sorted appearance suggests an aeolian origin. As there is insufficient calcium carbonate in the Encounter Bay Granites for massive calcrete development, a marine source for calcium carbonate seems to be most likely in this environment. No excavations penetrate the calcrete, but similar calcrete occurs on nearby Newland lowland, at Port Elliot and on Newland Head where it overlies dune and/or beach sands. Although the depth of these superficial (?) Quaternary deposits on Granite Island is unknown, clearly the summit morphology does not reflect glacial activity.

An excavation on the southeastern corner of the island has exposed two core-stones surrounded by *gruss*. These incipient tors developed by subsurface weathering, (Linton, 1955), are the only exposed examples known to the writer in the area (Plate 17). In other locations, such as the

FIGURE 26



Granite Island
Causeway
Screwpile
Jetty
Breakwater
Quarry
Tafoni, micro pediments, etc.
100'
50'
C
N
0 Metres 100 200 300
0 Yards 100 200 300
GRANITE
JOINTING
RECENT SOIL COVER - in places overlying calcrete
SAND
BEACH
C CORESTONE
CLIFFS
SOURCE: MILNES(1967), AERIAL PHOTOGRAPHS, FIELD OBSERVATIONS

Plate 17. Corestones of unweathered granite surrounded by gruss on the southeastern corner of Granite Island.

extensive faces exposed by quarrying of granite for breakwater construction, there is no indication of deep weathering. Here, however, joints are tight and very widely spaced. The weakly embedded tors, described above are surely a post-glacial phenomena, as they could not have survived the passage of a thick ice sheet.

Other minor post-glacial include *tafoni*, shield and boss forms and weathering pans. These features are best developed on the open ocean side of the island, suggesting that their distribution and development may be related to sea spray and rain driven by prevailing south and southwesterly winds.

Present marine processes have cut joint controlled bays and cliffs around the periphery of the island, especially on the southern side. As relative sea level has stood higher than at present other higher areas of the 110' (33m) prominence have been similarly affected.

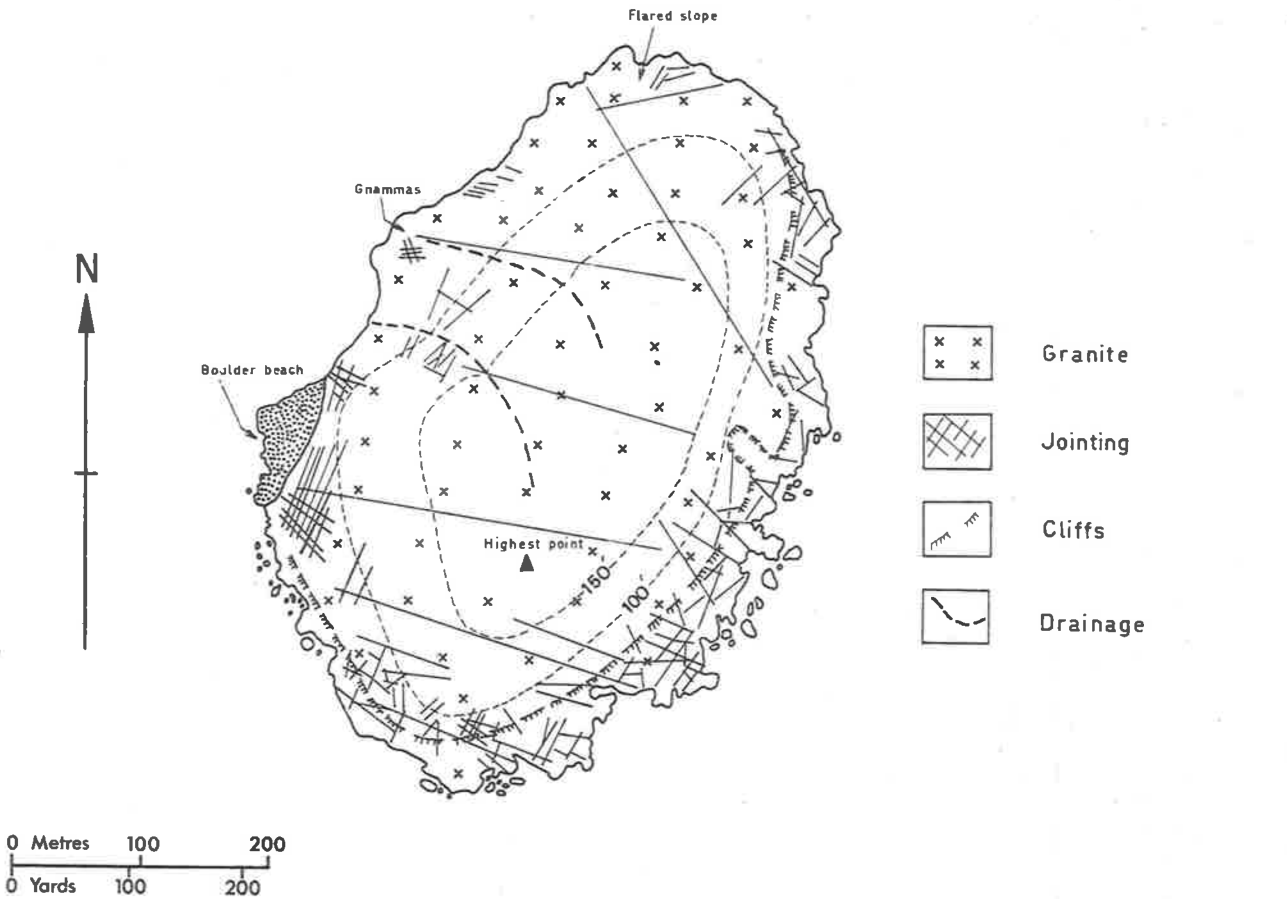
Thus no evidence of glacial activity on Granite Island has been observed to date, and other features on the island illustrate modification of the morphology of the island in post-glacial time.

West Island (Figure 27) which displays a very smooth and rounded appearance has been most frequently cited as an example of an ice-smoothed island. Like Granite Island, no areas of glaciated bedrock were noted. Similarly, shield and boss forms and gnammas as well as tors of disintegration and flared slopes attest to processes acting under non-glacial conditions. In transverse profile, West Island is markedly asymmetrical, but the asymmetry is disposed the opposite way for West Island to be a *roche moutonnée* given that the ice approached from the east and southeast. Although some *roches moutonnées* have been observed with reversed asymmetry (Demorest, 1937), the steeper ocean-facing side of West Island appears to be a result of marine cliffing processes.

The smooth whaleback form of West Island is shown on Plate 18, which also shows a massive sheeting plane trending through the island. Although there is not complete parallelism

FIGURE 27

WEST ISLAND



SOURCE : AERIAL PHOTOGRAPHS, FIELD OBSERVATIONS

Plate 18. West Island viewed from the southwest, revealing the presence of a major sheeting plane.

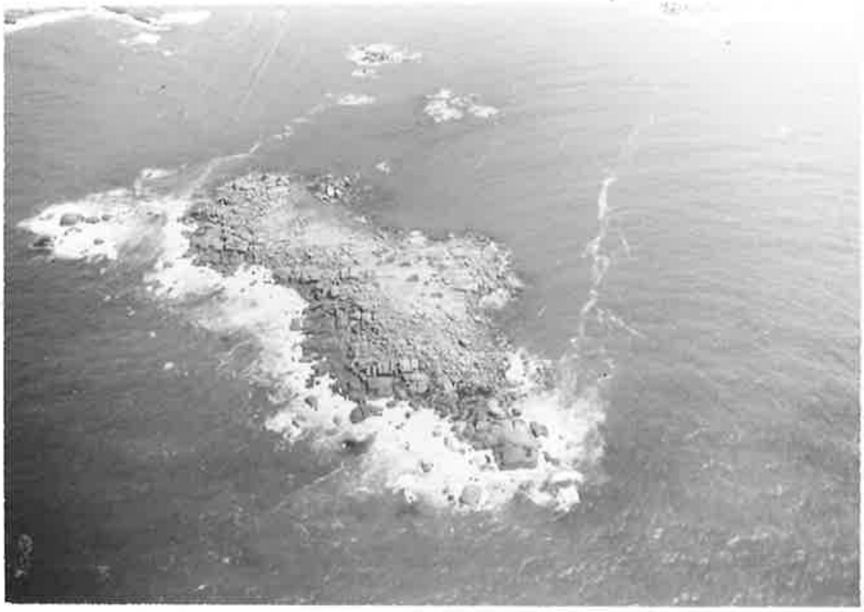


Plate 19. Aerial photograph of Pullen Island indicating the strong influence of jointing on its morphology.

between the sheeting plane and the topography of the island, clearly sheeting structures have played an important role in the development of its morphology.

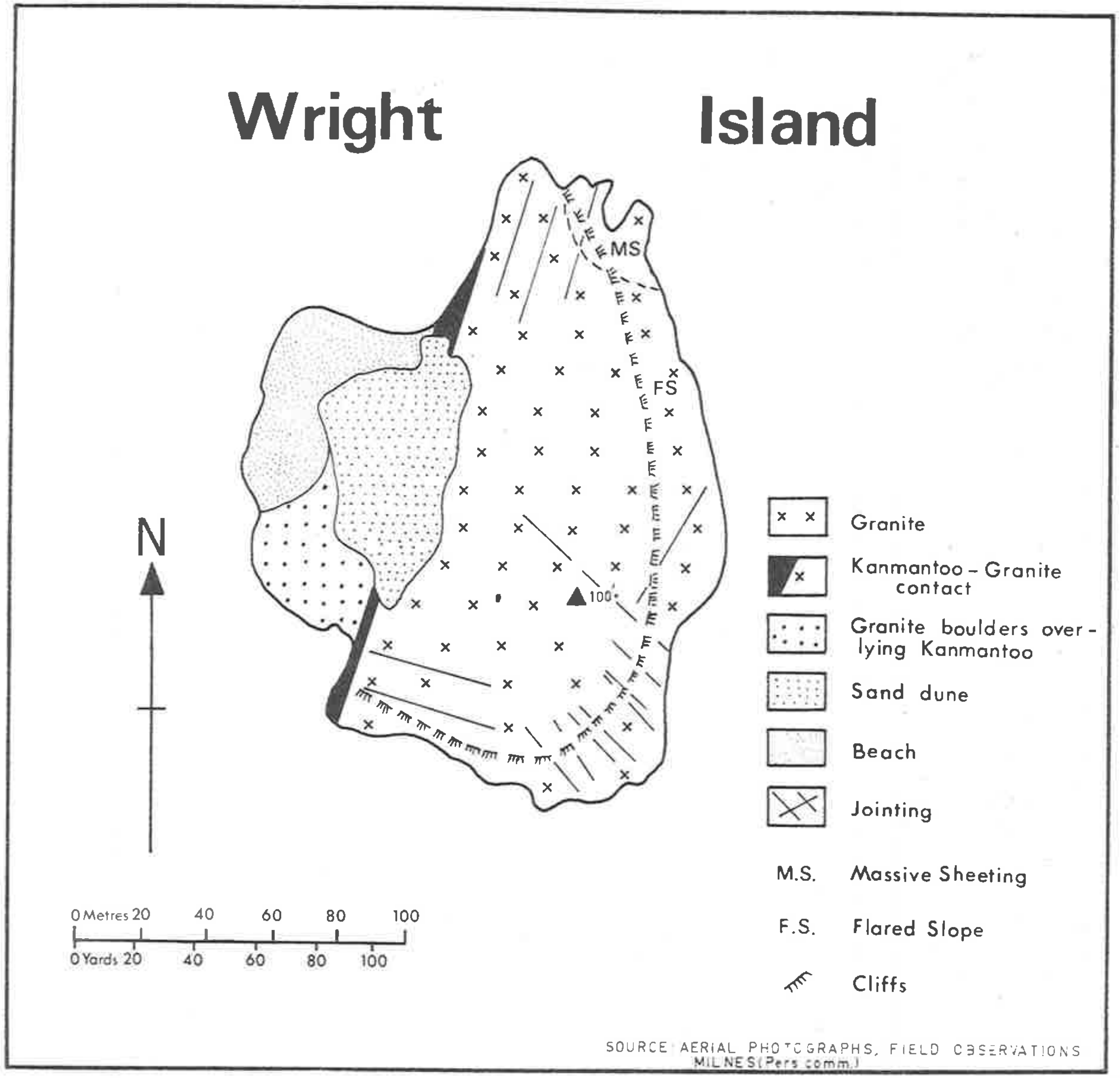
Jahns (1943) used sheet structures in granite as a measure of Pleistocene glacial erosion in New England. He noted relationships between sheeting structures and bedrock topography except on the south side (lee side) of granite hills, where he claimed that glacial erosion had steepened slopes. Numerous exposures in granite quarries showed thicker, less irregular and more horizontally disposed sheets with increasing depth. Sheet structures were interpreted as the result of offloading and Jahns (1943) concluded that sheeting broadly controls topography when denudation is slow and long continued, but is reoriented when strongly concentrated erosion creates rapid topographical change.

Sheeting structures may be the result of many processes (Twidale, 1971b), notable among them being compressive forces, which may account for discrepancies between sheeting structures and topography. Consequently, sheets at depth may not reflect erosion at the surface.

Three islands display sheeting planes clearly; Pullen, West and Wright Islands. Because of post-glacial modification of the islands, particularly by marine action, and because of the immensity of time since glaciation, it is not possible to draw conclusions from relationships between sheets and topography, especially with regard to possible glacial deepen-ing on the western sides of the islands, except that there are close relationships between the present broad scape topography of the islands and major sheeting planes. Moreover, such structures might cause similar morphology, with or without glaciation (see, for example, the description of the Pearson Islands in Twidale, 1971a).

Wright Island also has a pronounced asymmetrical profile oriented the wrong way to be a classic *roche moutonnée*. However, it is not necessary to invoke glacial processes to account for the shape of Wright Island, as structure and

FIGURE 28



Wright Island
MS
FS
100
N
0 Metres 20 40 60 80 100
0 Yards 20 40 60 80 100
Granite
Kanmantoo - Granite contact
Granite boulders over-lying Kanmantoo
Sand dune
Beach
Jointing
M.S. Massive Sheeting
F.S. Flared Slope
Cliffs
SOURCE: AERIAL PHOTOGRAPHS, FIELD OBSERVATIONS MILNES (Pers. comm.)

present processes can do this. The highest part of the island has a dome-like form apparently following massive sheeting planes. Where present marine processes are most active huge joint blocks support steep coastal cliffs, the slopes of which follow the joint planes closely. The gentler slopes of the landward side are underlain by smaller joint blocks and less resistant Kanmantoo Group meta-sedimentary basement rocks, for the granite/country rock contact passes through this part of the island (Figure 28). Waves refracted by the island sweep around both sides of the island, meeting on the eastern extremity where they have built up a small sandy beach.

The morphology in plan of *Pullen (Seagull) Island* is strongly influenced by jointing (Plate 19). Huge sheeting planes dip landward, while to seaward they have been truncated, suggesting the former presence of a huge dome structure extending far to the south. On Pullen Island spectacular examples of onion weathering, scattered isolated boulders and well developed weathering pits represent non-glacial processes.

Similarly *Seal Island* possesses a large number of apparently loose tors which could not have survived the passage of the huge ice sheet, which transgressed the area in Late Palaeozoic times. Clearly, the present morphology of Seal Island is not related to glacial processes.

The submarine topography of Encounter Bay reveals no evidence of deepening on the landward sides of Granite, West, Wright and Pullen Islands, which might be used to indicate the effects of glacial erosion. However, a deep area occurs landward of Seal Island, though this feature may be the now drowned former valley of the Inman River.

It is quite possible that glacial bedrock depressions occupy the regions landward of the islands, but they are filled with glacigene, marine and fluviatile deposits. Certainly much calcareous sandstone, capped by calcrete underlies a great deal of the critical areas. Bores near the mouth of the Inman River, directly inland from Granite Island, have reached almost 150' (45m) below sea level without encountering bedrock, suggesting glacial deepending in this area. Below 40' (12m) the sediments have been logged as glacigene. Alternatively the sediments may be non-glacial fluviatile deposits occupying a river valley cut along the structural boundary of the granite/country rock contact during a lower stand of the sea.

The discovery of a glaciated bedrock surface on granite at Port Elliot (Milnes and Bourman, 1972) throws some light on this question, as well as on several other features significant in the geomorphic evolution of the region.

The basement rocks of the area, as part of the Adelaide Geosyncline, were folded and metamorphosed at a time broadly coincidental with granite emplacement (Milnes, 1973). The glaciated pavement on the granite outcrop together with the abundance of erratics throughout South Australia, derived from the Encounter Bay Granites, indicates that the granite, which had been intruded at depth, had been exposed before or during the Late Palaeozoic glaciation. Xenoliths of metasedimentary rock of similar lithology to the surrounding country rock have been interpreted as roof pendants (Milnes and Bourman, 1972), which suggests that the presently exposed granites were close to the original roof of the pluton and form the northwestern wall and roof of a granite mass, which may have had greater extent than now apparent. Sheeting evidence for this former extension has already been mentioned. Thus the total amount of erosion of the granite at Port Elliot is probably limited.

Features of the granite mass suggest that it may have originally cooled at a depth of less than 6 miles (10km) (Milnes, 1873), this overlying cover of Palaeozoic rocks being removed by erosion in approximately 200 million years.[1]

[1] Harris and McGowran, 1971, suggest that reworked Devonian microfossils discovered at Waterloo Bay, Yorke Peninsula, had an origin in the Mt. Lofty arc.

Thus the fold belt, which developed during Early Palaeozoic orogeny, would have been severely denuded by the onset of glaciation.

Nevertheless, relief would have been considerably in excess of that at present, for glacigene sediments extending to depths of 575'(173m) and 300' (90m) have been logged in a basin northeast of Port Elliot (Crawford and Thomson, 1959) and presumed glacigene sediments extend approximately 965' (290m) below sea level (Howchin, 1926) in a glacial basin below Back Valley. Erosion of the present summit surface during the Mesozoic and Tertiary prevents a complete reconstruction of glacial relief, but it was probably more comparable with the Mount Kosciusko area today, rather than being occupied by young Apline mountains and irregular valley glaciers as suggested by Campana and Wilson (1955) and reiterated by Crowell and Frakes (1971). Striae directions over considerable distances are too constant to be formed by irregular valley glaciers (Milnes and Bourman, 1972). Furthermore, the characteristic, extensive and large scale basin and bar topography with a maximum demonstrable relief in excess of 900' (450m) (from the top of Crozier Hill to the bottom of the glacial basin underlying Back Valley, back to the elevation of the summit surface) would seem to require a huge ice sheet for its formation, rather than isolated valley glaciers.

Although none of the granite islands display direct evidence of glacial action and much evidence of post-glacial modification, the presence of a glaciated granite pavement at Port Elliot, overlain by sediments interpreted as glacigene (Milnes and Bourman, 1972), together with the occurrence of exotic erratics at the coast at King Beach and Rosetta Head and glacigene sediments near and below present sea level at King Beach, Chiton and Port Elliot, suggest that the granite islands may have been stripped of glacigene sediments only in recent geological times.
(?) Pleistocene beach and/or dune calcareous sandstone overlies glacigene sediments and granite at Port Elliot and

granite at Granite Island. In view of the glacigene outcrops at the coast, and the evidence for high Tertiary shorelines, exhumation may have occurred in the Late Tertiary or Early Pleistocene. If this is so, then the present broad distribution of granite outcrops was probably accomplished by Late Palaeozoic ice, exploiting structural and topographic features in the granite mass (Milnes and Bourman, 1972).

However, despite the evidence favouring the role of Late Palaeozoic ice in determining the broad outcrop pattern of granites in Encounter Bay, the present morphology of the granite islands cannot be interpreted as the result of glaciation, especially in view of the expression of non-glacial processes on them.

CHAPTER VII. CONCLUSION

The object of this investigation has been to map, describe and account for the origin of the morphological features of Southeastern Fleurieu Peninsula. Evidence of a wide variety of geomorphic processes including orogenic, fluvial, glacial, coastal and aeolian are manifested in the present landscape. These processes have acted on resistant igneous and metamorphic rocks, and less resistant alluvial, marine and glacigene sediments.

Many of the features in the landscape are of considerable antiquity, being inherited from Late Palaeozoic glacial activity and fromMesozoic and Tertiary erosion phases, which were interrupted by tectonism and eustatically controlled sea level movements.

Landforms such as Crozier Hill, Stone Hill, Rosetta Head, and the granite islands of Encounter Bay and certain granite boulders have been interpreted by some earlier workers as being of glacial origin. While in some cases there is clear evidence of glacial activity, in others the evidence is not equivocal as a considerable amount of post-glacial weathering and erosion has occurred. Structures have played an important role in the morphology of many of the features, which have been shaped by marine and fluviatile processes as well as possibly glacial.

Although striae may result from non-glacial processes (Embleton and King, 1968), the distribution and orientation of the striated bedrock surfaces of Fleurieu Peninsula leave little doubt that they resulted from glaciation. Similarly the widespread exotic boulders of Fleurieu Peninsula are glacial erratics. Apart from one or two recently exhumed *roches moutonnées*, carrying evidence of ice action, the interpretation of other features as glacial landforms must be approached with caution.

Planate surfaces of low relief, now situated at high elevations in the landscape attest to the role of fluvial erosion over long periods of time. The erosion of the high surface, which is underlain by laterite of probable Early Tertiary age, is assigned to the Cretaceous, and the low surface capped by ferricrete is considered to be of Pliocene age. Two sedimentary surfaces are Pliocene to Holocene in age. The surfaces and phases of tectonism have been dated by reference to Eocene and Oligocene(?)-Miocene marine transgressions.

Sea level varied dramatically during and since the Tertiary. Stranded and submerged coastal landforms, and marine and terrestrial deposits together with evidence of alternate periods of cut and fill in the lower reaches of the major streams of the area suggest that there was a eustatically-controlled fluctuating sea level during the Late Pleistocene and Holocene. Tectonic influences may be superimposed on these eustatic fluctuations. These findings are compatible with the results of research from other areas, supporting the view of eustatically-controlled world-wide sea level changes.

Climatic conditions fluctuated spectacularly throughout geologic time, attested to by the presence of glacial activity, laterite formation, presumably related to humid tropical climates, fossil parabolic dunes and converging river terraces.

The axial orientation of the fossil parabolic dunes of Newland Head lies 48° west of the present effective wind resultant suggesting that since the formation of the dunes there has been a northward shift of the climatic belt. The clifftop parabolic dunes migrated from the inlet of Waitpinga Beach to the west.

The fossil dunes are of Holocene age as are the converging terraces of McKnight Creek, which reflect a climatic influence. The dunes and the terraces may be coeval.

The evolution of the study area has been interpreted in terms of the observed field evidence. While in detail some problems remain unresolved, general hypotheses have been formulated, those found wanting have been eliminated and the most likely accepted in the light of the available evidence.

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