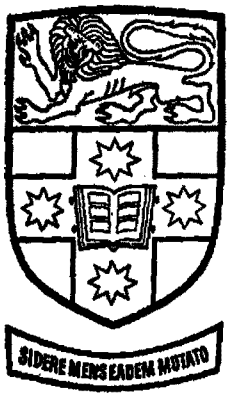
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ERRATA

The Quaternary History of Three Areas on the New South Wales Coast, Australia

By John R. Hails

P. viii, line 4	Stevens should read Strevens
P. 6, line 3	extend should read extent
P. 17, para. 3, line 9	indicate should read indicates
P. 17, para. 4, line 3	Creascent should read Crescent
P. 21, para. 2, line 2	for the most should read for most
P. 24, ~~para.~~ 3, line 1	settlement should read settlements
P. 26, para. 3, line 2	Pleistocene embayed should read Pleistocene) embayed
P. 27, line 2	(Figure 3.9) should read (Figure 3.10)
P. 29, para. 2, line 3	(near borehole 7). should read (near borehole 7),
P. 31, para. 2, line 3	Acacia soporae should read Acacia sophorae
P. 32, para. 3, line 2	mangrovers should read mangroves
P. 36, para. 1, line 7	Hails, 1965 should read Hails, 1965b
P. 36, para. 2, line 4	Halligan's (1908) should read Halligan's (1906)
P. 50, line 12	reponsible should read responsible
P. 56, para. 2, line 17	Shepard, 1963 should read Shepard, 1963a
P. 58, para. 2, line 15	Chapter 0 should read Chapter 9
P. 60, para. 3, line 8	Shepard (1963) should read Shepard (1963a)
P. 61, line 8	present should read prevent
P. 75, para. 4, line 3	Jennings, 1957 should read Jennings, 1967
P. 76, para. 2, line 11	strandard should read stranded
P. 86, line 7	floodbains should read floodbasins
P. 87, line 3	aluvial should read alluvial
P. 91, para. 2, line 7	noticable should read noticeable
P. 94, line 1	Melaleuca spp., should read Melaleuca spp.
P. 94, line 2	Plate 5.1B and 5.1C should read Plates 5.1B and 5.1C

P. 99, para. 2, line 2	uinterrupted should read uninterrupted
P. 102, line 15	Course 2 should read Course 2a
P. 103, Table 6.1, 3	now to the should read now restricted to the
P. 114, para. 3, line 3	on Trask should read of Trask
P. 127, last line	corasest should read coarsest
P. 134, line 4	Friedman (op. cit.) should read Friedman (op. cit.)
P. 135, para. 2, line 3	shape should read shapes
P. 135, para. 3, line 6	more than population should read more than one population
P. 145, line 4	Jones(1964) should read Jones (1946)
P. 146, two lines up	with micro-splitter should read with a micro-splitter
P. 150, para. 2, line 3	which according to should read which, according to
P. 153, line 4	complimentary should read complementary
P. 154, para. 3, line 4	persistant should read persistent
P. 157, para. 3, line 2	illustrate should read illustrates
P. 164, Table 8.4	Heamatite should read Haematite
P. 184, Table 9.2	quinqenervia should read quinquenervia
P. 185, Table 9.3	Melaleuca quinquenevia should read Melaleuca quinquenervia
P. 187, Table 9.4, 9	Lj-451 should read LJ-451
P. 189, para. 3, line 4	may be resolved should read may only be resolved
P. 190, line 8	New South Wales Coast should read New South Wales coast
P. 193, line 1	Harbors should read Harbours
P. 213	Connah, T. H. 1961 should read Connah, T. H. 1962
P. 215	Following reference to be added: Gill, E.D., 1966: New South Wales and Queensland Report in Australasian Research on Quaternary Shorelines, Aust. J. Sci., 28, 407-411.
Figure 3.2	Kay should read Key
Figure 3.4	Table 9.3 should read Table 9.4
Plate 3.2D	* Mineral seams should read Eolian-bedded mineral seams
Plates 4.1A - 4.1F, Last line	5.1E should read 4.1E

SUMMARY

A combined geomorphological and sedimentological study has been made of three coastal areas in New South Wales, Australia. The three areas, which differ geologically and physiographically, are the Mid-North Coast between Port Macquarie and Scott's Head, Broken Bay near Sydney, and Twofold Bay and neighbouring districts on the south coast. The main objectives of the study have been to examine the importance of oceanic and nearshore processes during the construction of sand barriers; to outline the geomorphological history of fluvial-deltaic plains and other depositional environments in relation to relative changes of the land and sea; to determine the significance and limitations of statistical parameters for distinguishing sedimentary environments, and to analyze the relationship between the concentration of heavy minerals and the following: longshore drift, eolian activity, and the shoreward movement of material along the sea floor during marine transgressions.

The study has shown that large sand barrier systems are generally absent from fairly steep and rugged sectors of the central and southern New South Wales coast, but are located on the north coast where they flank large fluvial-deltaic plains. Dual barrier systems, separated by inter-barrier lagoonal-swamps, have been located in the Mid-North region. An Inner Barrier is considered to be Pleistocene, and an Outer Barrier Recent (Holocene) in age.

So far, no evidence has been found to support the argument for a Holocene (Recent) high stand of the sea which has been reported in areas widely scattered around Australia, and commonly attributed to the post-glacial Hypsithermal period, 4000-6000 B.P. Accumulated evidence in the study areas suggests that the level of the sea has not risen appreciably since about 3500-5000 B.P. during which time the fluvial-deltaic plains prograded.

Graphical and moment measures have shown that Pleistocene and Holocene polygenetic coastal deposits can be distinguished by skewness. However, Pleistocene dune and barrier sands cannot be differentiated conclusively by using this parameter. Generally, dune sands are positively skewed, and beach and Holocene barrier sands are negatively skewed. Roundness analysis cannot be employed to distinguish between dune and barrier, or beach, sands of polygenetic origin.

Mineralogical studies have been made in an attempt to trace the source and origin of barrier and dune heavy mineral concentrates. The percentage variations of different minerals in both the Pleistocene and Holocene sediments have also been evaluated. Diagnostic heavy minerals have been traced in some barrier and dune sands, and it is believed that these were moved shoreward during fluctuations of sea level during the Pleistocene and Holocene epochs.

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The Quaternary History of Three Areas on the New South Wales Coast, Australia.

Thesis submitted for the Degree of Doctor of Philosophy.

The University of Sydney.

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PREFACE

A combined geomorphological and sedimentological study has been made of three coastal areas in New South Wales, Australia, in order to trace the origin of sand barriers, fluvial-deltaic plains and other depositional environments. An appraisal has also been made of eustatic changes of sea level, coastal configuration and coastal stability, as well as the topography of the continental shelf. An evaluation has been made of the significance and limitations of statistical parameters for distinguishing sedimentary environments.

The information obtained during field investigations has been supplemented by a detailed study of aerial photographs. Borehole data, geological maps and other sources of information have been examined, all of which are mentioned in the text. Standard methods used in the laboratory are described in the relevant chapters, and appendices.

The persons and organizations contributing to the writer's work, by supplying information and identifying scientific specimens, are acknowledged on Page vii. Published papers and reports, from which the writer derived certain facts, are listed in the text and at the end of the study. As far as the writer knows only three papers refer directly to the geomorphology of the study areas; these are referred to on Page 2.

Since no detailed geomorphological work has been completed previously in the areas studied by the writer, it was decided to publish the results of field investigations and laboratory analyses as the work progressed. The writer was also stimulated to report his findings because of the controversy about a Holocene(Recent) higher sea level in Australia. The

new evidence that came to light, and the conclusions reached in this study, have been (and will be) published in the papers referred to in the text.

Finally, the writer claims that the combined geomorphological and sedimentological study is the first of its kind in the respective areas (and in New South Wales). The first geomorphological maps of the areas are presented in this study; these are based mainly on field mapping. Survey work in most cases was completed by the writer with the kind assistance of Dr. T. Langford-Smith.

CONTENTS

		Page
PREFACE		i
CHAPTER		
1	INTRODUCTION	1
2	A GENERAL DESCRIPTION OF THE STUDY AREAS - PHYSIOGRAPHICAL AND GEOLOGICAL BACKGROUND	4
3	THE MORPHOLOGY AND ORIGIN OF THE BARRIER SYSTEMS	11
4	COASTAL DUNES IN THE STUDY AREAS WITH PARTICULAR REFERENCE TO THE MID-NORTH COAST	64
5	COASTAL LAGOONS AND COASTAL-SWAMPS	78
6	THE GEOMORPHOLOGICAL HISTORY OF THE FLUVIAL-DELTAIC PLAINS ON THE MID-NORTH COAST OF NEW SOUTH WALES	85
7	THE SIGNIFICANCE AND LIMITATIONS OF TEXTURAL PARAMETERS AND ROUNDNESS ANALYSIS FOR DISTINGUISHING ANCIENT AND MODERN SEDIMENTARY ENVIRONMENTS IN THE STUDY AREA	111
8	THE NATURE AND OCCURRENCE OF HEAVY MINERALS IN THE THREE STUDY AREAS	145
9	EUSTATIC CHANGES OF SEA LEVEL IN EASTERN AUSTRALIA WITH PARTICULAR REFERENCE TO THE STUDY AREAS	167
10	GENERAL SUMMARY AND CONCLUSIONS	189
APPENDICES		
3.1	WAVE REFRACTION DIAGRAMS	192
3.2	TIDAL PLANES AND PRINCIPAL COMPONENTS	193
3.3	PEARL BEACH BOREHOLE RECORDS	194
4.1	WIND RESULTANTS	198
6.1	METHODS USED FOR MECHANICAL AND CHEMICAL ANALYSES OF SOILS	199

7.1 METHODS OF PROCESSING OF DATA 203

8.1 A BRIEF DESCRIPTION OF THE HEAVY MINERALS IDENTIFIED IN THE BARRIER, BEACH AND DUNE SANDS 208

REFERENCES 211

TABLES

		Page
TABLE 4.1A	Wind resultants for stations in or near the study areas	77
TABLE 4.1B	Wind resultants for eight major compass directions and for NE, E, SE and S winds for the period 1935-1945	77
TABLE 6.1	Identified molluscs from estuarine mud flat shell-bed, Clybucca Creek-Anderson inlet area of the Macleay fluvial-deltaic plain . .	103
TABLE 6.2	Composition of samples collected from boreholes sunk on the Inner Barrier swamp flat	104
TABLE 6.3	Composition of samples collected from boreholes sunk on the two fluvial-deltaic plains . . .	105
TABLE 6.4	Roundness values (Powers' scale x 100) of fine- and coarse-grained sands from the Inner Barrier swamp flat; and heavy mineral percentage of the fine-grained sands	106
TABLE 6.5	Roundness values (Powers' scale x 100) of fine- and coarse-grained sand from the Macleay and Maria-Wilson fluvial-deltaic plains; and heavy mineral percentage of the fine-grained sands .	107
TABLE 6.6	pH values, chloride composition, total water soluble salt content and the ratio of carbon to nitrogen (C/N ratio)- Inner Barrier swamp flat samples	108
TABLE 6.7	pH values, chloride composition, total water soluble salt content and the ratio of carbon to nitrogen (C/N ratio)- Fluvial-deltaic plain samples	109
TABLE 6.8	Logs of bores sunk on Inner Barrier swamp flat	110
TABLE 7.1	Average graphic and moment measures of barrier and dune samples from the Mid-North Coast . .	138
TABLE 7.2	Average graphic and moment measure values of barrier and offshore samples from Broken Bay	140
TABLE 7.3	Average graphic and moment measure values of barrier samples from Twofold Bay and adjacent south coast areas	141

TABLE 7.4A	Percentage of beach and offshore samples that are nearly symmetrical	142
TABLE 7.4B	Percentage of beach samples that are positively skewed	142
TABLE 7.5	Statistical parameters and roundness values for dune and barrier sands	143
TABLE 7.6	Correlations between different sorting measures	144
TABLE 8.1	Average percentage occurrence (by number) of heavy minerals in some Mid-North Coast, Broken Bay and south coast barrier, and dune samples	161
TABLE 8.2	Average percentage occurrence (by number) of heavy minerals in Broken Bay barrier samples	162
TABLE 8.3	Percentage occurrence of minerals in Pearl Beach and Patonga Beach samples	163
TABLE 8.4	Average percentage occurrence of heavy minerals in south coast barrier samples	164
TABLE 8.5A	Specific gravity and hardness values of heavy minerals identified in cliff-top dunes . . .	165
TABLE 8.5B	Order of persistence of heavy minerals in the geologic column	165
TABLE 8.6	Range and average percentage concentration of heavy minerals in Pleistocene and Holocene sediments	166
TABLE 9.1	Shells found on the marine bench near Toallo Point	183
TABLE 9.2	Pollen analysis of Delicate Nobby peat sample collected at about high-water mark approximately a quarter of a mile north of the headland . .	184
TABLE 9.3	Palynological analyses of peat samples from Delicate Nobby, and Front Beach to the north of Crescent Head	185
TABLE 9.4	Radiocarbon dates of peats, shells, humate and stumps collected on the New South Wales Coast and plotted in Figure 9.1A	187

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This study was completed during the tenure of British Commonwealth and The University of Sydney research scholarships. Field work was assisted by grants associated with each scholarship and by the equipment of the Department of Geography, The University of Sydney.

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CHAPTER 1

INTRODUCTION

In many ways, sand barrier systems are the most striking features of the coastal scenery of New South Wales. Unfortunately, only a relatively few detailed investigations have been undertaken so far to explain their origin and development. An attempt is made here to describe the morphological characteristics of barriers in three areas of New South Wales and to outline the geomorphological evolution of these areas in relation to Quaternary eustatic changes of sea level. The three areas, which differ geologically and physiographically, are the Mid-North Coast between Port Macquarie and Scott's Head, Broken Bay near Sydney, and Twofold Bay and neighbouring districts on the south coast. Reconnaissance surveys have been made in other areas as well, and these will be mentioned briefly for comparative reasons.

The work reported here was completed during the tenure of British Commonwealth and Sydney University research scholarships. During the period 1962-1965, mapping and boring programmes were undertaken in the field in order to determine the near-surface stratigraphy of each area, and sedimentological and petrological studies of samples collected from boreholes were made in the laboratory.

One of the critical problems facing the coastal geomorphologist in eastern Australia is to determine precisely the heights of coastal features because of a lack of accurate datum points and topographical maps. Suitable topographical maps of the study areas were not available at the time of the survey, and all heights above mean sea level were obtained by dumpy

level traverses based on local bench marks or sea level datum, or by survey aneroid checked to a datum before and after each reading. These heights were supplemented with those shown on maps especially compiled for flood mitigation schemes on the Mid-North Coast. On a few sectors of the coast survey transects had to be confined to those areas where surveying was not interrupted by dense vegetation.

The maps presented in this thesis are the first detailed geomorphological records of each area. They were compiled from field work, aerial photographs, borehole data, and other sources.

Apart from three important papers by Voisey (1934a), Maze (1933), and Burges and Drover (1953) which are discussed in the following chapters, there is virtually no record of former geomorphic work in the study areas. Again, as far as the writer is aware, no previous studies have been made of the textural parameters and of the heavy mineral composition of the various sedimentary environments in the respective areas. Approximately 1500 samples were analyzed, and boreholes totalling more than 2000 feet were sunk by hand auger and with the aid of a high-frequency core-sampler, in an attempt to evaluate the various depositional environments.

The main objectives of the thesis are:

1. An evaluation of the significance of oceanic and nearshore processes on barrier development;
2. An evaluation of the significance and limitations of statistical parameters for distinguishing sedimentary environments;
3. An analysis of the relationship between heavy mineral concentrations and the following:

(i) longshore drift, (ii) eolian activity, and (iii) the shoreward movement of material from the sea floor during marine transgressions.

4. An appraisal of sea level changes during the Holocene epoch, particularly since 7000 years B.P., and of the evolution of the fluvial-deltaic plains that are bordered by the barrier systems.

CHAPTER 2

A GENERAL DESCRIPTION OF THE STUDY AREAS-
PHYSIOGRAPHICAL AND GEOLOGICAL BACKGROUND

The Mid-North Coast

The area designated the Mid-North Coast extends from Scott's Head to Port Macquarie (Figure 2.2). Like much of the east Australian coast between Newcastle in New South Wales and Sandy Cape on Fraser Island in Queensland - a distance of approximately 650 miles - the Mid-North region is characterized by arcuate bays separated by resistant bedrock headlands and backed by sand barriers which border the Macleay and Maria-Wilson fluvial-deltaic plains. By referring to Figures 2.2, 3.4 and 3.7, it can be seen that prior to the development of the dual sand barrier systems and fluvial-deltaic plains, the coast was deeply embayed and most of the present headlands may well have been offshore islands during high stands of the sea.

A geological sketch map of the region first appeared in 1867. This was drawn by W. E. Rudder and was published in a catalogue of the natural and industrial products of New South Wales for the Paris Universal Exhibition. Some explanations were given on the map (Figure 2.3), but no text was included, and so far as the writer can ascertain from an extensive survey of the literature, later workers have not referred to Rudder's map.

After a preliminary investigation by Woolnough (1911) and a more detailed survey by Voisey (1934b), no further geological work was undertaken on the Mid-North Coast until Lindsay (1963) studied the Macleay

valley above Kempsey. According to Voisey, Crescent Head, Race Course Headland and Big Hill are composed of sandstones, tuffs, mudstones, claystones and shales with minor conglomerate bands. These deposits, termed the Kempsey series, are believed to be of Permian age. Massive conglomerate crops out at Korogoro Point, and there are igneous intrusive rocks, probably of late Permian age, at South West Rocks and Smoky Cape. Lower Permian strata (Macleay Series) crop out at Rudder's Hill, near the outlet of the Macleay River. Here the Macleay Series, composed of slate, sandstone and conglomerate, has been slightly indurated by neighbouring intrusive rocks.

The hinterland of the Mid-North Coast forms part of the New England plateau which is composed mainly of Palaeozoic rocks and Tertiary basalts. The plateau, traditionally referred to as the Miocene peneplain by David (ed. W. R. Browne, 1950), is capped by remnants of laterite. According to David, most of the eastern margin of the continent was affected by earth movements during the Tertiary period, and the New England plateau was intermittently uplifted, gently warped and faulted during Mio-Pliocene times. Wide Pliocene valleys were cut into the Miocene planation surface. During what E. C. Andrews called the Kosciusko epoch, which marked the close of the Tertiary period, further uplifts occurred, producing valley-in-valley structures as rivers were rejuvenated and cut deep gorges. However, the possibility cannot be discounted that some of the valley-in-valley features may be the products of climatic change rather than uplift, or possibly a combination of both factors (T. Langford-Smith, personal communication).

Some of the headwaters of the Macleay River occupy valleys on the New England plateau, while in the upper part of the main valley widely scattered gravels, now capping low hills, mark the extend of a wide Pliocene valley floor, prior to its incision by the Macleay River. The origin of the terraces along the present river demands an independent investigation which has been beyond the scope of this study.

Broken Bay

Broken Bay (Figure 3.8, and inset map in Figure 3.9) includes the mouth of the dendritic drowned valley of the Hawkesbury River which cuts into a terrain of horizontal structure. Thus although the bay, like Port Jackson (Sydney Harbour) and Botany Bay, is well known for its ria-like characteristics it is not a ria *sensu stricto* according to the original definition proposed by Richthofen (Cotton, 1956). Depositional features are generally poorly represented on this sector of the central coast of New South Wales and the only barriers are Patonga Beach, Pearl Beach, and the Umina-Woy Woy beach ridge system which, however, is of some considerable size.

Much of Broken Bay is partially protected from high wave energy by the enclosing Box Head and Barranjoey headlands, and is dominated by vertical cliffs cut in resistant, almost horizontally-bedded Hawkesbury and Narrabeen sandstones of Triassic age. Lenticular layers of shale are interbedded with these sandstones which, according to David (ed. W. R. Browne, 1950), are characterized by major systems of vertical joints. Tertiary dykes and sills have also been reported in a few areas (David, *op. cit.*). Like much of the east Australian coast, the Sydney region during the Tertiary period was subjected to earth movements which may

have continued well into the Pleistocene epoch. If this contention is correct, Pleistocene tectonic movements may have played some part in the formation of terraces in some of the coastal river valleys, like the Hawkesbury. Apart from reconnaissance studies, no work has been conducted on the Hawkesbury terraces although it has been reported that the lower terraces disappear downstream of Mangrove Creek, and it has been suggested by Langford-Smith and Thom (1969 in press) that these may dip beneath Holocene sediments and present sea level. A more detailed investigation may show that Broken Bay and adjacent areas have been affected by epeirogenic movement such as tilting and warping (Walker and Hawkins, 1957; Hails, 1965b).

Twofold Bay and Adjacent Areas of the South Coast Between Turingal Rock and Lennards Island

Arcuate-shaped bays backed by beaches and cliffs cut in Tertiary (?) gravels are characteristic of the south coast between Turingal Rock and Lennards Island (Figure 2.4). South of Worange headland the coastal physiography changes somewhat abruptly and is dominated by Twofold Bay, the largest embayment on the far south coast of New South Wales. The bay, bounded by Worange and Red Point headlands, is actually a succession of smaller bays which are separated by headlands and small promontories.

Twofold Bay and adjacent areas are composed of strongly folded and faulted rocks of Devonian age, with Ordovician metamorphic rocks and Tertiary basalts (Brown, 1930, 1933; Steiner, 1966). The sedimentary rocks are of variable composition, and are associated with rhyolites, basalts and dolerites.

Although small bayhead beaches are quite common in Twofold Bay, and sand barriers almost completely enclose the mouths of most drowned river valleys on the far south coast, large barrier systems like those on the Mid-North Coast are quite rare (see Chapter 3). In fact, Pambula barrier is the only one of some size in the study area.

Although the denudation chronology of the south coast hinterland is not the immediate purpose of this study, the writer made reconnaissance surveys of a few coastal river valleys in an attempt to obtain some evidence on the relative movement of land and sea during the Quaternary period.

The Yowaka and Pambula Rivers (Figure 2.4, and inset map in Figure 2.5) rise near the coast and flow through narrow, steep-sided gorges which separate small basins, three of which are occupied respectively by Pambula Lake and the flood plains of both the rivers. The flood plain of the Yowaka River is commonly known as Greigs Flat (Figure 2.4). The Pambula River, which is tidal almost to the site of Pambula township, flows into the ocean by way of Pambula Lake and the Pambula River gorge. In contrast, the Towamba (Kiah) River rises 2,700 feet above sea level and flows through an incised valley for about 60 miles before draining into East Boyd Bay.

The writer has mapped river terrace fragments in several of the south coast valleys. Three terraces have been identified on the southern margin of the Nullica River valley near the Prince's Highway, less than 1 mile from the modern coast (Hails, 1965b). A road cutting on the highway, about 200 yards south of the road bridge, provides an excellent section through the middle terrace which consists of well rounded river gravels, silt and clay (Plates 2.1T-2.1U). Dumpy level surveys of the two lower terraces showed that they stand about 30-35 feet and 12-15 feet respectively above present mean sea level. River terraces, corresponding in height to the

two lower ones on the Nullica River, were also found near the mouth of Shadrack's Creek, and Leo's Creek, a small tributary of the Nullica River.

Plates 2.1W and 2.1X show gravels which are exposed in quarries beside the Prince's Highway between Eden and Pambula townships. One of these gravel outcrops continues beyond the highway and terminates abruptly along the western shore of Pambula Lake. The gravels consist of rounded pebbles which, as far as the writer can ascertain, have been derived from neighbouring Palaeozoic rocks. It can only be assumed from available evidence that the gravels are fluviatile in origin, although their distribution does not follow very closely the present drainage system. However, the possibility exists that former river courses may have been disrupted by local warping or tilting.

According to David (op. cit.), many rivers in southern New South Wales were rejuvenated by uplift in late Miocene time and again at the close of the Pliocene epoch. The second period of major uplift was accompanied by warping, tilting and coastal faulting in some areas, while other parts of southern New South Wales were little affected by uplift, if at all. On the foregoing evidence, it seems likely that the cutting of the present gorges and basins began during the Tertiary period, and possibly continued intermittently into the Pleistocene epoch. Nevertheless, the origin of the south coast rivers in the writer's study area must inevitably remain in doubt until the age is actually established of the so-called Tertiary(?) sediments (the location of some of these sediments is shown in Figure 2.4 between Turingal Rock and Lennards Island). The sediments are poorly consolidated sands and gravels of varying thickness which directly overlie Devonian rocks. They have been designated Tertiary, although no fossil evidence of age has been found (Hall , 1957). Actually, there are only

two records of Tertiary marine rocks on the south coast of New South Wales. Near Narooma, about 55 miles north of Turingal Rock, a cast of Glycymeris (?) was recovered from ferruginous grits and tentatively designated Upper Tertiary by Singleton (David, op. cit.), and Brown (1933) referred to the possibility of late Tertiary fossils near Corunna Lake about 7 miles south of Narooma.

The writer could find no convincing evidence for the age of the poorly consolidated sediments. They could be pre-Tertiary, or they might be residual deposits derived locally from Devonian rocks during prolonged periods of Tertiary weathering.

Of course, marine transgressions and regressions during the Pleistocene have made it extremely difficult to distinguish between tectonic movements and eustatic changes of sea level. As David stated: 'By far the greater part of the present topography in Australia has resulted from processes that operated in Tertiary and post-Tertiary times, but since over most of the continent there are no marine fossiliferous deposits to act as time markers any dating of the physiographic events can only be approximate.' These remarks epitomize the general conclusions of most coastal geomorphologists and portray the reasons why Australia does not as yet offer valuable clues on Quaternary changes of sea level. Yet, paradoxically, the continent still holds the attention of many overseas geologists who are interested in Pleistocene and Holocene coastlines, probably because of the lack of agreement at present in Australia on that subject.

Figure 2.1 Map to show the location of the three study areas.

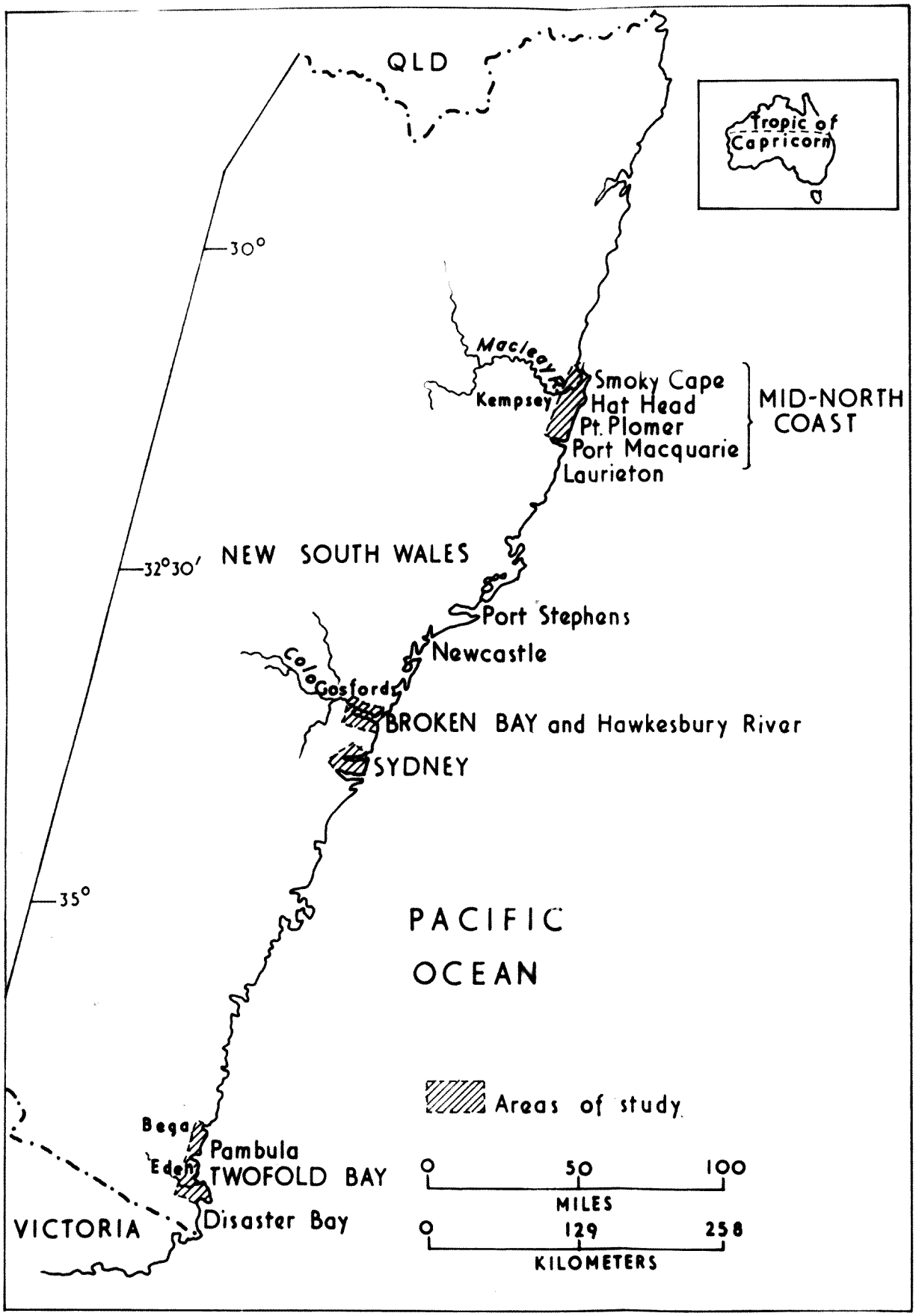

QLD
Tropic of Capricorn
30°
Macleay R.
Kempsey
Smoky Cape
Hat Head
Pt. Plomer
Port Macquarie
Laurieton
MID-NORTH COAST
32°30'
NEW SOUTH WALES
Port Stephens
Newcastle
Cole
Gosford
BROKEN BAY and Hawkesbury River
SYDNEY
35°
PACIFIC
OCEAN
Areas of study
Bega
Pambula
Eden
TWOFOLD BAY
VICTORIA
Disaster Bay
0 50 100
MILES
0 129 258
KILOMETERS

Figure 2.2 The Mid-North Coast between Port Macquarie and Scott's Head.

Figure 2.2

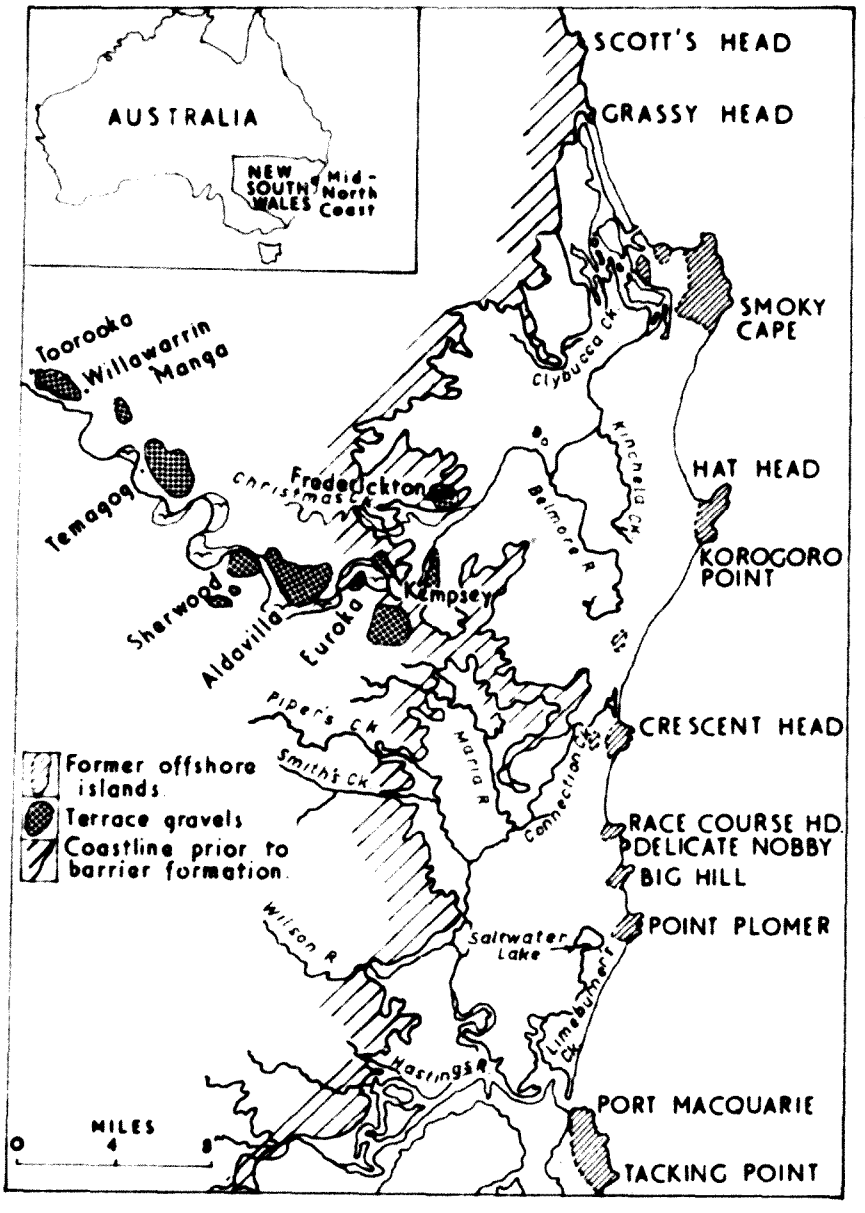

AUSTRALIA
NEW SOUTH WALES
Mid - North Coast
SCOTT'S HEAD
GRASSY HEAD
SMOKY CAPE
HAT HEAD
KOROGORO POINT
CRESCENT HEAD
RACE COURSE HD
DELICATE NOBBY
BIG HILL
POINT PLOMER
PORT MACQUARIE
TACKING POINT
Toorooka
Willawarrin
Manga
Temagog
Sherwood
Aldavilla
Euroka
Kempsey
Frederickton
Christmas Ck
Clybucca Ck
Kinchela Ck
Belmore R
Pipers Ck
Smiths Ck
Maria R
Connection Ck
Wilson R
Saltwater Lake
Limeburners Ck
Hastings R
Former offshore islands
Terrace gravels
Coastline prior to barrier formation
MILES
0
4
8

Figure 2.3 W. E. Rudder's geological sketch map of the Lower Macleay Valley, 1867.

Figure 2.3

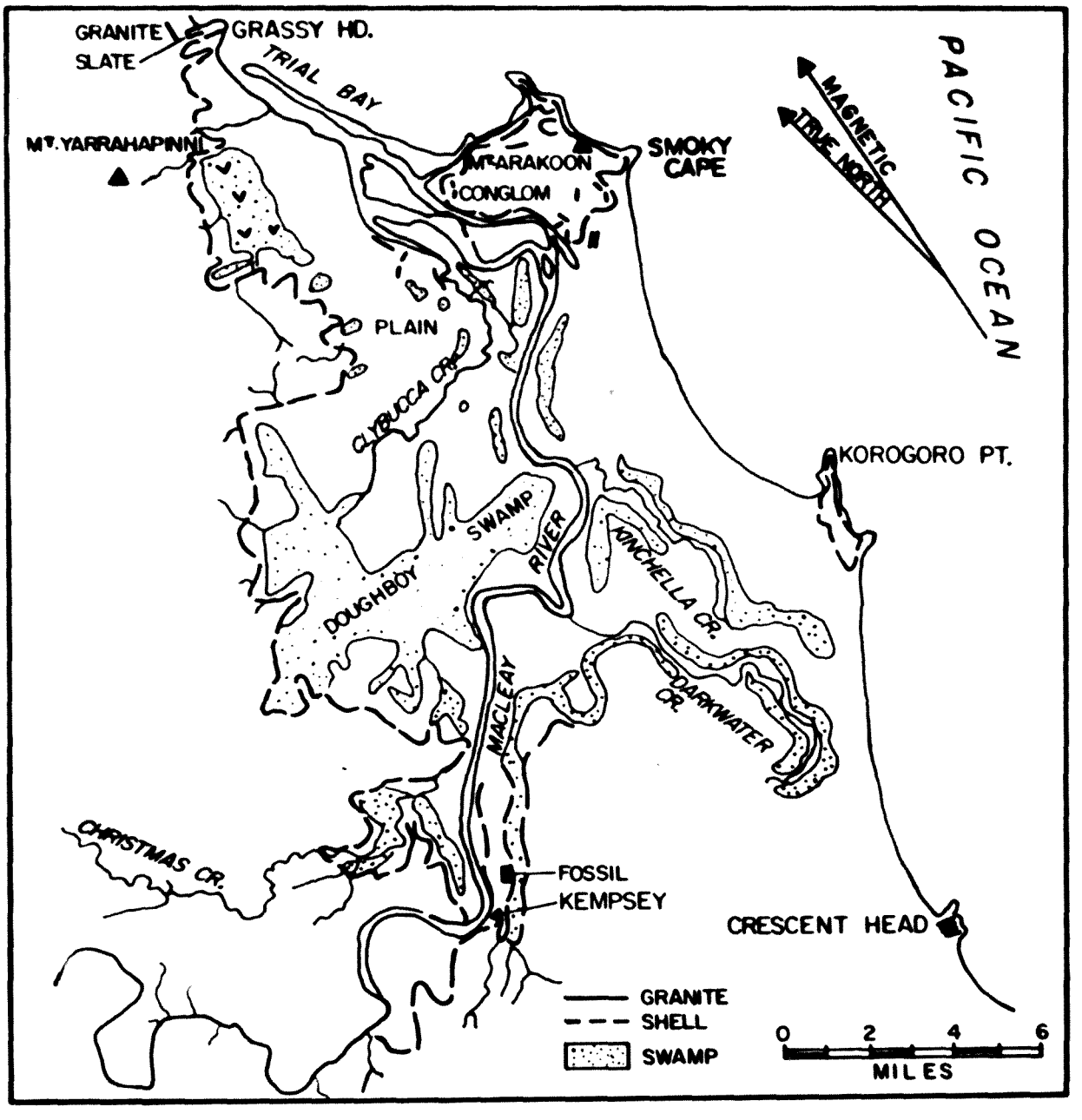

GRANITE
SLATE
GRASSY HD.
TRIAL BAY
MT. YARRAHAPINNI
MT. ARAKOON
CONGLOM
SMOKY CAPE
MAGNETIC
TRUE NORTH
PACIFIC OCEAN
PLAIN
CLYBUCCA CR.
KOROGORO PT.
SWAMP
RIVER
KINCHELLA CR.
DOUGHBOY
MACLEAY
DARKWATER CR.
CHRISTMAS CR.
FOSSIL
KEMPSEY
CRESCENT HEAD
GRANITE
SHELL
SWAMP
0 2 4 6
MILES

Figure 2.4 (in pocket on inside back cover):

Geological and geomorphological map of the South Coast between Lennards Island and Wallagoot Lake.

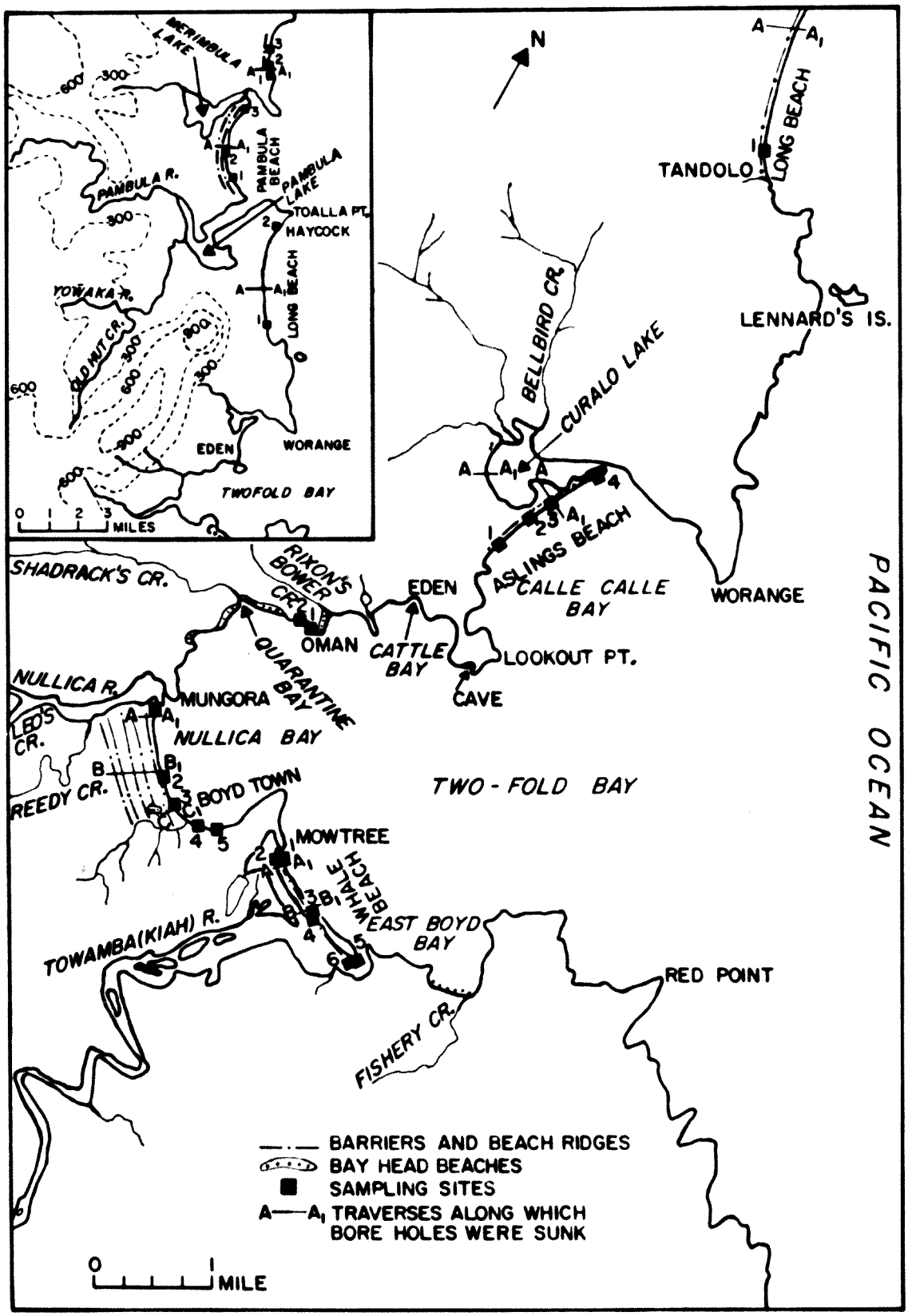
Geology based on Brown (1930, 1933), Hall (1957) and Steiner (1966).

Figure 2.5 Twofold Bay and adjacent areas of the south coast.

Twofold Bay, with its flanking headlands Worange and Red Point, is the largest embayment on the far south coast, and is a succession of smaller bays separated by headlands and promontories.

Surveyed profiles along traverses A-A_1 and C-C_1 (Boyd Town), and A-A_1 Eden barrier spit (Aslings Beach) are shown in Figure 3.13. Inset map shows the coastal area north of Twofold Bay and the location of Pambula barrier spit (cf. Figure 2.4, and Plates 3.10 and 3.11).

Figure 2.5


N
MERIMBULA LAKE
PAMBULA BEACH
PAMBULA LAKE
PAMBULA R.
TOALLA PT.
HAYCOCK
LONG BEACH
YOWAKA R.
OLD MIT CR.
EDEN
WORANGE
TWOFOLD BAY
0 1 2 3 MILES
TANDOLO
LONG BEACH
LENNARD'S IS.
BELLBIRD CR.
CURALO LAKE
ASLINGS BEACH
CALLE CALLE BAY
WORANGE
SHADRACK'S CR.
RIXON'S BOWER CR.
EDEN
OMAN
CATTLE BAY
LOOKOUT PT.
CAVE
QUARANTINE BAY
NULLICA R.
MUNGORA
LEO'S CR.
NULLICA BAY
REEDY CR.
BOYD TOWN
TWO-FOLD BAY
MOWTREE
WHALE BEACH
EAST BOYD BAY
TOWAMBA(KIAH) R.
RED POINT
FISHERY CR.
PACIFIC OCEAN
BARRIERS AND BEACH RIDGES
BAY HEAD BEACHES
SAMPLING SITES
A—A1 TRAVERSES ALONG WHICH BORE HOLES WERE SUNK
0 1 MILE

Plates 2.1T - 2.1Y

2.1T A view of the lower (t_1) and middle (t_2) Nullica River terraces.

2.1U Looking from the middle terrace (t_2) towards the lower terrace (t_1) and the Prince's Highway (r).

2.1V Erosion of the lower terrace by floodwater. X shows silt and clay with coarser debris.

2.1W and 2.1X Gravels alongside of the Prince's Highway between Eden and Pambula. Well rounded gravels clearly shown above tree trunk in 2.1X.

2.1Y View of part of Merimbula Lake and the extreme northern end of Pambula barrier spit (dotted line). Dissected coastal range in background. Note fairly steep slopes to edge of lake.



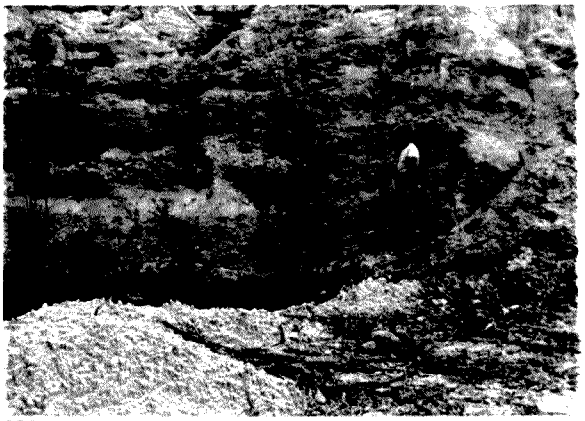
T



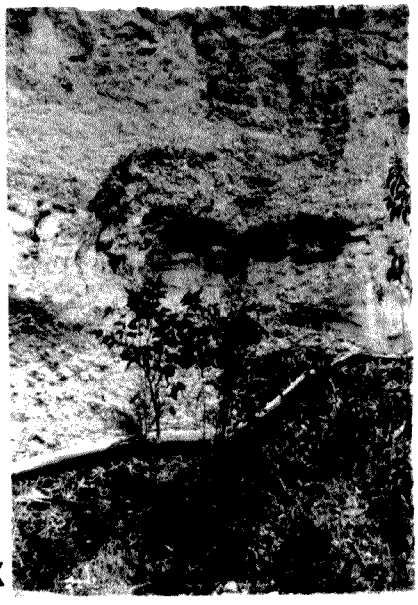
U



V



W



X



Y

Plates 2.2E - 2.2J

2.2E View of part of Pambula barrier foredune (b) looking north, north-west. Incipient foredune (a) is stabilized by Spinifex hirsutus. The foredune is also vegetated with succulent and mat-binding plants, including Lomandra longifolia.

2.2F Partially dissected foredune (b) of Pambula barrier. View looking in opposite direction to that of 2.2E. Incipient foredune (a) protects foredune from wave attack.

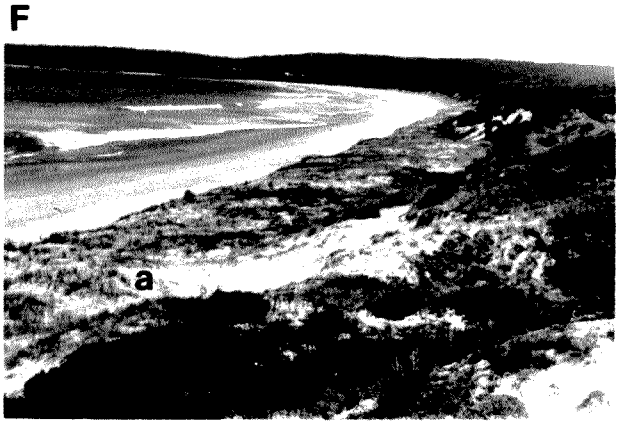
2.2G Eden barrier spit with incipient foredune (a). View looking south towards Eden township. Banksia trees on the crest of the foredune.

2.2H Whale Beach barrier, Twofold Bay, looking south. The debris (branches and tree trunks) covering the seaward side of the barrier was washed up by wave action, after reaching East Boyd Bay through the Towamba River outlet now at the southern end of Whale Beach barrier.

2.2I View looking west (landward) from the crest of Whale Beach barrier (foreground). Mangroves colonize the ridges in the middle distance. The area of water is actually the impounded estuary of the Towamba (Kiah) River. (See Plate 3.10B).

2.2J X shows the position of a former breach at the northern end of Whale Beach barrier. Floodwater debris shown in the foreground.


E
a
b


F
a


G


H


I


J

CHAPTER 3

THE MORPHOLOGY AND ORIGIN OF THE BARRIER SYSTEMS

PART 1

Regional Descriptions

Introduction: Most of the northern New South Wales coast is bordered by dual barrier* systems which have been termed Inner (Pleistocene) and Outer (Recent)** barriers by Langford-Smith and Thom (1969 in press). These are separated by inter-barrier lagoons and swamps which apparently indicate a time interval between the development of the two barriers. The best examples of composite Inner and Outer Barrier systems studied by the writer border the large fluvial-deltaic plains of the Mid-North Coast. In contrast, the beach ridges*** on the central and south coast are mainly confined to narrow Outer Barrier systems.

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* The term barrier is used here in the sense defined by Price (1951) and Shepard (1952) for littoral constructional features, such as beaches, spits and islands, which stand premanently above high-water mark, and partly or completely enclose lagoons or shallow bays. On the east Australian coast barriers consist almost entirely of sand. However, they differ morphologically; some barriers have multiple beach ridge systems while others completely lack such clearly defined features, and a few consist of a single ridge. The term barrier in this study also includes beach ridge systems which are not always entirely separated from bedrock by lagoons.

** In this study the term Holocene (Recent) will be used for the period 18,000 B. P. (before present) to the present.

*** Since practically all beach ridges are invariably capped by some windblown sand they should strictly be called dune ridges. However, since it is often difficult to determine an eolian-marine boundary in the writer's study areas, the term beach ridge (or beach ridge system) will be used.

The purpose of this chapter is to examine the morphological and pedological characteristics of the barrier systems in each of the three study areas, and then to discuss their origin and possible age. Most of the conclusions reached here apply to the study areas, and are necessarily tentative because they are mainly based on evidence from relatively shallow borings, and the morphological and pedological features of the respective barriers. What is needed now is a comprehensive programme of deep-boring - a project planned on a long-term basis by the University of Sydney.

Mid-North Coast

Both the Inner and Outer Barrier systems on the Mid-North Coast consist predominantly of quartzose sand with an extremely small percentage of comminuted shells. Despite their composition, the two barriers can be distinguished by their pedological and, to a lesser degree, their ecological differences.

Inner Barrier System: The Inner Barrier consists of abandoned beach ridges and intervening swales which trend approximately parallel to the modern shoreline. In several localities, the ridges and swales are surmounted by dunes which attain heights ranging from a few feet to a maximum of about 200 feet above present sea level. The Inner Barrier sands are deeply podzolized and the pH value of the surface sand is usually between 3.0 and 5.0, but occasionally the values are slightly higher.

The ridges are stabilized by dune or heath woodland. The most common tree is the saw-banksia (Banksia serrata) although various species of Eucalyptus, and Angophora costata, are also widely distributed. Generally, there is a thick ground cover of bracken (Pteridium aquilinium),

ferns and sand-binding plants, with Leptospermum thicket.

The ash-grey upper A_1 horizon of the podzols varies in thickness from a few inches to 2 feet, but in a few localities it is almost entirely absent, for example, near Crescent Head (see section A-A^1 in Figure 3.5). Where it is present, the A_1 horizon overlies a predominantly white A_2 horizon which is often leached to a depth of 20 feet or more below the crest of the sand ridges. In some places, this leached horizon is underlain by humate-cemented sand which often extends from a few feet above, to at least several feet below, present mean sea level.

Humate (Swanson and Palacas, 1965), a dark brown to black organic substance, is widely distributed in southeastern Australia between Tasmania and the coastal lowlands ("Wallum") of southern Queensland. Although it is listed as 'indurated sand' in many commercial borehole records, humate has been termed coastal sandrock by Coaldrake (1955, 1961, 1962) and McGarity (1956), Coffee Rock by Bird (1961), and Waterloo Rock by Griffin (1963). According to Swanson and Palacas, humate is the product of natural flocculation or precipitation of those soluble and colloidally dispersed humic substances in water that have been derived by natural leaching of decaying plant and animal material, or humus. This process commonly cements or impregnates barrier or dune sands. Humate can also accumulate in and beneath marsh or swamp deposits, near groundwater seepages, and as a type of organic sediment in brackish or saline water. Even so, as Swanson and Palacas point out, many questions about the origin and geochemistry of humate still remain unanswered.

Probably one of the best natural exposures of humate can be seen

along the east bank of the large meander of the Maria River (Figure 3.7). Here the humate, which is overlain by 4-5 feet of white leached sand, is more than 10 feet thick and extends at least several feet below mean sea level. Another excellent exposure is located at the drainage cutting which links the extreme southern part of Belmore Swamp with Killick Creek (Figure 3.5). This cut through the Inner Barrier was made by the Macleay County Council in order to control the level of water in Belmore Swamp during floods. In fact, the humate is so indurated that it had to be blasted with gelignite when the cutting was made. By boring, the writer has traced this particular humate horizon several hundred feet along the Inner Barrier towards Crescent Head, and it can also be seen in the banks of an artifically-cut pit to the south of the settlement.

Except for the two exposures just described, it appears from the evidence of boring that many humate horizons do not extend over great distances. Even the humate horizon traced along section A-A^1 in Figure 3.5 was not encountered again in the area north of the artificial cutting. But it is possible that some borings sunk by the writer have not been sufficiently deep to make contact with different horizons, or that humate may occur in other localities not yet investigated in detail.

Local variations in the level of the water table can partly account for the occurrence of humate at different depths, but the writer is generally unable to say exactly when its development took place. Although many of the horizons underlying the Inner Barrier ridges probably developed before the late Wisconsinan lowering of sea level, it seems reasonable to suggest that some colloids accumulated below present low-water mark during periods of lower sea level. The humic colloids must

post-date the development of the Inner Barrier. There were probably periodic fluctuations in the water table level as the sea fell during glacial times, and again during a subsequent rise of sea level, as for example during the postglacial (Holocene or Flandrian) transgression. In the case of the Inner Barrier, it would seem that some of the humate horizons may have gradually thickened, as water tables rose, until the sea reached its present level.

Comminuted shells are widely scattered along the crest of the Inner Barrier and are sometimes associated with charcoal, and more rarely, unbroken shells. One may well enquire why this should be so when the Inner Barrier sands are so deeply leached of calcium carbonate. In the writer's view, there seems little doubt that the comminuted shells are the remains of aboriginal kitchen-middens and are not in situ remnants of former beach deposits. Furthermore, because of the low pH value of the sand, it appears that they were left on the Inner Barrier at a time which post-dates the development of the podzols.

Morphological Variations of the Inner Barrier System: The width of the Inner Barrier system varies significantly on different sectors of the Mid-North Coast and, morphologically, it displays a variety of forms. The majority of the ridges, except those that comprise the Maria-Wilson barrier plain, generally stand between 20 and 25 feet above present sea level. For descriptive purposes, the writer has sub-divided the barrier into three physiographic units:

1. An abandoned beach ridge system adjacent to the old (1895) course of the Macleay River immediately south of Grassy Head,

designated here as the Grassy Head beach ridge system (Figures 3.4 and 6.1).

2. A relatively narrow barrier, between Smoky Cape and Race Course Headland, consisting of only a few sand ridges (Figures 3.1, 3.2, 3.3, 3.4 and 3.14);

3. A comparatively wide series of abandoned beach ridges, adjacent to the Maria-Wilson fluvial-deltaic plain, which the writer has designated the Maria-Wilson barrier plain (Figure 3.7).

1. Grassy Head Beach Ridge System: The most uniform series of parallel abandoned beach ridges on the Mid-North Coast is situated immediately south of Grassy Head, between an ancient bedrock coastline, characterized by degraded sea cliffs, and the old 1895 course of the Macleay River. This part of the Inner Barrier system is approximately 1 mile wide, and consists of fairly closely spaced ridges with intervening swales, some of which are occupied by swamps. The interval between the respective ridges varies from 12-35 yards. The crests of the ridges are reasonably accordant and stand slightly less than 30 feet above present mean sea level, and about 5 feet above the swales. Because of the dense vegetation in this area it was impossible to survey the ridge system with a dumpey level. The heights reported here were recorded with a survey aneroid, checked to a datum point before and after each reading.

There is little evidence to suggest that the ridges were modified appreciably, either by accretion or deflation, before they were eventually stabilized by a cover of Banksia serrata woodland. Some of the vegetative cover has been destroyed by bush fires in the past, but this seems to have regenerated quite quickly so that the ridges have been modified very little by wind action. However, the southern and seaward margin of this ridge

system has been truncated by the Macleay River, probably when the river was deflected to the north after the initiation of the Outer Barrier.

Although the sands are quite deeply podzolized, with the A_2 horizon varying between 2 and 8 feet in thickness, humate was not located at all during boring operations; only an incipient 'B' horizon was found.

The morphological characteristics of the Grassy Head beach ridge system are very similar to those of the Umina-Woy Woy system in Broken Bay and the Boyd Town system in Twofold Bay, the implications of which are reviewed later.

2. Inner Barrier System between Smoky Cape and Race Course Headland: The Inner Barrier in this area lies behind three arcuate bays which are linked by Smoky Cape, Korogoro Point-Hungry Hill, Crescent Head and Race Course headlands. The three sectors of the Inner Barrier system between Smoky Cape and Race Course Headland vary in length between 8 and 11 miles. The maximum width of the barrier is no more than half a mile, but usually each sector is only 200 or 300 yards wide. Figures 3.2 and 3.3 show that the barrier has been breached in several places, and the distribution of Inner Barrier deposits strongly indicate that there was formerly a continuous barrier system between Smoky Cape and Race Course Headland. Some of the gaps in the barrier are quite wide, like the large break behind Hat Head village. An explanation of the breaches involves several considerations and these will be evaluated in the discussion on the origin of the barriers.

Although the Inner Barrier is fairly long and narrow, it branches rather conspicuously into a series of smaller components about 5 miles north of Creascent Head (Figure 3.3). Each component is surrounded by

swamps. Many of these barrier remnants (particularly those just to the southwest of and adjacent to Hungry Hill) consist of densely vegetated dunes, some of which are more than 150 feet above mean sea level. Depressions between the dunes invariably contain small lakes or swamps. If Figures 3.2 and 3.3 are compared it can be seen that a similar, although less well-defined, pattern of barrier remnants can be traced just south of Smoky Cape. Here the dunes have completely buried what may have been former beach ridges and consequently it is difficult to reconstruct the original pattern of ridges. In fact, the exact nature of the dune terrain is masked by extremely dense undergrowth, but a view from the lighthouse on Smoky Cape Headland, looking to the south, shows that the dunes trend southeast to northwest (Plate 3.3C).

One of the main features of the morphology of the Inner Barrier system is the contrast between its smooth former seaward margin and the inner lobate margin which abuts Belmore and Kinchela Swamps (Figure 3.4). The lobate margin may be a degraded cuspate lagoonal shoreline, originally shaped when the area now occupied by Belmore and Kinchela swamps was a lagoon (Chapter 6). Borings sunk along sections B-B^1 and C-C^1 (Figure 3.2) north of Hat Head showed a distinct boundary between the barrier sands and bankswamp sediments. There is no evidence to suggest that these deposits interfinger at depth. A few deep borings made by the Department of Mines, New South Wales, penetrated more than 100 feet of sand without reaching bedrock, but the exact thickness of the Inner Barrier is still unknown.

3. Maria-Wilson Barrier Plain: Situated between the Maria-Wilson fluvial-deltaic plain and Limeburners Creek, the Maria-Wilson barrier plain covers an area of some 40 square miles, is between 2 and 4 miles wide, and has an

approximate length of 12 miles (Figure 3.7). It is characterized by a system of slightly arcuate abandoned beach ridges, with intervening swales, which trend approximately parallel to the modern shoreline. The ridges are irregularly spaced, and the majority of them stand between 1 and 5 feet above the adjacent swales, although a few rise between 5 and 20 feet above present sea level. Some of the ridges show evidence of breaching and large gaps are evident, similar to those already described (Plate 3.3F). In a few places on the barrier plain the remnants of former ridges are so low in elevation that they can only be distinguished by their vegetative cover.

Most of the swales, which stand less than 3 feet above present sea level, are either waterlogged or occupied by tracts of swamp land, primarily because they are underlain by impermeable humate. Borings show that most of the humate horizons underlying the swamps, and also some of the lowest sand ridges, are only 2 or 3 feet below the ground surface. Most of the horizons are more continuous than those on other sectors of the Mid-North Coast.

Along the northern margin of the barrier plain, there is a distinct morphological contrast between the relatively subdued sand ridges and an almost continuous chain of dunes extending inland from Big Hill (Figure 3.7). Practically all these dunes, which are deeply podzolized, are aligned southeast to northwest, and for the most part stand about 100 feet above the surrounding country. The continuity of the dune system is interrupted by small drainage channels that link the swamps behind Delicate Nobby and Race Course Headland with those at the northern end of the barrier plain. In contrast, the southern part of the barrier consists of sand ridges fixed by a cover of dune heath and Banksia serrata woodland.

Outer Barrier System of the Mid-North Coast: The Outer Barrier has not been sub-divided into physiographic units because morphologically it is less diversified than the Inner Barrier. The soil profiles of the Outer Barrier are very poorly developed compared with those of the Inner Barrier. For example, the pH value of the surface sand usually ranges from 7.5 to 8.5 whereas, as already stated,that of the surface sand of the Inner Barrier is between 3.0 and 5.0. Comminuted shells are quite common in the Outer Barrier sand, but unbroken shells are confined to the foredune.

The Outer Barrier ridges are stablized by a cover of sand-binding grasses (Spinifex hirsutus and Festuca littoralis), mat-forming succulent plants of which Hibbertia volubilis, Scaevola suaveolens, Acacia sophorae and Mesembryanthemum aequilaterale are the most common, with dune scrub communities including Leptospermum laevigatum, and coastal banksia, chiefly B. integrifolia. Despite the general lack of well developed podzolic profiles, borehole samples and soil pits dug on the crests of the ridges show that the older ridges at the back of the barrier are slightly more leached than those nearer the front and humate is entirely absent; the degree of leaching is negligible compared with that of the Inner Barrier. The increase in the degree of podzolization landwards is partly shown by a change in the vegetation from dune scrub, with the coastal banksia (Banksia integrifolia) on the seaward side of the barrier, to areas of dune woodland, with the saw banksia (Banksia serrata) on the oldest ridges.

The Outer Barrier has been considerably modified since it was first established. It is pertinent to record that on a few sectors of the north New South Wales coast, for example between Iluka and Ballina, the Outer Barrier has been completely destroyed together with the frontal part of the

Inner Barrier (Langford-Smith and Hails, 1963 unpublished; also reported in Langford-Smith and Thom, 1969 in press). By far the greatest changes that have occurred on the Mid-North Coast are evident between Grassy Head and Crescent Head where the nature and effects of Outer Barrier erosion are strikingly displayed.

The barrier in Trial Bay has been reduced to a mobile sheet of sand for the most of its length, and has retreated landward so rapidly in recent times that it has already filled in much of the old course of the Macleay River. Parts of the infilled course have been stabilized by a cover of Scirpus nodosus, S. validus, Casuarina glauca (she-oak) and Melaleuca (paper-bark) spp. which is quite different from the mangroves that line the opposite bank of the old river course. At its widest point, the Outer Barrier is little more than a quarter of a mile.

Some of the erosion can be attributed to the effects of northeasterly storm waves since a large part of Trial Bay faces slightly east of north and is therefore comparatively sheltered from the effects of southeasterly storms. Also southeasterly storms are less effective because of the partial shelter afforded Trial Bay by Laggers Point (Figure 3.1), around which southeasterly ocean swell is refracted.

However, most of the Outer Barrier system to the south, between Smoky Cape and Crescent Head, is relatively exposed to southerly storm waves and predominant and effective southerly winds. Consequently, a large part of the barrier has been appreciably eroded, and in some localities it is difficult to identify a regular pattern of beach ridges. The areas immediately north of Korogoro Point and Crescent Head are afforded some protection from southerly storm waves, but in general on this section of the coast parts

of the frontal dune, and some of the ridges immediately behind it, have been eroded so extensively that the Outer Barrier is an almost continuous belt of mobile sand and migrating dunes (Figures 3.2 and 3.3). The dunes have spilled over into the inter-barrier lagoons and swamps, parts of which have been infilled already. Ultimately, if the landward migration of the barrier continues at its present rate, the tract of lagoonal-swamps will be overrun and Outer Barrier sands will start to bury parts of the Inner Barrier.

In fact, this has happened already in a few places between Delicate Nobby and Point Plomer where the present foredune has buried Inner Barrier ridges. As a result of the burial of Pleistocene deposits beneath fixed and active dunes, it is sometimes extremely difficult to resolve chronological problems (see also Langford-Smith and Hails, 1966), especially if the lagoonal-swamp behind the foredune occupies an Inner Barrier swale. Just north of Race Course Headland (to the north of Delicate Nobby) the Outer Barrier has advanced over adjacent lagoonal sediments so that peat beds exposed by wave action now outcrop on the seaward side of the Outer Barrier (Plate 3.1E - 3.1F). It can be seen in Plates 3.1B and 3.1E that the foredune is undergoing erosion and has already been dissected into a series of small knolls.

Conical-shaped hillocks, anchored by dune scrub, are prominent landform features for about 5 miles south of Hungry Hill. Some of these sandhills are shown in Plates 3.1H, 3.1L and 4.1A, and their alignment approximately parallel to the modern shoreline is fairly substantial evidence that they are the remnants of dissected beach ridges. They consist of remarkably fresh sand which shows practically no sign of leaching or soil profile development.

Near Hat Head village, a most striking feature in the frontal dune is a shell bed buried beneath more than 8 feet of unleached sand which is stabilized by dune scrub (Plate 3.2C). Since the writer found many shells with broken posterior margins as well as pieces of charcoal in the shell bed, there seems little doubt that it is actually an aboriginal kitchen-midden and not a 'stranded' beach deposit. Such shell beds are not uncommon on the New South Wales coast. However, as Shepard (1961) correctly pointed out, some of them have been mistaken (particularly by overseas workers) for in situ beach deposits associated with a 10-ft Holocene higher sea level.

About 1 mile north of the Hat Head kitchen-midden unleached sand overlies a podzol with an incipient illuvial 'B' horizon at the base of the foredune (Plates 3.2A and 3.2B). Actually, the buried podzol and midden are not such anomalous features as their position in the frontal dune seems to indicate. The original site of the aboriginal midden was probably near the landward edge of the Outer Barrier, that is, in the lee of a foredune which may have been some distance seaward of the present frontal dune. All the available evidence indicates that the barrier must have been fixed by vegetation sufficiently long for percolating rain water to leach out any comminuted shells that were present in the upper horizons of the innermost ridges at that time, and to remove iron oxides and organic material to lower horizons in order to develop a podzolic profile. It would appear that the aboriginal kitchen-midden near Hat Head post-dates such leaching. Subsequently, the Outer Barrier was eroded and driven back by wave and wind action so that the kitchen-midden and podzolized ridges were buried. Now the modern foredune has also been cut back so that both

features are visible in the foredune at the back of the modern beach.

It has already been mentioned that there is a narrow belt of fixed and active dunes between Delicate Nobby and Point Plomer. The fixed dunes are testimony of stabilization after periods of erosion in the recent past. The continuity of the Outer Barrier foredune between Crescent Head and Race Course Headland is interrupted in places by parabolic dunes and blowouts, but these features are small, and generally erosion is limited on this sector of the Mid-North Coast compared with the advanced stages of barrier destruction north of Crescent Head, some of the causes of which will be examined in the discussion.

Broken Bay

Umina-Woy Woy Beach Ridge System: Several parts of this barrier system have been cleared and levelled for residential building, and if this continues morphological work will be seriously restricted in the future. The investigation reported here is an attempt to provide useful information while there is yet time. It is still possible to trace the trend of most of the beach ridges which comprise an exceptionally regular pattern parallel to the present beach (Figures 3.9 and 3.10; Plate 3.7).

The settlement of Woy Woy, Ettalong and Umina are built on a $2\frac{1}{2}$-mile wide beach ridge system, between Woy Woy Creek and Umina (Ocean) Beach, the largest depositional area in Broken Bay. The ridges and intervening swales trend northeast to southwest. The reconstructed beach ridge pattern shown in Figure 3.10 has been based on the contouring of large-scale maps compiled by Gosford Shire Council, and data from dumpy level traverses completed by the writer (Figure 3.9). Figure 3.10 does not show every ridge, only the generalized pattern. Ridge crests are between 16 and 22 feet above present sea level, with no apparent seaward decrease in height.

Swales are fairly evenly spaced and stand approximately 3-4 feet below the ridge crests. Many ridges and swales are leached and there is a distinct intensification in podzol development landward from Umina Beach towards Woy Woy Creek. At the back of the barrier system, between Woy Woy Creek and the swamps to the south of it shown in Figures 3.9 and 3.10, A_2 horizons of the podzols vary in thickness from 1-4 feet (and occasionally more than 4 feet) and are sometimes underlain by humate.

Non-podzolized sands have only been traced on the southern margin of the ridge system between Ettymalong Creek and the swamps behind Ettalong Beach. The location of individual boreholes and sections along which other borings were made are shown in both Figures 3.9 and 3.10.

The podzolized ridges are stabilized by a cover of dune heath and scrub with Banksia serrata and Angophora trees (Plates 3.8A, 3.8B and 3.8D). The unleached sands are held in place by dune scrub (dominated by Leptospermum laevigatum) with Banksia (chiefly B. intermedia and B. integrifolia and Eucalyptus (E. botryoides) trees, and ferns and bracken. Blackbutt (E. pilularis) is common in the Woy Woy-Ettalong area, but is absent from Ocean Beach and Umina near the foredune and beach. E. botryoides and E. gummifera are present in the vicinity of Woy Woy, Ettalong and Blackwall Mountain, but are replaced by Angophora intermedia near Umina.

Banksia trees on the crest of the foredune seem to indicate that shoreline recession has occurred because these are rarely found on the exposed sectors of beach ridge systems. The frontal dune is fixed by Festuca littoralis and Spinifex hirsutus which often trails into the tidal zone in more sheltered areas. These sand-binding grasses merge into a cover of succulent plants which include Hydrocotyle spp., Hibbertia

volubilis, H. scandens and Sporobolus capensis with Lomandra longifolia. Near the swale swamps, banksia trees are replaced by the she-oak (Casuarina littoralis; C. glauca). Some of the swales between the unleached ridges contain swamps with Typha, and the swamp paper bark or tea-tree (Melaleuca spp.).

A few ridges immediately behind the frontal dune at Umina (Ocean) Beach are manifestly capped by windblown sand. Irregular small sandhills between 22 and 24 feet high can also be seen in a few places behind the foredune. However, as one moves inland from the foredune it becomes extremely difficult to determine whether or not the crests of the beach ridges have been heightened considerably by windblown sand. The well-known sedimentary structures of dunes and beaches can usually be of value, but the writer found practically no cross-bedding or stratification of any kind to help his interpretation. Possibly such structures have been destroyed by pedogenic processes.

The Umina-Woy Woy beach ridge system abuts an ancient (presumably Pleistocene embayed bedrock coastline, and there is usually a very sharp break of slope between the two features (Plate 3.7). Prior to the development of the beach ridges, Blackwall Mountain could have been an island, like Lion Island today. Some of the innermost beach ridges enclose swamps at the head of the small embayments which, on morphological grounds, must have been saltwater barrier lagoons. The lagoons would have been converted into brackish or freshwater swamps by the seaward growth of the beach ridge system. At present, the swamps are colonized by reeds (Phragmites communis), sedges, swamp paper-bark (Melaleuca spp.), swamp

mahogany (E. robusta) and swamp oak (Casuarina glauca).

In the vicinity of Ettalong Beach (Figure 3.9), there is a break of slope between the northeastern edge of the beach ridge system and a swampy area which stands about 6 feet above sea level. It is difficult to establish what actually happened in the past, but it seems most likely that the ridges were formerly truncated by extremely strong tidal currents. Alternatively, they may have been cut back by storm waves during a period of exceptionally bad weather.

At the other end of the system, Ettymalong Creek and its tributaries form an irregular drainage pattern through the ridges and swales near Mt. Ettalong (Figures 3.9 and 3.10). The creek system drains swamps and relict lagoons between the innermost abandoned ridges and the bedrock coastline. It seems likely that Ettymalong Creek was deflected northwards for approximately half a mile when its outlet was blocked by prograding beach ridges. Field investigations showed that the creek flowed along a swale, and then cut across a few ridges before flowing southwards along another swale, to enter Broken Bay, immediately north of Mt. Ettalong headland at a point where the level of wave energy is lowest (see also Appendix 3.1). The possibility of a small barrier spit formerly extending from the headland seems remote.

Pearl Beach Barrier: Pearl Beach is an extremely narrow, arcuate-shaped barrier which originally formed across the mouth of a small embayment in Broken Bay, between Mt. Ettalong and Green Point headlands. In fact, the lagoonal-swamp shown on the inset map in Figure 3.8 is the only trace of this embayment which has been infilled almost completely by colluvium at the back of the embayment, and by fluvial sediments transported by the three coastal streams.

The southern end of the barrier behind the foredune has been extensively levelled for residential building and therefore it has been extremely difficult to reconstruct, with accuracy, any former beach ridge pattern. However, from the evidence of borings made in areas not cleared for property development, it appears that there may be two generations of barrier sediments as shown by a thin veneer of unleached sand containing comminuted shell fragments overlying podzolized sand. The leached A_2 horizons of the podzols are about 3 feet thick, and are no more than 1 foot or so below ground level. The borehole data listed in Appendix 3.3 also show that podzolized sand at the back of the infilled embayment sometimes overlies mottled reddish-grey clays, mixed with light brown and orange-coloured sand containing a high percentage of quartz pebbles (see borehole 17, the location of which is shown in Figure 3.8). There seems little doubt from the available evidence that these clays and sands are not estuarine sediments but colluvium, derived from weathered Triassic sandstone and shale, which has gradually moved down the steep slopes and accumulated at the foot of the cliffs.

The suggestion made here that the modern barrier may overlie ancient barrier sands is partially supported by the presence of lagoonal-swamp sediments (chiefly sandy clays) which are now exposed at the base of the foredune between the outlets of the middle and southernmost streams shown in Figure 3.8. The occurrence of these sediments at the back of the modern beach is a good indication that in the recent past the barrier retreated landward under wave attack and spilled over into a much larger lagoonal-swamp than can be located today. The barrier has been breached

in several places. The largest gap occurs near the location of borehole 8 (Figure 3.8), while smaller ones have been noted by the writer between boreholes 11 and 13.

Most of the foredune is stabilized by dune scrub, mainly Leptospermum laevigatum. Paperbark trees (Melaleuca spp.) immediately behind the foredune, and near the stream draining the lagoonal-swamp (near borehole 7). mark the site of part of the lagoonal-swamp before it was infilled by sand. The remnant swamp is so shallow that it is completely drained during long periods of dry weather. The absence of Salicornia indicates that the water is brackish; the shore rush, Juncus maritimus, is common on the edge of the swamp, but away from the swamp proper it gives way gradually to Casuarina glauca and C. littoralis together with Melaleuca quinquenervia and the swamp mahogany (E. robusta).

A few sand ridges between the lagoonal-swamp and the sandstone cliffs are stabilized by Banksia serrata, Angophora costata, E. maculata (spotted gum), and Syncarpia glomulifera (turpentine). The location of the turpentine is unusual since it is usually found on fertile soils rather than sandy soils or colluvium. Its presence in this locality is therefore attributed to the occurrence of slightly deeper soils provided by the colluvium underlying the sand ridges, and also to the sheltered gullies at the back of the embayment.

Patonga Beach Barrier: Patonga barrier spit, which almost completely encloses the mouth of Patonga Creek in Brisk Bay (Plate 3.9A; Figure 3.11), consists of abandoned arcuate-shaped beach ridges and intervening swales aligned parallel to the modern beach. It is approximately three-quarters

of a mile long and 260 yards wide (Figure 3.12). Although the ridges are somewhat irregularly spaced across the barrier (for example between 30 and 180 feet apart along section $A-A_1$, $B-B_1$ and $C-C_1$ in Figures 4.11 and 4.12), their crests are fairly uniform in height and stand between 3 and 4 feet above mean sea level, and between 1 and 2 feet above the adjacent swales. The barrier is composed of unleached quartzose sand with comminuted shells. Even so, the content of calcium carbonate is extremely low and generally averages less than 2 per cent. A few samples collected from boreholes showed evidence of iron staining, and the presence of organic material. Borings showed that the barrier sands are more than 15 feet thick along the sections shown in Figure 3.11. Bedrock was only encountered at Dark Corner near the edge of the sandstone cliffs.

Although the oldest ridges at the back of the barrier are stabilized by a cover of succulent plants, bracken (Pteridium esculentum; P. aquilinium), Llantana camara, and dune scrub with banksia trees (B. integrifolia),and Angophora intermedia, borehole samples and soil pits showed that there is little evidence of soil profile development across the barrier. The pH value of the surface sand varies between 4.8 and 8.4, and the value of sand collected at depths between 7 and 10 feet varies between 7.3 and 8.3.

Unlike neighbouring Pearl Beach, Patonga Beach does not appear to have been breached or eroded appreciably since it first formed. This lack of erosion is a result of the barrier's sheltered position and relative protection from most storm waves. Even constructive ocean swell is refracted considerably by the time it reaches Brisk Bay and, under normal

conditions, wave heights rarely exceed 2 or 3 feet. At present, Patonga Beach is the only barrier which shows evidence of progradation in Broken Bay, and this is demonstrated by the presence of an incipient foredune along the back of much of the beach.

The occurrence of Banksia integrifolia, Leptospermum laevigatum and Erythrina (Coral tree) on the frontal dune in the vicinity of Dark Corner, and Banksia integrifolia and Acacia soporae along the entire length of the third ridge behind the beach not only reflects the protection afforded the barrier by its flanking headlands, but possibly the influence of a microclimate on vegetative growth, as illustrated by the slightly higher temperatures recorded at Patonga Beach.

Despite the fact that Patonga Beach is little affected by erosion, the distal end of the barrier has been reshaped intermittently by Patonga Creek. Figure 3.11 and Plate 3.9A show that the creek drains into Brisk Bay through an extremely narrow tidal outlet. A fairly wide bar, exposed between mid- and low-tides, exists for most of the year near this outlet. The writer studied the shape and characteristics of the bar at bi-weekly and monthly intervals for 18 months and found that it is only dissected, or removed temporarily, after heavy rains cause the discharge of Patonga Creek to increase appreciably and when ebb tides are exceptionally strong. Immediately after the bar is breached, a small submarine delta usually forms and is nourished by sediment carried a short distance offshore (Plate 3.9A), as well as by sand moved shoreward during the normal tidal cycle. Although some sand is moved through the outlet of Patonga Creek during flood tides, the succeeding ebb tides are always sufficiently strong to maintain a deep channel between the distal and of the barrier

and the bedrock headlands opposite. Occasionally, however, when the creek is swollen with floodwater from its catchment, the edge of the barrier is scoured and partially eroded by water overflowing the channel banks.

Of course, there is always the possibility that the barrier completely enclosed Patonga Creek at some time in the past, and was subsequently breached. But this seems unlikely in view of the writer's records and observations. But it is possible that observations were not made over a sufficiently long period to show all the processes that may take place at the distal end of the barrier.

The main channel of Patonga Creek is flanked by intertidal mud flats which are stabilized by mangrovers - Aegiceris (yellow mangrove) and Avicennia (grey mangrove). Sand banks are also conspicuous in mid-channel during low tides. On Plate 3.9A sand banks and mangroves are shown in juxtaposition, the latter occupying the darker areas.

South Coast

Twofold Bay: (1) Boyd Town Beach Ridge System: The Boyd Town beach ridge system is situated between the Nullica River and Boyd Town Creek. It is approximately three-quarters of a mile wide and is backed by degraded sea cliffs (Plate 3.10B). The ridge crests stand between 6 and 9 feet above sea level and parallel a 12-ft frontal dune, but they are somewhat irregularly spaced across the barrier (Figure 3.13). There is practically no evidence of leaching even on the oldest ridges. Most of the barrier is anchored beneath a cover of dune scrub with Banksia integrifolia.

(2) Whale Beach Barrier: South of Mowtree Headland, Whale Beach barrier encloses the Towamba (Kiah) River estuary (Plate 3.10B). This barrier is quite narrow, and is comparatively steep because it consists of coarse-grained sand. Only the landward side of the barrier is vegetated, and then with a poor cover of Leptospermum laevigatum and other dune scrub plants. In contrast, the seaward side of the barrier is devoid of vegetation and covered with storm wave debris (Plate 2.2H and 2.2J). The barrier has been breached at both ends (see Chapter 5).

(3) Eden Barrier: Aslings Beach, designated here Eden barrier, impounds Curalo Lake which occupies the drowned valleys of Bellbird Creek and adjacent coastal streams. Like Whale Beach, it is an extremely narrow barrier and is essentially a frontal dune which stands about 20 feet above present sea level (Figure 3.13; Plate 3.10A). From the evidence of boring (and like all the barriers in Twofold Bay), there is practically no indication of leaching. The northern end of the barrier is fronted by an incipient foredune (Plate 2.2G) which reflects the relative shelter afforded the barriers in Twofold Bay.

Pambula Barrier: Pambula barrier, which is the largest in the south coast study area, is 3 miles long and approximately three-quarters of a mile wide (Figure 3.13; Plates 3.11A and 3.11B). The inner margin of the southern part of the barrier is separated from a densely vegetated ancient bedrock coastline by a narrow tract of partially infilled lagoons, and swamps. In contrast, the northern end of the barrier encloses Merimbula Lake. Pambula barrier consists of a series of slightly arcuate beach ridges and intervening swales which trend approximately north-south parallel to the

frontal dune. The ridges and swales are fairly regularly spaced across the barrier. Ridge crests vary between 22 and 26 feet above sea level (apart from the oldest ridge which is 30 feet high), and stand between 2 and 4 feet above the swales. It is interesting to note that these heights correspond closely to those of the Umina-Woy Woy beach ridge system in Broken Bay.

Samples collected from boreholes sunk across the barrier show that podzolic profiles are very poorly developed (Figure 3.13). Poorly-cemented humate was found in one borehole only. However, since this particular boring was made on the edge of the inner flat of the barrier (behind the oldest ridge) which is swampy, it seems most likely in this instance that the humate accumulated in a swamp environment because it is not the product of deeply leached barrier sands. It is also inferred, because of the lack of podzolic profiles and absence of humate (apart from the one example cited above), that there is no Inner Barrier on the south coast, the reasons for which are evaluated a little later in this chapter.

PART II
Discussion

Introduction: So far, little has been said in this chapter about the origin and development of barriers, a subject which has held the interest of both geologists and geomorphologists for many years, probably because few investigators have been able to agree. Here, a short summary is given of some of the important contributions on barrier development, and a few new concepts are discussed briefly before a more detailed account is given of the barriers in the respective study areas.

The theories of de Beaumont (1845) and Gilbert (1885) on the evolution of barriers were summarized and reviewed by Johnson (1919) in his classical shoreline treatise. De Beaumont related the development of barriers to locally derived sediment, whereby waves erode the sea floor outside the breaker zone and deposit material to form a barrier on the inside. But as Johnson pointed out, de Beaumont's theory did not entirely exclude longshore drift, although this process (according to de Beaumont) would have been of minor importance. On the other hand, Gilbert attributed the formation of barriers to the growth of spits by longshore drift, the spits eventually being converted into barrier islands by subsequent breaching. Shepard (1960), based on his study of Gulf Coast barriers, suggested that both processes are probably important, although the problem of local as against longshore drift has not been resolved.

Johnson's (op cit.) traditional theory of barrier island development from offshore bars did not explain adequately the nearly universal distribution of barriers along the coastal plains of the world. Even so, it was not seriously challenged until Russell (1958) drew attention to the fact that barriers commonly protect and preserve an inner shoreline of submergence which developed within the past 5000 years during a stillstand of sea level. Since Russell's work, several other workers including Shepard (1960), Zenkovitch (1962), and McIntire and Morgan (1962) have challenged Johnson's theory.

It is now generally accepted that the majority of the world's barriers are characteristic features of submerged coasts, even those that have been slightly affected by tectonic movements (including recovery from isostatic downwarping owing to ice loading). Nevertheless, agreement

on the origin and development of these depositional features is complicated by the dissension on Quaternary changes of sea level, especially changes during the past 7000 years. For example, Leontyev and Nikiforov (personal communication ;1966) suggested that barriers have developed from offshore bars, exposed during a general lowering of sea level in late Holocene time. Certainly, there is no conclusive evidence of a Holocene higher sea level in New South Wales (Hails, 1965; Thom, 1965; Langford-Smith and Thom, 1969 in press). Therefore an important and perhaps key question concerning barrier development is whether there has actually been a Holocene higher sea level in all those areas where barriers are reported to have developed from offshore bars.

Any account of the evolution of the barrier systems on the New South Wales coast should attempt to explain the processes involved in transporting the enormous quantities of sand that must have been available during barrier progradation. As yet, there is little evidence to support Halligan's (1908) traditional view that sand is moved along the coast by ocean currents, or by counter currents deflected by projecting headlands. According to Halligan, longshore drifting on the Mid-North Coast of New South Wales forced the rivers either to the north or south until they encountered a headland - where the struggle between drifting sand and tidal currents ensued.

The wave refraction diagrams in Appendix 3.1 show that the creek and river mouths, and entrances to lagoons, are situated near the headlands flanking the bays in the study areas, but at a point where the level of wave energy is lowest (cf. also Bascom, 1954). Thus, Halligan's observations on the position of river outlets on the Mid-North Coast were basically

correct, but the reasons he cited to account for their location ignored the effects of wave energy.

So far, the writer has found no direct evidence in the field of barrier growth by the elongation of spits, either northwards or southwards across the mouths of embayments, as might be expected with longshore drifting of material. In addition, there are no traces of preserved recurves anywhere on the landward side of the barriers, although the absence of such features does not automatically exclude their former existence. Also, the movement of material alongshore does not convincingly account for the arcuate pattern of Inner and Outer Barrier beach ridges, particularly when these ridges trend approximately parallel to the modern shoreline which is shaped predominantly by refracted southeasterly swell waves. In fact, the presence of arcuate-shaped ridges in each study area is strong evidence of barrier growth seaward by the addition of individual beach ridges, and therefore the writer is unable to support Halligan's thesis.

However, no one will deny that waves reaching a shoreline at an angle can induce nearshore currents capable of moving some material alongshore. Unfortunately, the writer has been unable to undertake nearshore experiments with radioactive or fluorescent tracer sand in order to assess the amount of material that can be moved in this way.

Ewers and Foster (1964) calculated theoretically the strength of littoral currents and the volume of material transported alongshore at Budgewoi Beach, about 40 miles north of Sydney. According to their results, 2.6×10^4 cubic yards of material per day can be moved when there are southeasterly winds, and when waves with a deep water wave height of 10 feet and wave period of 10 seconds reach the coast. Obviously, there is an urgent

need for quantitative research to establish the importance of waves and currents in fashioning depositional coastal formations. It would be premature, even with the results of wave tank experiments, to generalize about the movement of material on all sectors of the New South Wales Coast. Even if one agrees with the view that longshore drifting has contributed significantly to the growth and shaping of some parts of the Australian coast (for example see Bird's (1965) account of the East Gippsland barriers) one must also conclude (as indeed Bird did) that its influence is virtually insignificant compared with the landward movement of sediment from the sea floor by wave action.

In many ways it is unfortunate that the quartzose sand barriers on the Mid-North Coast do not readily provide clues on the movement of material alongshore since they contain very few distinctive heavy minerals whose source of origin is definitely known (see also the discussion in Chapter 8).

As already mentioned in this chapter, the barrier systems of the central and south coast of New South Wales are not as clearly represented by Pleistocene and Holocene components as those on the north coast, while relatively large barriers are almost exclusively confined to the north coast. This is because former broad protected bays of the north coast, and an abundant supply of sand from large rivers, favoured the development of wide barriers, while the more rugged embayments and general absence of large rivers on the central and south coast did not. Thus, although beach ridge systems are common practically everywhere on the New South Wales coastline, they are generally less well-developed on rugged sectors.

However, comparison of the relatively wide beach ridge systems on the Mid-North Coast and the Umina-Woy Woy system in Broken Bay suggests certain correlations. Of these, the most obvious is that between beach ridge systems and large rivers which have brought sediments to the coast; the rivers are the Macleay and Hastings on the Mid-North Coast and the Hawkesbury in Broken Bay. But in each area, the vast quantity of sand comprising the beach ridge systems is fairly conclusive evidence that the sediment cannot relate directly to the present-day rivers. New South Wales rivers are now transporting little if any sand downstream (except in times of flood) and even fine-grained sediments are rarely reaching the outlets (Ford, 1963). In fact, Ford suggests that there is a present net movement of sand into the rivers and through lagoon entrances from the offshore zone. This suggestion is supported by the occurrence of 'reverse' tidal deltas which are still being built in several of the south coast lagoons (Plate 3.11A), because flood tides are carrying more sediment into the lagoons than is being returned to the ocean by ebb tides.

The inference, then, is that large quantities of sand must have been delivered to the coast and continental shelf during the past when river discharges were presumably considerably greater than now. The actual point of deposition would have been related to sea level (and thus to the position of the shoreline) at any particular period. It would seem therefore that the offshore zone was formerly the most direct source of sand. The material on the sea floor was reworked and moved shoreward by wave action, and eventually incorporated in the barriers during, and subsequent to, a series of marine transgressions.

Recent work (Russell, 1958; Shepard, 1960; Curray, 1960; Hails, 1964b, 1968; Bird, 1965; Hoyt, 1967) tends to favour strongly a rising sea level as a factor responsible for making available large quantities of sediment from the offshore zone, and evidence from the study areas certainly supports this correlation. During a period of stillstand following a rise in sea level, a barrier can continue to build seaward as long as there is an abundant supply of material delivered to the coast by constructional waves. Similarly, a barrier is able to prograde during a very slow transgression as long as its growth is able to keep pace with the rise in sea level. This seems to have been the case with the beach ridge systems south of Grassy Head, at Umina-Woy Woy in Broken Bay, and at Boyd Town in Twofold Bay.

The maximum depth at which material on the sea floor cannot be moved by wave action depends upon the type of wave and its magnitude, and the grain-size and density of the material to be moved, but as yet there is inconclusive evidence on this topic and the processes that may operate are not fully understood. However, the submarine contours in Figure 3.8 show that the water is not much deeper than about 30 feet in Broken Bay, and it is unlikely that this depth has varied by more than a few feet during the pass 5000 years, if the generally accepted view is correct that sea level has been fairly stable during this period of time (see Chapter 9). In this instance the depth of water could be significant, because it is well within what the majority of coastal workers at present consider to be the limits of effective normal wave action.

In the writer's opinion (Hails, 1964b, 1968; Hails and Hoyt, 1968) it is quite likely that during a late phase of the postglacial rise of sea

level, when the sea stood only a few feet below its present level, ephemeral barriers were established seaward of the present coast, perhaps at a distance not much greater than that between the Inner and Outer Barrier today. But as the sea continued to rise to its present level these barriers were destroyed subsequently and material was driven landward for the construction of the modern Outer Barrier. Phipps (personal communication) reported submerged features off parts of the New South Wales coast which could possibly be relict submerged barriers that have survived total destruction. However, his evidence is still inconclusive because parts of the inner shelf are covered by fine-grained terrigenous sediments which have at present made submarine boring somewhat difficult. Still it is interesting to record that submerged relict barriers have been reported elsewhere (Curray, 1960), and possible relics of submerged barriers may exist in parts of Bass Strait (Jennings, 1959). Shirley (1964) distinguished three belts of sediment on the continental shelf between Crowdy Head and Bateman's Bay. The nearshore belt consisted of coarse sediments, mainly rounded sand grains which strongly resembled dune sands. Of course it is possible that these may have been derived from the mainland, but the possibility cannot be dismissed that they may have been moved shoreward from submerged barrier relics.

Erosion of headlands and transportation of sand by longshore drift may have provided some material for shoreline progradation in the past, but these processes have been negligible in their overall effect and could not have been major causative factors, because of the enormous volume of sand incorporated in the barriers.

Burges and Drover (1953) are of the opinion that much of the sand contained in the Umina-Woy Woy beach ridge system came directly from the sandstone headlands in Broken Bay although they are particularly resistant to weathering and erosion. Therefore their explanation is questionable considering the size of the barrier, and the alternative theory already put forward here about the source of sediment in the past seems more satisfactory.

It seems reasonable to suggest that if barriers develop from offshore bars, as Johnson postulated, various stages of their development are likely to be observed along modern shorelines. Yet, as far as the writer is aware, these stages have not been recorded, except as minor temporary features. Studies of barrier islands and lagoons on the Gulf Coast by Fisk (1959), LeBlanc and Hodgson (1959), Rusnak (1960), and Shepard (1960), and of barriers elsewhere by Zenkovitch (1962), Van Straaten (1965), Hails (1964a), and Hoyt and Hails (1967), indicate that lagoons were not exposed to open marine conditions during the development of major barrier island chains. In addition, the writer has found no evidence of cliffing to suggest that the Inner Barrier on the Mid-North Coast was exposed to the open sea or modified by wave action when the Outer Barrier was built. Neither for that matter is there any evidence to indicate that the Inner Barrier was modified by lagoonal waves, before the inter-barrier lagoons were reduced in size by the development and encroachment of swamp land.

Holocene beach deposits, and open marine and fossiliferous neritic sediments, have not been found along the seaward side of the Inner Barrier although borings have been made along almost the entire length of the

contact of this Pleistocene feature with the Holocene tract of swamps and lagoons. Deep commercial borings, and shallow borings made by the writer, have only penetrated estuarine sediments beneath the two fluvial-deltaic plains on the Mid-North Coast.

Admittedly, the evidence on the Mid-North Coast does not entirely preclude the possibility that Holocene marine beach or fossiliferous neritic sediments have been removed, or buried beneath lagoonal-swamp sediments. However, as just mentioned, the borings have failed to contact any such sediments, and it seems unlikely that all traces of open marine sediments and fauna would be completely destroyed.

One cannot state categorically that barriers are confined exclusively to coastlines of submergence, but certainly there is little evidence in the writer's study areas to corroborate Johnson's remarks on the evolution of barriers. Thus the origin and development of barriers demand an alternative explanation. An hypothesis, somewhat of a modification of that of Russell (1958), has been put forward by Hoyt and Hails (1967), and Hoyt (1967), which maintains that barriers are established during a slow rise of sea level and initially constructed as ridges immediately landward of a shoreline from wind- or water-deposited sediments. A slow rise of sea level, as during late Holocene time, floods the area landward of the ridge forming a barrier and lagoon - as in the case of the Outer Barrier on the New South Wales coast. Presumably, similar processes may have operated during late Pleistocene time when the Inner Barrier was established. Actually, Bird (1965) has also made a similar suggestion independently to account for the construction of the Gippsland barriers; he envisaged barriers being driven towards former shorelines.

Obviously, with a slow rise of sea level, the existence of a barrier depends upon several interrelated but exceedingly complex factors, such as the rate of sediment supply, coastal configuration, nearshore bottom slope, wave-induced currents which are influenced by water depth, as well as the effects of tidal ranges, and the effective limits of the waves themselves. However, many nearshore processes are still not fully understood, despite the numerous wave tank experiments that have been undertaken in recent years to see how various littoral constructional features develop.

If a rise in sea level is extremely slow, a shoreline can occupy an infinite number of positions, and ephemeral barriers can be established according to the balance between the rate of sediment supply and the rate of sea level rise. It is during the major stillstand of a rise in sea level that the coast and shoreline are shaped and major barriers develop. With the preceding discussion in mind it seems appropriate to examine the origin and development of the barriers in the study areas in more detail.

Development of the Inner Barrier: It seems most likely that the Inner Barrier was established a short distance from an indented bedrock coastline and then prograded seaward by the addition of beach ridges. As stated previously, the slightly arcuate outline of these ridges indicates that they were shaped by the refracted fronts of ocean swell waves.

The highest 20-ft ridges on the Maria-Wilson barrier plain, although comparable in height with most of the other Inner Barrier ridges on the Mid-North Coast, may be relict frontal dunes. Despite the fact that several ridges on the barrier plain have had their surfaces lowered by deflation, and erosion by stream floodwaters, variations in the height and spacing of the ridges could also indicate changes in the rate of barrier

growth seaward. Based on the evidence of actively prograding sectors of the coast (for example, parts of Pambula barrier and the comparatively sheltered barriers in Twofold Bay), it seems likely that the beach ridges developed from incipient foredunes (Plates 2.2E and 2.2F). Following the cut and fill hypothesis of Davies (1957), the incipient foredunes probably originated as berms which remained undisturbed long enough to be fixed by vegetation. Beach ridges, once stabilized, increase their height by the accumulation of windblown sand. Eventually, if the rate of building seaward has been extremely slow, a beach ridge can attain the height of a frontal dune. As Davies suggested, beach ridges and frontal dunes are essentially similar except for the amount of windblown sand which they contain. Certainly, the variations in height and spacing of the beach ridges across the Maria-Wilson barrier plain may have been controlled primarily by changes in the rate of sediment supply, and by seasonal variations of the offshore profile, rather than minor fluctuations of sea level.

Morphologically, this barrier plain is very similar to the Inner Barrier in the Port Stephens-Myall Lakes area described by Thom (1965), but additional evidence supported by radiocarbon dates is needed before any correlation can be made.

The area drained by Limeburners Creek, tidal to Saltwater Lake (Figure 3.7), may be equivalent to an inter-barrier lagoon because it interrupts the sequence of deeply podzolized beach ridges. The sands east of Limeburners Creek have very poor podzol profiles. Although humate was located at boreholes 32 and 35 (Figure 3.7), and along the west bank of Limeburners Creek, it was not encountered beneath the ridges at boreholes

33,34,36 and 37, nor in the boreholes sunk along section B-B_1 east of Saltwater Lake. Estuarine sands and clays were found within 3 feet of ground level at borehole 30 on the east bank of Limeburners Creek.

Absolute dating has been impossible because the sands east of Limeburners Creek lack carbon-rich material. However, the fact that the ridges are seaward of an apparent inter-barrier lagoon, together with their conspicuous lack of podzolization, leaves little doubt that they pertain to an Outer Barrier system. It is also virtually certain that the occurrence of estuarine sediments beneath the low ridges at the back of the Outer Barrier is evidence of a larger tidal estuary that has been subsequently reduced in size by the landward migration of the Outer Barrier. Swamp land now occupies a large area of this former estuary, and the entrance to Saltwater Lake has been partly infilled with large quantities of sand carried up Limeburners Creek during flood tides.

Umina-Woy Woy Beach Ridge System: The Umina-Woy Woy beach ridge system is of unusual interest because there has been considerable speculation in respect of the age of the beach ridges - whether they pertain to the Inner Barrier, the Outer Barrier, or comprise some units of both systems (Hails, 1969 in press). There is no sharp morphological break or pedological difference between the ridges as elsewhere between the Inner and Outer Barriers. Although the height of the beach ridge crests is fairly constant, there is a gradual, but distinct, increase in the degree of podzolization away from the foredune towards Woy Woy Creek. Another problem is whether or not the swamp tract (Figure 3.9) is an inter-beach ridge area which represents an interruption in the progradational sequence. It could be aruged that the area is a large swale swamp, since it extends along the

length (approximately northeast to southwest) of the beach ridge system. It is conceivable that a period of erosion interrupted shoreline progradation, leaving a relatively low-lying area prior to the continuation of beach ridge development. Alternatively, sediment supply may have diminished for a short period, or the swamps could now occupy the remnants of a very narrow lagoon which formed behind a new series of ridges. Boreholes sunk by the writer show that the swamp facies does not extend under the ridges, so an offlap-onlap sequence cannot be established. If a marine regression occurred after the formation of the innermost ridges, a difference in crest heights might be expected.

All that can be done at present is to correlate tentatively the Umina-Woy Woy system with other beach ridges of known age in similar environments in New South Wales. But in such a correlation the factors causing variations in beach ridge height, coastal stability, and the general lack of agreement about eustatic changes of sea level during the Holocene must be appraised. However, in the absence of contrary evidence, it seems reasonable to suggest that beach ridges of different ages are in juxtaposition at Umina-Woy Woy, and that the occurrence of humate is a fairly reliable indication of Pleistocene deposits.

Burges and Drover (1953) attempted to determine the age of the beach ridges by considering the rate of podzol development in the sands, based on the rate of shoreline progradation at approximately 1 yard per annum. The total length of the transect studied by them was approximately 4500 yards, and they considered that ridge-building processes began about 4000 years ago during a fall of sea level. These explanations seem inadequate and over-

simplified. Burges and Drover have overlooked two important facts. One is that it is virtually impossible, without radiocarbon dates, to assess the time required to build beach ridges, as several shoreline processes are involved. Any variation in these processes can affect or interrupt the rate at which a particular shoreline progrades. Yet Burges and Drover, in reaching their conclusions, assumed that the rate of beach ridge progradation was absolutely constant.

Second, they assumed that the annual temperatures and amount of rainfall remained approximately the same throughout the period of beach ridge progradation although it is known that there have been notable changes in climate during historical times, and similar changes could have occurred in the past. Assessing the effects of climatic change on soil profile development is extremely difficult, particularly when there are no pollen profiles or macro-plant analyses available for evaluation.

Beach Ridge Heights as Indicators of Changes in Sea Level: It is now necessary to evaluate briefly the significance, if any, of beach ridge heights in determining the level of former higher stands of the sea. In his exposition of the origin of beach ridges, Johnson (1919) paid considerable attention to their value as records of changes in sea level. However, the significance of sand ridges in attempting to establish relative changes of land and sea, depends upon whether they are actually dune or beach ridges, but from the evidence of the literature this distinction is seldom brought to the attention of the reader. There is no single adequate explanation to account for all known examples of beach ridges, but a review of the numerous published papers dealing with this subject is inevitably outside the scope of this chapter.

Some of the traditional views that beach ridges and beach plains result from a relative fall in sea level are debatable (see Johnson, op. cit.). On parts of the east Australian coast, some Outer Barrier formations have gained height by accretion on ridges and alluviation in swales (Langford-Smith and Hails, 1966) and, as already mentioned, some Inner Barrier systems have also had their surfaces lowered by deflation and by floodwater erosion. On some sectors of the New South Wales coast, the crests of beach ridges tend to decrease in height towards the sea, and this gradient correlation has sometimes been taken to support the proposition of a falling sea level during beach ridge construction. However, beach ridge crests are unreliable indicators of sea level. For example, one such series of descending ridges at Seven Mile Beach, New South Wales, has been examined in detail by L. D. Wright (unpublished) who found the marine-eolian cap boundary in the ridges to be approximately horizontal, but with a slight tendency to slope landward.

In the study areas, ridge crests do not show any tendency to slope either landward or seaward although a marine-eolian boundary in the case of the Inner Barrier is almost impossible to define for the reasons stated earlier in this chapter. The fairly accordant crest heights of the beach ridge systems in the study areas (with the exception of the Maria-Wilson barrier plain) may be explained by a reasonably constant and abundant supply of sand during progradation, and the generally well-preserved ridges and swales suggest that a period of rapid stabilization immediately followed beach ridge construction.

The problem at Umina-Woy Woy, however, is that the non-podzolized ridges stand between 16 and 22 feet above present sea level which seem to

be somewhat excessive heights. It is unlikely that all these ridges are storm beaches thrown up above high-water mark because of the relatively sheltered position of the barrier system inside Broken Bay (see Appendix 3.2 for details on Tidal Planes). If these ridges formed during the post-glacial marine transgression, which on present evidence seems most likely, they are of Holocene age. A critical question therefore is whether all the Umina-Woy Woy ridges are capped by windblown sand, and if so, to what depth. Although it is extremely difficult to establish the amount of sand that has probably been blown onto the original beach ridges, on the basis of morphological evidence alone it seems improbable that all the ridges could have been capped by equal quantities of eolian material. While discussing the processes reponsible for the height of the Umina-Woy Woy ridges the possibility of coastal instability must be considered, but as already mentioned in Chapter 2 little is known as yet about this in the Sydney region. However, this subject will be evaluated later when changes in sea level are discussed (Chapter 9).

Beach Ridges Fronting the Clybucca Shoreline: The abandoned beach ridges fronting what the writer has termed the Clybucca shoreline are of particular interest since they are separated from the Grassy Head beach ridge system by a 2-mile wide tract of swamp (Figure 3.4 and Plate 3.6). Owing to an absence of bench marks and the almost impenetrable vegetation in places, it has been difficult to establish precisely the height of these ridges although they stand approximately between 3 and 9 feet above mean sea level. A traverse across accessible areas on foot showed that they are irregularly spaced and stabilized by dune heath and scrub, and borings showed that the ridges are deeply podzolized and underlain by humate in places.

Field investigations also showed that the area of swamp between the Clybucca and Grassy Head beach ridge systems was formerly drained by large streams since the lobate inner edge of the Grassy Head system is flanked by infilled drainage channels. Today, the swamp area is drained by small tidal distributaries of the Macleay River system. Since all the podzolized sand ridges are pedogenically similar, and there is a lack of organic material suitable for radiocarbon dating, it is difficult to determine whether the two beach ridge systems were established during one or more higher stands of sea level. However, the following suggestions are made in an attempt to explain former events.

First, since the two beach ridge systems are not continuous they were possibly built during two entirely different Pleistocene higher stands of sea level. Second, an abrupt change or fluctuation in the rate of sediment supply resulted in a lower area between the two beach ridge systems which was subsequently removed by stream incision as the sea retreated to a lower level in Pleistocene time. Third, a fluctuation in the level of the sea whereby a rapid fall in level was followed by an immediate rise might be invoked, although the swamp facies does not extend beneath the Grassy Head beach ridge system to support the idea of an offlap-onlap sequence.

Barrier Breaching: There is little evidence of Inner Barrier breaching by stream incision on the Mid-North Coast between Smoky Cape and Race Course Headland. Although parts of this barrier system have been removed, a notable absence of infilled drainage channels between and landward of the barrier remnants is a good indication that dissection in the past can be attributed almost entirely to floodwater erosion and storm wave

action rather than relative changes in the level of the land and sea. The writer's contention is strongly supported by similar breaches in the adjacent Outer Barrier.

About 1 mile north of Hat Head village, both Inner and Outer Barriers were extensively breached by floodwater from Kinchela Swamp during successive 100-year floods in 1949 and 1950 (Figure 3.2). The Outer Barrier was almost breached again in the same locality in 1963 when unusually heavy rain fell in the catchment of the Macleay River. In that year, the lower Macleay Valley was inundated by floodwater which not only filled the inter-barrier lagoonal swamps to capacity, but also submerged the lowest parts of the Inner Barrier. The Outer Barrier was breached about 7 miles north of Crescent Head, and about 1 $\frac{1}{2}$ miles north of the 1949 and 1950 breaches (Figure 3.3), when floodwater from Ocean Swamp removed a large section of the barrier and the upper beach, and exposed an extensive peat bed which the writer traced below present sea level LWM. Therefore on the basis of this evidence it seems likely that similar events may have occurred in the past after the formation of the Inner Barrier.

The dissection of beach ridges on the Maria-Wilson barrier plain can also be explained in terms of floodwater breaching, particularly since the numerous boreholes made by the writer failed to trace any infilled drainage channels between the dissected ridges.

Likewise Pearl Beach barrier has been breached by the floodwaters of the three streams draining into Broken Bay. During periods of shoreline progradation, the mouths of these small streams are blocked by sand sufficiently long for water to be ponded behind temporary barriers and

are only reopened after exceptionally heavy rain. Also water in the lagoonal-swamp sometimes overflows and drains into the sea by way of the stream at the northern end of the embayment.

The story of barrier breaching is not so straightforward south of Delicate Nobby. The areas of deeply podzolized sand which stand less than 3 feet above the surrounding swamps between Delicate Nobby and Big Hill (marked 'd' in Plate 3.4A and shown in Plate 3.3A) may be the scattered remnants of an Inner Barrier. The well-defined abandoned drainage channels shown in Plate 3.4A and marked (C) in Figure 3.7 may be the vestiges of streams that formerly drained into the ocean near the present headlands when sea level was slightly lower. Such a drainage system could have dissected an Inner Barrier as the sea regressed in the past. Of course, the writer is not discounting the possibility that the Inner Barrier south of Delicate Nobby (particularly if it had been lowered by deflation) may have been partly removed in Holocene time by floodwater, particularly since the Outer Barrier shows some evidence of breaching on the northern side of Big Hill headland.

To the north, the Inner Barrier is intact between Delicate Nobby and Crescent Head. It can be seen in Plate 3.4A that a few of the abandoned drainage channels appear to have been deflected by the Inner Barrier which links Race Course Headland and Delicate Nobby. Furthermore, no traces of drainage channels or fluvial sediments have been found in the area between the Inner and Outer Barriers linking these two headlands.

Dissected Barrier Near Spencers Creek: Barrier breaching by floodwater does not adequately account for the dissected barrier adjoining the sinuous bedrock area east of Spencers Creek (Figures 3.1 and 3.4). This

barrier consists of beach ridges which have been lowered considerably by deflation. One end of the barrier terminates abruptly as a 30-ft high cliff at Spencers Creek (Plate 3.3B). The deeply podzolized sand of the cliff face is underlain by humate which extends at least several feet below the low water level of the tidal creek. The barrier does not continue on the opposite side of Spencers Creek where shallow borings show that estuarine sediments underlie fluvial-deltaic deposits. This stratigraphic sequence implies that if the barrier formerly continued to the southwest of Spencers Creek it was ultimately destroyed, most likely during a fall in sea level.

It can be seen in Figure 3.1 that the dissected barrier is separated from the barriers bordering Trial Bay by an area of swamp containing Saltwater Lagoon, and from the Inner Barrier adjoining Smoky Cape headland by swamps and high fixed dunes. The position, height and northeast-southwest alignment of this relict barrier suggest that it may actually be older than the Inner Barrier and was built during a high stand of the sea when the bedrock areas were islands.

Because of the dense vegetation now covering most of the bedrock near Spencers Creek, the writer has been unable to reconstruct accurately the morphological characteristics of the area, and therefore the bedrock configuration shown in Figures 3.1 and 3.4 is somewhat generalized. Consequently, it has been extremely difficult to reconstruct accurately the former pattern of refracted waves around the islands (for example, Little and Big Smoky) during a higher sea level. All that can be said from the available evidence is that southeasterly and northeasterly waves

were probably dominant at the time. Whether this relict barrier system formed during a high stand of the sea long before the initiation of the Inner Barrier is a matter of conjecture at present. Nevertheless, the writer is of the opinion that the bedrock areas shown in Figures 3.1 and 3.4 were formerly linked by the barrier before is was breached, probably by a proto-Macleay River (see Chapter 6). Dissection could easily have taken place as the Macleay, like many other New South Wales rivers, incised its course in response to a lowering of sea level during glacial times, when the coast may have been several miles to the east of the modern shoreline.

Evidence of Stream Incision in the Past: Submarine surveys across the shelf have generally failed to trace former stream channels (or deeply incised valleys), but since most of the coast of southeastern Australia has been surveyed by echo-sounding methods to a depth of 100 fathoms along widely-spaced traverses at right angles to the coast, relict channels may not have been recorded. But according to Standard (1961), a possible submarine canyon has been traced off Smoky Cape and northeast of Coffs Harbour (just to the north of the writer's study area on the Mid-North Coast), and a few canyon-like features have been located near the mouth of the Hawkesbury River at Broken Bay.

Evidence of stream incision has come from commercial borings made for road bridge construction in the lower river valleys of the study areas. The commercial borehole data, and shallow borings made by the writer, show that most of the streams draining into Twofold Bay now occupy valleys that have been infilled with fossiliferous estuarine sediments

which underlie fluvial deposits containing much organic debris, including the remains of banksia trees. Depths to bedrock vary from 22 to 100 feet, according to the location of the boreholes. A few valley meanders have been traced, particularly in the vicinity of Whalan's Swamp about 2 miles upstream from Whale Beach barrier.

Bedrock has been located at 280 feet below sea level near the Hawkesbury road bridge (David, ed. W. R. Browne, 1950), and bore logs show that a deep, gorge-like valley has been cut in the local sandstone. Of course, it is possible that this gorge (and others elsewhere on the coast) is the cummulative result of incision during more than one phase of low sea level, but at least a gorge has been cut and subsequently infilled. The submarine canyon-like features reported by Standard may represent a former continuation of the Hawkesbury beyond the present coast. On the other hand, Hedley (1910) reported no trace of submarine gorges crossing the Australian shelf in continuation of present valleys, and concluded that if such gorges were once cut on the shelf they have since been infilled like the Hawkesbury gorge itself. Statements that only a thin veneer of terrigenous sediments cover the shelf (see Shirley, 1964) have not, as yet, automatically disproved the existence of a former Hawkesbury extension; certainly an extension of the Macleay and Hawkesbury rivers as reported by Standard (op. cit.) is consistent with evidence from rivers elsewhere (Shepard, 1963).

Age of the Barriers: It is necessary now to enquire about the age of the barrier systems. Despite the various studies of coastal barriers in Australia, there is still speculation about the actual age of the

Inner Barrier in New South Wales. Langford-Smith and Hails (1966) suggested that the Inner Barrier developed when the sea stood about 12-15 feet above its present level, possibly during the last Pleistocene interglacial.

The speculation arises mainly because barrier sands usually lack fossils and other material suitable for radiocarbon dating. However, two peat samples and one sandrock (humate) sample collected by T. Langford-Smith and the writer have been dated. One peat sample from Broadwater beach, near Evans Head on the north coast of New South Wales, was dated 15,530±650 B.P. (Gx-0090). The peat, 16 feet above present sea level HWM, overlies sandrock and, in turn, is overlain by podzolized dune sand. Since the sample included a mass of very fine root material, the C-14 date may have been reduced. Another sample of peat from the same formation gave an age of 12,150±230 B.P. (GaK-836) which is of the same order as the original date. However, a peaty sandrock sample overlain by fixed dune sand, at Jerusalem Creek south of Evans Head, which is part of the same barrier system as the Broadwater peat, gave an age of 25,900± 1100 B.P. (GaK-837). This particular sample was collected from cliffs cut in sandrock, 16 feet above high-water mark.

Since the peat was contaminated by very fine root material, and possibly the sandrock was also similarly affected, the true date of each sample is probably older than the figures would suggest. In any case, the dates indicate that the barrier formation between Ballina and Iluka is Pleistocene. Morphologically, it is a typical Inner Barrier formation.

If the dates from New South Wales are used as minimum dates because of the likelihood of contamination it is possible that the Inner Barrier

was established during a high stand of the sea correlative with a general ice retreat in North America and Eurasia more than 25,000 years ago. On the other hand, they may simply date an accumulation of organic material over a prolonged period, for the peat and sandrock are apparently freshwater to only slightly brackish in origin.

The list of radiocarbon dates of peats at the end of Chapter 9 give an approximation of the time when the Outer Barrier was established on the New South Wales coast. It seems that it was initiated sometime after 7000 years B.P., probably when the rate of the postglacial rise of sea level slowed down appreciably and the sea stood about 30 feet or more below its present level (Shepard, 1963b; Curray, 1965). Although the position of sea level in Australia during the past 5000 years has been the subject of considerable controversy, it appears from the evidence of the New South Wales coast that there has been a fairly stable sea level during this time (Hails, 1965b; 1968; see also discussion in Chapter 0). Of course the writer's view depends upon the accuracy of the radiocarbon dates and the relative stability of the areas used as evidence.

Outer Barrier Erosion: Yet, as already mentioned in this chapter, there is substantial evidence of Outer Barrier retreat in recent years and in view of this apparent contradiction - between a stable sea level and Outer Barrier erosion - the reasons why there is a predominance of cut over fill must be explained, if possible. Bird (1965) suggested that a renewed eustatic rise of sea level may well account for the recent phase of shoreline recession which is so widespread in southeastern Australia, and Davies (1957) suggested a change in level may have been accompanied by increasing storminess in coastal waters. Unfortunately, since tide-gauge

data and meteorological records are often so incomplete or unavailable for many sectors of the coast, it is extremely difficult to assess the exact causes of shoreline recession.

In the writer's view, the natural recent erosion may also be a direct result of an interruption in shoreline equilibrium, whereby material removed from sandy shores is not replenished naturally either by an onshore or alongshore supply of sand. Unlike some of the barriers on the south and east coasts of England, and on the Georgia Coastal Plain, for example, where alongshore drift is apparently dominant in one direction and erosion at the end of a barrier is usually balanced by deposition at the other, the barriers on the New South Wales coast are undergoing erosion along almost their entire length. Certainly there is evidence on the Mid-North Coast to suggest that short periods of coastal recession interrupted longer periods of progradation after the Outer Barrier was first established. For example, immediately to the east of Limeburners Creek, fixed dunes interrupt the continuity of old beach ridges at the back of the barrier (Figure 3.7). There is no evidence to suggest that these dunes have migrated landward from the modern shoreline since they are fronted seaward by a regular series of ridges and swales.

A general depletion of material in the offshore zone could be a causative factor of shoreline recession at present, and presumably in the past too. Apart from the very small quantities of sand that are moving through the tidal lagoonal entrances, and into the rivers during flood tides, there appears to be very little other sand available to nourish the Outer Barrier and to arrest its erosion. As already mentioned only

relatively small quantities of sand are now reaching the coast by way of the rivers, and it appears that former offshore supplies have now been either exhausted or buried beneath fine-grained terrigenous sediments. Thus in contrast to the past, practically no sand is available to be moved landward now by wave action.

Therefore a renewed rise of sea level need not necessarily be postulated to account for the current phase of erosion. At present, destructional wave action has replaced constructional processes. It also follows that the net result of a depletion of material offshore is a landward migration of the barriers. Thus if sea level has been reasonably stable during the past 3000 years, as suggested by many workers now, the Outer Barrier has been subjected to movement by waves approximately at present sea level.

The Outer and Inner Barriers on the Mid-North Coast are closely spaced mainly because of the character of the continental shelf. Off the Mid-North Coast the shelf is quite steeply sloping, averaging about 37 feet per mile, and terminating at about 80 fathoms. The average width of the shelf is only 13 miles which is fairly narrow compared with the average width of 20 to 30 miles for the shelf off eastern Australia south of Sandy Cape, and the average width of 40 miles for all other continental shelves reported by Shepard (1963).

Finally, it must not be overlooked that the destruction of the Outer Barrier by wave and wind action is often assisted to a considerable extent by floodwater, draining seaward from the inter-barrier lagoonal swamps, which invariably breaches the barrier from the landward side. During

severe storms, waves often penetrate such breaches and deposit material behind the frontal dune. Although the breaches are closed by natural progradation they are never completely healed, and remain as a line of weakness which is particularly prone to subsequent storm wave attack. Of course, some erosion is a direct result of man's activities, such as the mining of heavy mineral beach concentrates on the Mid-North Coast. Although several conservation schemes have been implemented in this area to present erosion after mining has ceased, hitherto they have been unsuccessful in stabilizing the sand. Also, on parts of the Outer Barrier grazing cattle have also undoubtedly contributed to erosion in a minor way.

Summary

1. Most of the barrier systems in the study areas on the central and south coast of New South Wales protect an inner shoreline of submergence as did those on the Mid-North Coast before the formation of the fluvial-deltaic plains. The exceptions are those barrier systems that abut an ancient bedrock coastline, for example, the Grassy Head beach ridge system on the Mid-North Coast, the Umina-Woy Woy beach ridge system in Broken Bay, and the Boyd Town system in Twofold Bay.
2. The barriers have smooth arcuate-shaped oceanic beaches and irregular, lobate inner margins, and generally consist of a series of abandoned ridges and swales which trend parallel to the modern shoreline.
3. The arcuate pattern of both Inner and Outer Barrier systems is good evidence of shoreline progradation by the construction of individual ridges that were shaped by the refracted fronts of predominant southeasterly swell waves.
4. Inner Barrier sands are deeply podzolized and are invariably underlain by humate, and stabilized by dune heath and woodland. By comparison, Outer Barrier sands are only slightly podzolized and are not underlain by humate; they are fixed by a cover of dune scrub and succulent, sand-binding plants.
5. The barrier systems of the central and south coast are not as clearly represented by Pleistocene and Holocene components as those on the north coast.
6. The contrast in size between the barriers on the Mid-North Coast and those on the south coast is mainly the result of the size of rivers

draining the adjacent coastlands. Rivers on the south coast have small catchments and small sediment yields compared with those of the Mid-North, and parts of the central coast. Bedrock configuration and composition are minor factors influencing the size of the barriers.

7. The barriers were initiated during marine transgressions, not regressions. The Inner Barrier probably developed when the sea stood about 12-15 feet above its present level in late Pleistocene time. However, the age of the barrier cannot be determined accurately yet, although it seems likely from the evidence of radiocarbon dates that it may be older than 25,000 years. There are relict barriers on the Mid-North Coast which may have formed before the Inner Barrier.

8. The Outer Barrier was probably established sometime after 7000 years B. P. when the rate of the postglacial rise of sea level is reported to have slowed down appreciably, and when the sea stood 30 feet or so below its present level.

9. Pronounced Outer Barrier erosion may well be the result of an interruption in shoreline equilibrium caused by an extremely small quantity of sand being delivered to the coast at the present time - either onshore or alongshore.

Figure 3.1 Map to show the lower Macleay River and adjacent coastal areas.

Erratum: OFFSHORE IS. should read FORMER OFFSHORE IS.

Figure 3.1

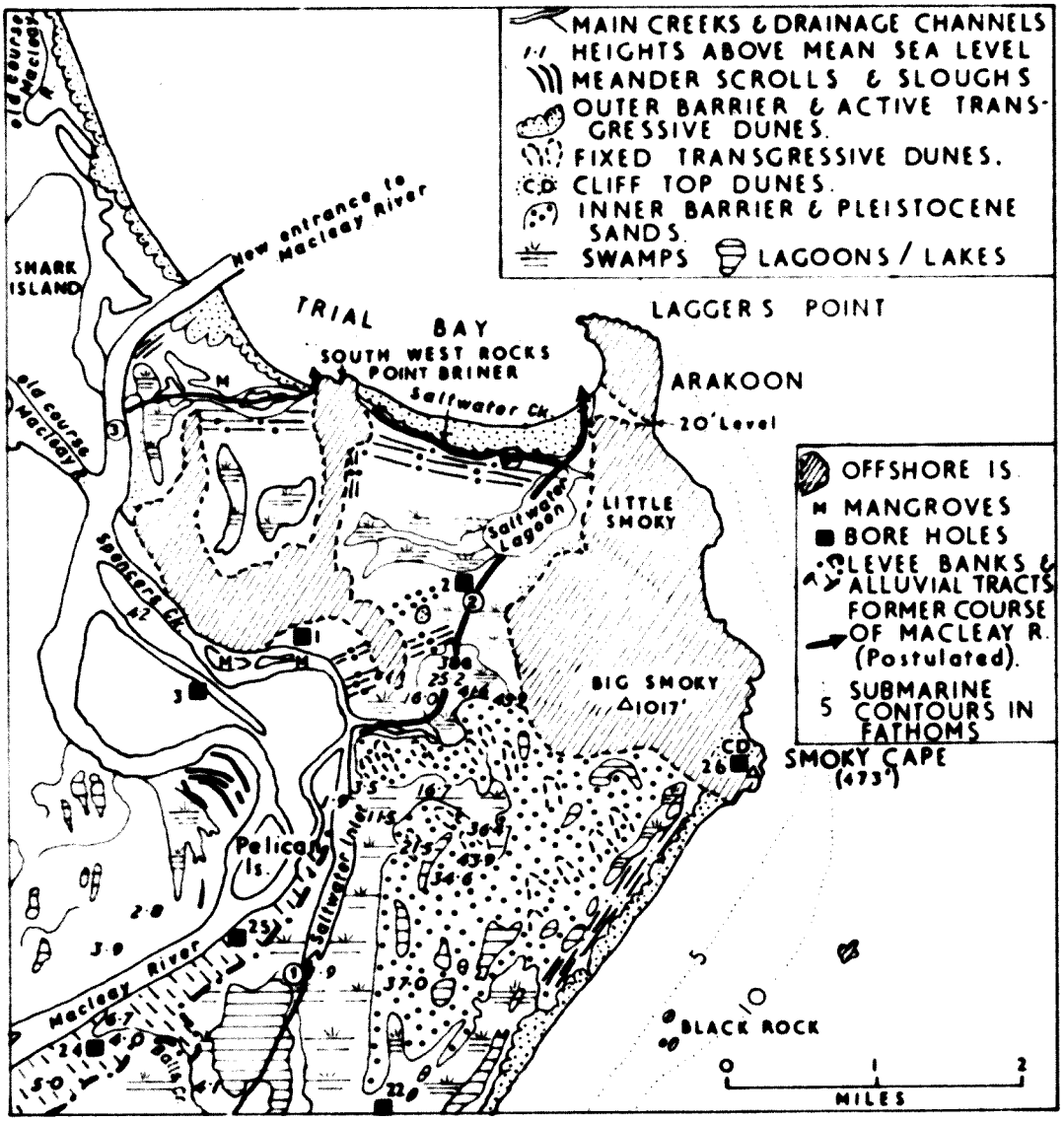

MAIN CREEKS & DRAINAGE CHANNELS
HEIGHTS ABOVE MEAN SEA LEVEL
MEANDER SCROLLS & SLOUGHS
OUTER BARRIER & ACTIVE TRANSGRESSIVE DUNES.
FIXED TRANSGRESSIVE DUNES.
CD CLIFF TOP DUNES.
INNER BARRIER & PLEISTOCENE SANDS.
SWAMPS
LAGOONS / LAKES
OFFSHORE IS.
M MANGROVES
BORE HOLES
LEVEE BANKS & ALLUVIAL TRACTS
FORMER COURSE OF MACLEAY R. (Postulated).
5 SUBMARINE CONTOURS IN FATHOMS
Old course Macleay
New entrance to Macleay River
SHARK ISLAND
TRIAL BAY
SOUTH WEST ROCKS
POINT BRINER
Saltwater Ck.
LAGGERS POINT
ARAKOON
20' Level
Old course Macleay
Saltwater Lagoon
LITTLE SMOKY
Spencers Ck.
BIG SMOKY
△1017'
SMOKY CAPE
(473')
Pelican Is.
Saltwater Inlet
Macleay River
BLACK ROCK
0
1
2
MILES

Figure 3.2 Map of the area between Smoky Cape and Hungry Hill, Mid-North Coast, showing the location of boreholes and surface morphology. The southern part of the map is an overlap of Figure 3.3

Kay for Inner Barrier and Pleistocene sands is shown in Figure 3.3

Figure 3.2

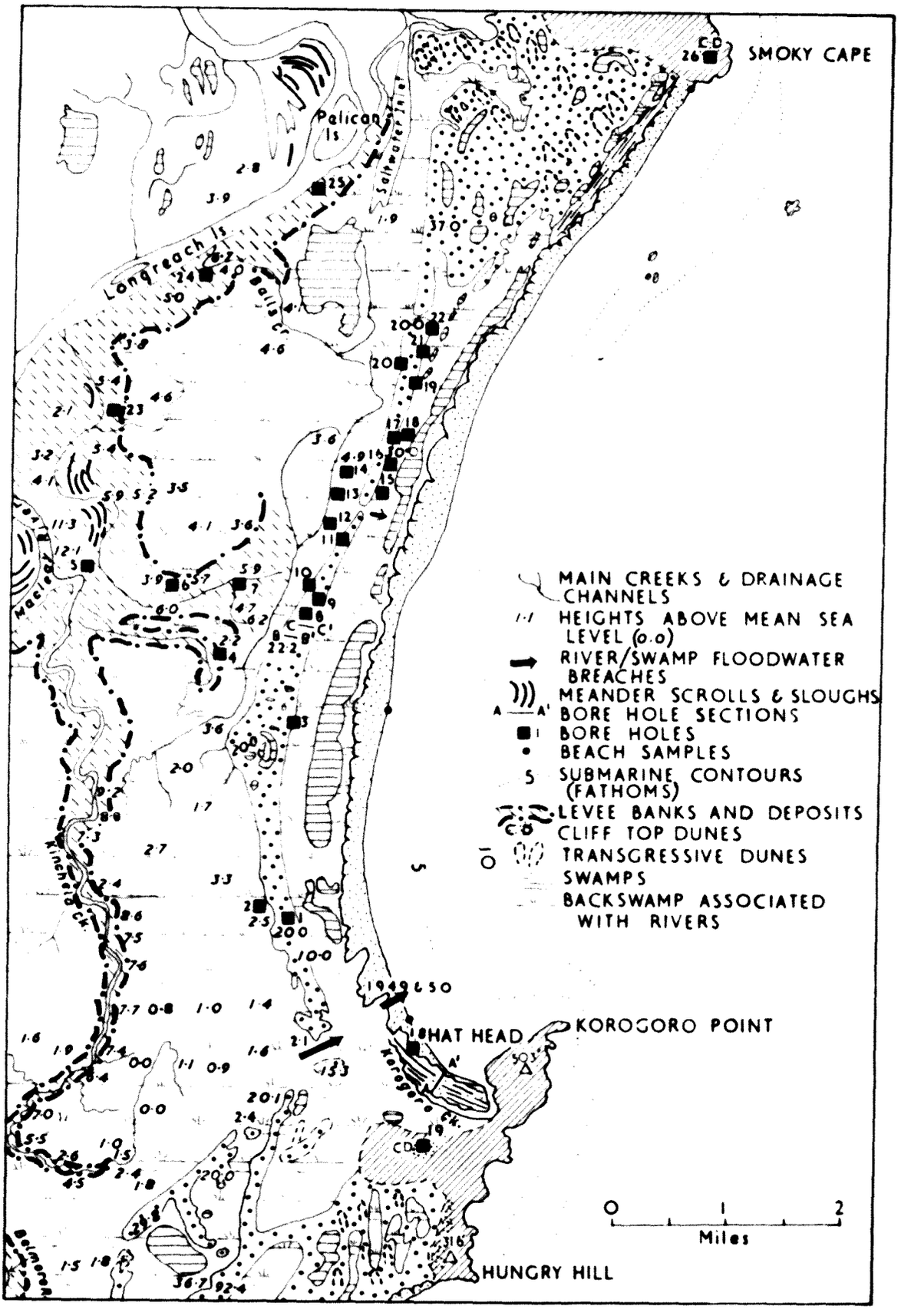

SMOKY CAPE
Pelican Is
Saltwater Inlet
Longreach Is
Sails Ck
Macleay R
Kinchela Ck
Korogoro Ck
HAT HEAD
KOROGORO POINT
HUNGRY HILL
MAIN CREEKS & DRAINAGE CHANNELS
HEIGHTS ABOVE MEAN SEA LEVEL (0.0)
RIVER/SWAMP FLOODWATER BREACHES
MEANDER SCROLLS & SLOUGHS
BORE HOLE SECTIONS
BORE HOLES
BEACH SAMPLES
SUBMARINE CONTOURS (FATHOMS)
LEVEE BANKS AND DEPOSITS
CLIFF TOP DUNES
TRANSGRESSIVE DUNES
SWAMPS
BACKSWAMP ASSOCIATED WITH RIVERS
0 1 2
Miles

Figure 3.3 Map of the area between Hungry Hill and Crescent Head, Mid-North Coast, showing surface morphology and the location of boreholes.

Heights above mean sea level are shown on the map.

Figure 3.3

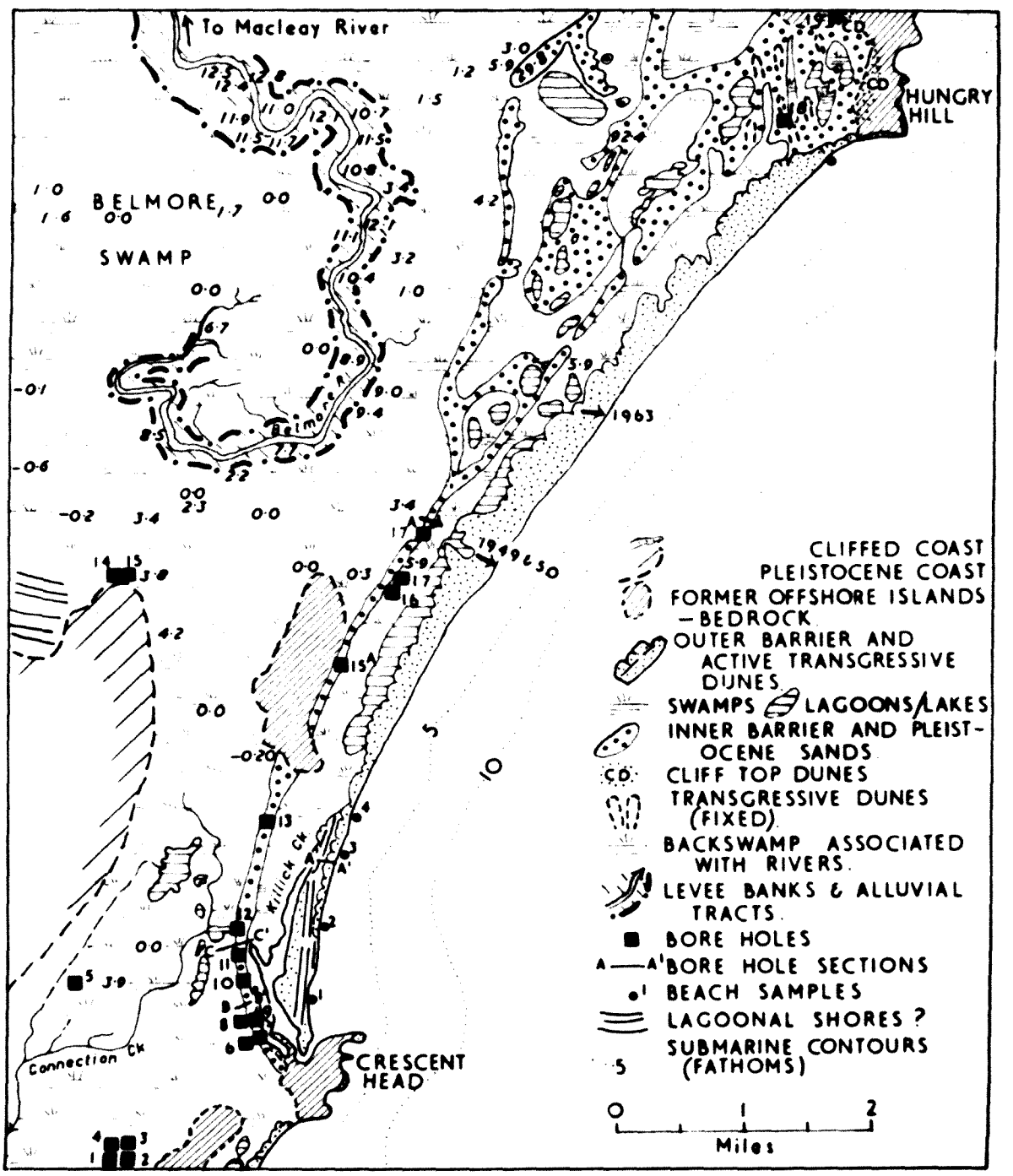

To Macleay River
HUNGRY HILL
BELMORE SWAMP
1963
1962
Killick Ck
Connection Ck
CRESCENT HEAD
CLIFFED COAST
PLEISTOCENE COAST
FORMER OFFSHORE ISLANDS —BEDROCK
OUTER BARRIER AND ACTIVE TRANSGRESSIVE DUNES
SWAMPS
LAGOONS/LAKES
INNER BARRIER AND PLEISTOCENE SANDS
C.D. CLIFF TOP DUNES
TRANSGRESSIVE DUNES (FIXED)
BACKSWAMP ASSOCIATED WITH RIVERS.
LEVEE BANKS & ALLUVIAL TRACTS.
BORE HOLES
A—A' BORE HOLE SECTIONS
BEACH SAMPLES
LAGOONAL SHORES ?
5 SUBMARINE CONTOURS (FATHOMS)
0 1 2
Miles

Figure 3.4 (in pocket on inside back cover):

The surface morphology of the Mid-North Coast between Crescent Head and the Macleay River. The submarine contour pattern has been compiled from the 'fair sheets' of recent Royal Australian Navy surveys. The large black dots show the location of some peat(P) and humate(H) samples, the radiocarbon dates of which are listed in Table 9.3. For details on boreholes and sub-surface profiles, see Chapter 6.

Figure 3.5 Map and section to show the location of boreholes and sub-surface profiles in the Crescent Head-Killick Creek area. $1\text{-}1_1$ to $4\text{-}4_1$, and $A\text{-}A^1$ are sections along which boreholes were sunk.

Erratum: INFILLED SWAMP should read BELMORE SWAMP (see inset map).

Figure 3.5

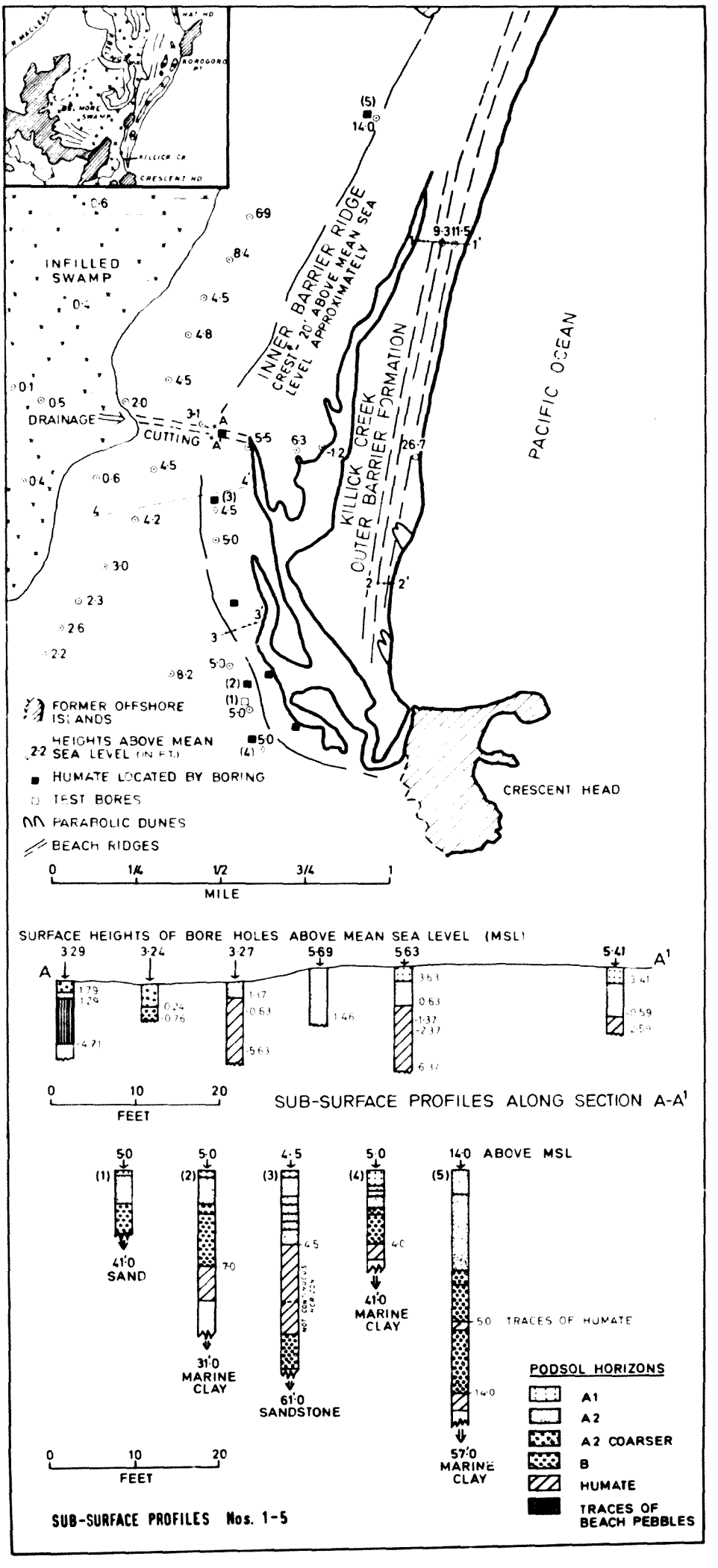

INFILLED SWAMP
DRAINAGE
CUTTING
INNER BARRIER RIDGE
CREST 20' ABOVE MEAN SEA LEVEL APPROXIMATELY
KILLICK CREEK
OUTER BARRIER FORMATION
PACIFIC OCEAN
CRESCENT HEAD
FORMER OFFSHORE ISLANDS
HEIGHTS ABOVE MEAN SEA LEVEL (IN FT)
HUMATE LOCATED BY BORING
TEST BORES
PARABOLIC DUNES
BEACH RIDGES
0 1/4 1/2 3/4 1
MILE
SURFACE HEIGHTS OF BORE HOLES ABOVE MEAN SEA LEVEL (MSL)
A
A1
3·29
3·24
3·27
5·69
5·63
5·41
0 10 20
FEET
SUB-SURFACE PROFILES ALONG SECTION A-A1
5·0
(1)
41·0 SAND
5·0
(2)
31·0 MARINE CLAY
4·5
(3)
61·0 SANDSTONE
5·0
(4)
41·0 MARINE CLAY
14·0 ABOVE MSL
(5)
5·0 TRACES OF HUMATE
57·0 MARINE CLAY
PODSOL HORIZONS
A1
A2
A2 COARSER
B
HUMATE
TRACES OF BEACH PEBBLES
SUB-SURFACE PROFILES Nos. 1-5

Figure 3.6 Surveyed profiles across Inner and Outer Barriers on the Mid-North Coast.

Erratum: Front Beach-Killick Creek (Outer Barrier): A-A_1 should read 1-1_1.

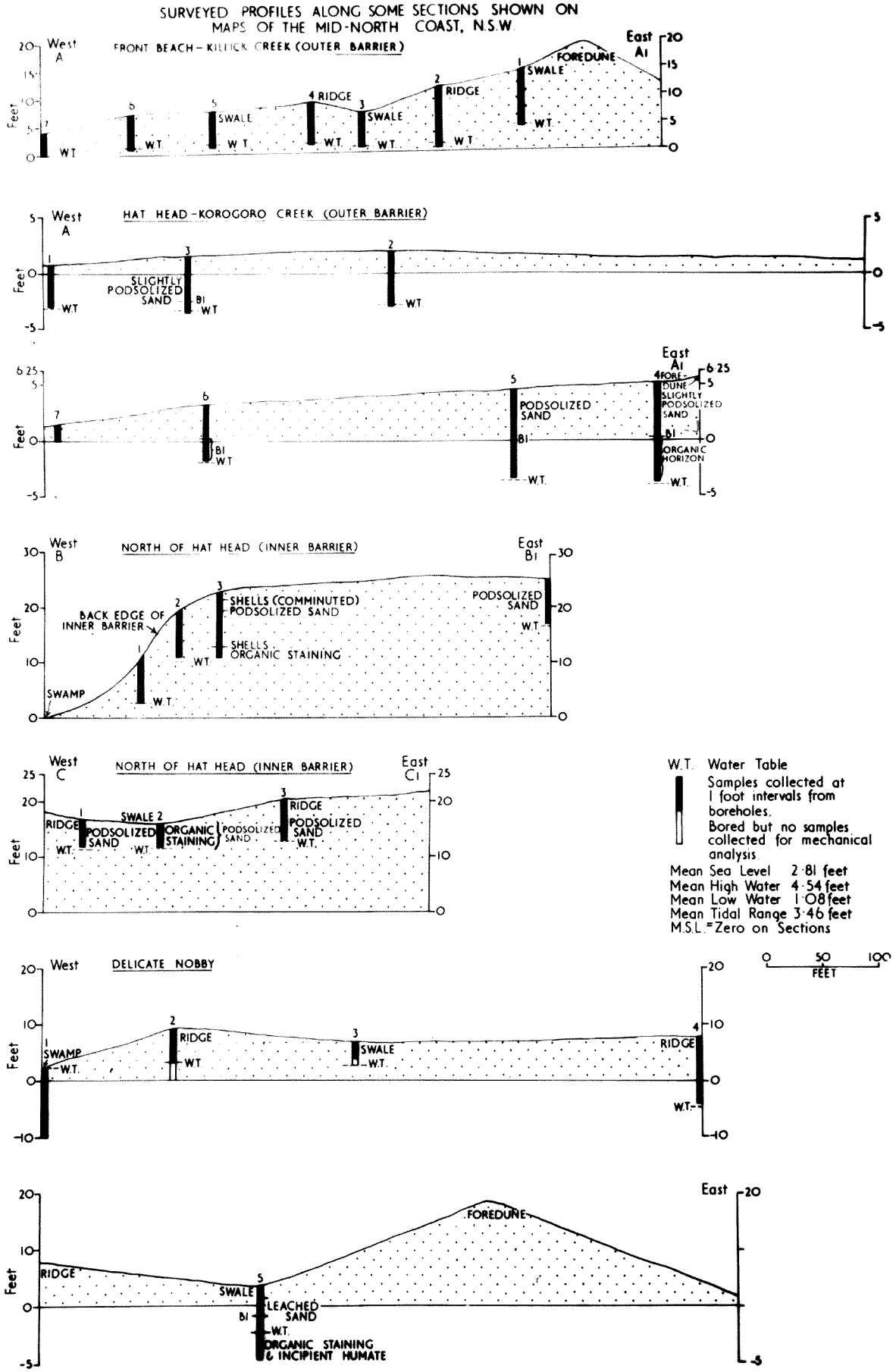

SURVEYED PROFILES ALONG SOME SECTIONS SHOWN ON MAPS OF THE MID-NORTH COAST, N.S.W.
FRONT BEACH – KILLICK CREEK (OUTER BARRIER)
West A
East A1
Feet
FOREDUNE
SWALE
RIDGE
SWALE
RIDGE
SWALE
W.T.
HAT HEAD – KOROGORO CREEK (OUTER BARRIER)
SLIGHTLY PODSOLIZED SAND
B1
PODSOLIZED SAND
FORE-DUNE
SLIGHTLY PODSOLIZED SAND
ORGANIC HORIZON
NORTH OF HAT HEAD (INNER BARRIER)
West B
East B1
BACK EDGE OF INNER BARRIER
SHELLS (COMMINUTED) PODSOLIZED SAND
SHELLS ORGANIC STAINING
SWAMP
NORTH OF HAT HEAD (INNER BARRIER)
West C
East C1
RIDGE
SWALE 2
PODSOLIZED SAND
ORGANIC STAINING
PODSOLIZED SAND
RIDGE
PODSOLIZED SAND
W.T. Water Table
Samples collected at 1 foot intervals from boreholes.
Bored but no samples collected for mechanical analysis.
Mean Sea Level 2·81 feet
Mean High Water 4·54 feet
Mean Low Water 1·08 feet
Mean Tidal Range 3·46 feet
M.S.L. = Zero on Sections
0 50 100 FEET
DELICATE NOBBY
West
SWAMP
RIDGE
SWALE
RIDGE
FOREDUNE
East
RIDGE
SWALE
LEACHED SAND
ORGANIC STAINING & INCIPIENT HUMATE

Figure 3.7 Maria-Wilson barrier and fluvial-deltaic plains, Mid-North Coast.

Plate 3.3A was taken from Big Hill at the position shown by the arrow immediately south of (cave). $A\text{-}A_1$ - $D\text{-}D_1$ are traverses between the Outer Barrier and the ancient bedrock coastline along which many boreholes were sunk.

1. Maria-Wilson fluvial-deltaic plain.
2. Maria-Wilson barrier plain.
3. Outer Barrier.

Figure 3.7

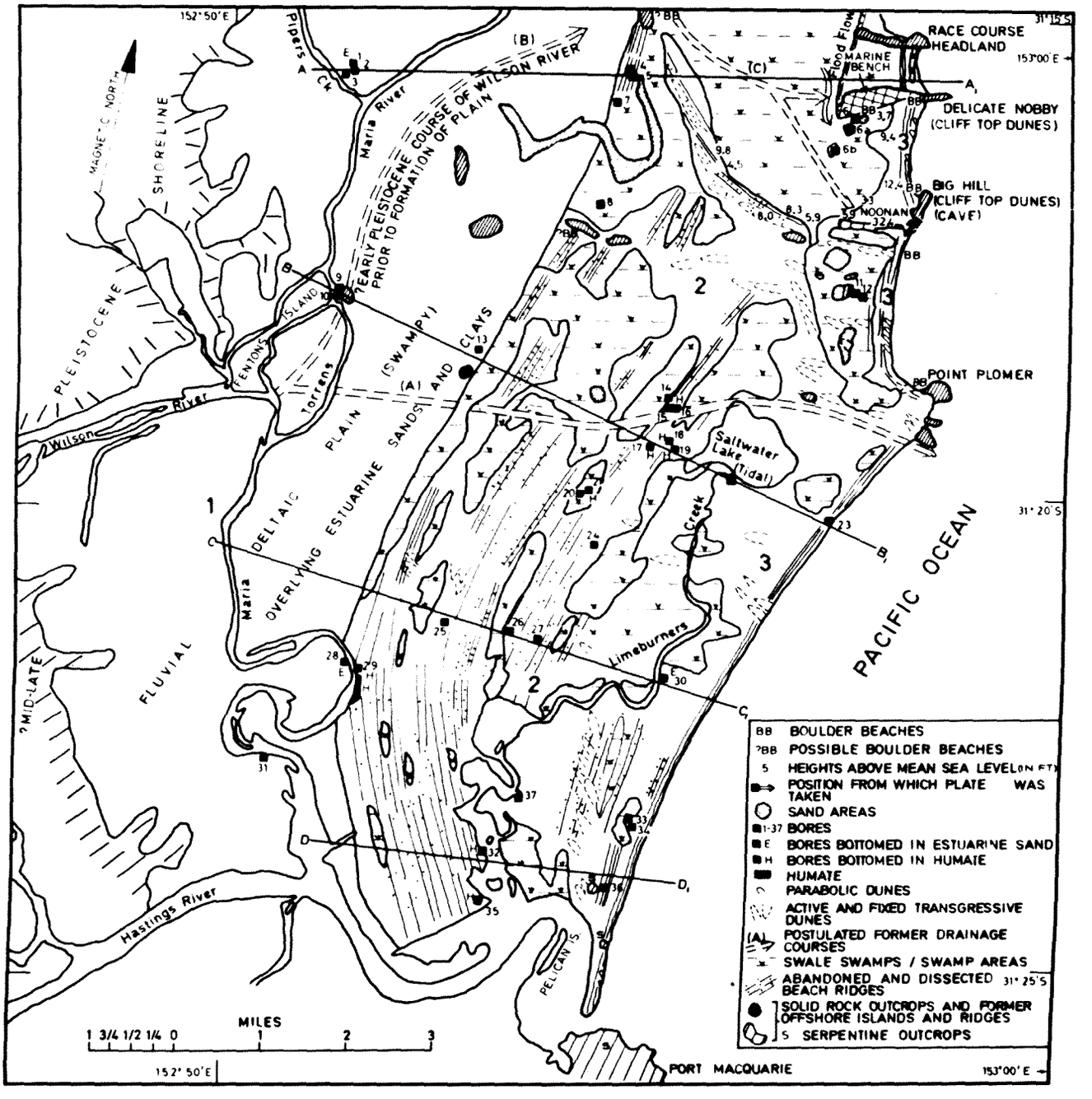

152°50'E
153°00'E
31°15'S
31°20'S
31°25'S
Piper's Ck
Maria River
(B)
(C)
A
A1
RACE COURSE HEADLAND
MARINE BENCH
DELICATE NOBBY (CLIFF TOP DUNES)
BIG HILL (CLIFF TOP DUNES) (CAVE)
NOONANS
POINT PLOMER
EARLY PLEISTOCENE COURSE OF WILSON RIVER PRIOR TO FORMATION OF PLAIN
MAGNETIC NORTH
SHORELINE
PLEISTOCENE
ISLAND
FENTONS
Torrens
(A) AND CLAYS
(SWAMPY)
PLAIN
Wilson River
DELTAIC
OVERLYING ESTUARINE SANDS
Maria
Saltwater Lake (Tidal)
Creek
Limeburners
PACIFIC OCEAN
?MID-LATE
FLUVIAL
Hastings River
PELICAN IS
B
B1
C
C1
D
D1
MILES
1 3/4 1/2 1/4 0 1 2 3
PORT MACQUARIE
BB BOULDER BEACHES
?BB POSSIBLE BOULDER BEACHES
5 HEIGHTS ABOVE MEAN SEA LEVEL (IN FT)
POSITION FROM WHICH PLATE WAS TAKEN
SAND AREAS
1-37 BORES
E BORES BOTTOMED IN ESTUARINE SAND
H BORES BOTTOMED IN HUMATE
HUMATE
PARABOLIC DUNES
ACTIVE AND FIXED TRANSGRESSIVE DUNES
(A) POSTULATED FORMER DRAINAGE COURSES
SWALE SWAMPS / SWAMP AREAS
ABANDONED AND DISSECTED BEACH RIDGES
SOLID ROCK OUTCROPS AND FORMER OFFSHORE ISLANDS AND RIDGES
S SERPENTINE OUTCROPS

Figure 3.8 Part of Broken Bay showing the position of the Umina-Woy Woy beach ridge system (cf. Plates 3.7 and 3.9B; Figure 3.9). Inset map shows the location of boreholes in the Pearl Beach area.

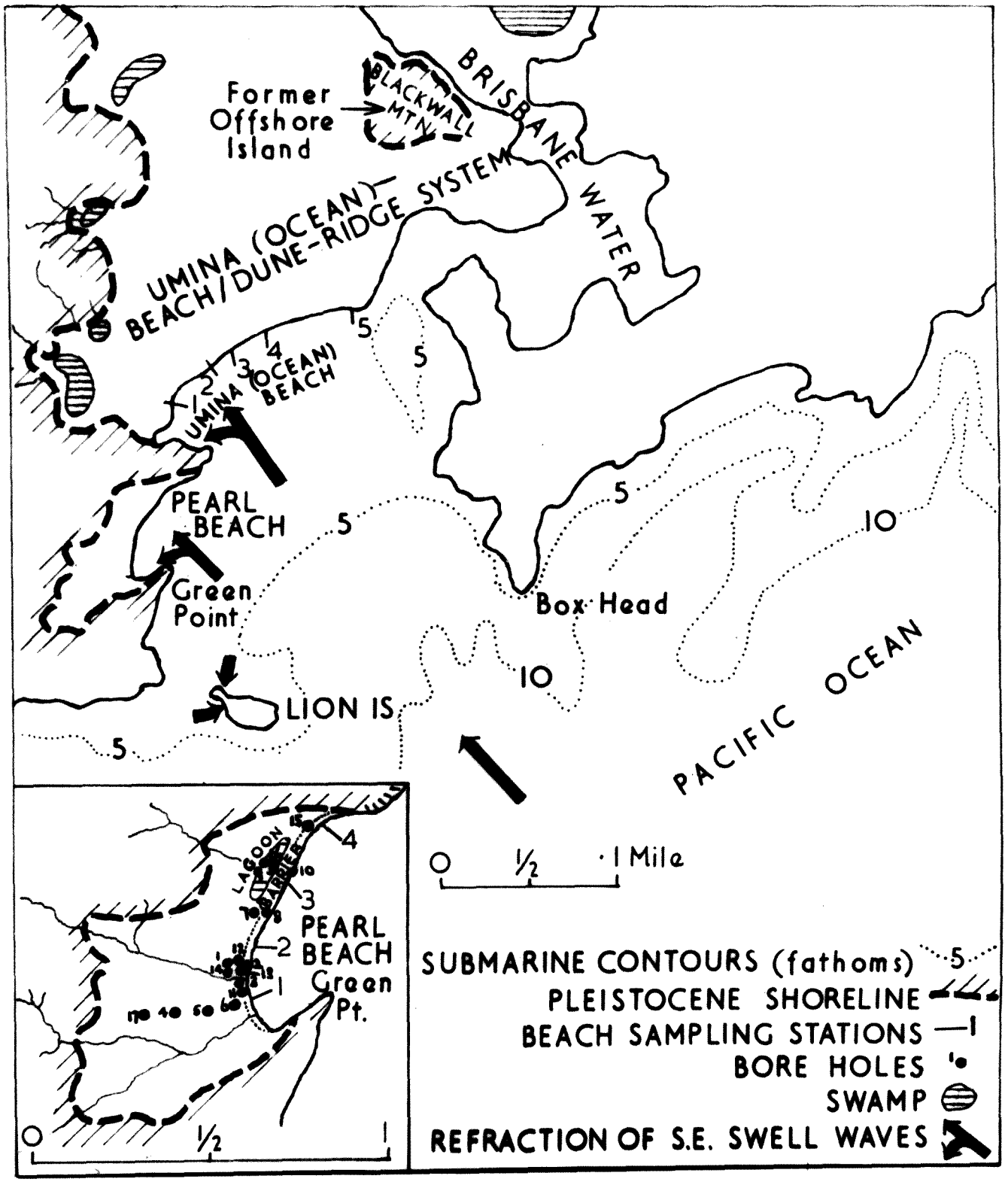

Former Offshore Island
BLACKWALL MTN
BRISBANE WATER
UMINA (OCEAN) BEACH/DUNE-RIDGE SYSTEM
UMINA (OCEAN) BEACH
PEARL BEACH
Green Point
Box Head
LION IS
PACIFIC OCEAN
5
10
1 2 3 4
0 ½ 1 Mile
LAGOON
BARRIER
PEARL BEACH
Green Pt.
0 ½ 1
SUBMARINE CONTOURS (fathoms)
PLEISTOCENE SHORELINE
BEACH SAMPLING STATIONS
BORE HOLES
SWAMP
REFRACTION OF S.E. SWELL WAVES

Figure 3.9 (in pocket on inside back cover).

The surface morphology of the Umina-Woy Woy beach ridge system, Broken Bay; based on detailed surveys.

Figure 3.10 (in pocket on inside back cover).

Reconstructed beach ridge pattern at Umina-Woy Woy, Broken Bay.

Figure 3.11 Patonga Beach barrier spit, Broken Bay.

Former shape of the distal end of the barrier is shown by broken lines.

Broken lines in Brisk Bay are the 1-and 2-fathom submarine contours.

Erratum: For tranverses read traverses.

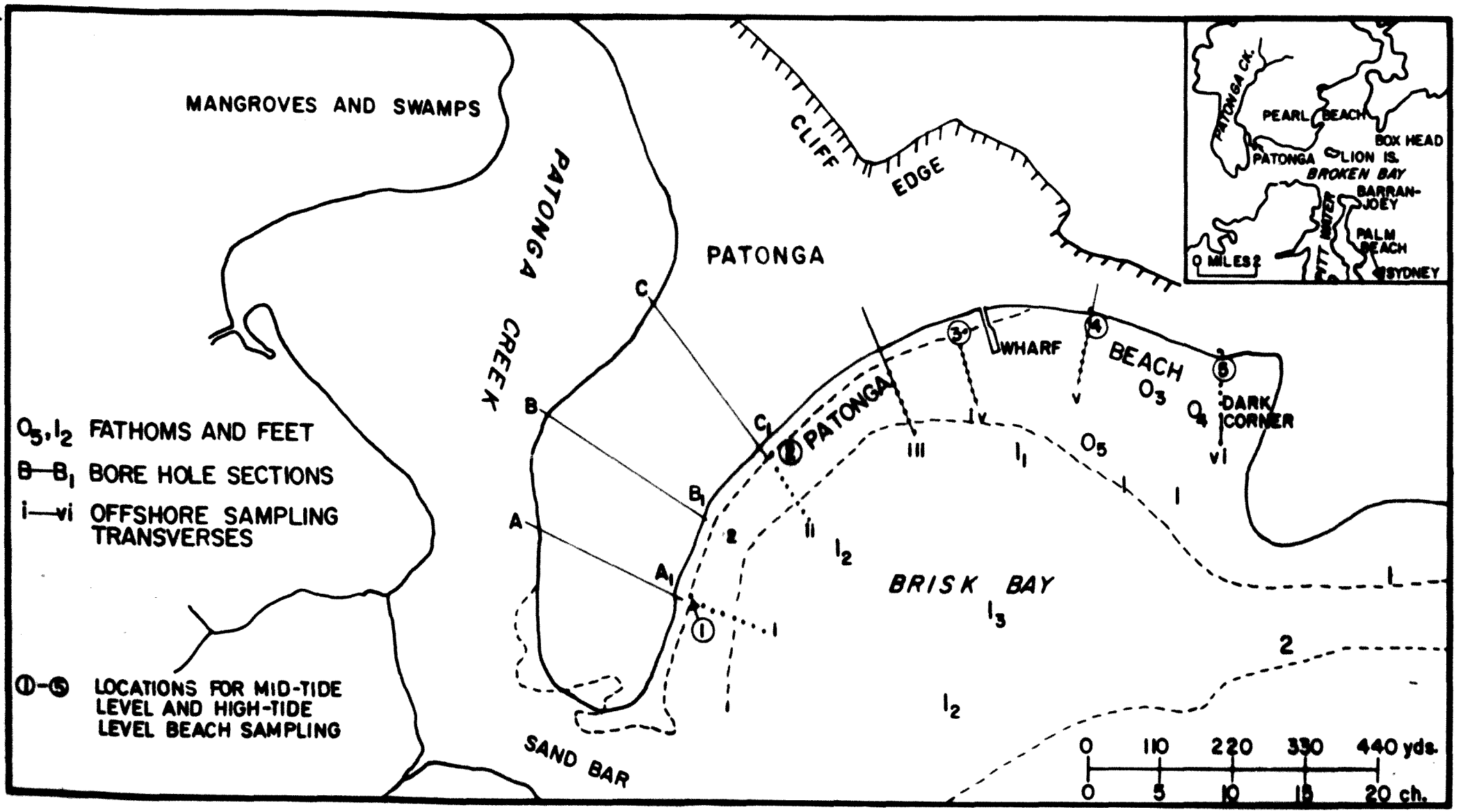

MANGROVES AND SWAMPS
PATONGA CREEK
CLIFF EDGE
PATONGA
WHARF
BEACH
DARK CORNER
BRISK BAY
SAND BAR
O_5, I_2 FATHOMS AND FEET
B—B_1 BORE HOLE SECTIONS
i—vi OFFSHORE SAMPLING TRANSVERSES
①-⑤ LOCATIONS FOR MID-TIDE LEVEL AND HIGH-TIDE LEVEL BEACH SAMPLING
PATONGA CK.
PEARL BEACH
BOX HEAD
PATONGA
LION IS.
BROKEN BAY
BARRAN-JOEY
PALM BEACH
SYDNEY
0 MILES 2
0 110 220 330 440 yds.
0 5 10 15 20 ch.

Figure 3.11

Figure 3.12 Surveyed profiles across Patonga barrier spit, Broken Bay, showing the location of boreholes.

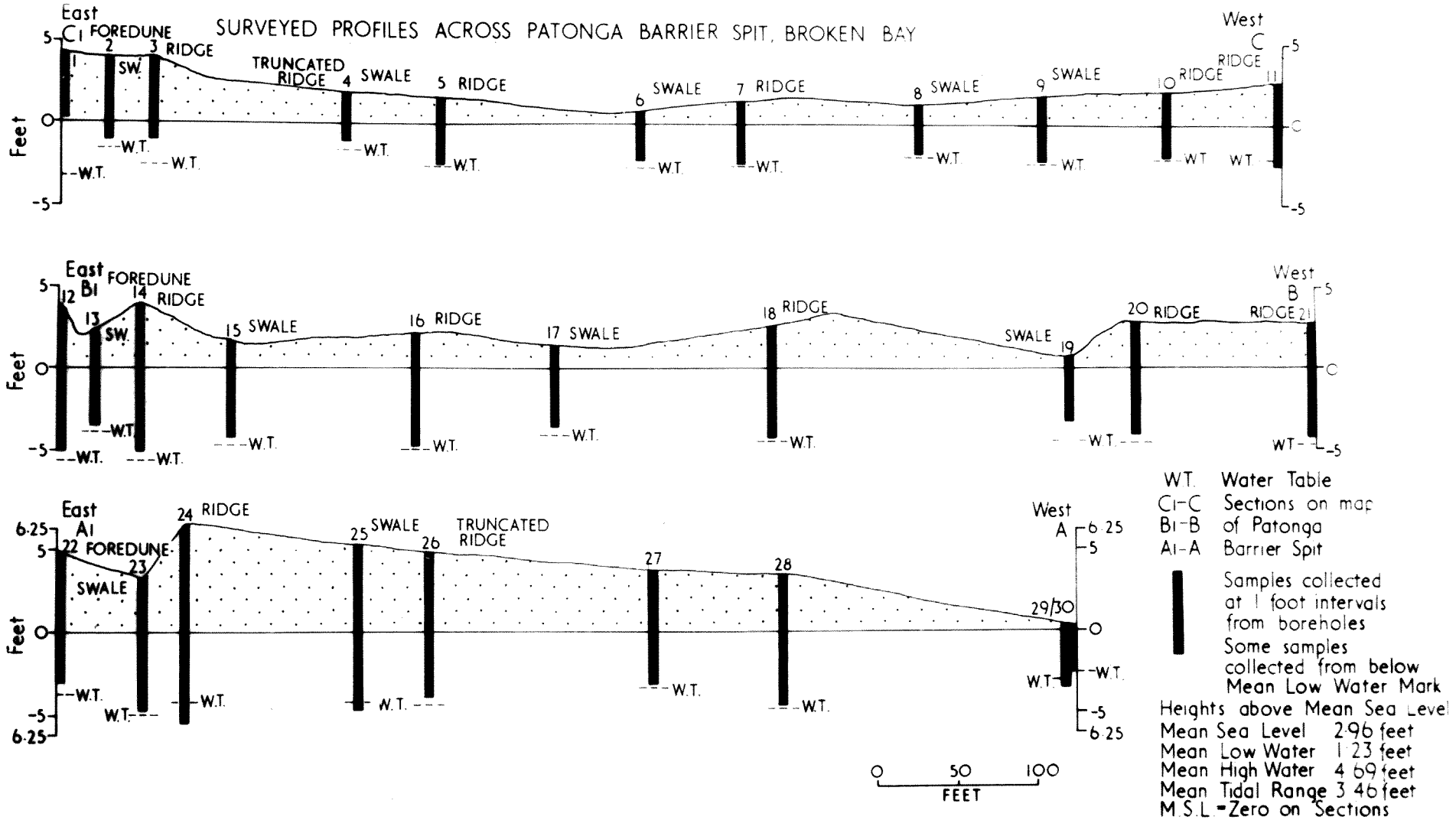

SURVEYED PROFILES ACROSS PATONGA BARRIER SPIT, BROKEN BAY
East
C1
FOREDUNE
RIDGE
SW.
TRUNCATED RIDGE
SWALE
RIDGE
SWALE
RIDGE
SWALE
SWALE
RIDGE
RIDGE
West
C
Feet
W.T.
East
B1
FOREDUNE
RIDGE
SW.
SWALE
RIDGE
SWALE
RIDGE
SWALE
RIDGE
RIDGE
West
B
East
A1
FOREDUNE
SWALE
RIDGE
SWALE
TRUNCATED RIDGE
West
A
WT. Water Table
C1-C Sections on map
B1-B of Patonga
A1-A Barrier Spit
Samples collected at 1 foot intervals from boreholes
Some samples collected from below Mean Low Water Mark
Heights above Mean Sea Level
Mean Sea Level 2·96 feet
Mean Low Water 1·23 feet
Mean High Water 4·69 feet
Mean Tidal Range 3·46 feet
M.S.L.=Zero on Sections
0 50 100
FEET

Figure 3.12

Figure 3.13 Surveyed profiles across south coast barriers.

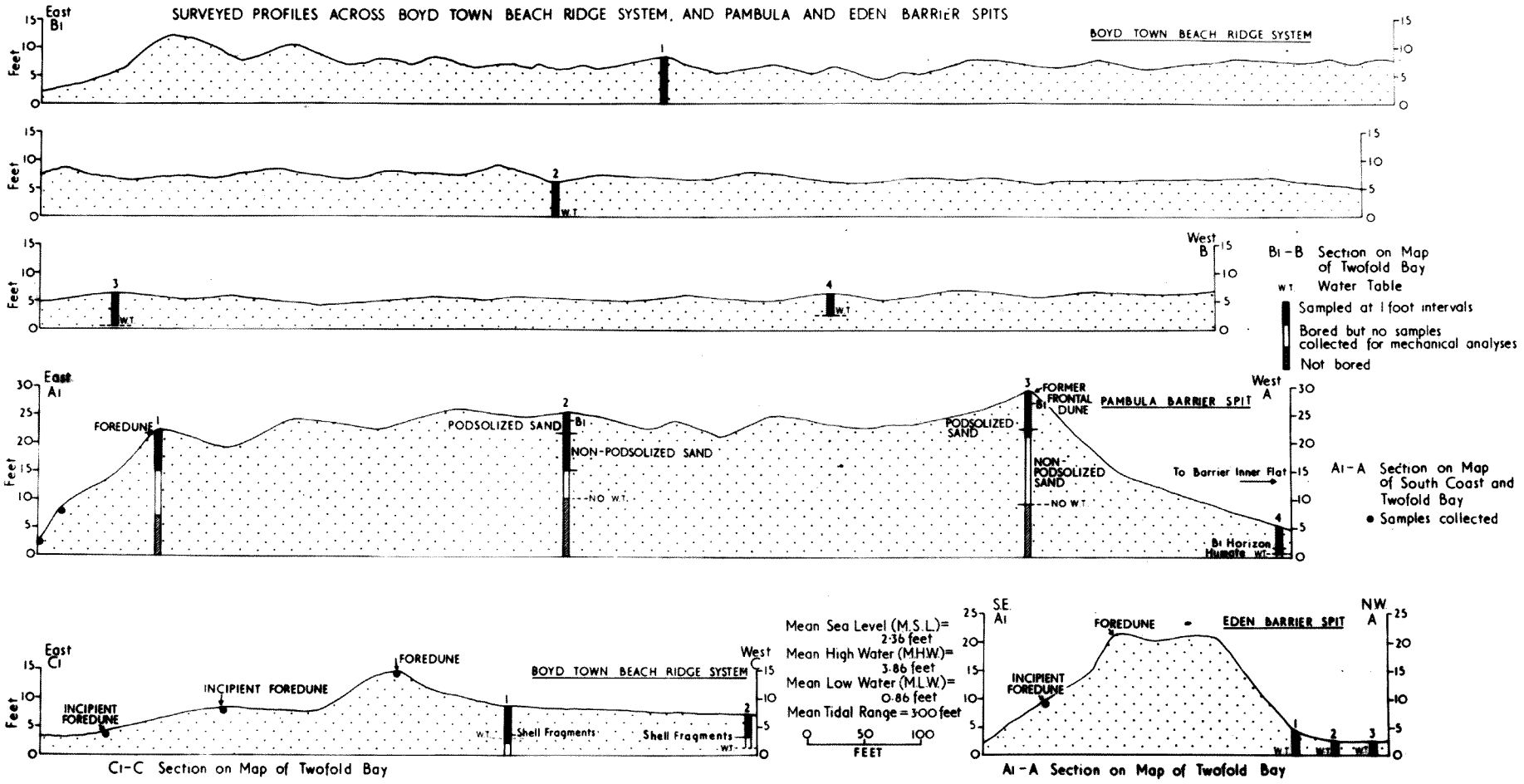

SURVEYED PROFILES ACROSS BOYD TOWN BEACH RIDGE SYSTEM, AND PAMBULA AND EDEN BARRIER SPITS
East B1
West B
BOYD TOWN BEACH RIDGE SYSTEM
Feet
W.T.
B1 – B Section on Map of Twofold Bay
W.T. Water Table
Sampled at 1 foot intervals
Bored but no samples collected for mechanical analyses
Not bored
East A1
West A
FOREDUNE
PODSOLIZED SAND
NON-PODSOLIZED SAND
NO W.T.
FORMER FRONTAL DUNE
PAMBULA BARRIER SPIT
To Barrier Inner Flat
B1 Horizon Humate
A1 – A Section on Map of South Coast and Twofold Bay
Samples collected
East C1
West C
INCIPIENT FOREDUNE
FOREDUNE
BOYD TOWN BEACH RIDGE SYSTEM
Shell Fragments
C1 – C Section on Map of Twofold Bay
Mean Sea Level (M.S.L.)= 2·36 feet
Mean High Water (M.H.W.)= 3·86 feet
Mean Low Water (M.L.W.)= 0·86 feet
Mean Tidal Range = 3·00 feet
0 50 100
FEET
SE. A1
NW. A
INCIPIENT FOREDUNE
FOREDUNE
EDEN BARRIER SPIT
A1 – A Section on Map of Twofold Bay

Figure 3.13

Figure 3.14 The development of the Mid-North Coast since 7000 years B.P.

For numbers on map read:

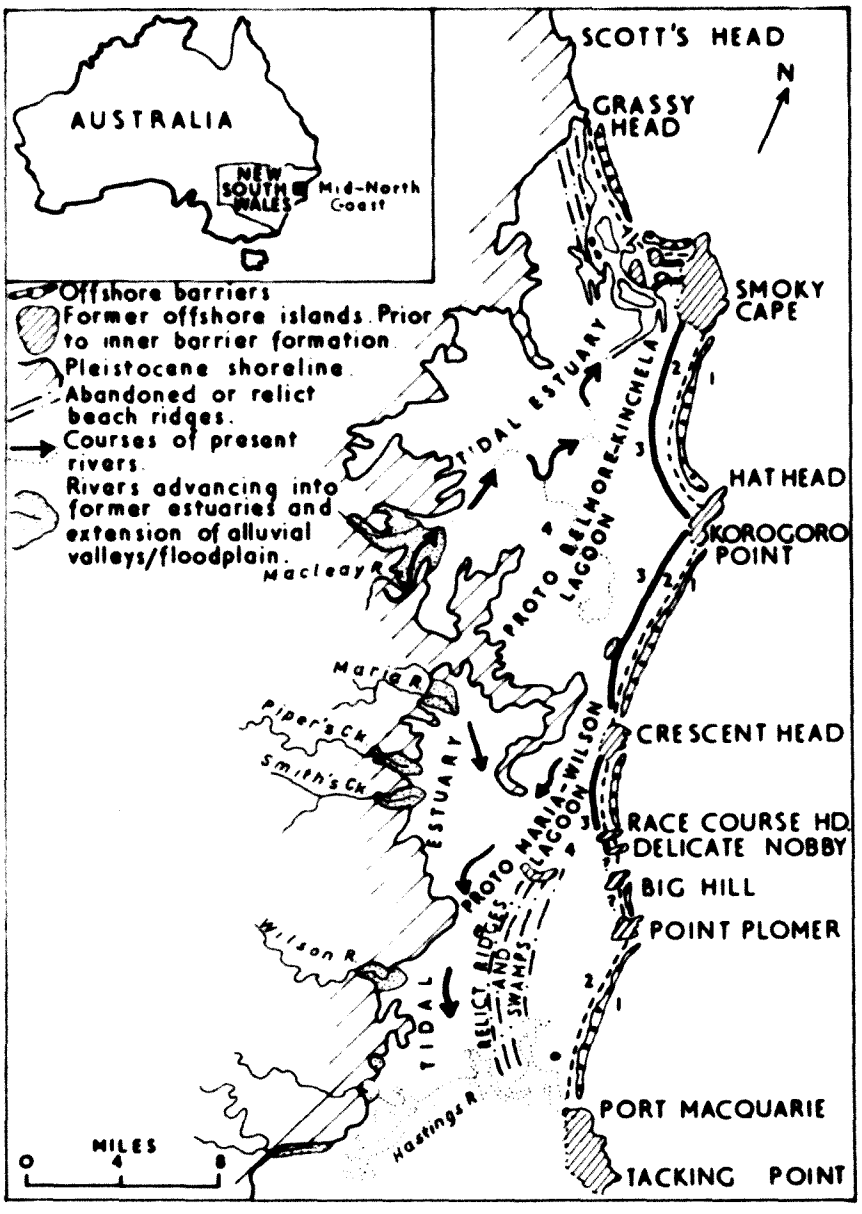
1. Possible position of former barriers before the Holocene stillstand.

2. Present coastline; development of Outer Barrier since about 7000 years B.P.

3. Pleistocene Inner Barrier.

4. Sedimentation and infilling of shallow coastal estuarine lagoon behind barriers and formation of fluvial-deltaic plains since about 4000-6000 years B.P.

Figure 3.14


AUSTRALIA
NEW SOUTH WALES
Mid-North Coast
Offshore barriers
Former offshore islands. Prior to inner barrier formation.
Pleistocene shoreline.
Abandoned or relict beach ridges.
Courses of present rivers.
Rivers advancing into former estuaries and extension of alluvial valleys/floodplain.
SCOTT'S HEAD
N
GRASSY HEAD
SMOKY CAPE
HAT HEAD
KOROGORO POINT
CRESCENT HEAD
RACE COURSE HD
DELICATE NOBBY
BIG HILL
POINT PLOMER
PORT MACQUARIE
TACKING POINT
TIDAL ESTUARY
PROTO BELMORE-KINCHELA LAGOON
PROTO MARIA-WILSON LAGOON
RELICT BEACH RIDGES AND SWAMPS
TIDAL ESTUARY
Macleay R.
Maria R.
Piper's Ck
Smith's Ck
Wilson R.
Hastings R.
MILES
0
4
8

Plates 3.1A - 3.1F

3.1A - 3.1C Dissected Outer Barrier foredune, Race Course Headland. The boulder beach is at storm-wave level.

3.1D Humate (dark layer), overlain by deeply podzolized sand, on the edge of a sludge pond near heavy mineral plant, Point Plomer. The leached sand below the humate has slumped from above.

3.1E - 3.1F Part of the dissected foredune, shown in Plates 3.1A-3.1C. Peat (P) located about 1 foot above high-water mark, and intercalated between two boulder beaches overlain by the Outer Barrier.

Plates 3.1A - 3.1F



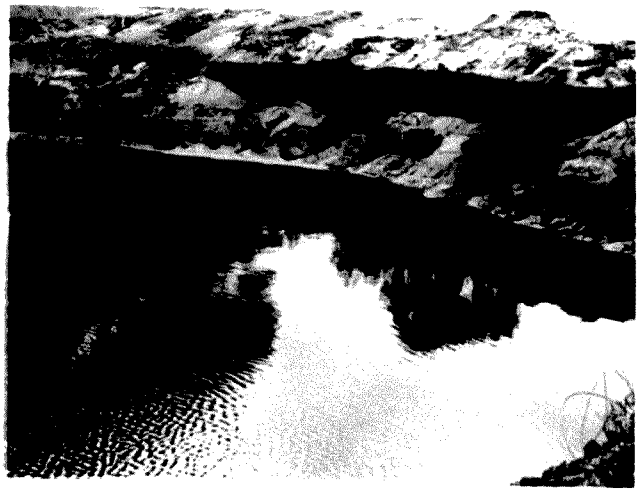
A

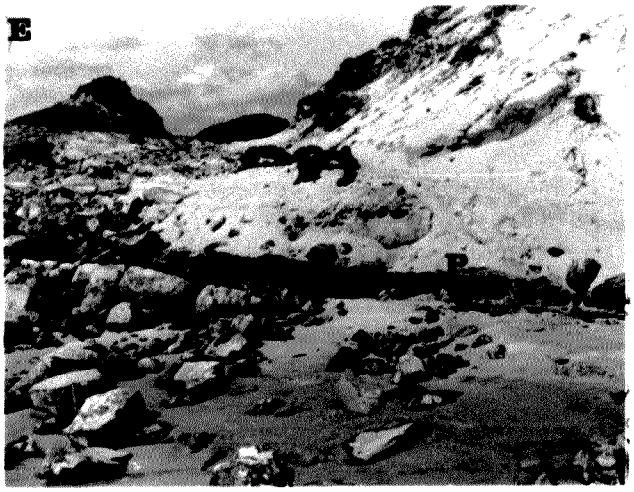


B



C





E



F

Plates 3.1G - 3.1L

3.1G Breached Outer Barrier foredune, Front Beach north of Crescent Head. Hungry Hill and high vegetated transgressive dunes in background.

3.1H View looking south towards Crescent Head from remnant foredune shown in 3.1G. Note remnant knolls of dissected Outer Barrier.

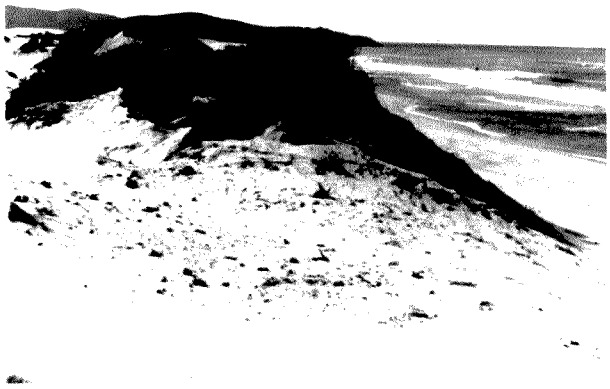
3.1'I' Exhumed boulder beach south of Big Hill. View looking south towards Point Plomer. Part of dissected foredune just beyond shells and boulders.

3.1J Partially dissected foredune and incipient foredune seaward of it, Pambula barrier spit. View looking south. (cf. Plates 2.2E and 2.2F).

3.1K Outer Barrier enclosing the old course (1895) of the Macleay River, immediately south of Grassy Head. Trial Bay to left of photograph. Sand in foreground anchored by Spinifex hirsutus.

3.1L View looking south along Front Beach from Hungry Hill. Knolls - remnants of part of the Outer Barrier stabilized by Spinifex hirsutus. A wave-cut cliff shows the contact of the Outer Barrier with the beach. Active transgressive dunes between the knolls in middle distance.

G



H



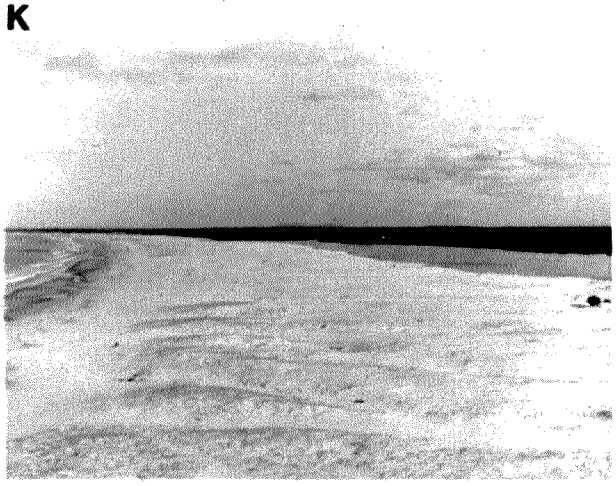
I



J



K



L



Plates 3.2A - 3.2F

3.2A Part of Hat Head Outer Barrier showing vegetated fresh sand (F) overlying the A and B horizons of a podzol.

3.2B Part of the foredune section shown in 3.2A. Note fresh sand masking the podzolized sand in part of the photograph.

3.2C Part of Hat Head Outer Barrier foredune showing fresh, unleached sand (F) overlying midden shells (X).

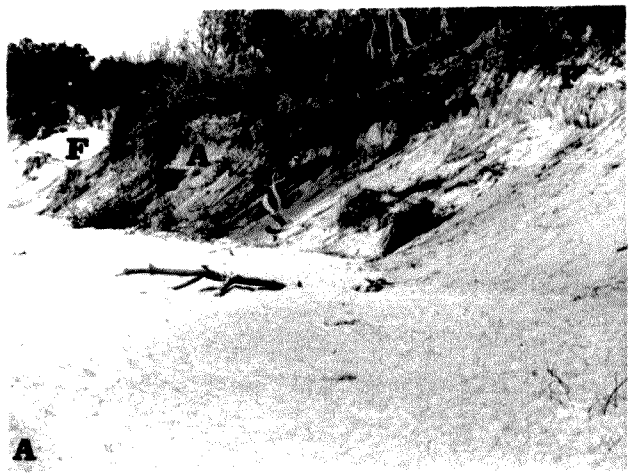
3.2D Face of open cut, Point Plomer. Eolian-bedded heavy mineral seams overlying wave-concentrated deposits. *

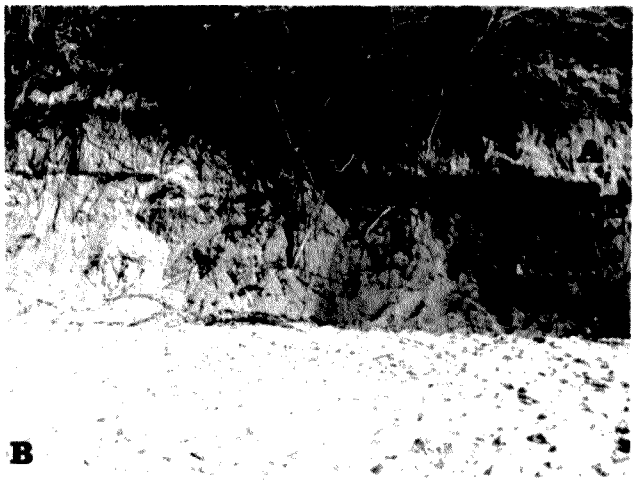
3.2E Breached foredune, Front Beach, Crescent Head. This breach was caused by storm wave action, and floodwater from Ocean Swamp, in May 1963.

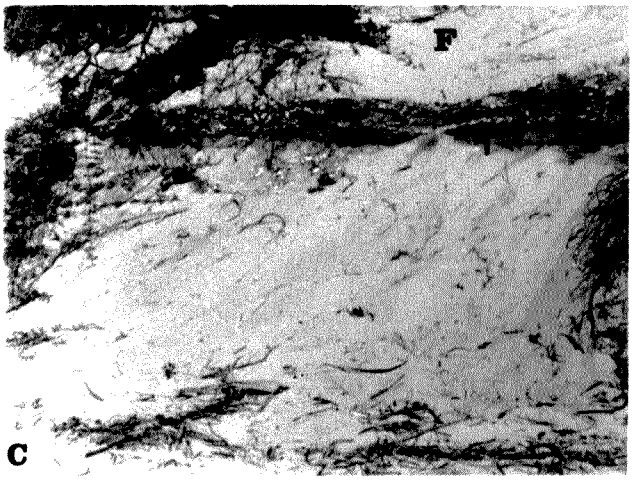
3.2F Transgressing Outer Barrier sand; just to the north of Delicate Nobby headland.

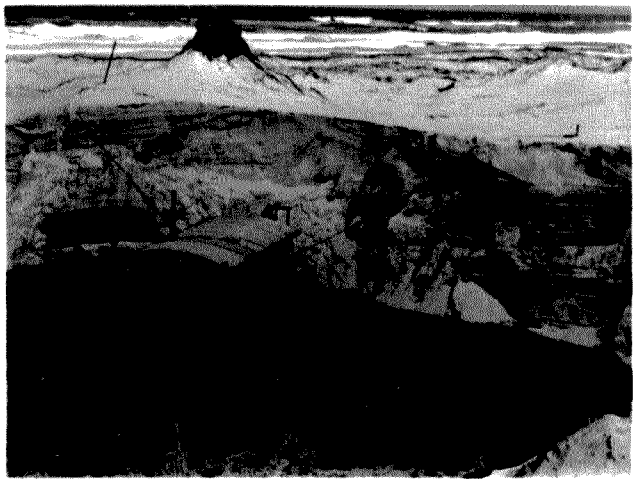
* Mineral seams on this plate are marked (x) and wave-concentrated deposits (y).

Plates 3.2A - 3.2F













Plates 3.3A - 3.3F

3.3A View looking south-west from Big Hill towards the Maria-Wilson barrier plain. The position from which this photograph was taken is shown in Figure 3.7. Vegetated transgressive dunes of Pleistocene age form a prominent line of hills in the background.

Darker patches in front of the dunes are areas of sand which stand a few feet above intervening swamps, similar to those between Delicate Nobby and Big Hill headlands (cf. Plate 3.4A).

3.3B East bank of Spencers Creek comprised of podzolized Pleistocene sand. Humate which outcrops below the caravan (a) forms an almost continuous horizon, but is masked by sand which has slumped from the top of the barrier. Note dense vegetation in background.

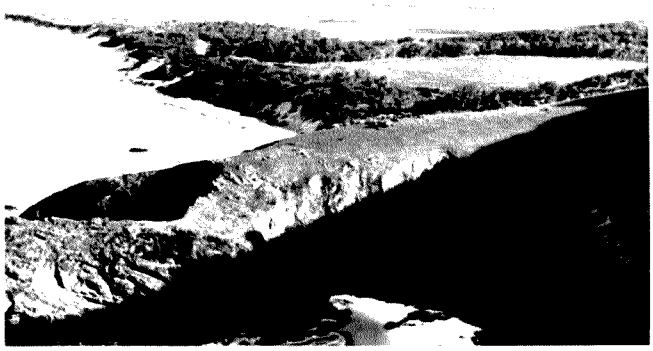
3.3C View of fixed transgressive dunes, about 200 feet high, (crests shown by dashed lines), from the lighthouse on Smoky Cape. Lighter area (middle distance) between the dunes shows part of the swamp between the Inner and Outer Barriers. Macleay River and part of the fluvial-deltaic plain in background. X denotes creek outlet along the contact of Outer Barrier with the bedrock headland of Smoky Cape.

3.3D Aboriginal kitchen-midden at base of barrier sand ridge near the Clybucca shoreline.

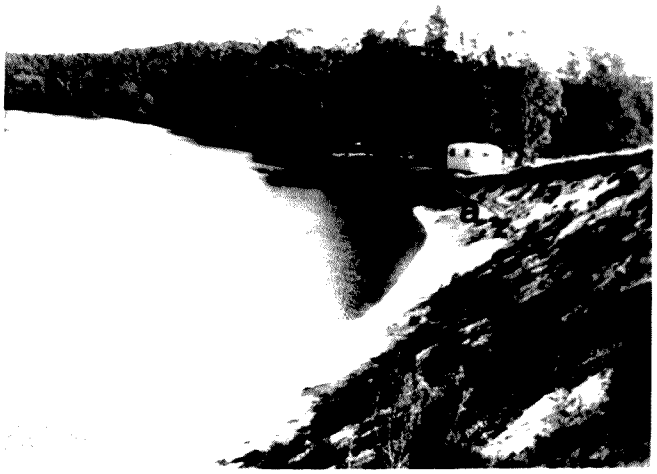
3.3E Vegetated cliff-top dunes above Big Hill cave. Banksia serrata trees on skyline. Bedrock is shown in the foreground, southwestern corner of photograph.

3.3F Dissected relict sand ridge (background), Maria-Wilson barrier plain. The ridge stands about 3½ feet above swamp level. Boreholes showed that humate was 2 to 3 feet below the surface of the swamp. Melaleuca spp. behind breach. Banksia serrata predominate on sand ridge.

A



B



C



D



E



F



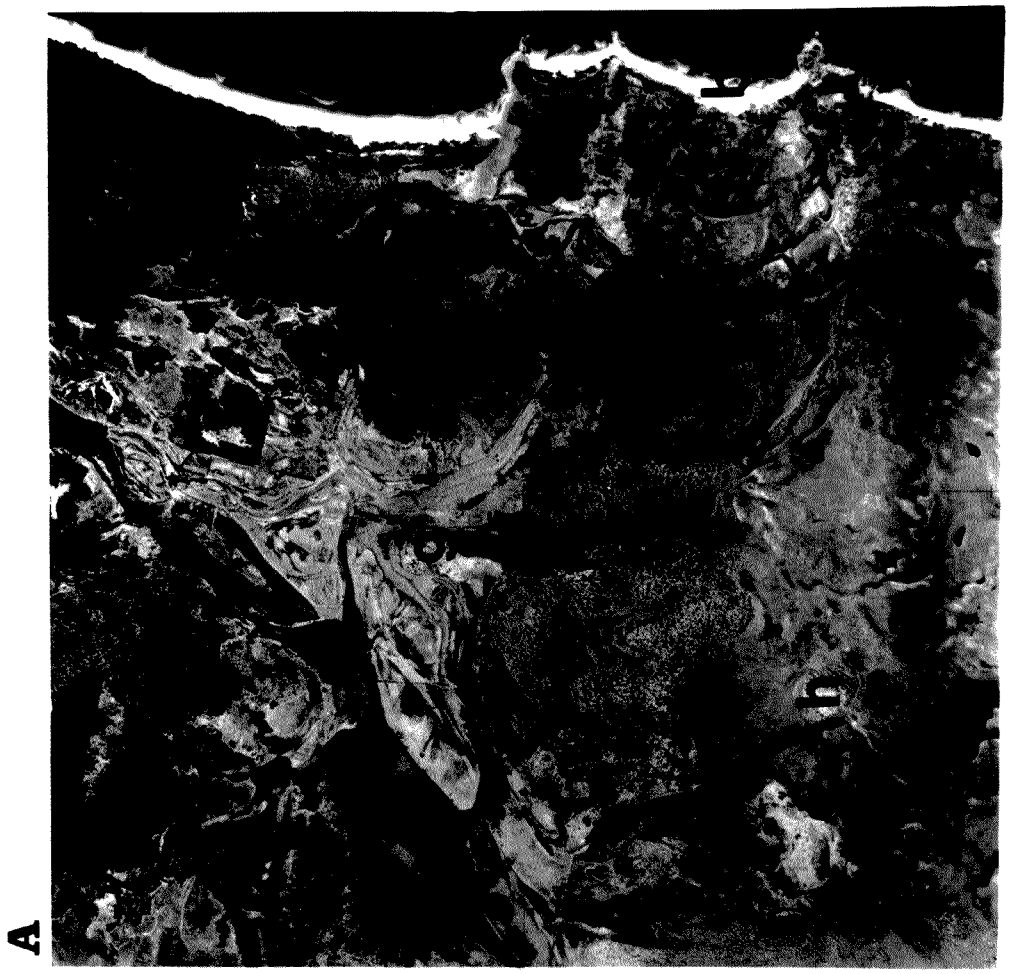
Plates 3.4A - 3.4B

3.4A Vertical aerial photograph of the Mid-North Coast between Point Plomer and Back Beach, immediately south of Crescent Head. (N.S.W. 277-5002).

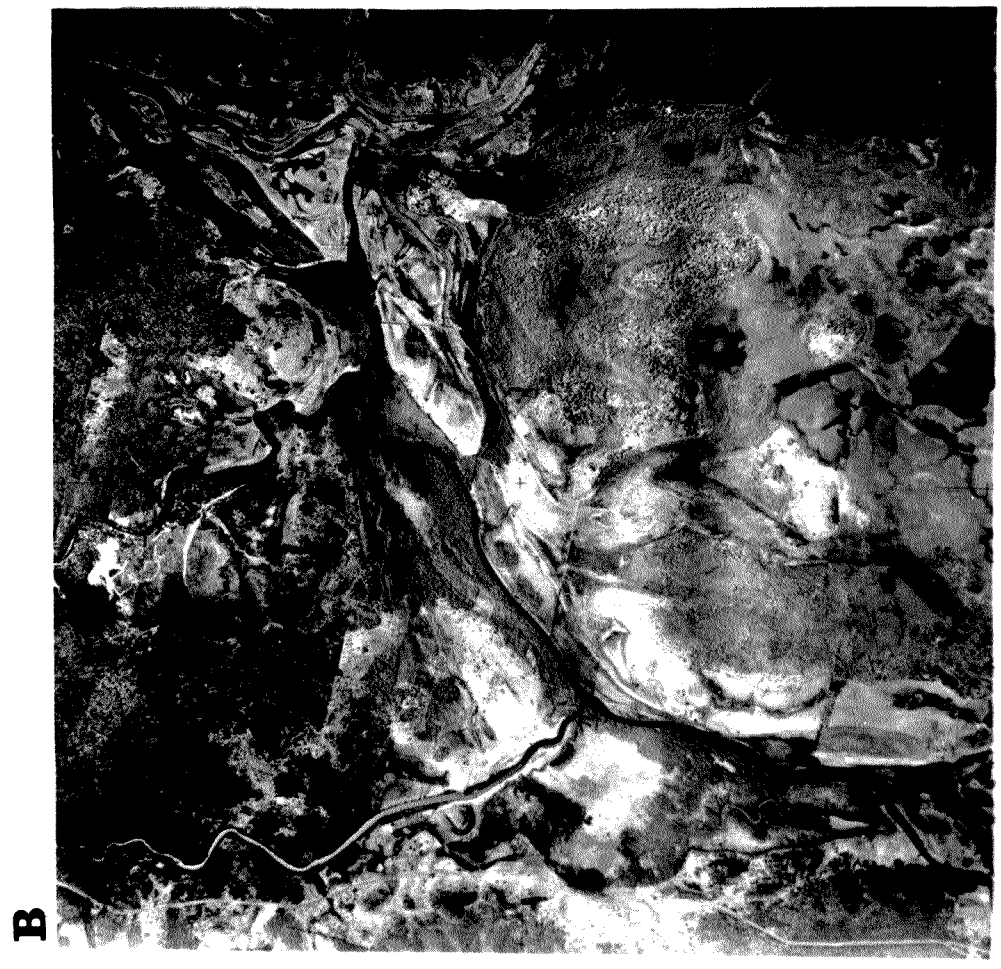
a - Back Beach Inner Barrier.
b - Active transgressive dunes of the Outer Barrier.
c - Inner Barrier between Race Course Headland and Delicate Nobby.
d - Possible remnants of a dissected Inner Barrier.
e - NW-SE trending fixed transgressive dunes of Pleistocene age. Drainage channels from the swamp areas interrupt the continuity of the ridges.
f - Relict, podzolized sand ridges.
g - Former offshore island (cf. Figure 3.7).
h - Former offshore island.
i - Dissected ridge system bordered by swamps.

3.4B Continuation of Plate 3.4A (N.S.W. 277-5003).

Both plates: Scale approximately $\frac{3}{4}$-inch to one mile. Reproduction by courtesy of the Under Secretary for Lands, New South Wales.



A



B

Plates 3.5A - 3.5B

3.5A Vertical aerial photograph of the Crescent Head area Mid-North Coast. (N.S.W. 189-5307).

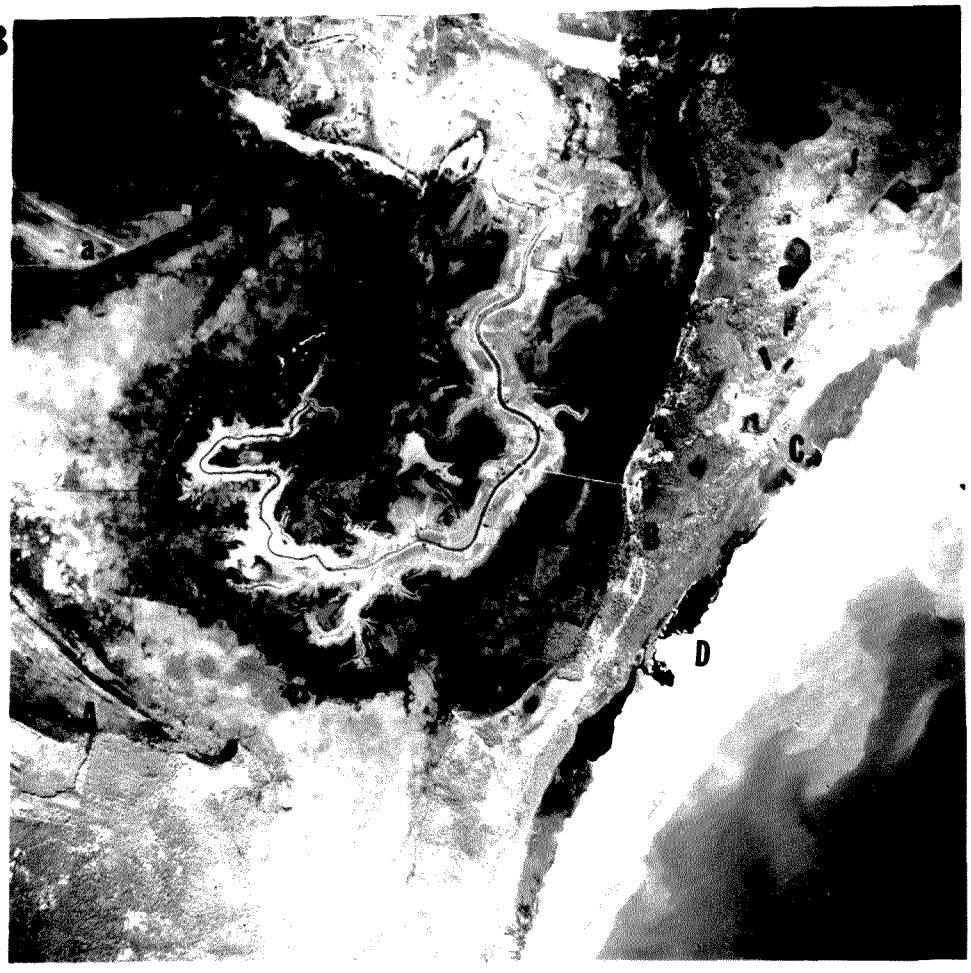
A - Southern end of Belmore Swamp between the Inner Barrier and Pleistocene bedrock coastline.
B - Connection Creek.
C - Location of borings - numbers 1 - 4 on Figure 3.3. Buildings stand on former offshore island.
D - Inner Barrier. Lighter area shows drainage channel through which Belmore Swamp drains into Killick Creek.

3.5B Northward continuation of 3.5A (N.S.W. 196-5169). Compare with Figure 3.3.

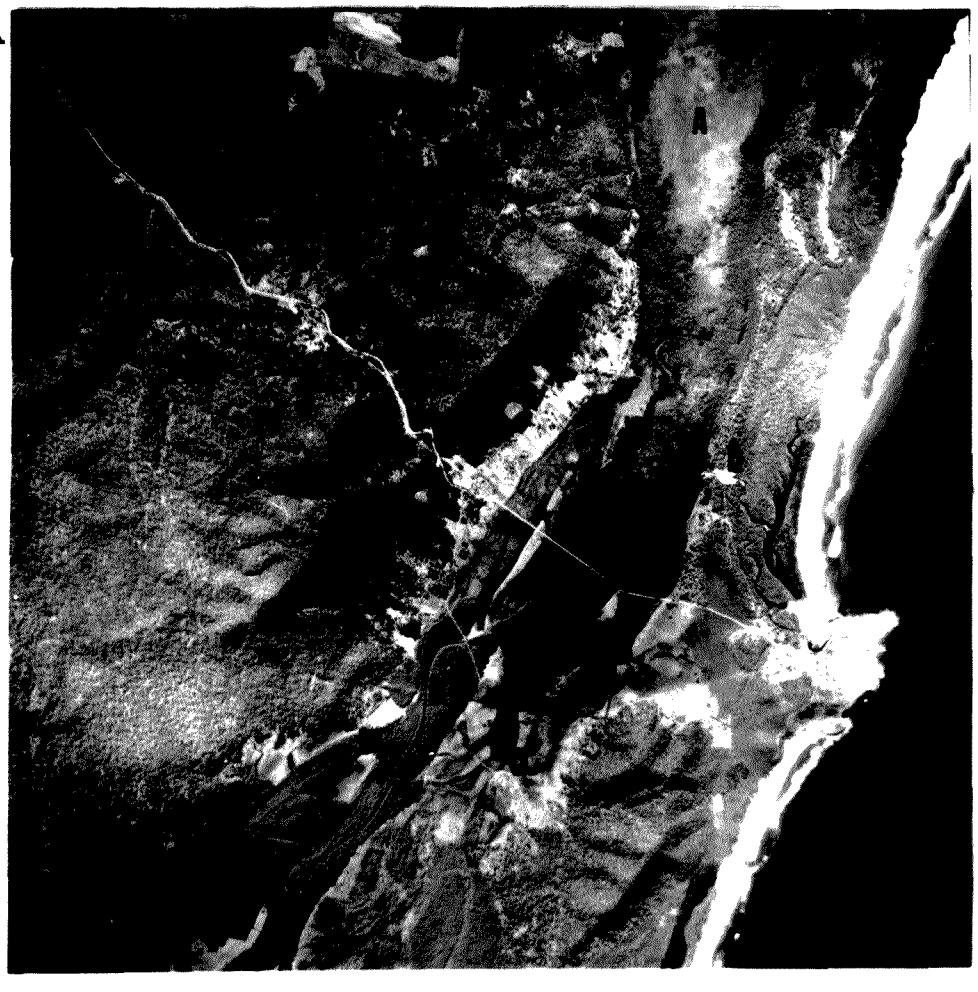
a and A - Former lagoonal shore ridges(?)
B - Lobate inner margin of Inner Barrier.
C - Ocean Swamp - partially infilled by migrating Outer Barrier sand.
D - Transgressive dunes.

Both plates: Scale approximately $\frac{3}{4}$-inch to one mile. Reproduction by courtesy of the Under Secretary for Lands, New South Wales.

B



A



Plates 3.5C - 3.5D

3.5C Vertical aerial photograph of the Hat Head area, Mid-North Coast. (N.S.W. 195-5108).

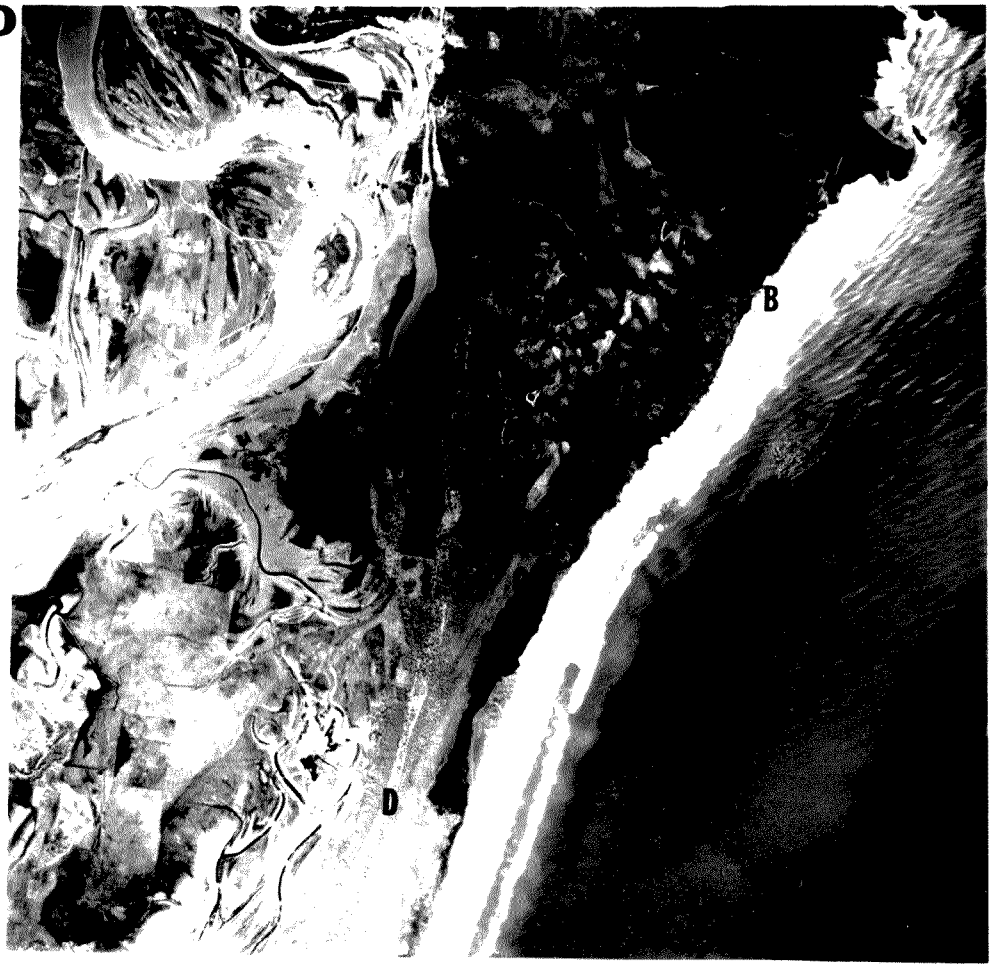
A - Former lagoonal shore ridges (?) along edge of Belmore River levee.
B - Inner Barrier.
C - Inter-barrier lagoonal-swamp being infilled by transgressive dunes.
D - Dissected Outer Barrier and transgressive dunes.

3.5D Vertical aerial photograph of the area between Hat Head (north of 3.5C) and Smoky Cape. (N.S.W. 196-5164).

A - Fixed transgressive dunes immediately south of Smoky Cape headland (cf. Plate 3.3C).
B - Migrating Outer Barrier.
C - Inter-barrier lagoonal-swamp.
D - Inner Barrier.

Both plates: Scale approximately $\frac{3}{4}$-inch to one mile. Reproduction by courtesy of the Under Secretary for Lands, New South Wales.

D



C

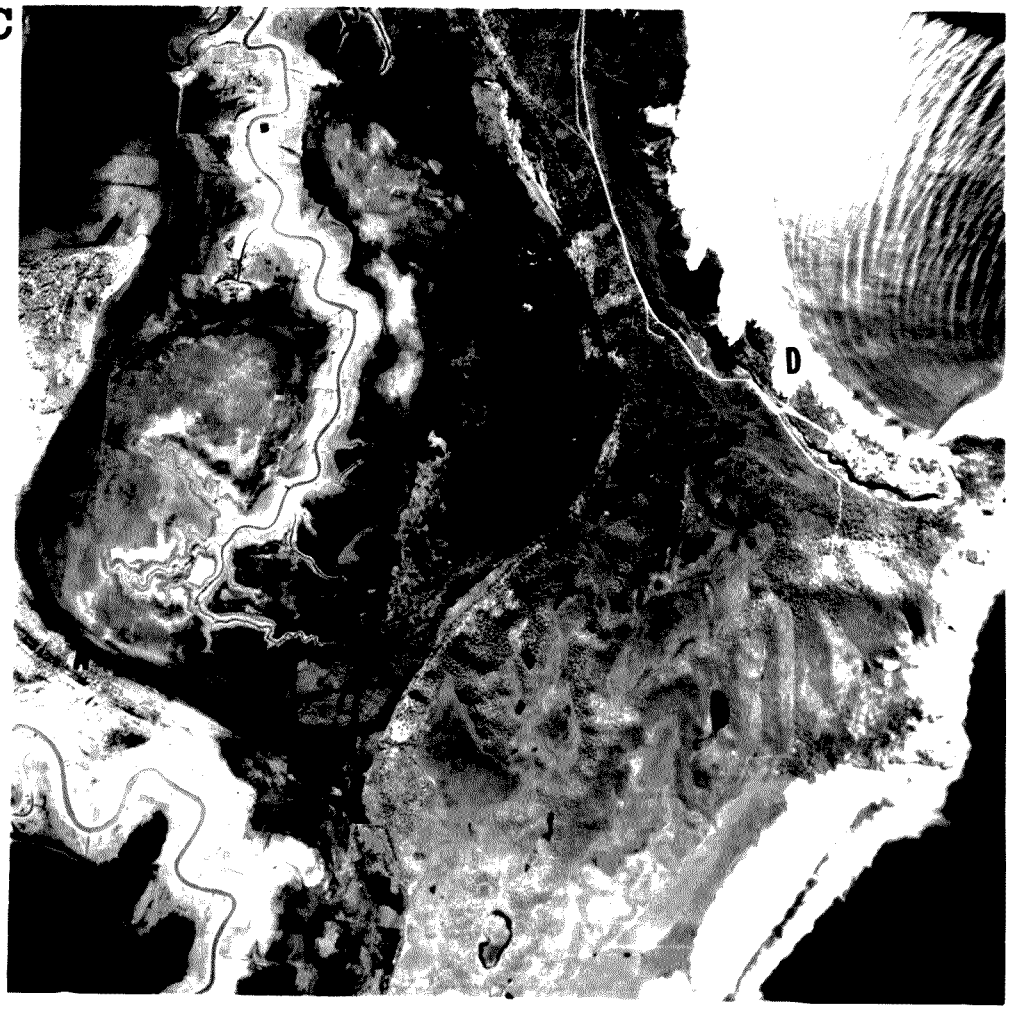


Plate 3.6 Vertical aerial photograph of the area between the Clybucca shoreline and the old course (1895) of the Macleay River. (N.S.W. 196-5133).

A - Bedrock coastline.
B - Relict sand ridges and intervening swale swamps of the Clybucca shoreline.
C - Series of abandoned sand ridges south of Grassy Head immediately landward of the old course of the Macleay River.

Lagoons and swamps shown by oblique shading.

Scale approximately 3 inches to one mile.

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Plate 3.6

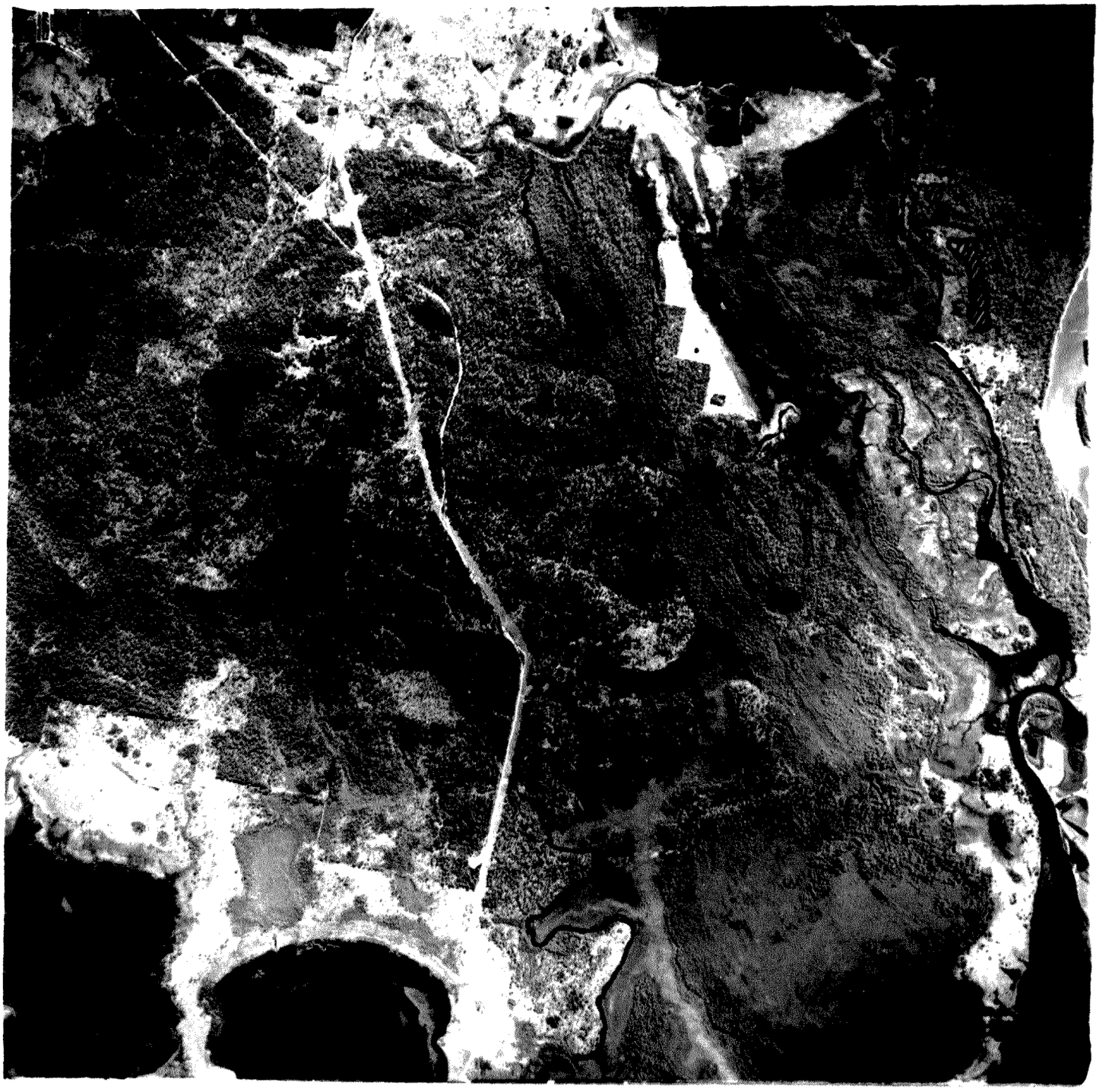


Plate 3.7 Aerial mosaic of part of the Umina-Woy Woy beach ridge system, Broken Bay, showing configuration of the bedrock Pleistocene coastline (dashed line), and lagoonal-swamps (L). Ocean Beach (O). (Compare with Plate 3.9B).

Reproduction by courtesy of the Under Secretary for Lands, New South Wales.

Plate 3.7



Plates 3.8A - 3.8D

3.8A and 3.8B — Vegetated Pleistocene (?) beach ridges, Woy Woy. *Banksia serrata* with a ground cover of *Pteridium aquilinium* and other sand-binding plants.

3.8C — Part of the lagoonal-swamp tract between the Holocene and Pleistocene (?) beach ridges. (cf. Figure 3.9). *Melaleuca* spp. dominate this part of the swamp.

3.8D — Gap in the vegetation showing small part of the lagoonal-swamp between the beach ridges.

Plates 3.8A - 3.8D



A



B



C



D

Plates 3.9A - 3.9B

3.9A Vertical aerial photograph of Patonga barrier spit (cf. Figure 3.11).

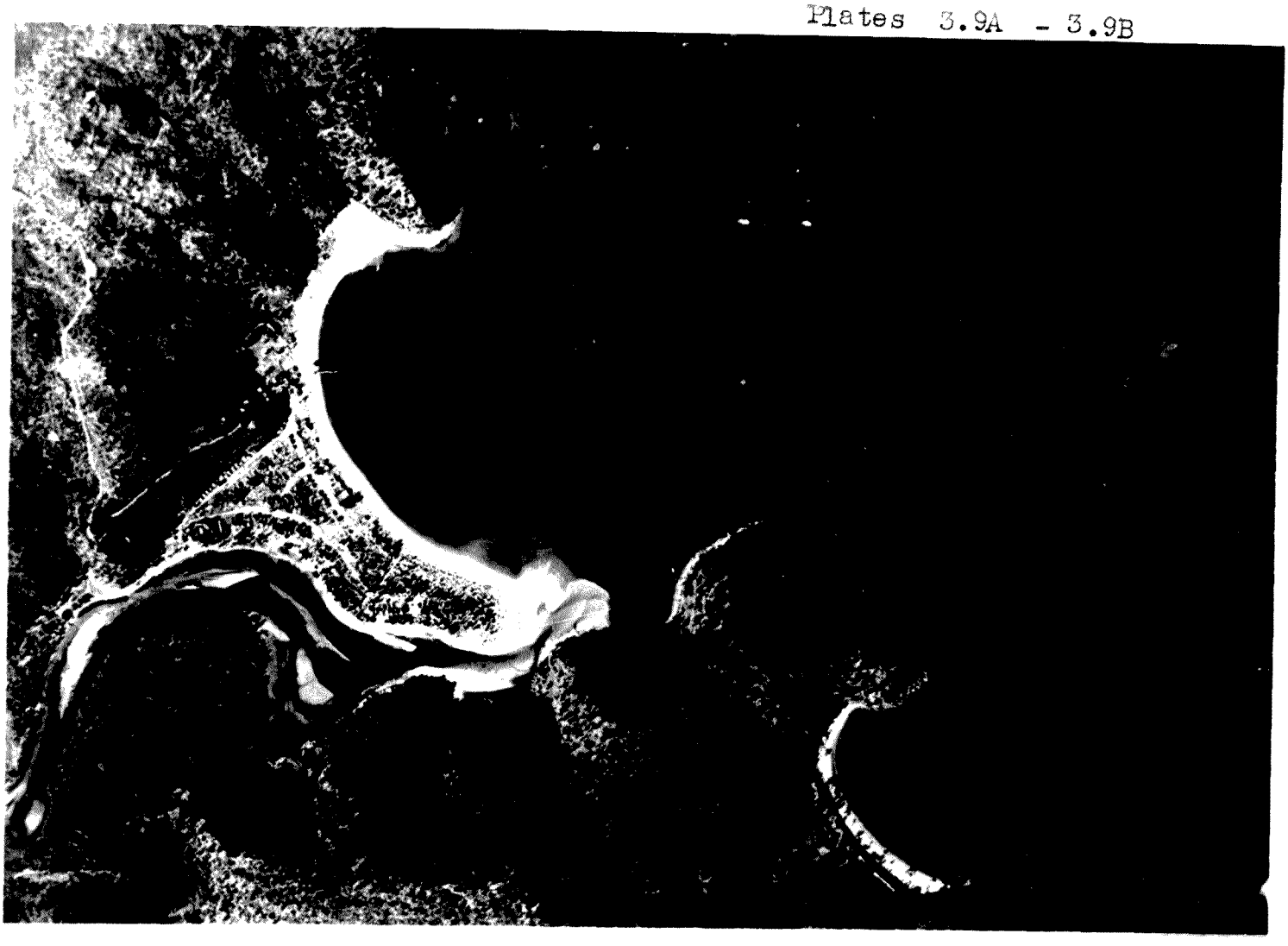
Mangroves occupy darker areas in mid-channel. Note the small delta at the mouth of Patonga Creek.

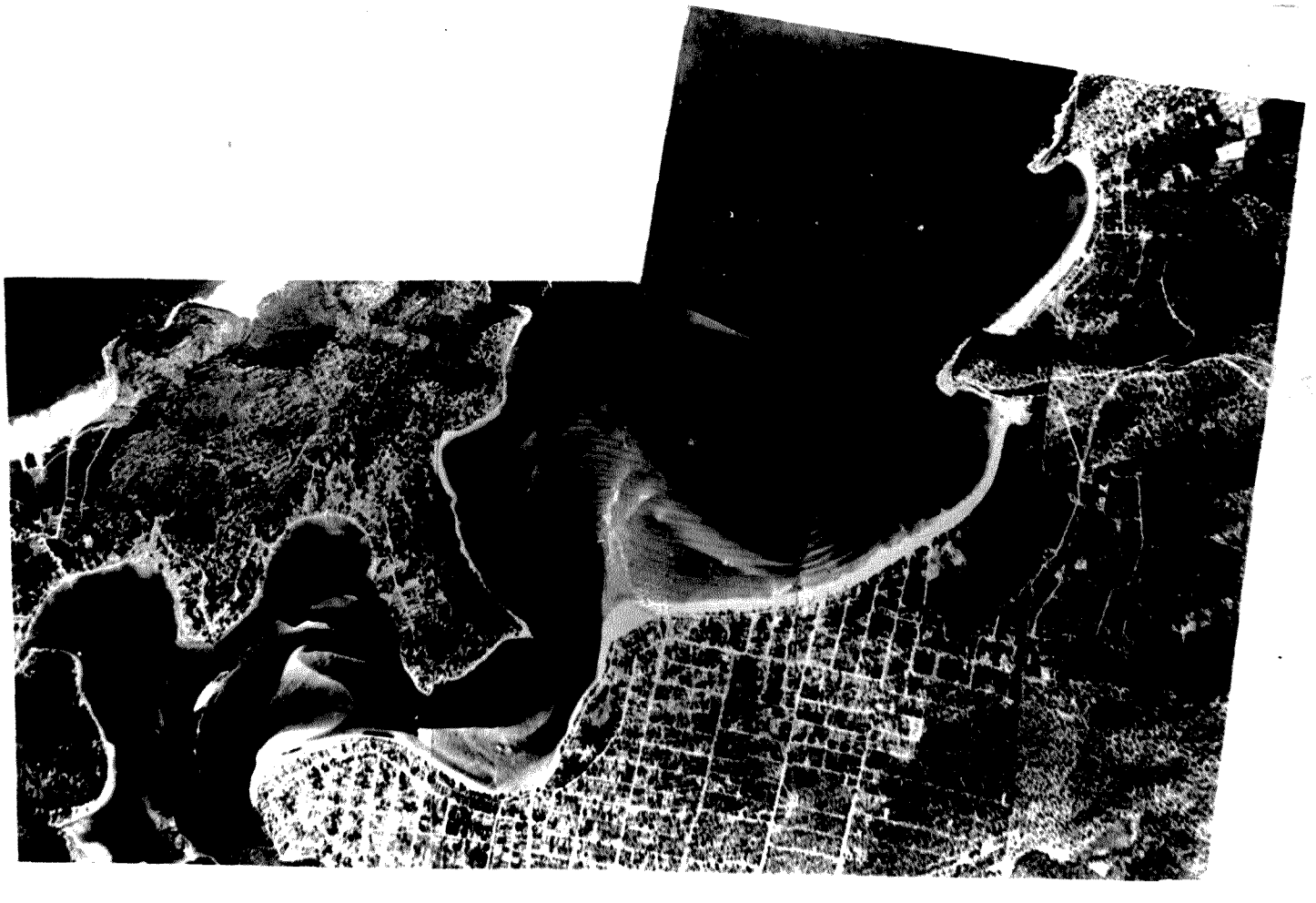
3.9B Vertical aerial photograph of part of the Umina-Woy Woy beach ridge system, Broken Bay.

View looking south-east (cf. Plate 3.7 and Figure 3.8).

Both plates reproduced from aerial mosaics by courtesy of the Under Secretary for Lands, New South Wales.

Plates 3.9A - 3.9B





Plates 3.10A - 3.10B

3.10A Vertical aerial photograph of Twofold Bay. (N.S.W. 122-43).

a - Eden barrier spit and Curalo Lake.
b - Quarantine Bay.
c - Nullica River outlet.
d - Boyd Town Creek.
e - Part of Whale Beach barrier and enclosed Towamba (Kiah) River estuary.

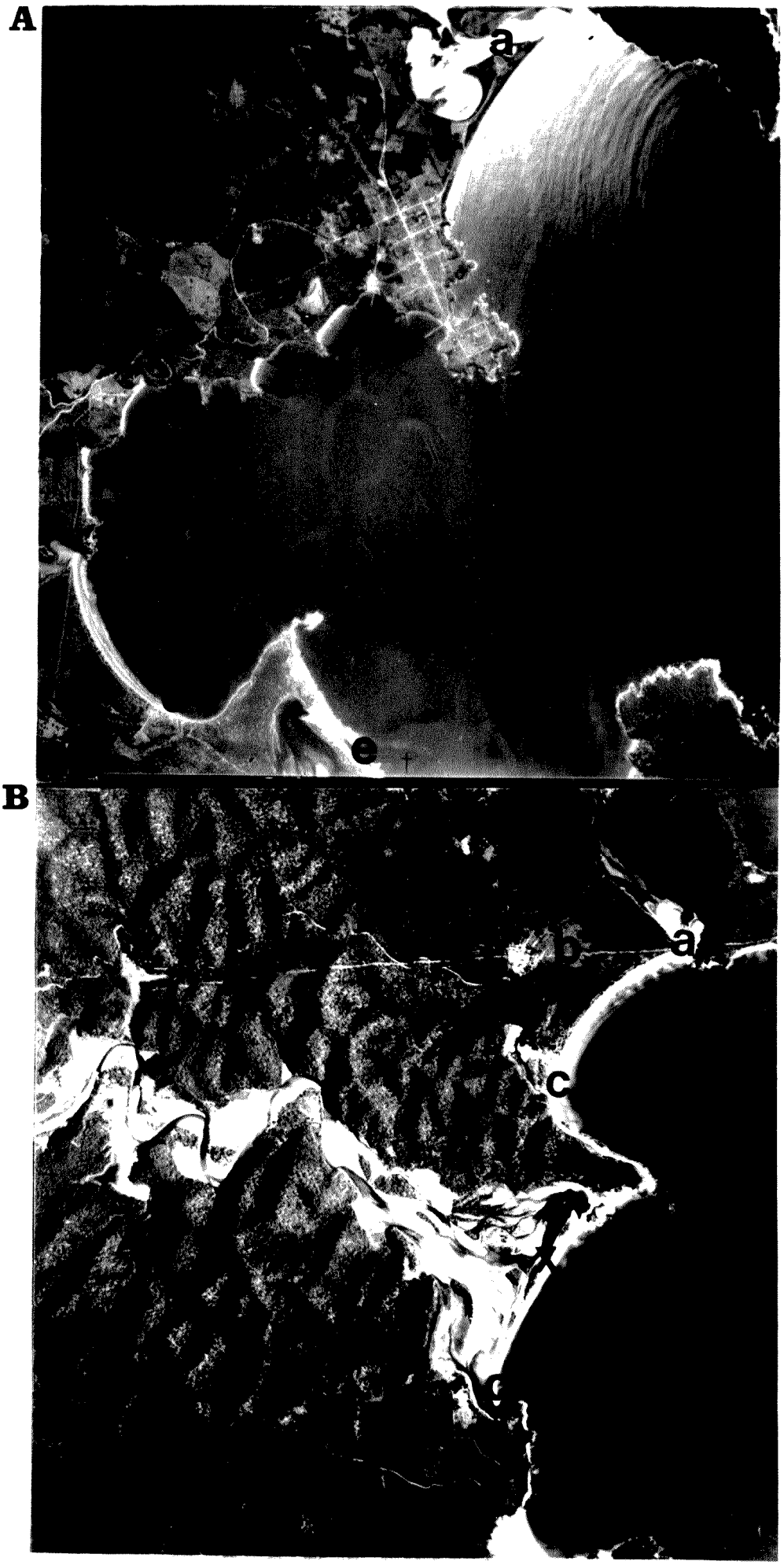
3.10B Vertical aerial photograph of part of Twofold Bay, showing continuation of 3.10A (N.S.W. 146-40).

a - Nullica River.
b - Boyd Town beach ridge system.
c - Boyd Town Creek.
d - Outlet of Towamba (Kiah) River at the southern end of Whale Beach barrier.

x - position from which Plate 2.2'I' was taken.

Both Plates: Scale approximately $\frac{3}{4}$-inch to one mile.

Reproduction by courtesy of the Under Secretary for Lands, New South Wales.


A
a
e
f
B
b
a
c
e

Plates 3.11A - 3.11B

3.11A Vertical aerial photograph of Pambula barrier spit and adjacent areas. (N.S.W. 1156-5079).

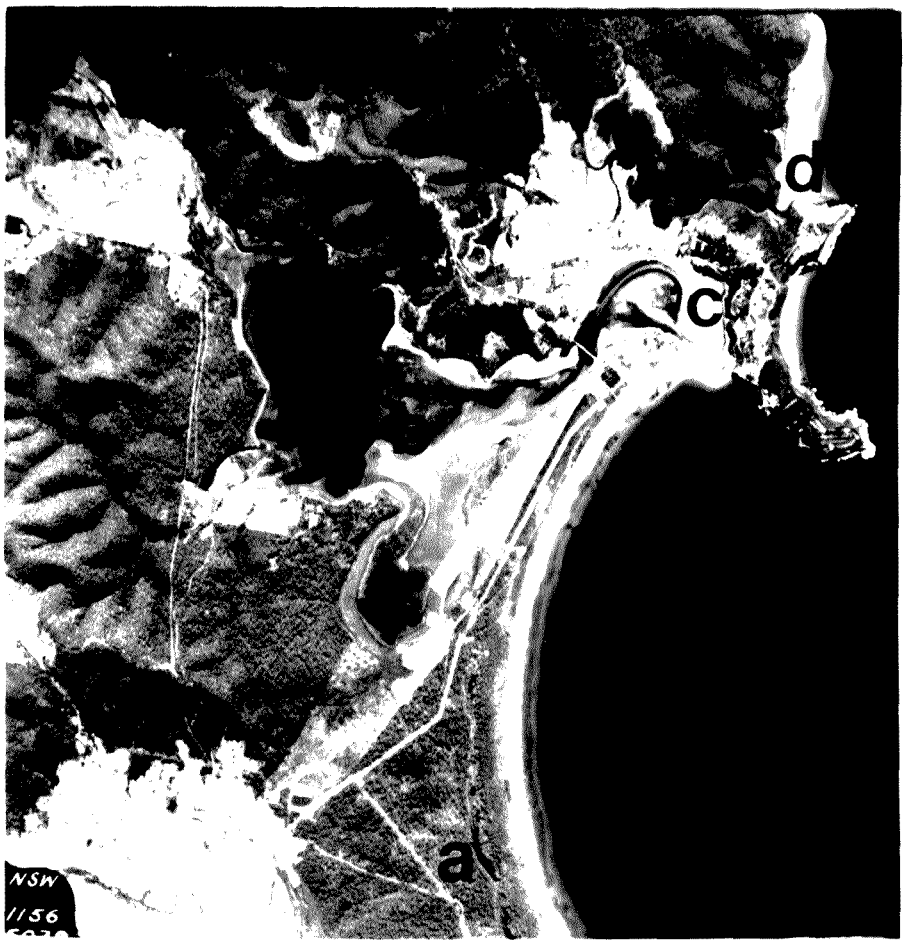
a - Pambula barrier separated from bedrock by a lagoonal-swamp.
b - 'Reverse' tidal delta, Merimbula Lake.
c - Entrance of Merimbula Lake almost blocked by onshore movement of material.
d - Part of the Outer Barrier between Merimbula Point and Tura Head (cf. Figure 2.4).

3.11B Southward continuation of 3.11A, showing Pambula Lake and the Pambula River. (N.S.W. 1156-5086).

Both Plates: Scale approximately $\frac{3}{4}$-inch to one mile

Reproduction by courtesy of the Under Secretary for Lands, New South Wales.

A



B



Plate 3.12 Aerial mosaic of the Mid-North Coast between Point Plomer and Front Beach, north of Crescent Head.

Reproduction by courtesy of the Under Secretary for Lands, New South Wales.

Plate 3.12


LAGOON SHORES
OUTER BARRIER LAGOON
INNER BARRIER
OUTER BARRIER
KILLICK CK.
CRESCENT HEAD
CONNECTION CK
MARIA RIVER
INNER BARRIER
INTER BARRIER LAGOON
OUTER BARRIER
PIPERS CREEK
MARIA RIVER
RACE COURSE HEADLAND
DELICATE NOBBY
BIG HILL
OUTER BARRIER
SWAMP & LAGOONS
TORRENS
POINT PLOMER
SALT WATER LAKE
WILSON RIVER
LIMEBURNERS CK.
ABANDONED BEACH RIDGES

CHAPTER 4

COASTAL DUNES IN THE STUDY AREAS WITH PARTICULAR REFERENCE TO THE MID-NORTH COAST

Individual dunes and active and fixed dune complexes are particularly ubiquitous on the Mid-North Coast of New South Wales but, by comparison, such landform features are almost entirely absent from the other two study areas. In fact, apart from the small sandhills behind the frontal dune at Umina (Ocean) Beach there are no dune formations in Broken Bay, because the barriers are relatively sheltered by headlands from storm waves and onshore winds. Similarly, there is a marked absence of dunes from the smaller embayments of Twofold Bay. However, parabolic dunes and blowouts have been observed along the foredune of the Eden and Pambula barriers on the south coast. The continuity of the foredune along almost the entire length of the Mid-North Coast between Laggers Point and Port Macquarie is invariably interrupted by blowouts of variable size, and parabolic dunes in different stages of development.

Parabolic Dunes: The problem of parabolic dune orientation has been discussed by Schou (1945), Landsberg (1956) and Jennings (1957). Jennings demonstrated that parabolic dune orientation along meridional shorelines is mainly determined by effective onshore winds. In an attempt to evaluate the importance of onshore winds in controlling parabolic dune orientation, the writer obtained wind data from the unpublished records of the Commonwealth Bureau of Meteorology. Four of the few stations on the New South Wales coast were selected for comparison; these were Gabo Island, Jervis Bay, Port Macquarie and Smoky Cape, three of which are either in or very near the study areas. As far as possible, the same period of time (1935-1945) was selected

for each station. However, it must be noted that the wind data analyzed are only valuable for obtaining a generalized picture. For example, the stations vary in height above sea level, and many of the early records are incomplete (Smoky Cape only has records from 1939 onward). Also, Gabo Island is the only station that has an anemometer. Post-1945 records were also studied but since these showed very similar trends to the 1935-1945 wind speeds and directions they were not used in the analyses.

The 9 a.m. and 3 p.m. records for the 1935-1945 period show quite distinctly that there is a marked seasonal trend in wind direction on the coast. In winter offshore winds are the most frequent but generally have a low velocity (except at Smoky Cape), whereas onshore winds predominate in the summer season and have the highest speeds. Despite the fact that the winds from the westerly quadrants have a fairly high percentage frequency occurrence, the most effective winds are onshore. Wind roses, showing the percentage frequency and velocity of winds at the four stations, are shown in Figure 4.1B.

The two sets of wind resultants in Figure 4.1A, and the values listed in Tables 4.1A and 4.1B, were obtained by constructing vector diagrams (see Appendix 4.1) following the Landsberg-Bagnold method, modified by Jennings (op. cit.). The axial trends of the parabolic dunes on the Mid-North Coast are predominantly southeast-northwest. It can be seen in Figure 4.1A that the resultants of onshore winds only (from the northeast, east and southeast, shown in solid lines) for the respective stations differ quite significantly. Except for Gabo Island, at each station the resultants show different directions for the 1935-1939 and 1940-1945 periods. However, when onshore winds are

combined with those from the south and are shown in a plot (dashed lines) there is a better correlation between the resultants for the same two periods, and a fairly good correspondence with the trend of the parabolic dunes on the Mid-North Coast. These results show that winds from the south apparently have some significance in controlling the orientation of the parabolic dunes despite the fact that the most effective winds appear to be from the southeast-see the section on transgressive dunes. Nevertheless, the different directions of the respective resultants of onshore winds deserve some comment since the ten-year period of records is relatively short and it is reasonable to suppose that there would be little difference in the direction and speed of the winds during that period of time.

It seems that the accuracy of the original records must be considered. Without an anemometer it is extremely difficult to measure the force or velocity of the wind precisely. The writer found that the records at Smoky Cape were based on the observations of the lighthouse keeper who used only the descriptions of the Beaufort Scale to guide him. Therefore the resultants of onshore winds for Gabo Island - which has an anemometer - may be the most reliable. Until more detailed research can be undertaken on the subject of parabolic dune orientation on the New South Wales coast, the writer is reluctant to draw conclusions from the results presented here, and thinks that the existing meteorological records must be interpreted with caution.

Mid-North Coast Dunes

Since little is known about the complex history of the coastal dunes on most parts of the New South Wales coast it is not easy to give a

comprehensive account of the dune systems in the Mid-North study area. Observations and measurements made during field investigations and reconnaissance surveys are presented here with the view that they may provide some reference for other studies in adjacent areas. The information was obtained under a variety of weather conditions, but mainly during the winter seasons of the three-year period of study. However, long-term measurements of the rate of sand accumulation and of the changes in form and orientation of active dunes at selected stations are essential before any definite conclusions can be made. Unfortunately, such very detailed measurements are lacking in this study since the writer was unable to make the necessary repeated visits to the Mid-North Coast, which would have involved several months each time.

The writer has made the first study of the textural parameters and heavy mineral composition of the dune sands on the Mid-North Coast and compared these with the properties of the adjacent barriers and modern beach sands; the results are discussed in Chapters 7 and 8. The mechanical analyses show that the dunes are composed of well sorted, medium- to fine-grained quartzose sands and that practically all the sand grains are well rounded (Figure 7.6).

The dunes of the Mid-North Coast can be grouped basically into three main classes: parabolic or U-shaped dunes which have already been discussed, active and fixed transgressive dunes, and cliff-top dunes.

Transgressive Dunes: The most common and largest type of coastal dune in New South Wales is what Gardner (1955) has called the transgressive dune. Such dunes on the Mid-North Coast are aligned approximately parallel to each other and to the direction of southeast-northwest winds, but at an oblique angle to the trend of the coast. They are similar to longitudinal

dunes and transgressive dune sheets which generally extend parallel to the direction of dominant dune-building winds. The pattern of some of the dunes is shown in Plates 3.5C - 3.5D, and Plate 3.3C which was taken from the lighthouse on Smoky Cape.

Both fixed and active transgressive dune complexes are common features towards the northern ends of the larger arcuate bays. The dune topography is quite pronounced, but the local relief varies from place to place. Most active dunes are less than 100 feet high, but some fixed dunes attain heights of 150 feet or more, and a few even exceed 200 feet; for example some of those near Smoky Cape, Hungry Hill and Big Hill headlands.

The majority of the stabilized transgressive dunes are confined to the Inner Barrier, including the Maria-Wilson barrier plain, but there are some at the back of the Outer Barrier to the east of Limeburners Creek (Figure 3.7) and immediately behind the frontal dune between Delicate Nobby and the Hastings River. Those surmounting the Inner Barrier are old enough to have well-developed podzolic profiles, with A_2 horizons several feet thick often grading into humate, which is a good indication that the dunes are Pleistocene in age. In contrast, the fixed dunes on the Outer Barrier show little evidence of soil profile development.

Shallow pits and sections cut along the lee face of the Pleistocene dunes revealed that there is no eolian cross-bedding or other diagnostic sedimentary structures and it is inferred, as in the case of the Inner Barrier beach ridges, that these features must have been destroyed by pedogenic processes during the development of the podzols. The fixed transgressive dunes on the Inner Barrier are covered with dune heath and woodland which is also the characteristic vegetation of the Inner

Barrier ridges, whereas those on the Outer Barrier are stabilized by dune scrub (Leptospermum laevigatum) and Banksia integrifolia.

Although a few of the active dunes are encroaching upon the Inner Barrier, they are usually confined to the Outer Barrier, particularly where it is being cut back by marine erosion and also where extensive areas of sand have been left bare after the mining of heavy mineral beach concentrates (Plates 4.1B-4.1F).

Like the majority of dunes that are elongated parallel to effective winds most of the active transgressive dunes on the Mid-North Coast are characterized by a gentle windward slope, which varies between 3 and 12 degrees (with an average value of about 6 degrees). By comparison, most of the leeward slopes vary between 29 and 33 degrees, but on occasions the writer measured angles up to 35 degrees which proved to be about the maximum natural angle of repose for dry sand. The active leeward slopes are modified continually by wind action and shaped by slumping - giving rise to fresh slip faces, some of which are more than 20 feet high (Plates 4.1C-4.1E), (see also Bagnold, 1941); barchanoid forms are also prominent (Plate 4.1B).

The writer made short-term records of wind speeds during field investigations by using a portable anemometer in the small fixed dune complexes on the Maria-Wilson barrier plain, and in the active transgressive dune belt seaward of Ocean Swamp about 5 miles south of Hungry Hill (Figures 3.4 and 3.7). Maximum wind speeds recorded south of Hungry Hill were equivalent to force 5 on the Beaufort Scale, and on practically every occasion the winds were from the southeast. Offshore westerly winds were recorded occasionally but their speeds were less

than force 3 on the Beaufort Scale. Force 5 is strong enough to transport heavy minerals and comminuted shells by saltation and surface creep, which the writer frequently observed, and to remove the lighter quartz grains from the windward slope of the dunes - to leave a concentration of heavy minerals behind as a lag deposit. The different wind velocities recorded on various occasions in the active dune belt reflect not only the shelter afforded by extremely high dunes, but also the marked variations that can be recorded between the exposed oceanic (windward) side and the relatively sheltered leeward side of individual dunes or dune ridges.

Dune lakes and swamps occupy both large and small depressions within the fixed transgressive dune belts that surmount the Inner Barrier immediately south of Smoky Cape and Hungry Hill headlands. Both the lakes and swamp tracts are of variable shape; some are predominantly oval, others elongated like small ribbon lakes, whilst a few are distinctly triangular (Plates 3.5C and 3.5D). There is no indication that they occupy the axial hollows of ancient dunes. On the contrary, they illustrate the effects of the combined action of deposition and deflation by wind, as can also be seen in the active dune areas. However, there is no evidence to suggest that the triangular lakes on the Mid-North Coast owe their development to the blocking of coastward-draining river valleys by dunes advancing inland, as described by Cotton (1948).

Survey aneroid traverses made by the writer in the more accessible parts of these fixed dune belts showed that the relief is irregular and that the lakes and swamps are at different heights between 20 and 150 feet above mean sea level. These variations in height can be partly

explained by differences in the level of the water table which borings showed to be perched on impermeable humate in many places. The humate was found at various depths, but generally no more than 6 to 10 feet below the level of the swamps. Surface drainage into the swamps and shallow lakes is only visible after exceptionally heavy rain.

Migration and Origin of the Transgressive Dunes: Based on the evidence available on the coast today, there seems little doubt that the fixed and active transgressive dunes are characteristic of retrograding shorelines. The large volume of sand incorporated in the active dunes on the modern coast is advancing inland quite rapidly as the Outer Barrier retreats under wave and wind attack. At the northern end of the arcuate bays the sand is invariably piled high against the bedrock headlands. The few short, intermittently-flowing streams that drain the flanks of these headlands reach the ocean by way of 'gorges' deeply cut along the contact of the encroaching dune sand and bedrock (Plate 3.3C). In a few places, for example immediately to the south of Smoky Cape and Hungry Hill, active transgressive dunes are lying adjacent to, and invading quite rapidly, the older vegetated transgressive dunes. There are no pioneer sand-binding plants on the lee slopes of these active dunes.

The writer's measurements of the rate of slip face advance have been too infrequent to present any definite conclusions on dune activity. Although there are no records on the general rate of dune movement on the Mid-North Coast (nor any series of maps or aerial photographs from which calculations of dune advance landward can be made) it appears from the information the writer has been able to obtain from local residents that the active transgressive dunes between Smoky Cape and Crescent Head, which

have already buried large areas of Ocean Swamp and the swamp tract to the north of Hat Head village, have advanced inland for the past 30 years. If the reports are reliable, the dunes have migrated inland at the rate of about 45 feet per annum

The dead banksia trees on the Outer Barrier (Plate 4.1C), formerly completely buried by sand but now partly exhumed, are testimony of contemporary dune movement inland. Even so, where the rate of advance of fresh sand has been reduced a few parts of the periphery of this particular dune system are being stabilized by sand-binding grasses and succulent plants (Plates 4.1D-4.1F).

Several of the Pleistocene dune systems on the Mid-North Coast have pronounced relief and display little evidence of being appreciably modified by degradational processes. They appear to have been permanent landform features since they were first stabilized indicating that the vegetative cover must have regenerated continuously(and quite rapidly after any natural bush fires) to maintain a stable dune complex. The stability of the fixed transgressive dunes can also be attributed directly to their high permeability.

Only a few dunes are being stabilized on the Mid-North Coast today. The rate at which these dunes are stabilized depends basically upon three interrelated factors. First, there is the amount of sand that is available to be moved inland by effective winds. At present this is determined largely by the rate of Outer Barrier erosion. A reduction in the volume of sand in moving dunes, and the rate of advance inland, will facilitate the partial stabilization of the peripheral areas of a dune complex (Plates 4.1D-4.1F). Conversely, an increase in sand supply in an active

mass can increase the height of the dunes. Second, there is the rate at which pioneer sand-binding plants become established and spread over the surface of the dunes, thus reducing the size of the active area. The rate of colonization often determines the ultimate shape of dune masses. As mentioned in Chapter 3, the conservation schemes that have been implemented on the Mid-North Coast have met with practically no success, because sand is being driven inland by onshore winds and is burying the vegetation that has been planted. Third, the vagaries of local climate may favour plant growth and hence stabilization, or promote erosion and consequently the destruction of the existing vegetation.

As Bagnold (1941) pointed out, the type of dune developed in any area is determined not only by the dominant wind directions, but also by the strength of the wind. It appears from the orientation of the fixed and active transgressive dunes on the Mid-North Coast that southeasterly winds have been the most effective in the past, as well as today.

There are a few fixed dunes on the Maria-Wilson barrier plain that are aligned east-west, whilst some others are oriented north-south (those just to the north of traverse C-C_1 in Figure 3.7). These trends have not been noted in the active dune complexes. Since it is impossible to say whether all the various dunes on the barrier plain are approximately the same geological age because there is a lack of material suitable for radiocarbon dating, it can only be inferred that those with directional trends departing from the general southeast-northwest alignment probably originated during earlier or later episodes of dune building. Of course, the possibility cannot be discounted that the different dune trends simply reflect variations in the direction and speed of local winds at the time of dune building, but unfortunately there are no well-defined

sedimentary structures to resolve this problem.

Whether the fixed dunes, regardless of their orientation, were built in a comparatively short period of time, or intermittently during periods of stabilization alternating with erosion is a matter for speculation. At least the evidence of the fixed and active dunes surmounting the Outer Barrier suggests that there were probably several different phases of dune advance. This view is partly supported by the variation in shape of the dune lakes and swamps which may reflect several periods of dune building in the past, possibly at a time when the Inner Barrier was cut back periodically, or possibly during more than one high stand of the sea during the Pleistocene epoch.

Some of the fixed dunes may have been built when sea level was lower during late Pleistocene time. Unconsolidated sand, and possibly unstable dune masses on the exposed shelf could have been moved landward by predominant onshore winds and piled against what are now the coastal bedrock headlands. It is also possible that the sand migrated landward as ephemeral shorelines seaward of the present coast were destroyed during one or more Late Pleistocene marine transgressions.

Current evidence indicates that there may have been three episodes of dune building during and since the formation of the Outer Barrier. First, the fixed non-podzolized transgressive dunes east of Limeburners Creek at the back of the Outer Barrier (Figure 3.7) may have been built during a minor interruption of shoreline equilibrium as the barrier was prograding seaward. As mentioned in Chapter 3, there is no evidence to suggest that these dunes have migrated landward from the modern shoreline since they are fronted by a regular series of ridges and swales.

Second, the stabilized transgressive dunes immediately behind the modern foredune between Delicate Nobby and the Hastings River probably advanced landward when the Outer Barrier was cut back from a position slightly seaward of the present shoreline. Third, the present active dune masses reflect an excess of cut over fill on a retrograding shoreline. Some contemporary dune building can be indirectly attributed to the 'trigger action' of man's activities on the coast and to natural bush fires.

Cliff-Top Dunes: The cliff-top dunes on the Mid-North Coast stand between 100 and 350 feet above mean sea level and mantle Smoky Cape (320-350 feet), Hat Head (150-200 feet), Korogoro Point (200 feet) and Big Hill (120 feet) headlands (Plate 3.3E). These dunes are anchored beneath a very dense cover of scrub and forest. Borings made by the writer show that they have well-developed podzolic profiles, with the leached white sand of the A_2 horizon often exceeding 20 feet in thickness. No humate underlies the A_2 horizon although incipient B horizons several feet thick have been traced in a few localities. Nevertheless, there seems little doubt that the cliff-top dunes are of Pleistocene age since they are so deeply leached.

Since most borings were made with a hand auger it has been difficult to establish the actual thickness of the cliff-top dune sands. Natural exposures beside the track leading to Smoky Cape lighthouse show that the dune sands there are more than 30 feet thick.

Origin of the Cliff-Top Dunes: One view that has been expressed about the origin of the cliff-top dunes is that they are the highest remnants of dunes that advanced up bedrock slopes (Jennings, 1957). While this may be true for some cliff-top dunes on the southern side of Hungry Hill, where sand has been piled high against the headland by effective southerly

winds, this explanation becomes increasingly improbable in the case of those dunes that stand about 350 feet above sea level on the west (landward) side of Smoky Cape headland. Their origin is somewhat complex and requires an alternative explanation. In this case there is no immediate source area to the west and movement of sand from the south would have been virtually impossible in the past owing to the position of the dunes on the headland. It seems more likely that unless a higher sea level can be invoked the dunes may have been emplaced when offshore westerly winds moved sand from the ancient sand ridges about two miles west of the Inner Barrier, or from areas of sand that were exposed seaward of the ancient bedrock coastline but to the west of Smoky Cape during times of lower sea level.

So far, it has been difficult to establish a definite relationship between the cliff-top dunes and possible former high stands of sea level during Pleistocene time. The discovery of boulder-beach relics at heights more than 80 feet above present sea level HWM by Langford-Smith and Hails (1966) on several headlands on the north coast of New South Wales does suggest (without necessarily challenging the views on the origin of cliff-top dunes) that some of the highest dunes may have a more complex origin than has hitherto been supposed. Attention has been drawn already in this study to the difficulties facing the coastal geomorphologist in attempting to determine eustatic changes of sea level without evidence of fossils or standard shoreline deposits. All that can be said here, in conclusion, is that higher stands of the sea during the Pleistocene epoch could account for many of the cliff-top dunes found on the headlands on the New South Wales coast.

TABLE 4.1A

Wind Resultants for Stations In or Near the Study Areas

Stations	Year Opened	Anemometer	Wind Resultants (eight major compass directions) 1935-39	1940-45	(NE, E and SE Winds) 1935-39	1940-45
*Gabo Island	?	yes	57°	56°	65°	53°
Jervis Bay	1867	no	219°	210°	130°	85°
Port Macquarie	1840	no	136°	162°	57°	80°
Smoky Cape	1939	no	202° (1939-45)		74° (1939-45)	

* Many of the early records for the first three stations are incomplete.

TABLE 4.1B

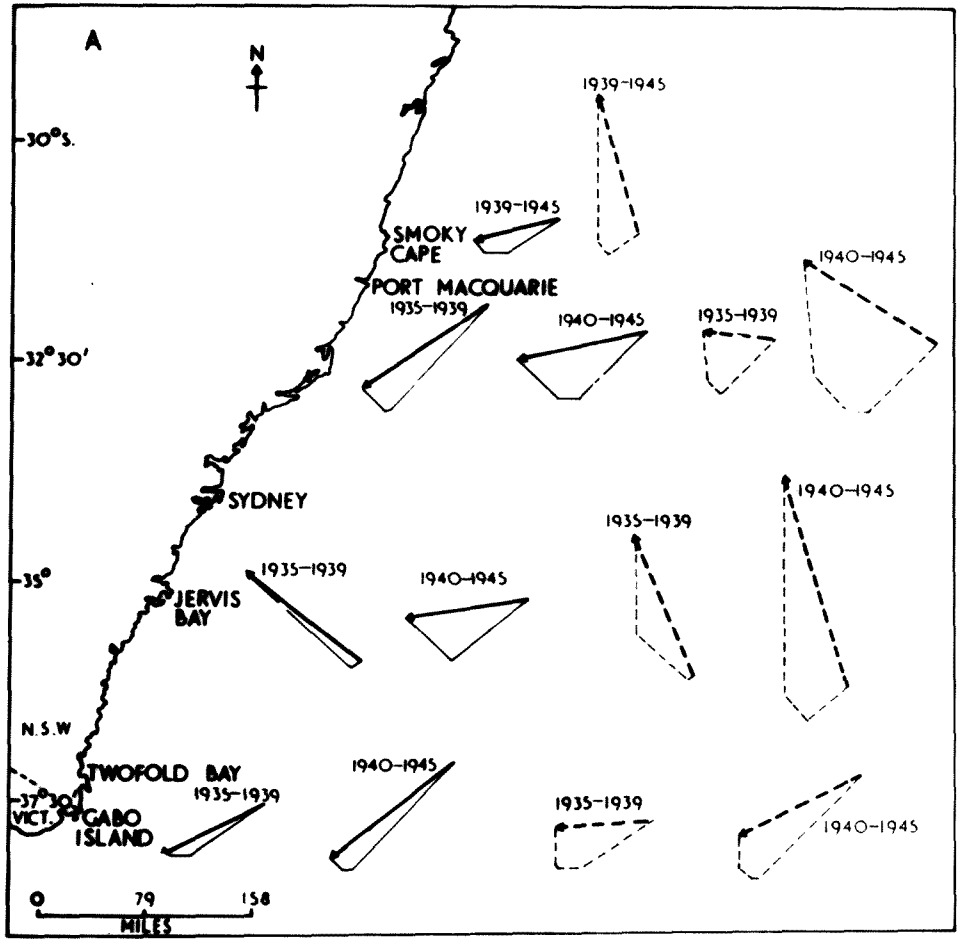
In this table resultants are given for eight major compass directions and for NE, E, SE and S winds for the period 1935-1945 (see Figure 4.1). Vectors for Smoky Cape, Port Macquarie, and Jervis Bay were divided by two to make them comparable with those for Gabo Island.

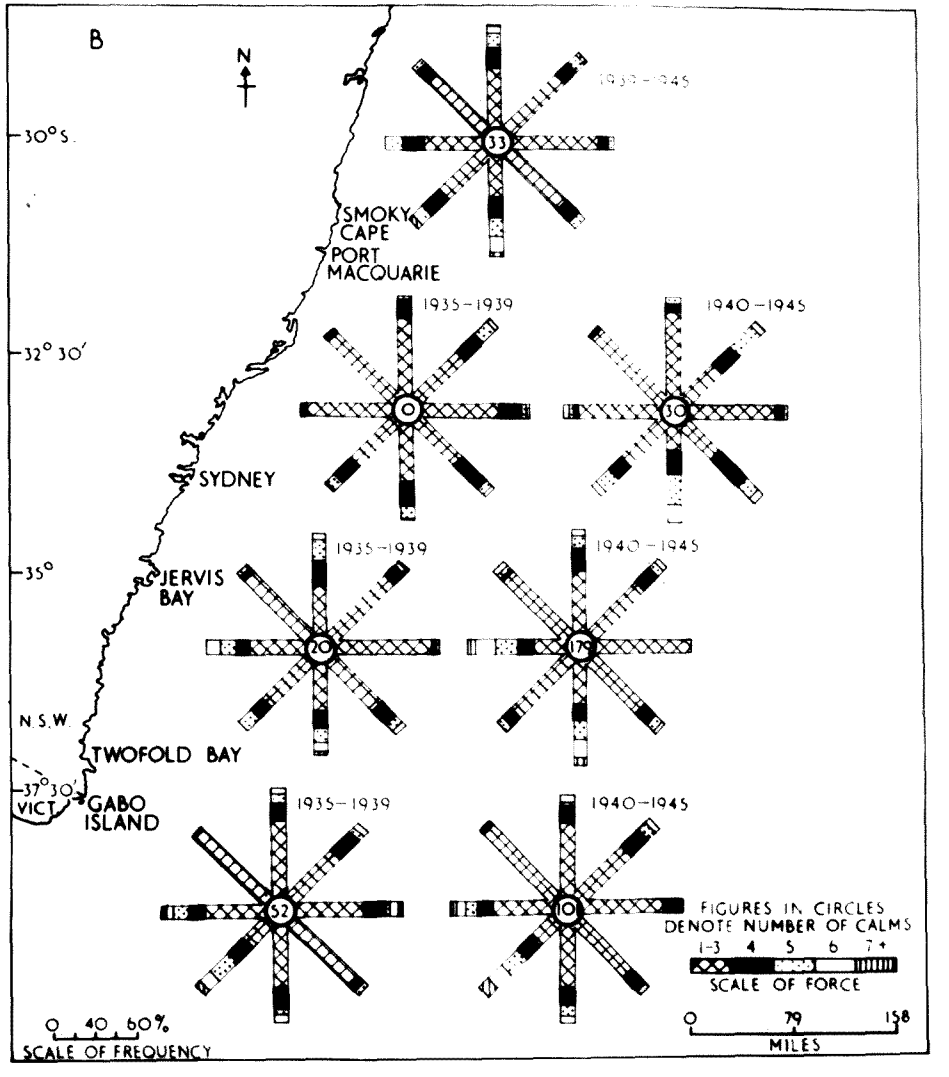
	Wind Resultants (Eight major compass directions) 1935-39	1940-45	(NE, E, SE and S Winds) 1935-39	1940-45
Gabo Island	57°	56°	85°	65°
Jervis Bay	219°	210°	159°	164°
Port Macquarie	136°	162°	100°	125°
Smoky Cape	202° (1939-1945)		163° (1939-1945)	

Figures 4.1A and 4.1B

Wind resultants (4.1A), and percentage frequency of wind speeds (4.1B), for stations in or near the study areas.

From south to north the stations are: Gabo Island, Jervis Bay, Port Macquarie and Smoky Cape.





Figures 4.1A - 4.1B

Plates 4.1A - 4.1F

4.1A View looking south towards Crescent Head showing dissection of Front Beach Outer Barrier.

4.1B View to the west of 4.1A. Active transgressive dunes infilling part of Ocean Swamp.

4.1C Long-walled transgressive dune. Dead Banksia branches protruding through sand. Note sand ripples.

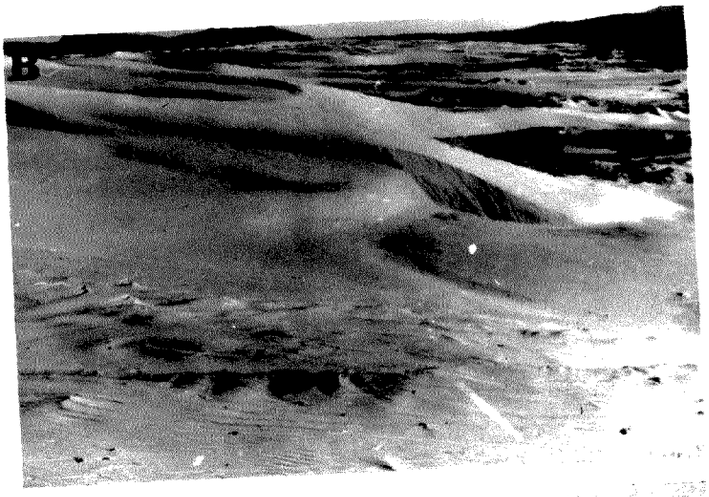
4.1D Partly stabilized sand in front of large transgressive dune. Large sandhill in background.

4.1E Small sand plain in transgressive dune field.

4.1F Active transgressive dunes infilling Ocean Swamp. View looking north towards Hungry Hill. Fixed transgressive dunes in background.

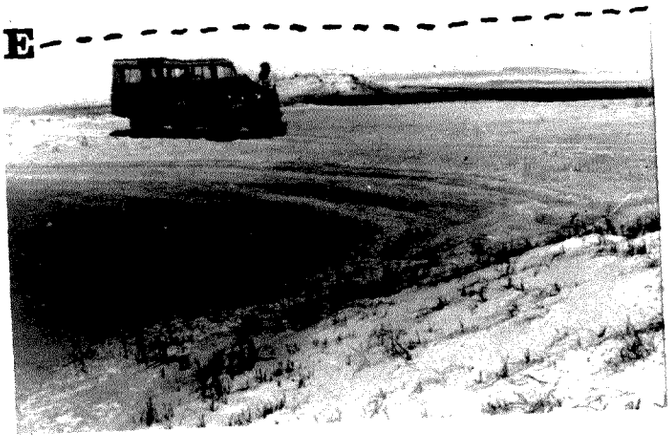
Dashed line in 5.1E. shows crest of transgressive dunes.


A


B


C


D


E


F

Plates 4.2A - 4.2F

4.2A Transgressive dunes spilling over into Ocean Swamp, about 5 miles south of Hungry Hill.

4.2B View looking southeast across Ocean Swamp and transgressive dunes of the Outer Barrier. Photograph taken from high, fixed transgressive dunes south of Hungry Hill. Continuation of 4.2A.

4.2C Crest of active transgressive dune and partially infilled Ocean Swamp. Inner Barrier in the background. View looking west.

4.2D Dune sand partly stabilized in foreground, migrating in middle distance. View looking south from edge of Ocean Swamp.

4.2E and 4.2F Active transgressive dunes invading Ocean Swamp. Inner Barrier in background.

Dashed lines in 4.2A and 4.2B show crests of Outer Barrier transgressive dunes.

Plates 4.2A - 4.2F

A



B



C



D



E



F



CHAPTER 5

COASTAL LAGOONS AND LAGOONAL-SWAMPS

Introduction: The term lagoon in this study is used for areas of relatively shallow water that have been completely or partially cut off from the sea by sand barriers, and the term lagoonal-swamp is used to describe former lagoons that have now been considerably filled with sediments (almost completely in some areas) and partly converted into swamps.

It is proposed here to present a summary of the geomorphological characteristics of these lagoonal and paludal environments, based on evidence the writer collected during field investigations. Despite the general conclusions on the geomorphology of coastal lagoons in other areas of Australia (for example, Bird, 1965a) essentially nothing is known about the existence of lagoons and estuaries during Late Pleistocene time in New South Wales. Apart from a recent descriptive paper by Bird (1967) dealing with depositional features in estuaries and lagoons in and near one of the writer's study areas, no detailed studies have been undertaken to evaluate rates of sediment accumulation in modern lagoons and to examine the behaviour of tidal lagoonal inlets.

There is a marked difference in the shape and size of the lagoons on the Mid-North and far south coast of New South Wales. In part, these morphological contrasts are a reflection of the variations in the bedrock configuration of the two sectors. For example, on the Mid-North Coast the lagoons (now mostly lagoonal-swamps) separating the Inner and Outer Barriers are long and narrow. Since they trend parallel to the modern coast, they are slightly arcuate in shape, like the barriers that enclose them (Figure 3.4). The narrow lagoons illustrate partly how the spacing of the dual

barrier systems has been mainly controlled by the steeply sloping continental shelf. By comparison, barriers on gently shelving coasts are invariably separated from each other either by areas of salt marsh, often several miles wide, or by large tidal estuaries (Hails and Hoyt, 1968).

On the south coast, however, lagoons have formed where Holocene sand barriers have completely or partly enclosed the mouths of submerged river valleys. Despite the somewhat irregular configuration of the south coast lagoons, Figure 2.4 shows that they are predominantly oval, or elongated almost normal to the modern coast. The oval lagoons, like Wallagoot and Merimbula Lakes, occupy former river basins (compare also Pambula Lake; see Chapter 2). Some of the elongated lagoons between Tura Head and Merimbula Point have been infilled by sedimentation and alluviation, and are now nothing more than swamp tracts (Figure 2.4).

There are no lagoons *per se* in Broken Bay, apart from the estuarine lagoon enclosed by Patonga Beach barrier. There is only a small lagoonal-swamp behind the northern sector of Pearl Beach barrier. The lagoonal-swamps of the Umina-Woy Woy barrier system have been discussed already in Chapter 3. Inter-Barrier Lagoons and Lagoonal-Swamps of the Mid-North Coast: Most of the long, narrow lagoons that came into existence when the Outer Barrier was built a short distance seaward of the Inner Barrier on the Mid-North Coast have been considerably filled with sediment and converted into lagoonal-swamps. The only remnants of the original inter-barrier lagoons are some small lagoons surrounded by swamp land (Figure 3.4).

The reduction in size of the inter-barrier lagoons is a result of the encroachment of swamp and, most of all, the rapid accumulation of terrigenous sediments as the Outer Barrier has migrated landward.

Consequently, there are no definite conclusions on the amount of sediment that may have been carried into these lagoons in the past by the tidal creeks.

There is no direct evidence of segmentation whereby long narrow lagoons are eventually converted into oval or rounded lagoons (Price, 1947; Zenkovitch, 1959). The process of segmentation is mainly dependent upon waves and currents generated in lagoons by winds blowing over large stretches of open water (fetch), the development of spits, and erosion and deposition along the shores of a lagoon.

There are three possible reasons why segmentation may not have occurred on the Mid-North Coast. Firstly, as mentioned in Chapter 4, the predominant and effective wind in this region is from the southeast. However, the configuration of the inter-barrier lagoons is such that the most effective winds would be from the north or south. Secondly, the relatively narrow inter-barrier lagoons were quite shallow and were rapidly infilled by windblown sand and the landward advancing sand sheets of the Outer Barrier (Plates 4.1F, 4.2A-4.2B). Thirdly, a restricted inflow of saltwater through small tidal entrances (if the size of the modern tidal creeks can be taken into consideration) brought about a general dilution of the saline and brackish water which in turn, together with shallow-water conditions, favoured the rapid growth and encroachment of reedswamp, and ultimately swamp land. Since no rivers drain into the lagoonal-swamps, and there is no surface runoff from the adjacent barriers, the change from saline to slightly brackish and freshwater conditions can also possibly be related to former changes in the climate, for example, periods of higher rainfall.

Mechanical analyses show that the sediments of Ocean Swamp and other lagoonal-swamps consist essentially of well rounded, fine- to medium-grained quartzose sand. Most of this appears to be windblown sand and the grain-size characteristics in general reflect the immediate source of supply - the Outer Barrier. Nevertheless, the values of the sands do not necessarily indicate rounding by wind action (see Chapter 7). There is a relatively low percentage of silt and clay in the sediments and this seems to be a result of the fact that no rivers drain into the inter-barrier lagoonal-swamps.

Most of the inter-barrier lagoonal-swamps are colonized by swamp paper bark or tea-tree (Melaleuca spp.), reedswamp (Phragmites communis), Potamogeton, Cladium and Juncus (Plates 5.1D and 5.1E). Phragmites communis is indicative of fresh, or only very slightly brackish water conditions. Mangroves are prominent along the tidal creeks draining the lagoonal-swamps.

As yet no detailed studies have been made of the characteristics and behaviour of tidal inlets in New South Wales. Wave refraction diagrams (Appendix 3.1) show that the lagoon entrances, and the outlets of the tidal creeks draining the lagoonal-swamps, are at a point on the coast where the level of wave energy is lowest. The writer has observed that the closing of lagoon entrances, and sometimes the periodic breaching of the enclosing barriers, is related to seasonal changes in the beach profile. Since the causes of barrier breaching have been discussed in Chapter 3, it is only pertinent to record here that the entrances to lagoons can be re-opened when ponded water, often perched a few feet above high-water mark, eventually spills over and breaches the enclosing barrier. Often this breaching is assisted by storm wave erosion on the seaward side of the enclosing barrier.

South Coast Lagoons: Several inter-related depositional processes are currently operating on the south coast and are contributing to the filling in of the coastal lagoons. These include the construction of sedimentary jetties and small deltas by streams draining into the lagoons; the growth of 'reverse' tidal deltas in the lagoons behind the enclosing barriers, the migration of sand from the unvegetated distal end of the enclosing barriers, and sedimentation in the lagoons where reedswamp predominates.

So far none of these processes has significantly modified the shape of the lagoons. The rate of infilling is slow because the south coast streams have small catchments and transport relatively small sediment loads to the coast. Since some of the south coast lagoons are fairly large, it will probably take several centuries at the current rate of infilling before fluvial-deltaic plains of some dimension are constructed (see also Chapter 6).

Sedimentary jetties similar to, but very much smaller than, those described by Bird (1962) have been located on the western shores of Wallagoot and Merimbula Lakes (Plate 5.3B; Figure 2.4). Reference has already been made in Chapter 3 to the 'reverse' tidal deltas which are being built in several of the south coast lagoons (Plate 3.11A).

In contrast to the Mid-North Coast, the effects of westerly offshore winds are a little more pronounced in southern New South Wales. These effects are well-displayed at Whale Beach barrier which almost completely encloses the mouth of the Towamba (Kiah) River (Figure 2.5). The Towamba estuarine lagoon is sufficiently long for offshore winds to generate fairly large waves which are driven against the barrier and cause marked cliffing. The writer noted that a vertical cliff, which stands between 6 and 10 feet above the level of the lagoon, at the back

of Whale Beach has a steep beach of coarse material, covered with storm and floodwater debris, at its base. When the Towamba River is swollen with floodwater the barrier is frequently breached at the end adjoining Mowtree Headland - its former natural outlet (Plates 2.2H and 2.2J). Thus paradoxically, the lagoon side of Whale Beach is eroded more by wave attack than the front of the barrier which faces East Boyd Bay. This example of barrier erosion by lagoonal waves has not been noted in such detail elsewhere in the study area and it appears to be the direct result of the combination of several factors. Firstly, the Towamba estuarine lagoon is quite small compared with most other south coast lagoons, but it is frequently swollen with floodwater which cannot always drain into East Boyd Bay through the narrow lagoon outlet without eroding and breaching Whale Beach barrier. Secondly, the estuarine lagoon is normal to the trend of the coast and provides a sufficiently large fetch for offshore winds to be most effective. In contrast, the oval-shaped lagoons are large enough for winds from several directions to generate waves. Thirdly, the Towamba estuarine lagoon is not so deep as some of the other lagoons. The relationship between the average width of an enclosed water body and its depth will be examined in the next chapter.

Besides the depositional features of the south coast lagoons that have already been mentioned, there are very small recurved spits on the sheltered shore of Curalo Lake immediately behind Eden barrier spit (Plate 5.2L), which are due to sediment movement in the lagoon. Most of these spits are being colonized by the shore rush, Juncus maritimus, and other plants, although there is evidence of erosion along a few of them.

In conclusion, it can be said that the lagoons in the study area display a variety of characteristics that merit more attention than the writer has been able to give to this part of the study. In fact, to examine in detail all the inter-related processes that contribute to the 'geomorphology of lagoons' in the broadest sense of the term necessitates a separate study.

Plates 5.1A - 5.1E

5.1A View looking north from the southern end of Belmore Swamp. Photograph taken from base of ancient bedrock coastline.

5.1B Slightly higher part of Belmore Swamp, looking northeast. Melaleuca spp. in background.

5.1C Melaleuca viridiflora, in Belmore Swamp.

5.1D Southern end of Ocean Swamp colonized by the Swamp Paper Bark (Melaleuca spp.) and other amphibious species. Part of migrating Outer Barrier just visible in background.

5.1E Swamp Paper Bark trees near Delicate Nobby. Bracken in foreground on sand.

Plates 5.1A - 5.1E

A



B



C



D



E



Plates 5.2J - 5.2'0'

5.2J View looking south from headland overlooking the northern end of Pambula barrier spit. Dotted line shows part of spit which almost encloses the entrance to Merimbula Lake.

5.2K View of northern end of Eden barrier spit, looking south. Curalo Lake on western side of barrier.

5.2L Curalo Lake. View looking north with Eden barrier spit to the east.

5.2M Vegetated shoreline of Curalo Lake.

5.2N Northern end of Eden barrier spit. View looking north towards bedrock coastline. Note stabilization by sand-binding plants, including Spinifex hirsutus.

5.2'0' View looking north from headland at southern end of Eden Barrier spit. Curalo Lake (C) enclosed by Eden barrier (X).

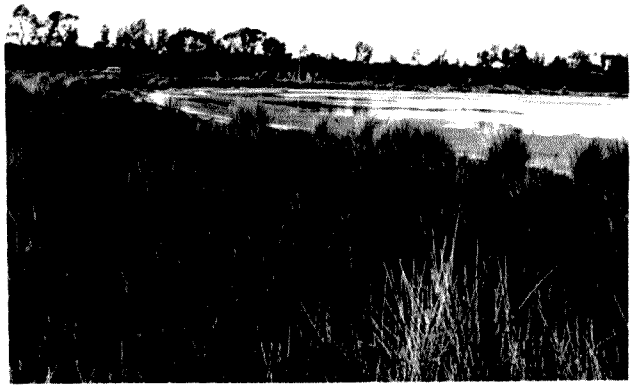
K



L



M





N

J





O

Plates 5.3A - 5.3B

5.3A View of one of the zeta-curved bays on the Mid-North Coast, looking towards Point Plomer.

5.3B Sedimentary jetty extending into a coastal lagoon, south coast.

A



B



CHAPTER 6

THE GEOMORPHOLOGICAL HISTORY OF THE FLUVIAL-DELTAIC PLAINS ON THE MID-NORTH COAST OF NEW SOUTH WALES

Introduction: There are no deltas seaward of the modern shoreline in northern New South Wales. Instead, fluvial-deltaic plains have been constructed between an ancient bedrock coastline and the barrier systems.

The Macleay and Maria-Wilson fluvial-deltaic plains on the Mid-North Coast are separated by a somewhat sinuous bedrock 'promontory', and a narrow swamp flat which lies between an ancient bedrock coastline and the Inner Barrier behind Crescent Head. The writer has used the term Inner Barrier swamp flat to denote this tract of swamp which stands about 3 feet above mean sea level, and which is the drainage divide between Belmore Swamp and the headwaters of Connection Creek that drains into the ocean by way of the Maria-Wilson drainage system (Figure 3.4 and 3.14). The term drainage divide is rather tenuous since floodwaters from the Maria-Wilson-Hastings catchment are known, on occasion, to flow into Belmore Swamp and the lower Macleay Valley.

Apart from reconnaissance of the Mid-North Coast by Voisey (1934a) and a brief account of the geomorphological history of the Macleay fluvial-deltaic plain by the writer (Hails, 1965a), no previous work has been reported in the literature. The writer's intention here is to describe briefly the morphological characteristics of the fluvial-deltaic plains, and to outline their history in relation to changes of sea level. The stratigraphy has been determined from the records of more than 100 deep and shallow borings made by various New South Wales State departments, commercial organizations, and the writer. Some of the borehole locations are shown in Figures 6.1 and 3.3, and some sub-surface profiles are shown

in Figures 6.2 and 6.3

Macleay Fluvial-Deltaic Plain: The Macleay is the second largest river on the north coast of New South Wales, and its drainage basin covers an area exceeding 4000 square miles. Downstream from Kempsey, the Macleay alluvial flood plain merges with a fluvial-deltaic plain characterized by well-defined relict meander belts, point bar deposits, meander scrolls and backswamps (or floodbains), (Figure 3.4; Plate 6.2). The fluvial-deltaic plain, which covers an area of some 250 square miles, extends inland from the coast for a maximum distance of about 10 miles and stands less than 10 feet above present sea level. Except for the natural levees and swamps, dumpey level surveys show that the fluvial-deltaic plain is almost uniformly level and seldom varies in height by more than 1 or 2 feet. It is drained by the Macleay River (tidal to Aldavilla above Kempsey), the Belmore River, and Kinchela, Christmas and Clybucca Creeks which are also tidal. The Clybucca, Belmore and Kinchela swamps cover an estimated 40 per cent of the fluvial-deltaic plain area and seldom rise more than 3 or 4 feet above mean sea level; in fact, some parts of these swamps are slightly below sea level.

Natural levees, composed essentially of silt and clay deposited by floodwaters, border the Macleay River and its two main tributaries, Belmore River and Kinchela Creek. The levee banks along the Macleay River near Kempsey stand less than 20 feet above mean sea level and gradually decrease in height, width and thickness in a downstream direction. Those flanking Belmore River and Kinchela Creek only rise to a maximum height of 8 feet above the adjacent backswamp depressions.

Widely and closely-spaced borings indicate that the Macleay fluvial-deltaic plain, for the most part, consists of a fairly thin covering of aluvial sediments overlying an interbedded sequence of fossiliferous estuarine sands, silts and clays (Figure 6.2), no more than 3-4 feet below present sea level LWM. The borehole data indicate that there is a distinct boundary between the fluvial and estuarine sediments and so far there is no evidence of interfingering laterally.

According to Voisey (1934a), a borehole sunk near Smithtown penetrated estuarine sands and clays, interbedded with shell-beds at 30, 50 and 70 feet, until bedrock was reached. The shell beds mainly contained Spisula trigonella and Arca (Anadara) trapezia, two molluscs that are common in estuaries on the east Australian coast today.

Shells of Spisula trigonella and Anadara trapezia (Deshayes) have also been collected by the writer and Langford-Smith from an estuarine mud flat shell-bed, about 4 feet below present sea level LWM, in the Clybucca Creek-Andersons inlet area of the Macleay fluvial-deltaic plain (Figure 3.4). Notospisula parva producta (Angas)and Crassostrea commercialis (Iredale and Roughly) were also found in the same shell-bed, and other shells that have been identified are listed in Table 6.1. According to Dr. D. F. McMichael (personal communication) who identified the shells, Anadara trapezia and Notospisula live in the inter-tidal zone, but there is the possibility that they could live in very shallow water, perhaps to depts of 5-10 feet below low tide-level. The exception is Crassostrea commercialis, the rock oyster, which is confined to the inter-tidal zone. The oyster shells may have been transported into subtidal areas, or they may have accumulated on an exposed mudflat in

the past as 'dead' shells. The shells have been dated at $4220^{+}_{-}90$ years B.P. and the significance of this age will be discussed shortly.

Some rounded boulders, encrusted with barnacles, were recovered from a depth of 55-60 feet below the north bank of the Macleay River near Kempsey during boring operations, prior to the sinking of new supports for the railway bridge over the river. The barnacles were studied in detail for the writer by Miss E. Pope of the Australian Museum in Sydney who found them to be related to Balanus (Balanus) amphitrite (amphitrite)- a modern fouling species of barnacle common throughout the warmer seas of the Indian and Pacific Oceans - which may be found in river mouths or harbours where the salinity content of the water is slightly less than that of the open sea. This evidence is a strong indication that an estuary formerly extended at least as far as Kempsey, which is now 9 miles from the Ocean. The borehole data studied by the writer show that bedrock is between 70 and 80 feet below mean sea level in the Kempsey area.

According to borings made by the Department of Lands, New South Wales, cemented fluvial sands and gravels (denoted 'river drift' in Figure 6.2) have been located between 80 and 108 feet below present sea level (Boreholes 5 and 8, Figure 6.2), and decayed timber has been found at 98 feet below the same datum, but no oxidized deposits, indicative of subaerial weathering, have been traced in any of the boreholes.

Inner Barrier Swamp Flat: Boreholes sunk by the writer in this area show that hydromorphic soils (gleys) no more than 4-8 feet thick in places, overlie estuarine sands and clays that contain comminuted shells. Again the borings did not penetrate any oxidized deposits. In many places, dark organic clays grade downward into mottled plastic clays. For example,

at boreholes 14 and 15 (Figure 3.3) near the ancient bedrock coastline, the southern part of Belmore Swamp is underlain by mottled grey clay and yellow catclay. These clays were also traced over quite a wide area of the Macleay fluvial-deltaic plain and underlie the Upper Kinchela and Clybucca swamps as well. According to Walker (1963), the catclay is produced by the aeration of sulphide-rich estuarine clay. Since only a thin veneer of either brown alluvial clay or swamp sediments overlies the estuarine clays on the Mid-North Coast, the latter are sufficiently near the surface to be aerated during dry seasons and to produce highly acidic soils when the water table falls to a low level (Walker, op. cit.; Figure 6.4). The writer found that some parts of Belmore Swamp are also underlain by leached semi-indurated sands, but no humate was encountered.

In contrast, black swamp soils, about 1 foot thick, and a tough, plastic white (slightly weathered) clay were encountered at boreholes 1-4 (Figure 3.3) to the south of Connection Creek. The actual thickness of the clay could not be determined in this area because the water table was no more than about 3 feet below the level of the ground.

Maria-Wilson Fluvial-Deltaic Plain: The Maria-Wilson fluvial-deltaic plain covers an area of some 120 square miles. It is drained by the Maria and Wilson Rivers, and their tributaries, and stands at approximately the same height above sea level as the Macleay fluvial-deltaic plain. The tidal limit of the rivers extends inland as far as the ancient Pleistocene bedrock coastline shown in Figure 3.14.

Borings show that there is a similar stratigraphical sequence to that of the Macleay fluvial-deltaic plain. Generally, the fluvial sediments

are less than 6 feet in thickness, but near the confluence of Pipers Creek and the Maria River fossiliferous estuarine sands and clays are only 3 feet below the surface at boreholes 1, 2 and 3 (Figure 3.7). Unbroken shells of Holocene age (Dr. D. F. McMichael, personal communication) have been recovered by the writer from various boreholes.

The well-defined abandoned drainage channels shown in Plates 3.4A and 3.4B, one of which is marked (C) in Figure 3.7), are of particular interest. These are only occupied by ephemeral streams when most of the surrounding area is flooded. Many of these channels are flanked by very low, narrow levees which are shown by borings to be underlain by estuarine sands containing comminuted shells.

The writer has found that the natural levees bordering the Maria River are not as well-defined as those along the distributaries of the Macleay River, possibly because less sediment is carried in suspension during floods. However, other possibilities will be evaluated in the section dealing with the origin of the deltaic plains.

Analyses of Borehole Samples: Samples for chemical and mechanical analyses were collected during dry weather and the drought of 1964-65 because the lower parts of the fluvial-deltaic plains adjacent to the larger swamps, and the Inner Barrier swamp flat, are often flooded, particularly after exceptionally heavy rain. During the drought several of the lagoonal-swamps on the Mid-North Coast were almost completely drained for the first time in many years and this enabled the writer to make deeper borings, particularly on the Inner Barrier swamp flat and in Belmore Swamp.

Generally, analyses have been made of samples collected within 7 feet of the surface from various parts of the fluvial-deltaic plains and

the Inner Barrier swamp flat. The methods used in the laboratory by the writer are described briefly in Appendix 6.1. The results of some of the analyses, together with borehole locations, are listed in Tables 6.2-6.8, and these will be discussed here.

Tables 6.2 and 6.3 show that the sediments of the Inner Barrier swamp flat and the two fluvial-deltaic plains range from clays to coarse sands, but the grain-size characteristics of individual samples vary according to the location of the boreholes. In general, clays and silts are by far the most abundant sediments (constituting between 54 and 81 per cent of the total content) in the centre of the Inner Barrier swamp flat and near the bedrock coastline (Table 6.2). However, there is a noticable increase in the percentage concentration of coarse sand towards the Inner Barrier, and this can probably be attributed to the accumulation of eolian material. For example, samples 6A and 8A (Table 6.2) contain more than 76 and 85 per cent of coarse sand respectively. Generally, fine-grained sand makes up less than 5 per cent of the total sand content of these two samples.

A perusal of Table 6.3 reveals some marked differences in the composition of the samples collected from the two fluvial-deltaic plains; these differences were also noted in other samples not listed in the table. Firstly, silt and clay comprise between 12 and 67 per cent of the Maria-Wilson fluvial-deltaic plain sediments (with an average value of 40 per cent) whereas they constitute between 53 and 90 per cent (with an average value of 68 per cent) of the Macleay fluvial-deltaic plain sediments. Secondly, coarse sand is quite abundant on the Maria-Wilson fluvial-deltaic plain, averaging 40 per cent, with a percentage concentration between 11 and 66 per cent in individual samples. But on average, coarse sand

generally makes up less than 8 per cent of individual Macleay fluvial-deltaic plain samples, with a range between $2\frac{1}{2}$ and 25 per cent.

The roundness values listed in Tables 6.4 and 6.5 show that the coarse-grained sands are generally slightly more rounded than the fine-grained sands, but there is a close correspondence between the values of the Inner Barrier flat and fluvial-deltaic plain sands. In general, though, the values are lower than those of the barrier and dune sands (see values in the tables, and the distribution plot in Figure 7.6). The significance of roundness analysis will be evaluated in Chapter 7.

The ratio of carbon to nitrogen (C/N ratio), pH value, chloride composition and total water soluble salt content were determined for each sample analyzed. The organic carbon content was obtained by Tinsley's method and the total nitrogen content by the Kjeldahl method (see Appendix 6.1). The average C/N ratio of the Inner Barrier swamp flat samples is 28:1 and this indicates that the over-all amount of organic matter is quite high.

There are again marked variations in the amount of organic matter, as shown by the C/N ratios of samples collected from boreholes 1-4 (see Figure 3.3 for locations) which vary from 5:1 to 37:1. The anomalously high 98:1 ratio in Table 6.6 is considered to be erroneous. The variation in the C/N ratios may indicate that different types of organic matter accumulated. Certainly the high values reflect abundant terrestrial plant debris which is fairly consistent with the pH values of the soil solutions of the samples.

All the Inner Barrier swamp flat soils show low pH values (3.1 to 4.8; and an average value of 4.2) which are indicative of acid conditions associated with the bacterial decay of organic matter. This is well

demonstrated also by the pungent smell of hydrogen sulphide in some of the boreholes. None of the soils contains carbonate to buffer the low pH values. The pH values of water table samples range from 2.8 to 5.4, but two samples from borehole 5 (Table 6.6) gave readings of 6.1 and 7.1 respectively.

The chloride values vary considerably and Table 6.6 shows that there is no correlation between the values obtained for soil and water table samples. In fact, the highest values have been recorded for the soils. Variations in rainfall, seasonal temperatures and seasonal tide levels can modify the chlorinity. Changes in value resulting from any of these factors are more likely to be detected in water table samples than in soil samples. However, any conclusions that might be drawn from the results reported here must be tentative since the results probably reflect the conditions existing at the time the samples were collected. Table 6.6 also shows that the soluble chloride values change at different depths within the same borehole and there is some trend towards slightly higher values with depth in a few boreholes.

The C/N ratios of fluvial-deltaic samples range from 10:1 to 55:1 (average value of 26:1) again indicating a high content of terrestrial organic matter, at least in the first few feet of the sediments, and it is interesting to record that the pH values which range from 3.2 to 4.7 (average value of 4.2) are almost identical with those of the Inner Barrier swamp flat samples. The soluble chloride values listed in Table 6.7 again show marked variations, but there is no trend towards higher values with depth.

Vegetation of the Inner Barrier Swamp Flat and Fluvial-Deltaic Plain Swamps: The swamp terrain, per se, is colonized by amphibious species, but on slightly higher ground near the ancient bedrock coastline swamp oaks (Casuarina glauca),

swamp mahogany (E. robusta) and tea-tree (Melaleuca spp., but chiefly M. viridiflora) fringe the swamps (Plate 5.1B and 5.1C). Some parts of the Inner Barrier swamp flat have been cleared and the better drained areas used for cattle grazing. Near Crescent Head, ambitious attempts have even been made to artificially drain the slightly higher ground in an attempt to grow hardy cereals, but the analyses reported here suggest that such attempts will be fruitless.

The Origin and Development of the Fluvial-Deltaic Plains

It is now possible, from the preceding evidence, to outline the geomorphological history of the fluvial-deltaic plains on the Mid-North Coast during late Quaternary time, but obviously there are still many questions that cannot be answered until further evidence comes to light. The Late Pleistocene and Early Holocene courses of the Mid-North rivers may be the subject of speculation for several years, owing to the type of boring equipment that is needed to obtain the necessary detailed information. The writer has considered several possibilities pertaining to this subject, on the limited evidence available at present, and these will be mentioned in this section.

Relative changes of sea level and rates of deposition have been instrumental in the construction of the fluvial-deltaic plains on the Mid-North Coast. Probably a large estuary was initiated in the area now occupied by the two fluvial-deltaic plains when the Inner Barrier was built during a late Pleistocene higher sea level. It is impossible to say whether or not terrigenous sediments were deposited in the estuary at that time since there has been no trace of Pleistocene lagoonal or estuarine sediments in the boreholes sunk so far. In addition, there are

no stranded Pleistocene lagoonal-estuarine sediments above present sea level HWM on the Mid-North Coast.

If an estuary existed it was probably drained during the maximum late-Wisconsinan low stand of sea level between about 20,000 and 17,000 B. P. (Curray, 1965). As a result of this change in sea level, the Mid-North Coast rivers must have had increased gradients, and consequently greater energy, as they extended and incised their courses across the emerged steeply sloping continental shelf. The absence of Pleistocene sediments may well imply that former deltaic or neritic sediments between the Inner Barrier and the ancient bedrock coastline were deeply weathered and ultimately eroded. It is also possible that regressive sediments were eroded by coastal streams adjusting to new base levels, as the sea fell in the past. Alternatively, sediments that managed to survive erosion and subaerial weathering may have been buried subsequently beneath Holocene deposits. If the latter suggestion is correct, the borings made on the modern fluvial-deltaic plains have not been deep enough to penetrate relict Pleistocene deposits. No oxidized sediments have been located so far to indicate that subaerial weathering actually occurred during lower stands of the sea.

The exact nature of the sub-surface bedrock topography on the Mid-North Coast is still unknown. However, if the borehole data are accurate, the cemented fluvial deposits found between 80 and 108 feet below present sea level may pertain to an old channel of the Macleay River which existed during late Wisconsinan time. The possibility of incised valleys extending across the continental shelf at this time has been mentioned already in Chapter 3.

Approximately at, or possibly shortly after the time the Outer Barrier was established, and the inter-barrier lagoons came into existence, the area now occupied by the fluvial-deltaic plains was invaded by the sea and virtually became a semi-enclosed embayment or estuary (see Figure 3.7 and 3.14). The area now occupied by the Inner Barrier swamp flat was the narrowest part of this estuary.

It appears that the infilling of the estuary in the past was completed by deltaic sedimentation and by alluviation along the river channels - the deposition of traction and suspended loads. As the borings indicate, sedimentation occurred in relatively shallow water. Overbank deposition has played an important role in the construction of the fluvial-deltaic plains on the Mid-North Coast. Fisk (1947), and Wolman and Leopold (1957) have shown that vertical accretion deposits cannot be formed without suspended material in the overbank flow. Fisk referred to certain Mississippi tributaries which lacked well-developed levees and which carried small suspended loads. Wolman and Leopold observed that many streams show a maximum concentration of suspended load at stages well below the bankfull, and not at the flood stage. This has not been the case on the Mid-North Coast because of the reasonably well-developed levees along the larger rivers and their main distributaries.

The Macleay County Council have classified floods on the Macleay River into four categories of which 'major' floods are the most disastrous. Based on a statistical study of records compiled for the period 1931-1959, the possibility of a 'major' flood occurring in the Macleay valley is once in 20 years, although the fluvial-deltaic plains are flooded almost

annually. After the 'major' flood of 1963 large quantities of silt and clay were deposited over a large area of the fluvial-deltaic plain. During major floods the Macleay River carries some of its sediment load to Trial Bay. Evidence of this can be seen on aerial photographs, taken after floods, which show large areas of turbid water continuing offshore from the river mouth. However, mechanical analyses have shown that samples from the Macleay valley are composed of a higher percentage of silt and clay than those from the Maria-Wilson fluvial-deltaic plain.

Since natural events are not always systematic and regular it is possible that there were periods of low and high rate deposition during the building of the fluvial-deltaic plains. From the avilable evidence on other sectors of the New South Wales coast, including the south coast study area, the rate of supply of terrigenous sediments to the modern estuarine lagoons depends upon several interdependent factors which cannot necessarily be evaluated separately. These include the regional geology, particularly the resistance of rocks to weathering and erosion, regional stability, changes in the local climate, especially variability in rainfall, eustatic changes of sea level; and the size of the river catchments.

There is still some disagreement on the actual rate of sea level rise during the past 5000 years, by which time most of the estuaries on the coast had come into existence. However, there is substantial evidence from several widely scattered regions of the world to suggest that the sea has risen to its present level at a rate not exceeding approximately 1 foot every 200 years since about 2600 years ago (Shepard, 1964). Taking into consideration the evidence of the borings and of the surface elevation

of the Mid-North Coast fluvial-deltaic plains it appears that there has been a fairly consistent balance between progradation and sea level rise, especially if the same general rate reported for other parts of the world is applicable to Australia. Obviously, any estimate of the rate of deposition and rate of sea level rise must take into consideration the problem of coastal stability and this will be examined in Chapter 9.

No evaluation of the origin of the fluvial-deltaic plains would be complete without reference to the possibilities of climatic change during the past 5000 years, not so much because of the disagreement about higher sea levels associated with a postglacial thermal maximum about 4000-6000 years B. P. (Gill, 1955), but because of the likelihood of a pluvial (or several) period(s). Langford-Smith and Hails (1966) have tentatively suggested, from evidence of preliminary surveys, that the fluvial-deltaic plains on the north coast of New South Wales are markedly over-fit in relation to the present rivers, but quantitative work is necessary to verify these views. The well-preserved abandoned drainage channels shown in Plate 3.4A could be the surviving traces of prior streams pertaining to the Maria River-Connection Creek drainage system which appears to have formerly covered a much larger area than the present system.

An increase in runoff and higher sediment yields from the adjacent landmass could be invoked if the climate has been wetter at sometime during the past 5000 years. The composition of the fluvial-deltaic plain sediments indicates that the former estuary was mainly filled with fluvial sediments.

The age of the fluvial-deltaic sediments is partly demonstrated by their fossil content, and radiocarbon dates of various peat samples from adjacent areas (Chapter 9). The radiocarbon date of the shells from the Clybucca Creek-Andersons inlet area could be significant provided the molluscs were in situ, and contamination has not drastically affected the actual age of the shells. Driftwood collected by Langford-Smith and Hails from the lower horizon of a deep alluvial fill near Little Cooperabung (just south of the confluence of Pipers Creek and the Maria River) on the Maria-Wilson fluvial-deltaic plain has been dated at $8240^{+}_{-}140$ years B.P. (see Australian Quaternary strandline report, ed. E.D. Gill, 1966). It seems likely that the driftwood is much older than the sediments that buried it. Thus, the evidence reported in this chapter points strongly to the fact that the Mid-North Coast fluvial-deltaic plains were constructed as the rate of sea level rise slowed down considerably during the past 5000 years.

The absence of peat beds from the sequence of estuarine sediments beneath the alluvial cover indicates uinterrupted sedimentation and the fairly rapid infilling of a former estuary. The size of the fluvial-deltaic plains is undoubtedly related to the high sediment yields from the large catchments of the Mid-North Coast rivers, but the influence of man as a geomorphological process in promoting erosion (and indirectly higher sediment yields downstream) in the valleys cannot be ignored. How much material is removed from the valley slopes upstream from the deltaic plains by clearing and burning the natural vegetation may never be known unless some systematic study is made. Nevertheless, the importance of human interference in affecting natural processes must not be under-estimated.

It seems likely that Belmore, Kinchela and Clybucca swamps now occupy the sites of former estuarine-lagoons. The factors involved in bringing about the initiation of the Belmore-Kinchela lagoon are not fully known, but it seems probable that a large body of water was enclosed between the Inner Barrier, and the fluvial-deltaic plain as it prograded seaward. A detailed examination of aerial photographs has revealed what may well be relict lagoon ridges, now buried beneath a thin veneer of paludal sediments but still prominent enough for their topographic characteristics to be detected from the air. It can be seen in Plates 3.5A and 3.5D that these are visible at the southern end of Belmore swamp near the ancient bedrock coastline (see also Figure 3.4) and on the edge of the same swamp where it abuts the levee of Belmore River almost immediately opposite the headwaters of Kinchela Creek.

It would seem to appear from this evidence that winds in the past were effective over a sufficiently long fetch to generate waves in the lagoon. According to Price (1947), enclosed tidal basins (coastal lagoons) maintain width-depth ratios - that is, the greater the average width of a lagoon, the greater its depth. Also, the width of a lagoon determines the fetch, which in turn is directly proportional to wave depth and determines the depth of effective wave scour. If Price's thesis is correct, there is a limit to the size of lagoons dependent upon their depth. Wave scour and the removal of sediment from the floor of a lagoon can increase its depth. This process may well have operated in the Belmore-Kinchela lagoon in the past. Although some material may have been removed through the tidal channels of Belmore River and Kinchela Creek, it is also seems likely that some may have been piled up in low

ridges around the edge of the lagoon in a few places.

The few shallow bores that the writer was able to make failed to contact any ridges in the areas where, according to aerial photographs, they might occur. Therefore their existence has yet to be proved. If for the sake of argument it is assumed that the ridges exist, the natural levees along the Belmore River were probably built long before the ridges were piled up on the edge of the proto-Belmore-Kinchela lagoon, otherwise it is likely that the ridges would have been completely buried by alluvial sediments. Certainly Kinchela Creek does not appear to have been large enough in the past to have reduced the area of open water over which winds were effective. On the other hand, the ridges at the southern end of Belmore Swamp may have been built before the fluvial-deltaic plain had prograded very far beyond the bedrock coastline in that area.

Eventually ecological conditions favoured the growth of reedswamp and the encroachment of swamp land in the Belmore-Kinchela lagoon. Borings show that only a very thin cover of swamp sediments overlies the estuarine sands and clays. By inference, it can be said that Clybucca swamp originated in a similar way. However, relict ridges have not been noted along the edge of this swamp.

The writer disagrees with Voisey (1934a) who suggested that deposition in the lower Macleay valley was supplemented by uplift which caused much of the swampy land to be drained. The detailed surveys made by the writer show that parts of the swamps are at, and below, mean sea level. However, one can still speculate about the origin of Belmore River and Kinchela Creek. They may be narrow distributaries of a former prograding delta,

or open-ended channels in a former estuary which were sufficiently large not to be dammed off completely by the Macleay River channel.

Finally, in dealing with the geomorphological history of the deltaic plains a brief word is apposite about the possible courses of a proto-Macleay which are shown in Figure 3.4, Because the reconstruction of former drainage channels has been based on limited surface morphology, and on the evidence of shallow borings, it must inevitably be tentative until additional information is available to remove some of the present obscurities. It seems likely that Saltwater inlet may be a remnant channel of the Macleay which formerly followed a course slightly to the west of Little and Big Smoky headland to enter Trial Bay near Laggers Point. The writer mapped a large depression, trending NNE-SSW (course 2), in this area, and it is significant to record that such a course could have dissected the barrier, referred to earlier, which trends approximately NE-SW. Course 2 shows an alternative outlet near Point Briner. There is, however, conclusive evidence of course 3 which was in existence before the 'old course' of the Macleay River was established.

TABLE 6.1

Molluscs identified from estuarine mud flat shell-bed, about 4 feet below present sea level LWM. (Identification kindly made by Dr. D. F. McMichael of the Australian Museum, Sydney).

1. Anadara trapezia (Deshayes) (=Arca trapezia Deshayes)
2. Notospisula parva producta (Angas)
3. Tapes watlingi (Iredale) (= Tapes turgida olim, now to the Western Australian shell)
4. Crassostrea commercialis (Iredale and Roughly)
5. Notovola fumata (Reeve) (= Pecten fumata Reeve)
6. Meropesta meridiana (Iredale)
7. Fallartemis sculpta (Hanley)
8. Velacumantus australis (Quoy and Gaimard)
9. Glossaulax aulacoglossa (Pilsbry and Vanatta)
10. Conuber conicum (Lamarck).

TABLE 6.2

Composition of samples collected from boreholes sunk on the Inner Barrier swamp flat.

Figure Number	Borehole Number	Location	Percentage Clay	Silt	Fine Sand	Coarse Sand	Depth of Sample
3.3	1	South of Connection Creek	25.25	29.25	26.68	18.82	2-ft.
3.3	1	"	44.00	18.08	19.92	18.00	3-ft.
3.3	1	"	55.25	12.84	14.95	16.95	4-ft.
3.3	2	"	51.53	12.08	10.23	26.16	1-ft.
3.3	2	"	20.50	6.75	14.60	58.15	1-6"
3.3	3	"	39.50	16.00	16.45	28.05	1-ft.
3.3	4	"	41.66	17.65	16.54	24.15	1-ft.
3.3	4	"	57.18	24.25	13.21	5.36	2-ft.
-	4A	85 yards west of number 4	56.66	16.18	22.41	4.75	3-ft.
-	4A	"	47.83	10.93	38.38	2.86	3-6"
-	5	200 yards west of number 4	47.33	17.84	18.26	16.57	3-ft.
3.3	15	Near bedrock coastline Belmore swamp	51.66	19.50	22.56	6.28	0-9"
3.3	15	"	59.00	18.08	15.16	7.76	1-6"
-	8A	Behind Inner Barrier (B.H. No. 8) Crescent Head (Figure 3.3)	9.33	5.00	5.00	80.67	3-ft.
-	8A	"	10.50	1.33	2.85	85.32	3-6"
-	6A	Behind Inner Barrier (B.H. No. 6) Crescent Head Figure 3.3)	17.33	2.83	3.56	76.28	2-ft.

TABLE 6.3

Composition of samples collected from boreholes sunk on the two fluvial-deltaic plains.

Figure Number	Borehole Number	Depth of Sample	Location	Percentage Clay	Silt	Fine Sand	Coarse Sand
3.2	-	1-ft.	Between boreholes 7 and 10 in Figure 3.2 on edge of levee bank	36.33	21.66	37.31	4.70
3.2	-	2-ft.	"	31.33	21.66	42.50	4.51
3.2	-	3-ft.	"	40.00	19.50	36.85	3.65
3.2	-	4-ft.	"	45.00	22.83	28.95	3.22
3.2	-	5-ft.	"	46.34	23.16	26.20	4.30
3.7	31	3-ft.	Maria River Bank	41.66	21.16	21.20	10.98
3.7	31	4-ft.	"	11.67	1.91	20.02	66.40
3.7	31	5-ft.	"	33.08	3.34	16.26	47.32
3.7	31	6-ft.	"	34.50	6.16	19.16	40.18
3.7	31	7-ft.	"	30.66	3.08	20.72	45.54
3.7	9	2-ft.	Edge of fluvial-deltaic plain opposite Fentons Is.	32.08	35.00	17.31	15.61
3.7	1	2-ft.	Confluence of Pipers Ck. and Maria River	23.58	10.66	8.42	57.34
6.1 and 6.2	18	2-ft.	Near triangle on Figure 6.1	44.75	45.25	7.50	2.50
6.1 and 6.2	18	3-ft.	Near triangle on Figure 6.1	31.66	52.58	12.60	3.16
3.2	7	22-ft.	Macleay fluvial-deltaic plain	56.33	13.16	10.66	19.85
3.2	6	25-ft.	West of No. 7	50.00	10.84	14.16	25.00

TABLE 6.4

Roundness values (Powers' scale x 100) of fine- and coarse-grained sands from the Inner Barrier swamp flat; and heavy mineral percentage of the fine-grained sands. Borehole locations are listed in Table 6.2

Figure Number	Borehole Number	Depth of Sample	Fine Sand Value	Coarse Sand Value	Heavy Mineral Percentage
3.3	1	2-ft.	27.20	31.28	0.1
3.3	1	3-ft.	29.80	27.58	
3.3	1	4-ft.	32.70	28.33	
3.3	2	1-ft.	32.80		< 0.1
3.3	2	1-6"	24.82	28.15	0.2
3.3	3	1-ft.	26.75		
3.3	4	1-ft.	38.00		
3.3	4	2-ft.	27.90		4.4
-	4A	3-ft.	23.60	26.92	
-	4A	3-6"	24.10	24.20	0.1
-	5	3-ft.			0.1
3.3	15	0-9"			1.4
3.3	15	1-6"	30.95	31.25	0.1

The method of roundness analysis is described in Chapter 7.
Blank spaces: samples not analyzed.

TABLE 6.5

Roundness values (Powers' scale x 100) of fine- and coarse-grained sand from the Macleay and Maria-Wilson fluvial-deltaic plains; and heavy mineral percentage of the fine-grained sands.
Borehole locations are listed in Table 6.3.

Figure Number	Borehole Number	Depth of Sample	Fine Sand Value	Coarse Sand Value	Heavy Mineral Percentage
3.7	31	3-ft.	26.25	35.28	0.2
3.7	31	4-ft.	29.64	32.88	0.2
3.7	31	5-ft.	28.07		2.0
3.7	31	6-ft.	29.95		2.0
3.7	31	7-ft.	25.20		0.1
6.1 and 6.2	18	2-ft.	29.90		0.2
6.1 and 6.2	18	3-ft.	33.05		0.1
3.7	9	2-ft.	26.52		0.1
3.7	1	2-ft.	24.55	27.90	0.1

Blank space: sample not analyzed.
Results listed in the above table should be compared with those in Table 6.4. Both tables show that the coarse-grained sands are generally slightly more rounded than the fine-grained sands.

TABLE 6.6

pH values, chloride composition, total water soluble salt content and the ratio of Carbon to Nitrogen (C/N ratio) - Inner Barrier swamp flat samples. (Laboratory methods and calculation procedures are listed in Appendix 6.1).

Borehole Locations - listed in Table 6.2			Specific Conductivity of 1:5 soil Suspension at 20° C	Specific Conductivity x 375	N/100 AgNo3 1ml. N/35.5 = ml.gm cl/gm. soil 20 gms. soil		1 ml. N dichromate =3mg. Carbon 25 mls. of 0.4N dichromate = x-ml. FeSO4	Mls. x 14/1000 =0.014		
Borehole Number	Figure Number	pH	Total Water Soluble Salts	Total Water Soluble Salts Per Cent	Soluble Chloride 20 gm	1 gm/cl.	Organic Carbon	Nitrogen	C/N Ratio	Depth
1	3.3	4.8	0.0000896	0.0336000	0.9940	0.0497	5.352	0.1442	37:1	2-ft.
1	3.3	4.5	0.0000433	0.0162375	0.46150	0.023075	0.824	0.0084	98:1	3-ft.
1	3.3	4.0	0.0000468	0.0175500	0.60350	0.030175	0.270	0.0112	ca. 24:1	4-ft.
2	3.3	4.8	0.0000992	0.037200	2.20100	0.11005	5.880	0.4788	ca. 12:1	1-ft.
2	3.3	4.8	0.0000541	0.020250	1.100	0.055	0.564	0.0364	ca. 15:1	1-6"
3	3.3	4.3	0.000433	0.162375	60.350	3.0175	4.7760	0.1352	ca. 36:1	1-ft.
4	3.3	4.4	0.000630	0.236250	230.750	11.5375	1.447	0.4326	ca. 33:1	1-ft.
4	3.3	4.2	0.000387	0.145125	10.8874	0.5413	1.254	0.0952	ca. 13:1	2-ft.
4A		3.1	0.000734	0.275250	280.450	14.225	0.952	0.0238	ca. 23:1	3-ft.
4A		3.1	0.00080	0.30000	280.450	14.225	0.204	0.0392	ca. 5:1	3-6"
5		3.9	0.000147	0.055125	2.0945	0.1047	5.8520	0.3780	ca. 15:1	3-ft.
15	3.3	4.1	0.0000809	0.0303375	1.029	0.0514	5.064	0.0294	ca.172:1?	0-9"
15	3.3	3.9	0.0000968	0.0363000	2.37850	0.11890	0.950	0.0994	ca. 9:1	1-6"
2	3.3	4.8	0.0002339	0.0877125	2.485	0.1245				ca. 1-6"
2	3.3	5.4	0.0002147	0.0805125	2.485	0.1246				ca. 1-6"
3	3.3	3.6	0.002094	0.785250	55.025	2.751				ca. 1-0"
3	3.3	3.7	0.002094	0.785250	28.400	1.42				ca. 1-0"
4	3.3	2.8	0.002991	1.121625	39.050	1.952				ca. 2-3"
4	3.3	2.8	0.002991	1.121625	41.890	2.094				ca. 2-3"
5		6.1	0.0001886	0.0707250	1.065	0.05325				4-0"
5		7.1	0.0001877	0.0703875	1.065	0.05325				4-0"

ca. = Approximate values / approximate depths.

TABLE 6.7

pH values, chloride composition, total water soluble salt content and the ratio of Carbon to Nitrogen (C/N ratio) - Macleay and Maria-Wilson fluvial-deltaic plain samples. (Laboratory methods and calculation procedures are listed in Appendix 6.1).

Borehole Locations listed in Table 6.3			Specific Conductivity of 1:5 soil Suspension at 20°C	Specific Conductivity x 375	N/100 AgNo3 1ml.N/35.5 = ml.gm cl/gm. soil 20 gms. soil		1ml. N dichromate =3mg. Carbon 25 mls. of 0.4N dichromate =x-ml. FeSO4	Mls x 14/1000 =0.014		
Borehole Number	Figure Number	pH	Total Water Soluble Salts	Total Water Soluble Salts Per Cent	Soluble Chloride 20gms.	1gm/cl.	Organic Carbon	Nitrogen	C/N Ratio	Depth
18	6.1 and 6.2	4.3	0.000118	0.44250	1.029	0.0514	1.236	0.1218	ca. 10.1	2-0"
18	6.1 and 6.2	4.0	0.000176	0.066000	2.556	0.1278	1.308	0.0252	ca. 55:1	3-0"
31	3.7	4.3	0.000337	0.126375	9.6560	0.4828	0.570	0.0252	ca. 22:1	3-0"
31	3.7	4.3	0.000418	0.0156750	0.8875	0.044375	0.258	0.0056	ca. 46:1	4-0"
31	3.7	4.2	0.0003950	0.148125	15.7975	0.7898	0.276	0.0210	ca. 13:1	5-0"
31	3.7	3.2	0.0032	1.200	128.9	6.44	0.354	0.0154	ca. 22:1	6-0"
31	3.7	4.7	0.001745	0.654375	70.290	3.5140	0.546	0.0364	ca. 15:1	7-0"
9	3.7	4.0	0.000273	0.102375	4.9345	0.2461	0.972	0.4312	ca. 2:1?	1-0"
1	3.7	4.5	0.00003717	0.01393875	0.3195	0.015975	1.272	0.742	ca. 17:1	1-0"

TABLE 6.8

Borehole Logs

Borehole No. 1 (Figure 3.3)

0 - 2-6 - Black loamy topsoil

2-6 - 3-6 - Weathered clay

3-6 - 6-0 - Clay (unbottomed).

Borehole No. 2 (Figure 3.3)

0 - 0-9 - Acidic swamp soil (peat surface)

0-9 - 1-6 - Sandy clay

1-6 - 3-6 - Clay becoming more plastic with depth.

Borehole No. 3 (Figure 3.3)

0 - 0-9 - Black acidic swamp soil

0-9 - 2-0 - Plastic white clay.

Borehole No. 4 (Figure 3.3)

0 - 1-0 - Topsoil

1-0 - 2-0 - weathered clay

2-0 - 3-0 - Clay becoming sandy.

Borehole No. 4A

0 - 2-0 - Thin veneer of topsoil overlying grey clay

2-0 - 3-0 - Grading into white clay

3-0 - 4-0 - White clay.

Borehole No. 5 (Figure 3.3)

0 - 1-0 - Topsoil

1-0 - 4-0 - Clay, slightly iron-stained, grading into white clay at 4 feet.

Borehole No. 8A (cf. No. 8, Figure 3.3)

0 - 4-0 - Dark organically-stained sand; grading into white sand at 4-6".

Depths in feet and inches.

Figure 6.1 The Macleay fluvial-deltaic plain and adjacent barriers, Mid-North Coast.

Black squares show the location of some of the boreholes sunk in the study area. Numbers refer to the sub-surface profiles shown in Figure 6.2.

Black areas show small lagoons which are the remnants of the original inter-barrier lagoons.

Figure 6.1

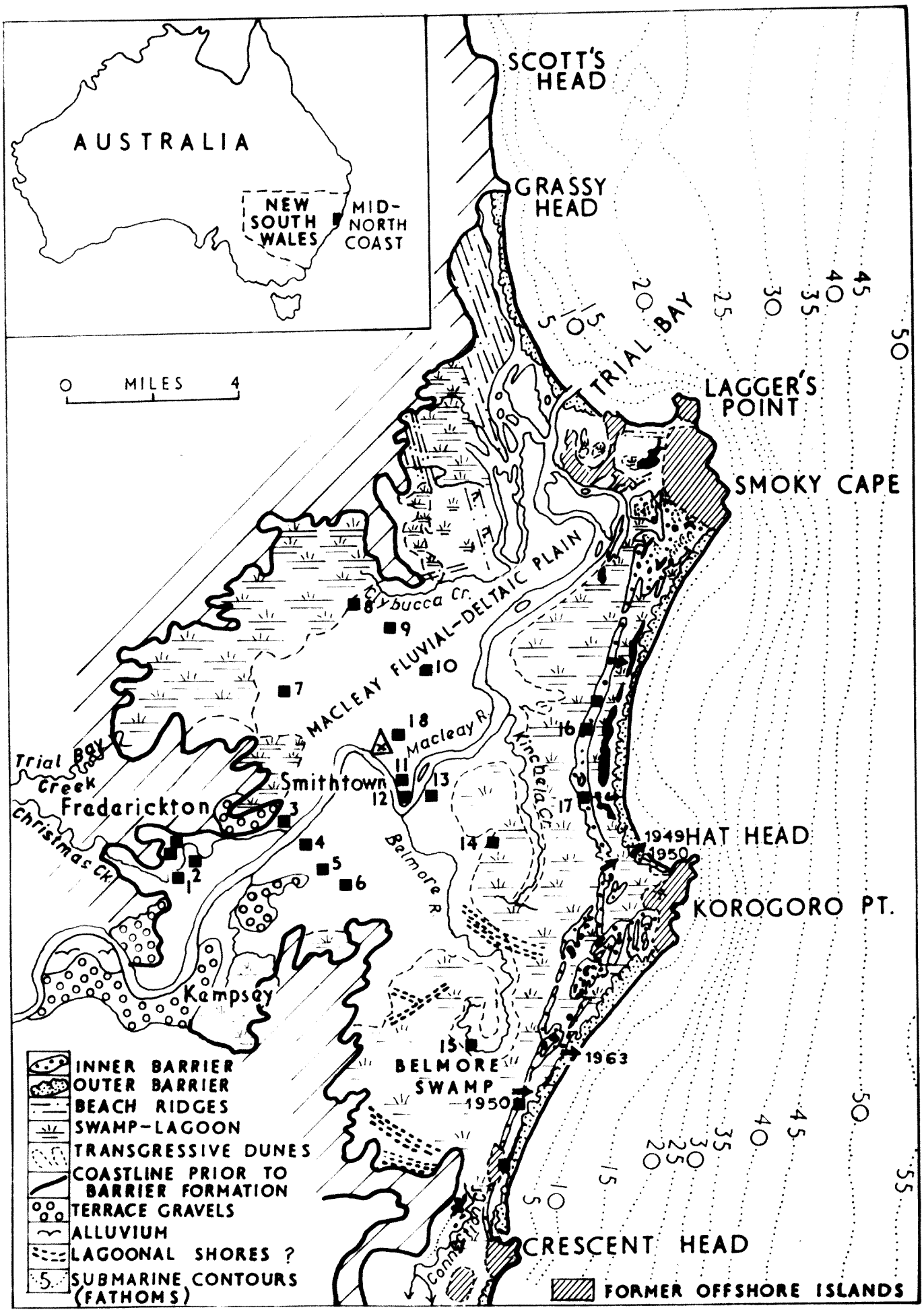

AUSTRALIA
NEW SOUTH WALES
MID-NORTH COAST
SCOTT'S HEAD
GRASSY HEAD
TRIAL BAY
LAGGER'S POINT
SMOKY CAPE
0 MILES 4
MACLEAY FLUVIAL-DELTAIC PLAIN
Ybucca Cr.
Macleay R.
Kinchela Cr.
Belmore R.
Trial Bay
Creek
Christmas Ck
Fredarickton
Smithtown
Kempsey
1949 HAT HEAD
1950
KOROGORO PT.
1963
BELMORE SWAMP
1950
CRESCENT HEAD
Connolly Ck
INNER BARRIER
OUTER BARRIER
BEACH RIDGES
SWAMP-LAGOON
TRANSGRESSIVE DUNES
COASTLINE PRIOR TO BARRIER FORMATION
TERRACE GRAVELS
ALLUVIUM
LAGOONAL SHORES ?
SUBMARINE CONTOURS (FATHOMS)
FORMER OFFSHORE ISLANDS

Figure 6.2 Sub-surface profiles at borehole locations shown in Figure 6.1.

Figure 6.2

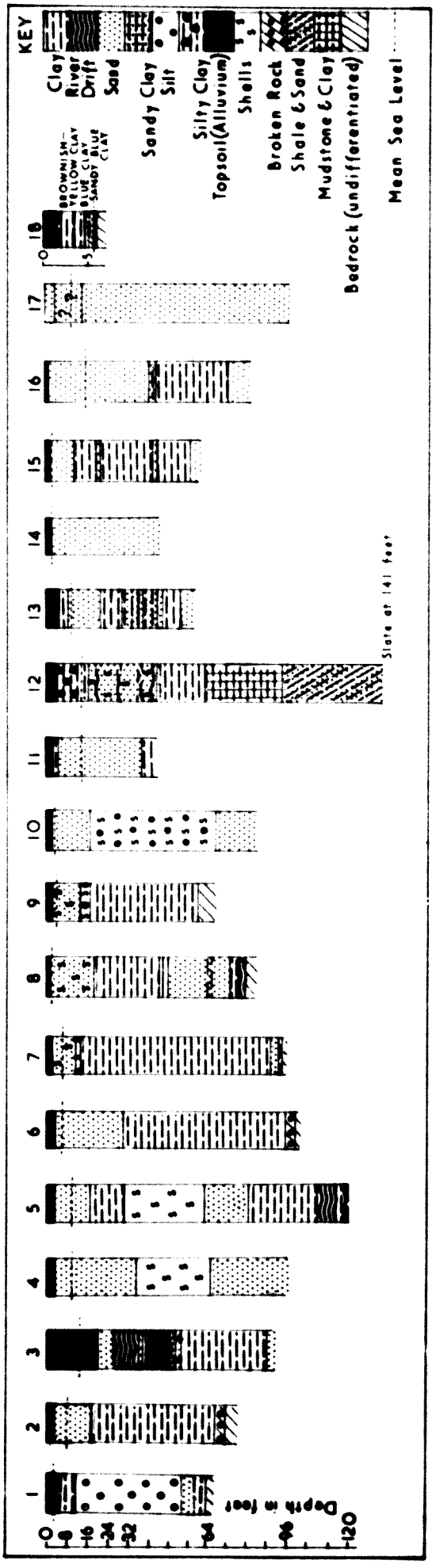

KEY
Clay
River Drift
Sand
Sandy Clay
Silt
Silty Clay
Topsoil(Alluvium)
Shells
Broken Rock
Shale & Sand
Mudstone & Clay
Bedrock (undifferentiated)
Mean Sea Level
BROWNISH-YELLOW CLAY
BLUE CLAY
SANDY BLUE CLAY
Depth in feet
0
40
80
120

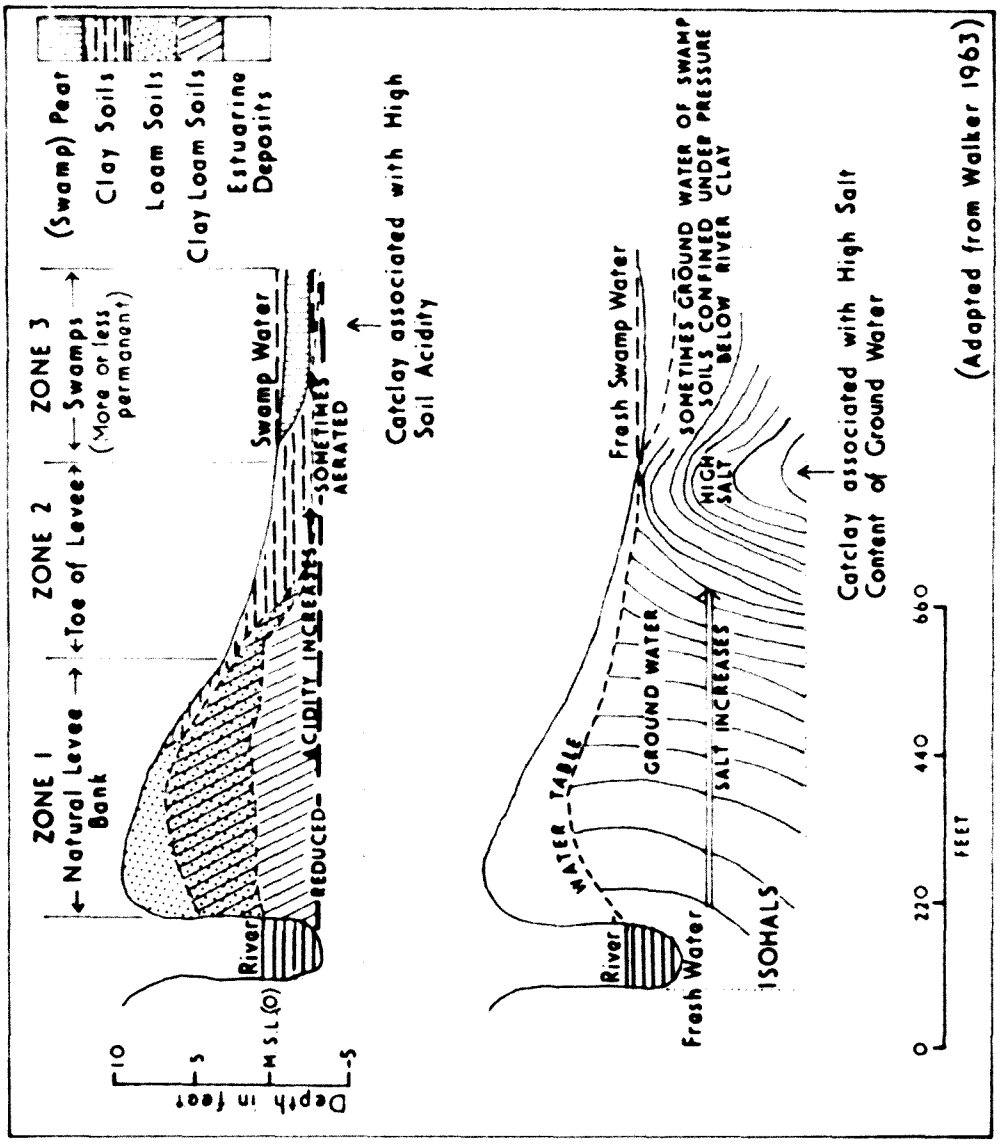
Figure 6.3 Sub-surface profiles of some boreholes shown in Figure 3.3.

Figure 6.3


17A
15A
14
Catclay
12
Marine Clay 57ft.
11
Sandstone 61ft.
9
Marine Clay 31ft.
8
Sand 41ft
6
Marine Clay 41ft.
4
3
2
1
Topsoil (Alluvium)
Clay
Sand
Sandy Clay
A1
A2
B
Humate
Podsol
Mean Sea Level
Depth in feet
0
-5
-10
-15
-20
-25
-30
-35
-40
-45
-50
-55
-60
-65
-70

Figure 6.4 Diagrammatic cross sections of Macleay River levee and backswamps, showing trends in acidity and salinity.

Figure 6.4


ZONE 1
Natural Levee
Bank
ZONE 2
Toe of Levee
ZONE 3
Swamps
(More or less permanent)
(Swamp) Peat
Clay Soils
Loam Soils
Clay Loam Soils
Estuarine Deposits
Swamp Water
SOMETIMES AERATED
REDUCED
ACIDITY INCREASES
River
M.S.L.(0)
Depth in feet
10
5
-5
Catclay associated with High Soil Acidity
Fresh Swamp Water
SOMETIMES GROUND WATER OF SWAMP SOILS CONFINED UNDER PRESSURE BELOW RIVER CLAY
HIGH SALT
WATER TABLE
GROUND WATER
SALT INCREASES
River
Fresh Water
ISOHALS
Catclay associated with High Salt Content of Ground Water
0
220
440
660
FEET
(Adapted from Walker 1963)

Plates 6.1A - 6.1F

6.1A View of the Macleay fluvial-deltaic plain from low, degraded cliffs of the ancient bedrock coastline, near Frederickton.

6.1B One of three isolated knolls that stand above the Macleay fluvial-deltaic plain near Smithtown. See triangle in Figure 6.1 for location.

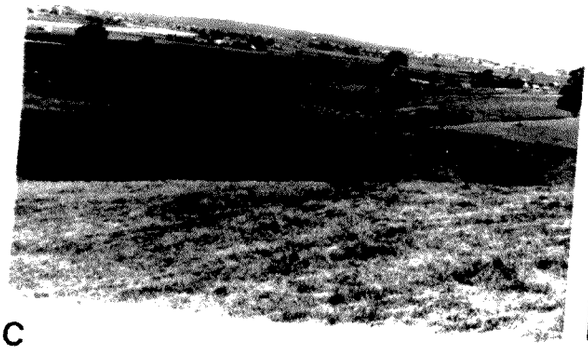
6.1C View of part of the Macleay fluvial-deltaic plain, looking northeast towards Smoky Cape (background). Photograph taken from one of the isolated knolls near Smithtown.

6.1D View of the lower Macleay and part of Spencers Creek. Photograph taken from a fixed Pleistocene transgressive dune near Smoky Cape.

6.1E View looking southwest across part of the lower Macleay valley. Photograph also taken from the crest of a fixed Pleistocene transgressive dune.

6.1F Old course (1895) of the Macleay River near Grassy Head. Part of the river infilled by sand from the Outer Barrier. Mangroves prominent near the water.

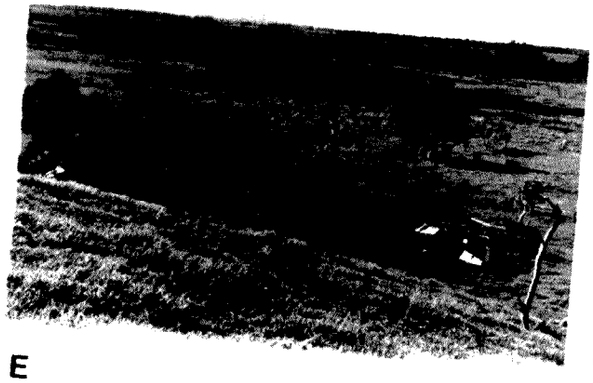
A



B



C



D



E

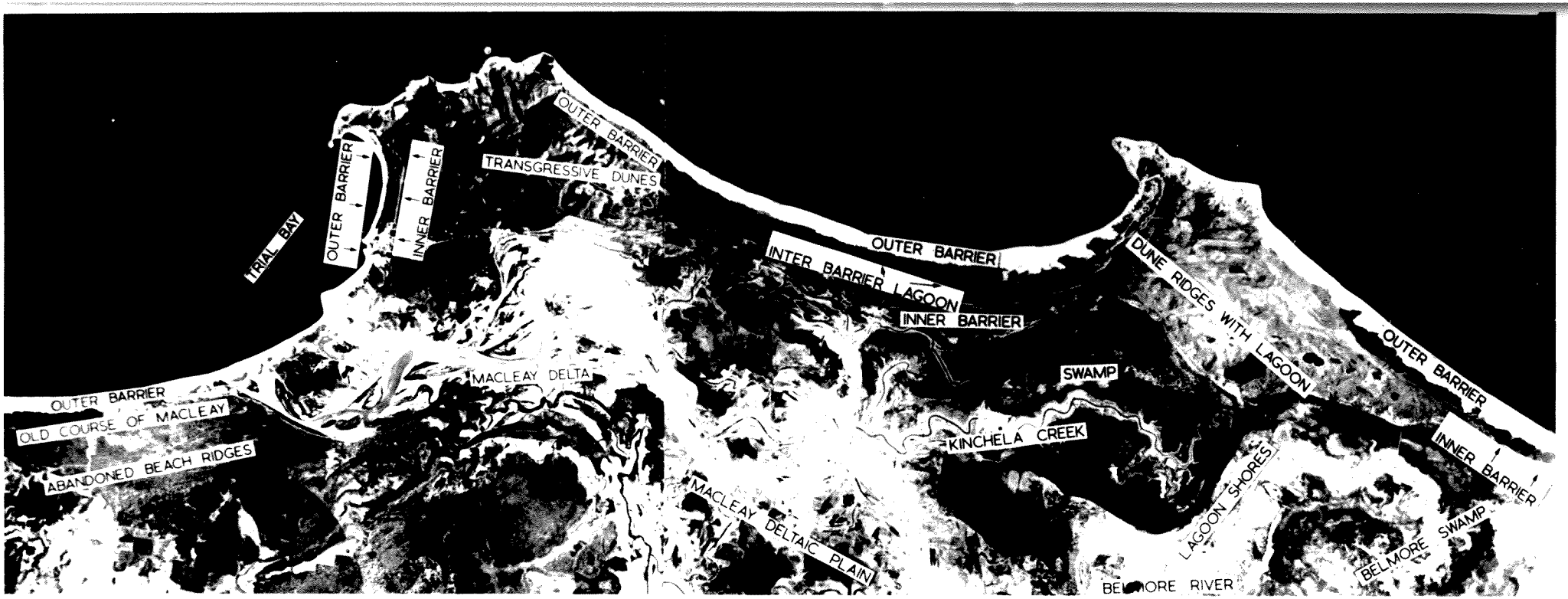


F



Plate 6.2 Aerial mosaic of the Macleay fluvial-deltaic plain near Kempsey; and of the coast between Hat Head and Smoky Cape - view looking south along coast with Smoky Cape and Trial Bay in foreground. Note prominent zeta-curved bays.

View of Macleay fluvial-deltaic plain looking approximately east across the Macleay and Belmore Rivers (cf. Figure 6.1).


TRIAL BAY
OUTER BARRIER
INNER BARRIER
OUTER BARRIER
TRANSGRESSIVE DUNES
OUTER BARRIER
INTER BARRIER LAGOON
INNER BARRIER
DUNE RIDGES WITH LAGOON
OUTER BARRIER
OUTER BARRIER
OLD COURSE OF MACLEAY
ABANDONED BEACH RIDGES
MACLEAY DELTA
SWAMP
KINCHELA CREEK
LAGOON SHORES
INNER BARRIER
MACLEAY DELTAIC PLAIN
BELMORE
SWAMP
BELMORE RIVER

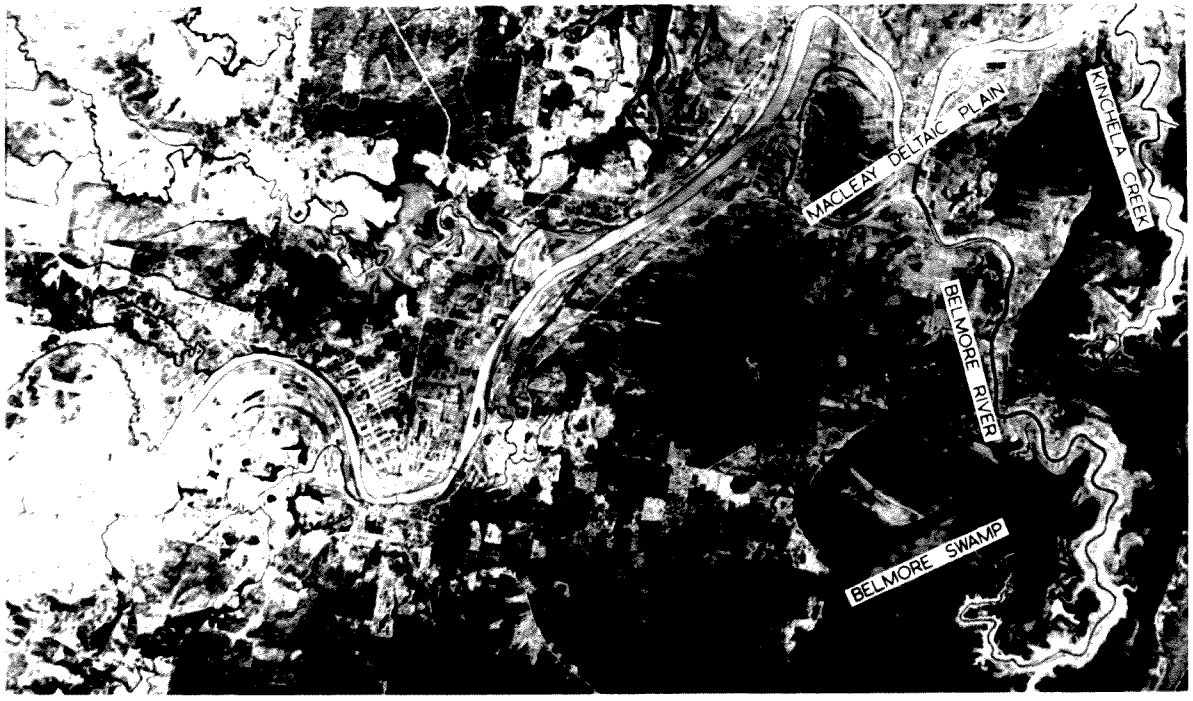

MACLEAY DELTAIC PLAIN
KINCHELA CREEK
BELMORE RIVER
BELMORE SWAMP

Plate 6.2

CHAPTER 7

THE SIGNIFICANCE AND LIMITATIONS OF TEXTURAL PARAMETERS AND ROUNDNESS ANALYSIS FOR DISTINGUISHING ANCIENT AND MODERN SEDIMENTARY ENVIRONMENTS IN THE STUDY AREAS.

PART I

Textural Parameters and Roundness Analysis

Introduction: It is considered that Hutton's axiom 'the present is the key to th past' is particularly pertinent to a study of littoral constructional features, since they are modified periodically by erosion and deposition before reaching sufficient stability to be incorporated in the geological record. It is therefore necessary to understand the changes produced near the modern shoreline in order to interpret the origin of preserved coastal deposits. In this connection, the Mid-North Coast is an invaluable study area because Holocene and Pleistocene barrier and dune sands are still sufficiently well preserved to provide some record of the geomorphological and sedimentological history, and modern and ancient sediments can be readily compared.

An examination of the literature shows that there are conflicting opinions on the usefulness of textural parameters calculated from grain-size data (mean diameter, standard deviation, skewness and kurtosis) for distinguishing ancient and modern sedimentary environments. Some sedimentologists and other workers claim that textural parameters are environmentally-sensitive and can be used to differentiate between modern beach, barrier, coastal dune, and river sands (Mason and Folk, 1958; Friedman, 1961; Duane, 1964; Martins, 1965; Hails, 1967; Hails and Hoyt, 1969 in press), while Shepard and Young (1961), Schlee and others (1964), Gees (1965) and Sevon (1966) are of the opinion that such parameters

cannot be used to differentiate between various depositional environments.

One of the major problems in studying depositional environments is to decide upon a suitable method of sampling, for it cannot be denied that many practical questions arise about the application of conventional sampling programmes. Krumbein (1953), and Krumbein and Slack (1956) have discussed the statistical significance and relative efficiency of beach sampling methods, but no such discussion on the sampling of barrier and dune environments has been published.

The Aims of the Study: As far as the writer is aware, there have been no detailed statistical studies of barrier, beach and dune environments in New South Wales, and therefore the work reported in this chapter has been undertaken primarily to:

1. evaluate the significance and limitations of statistical parameters for distinguishing Pleistocene and Holocene depositional environments;
2. test the significance of roundness analysis in differentiating between beach, barrier and dune sands;
3. assess the usefulness of the writer's experiment to correlate sedimentology with other aspects of geomorphology in an attempt to define depositional environments more accurately.

Field and Laboratory Procedures: More than 1500 samples were collected from various Pleistocene and Holocene depositional environments in the three study areas. Barrier, dune (including cliff-top dune) fluvial and offshore neritic environments were sampled. Beach samples were collected just below the swash line of high-water mark and approximately at Bascom's (1951) "reference point", - the part of the beach subjected to wave action at the mid-tide stage. Although mid-tide refers to a

level halfway between the previous high tide and the succeeding low, the intertidal zone varies from its predicted position according to local conditions at the time of sampling.

Offshore neritic samples were collected in Brisk Bay approximately at the positions indicated by the dots on the traverses shown in Figure 3.11. A nylon cord, marked at 50-ft intervals and anchored at the beach sampling stations shown in Figure 3.11, was fixed to a buoy so it floated on the surface of the water. A weighted directional line was attached to the nylon cord immediately above the position of sampling. The directional line was marked at intervals of 1 foot so an accurate record could be made of the depths from which the samples were collected. The line and cord were measured after sampling operations, although they were guaranteed to be shrink-resistant. Samples were collected in a specially constructed scoop attached to the end of a long pole which was marked at 1-foot intervals so that it could be used conveniently from a small boat. Because Brisk Bay is relatively protected from wave attack sampling was completed without much difficulty.

Several hundred shallow boreholes were sunk, with a 3-inch diameter bucket type auger and by the use of a high-frequency vibration core sampler, along surveyed transects extending from the beach across the barriers and fluvial-deltaic plains to an ancient and somewhat degraded bedrock coastline which can be traced throughout the length of the Mid-North Coast. Similar transects were made across the barrier systems in Broken Bay and on the south coast. Boreholes sunk with the hand auger were no more than 25 feet deep, whilst 40 feet was the maximum depth recorded with the core

sampler. Samples for analysis were collected near the surface of the barriers, dunes and fluvial-deltaic plains, and at 1-foot intervals until the water table was reached. No samples were collected below the water table because of the risk of contamination by material washed into the boreholes and by sediment collapsing from the walls.

As stated in Chapter 6, samples collected from the swamps and fluvial-deltaic plains which contained a high content of silt and clay were analyzed by the hydrometer method of Bouyoucos (1936) which is described in Appendix 6.1. All sand samples were oven dried and a 100-gram sample split was sieved through a set of B.S.S. 8-inch diameter screens at the $\frac{1}{4}$ ϕ (phi) interval with a Ro-Tap machine for 15 minutes. The fractions retained on the sieves were weighed on a Mettler Precision Balance to 0.01 gm. and amounts smaller than 1 gram were weighed to 0.001 gm. A KDF 9 electronic computer was used to calculate both graphic and moment measures. Two programmes were adapted from the one described by Collias and others (1963). In order to increase accuracy, the Collias programme locates the percentiles by non-linear interpolation for computation of the graphic measures. Interpolation is not used in connection with calculation of moment measures.

The programmes used in this study were a Sediment Description Programme to compute order statistics which included the graphic measures (percentile estimates) on Trask (Krumbein and Pettijohn, 1938), Inman (1952), and Folk and Ward (1957), and a Moment Measure Programme to compute the moment measures (see Appendix 7.1). The open end in the moment measures was closed at $\frac{1}{4}$ ϕ (phi) interval beyond the last measured interval.

Folk (1966) referred to some serious disadvantages of the method of moments which include the effects of erroneously-sized screens on the third and fourth moments, and the fact that many sedimentary distributions are open-ended, with material finer than 4ϕ (phi). New screens were used for this study and none of the samples was open-ended. Computer results were checked against those obtained by using conventional methods. Grain size parameters of 300 random samples (proportional to the total number of samples from each environment) were obtained by drawing cumulative curves from cumulative percentages, plotted against the phi scale diameter on arithmetic probability paper.

Although the roundness of a particle increases its sphericity, roundness must not be confused with shape. Roundness may be expressed: 'as the ratio of the average radius of curvature of the several corners or edges to the radius of curvature of the maximum inscribed sphere or to the nominal radius of the fragment' (Pettijohn, 1957). Several methods of roundness analysis have been described in the literature. However, the method of Shepard and Young (1961) was used because it was most suitable for the writer's purpose. They modified the scale developed by Powers (1953) by introducing 'pivotability' - whereby sand grains are viewed under a binocular microscope and compared visually with a scale of roundness (pivotability) which is divided into six categories.

Quartz grains, 0.353mm and 0.125mm in size, were used for roundness analysis and heavy minerals in the size range 0.251-0.074mm (see Chapter 8). A sample split of each of the sizes already noted was spread on a gridded tray and examined under a binocular microscope. In order to prevent operator bias, the samples were renumbered, so the writer was

unaware of their particular location. One hundred grains were counted in each size category. The number of grains assigned to each of the six categories was multiplied by the factor used by Powers (op. cit.) as follows: very angular (0.14), angular (0.21), subangular (0.30), subrounded (0.41), rounded (0.59), and well rounded (0.84).

Results: The graphic and moment measures of the sands collected from the Holocene and Pleistocene barrier, dune, swamp and beach environments in the three study areas have been compared on 17 scatter plots. Average graphic and moment measure values are summarized in Tables 7.1 to 7.3. Only Folk and Ward values are shown in these tables. Various textural parameters have also been shown against depth on four plots, and the roundness values of quartz grains and heavy minerals have been compared in a separate illustration.

Mid-North Coast Sands: Figures 7.1A-7.1D are scatter plots, using the phi (ϕ) scale, for Mid-North Coast sands. In Figure 7.1A the third moment (skewness) for barrier, dune and swamp sands is plotted against the standard deviation (sorting). These sands are somewhat crowded with a slight random overlap because the range of sorting values is extremely small. Although practically all the sands have standard deviation values less than 0.50ϕ, they can be separated into two distinct fields, the Pleistocene sands for the most part being positively skewed, and the Holocene sands negatively skewed. The first moment (mean grain-size) is plotted against the standard deviation in Figure 7.1B. Here the points representing the different types of sand are densely grouped because the range of the values of the statistical measures is extremely small. All except seven samples have standard deviation values between 0.20ϕ and 0.50ϕ,

and the majority of the mean grain-size values are between 1.70ϕ and 2.20ϕ. Consequently, many of the sands overlap, and although all the points cannot be shown separately, the various depositional environments can be identified without much difficulty.

Figure 7.1C is a graphic measure plot, and Figure 7.1D a moment measure plot, of mean grain-size and skewness for barrier and dune sands. By comparing the two plots it can be seen again that the sands from Pleistocene and Holocene environments fall into distinct groupings, but the method of moments measures a slightly different property than the graphic method (Middleton, 1962; Friedman, 1962; Folk, op. cit.). The two plots show that the differences between the two methods are not so marked that ancient and modern sands cannot be separated into different fields. Some Killick Creek Inner Barrier sands and a few transgressive dune sands, also of Pleistocene age, are negatively skewed, but the degree of negative skewness is negligible considering the scales used in the plots. A possible reason for the negatively skewed Pleistocene sands is examined in the following discussion.

Broken Bay Sands: Figures 7.2A-7.2F are scatter plots, using the phi scale, for Broken Bay barrier, beach, and offshore neritic sands. The first moment is plotted against the third moment in Figure 7.2A; the dashed line separates Umina-Woy Woy beach ridge sands quite clearly from the other barrier and offshore sands. More than 50 per cent of the Umina-Woy Woy sands are positively skewed, whereas most Pearl Beach and Patonga Beach barrier sands and Patonga offshore samples show negative skewness. Figure 7.2B is a plot of the first moment

versus the standard deviation and is the most effective for differentiating between the various types of sand. Despite the crowding of points, Umina-Woy Woy beach ridge sands may be distinguished from Patonga and Pearl Beach barrier sands on the basis of their mean grain-size values (see dashed lines). Whereas the Umina-Woy Woy values are between 1.40ϕ and 2.24ϕ the other sands have values between 0.64ϕ and 2.10ϕ. The sands of the Umina-Woy Woy and Patonga Beach barrier systems are distinguished from most Pearl Beach barrier and Patonga offshore sands on the basis of the sorting values, the latter are only mainly moderately well sorted. However, since the range of standard deviation values of the Pearl Beach barrier and offshore sands is small, many sands overlap and those two environments cannot be really separated.

A plot of the third moment against the standard deviation (Figure 7.2C) does not provide a good separation between the fields representing the four depositional environments and because many sands are negatively skewed, the standard deviation values are not so effective as in Figure 7.2B in differentiating between the various sands.

The textural parameters of Broken Bay beach sands are shown in Figures 7.2D-7.2F. High-water mark and mid-tide level sands have been compared with barrier sands in Figure 7.2D which is a plot of the first moment and the standard deviation. The beach sands cannot be distinguished from the barrier sands on the basis of their textural properties since both types have similar standard deviation and mean grain-size values. In fact, the bulk of the sands have mean grain-size values between 1.10ϕ and 1.80ϕ.

In Figures 7.2E and 7.2F the first moment is plotted against the third moment and standard deviation respectively for beach and offshore sands. These two figures show that only a relatively small percentage of the Broken Bay beach and offshore sands are positively skewed, and a large number are well sorted.

South Coast Sands: Figure 7.3A-7.3D are scatter plots, using the phi scale, for the south coast Holocene barrier and beach sands. In Figure 7.3A the first moment is plotted against the third moment. The dashed lines illustrate that the respective barrier sands can almost be completely separated into distinct fields. The third moment measure shows that a fairly large percentage of the barrier and beach sands are negatively skewed. There is a marked contrast between the textural parameters of the Pambula and Eden barrier sands. The values of mean grain-size for Pambula barrier sands plot closely, and all of them are higher than 1.70ϕ. In Figure 7.3B there is also a noticeable difference between the standard deviation values of the Pambula barrier and Twofold Bay barrier sands. Whereas the Pambula barrier sands are well sorted, most of the Twofold Bay barrier samples are moderately well sorted and more than 50 per cent of the sands have mean grain-size values lower than 1.50ϕ (Figure 7.3A). These properties reflect, in part, the influence of wave action outside the bays because Pambula barrier is on a more exposed sector of the south coast.

The dashed lines in Figure 7.3C, a plot of Inclusive Graphic Skewness against Graphic Kurtosis, distinguishes the properties of the Pambula and Eden barrier sands, but not those of the former barrier and the Boyd Town barrier sands because there is some degree of overlap. Nevertheless,

skewness and kurtosis in this plot do provide environmental separation for Pambula and Twofold Bay barrier sands. The first moment and standard deviation are plotted against each other for Pambula and Twofold Bay barrier sands in Figure 7.3D, and show similar groupings to those in Figure 7.3C.

Beach Sands: Beach sands from the three study areas are shown on the scatter plots in Figures 7.4A-7.4C, and Tables 7.4A and 7.4B show the percentage number of beach and offshore sands that are nearly symmetrical and positively skewed. Figure 7.4C, which is a representative plot of 340 beach sands shows that there are a few positively skewed sands in all areas.

Plots of Textural Parameters versus Depth: Plots of skewness, standard deviation and mean grain-size versus depth, for Mid-North Coast barrier and dune sands, are shown in Figures 7.5A-7.5D. The skewness values are not grouped, although there is a slightly denser concentration on the negative side of the plot for depths less than 8 feet. Most of the samples recovered from depths of less than 6 feet (Figure 7.5B) have sorting values between 0.30 and 0.40ϕ; those recovered from a greater depth are slightly better sorted. Mean grain-size values vary little with depth (Figure 7.5C) and most samples are concentrated between the 1.70ϕ and 2.30ϕ values. In Figure 7.5D barrier sands are shown to become slightly coarser with depth.

Discussion of Results: The various scatter plots show that several combinations of textural parameters are environmentally-sensitive in differentiating between barrier, beach, dune and swamp sands. In general, dune and Pleistocene barrier sands are positively skewed, and modern beach

and Holocene barrier sands are negatively skewed. However, it is difficult to differentiate between Pleistocene barrier and dune sands because they are positively skewed, as well as being well sorted. The plots are significant because most barriers and dunes on the New South Wales coast are predominantly composed of sands that have been reworked during Pleistocene fluctuations of sea level, and during the postglacial or Holocene marine transgression. Such sands can therefore be described as polygenetic since they have been derived from various sources and their origin is very complex in relation to both time and place. With the foregoing facts and general remarks in mind, the textural parameters can now be evaluated more fully.

Skewness is the measurement of the symmetry of a frequency distribution. Symmetrical curves have values of $SK_1 = 0.0$, and as skewness becomes more extreme the value approaches theoretical limit of -1.00 or + 1.00. Positive skewness indicates an excess of material in the fine tail of the distribution curve and negative skewness indicates an excess of material in the coarse tail. Skewness is considered to be an environmentally-sensitive grain-size parameter because minor fluctuations of energy within an environment of deposition will theoretically add material to or subtract it from the tails of a population (without the material affecting the bulk of the sediment). According to Friedman (1961) the skewness sign tends to reflect the environment and does not change with the mineralogy of the sands.

One interesting problem that has come to light during the writer's study of sedimentary environments is the difference in the sign of skewness of the Pleistocene and Holocene barrier sands, which are of marine origin. It is difficult to explain why most of the Pleistocene barrier sands are

positively skewed and the Holocene barrier sands are negatively skewed. If it is accepted that skewness is an environmentally-sensitive parameter it might be inferred that the Inner Barrier is capped with a considerable thickness of fine-grained windblown sand. But, as stated in Chapter 3, there is no conclusive field evidence to suggest that the Inner Barrier may have been manifestly capped with eolian material. Even so, there is really no reason to suppose that shoreline processes were basically very much different during the formation of the dual barrier systems.

However, there is one other possible explanation to account for the different skewness values. According to Friedman (1962), the tail end of distribution curves are affected by diagenetic processes, resulting in changes in the numerical values for skewness. The term diagenesis has several connotations, but it is mostly used to describe post-depositional physical and chemical processes including cementation, solution, precipitation, crystallization, recrystallization, oxidation, reduction and so forth (Pettijohn, op. cit.). Although the Pleistocene dune and barrier sands on the Mid-North Coast are deeply podzolized and invariably underlain by indurated humate they are, in fact, strictly non-lithified deposits, and cannot be classed as diagenetically altered sandstones. The question therefore is whether or not the skewness values of the vegetated Pleistocene sands have been affected by podzolization, or diagenetic processes such as bacterial action and the digestive processes of organisms. Since the Holocene barrier sands show little evidence of leaching, the writer suggests that the possible effects of diagenesis on the skewness values of the unconsolidated podzolized Pleistocene sands cannot be ignored. Unfortunately, practically no work has been done on this subject so the conclusion drawn

from the writer's results must inevitably remain tentative.

According to Pettijohn (op. cit.), Blackwelder (1947) and Krumbein (1947) have concluded (in the case of consolidated sediments) that although weathering and diagenesis are seemingly quite different and unrelated processes they are at times rather difficult to separate from one another. It is impossible to say whether or not less chemically stable components were destroyed by weathering (or diagenesis) after the formation of the coastal barriers in New South Wales, so no conclusions can be drawn about the possible effects of such processes on the skewness values of the coastal sands. The chemical and mechanical stability of heavy minerals (with a specific gravity greater than 2.85) will be discussed briefly in the next chapter.

An exhaustive petrological examination of the light fractions of all the barrier and dune samples collected by the writer revealed that detrital feldspar is almost entirely absent from the Holocene sands, and completely absent from the Pleistocene sediments. The writer has found similar results in his study of Pleistocene sedimentary environments on the Lower Georgia Coastal Plain (Hails and Hoyt, 1969 in press). The percentage occurrence of potash and soda-lime feldspars contained in the light fraction of the Georgia barrier, lagoonal-salt marsh, channel inlet, and dune sands was generally less than 0.6 per cent; and detrital feldspar was entirely absent from a large percentage of the samples.

There are conflicting reports in the literature on the significance of detrital feldspar, and whether, in fact, its presence in sediments is a reflection of its ability to survive chemical weathering (or diagenesis) under certain climatic conditions. There is some agreement though that feldspar is destroyed relatively rapidly in high energy environments, such

as the surf zone. This may explain why detrital feldspar is almost entirely absent from the Holocene barrier and dune sands on the Mid-North Coast, and occurs in very small quantities (usually less than 2 per cent) in most beach sands from the study areas. As stated at the beginning of the discussion, the majority of the coastal sands in New South Wales are considered to be polygenetic. Therefore, any detrital feldspar that survived transportation to the coast in the past was probably destroyed as sediments were reworked during fluctuations of sea level.

According to Pettijohn (op. cit.) the rate at which feldspar is decomposed by chemical weathering is largely controlled by climate and length of time. Thus it seems high likely that any detrital feldspar that may have been incorporated in the ancient Inner Barrier sands has been destroyed by pedogenic processes. Chemical weathering during late Pleistocene time may have been intensified by a much warmer and wetter climate than is experienced in New South Wales at present.

The writer has identified a very small percentage of detrital feldspar in some south coast beach samples and a fairly large percentage (greater than 10 per cent) in the Towamba (Kiah) River sands. Its presence in the latter sands suggests that the feldspar may be derived from an area that is undergoing fairly rapid erosion. Bird (1967), in an independent study after the writer's work was completed, also found a fairly high percentage of detrital feldspar in the Towamba River, and other fluviatile sands on the south coast, indicating that detrital feldspar is at least surviving transportation to the coast.

Although correlations exist between textural parameters, based on the size frequency distribution of sands, and various depositional

environments there are exceptions, as the writer has found. The few negatively skewed transgressive dune sands are somewhat anomalous because practically all the coastal dune sands are positively skewed. The transgressive dunes in question stand well back from the beach far beyond the range of contemporary wave action. Therefore, on a priori grounds, it seems that the negatively skewed dune sands may have been emplaced by exceptionally strong winds which removed an entire beach or barrier facies in the past. If this is so, the textural parameters do not really reflect the mode and energy of the transporting medium as reported by Friedman (1961) because winds usually remove fine-grained material only, from a beach.

The winnowing process of swash and backwash on the beach usually removes the fine-grained material so that the frequency curve of beach sands is negatively skewed. Wind action can also continue the winnowing process above water level, especially if there is a sustained occurrence of onshore winds and the beach is dry. Even diurnal sea breezes are effective in selectively removing fine-grained sediment from the beach.

Approximately 19 per cent of the total number of beach sands analyzed by the writer are positively skewed (Table 7.4B) and only 11 per cent are nearly symmetrical (-0.10 to + 0.10; Table 7.4A). Of the positively skewed beach sands, 29 per cent were collected from stations adjacent to river outlets. Another 35 per cent were collected just below the swash line of high-water mark, which suggests that the area of the beach covered by swash at high tide can be a zone where sediment supply exceeds energy. A concentration of fine-grained sand can positively skew the frequency distribution curve, as already stated. Since all the beach samples are composed of quartzose sand, positive skewness cannot be explained by the

presence of silt and clay. The beaches were wet when the majority of the samples were collected, so it is difficult to appraise the winnowing action of wind. However, the winnowing action of swash and backwash is readily demonstrated by the very high percentage of negatively skewed sands.

Fine-grained fractions are also removed by wave action and strong currents in high energy environments such as tidal inlets, and the littoral zone. It is therefore significant to record that only 4 per cent of the 82 offshore samples collected in Brisk Bay near Patonga Beach barrier were positively skewed.

Although many Broken Bay and south coast Holocene barrier sands are negatively skewed, indicating an excess of material in the coarse tail, there are a few exceptions, notably some of the Umina-Woy Woy samples (Figures 7.2A and 7.3B). The south coast barrier systems are stabilized by vegetation, but they display little evidence of podzolization and therefore it seems unlikely that the numerical values for skewness could have been changed by diagenetic process. Since the barriers are composed of quartzose sand, the presence of silt-clay fractions cannot be invoked to account for the positive values. However, a few ridges immediately behind the frontal dunes are capped by windblown sand and since all the positively skewed sands plotted in Figure 7.3B were collected less than 3 feet below the ridge crests, there is good evidence to demonstrate the value of skewness as an environment-sensitive parameter.

It is a little more difficult to explain why a large percentage of the Umina-Woy Woy sands are positively skewed because many ridges are

deeply leached, with a distinct intensification in podzol development landward from Umina Beach towards Woy Woy Creek; but only a few ridges immediately behind the frontal dune are known for certain to be capped with eolian material. Thus the possibility arises again that diagenesis may have been instrumental in affecting the skewness of the barrier sands.

The scatter plot in Figure 7.4A is most effective for showing two characteristics: firstly, that coarser sands are less well sorted than medium-or fine-grained sands, and secondly, the degree of sorting is not only dependent upon variations in wave energy on a coast, but also upon the origin of the sands. Wave refraction diagrams constructed by the writer show that wave energy is higher on some sectors of the south coast than on others, according to the effects of changes in the coastal configuration on the approach of swell waves (Appendix 3.1). This can be demonstrated by comparing the standard deviation (sorting) values for the barrier sands from Twofold Bay with those for the sands of Pambula barrier which is far more exposed to high wave energy. The Pambula barrier sands are well sorted, and are grouped with the Mid-North Coast samples, whereas the Twofold Bay samples are mostly moderately well sorted. Despite the relatively wide range of sorting values for most south coast samples (excluding Pambula barrier), the narrow range of values for the Holocene and Pleistocene sands of the Mid-North Coast show that the standard deviation is not a good environmentally-sensitive parameter for distinguishing beach, barrier and dune sands.

The writer made a comparative study of the grain-size properties and mineralogical composition of the Whale Beach barrier and Towamba (Kiah) River sands and found that they were almost identical. The Towamba River transports the coarsest material to the south coast study area

The largest quartz grains collected from the barrier were larger than 2.057 mm and several samples contained between 2 and 7 per cent sand 2.05 mm in size. The evidence supports, firstly, the claim put forward here that most of the sand transported from the south coast hinterland by the Towamba River and reaching East Boyd Bay is moved onshore to nourish Whale Beach barrier without moving outside the nearshore zone. Secondly, it also partly explains why Whale Beach sands are particularly poorly sorted (standard deviation values between 0.58ø and 0.87ø) compared with sands from most other parts of Twofold Bay (Table 7.3).

Although the Boyd Town and Whale Beach barriers are only separated by Mowtree Headland, Figures 7.3B and 7.3D show that the sands of each barrier can be differentiated by their textural parameters. Because the two barriers can be easily identified by different coloration of sand, it has not been difficult to determine that there has been no movement of material around Mowtree Headland and this conclusion is supported by the mineralogical composition of the respective barriers which is discussed in the next chapter.

It was mentioned in Chapter 3 that on some sectors of the Mid-North Coast the Holocene Outer Barrier has been eroded extensively and driven landward over lagoonal-swamp and Inner Barrier deposits. Sands from different sedimentary environments are therefore mixed as shorelines retreat under wave and wind attack. Similar instances of 'mixing' have been discussed by Hayes (1967) and Hails and Hoyt (op. cit.) who found that washover fans - composed of beach sands inter-mixed with lagoonal-salt marsh sediments - present interpretative problems of ancient sedimentary environments.

The writer has found that it has been virtually impossible to differentiate between beach and dune sands by roundness analysis. Roundness values for quartz grains and heavy minerals are plotted in Figure 7.6. Except for the Boyd Town samples, the values for heavy minerals and quartz are very similar, and it can be seen that the values of Pambula barrier sands compare favourably with those of the Mid-North Coast samples. The significance of the values of heavy minerals will be discussed in the next chapter, but there seems little doubt that the well rounded quartz grains reflect the polygenetic history of the New South Wales coastal sands. Therefore it is suggested, as this study has shown, that beach and dune sands cannot be distinguished if the sands have been previously reworked many times in the past, because the beach sands (from which the dune sands are derived) will mostly lack flat and angular grains.

Summary and Conclusions: The writer does not deny that unconsolidated Pleistocene sands and ancient lithified sedimentary deposits inevitably present some interpretative problems. Nevertheless, it is his opinion that statistical parameters can be significantly helpful in differentiating between beach, dune and barrier sands. Of course this particular study has realized some limitations of the use of such parameters, one of which has been the failure of the third moment measure (skewness) to distinguish adequately between dune and Pleistocene barrier sands on the Mid-North Coast. Yet another puzzling and critical problem to be resolved is whether the sign of skewness has any significance in the interpretation of palaeo-sedimentary environments in the stratigraphic record if such environments have been affected considerably by diagenetic processes.

The effects, if any, of diagenesis on the skewness values of the Mid-North Coast barrier sands may only be negligible, but as yet the evidence is still inconclusive until more work is done on this subject. However, it seems unlikely that the destruction of detrital feldspar by chemical weathering (or possibly diagenetic processes) has played an important role in affecting the skewness sign because it is unlikely that much feldspar was ever incorporated in the barrier sands for the reasons stated earlier, and because of the evidence of the mineralogical composition of the modern beach sands.

The results of this study tend to support the view that the sign of skewness can be mainly related to variations of energy in different environments. In high energy environments, such as tidal inlets, fine-grained fractions are removed by wave action and strong tidal currents. Similar winnowing processes operate along beaches and in the nearshore zone. This is why offshore and beach, and possibly the Holocene barrier, sands are negatively skewed. It could be argued perhaps that the Holocene barrier sands are negatively skewed because they show little sign of soil profile development, and the effects of diagenesis have therefore been negligible. But this seems unlikely in view of the fact that these sands (of marine origin) lack a fine-grained tail fraction, even if, as the writer supposes, some Holocene barrier ridges have subsequently been capped with a thin veneer of windblown sand. It seems more likely that wave action has been a most effective geological agent by removing the fine particles and skewing the frequency curve to the negative side; if so, could it possibly be inferred that the Inner Barrier, after it was built, was subsequently capped with a considerable thickness of fine-grained

sand, or has diagenesis been the cause of affecting the skewness values of these sands - also of marine origin?

The use of roundness analysis to distinguish between dune, barrier, and beach sands is considered to be rather tenuous, particularly when coastal sands are regarded as polygenetic.

In the light of the evidence presented in this chapter, it is suggested that the significance of statistical parameters outweighs their limitations for differentiating between environments of deposition. The results of this preliminary study partly support the conclusions of Mason and Folk (op. cit.) and Friedman (1961). The number of samples that have been analyzed is certainly sufficient, in the writer's opinion, to warrant further investigations elsewhere in New South Wales, in an attempt to examine more closely the usefulness of statistical parameters.

It is considered that the use of statistical parameters to supplement empirical geological and geomorphological data is a valid technique. The results presented here can be used in comparative studies of ancient sediments because barriers, beaches and dunes can be incorporated into the geologic column after burial, or during subsidence. Finally, despite criticism of the use of statistical parameters, a correlation appears to exist between grain-size analysis and depositional environments in New South Wales, and graphic and moment measures of polygenetic deposits show that skewness is basically environmentally sensitive.

PART II

Sorting Measures

Sorting is an important grain-size parameter in distinguishing sedimentary environments. Folk (op. cit.) briefly evaluated the various

sorting measures that have been employed in sedimentological studies during the past fifty years, but only three of these sorting measures are examined in this study - the Trask sorting coefficient, and the sorting measures of Inman, and Folk and Ward, the formulae of which are listed in Appendix 7.1.

Briefly, Trask's sorting coefficient (1930, 1932) used quartile measures. The Inman (1952) deviation measure employed the 16th and 84th percentiles instead of those used by Trask. The Inclusive Graphic Standard Deviation introduced by Folk and Ward (1957) was more adequate for bimodal or skewed distributions than the earlier sorting measures that had been employed. Folk (op. cit) pointed out that the Inclusive Graphic Standard Deviation 'made a better coverage of the tails of a distribution, wherein the differences between beach, river and dune sands chiefly lie'.

The writer has made empirical correlations between the standard deviation, the Trask sorting coefficient and the sorting measures of Inman, and Folk and Ward. These correlations were made for three reasons. Firstly, as far as the writer is aware, Friedman (1962) is the only one who has evaluated the usefulness of the three sorting measures. Secondly, Friedman made grain-size analyses of 1,000 recent sands and ancient sandstones. Since similar analyses were made of more than 1,500 Holocene and Pleistocene sands from the three study areas, the results presented here could also be significent. Thirdly, the writer wanted to compare the results obtained for the New South Wales coastal sands with those reported by Friedman. Figures 7.7A - 7.7G show the sorting measure of

Folk and Ward plotted against the standard deviation for barrier, dune, beach and offshore sands. The points in this plot show that a sixth-degree correlation between the two measures fits the data. Table 7.6 shows that mathematically a sixth-degree curve has a significantly smaller numerical value than the fourth-degree and linear curves.

In Figure 7.9A - 7.9G the sorting measure of Inman has been plotted against the standard deviation. The fourth-and sixth-degree correlations fit the data, although Table 7.6 shows that the sixth degree curve is the best fit. In Figures 7.10A - 7.10G the standard deviation has been plotted against the Trask sorting coefficient. All correlations appear to provide a good fit for the data as Table 7.6 shows, although mathematically a sixth-degree curve provides the best fit for the data.

A comparison of Figures 7.7, 7.9, and 7.10 shows that for barrier and beach sands, which have a standard deviation value of less than 0.55, there is less scatter of data about the various correlation curves. In the standard deviation range of 0.55 to 1.00 the scatter of data about the correlation curves is slightly less for the Inman measure, than for the Folk and Ward measure and the Trask sorting coefficient. The data in Table 7.6 indicate that the Folk and Ward measure provides the best correlation with the standard deviation; a similar conclusion was also reported by Friedman (op. cit.). The figures also show that, except for the Trask sorting coefficient, the scatter of barrier data about the regression lines is less than for the offshore and beach data.

In Figures 7.8A - 7.8F the sorting measure of Folk and Ward has been plotted against that of Inman. These figures, and Table 7.6, indicate

that a sixth-degree correlation provides the best fit.

Summary and Conclusions:1. The Folk and Ward measure provides the best correlation with the standard deviation. Similar results were reported by Friedman (op. cit.).

2. Both the sorting measure of Inman and the Trask sorting coefficient provide a reasonably good approximation of the standard deviation.

3. A sixth-degree curve between the respective sorting measures and the standard deviation provides a slightly better fit than a fourth-degree curve.

4. A quadratic correlation between the sorting measures and the standard deviation is not shown on the figures because the information that is necessary to calculate this parameter was mistakenly omitted from the computer programme by the programmer. However, this omission does not considerably alter the conclusions reported here.

PART III

An Evaluation of Grain-Size Distribution and Depositional Processes: Contrary to the findings of Friedman (1962), Harris (1958) and Rogers and Schubert (1963) reported that the grain-size distribution of most sands and sandstones follows a lognormal function. Lognormal sediment size distributions plot as straight lines on normal probability paper when the cumulative weight percentage is plotted against the grain-size in the phi scale - Krumbein's logarithmic transformation of the millimetre scale. Departures from straight line plots on probability paper are sometimes the result of a mixture of more than one population. Fuller (1961,1962) and Spencer (1963) considered that grain-size distributions are composed of one or more lognormal 'populations', and the mixing of these populations may

be an indication of depositional processes. Therefore, the purpose of this section is to outline and discuss very briefly the general characteristics shown by some of the cumulative frequency distribution curves in Figures 7.11 to 7.15, in an attempt to deduce whether the coastal sands in the study areas may be mixtures of one or more lognormal populations. The writer has not analyzed in any detail the degree of mixing, percentage, size range and degree of sorting of individual populations that may characterize a grain-size distribution.

Figure 7.11 shows average cumulated grain-size frequency distribution curves of barrier, dune and beach sands, and Figures 7.12 to 7.15 show the grain-size frequency distribution curves of individual samples. The shape of the cumulative curves of dune sands, shown in Figures 7.12, 7.13A and 7.14, are basically similar. It can be seen that approximately 95 per cent of the dune sand in individual samples, is coarser than 2.5 phi (0.1768 mm), the size interval at which inflections occur in the cumulative curves. Figures 7.13A and 7.13B are quite interesting because the cumulative curves of the cliff-top dune sands show minimum departure from an almost straight line plot compared with those of the Outer Barrier sands which show sharp inflections at the 2.5 phi fraction corresponding to the 90-98 per cent level on the probability scale. By contrast, inflections in the curves of the dune sands (in Figure 7.13A only) are almost at the 98-99 per cent level.

The fraction coarser than 2.5 phi in each dune sample plots almost as a straight line indicating that the dune sands probably are a single population which follows more or less a lognormal size distribution. The question is whether or not the departure from lognormality (at about the 95 per cent level corresponding to the 2.5 phi fraction) indicates a mixture of more than population. Figures 7.1A, 7.1C and 7.1D show that the majority of the dune and Pleistocene sands are positively skewed,

whereas the beach and Holocene sands are generally negatively skewed. Therefore, it is more likely that the inflections reflect the tendency for deviation from lognormality during deposition (Friedman op. cit.). In Part I of this chapter it was shown that deviation from lognormality of the grain-size distribution of sands as expressed by the skewness is essentially an environment-sensitive parameter.

According to Friedman (op. cit.), for most practical purposes a frequency distribution may be considered to be normal if it has a skewness of 0 and a kurtosis of 3. But the majority of the samples analyzed by the writer show departure from normality. The skewness values of the dune sands, for example, range from +0.10 to +0.64, with an average value of +0.30 (Table 7.5). Kurtosis values of dune samples range from 2.88 to 5.33, with an average value of 3.50. The cumulative frequency curves of samples collected at 1 foot intervals from a borehole sunk through an abandoned beach ridge on the 'Clybucca shoreline' (Chapter 9) are shown in Figure 7.12. Inflections on the curves occur at the 1 and 90 per cent levels which correspond to the 1 and 2.5 phi fractions respectively. Between these fractions the plot is almost a straight line for all samples. By comparing Figures 7.12 and 7.13B it can be seen that the cumulative frequency curves of the Clybucca and the Outer Barrier sands are fairly similar. Of the Clybucca samples numbers 2 and 3 are positively skewed and numbers 4 to 7 are strongly negatively skewed, and again it is most probable that the deviation from lognormality of the grain-size distribution of the Clybucca sands is essentially an environment-sensitive parameter, the positive skewness indicating that the beach ridge has a thin veneer of eolian material

(samples 2 and 3 being relatively near the surface).

Figure 7.15 shows various cumulative curves of some Patonga offshore samples which were collected over a period of one year from stations (i) to (vi) in Figure 3.11. The letters A,B, C and G represent samples collected from stations (i), (ii), (iii) and (v) respectively. The figure 2 or 3 before the letter represents a particular series of samples. For example, 2A1-2A7 is a second series of seven samples that were collected from station (i).

The cumulative curves of samples collected in March and October from station (i) are very similar, but at station (ii) the trends of the curves differ for the same two months. However, the curves in Figure 7.15 indicate that individual offshore samples are chiefly a mixture of sand coarser than 2.5 phi (80-98 per cent of the total) and sand finer than 2.5 phi (about 2-20 per cent of the total). As stated earlier in Part I of this chapter only 4 per cent of the offshore sands are positively skewed, indicating that the very fine-grained fractions may have been removed by wave action.

Thus it would seem that deviation from lognormality of the grain-size distribution of most of the sands as expressed by the skewnes appears to be a strongly environment-sensitive parameter. An analysis of log-probability plots of grain-size distribution in order to obtain information concerning depositional processes can be of some use. However, an investigation of the polycomponent aspect of lognormal distribution should be studied in far more detail than the writer has been able to do here.

TABLE 7.1

Average Graphic and moment measure values of barrier and dune samples from the Mid-North Coast. (Values are in phi units (ϕ). Only Folk and Ward values are shown in this table, although Inman and Trask values were obtained from the computer programme.)

BARRIER/DUNE LOCALITY	FIRST MOMENT (Mean)	RANGE OF VALUES	STANDARD DEVIATION (Sorting)	RANGE OF VALUES	INCLUSIVE GRAPHIC STANDARD DEVIATION (FOLK AND WARD)	RANGE OF VALUES
CLYBUCCA SHORELINE	1.804(0.2872 mm)	1.46(0.3635 mm) to 1.90(0.2679 mm)	0.50 (well sorted)	0.43 to 0.79	0.50 (well sorted)	0.40 to 0.75
BAT HEAD (INNER BARRIER)	1.784(0.2912 mm)	1.65(0.3186 mm) to 1.90(0.2679 mm)	0.30 (very well sorted)	0.22 to 0.35	0.29 (very well sorted)	0.22 to 0.34
BAT HEAD (OUTER BARRIER)	2.035(0.2449 mm)	1.99(0.2517 mm) to 2.13(0.2285 mm)	0.37 (well sorted)	0.33 to 0.43	0.36 (well sorted)	0.33 to 0.43
KILLICK CREEK (INNER BARRIER)	2.05(0.2415 mm)	1.96(0.2570 mm) to 2.18(0.2207mm)	0.41 (well sorted)	0.37 to 0.54 (only 2 values greater than 0.50)	0.39 (well sorted)	0.35 to 0.47
FRONT BEACH (OUTER BARRIER)	2.134(0.2285 mm)	1.58(0.3345 mm) to 2.26(0.2088 mm)	0.36 (well sorted)	0.27 to 1.03 (only 4 values greater than 0.50)	0.36 (well sorted)	0.27 to 1.05 (only 4 values greater than 0.50)
BACK BEACH CRESCENT HD. (INNER BARRIER)	1.87(0.2736 mm)	1.81(0.2852 mm) to 1.93(0.2624 mm)	0.30 (very well sorted)	0.29 to 0.35	0.29 (very well sorted)	0.28 to 0.31
DELICATE HONEY	1.864(0.2755 mm)	1.671(0.3143 mm) to 2.08(0.2365 mm)	0.30 (very well sorted)	0.27 to 0.40	0.32(very well sorted)	0.26 to 0.40
DELICATE HONEY SWAMP	1.799(0.2892 mm)	1.60(0.3299 mm) to 1.96(0.2570 mm)	0.44 (well sorted)	0.37 to 0.55 (only 2 values greater than 0.50)	0.44 (well sorted)	0.36 to 0.53
MARIA-WILSON BARRIER PLAIN	2.331 (0.1989 mm)	2.25 (0.2102 mm) to 2.46 (0.1817 mm)	0.40 (well sorted)	0.39 to 0.44	0.39 (well sorted)	0.38 to 0.43
CLIFF-TOP DUNES	1.946(0.2606 mm)	1.88(0.2717 mm) to 2.03 (0.2449 mm)	0.37 (well sorted)	0.32 to 0.40	0.37 (well sorted)	0.32 to 0.43
TRANSGRESSIVE DUNES	2.074(0.2582 mm)	2.04(0.2432 mm) to 2.10(0.2333 mm)	0.30 (very well sorted)	0.29 to 0.33	0.29 (very well sorted)	0.28 to 0.30

Graphic Mean is not plotted.

TABLE 7.1 Continued

BARRIER/DUNE LOCALITY	THIRD MOMENT (SKEWNESS) Range of Values	INCLUSIVE GRAPHIC SKEWNESS (FOLK AND WARD) Range of Values	FOURTH MOMENT (KURTOSIS)	RANGE OF VALUES	GRAPHIC KURTOSIS (FOLK AND WARD)	RANGE OF VALUES
CLYNUCCA SHORELINE	-1.89 to -0.15 +0.05 to +0.07 (only two positive values)	-0.27 to -0.10 +0.06 to +0.12	6.26	4.17 to 8.91	1.53 (Very Leptokurtic)	1.00 to 2.77 (Mesokurtic) (Very Leptokurtic
HAT HEAD (INNER BARRIER)	+0.03 to + 1.37	+0.02 to +0.46	3.62	2.66 to 7.72	0.97 (Mesokurtic)	0.82 to 1.32 (Platykurtic) (Leptokurtic)
HAT HEAD (OUTER BARRIER)	-0.57 to -0.03	-0.24 to -0.01	3.06	2.70 to 3.78	0.95 (Mesokurtic)	0.86 to 1.08 (Platykurtic) (Mesokurtic)
KILLICK CREEK (INNER BARRIER)	-0.73 to -0.05 +0.02 to +0.12	-0.25 to -0.01 +0.06 to +0.25	4.17	3.07 to 5.94	0.97 (Mesokurtic)	0.84 to 1.68 (Platykurtic) (Very Leptokurtic)
FRONT BEACH (OUTER BARRIER)	-1.54 to -0.03	-0.27 to 0.03	3.57	2.64 to 8.65	1.02 (Mesokurtic)	0.89 to 2.04 (Platykurtic) (Very Leptokurtic)
BACK BEACH CRESCENT HD. (INNER BARRIER)	+0.14 to +0.37	+0.01 to +0.14	3.71	2.84 to 6.02	1.01 (Mesokurtic)	0.98 to 1.06 (Mesokurtic) (Mesokurtic)
DELICATE BOBBY	+0.09 to +0.64 -0.13 to -0.11 (only three positive values)	+0.03 to +0.22	3.32	2.36 to 8.85	0.96 (Mesokurtic)	0.84 to 1.30 (Platykurtic) (Leptokurtic)
DELICATE BOBBY SWAMP	-0.77 to -0.04	-0.17 to -0.03 +0.01 to +0.08	3.56	3.13 to 4.44	1.05 (Mesokurtic)	0.94 to 1.27 (Mesokurtic) (Leptokurtic)
MARIA-WILSON BARRIER PLAIN	-0.63 to -0.38	-0.22 to -0.15	3.38	3.19 to 3.47	1.00 (Mesokurtic)	0.98 to 1.06 (Mesokurtic) (Mesokurtic)
CLIFF-TOP DUNES	+0.10 to +0.53	+0.01 to +0.15	3.45	2.80 to 4.11	1.02 (Mesokurtic)	0.94 to 1.19 (Mesokurtic) (Leptokurtic)
TRANSGRESSIVE DUNES	-0.21 to -0.008 +0.07 to +0.61	-0.07 to -0.02	3.45	2.90 to 5.38	0.96 (Mesokurtic)	0.93 to 0.99 (Mesokurtic) (Mesokurtic)

TABLE 7.2

Average graphic and moment measure values of barrier and offshore samples from Broken Bay. (Values are in phi units (ϕ). Only Folk and Ward values are shown in this table, although Inman and Trask values were obtained from the computer programme).

BARRIER LOCALITY	FIRST MOMENT (Mean)	RANGE OF VALUES	STANDARD DEVIATION (Sorting)	RANGE OF VALUES	INCLUSIVE GRAPHIC STANDARD DEVIATION(FOLK AND WARD)	RANGE OF VALUES
PATONGA	1.546(0.3439 mm)	0.64(0.6417 mm) to 2.10(0.2333 mm)	0.41 (well sorted)	0.29 to 0.68	0.39 (well sorted)	0.29 to 0.66
PATONGA (OFFSHORE)	1.64(0.3209 mm)	0.14(0.9075 mm) to 2.17(0.2222 mm)	0.64 (moderately well sorted)	0.24 to 1.08	0.52 (moderately well sorted)	0.25 to 1.14
PEARL BEACH	1.546(0.3439 mm)	0.81(0.5704 mm) to 1.94(0.2606 mm)	0.52 (moderately well sorted)	0.32 to 0.90	0.50 (well sorted)	0.31 to 0.95
UMINA-WOY WOY (?) PLEISTOCENE	1.839(0.2813 mm)	1.40(0.3789 mm) to 2.10(0.2333 mm)	0.42 (well sorted)	0.31 to 0.67	0.39 (well sorted)	0.31 to 0.66
UMINA-WOY WOY HOLOCENE	1.896(0.2698 mm)	1.60(0.3299 mm) to 2.84(0.2269 mm)	0.43 (well sorted)	0.31 to 0.53	0.41 (well sorted)	0.32 to 0.53

BARRIER LOCALITY	THIRD MOMENT (SKEWNESS) Range of Values	INCLUSIVE GRAPHIC SKEWNESS(FOLK AND WARD)	FOURTH MOMENT (KURTOSIS)	RANGE OF VALUES	GRAPHIC KURTOSIS (FOLK AND WARD)	RANGE OF VALUES
PATONGA	-1.41 to -0.01 +0.04 to +0.61 (only six positive values)	-0.32 to -0.01 +0.02 to +0.15	3.92	2.64 to 7.35	1.07(Mesokurtic)	0.78 to 1.51 (Platykurtic) (Leptokurtic)
PATONGA (OFFSHORE)	-2.77 to -0.10 +0.04 to 0.37 (only seven positive values)	-0.56 to -0.02 +0.01 to +0.20 (only eight positive values)	5.52	2.39 to 15.12	1.16(Leptokurtic)	0.85 to 2.12 (Platykurtic) (Very Leptokurtic)
PEARL BEACH	-1.25 to -0.02 +0.01 to +0.26 (only nine positive values)	-0.34 to -0.01 +0.01 to +0.21	3.94	1.94 to 7.41	1.24 (Leptokurtic)	0.75 to 1.52 (Platykurtic) (Very Leptokurtic)
UMINA-WOY WOY (?) PLEISTOCENE	-0.68 to -0.02 +0.04 to +0.60	-0.16 to -0.01 +0.01 to +0.18	3.76	2.41 to 6.55	1.07(Mesokurtic)	0.89 to 1.35 (Platykurtic) (Leptokurtic)
UMINA-WOY WOY HOLOCENE	-0.31 to -0.02 +0.02 to +0.39	-0.07 to -0.01 +0.01 to +0.11	3.42	2.57 to 4.84	0.97 (Mesokurtic)	0.81 to 1.19 (Platykurtic) (Leptokurtic)

Graphic Mean is not plotted.

TABLE 7.3

Average graphic and moment measure values of barrier samples from Twofold Bay and adjacent South Coast areas. (Values are in phi units (ϕ). Only Folk and Ward values are shown in this table, although Inman and Trask values were obtained from the computer programme).

BARRIER LOCALITY	FIRST MOMENT (Mean)	RANGE of VALUES	STANDARD DEVIATION (SORTING)	RANGE of VALUES	INCLUSIVE GRAPHIC STANDARD DEVIATION (FOLK AND WARD)	RANGE of VALUES
PAMBULA	2.082(0.2365 mm)	1.703(0.3078 mm) to 2.42(0.1895 mm)	0.35 (well sorted)	0.26 to 0.45	0.35 (well sorted)	0.26 to 0.48
EDEN	1.110(0.4633 mm)	0.24(0.8468 mm) to 1.72(0.3035 mm)	0.66 (moderately well sorted)	0.37 to 0.87	0.65 (moderately well sorted)	0.34 to 0.92
BOYD TOWN	1.809(0.2872 mm)	1.23(0.4263 mm) to 2.35(0.1961 mm)	0.50 (well sorted)	0.40 to 0.69	0.50 (well sorted)	0.40 to 0.71
WHALE BEACH	1.164(0.4475 mm)	0.82(0.5664 mm) to 1.52(0.3487 mm)	0.75 (moderately well sorted)	0.58 to 0.87	0.77 (moderately sorted)	0.57 to 0.87

BARRIER LOCALITY	THIRD MOMENT (SKEWNESS) Range of Values	INCLUSIVE GRAPHIC SKEWNESS(FOLK AND WARD) Range of Values	FOURTH MOMENT (KURTOSIS)	RANGE of VALUES	GRAPHIC KURTOSIS (FOLK AND WARD)	RANGE of VALUES
PAMBULA	-0.73 to -0.12 +0.01 to +0.31	-0.31 to -0.02 +0.05 to +0.18	2.80	2.22 to 4.36	0.94 (Mesokurtic)	0.80 to 1.30 (Platykurtic) (Leptokurtic)
EDEN	-0.94 to -0.05 +0.10 to +0.50	-0.44 to -0.01 +0.09 to +0.39	3.24	2.18 to 4.70	1.06 (Mesokurtic)	0.81 to 1.45 (Platykurtic) (Leptokurtic)
BOYD TOWN	-1.12 to -0.03 +0.01 to +0.41	-0.22 to -0.03 +0.01 to +0.23	3.33	2.40 to 6.18	1.03 (Mesokurtic)	0.79 to 1.28 (Platykurtic) (Leptokurtic)
WHALE BEACH	-0.66 to 0.07 to +0.13 (only one positive value)	-0.15 to -0.06 to 0.11 (only one positive value)	2.62	2.21 to 3.71	0.92 (Mesokurtic)	0.81 to 1.15 (Platykurtic) (Leptokurtic)

Graphic Mean is not plotted.

TABLE 7.4A

Percentage of beach and offshore samples that are nearly symmetrical (Skewness values between -0.10 and +0.10)

Locality	Beaches	Number of Beach Samples Analyzed		Percentage nearly Symmetrical (to the nearest whole number)
Broken Bay:				
Sydney Region	Pearl	64		8
	Umina (Ocean)	99		15
	Patonga	126		13
	Grand Total	289	Average	12
South Coast	Pambula and Twofold Bay	34		3
Mid-North Coast	Various beaches	16		19
	Total for Three Areas	339	Grand Average	12
Broken Bay:	Brisk Bay offshore samples	82		3

TABLE 7.4B

Percentage of beach samples that are positively skewed.

Locality	Beach	Percentage (to nearest whole number)	
Broken Bay:			
Sydney Region	Pearl	3	
	Umina (Ocean)	19	
	Patonga	24	
South Coast	Pambula and Twofold Bay	20	
Mid-North Coast	Various beaches	50	
Average		19	
Broken Bay: Brisk Bay offshore samples		4	
High-tide level samples		35	(No. of High tide level samples positively skewed: Broken Bay,15; South Coast 7; Mid-North Coast 2)

TABLE 7.5

Statistical Parameters and Roundness Values for Dune and Barrier Sands

Cliff-Top Dunes Mean Size (Grand Average)		Barriers Mean-Grain Size (Grand Average)	
ø	mm	ø	mm
1.98	0.2535	2.00	0.2500

Sorting (Graphical Standard Deviation)

0.34 (Grand Average) 0.38 (Grand Average)

Skewness (Third Moment): Range of Values

+0.10 to +0.64 -1.8 to -0.03

+0.03 to 1.37 (limited number of samples only show positive skewness)

Roundness Values (Powers' Scale x 100)

Cliff-top Dunes and Barriers

Heavy Minerals 36-50	Size range	0.210-0.074 mm
Quartz grains 32-44	Size	0.353 mm (44 mesh B.S.S.)
Quartz grains 27-41	Size	0.125 mm (120 mesh B.S.S.

TABLE 7.6

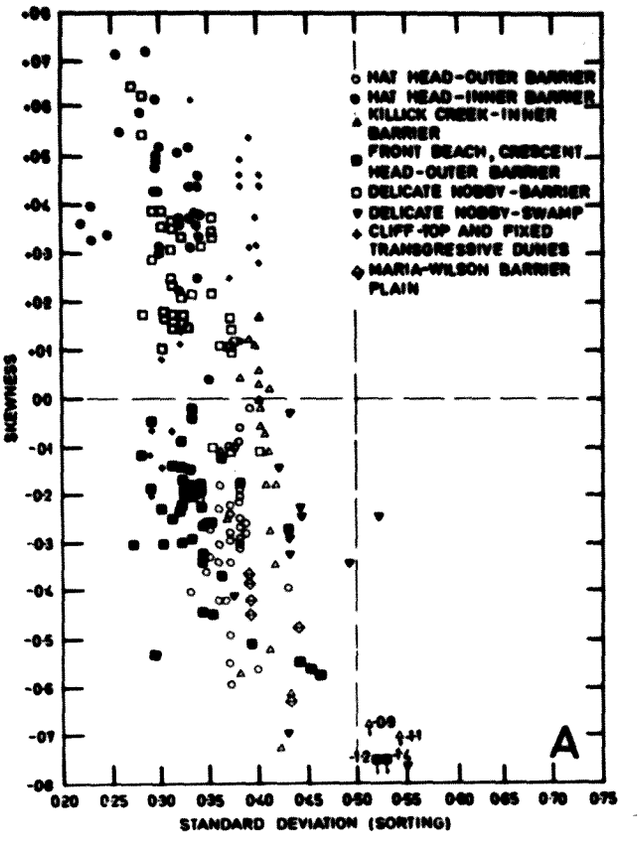
Correlations between different sorting measures.

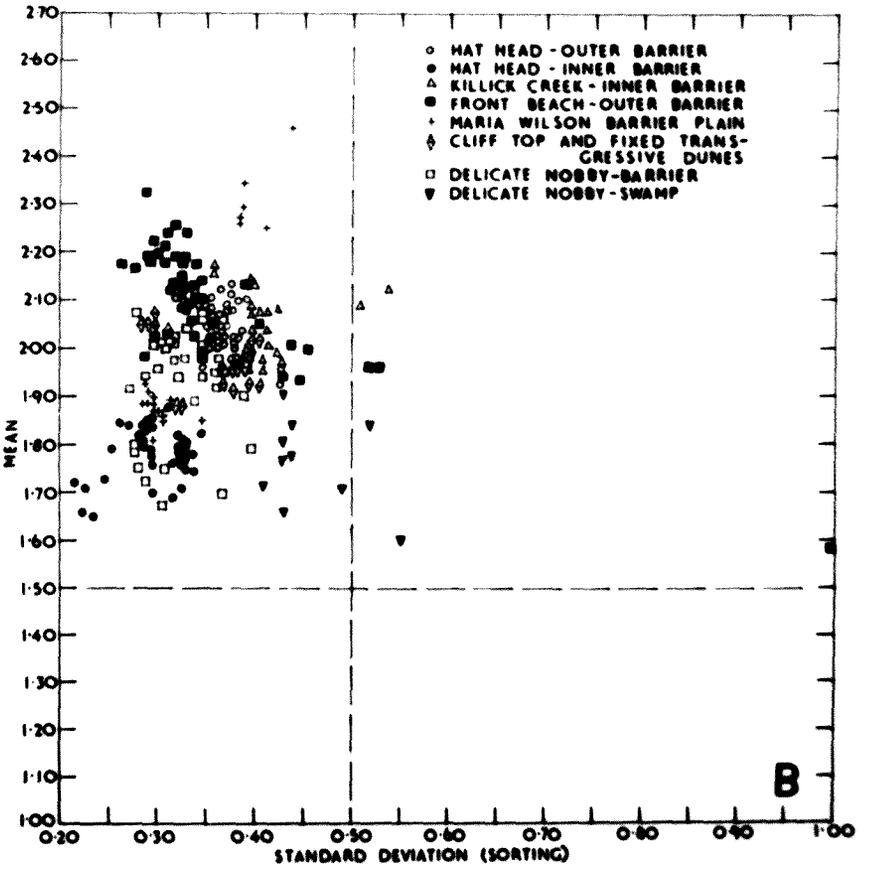
Correlation	Sum of Residuals Squared [Σ(Y obs. - Y calc.)^2]	No. of points plotted	Regression Equation (for Linear Regression)
Standard deviation and sorting measure of Inman	Linear curve 9.8972	1200	Sorting Measure of Inman = $1.0179\sigma\phi - 0.0383$
	Fourth-degree curve 7.5129	"	
	Sixth-degree curve 6.8772	"	
Standard deviation and sorting measure of Folk and Ward	Linear curve 119.029	"	Sorting Measure of Folk and Ward = $1.7759\sigma\phi - 0.3244$
	Fourth-degree curve 95.4168	"	
	Sixth-degree curve 92.7666	"	
Standard deviation and Trask sorting coefficient	Linear curve 1.9844	"	Sorting Coefficient of Trask = $0.5260\sigma\phi + 0.9794$
	Fourth-degree curve 1.86676	"	
	Sixth-degree curve 1.8490	"	
Sorting measure of Folk and Ward and sorting measure of Inman.	Linear curve 93.333	"	Sorting Measure Inman = -0.02423 +1.7075 (Folk and Ward)
	Fourth-degree curve 89.4300	"	
	Sixth-degree curve 86.7487	"	

Figures 7.1A and 7.1B

7.1A Plot of standard deviation (sorting) and third moment (skewness) using phi (ϕ) scale, for Mid-North Coast barrier, swamp and dune sands.

7.1B Plot of standard deviation (sorting) and first moment (mean), using phi (ϕ) scale, for Mid-North Coast barrier, swamp and dune sands.

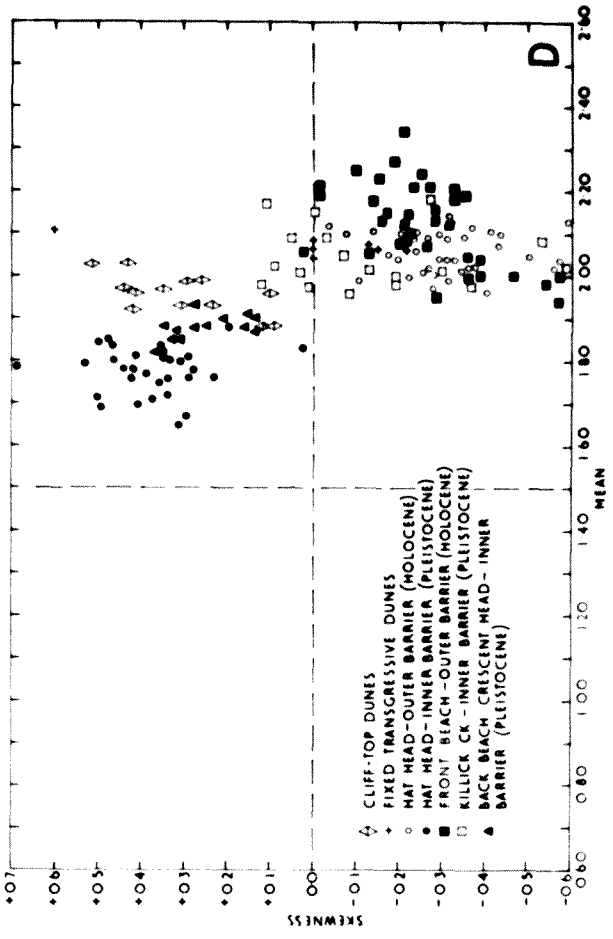

HAT HEAD-OUTER BARRIER
HAT HEAD-INNER BARRIER
KILLICK CREEK-INNER BARRIER
FRONT BEACH, CRESCENT HEAD-OUTER BARRIER
DELICATE NOBBY-BARRIER
DELICATE NOBBY-SWAMP
CLIFF-TOP AND FIXED TRANSGRESSIVE DUNES
MARIA-WILSON BARRIER PLAIN
SKEWNESS
STANDARD DEVIATION (SORTING)
A

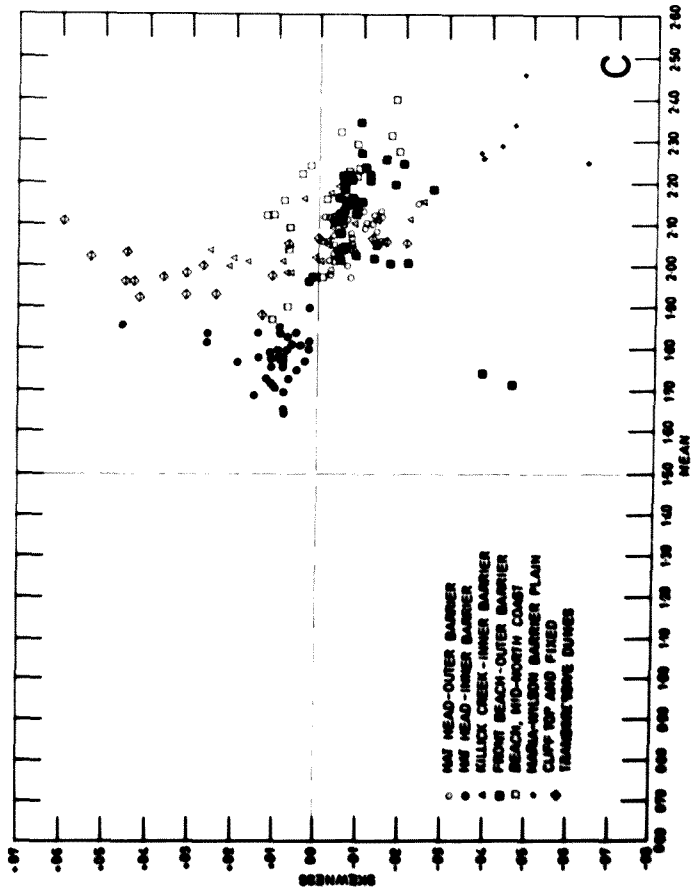

HAT HEAD - OUTER BARRIER
HAT HEAD - INNER BARRIER
KILLICK CREEK - INNER BARRIER
FRONT BEACH - OUTER BARRIER
MARIA WILSON BARRIER PLAIN
CLIFF TOP AND FIXED TRANS-GRESSIVE DUNES
DELICATE NOBBY-BARRIER
DELICATE NOBBY-SWAMP
MEAN
STANDARD DEVIATION (SORTING)
B

Figures 7.1C and 7.1D

7.1C Plot of mean and Inclusive Graphic Skewness (Folk and Ward), using phi (ϕ) scale, for Mid-North Coast barrier and dune sands.

7.1D Plot of first moment (mean) and third moment (skewness), using phi (ϕ) scale, for barrier and dune sands.


D
CLIFF-TOP DUNES
FIXED TRANSGRESSIVE DUNES
HAT HEAD-OUTER BARRIER (HOLOCENE)
HAT HEAD-INNER BARRIER (PLEISTOCENE)
FRONT BEACH-OUTER BARRIER (HOLOCENE)
KILLICK CK - INNER BARRIER (PLEISTOCENE)
BACK BEACH CRESCENT HEAD- INNER BARRIER (PLEISTOCENE)
SKEWNESS
MEAN


C
HAT HEAD-OUTER BARRIER
HAT HEAD-INNER BARRIER
KILLICK CREEK-INNER BARRIER
FRONT BEACH-OUTER BARRIER
BEACH, MID-NORTH COAST
MARSH-HELDEN BARRIER PLAIN
CLIFF TOP AND FIXED
TRANSGRESSIVE DUNES
SKEWNESS
MEAN

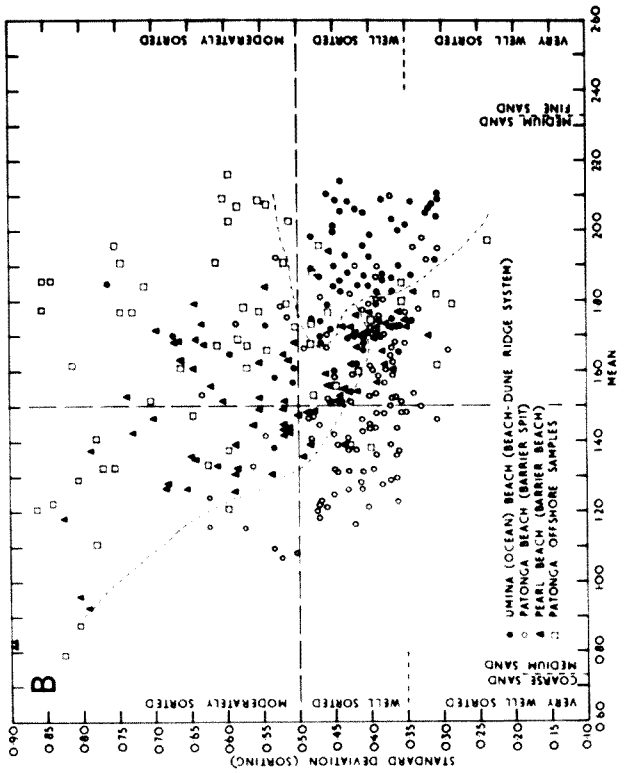
Figures 7.2A - 7.2C

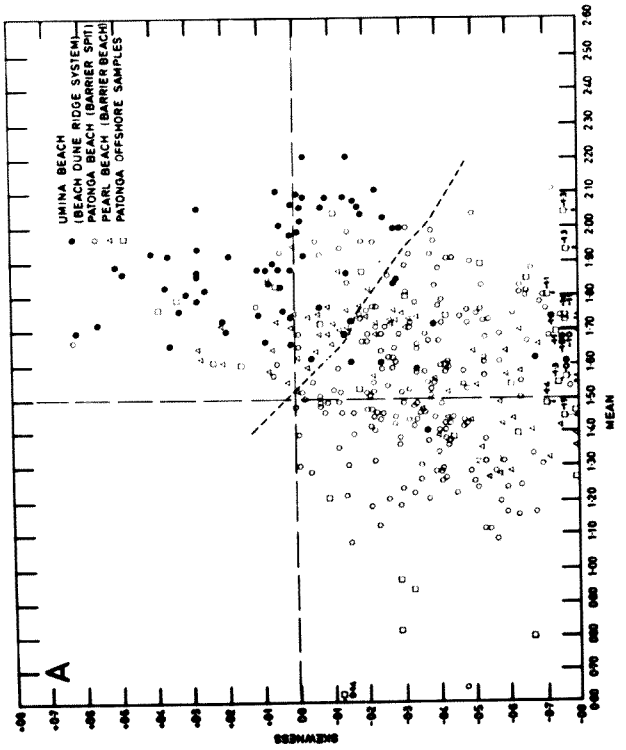
7.2A Plot of first moment (mean) and third moment (skewness), using phi (ϕ) scale, for Broken Bay barrier and offshore sands.

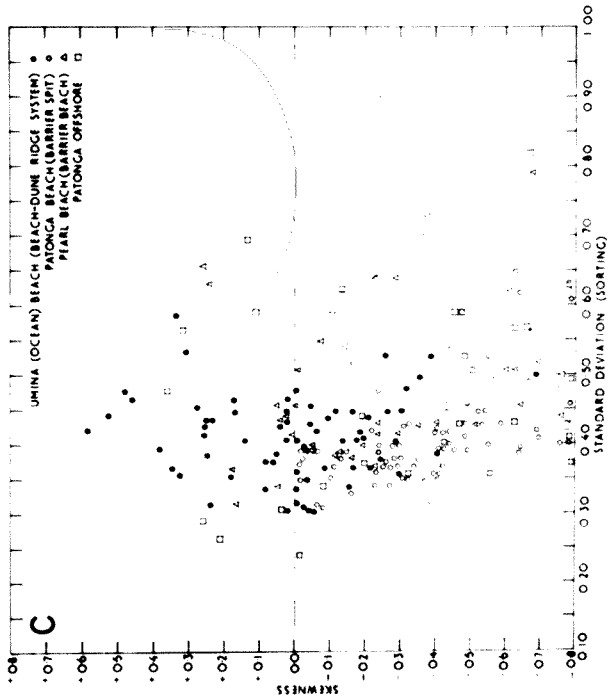
7.2B Plot of first moment (mean) and standard deviation (sorting), using phi (ϕ) scale, for Broken Bay barrier and offshore sands.

7.2C Plot of standard deviation (sorting) and third moment (skewness), using phi (ϕ) scale, for Broken Bay barrier and offshore sands.

Figures 7.2A - 7.2C







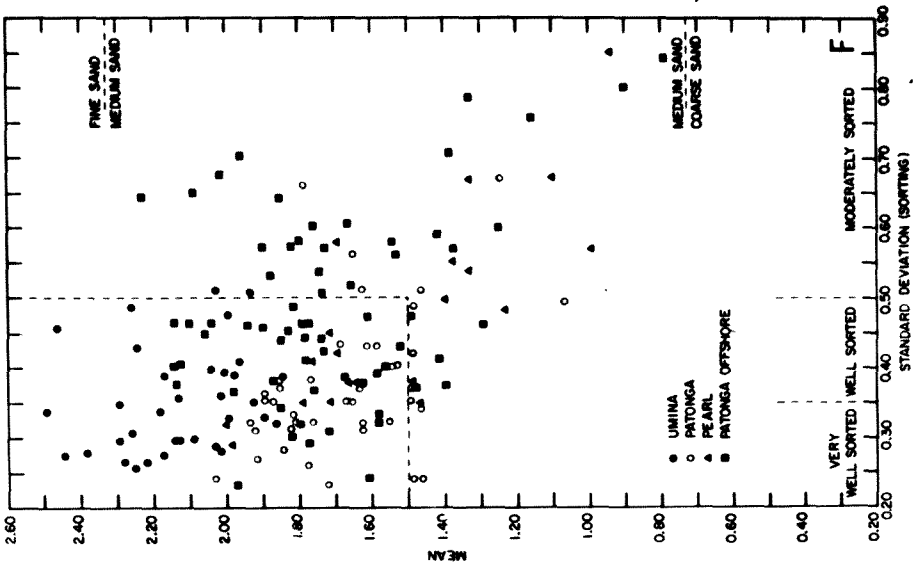
Figures 7.2D - 7.2F

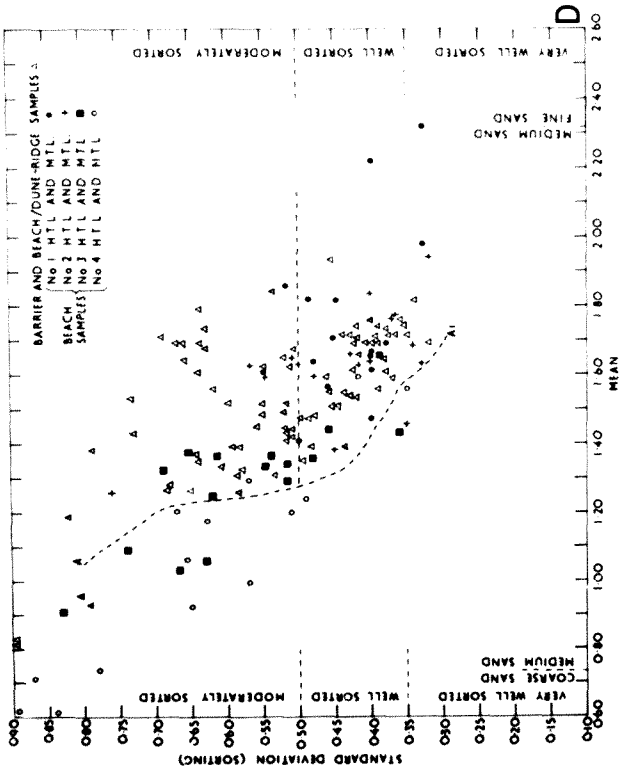
7.2D Plot of first moment (mean) and standard deviation (sorting), using phi (ϕ) scale, for Patonga beach sands.

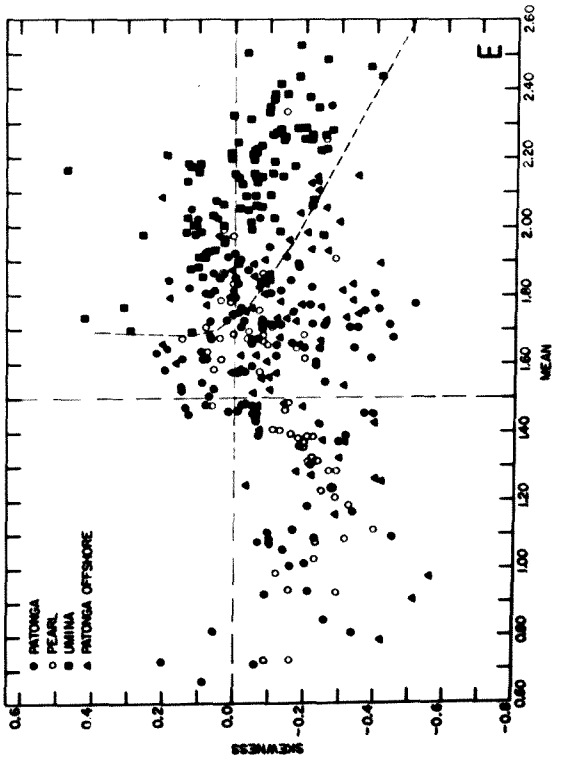
7.2E Plot of first moment (mean) and third moment (skewness), using phi (ϕ) scale, for Broken Bay offshore and beach sands.

7.2F Plot of standard deviation (sorting) and first moment (mean), using phi (ϕ) scale, for Broken Bay offshore and beach sands.

Figures 7.2D - 7.2F





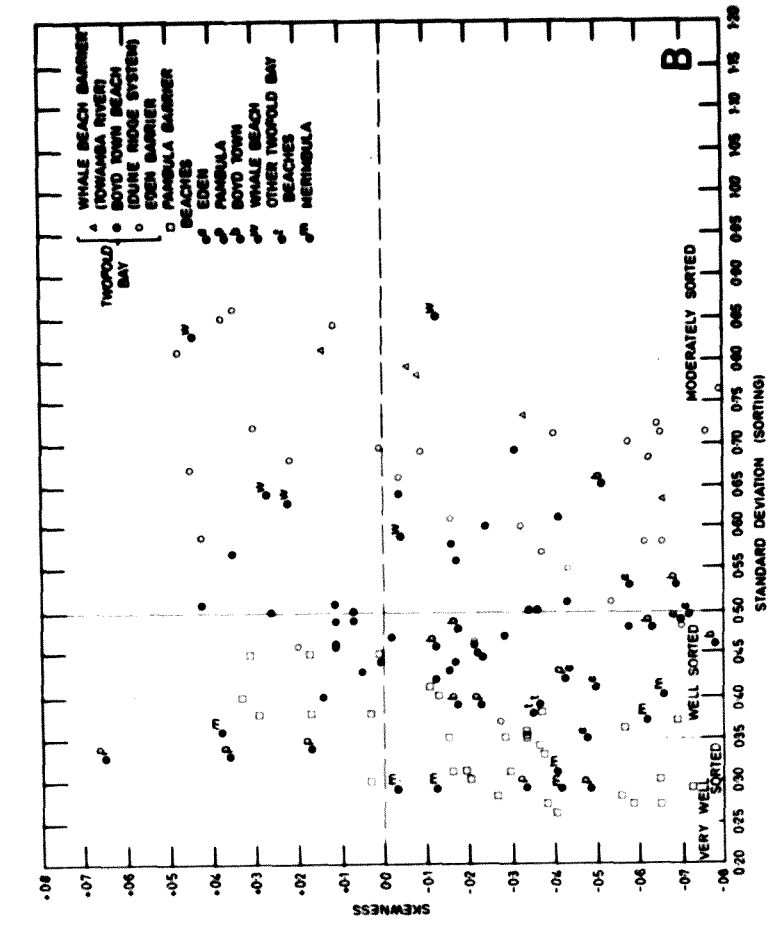


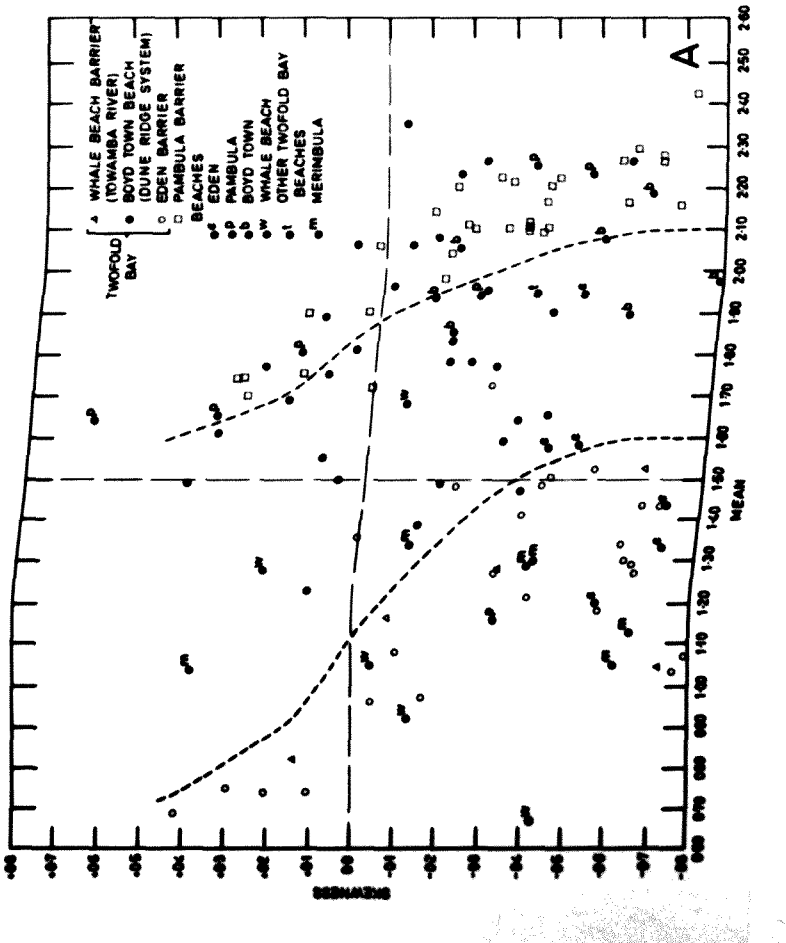
Figures 7.3A and 7.3B

7.3A Plot of first moment (mean) and third moment (skewness), using phi (ϕ) scale, for south coast barrier and beach sands.

7.3B Plot of standard deviation (sorting) and third moment (skewness), using phi (ϕ) scale, for south coast barrier and beach sands.

Figures 7.3A - 7.3B



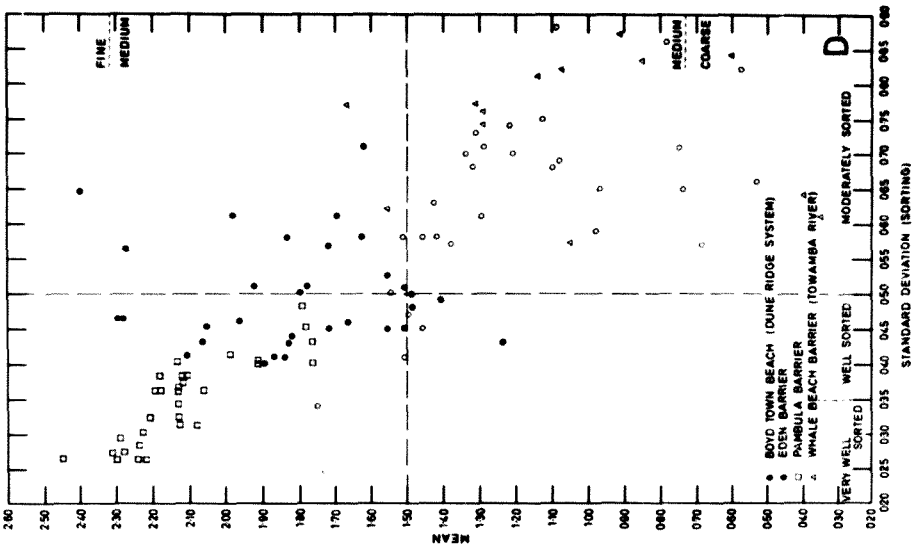


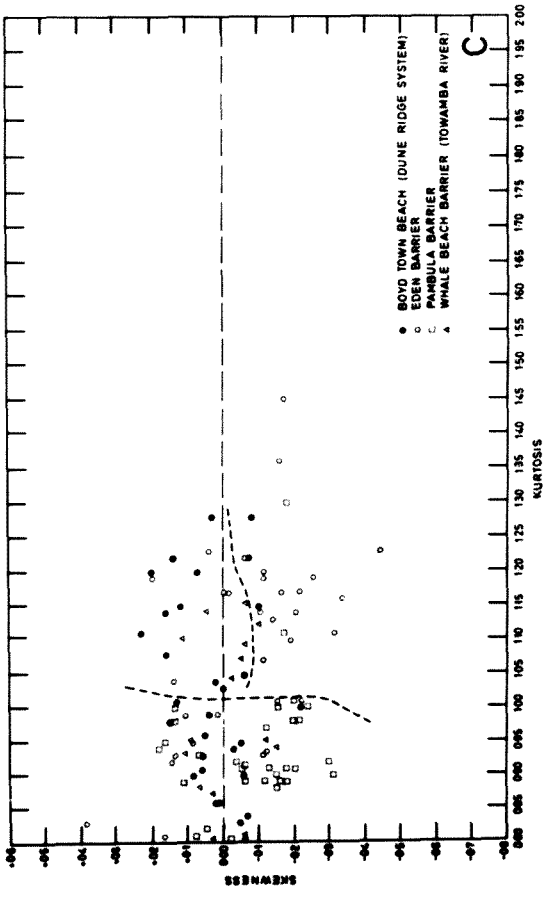
Figures 7.3C and 7.3D

7.3C Plot of Inclusive Graphic Skewness and Graphic Kurtosis (Folk and Ward), using phi (ϕ) scale, for south coast barrier sands.

7.3D Plot of standard deviation (sorting) and first moment (mean), using phi (ϕ) scale, for south coast barrier sands.

Figures 7.3C - 7.3D





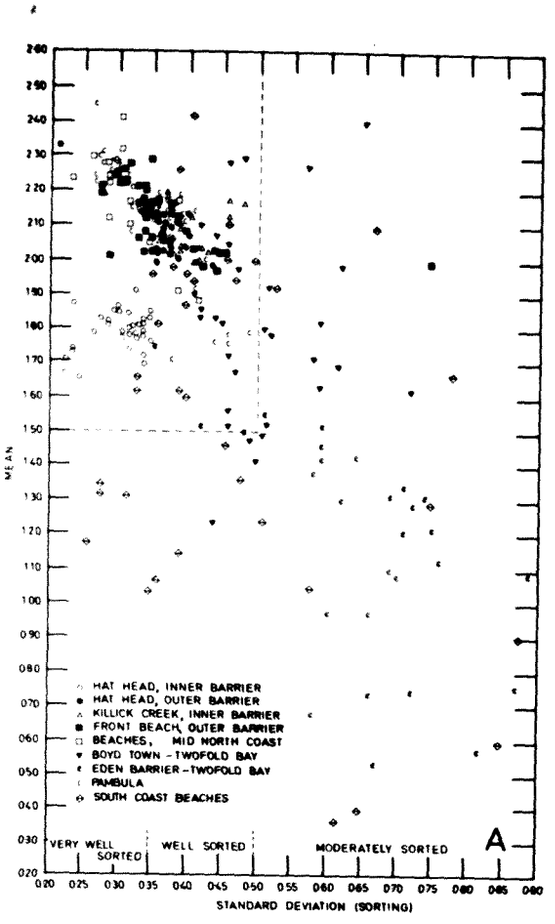
Figures 7.4A - 7.4C

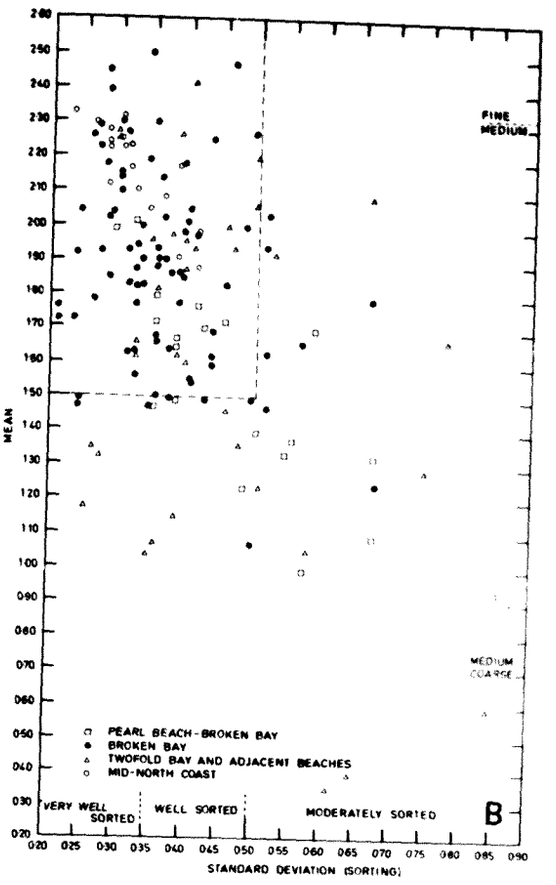
7.4A Plot of standard deviation (sorting) and first moment (mean), using phi (ϕ) scale, for barrier and beach sands from the Mid-North, and south coast.

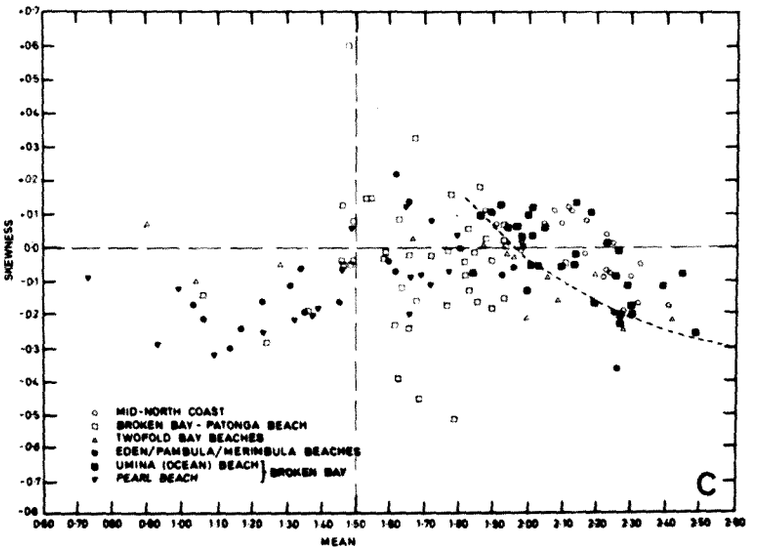
7.4B Plot of standard deviation (sorting) and first moment (mean), using phi (ϕ) scale, for beach sands from the three study areas.

7.4C Plot of first moment (mean) and third moment (skewness), using phi (ϕ) scale, for beach sands from the three study areas.

Figures 7.4A - 7.4C







Figures 7.5A - 7.5D

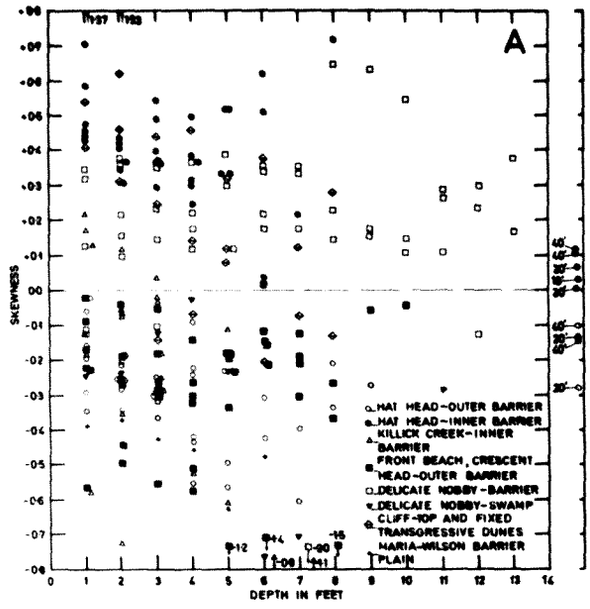
7.5A Plot of skewness versus depth.

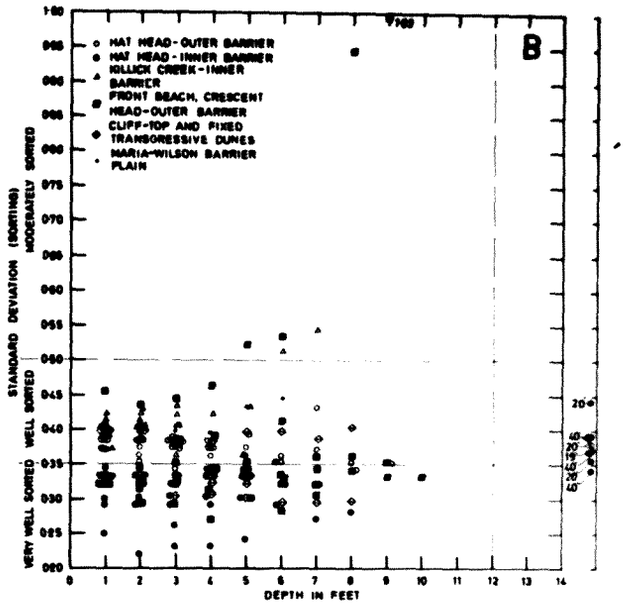
7.5B Plot of standard deviation (sorting) versus depth.

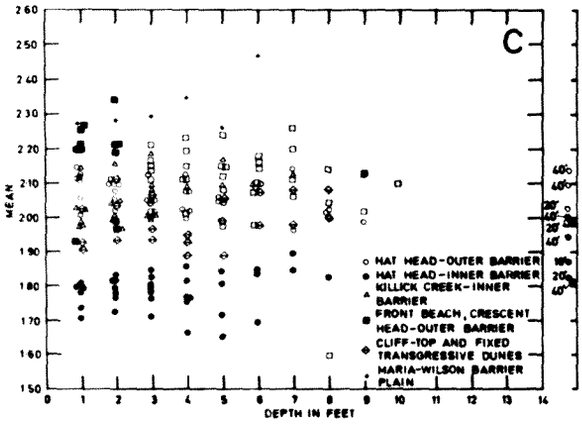
7.5C Plot of mean versus depth (barrier and dune samples).

7.5D Plot of mean versus depth (barrier and swamp samples).

Figures 7.5A - 7.5D







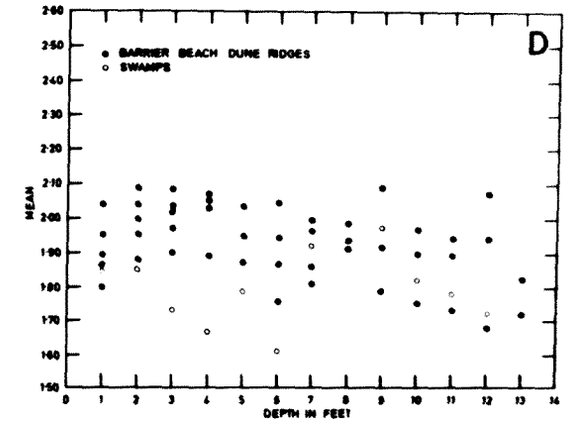
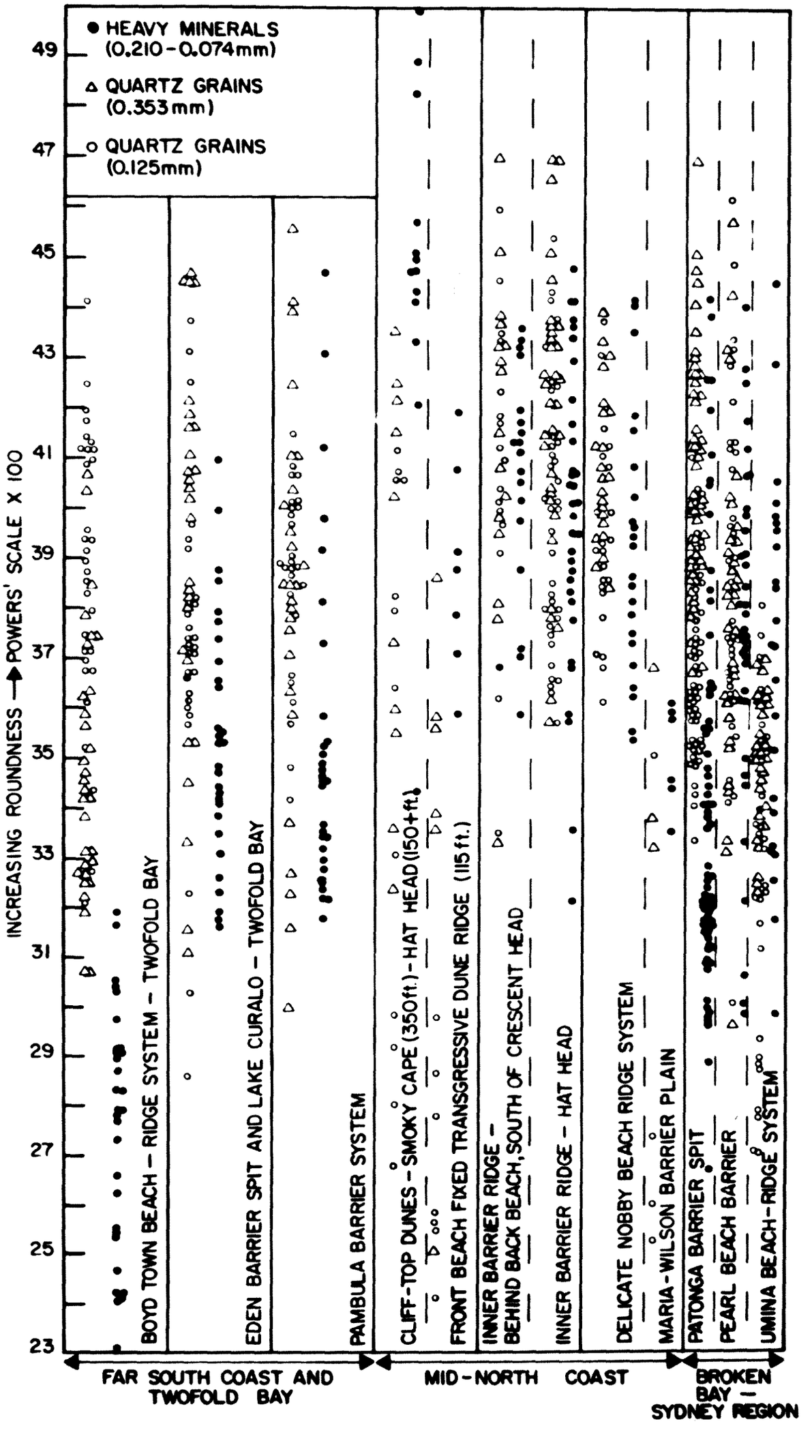


Figure 7.6 Roundness values for quartz and heavy minerals, plotted on the Powers' scale.


HEAVY MINERALS (0.210-0.074mm)
QUARTZ GRAINS (0.353mm)
QUARTZ GRAINS (0.125mm)
INCREASING ROUNDNESS → POWERS' SCALE X 100
49
47
45
43
41
39
37
35
33
31
29
27
25
23
BOYD TOWN BEACH – RIDGE SYSTEM – TWOFOLD BAY
EDEN BARRIER SPIT AND LAKE CURALO – TWOFOLD BAY
PAMBULA BARRIER SYSTEM
CLIFF-TOP DUNES – SMOKY CAPE (350ft.) – HAT HEAD (150+ft.)
FRONT BEACH FIXED TRANSGRESSIVE DUNE RIDGE (115 ft.)
INNER BARRIER RIDGE – BEHIND BACK BEACH, SOUTH OF CRESCENT HEAD
INNER BARRIER RIDGE – HAT HEAD
DELICATE NOBBY BEACH RIDGE SYSTEM
MARIA-WILSON BARRIER PLAIN
PATONGA BARRIER SPIT
PEARL BEACH BARRIER
UMINA BEACH-RIDGE SYSTEM
FAR SOUTH COAST AND TWOFOLD BAY
MID-NORTH COAST
BROKEN BAY – SYDNEY REGION

Figures 7.7A - 7.7D Correlation between standard deviation and sorting measure of Folk and Ward.

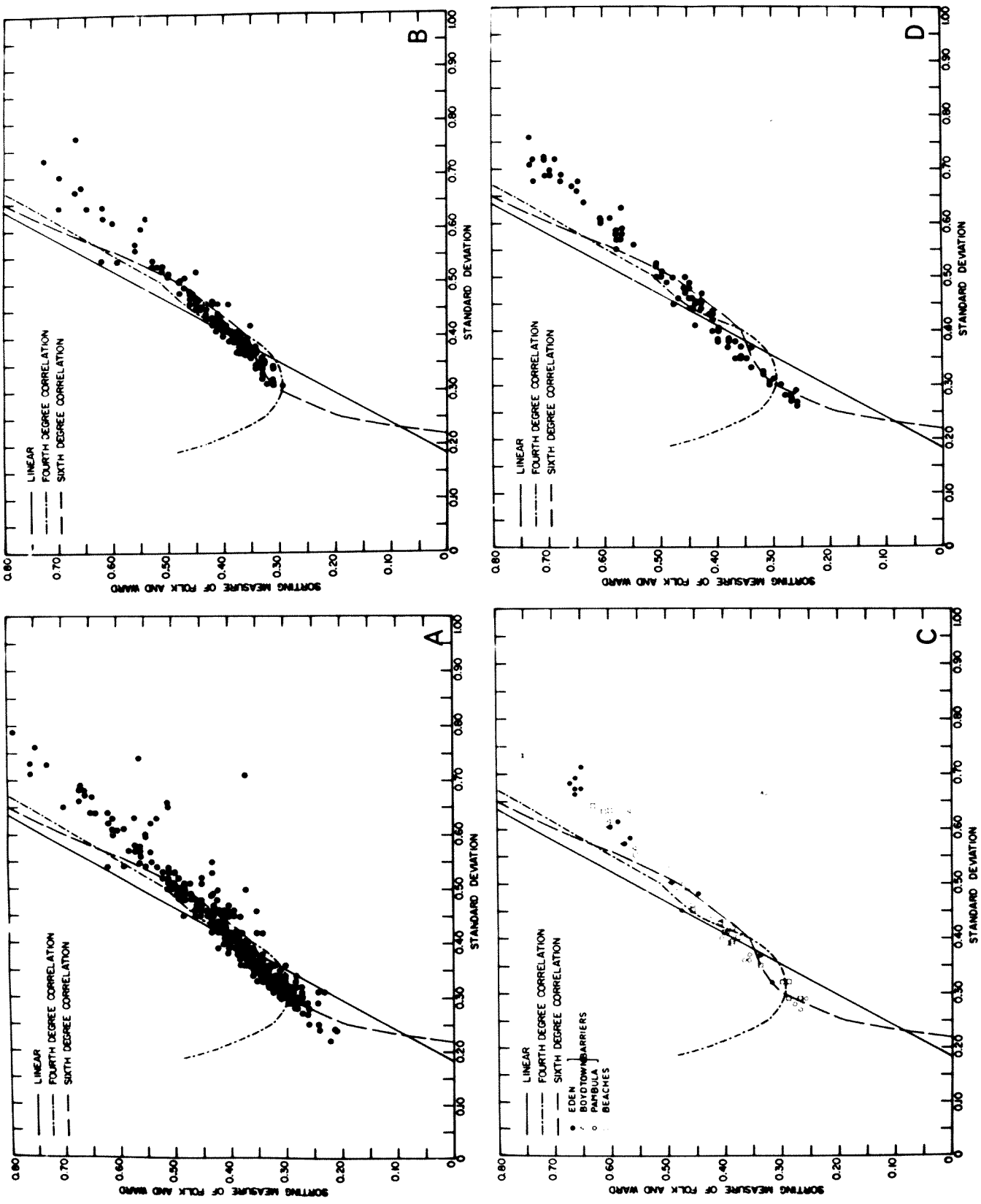
7.7A Barrier, dune and beach sands from the three study areas.

7.7B Broken Bay barrier samples.

7.7C South coast barrier and beach sands.

7.7D South coast barrier, beach and lagoonal sands.

Figures 7.7A - 7.7D



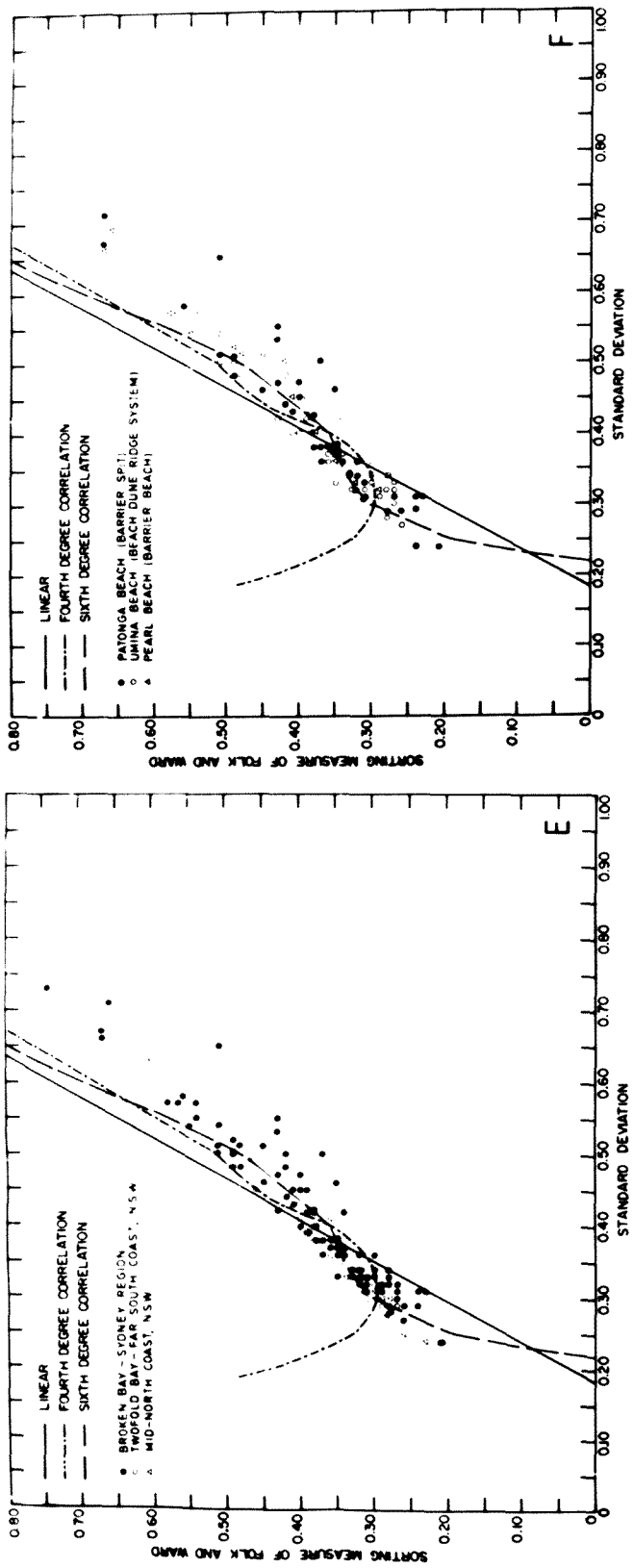
Figures 7.7E - 7.7G Correlation between standard deviation and sorting measure of Folk and Ward.

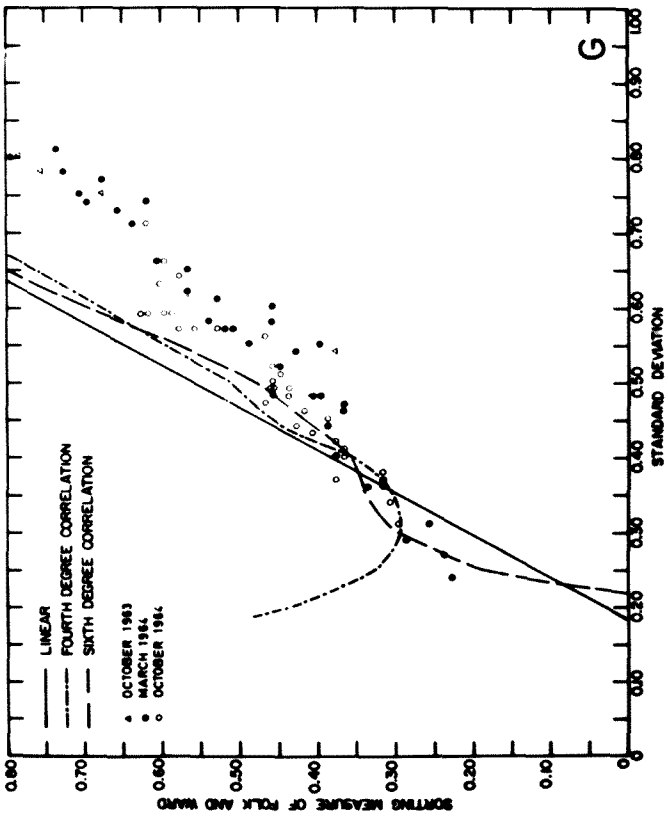
7.7E Beach sands from the three study areas.

7.7F Broken Bay barrier and beach samples.

7.7G Patonga (Brisk Bay) offshore sands.

Figures 7.7E - 7.7G





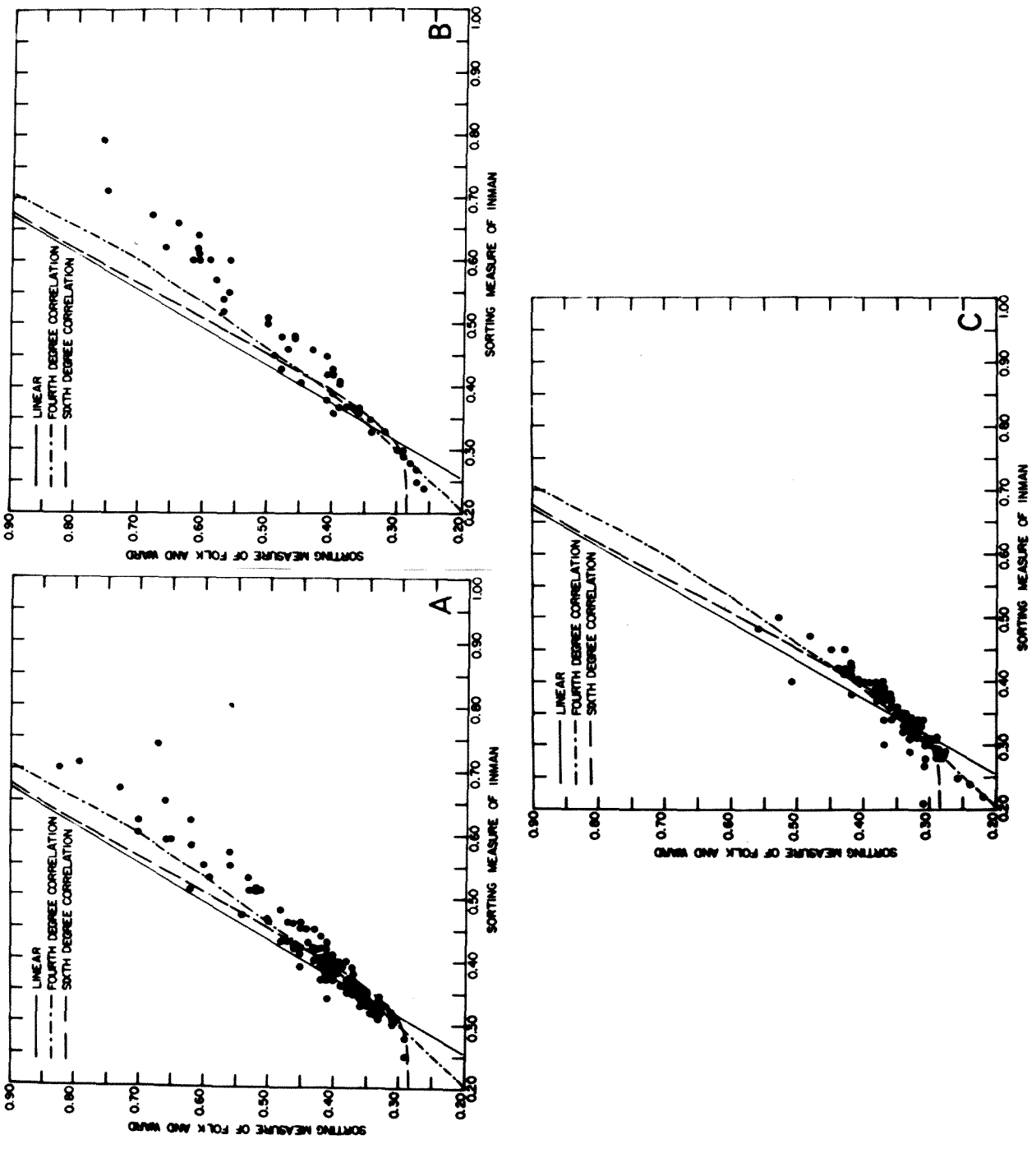
Figures 7.8A - 7.8C Correlation between sorting measure of Inman (1952) and sorting measure of Folk and Ward (1957).

7.8A Broken Bay barrier sands.

7.8B South coast barrier sands.

7.8C Mid-North Coast barrier and dune sands.

Figures 7.8A - 7.8C



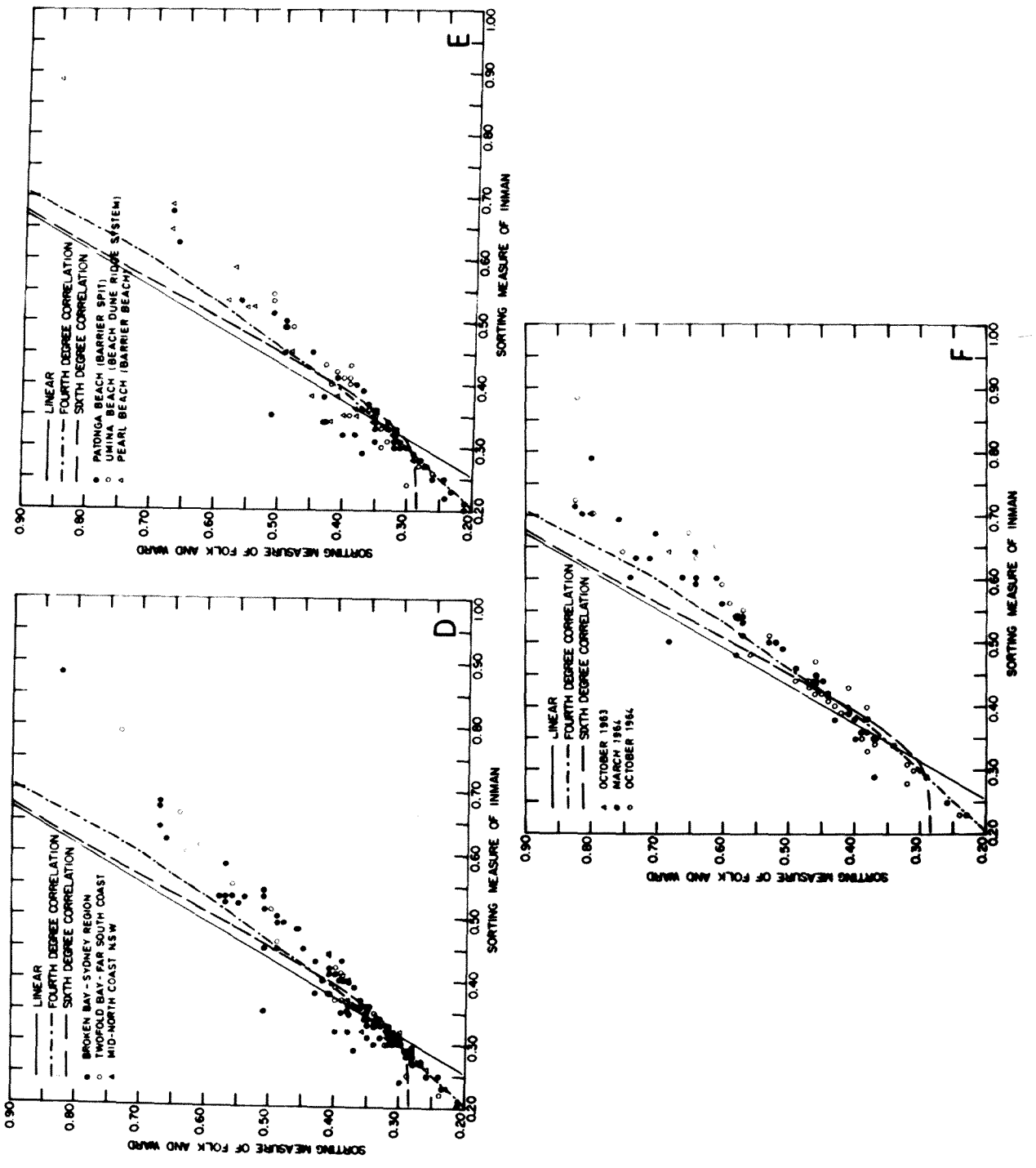
Figures 7.8D - 7.8F Correlation between sorting measure of Inman (1952) and sorting measure of Folk and Ward (1957).

7.8D Beach sands from the three study areas.

7.8E Broken Bay barrier and beach sands.

7.8F Patonga (Brisk Bay) offshore sands.

Figures 7.8D - 7.8F



Figures 7.9A - 7.9D Correlation between standard deviation and sorting measure of Inman (1952).

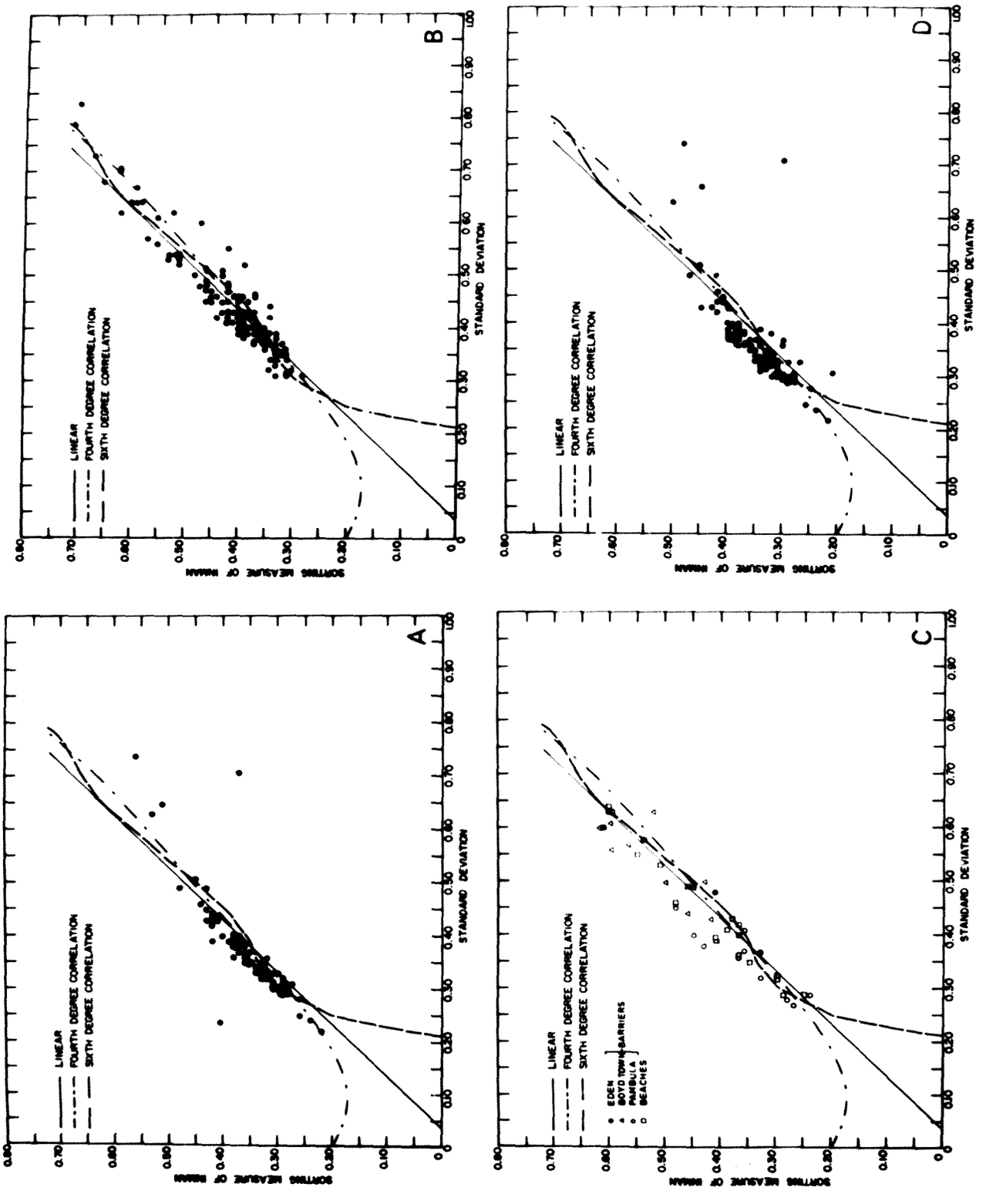
7.9A Sands from all coastal environments in the three study areas.

7.9B Broken Bay barrier sands.

7.9C South coast barrier and beach sands.

7.9D Mid-North Coast barrier and dune sands.

Figures 7.9A - 7.9D



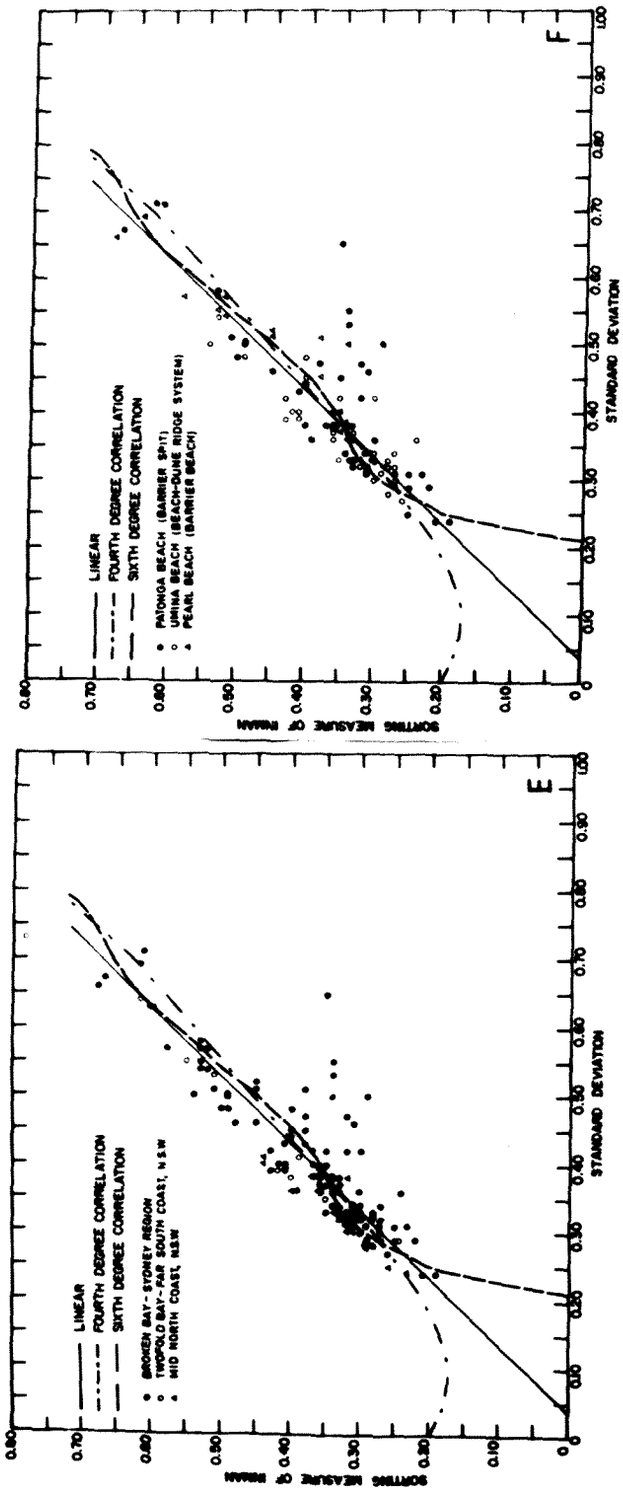
Figures 7.9E - 7.9G Correlation between standard deviation and sorting measure of Inman (1952).

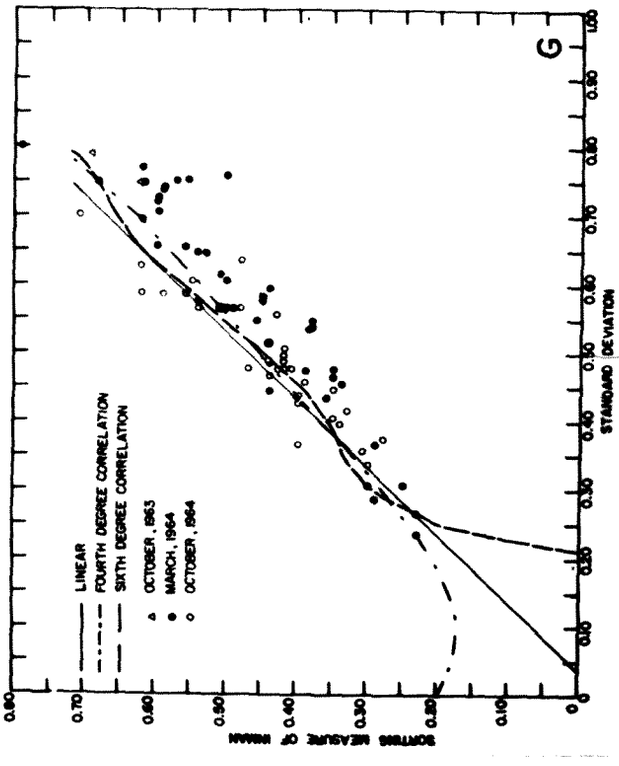
7.9E Beach sands from the three study areas.

7.9F Broken Bay barrier and beach sands.

7.9G Patonga (Brisk Bay) offshore sands.

Figures 7.9E - 7.9G





Figures 7.10A - 7.10D Correlation between standard deviation and Trask's (1932) sorting coefficient.

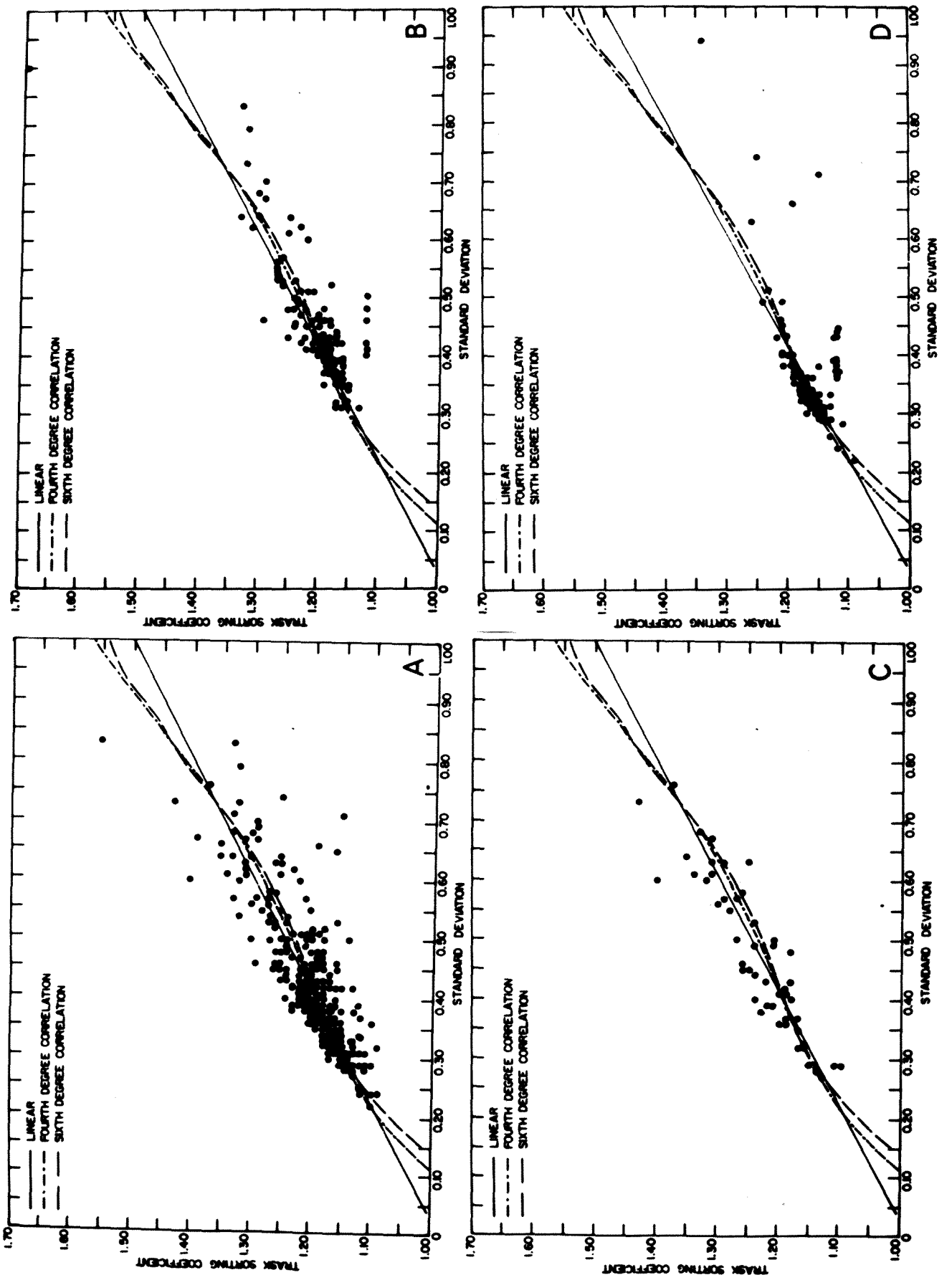
7.10A Sands from all coastal environments in the three study areas.

7.10B Broken Bay barrier samples.

7.10C South coast barrier and beach samples.

7.10D Mid-North Coast barrier and dune samples.

Figures 7.10A - 7.10D

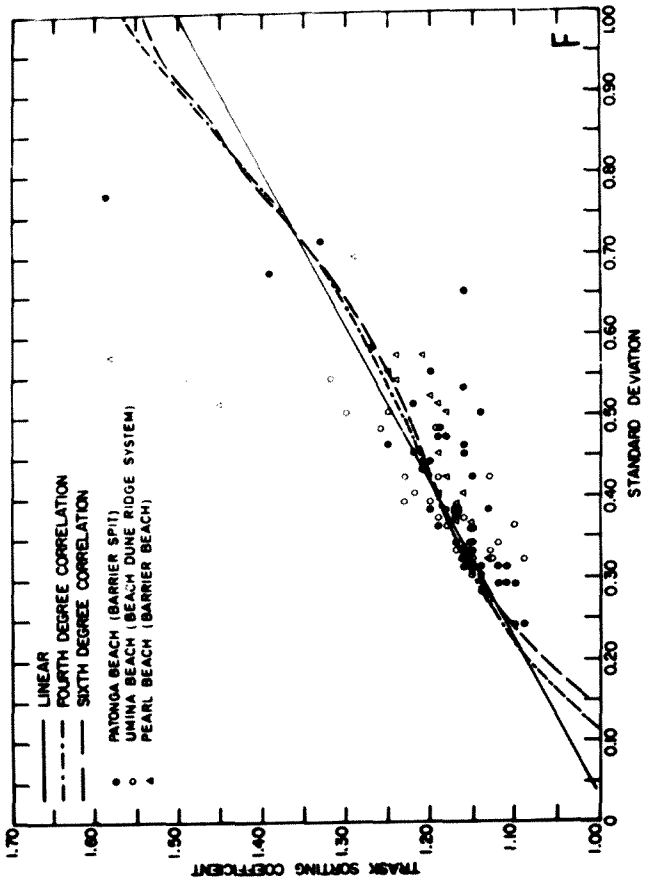


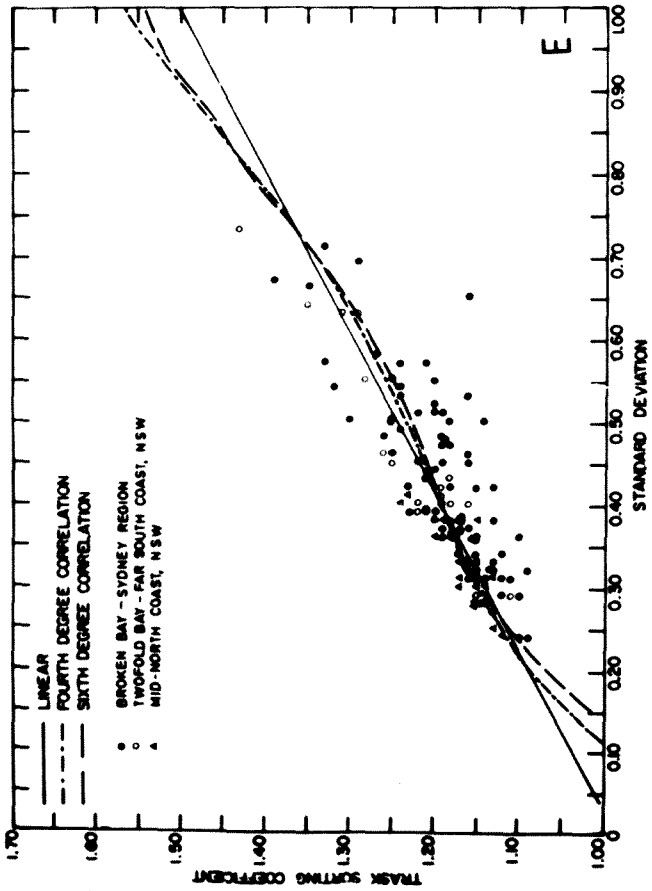
Figures 7.10E - 7.10G Correlation between standard deviation and Trask's (1932) sorting coefficient.

7.10E Beach sands from the three study areas.

7.10F Broken Bay beach sands.

7.10G Patonga (Brisk Bay) offshore sands.


F
LINEAR
FOURTH DEGREE CORRELATION
SIXTH DEGREE CORRELATION
PATONGA BEACH (BARRIER SPIT)
UMINA BEACH (BEACH DUNE RIDGE SYSTEM)
PEARL BEACH (BARRIER BEACH)
TRASK SORTING COEFFICIENT
STANDARD DEVIATION


E
LINEAR
FOURTH DEGREE CORRELATION
SIXTH DEGREE CORRELATION
BROKEN BAY - SYDNEY REGION
TWOFOLD BAY - FAR SOUTH COAST, NSW
MID-NORTH COAST, NSW
TRASK SORTING COEFFICIENT
STANDARD DEVIATION

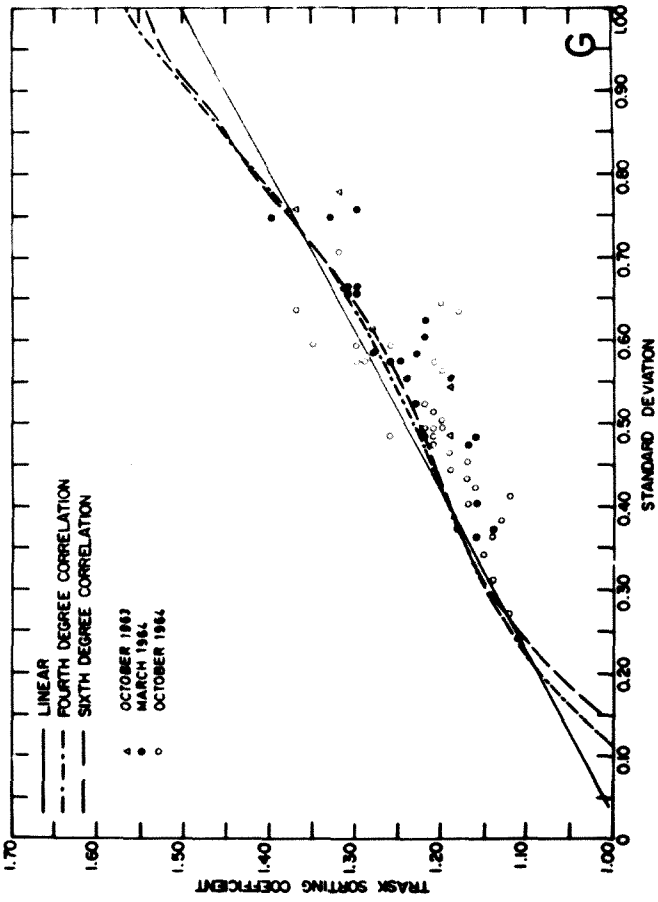

G
LINEAR
FOURTH DEGREE CORRELATION
SIXTH DEGREE CORRELATION
OCTOBER 1983
MARCH 1984
OCTOBER 1984
TRASK SORTING COEFFICIENT
STANDARD DEVIATION

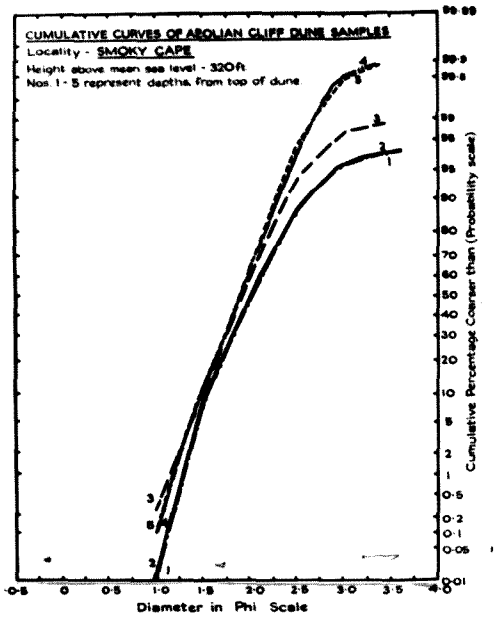
Figure 7.11 Average cumulated grain-size frequency distribution curves of barrier, dune and beach sands - the three study areas.

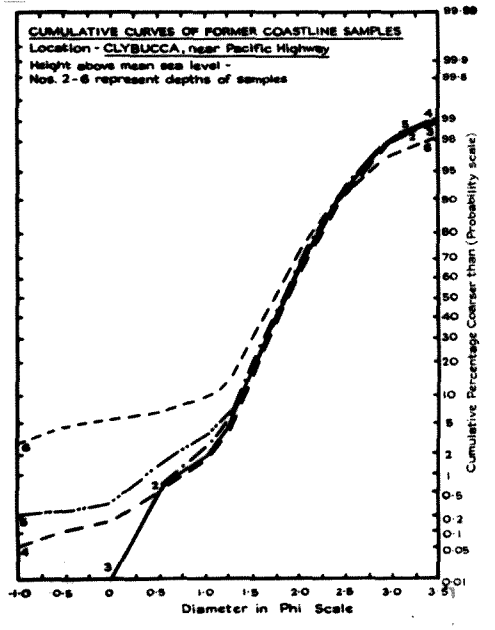
Figure 7.11

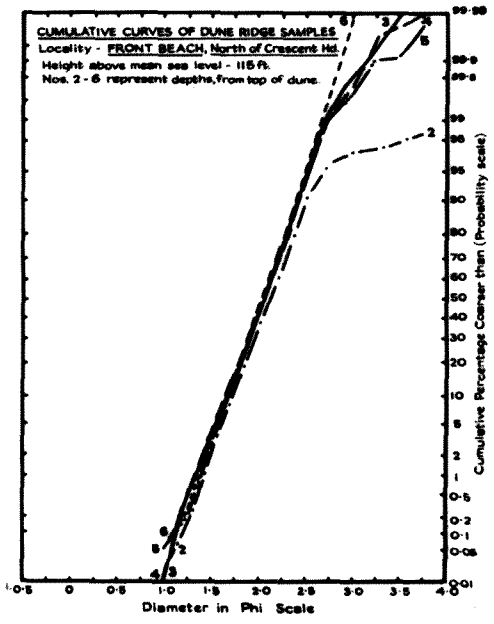
AVERAGE CUMULATED GRAIN-SIZE FREQUENCY DISTRIBUTION CURVES OF BARRIER AND BEACH SANDS- TWOFOLD BAY AND ADJACENT AREAS OF THE SOUTH COAST, NEW SOUTH WALES
Whale Beach Barrier-Beach Samples
Eden-Beach Samples
Boyd Town-Beach Samples
Pambula-Beach Samples
Whale Beach Barrier
Eden Barrier Spit
Boyd Town Beach Ridge System
Pambula Barrier Spit
Cumulative frequency percentage
Diameter in PHI Scale
AVERAGE CUMULATED GRAIN-SIZE FREQUENCY DISTRIBUTION CURVES OF BARRIER AND BEACH SANDS- BROKEN BAY, CENTRAL NEW SOUTH WALES COAST
Pearl Beach Samples
Patonga Beach Samples
Ocean Beach (Umina) Beach Samples
Umina-Woy-Woy Beach Ridge System
Pearl Beach Barrier
Patonga Border
Cumulative frequency percentage
Diameter in PHI scale
AVERAGE CUMULATED GRAIN-SIZE FREQUENCY DISTRIBUTION CURVES OF HOLOCENE AND PLEISTOCENE BARRIER AND PLEISTOCENE DUNE SANDS - NORTH COAST OF NEW SOUTH WALES
Swamps (Holocene)
Mid-North Coast Beach Samples
Clybucca shoreline (Pleistocene)
Outer Barrier (Holocene)
Inner Barrier (Pleistocene)
Pleistocene Dunes
Cumulative frequency percentage
Diameter in PHI scale

Figure 7.12 Grain-size frequency distribution curves of Mid-North Coast samples.

Figure 7.12


CUMULATIVE CURVES OF AEOLIAN CLIFF DUNE SAMPLES
Locality - SMOKY CAPE
Height above mean sea level - 320ft.
Nos. 1 - 5 represent depths from top of dune
Cumulative Percentage Coarser than (Probability scale)
Diameter in Phi Scale


CUMULATIVE CURVES OF FORMER COASTLINE SAMPLES
Location - CLYBUCCA, near Pacific Highway
Height above mean sea level -
Nos. 2 - 6 represent depths of samples
Cumulative Percentage Coarser than (Probability scale)
Diameter in Phi Scale


CUMULATIVE CURVES OF DUNE RIDGE SAMPLES
Locality - FRONT BEACH, North of Crescent Hd.
Height above mean sea level - 115 ft.
Nos. 2 - 6 represent depths, from top of dune.
Cumulative Percentage Coarser than (Probability scale)
Diameter in Phi Scale

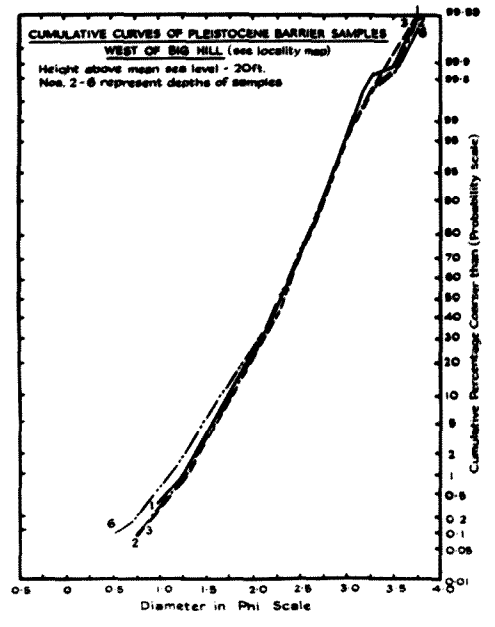
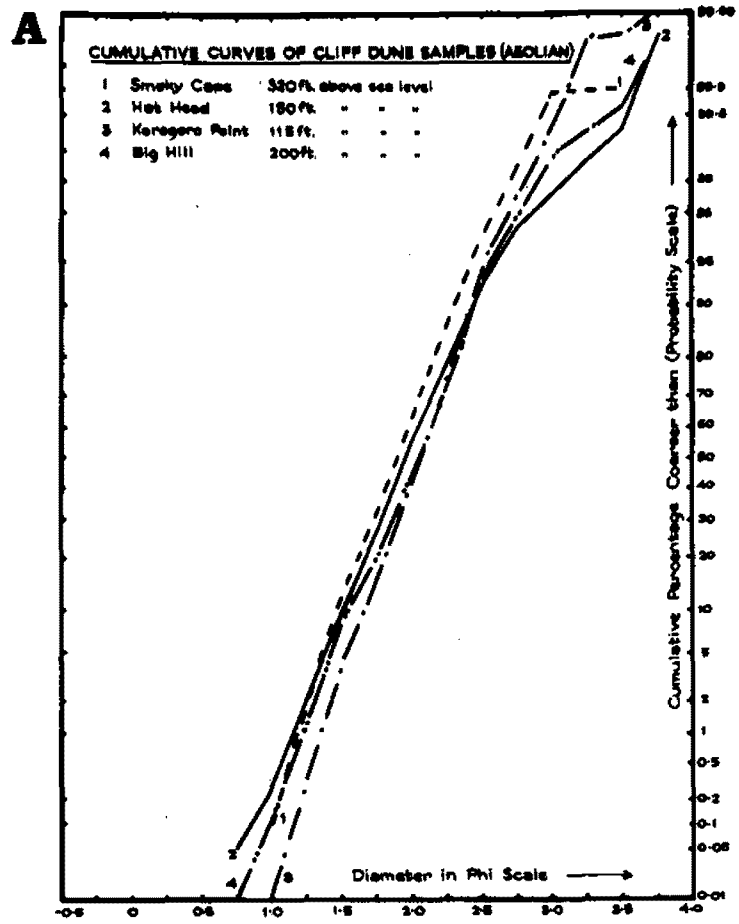

CUMULATIVE CURVES OF PLEISTOCENE BARRIER SAMPLES
WEST OF BIG HILL (see locality map)
Height above mean sea level - 20ft.
Nos. 2 - 6 represent depths of samples
Cumulative Percentage Coarser than (Probability scale)
Diameter in Phi Scale

Figure 7.13 Cumulative curves of cliff-top dune and Outer Barrier samples.

Figure 7.13


A
CUMULATIVE CURVES OF CLIFF DUNE SAMPLES (AEOLIAN)
1 Smoky Cape 320 ft. above sea level
2 Hat Head 150 ft. " " "
3 Keragera Point 115 ft. " " "
4 Big Hill 200 ft. " " "
Cumulative Percentage Coarser than (Probability Scale)
Diameter in Phi Scale
-0·5 0 0·5 1·0 1·5 2·0 2·5 3·0 3·5 4·0

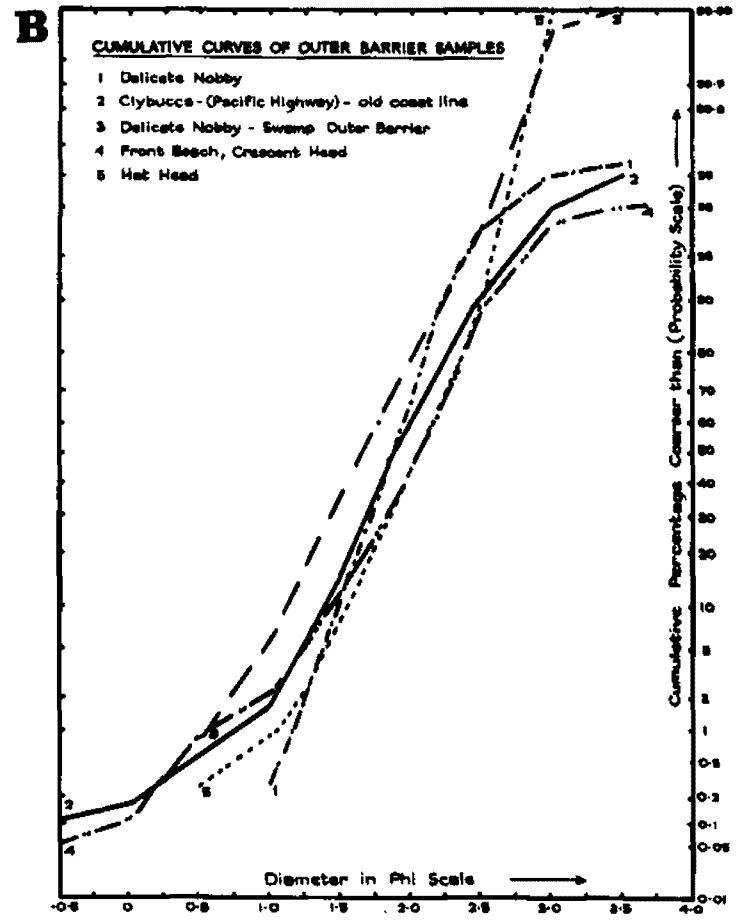

B
CUMULATIVE CURVES OF OUTER BARRIER SAMPLES
1 Delicate Nobby
2 Clybucca - (Pacific Highway) - old coast line
3 Delicate Nobby - Swamp Outer Barrier
4 Front Beach, Crescent Head
5 Hat Head
Cumulative Percentage Coarser than (Probability Scale)
Diameter in Phi Scale
-0·5 0 0·5 1·0 1·5 2·0 2·5 3·0 3·5 4·0

Figure 7.14 Cumulative curves of Hat Head cliff-top dune samples.

Figure 7.14

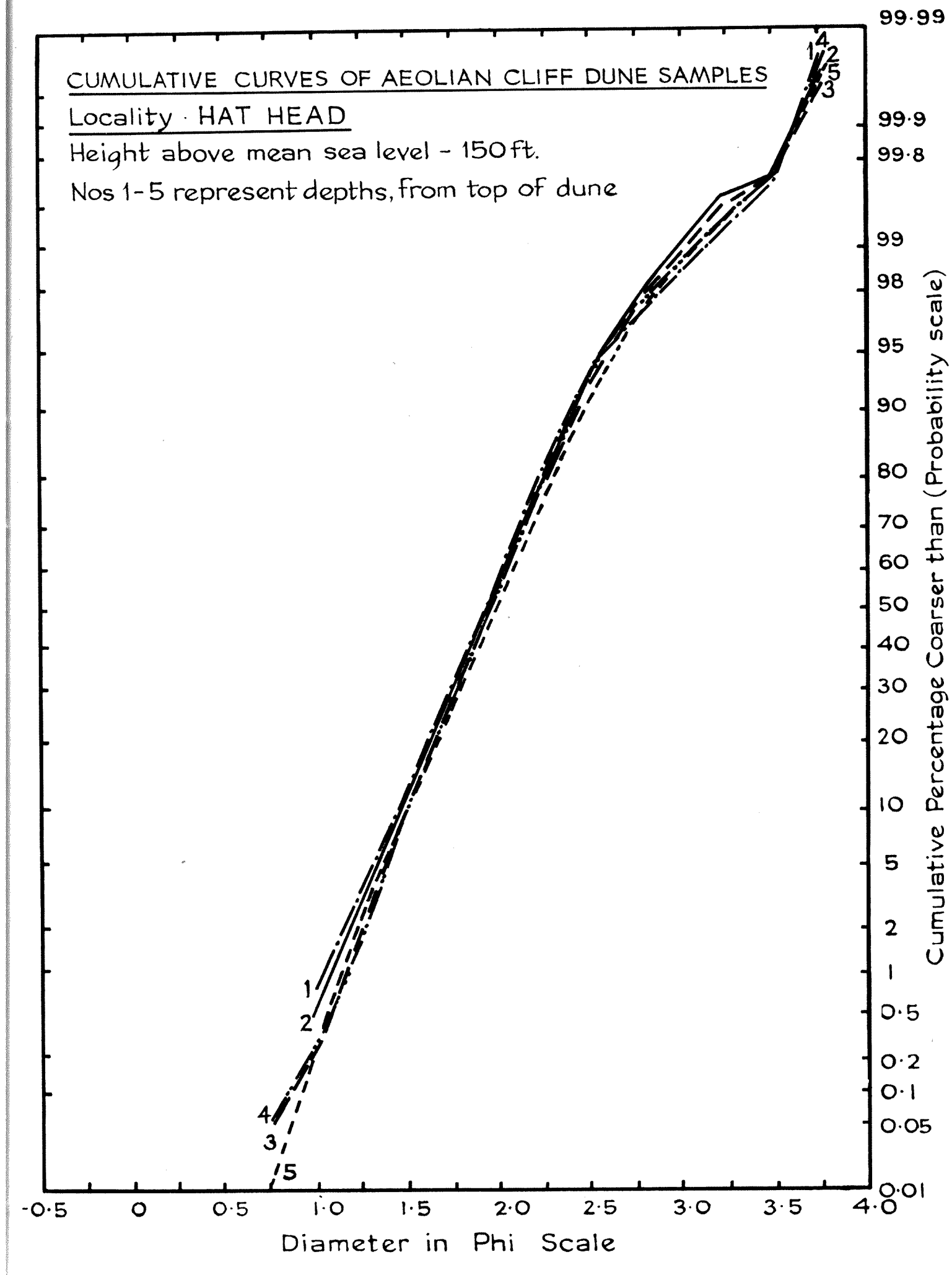
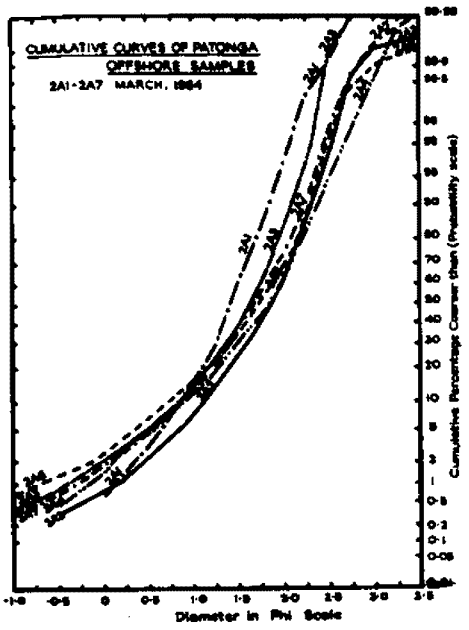
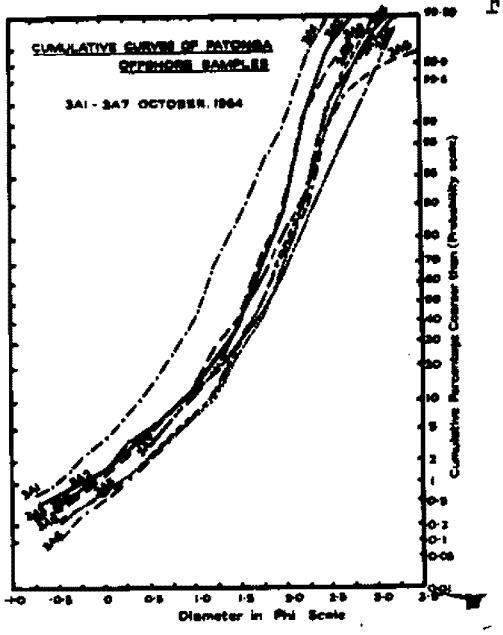
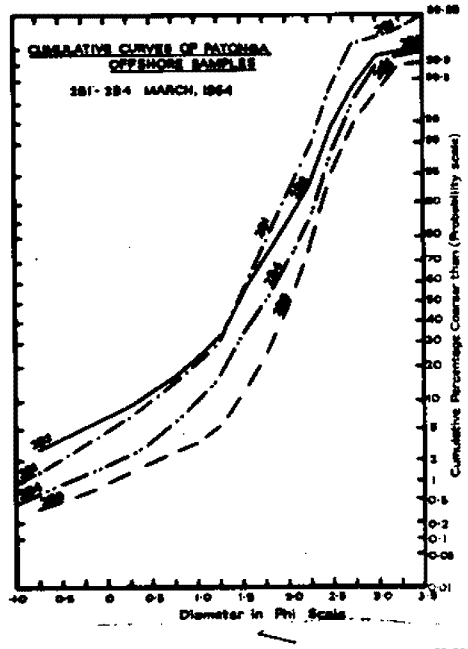

CUMULATIVE CURVES OF AEOLIAN CLIFF DUNE SAMPLES
Locality · HAT HEAD
Height above mean sea level - 150 ft.
Nos 1-5 represent depths, from top of dune
99·99
99·9
99·8
99
98
95
90
80
70
60
50
40
30
20
10
5
2
1
0·5
0·2
0·1
0·05
0·01
Cumulative Percentage Coarser than (Probability scale)
-0·5
0
0·5
1·0
1·5
2·0
2·5
3·0
3·5
4·0
Diameter in Phi Scale

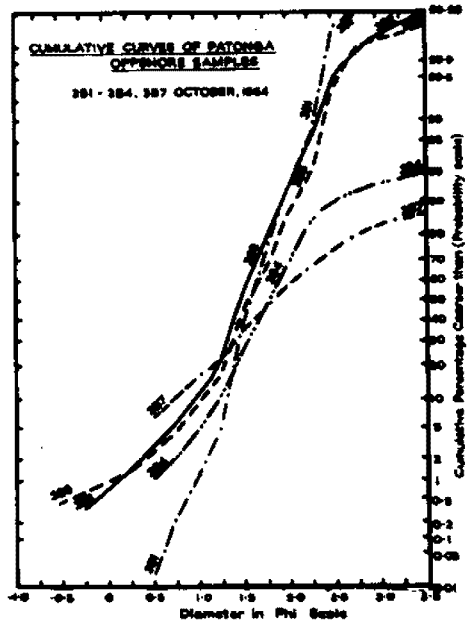
Figure 7.15 Cumulative curves of Patonga (Brisk Bay) offshore samples.

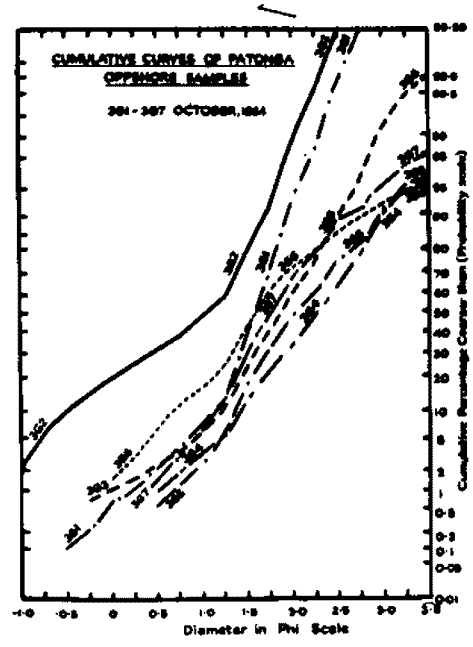
Figure 7.15

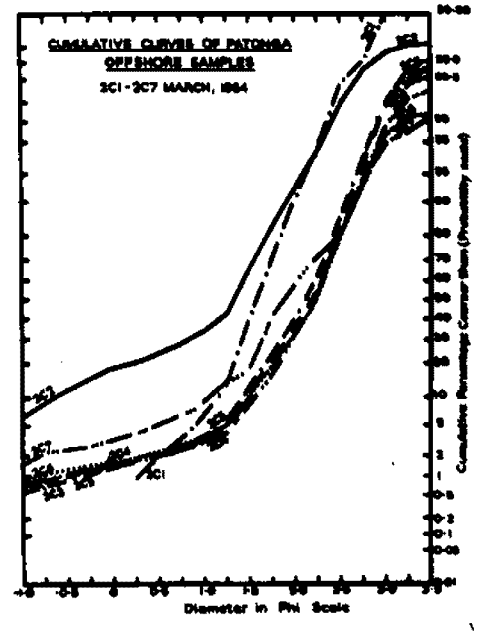

CUMULATIVE CURVES OF PATONGA
OFFSHORE SAMPLES
2A1-2A7 MARCH, 1964
Diameter in Phi Scale


CUMULATIVE CURVES OF PATONGA
OFFSHORE SAMPLES
3A1 - 3A7 OCTOBER, 1964
Diameter in Phi Scale


CUMULATIVE CURVES OF PATONGA
OFFSHORE SAMPLES
2B1 - 2B4 MARCH, 1964
Diameter in Phi Scale


CUMULATIVE CURVES OF PATONGA
OFFSHORE SAMPLES
3B1 - 3B4, 3B7 OCTOBER, 1964
Diameter in Phi Scale


CUMULATIVE CURVES OF PATONGA
OFFSHORE SAMPLES
3B1 - 3B7 OCTOBER, 1964
Diameter in Phi Scale


CUMULATIVE CURVES OF PATONGA
OFFSHORE SAMPLES
2C1 - 2C7 MARCH, 1964
Diameter in Phi Scale

CHAPTER 8

THE NATURE AND OCCURRENCE OF HEAVY MINERALS IN THE THREE STUDY AREAS

Introduction: The origin and distribution of heavy mineral beach sands in New South Wales and southeastern Queensland have been mentioned only briefly in technical reports by Gardner (1955), Whitworth (1956), and Connah (1962). Jones (1964) and Beasley (1948, 1950) have discussed the concentration of heavy minerals in beach deposits, and Culey (1933, 1939) and Carroll (1940) have studied the heavy mineral assemblages of the Narrabeen and Hawkesbury Sandstones. However, apart from the writer's study (Hails, 1969 in press), no detailed investigations have been made to determine the relationship, if any, between heavy mineral concentration and longshore drifting, eolian activity, and the shoreward movement of material from the sea floor during marine transgressions.

The Aims of the Study: In view of the foregoing remarks, the purpose of this study has been:

1. To trace the sources of the heavy minerals. Sources can be sub-divided into: indirect sources, such as material being reworked from immediately offshore, and direct sources, whereby minerals are derived from eroded adjacent cliffs and headlands.
2. To evaluate the percentage variation of the different minerals in Pleistocene and Holocene barrier and dune sands in order to determine whether there is any significant difference with age. An assessment has been made of the chemical stability of the heavy minerals and their resistance to abrasion. The percentage concentration of heavy minerals in barrier and dune sands has been examined in an attempt to assess the transporting effect of wind and wave action.

3. To compare the heavy minerals collected in the inland drainage basins of the Hastings and Macleay Rivers with those in coastal deposits to see if any diagnostic minerals have been transported alongshore. Also, to ascertain whether heavy minerals by-pass river, creek and lagoon outlets, and are transported around headlands or promontories by littoral currents.

Because serpentine outcrops on the Mid-North Coast south of the Hastings River, the area between Port Macquarie and Grassy Head has been studied in detail (Figure 8.1). The writer considered that a few diagnostic minerals derived from serpentine rocks might be transported around Point Plomer, Big Hill, Delicate Nobby and other headlands flanking the arcuate bays.

4. To determine the roundness values of the heavy minerals in order to ascertain, if possible, the relationship between roundness and depositional environments in the three areas, which differ physiographically

Laboratory Procedure: The methods employed in collecting and analyzing the samples from the various depositional environments in the three areas have already been described in Chapter 7. The -60+200 mesh (0.251-0.074 mm) fractions of all sands were retained for heavy mineral analysis. These fractions were used because tests showed that very few, if any, heavy minerals occurred in the -60 mesh (0.251 mm) grade of sand.

The light and heavy mineral fractions of a 5-gram sample split of each sample were separated in bromoform (S.G. 2.90) by using a centrifuge. The heavy residue was weighed and recorded as a weight per cent. A part of the heavy mineral residue, obtained with micro-splitter, was mounted in Canada balsam for microscopic examination and grain counts. In addition,

microscope slides were made of the light-heavy, and rutile-zircon-ilmenite fractions of samples specially treated at Mineral Deposits laboratory, Crescent Head, New South Wales. The percentage number of each mineral in an individual sample was determined by using a mechanical stage and by counting 300 grains. Dryden (1931) suggested that 300 counts is an optimum number, and also that the accuracy of the counts increases as the square root of the number of grains counted. The heavy mineral fractions of six samples collected from the Macleay and Hastings Rivers (Numbers 1, 2-2a, 3a-3b, and 306, Figures 8.1 and 8.6) were separated into magnetic and non-magnetic fractions by using a Model L-1 Frantz Isodynamic Separator. The minerals identified are described briefly in Appendix 8.1.

The unmounted portion of the heavy residue of each sample was examined under a binocular microscope, and roundness analyses were conducted by following the method of Shepard and Young (1961); see Chapter 7. In order to prevent operator bias the samples were renumbered, so the writer was unaware of their location. One hundred grains were counted in each sample.

The accuracy of heavy mineral analyses, depending upon errors in both field sampling and laboratory studies, has been discussed by Dryden (1931), Krumbein and Rasmussen (1941), Manning (1953) and other workers. Rubey (1933) stated that large variations in the relative abundance of various minerals will be found in different grain sizes of the same sample. On the other hand, van Andel (1955) and Poole (1958) concluded that only in special cases is it necessary to study various size fractions separately. In the light of more recent work by Carroll (1957) the writer considers that the method employed in this study has been valid and has not impaired

the final results. Carroll (op. cit.) pointed out that procedural errors can probably safely be neglected from the mineralogical point of view when minerals have been subjected to previous sorting and sedimentation processes, even though it is recognized that certain minerals tend to occur in larger or smaller grain sizes than others.

The Occurrence of Heavy Minerals

Mid-North Coast Samples: The minerals identified in the Mid-North Coast can be divided into three distinct groups: opaque minerals, which include ilmenite, magnetite and leucoxene; common detrital minerals, such as zircon, tourmaline and rutile, and those designated 'others', of which staurolite, andalusite, garnet, kyanite, epidote, picotite, hypersthene and spinel are considered to be the important diagnostic minerals. The first two groups together constitute more than 85 per cent of the heavy minerals present in the sedimentary environments that were sampled. Small quantities of monazite, apatite, amphiboles (hornblende), topaz, sphene and pyroxenes (chiefly augite) have been identified. The percentage occurrence (by number) of all these minerals is shown in Figures 8.2 and 8.3. The percentage range and mean of each mineral are plotted in Figure 8.3 which also shows the non-opaque heavy mineral composition of Pleistocene and Holocene barrier and dune samples. The variation in percentage of all the heavy minerals, except the opaques, is listed in Table 8.1, which compares the composition of barrier and dune sands in the three study areas.

Broken Bay Samples: The most abundant heavy minerals for all samples are the opaques, rutile, zircon and tourmaline (Figure 8.4;Tables 8.1 and 8.2). Together, they generally constitute almost 90 percent of the heavy minerals

in the Broken Bay barrier and beach sands, and offshore sediments. Other minerals present in significant quantities include those of the amphibole (chiefly hornblende) and epidote groups, andalusite and monazite. Minor constituents in order of decreasing occurrence are garnet (colourless and pink varieties), pyroxenes (chiefly augite), hypersthene, topaz, picotite, staurolite, sphene, spinel, enstatite and apatite (Tables 8.1 and 8.3).

South Coast Samples: Tourmaline, amphiboles (chiefly hornblende), pyroxenes (chiefly titan-augite and diopsidic augite), members of the epidote group, and the opaques are the most common minerals in the south coast beach and barrier samples. The opaque minerals and tourmaline constitute 70 and 80 per cent respectively of the heavy fraction in the Pambula and Eden barrier sands, whereas these minerals plus the amphiboles and epidote comprise 86 per cent of the total heavy mineral assemblage in the Boyd Town samples. In addition, andalusite, zircon, enstatite, topaz, rutile, sphene, garnet (colourless and pink), monazite and other minor constituents have been identified. With the exception of andalusite, the other minerals do not occur in sufficient quantities to be of importance. The variation in percentages of these minerals is shown in Figure 8.5, and listed in Tables 8.1 and 8.4.

Discussion of the Results

Mid-North Coast Samples: Distinctive constituents of the Mid-North Coast Pleistocene and Holocene barrier and dune sands are andalusite, staurolite, garnet, kyanite, zoisite and epidote. This heavy mineral suite suggests a medium-grade metamorphic source of which, however, there is no trace

in the areas drained by the Mid-North Coast rivers. Although sillimanite-bearing metamorphic rocks occur in the Wongwibinda Complex (Binns, 1965), north-east of Armidale, sillimanite is absent from the coastal samples either because of its low chemical and mechanical stability, or because the tributaries of the Macleay River do not drain the Wongwibinda area. It is possible, therefore, firstly, that the observed metamorphic minerals were derived from a source which has been entirely removed by erosion. Secondly, they were eroded from cliffs and headlands, or delivered to the coast by rivers, outside the region thus necessitating the longshore movement of material around headlands and over considerable distances. Thirdly, the minerals were deposited as rivers extended their courses across the emerged continental shelf during Pleistocene low stands of sea level and were reworked and transported shoreward by wave action during subsequent marine transgressions. Fourthly, they were derived from a metamorphic source that was submerged during the postglacial and Pleistocene marine transgressions.

A similar heavy mineral assemblage to that of the coastal sands has been identified in bed load samples collected from the Hastings River, and Stockyard Creek which according to Lindsay (1963), predominantly drains a serpentine rock area in the Macleay River catchment. However, the metamorphic minerals in the samples from Settlement Point on the Hastings River (Numbers 2-2a, in Figures 8.1 and 8.6) may have moved upstream from offshore because the river is tidal at this locality.

The presence of picotite in the river sands is also of some interest since as a detrital mineral it is of very restricted occurrence. Therefore it appears that the picotite identified in the Stockyard Creek samples, and those collected near Sherwood Bridge upstream from the

tidal limit of the Macleay River at Aldavilla (Number 306, Figure 8.1), has been derived locally from the serpentine rock area. The occurrence of this mineral in the modern beach and Holocene barrier sands north of the Macleay River outlet in Trial Bay suggests that the heavy minerals reaching the coast are not transported southwards around headlands by longshore currents, but nearshore experiments, using radioactive or fluorescent tracer sand, are needed to verify this opinion. A northerly movement of material alongshore is also suggested by the occurrence of picotite in the Pleistocene and Holocene coastal sands north of Port Macquarie because the only other major serpentine rock areas on the Mid-North Coast are located south of the Hastings River (Figure 8.6).

Enstatite, hypersthene, kyanite, spinel, hornblende and augite are generally absent from the Inner Barrier and Pleistocene dune sands. Therefore, eolian action seems the most plausible explanation to account for the unique presence of enstatite and augite in the Back Beach Inner Barrier sands between Race Course Headland and Crescent Head. These minerals have been identified in samples collected within 3 feet of the surface of the barrier. The reason why they should be transported from the adjacent Outer Barrier on this section of the Mid-North Coast and not elsewhere is still a problem that has to be resolved.

The persistence of certain heavy minerals in the Mid-North Coast sediments appears to be determined by either their chemical or mechanical stability. For example, staurolite has an extremely low stability to weathering index compared with zircon and tourmaline and therefore its occurrence is attributed to its resistance to abrasion. Despite its relatively high position in the Order of Persistence Table (8.5B),

biotite however appears to be an unstable mineral since it is absent from all the samples that have been analyzed, including the Holocene barrier sands and fluviatile sediments.

According to Baker (1962) though, differences in stability of any particular mineral undoubtedly exist in different areas according to variations in climate, topography and vegetation. Allen (1948), on the other hand, stated that the resistance of minerals to weathering depends upon the particular variety of the mineral in question. Dryden and Dryden (1946) in their study of the comparative rates of weathering of common heavy minerals in situ discovered that garnet is the least resistant to chemical alteration, even though most other workers list this mineral as highly stable.

It is generally accepted that the mechanical stability of minerals like tourmaline, rutile and zircon, for example, is controlled largely by their physical properties. Figure 7.6 shows that the heavy accumulates in the Mid-North Coast barrier and dune sands are composed of fairly well rounded minerals, and there is little difference between the values of Pleistocene and Holocene samples. This evidence partly supports the view put forward here that the minerals have been derived from ancient sediments and they have inherited their properties. Some minerals of course, can be derived locally and abraded in the surf zone before being redeposited as beach concentrates, but this seems unlikely on the Mid-North Coast because the mineralogical composition of the coastal sands differs from that of the adjacent bedrock headlands. Even so, the evidence does not entirely exclude the possibility that some minerals may have been derived from a source now submerged.

Contrary to the statements in some publications (Gardner, op. cit.; Beasley, op. cit.), the writer's analyses show that heavy minerals can be transported beyond the limit of high-water mark. Although wave action is the initial cause of concentrating stable heavy minerals, the complimentary effects of wind action seem to have been under-estimated (Hails, 1964b). The mineral composition of Pleistocene and Holocene dune and barrier (and also modern beach) sands is basically similar, and the average weight per cent of heavy minerals in dune samples is 2.16 compared with 1.78 in barrier sands. Furthermore, the weight per cent of heavy minerals in the cliff-top dunes does not vary appreciably, irrespective of height above mean sea level and distance from immediate source areas. Specific gravity values of the different minerals in the dunes range from 2.98 to 5.18 and their hardness values (Mohs scale) range from 5 to 8 (Table 8.5A).

There appear to be two main reasons to account for the difference in the concentration of heavy minerals (by weight) in the Pleistocene and Holocene sands (Table 8.6). Firstly, there may have been low sediment yields from the river catchments in the past because of reduced erosion and slow weathering, or there were few heavy minerals offshore to be reworked and redeposited by wave action as the Pleistocene barriers were established. Also, nearshore processes may have controlled deposition only in certain areas. Secondly, ephemeral barriers existing off the present coast during periods of lower sea level, may have been partly eroded or destroyed before complete submergence during the late Holocene transgression. This process could have provided large supplies of sand for the construction of the Holocene Outer Barriers. However, temporary shorelines may not have existed immediately before the formation of the Inner Barrier. Undoubtedly, slight fluctuations in sea level and variations in local wave and wind regimes have controlled the

concentration of heavy minerals since the major barriers were established (Hails, op. cit.).

Based on the accumulated evidence reported here, the writer has shown in Figure 8.6 the possible areas and sources from which some of the identified minerals have been derived. The closed arrows indicate the directions in which the minerals were transported to an embayed coast before the formation of the barriers and the deltaic plains. Dominant southeasterly swell waves, that arrived at an angle to the shore, undoubtedly moved some material northwards alongshore, and heavy minerals could have been concentrated locally as waves were refracted around promontories, as indicated by the dashed arrows. However, the longshore movement of material was incidental to that moved onshore (open dashed arrows). The open arrows in Figure 8.6 show that the most probable direction of longshore drift in the modern arcuate bays.

Broken Bay Samples: The analyses of Broken Bay samples provide some interesting information. Although hypersthene occurs in relatively few samples, its presence warrants some comment. Hypersthene is one of the least persistant minerals in the geologic column, and it is generally found in sediments derived from nearby hypersthene-bearing rocks, such as gabbros, norites, dolerites, basalts, andesites, and volcanic tuffs. According to David (ed. W.R. Browne, 1950), the Chocolate Shales of the Middle Narrabeen Series are usually regarded as redistributed fine basic tuff with a large admixture of purely clastic material. On the other hand, he states that the Hawkesbury Series is thought to be entirely free from volcanic material, though the Upper Wianamatta Stage is characterized by a large proportion of calcareous sandstone which is tuffaceous (see also Chapter 2). Therefore, it seems that the

hypersthene is being derived from such rocks in the Broken Bay hinterland since it has been identified in nearshore sediments collected by the writer from Brisk Bay. The mineral has been traced in four Holocene samples, but it is absent from the Umina-Woy Woy Pleistocene (?) barrier sands. The fact that hypersthene is not very resistant to abrasion is also supported by the results of Culey's (1933) mineralogical study of the Narrabeen Series; only one hypersthene grain was identified in samples collected at the Entrance, Tuggerah.

The contention that volcanic material is being weathered in the vicinity of Broken Bay is also supported by the appearance of titan-augite in a few samples. The presence of picotite is not considered particularly significant because the mineral occurs in minor proportions in the various horizons of the Narrabeen Series. Staurolite is seldom found in Broken Bay samples, but garnet and andalusite are more common minerals. Unfortunately, the heavy mineral assemblage of the Pearl Beach and Patonga barriers does not provide clues on the movement of material around headlands, because it is identical with that of the Umina-Woy Woy barrier system.

South Coast Samples: The same minerals are common to practically all samples, but their percentage occurrence (by number) varies significantly in the Twofold Bay deposits. These variations can be partly explained by the different types of rock in the immediate vicinity of Twofold Bay. Shadrack's Creek and the Nullica River, which flow into Nullica Bay, drain catchments of unconsolidated Tertiary (?) deposits, Devonian rhyolites, dolerites and felsites, and Ordovician metamorphic rocks. In contrast, Bellbird Creek, which enters Curalo Lake (almost entirely isolated from Calle Calle Bay by Eden barrier spit), drains a

catchment of predominantly sedimentary rocks - sandstones, siltstones, shales and quartzites. Therefore, it is not surprising that the analyses reveal significant differences in the percentage occurrence of epidote, titan-augite and the amphiboles in the barrier and beach sands of Nullica and Calle Calle Bays. For example, titan-augite is almost four times, epidote six times, and the amphiboles fourteen times more abundant in the Boyd Town barrier sands than in the Eden barrier samples (Table 8.4).

The percentage occurrence of hornblende is somewhat anomalous. Titan-augite and diopsidic augite, the most abundant of the pyroxenes identified, appear to have been derived locally. Probably, the former was derived from either the basalts or dolerites, in which it often replaces common augite, whilst the latter possibly originated in the rhyolites, such as the potash type at Eden. The comparatively small percentages of rutile, zircon and other minor constituents also seem to indicate the composition of the rocks being eroded in the Twofold Bay hinterland.

The variation in the percentage occurrence (by number) of the respective heavy minerals provides some evidence to discount the possibility that sediments, deposited within the smaller embayments of Twofold Bay, are transported around headlands. It is concluded, therefore, that the sediment yield, derived from the weathered rocks of the Twofold Bay hinterland and delivered to the nearshore zone by way of the rivers, is reworked and redeposited locally by wave action to nourish the barriers and bayhead beaches. This supply of sediment is supplemented, on a limited scale, by material derived from the erosion of adjacent headlands.

Fine-grained material carried a short distance offshore, also appears to be transported shoreward subsequently without drifting around the headlands that separate the smaller embayments.

Additional evidence supporting the argument that sediments carried into Nullica Bay are not transported around neighbouring headlands can be found in the roundness values of the heavy minerals from the Boyd Town barrier system. Generally, these values are lower than those of the samples collected from Whale Beach barrier. It can be seen from Figure 7.6 that the heavy minerals from the Eden and Pambula barriers are particularly well rounded when compared with those from the Boyd Town barrier system. Most of the smaller bays inside Twofold Bay are low wave energy environments compared with the exposed sectors of the far south coast. Therefore, in the smaller embayments like Nullica Bay, it is unlikely that minerals would be altered appreciably by abrasion in the surf zone. But it would be presumptuous, considering some of the points made already about the roundness values of the Mid-North Coast minerals, to make conclusive statements about the Boyd Town samples. Fairly sub-angular grains, derived from the various catchments, might undergo minimal abrasion only before being deposited in the nearshore zone, because they are moved relatively short distances by the small coastal rivers.

Figure 8.7 (D-F), which shows some heavy mineral grains from the Boyd Town, Whale Beach and Pambula barriers, illustrate the marked contrast between the angular and sub-angular grains of the south coast samples and the comparatively well rounded minerals collected from the other two study areas (Figure 8.7A-C; G-I). Both Twofold Bay and Broken Bay are fairly well sheltered from wave action compared with the arcuate

bays on the exposed Mid-North Coast, but even so, the Broken Bay minerals, except those of the Patonga barrier, are well rounded compared with the Boyd Town samples. The slightly lower values of the Patonga samples indicate that the material carried into Brisk Bay by Patonga Creek has travelled a relatively short distance from its source. In general, the roundness values reflect the polygenetic history of most of the Broken Bay minerals.

Summary and Conclusions

Locally derived titan-augite and diopsidic augite are the distinctive constituents of south coast sediments. The occurrence of hypersthene in the Broken Bay barrier samples seems to indicate a volcanic rock source in the Patonga Creek catchment.

All the Mid-North Coast minerals are polygenetic because they have been derived from various sources, and have survived several phases of rock formation and weathering.

Andalusite, staurolite, garnet, kyanite and epidote are the most distinctive constituents of the Mid-North Coast sands and suggest a medium-grade metamorphic source of which there is no trace in the areas drained by the Mid-North Coast rivers. It is therefore possible, firstly, that the minerals were derived from a source which has been entirely removed by erosion; secondly, from other regions by being transported alongshore; and thirdly, from offshore.

The picotite in the beach and barrier sands north of the Hastings and Macleay Rivers has been derived from the serpentine rocks in the Hastings River basin and from the small outcrops near Stockyard Creek.

The percentage occurrence (by number) of the common detrital minerals in the Pleistocene and Holocene barrier and dune sands does not vary appreciably. The most common detrital minerals on the Mid-North Coast and in Broken Bay are rutile, zircon, tourmaline and the opaques. Hornblende, the pyroxenes, and members of the epidote group are the most common minerals on the south coast. Most minerals in the dunes on the Mid-North Coast were probably derived from neighbouring barriers and beach sands. The mineralogical composition of the cliff-top dunes reflects the strength and transporting power of wind.

The sub-angular minerals derived from the various catchments on the south coast are not rounded appreciably by abrasion in the surf zone before being deposited as beach concentrates in the small embayments. Twofold Bay sediments are comparatively angular compared with those of the other two study areas. There is little difference between the roundness values of the Pleistocene and Holocene heavy minerals on the Mid-North Coast mainly because the minerals are polygenetic.

A possible sequence of events which led to the concentration of heavy minerals in the Holocene beach and dune deposits was the:

(i) formation and establishment of barriers a short distance from the coast;

(ii) complete or partial destruction of those barriers during a rise in sea level;

(iii) redeposition of heavy minerals along a newly established shoreline;

(iv) modification of that shoreline by eolian action and storm waves.

Finally, should coastal erosion cause foredune or beach ridge destruction, heavy minerals may become concentrated as the lighter quartz grains are removed. If erosion is followed immediately by a period of shoreline progradation, the minerals will be preserved as a concentrated deposit.

TABLE 8.1

Average percentage occurrence (by number) of heavy minerals in some Mid-North Coast, Broken Bay and South Coast barrier, and dune samples.

Locality / Environment \ Mineral	Rutile	Zircon	Tourmaline	Monazite	Garnet	Apatite	Staurolite	Kyanite	Epidote Gp.	Amphiboles (Chiefly Hornblende)	Andalusite	Topaz	Sphene	Pyroxenes (Chiefly Augite)	Hypersthene	Enstatite	Picotite	Spinel
MID-NORTH COAST																		
Delicate Bobby	21.23	16.29	50.60	0.21	2.08	0.02	1.25	0.08	1.93	0.27	4.08	0.19	0.02	0.21	0.27	0.95	0.32	-
Back Beach (Inner Barrier)	24.53	42.64	26.67	0.60	0.12	-	1.06	-	0.06	-	3.23	0.06	0.12	0.18	-	0.06	0.67	-
Killick Creek Nr. Crescent Head (Inner Barrier)	32.51	37.02	24.95	0.08	0.08	-	1.16	0.08	0.25	-	3.75	0.12	-	-	-	-	-	-
Front Beach (Outer Barrier)	15.77	17.41	53.73	0.40	0.90	0.04	1.50	0.21	1.64	1.18	5.00	-	0.37	0.37	0.41	1.03	0.04	-
Hat Head (Outer Barrier)	14.54	8.00	62.38	0.60	2.00	0.35	1.18	0.16	2.48	0.18	4.94	0.37	0.13	-	0.22	2.27	-	0.20
Hat Head (Inner Barrier)	9.72	32.40	52.69	-	0.06	0.11	1.08	-	0.28	-	3.60	0.06	-	-	-	-	-	-
Hat Head (Cliff-Top Dunes)	17.90	35.70	42.10	-	-	0.40	0.90	-	0.40	-	2.40	0.20	-	-	-	-	-	-
Smoky Cape (Cliff-Top Dunes)	14.20	40.40	44.20	-	-	-	-	-	-	-	1.20	-	-	-	-	-	-	-
Front Beach (Transgressive Dunes)	22.28	27.42	43.59	-	-	-	0.71	-	-	-	6.00	-	-	-	-	-	-	-
Clybucca Shoreline	24.53	71.03	3.83	-	0.16	-	0.16	-	0.16	-	0.33	-	-	-	-	-	-	-
Macia-Wilson Barrier Plain	39.00	38.69	19.83	-	-	-	0.83	-	0.16	-	1.16	0.33	-	-	-	-	-	-
BROKEN BAY																		
Umina-Woy Woy Beach Ridge System																		
Pleistocene (?) Samples	36.95	26.85	24.71	1.80	0.09	-	-	-	1.83	3.68	3.68	0.02	-	0.32	0.07	-	-	-
Holocene Samples	30.08	30.62	22.96	0.55	0.96	-	-	-	6.44	4.88	3.11	-	-	0.22	0.11	-	0.07	-
SOUTH COAST																		
Boyd Town Beach Ridge System	0.09	0.51	6.35	-	0.49	0.03	-	-	21.87	54.00	1.29	0.35	0.22	14.19	-	0.61	-	-
Bden Barrier Spit	0.55	6.66	64.99	0.52	1.74	-	-	-	6.74	4.26	10.49	0.44	0.07	3.33	0.14	0.07	-	-
Pambula Barrier Spit	0.45	1.55	46.20	0.19	1.70	-	-	0.06	19.23	16.35	12.42	0.40	0.13	0.64	-	0.68	-	-

TABLE 8.2

Average percentage occurrence (by number) of heavy minerals in Broken Bay barrier samples.

Mineral	Umina (Ocean Beach)-Woy Woy Beach Ridge System		Pearl Beach Barrier Numbers	
	Holocene*	Pleistocene (?)	1-7 (see Figure 8.4)	1-93
Opaques (Magnetite, Ilmenite, Leucoxene, Haematite, Limonite)	36	44	31	21
Zircon	18	16	29	31
Tourmaline	15	12	6	6
Amphiboles	2.50	1.78	-	-
Epidote Group	3.75	-	-	-
Rutile	20.50	22.25	33	40
Andalusite	2.25	2	-	1
Others	2	1.97	1	1

*Most of these samples were collected along Section B-B_1, shown in Figure 3.9.

TABLE 8.3

Percentage occurrence of minerals in Pearl Beach and Patonga Beach samples. Percentage occurrence is not expressed by numbers per sample, but number of times the minerals have been found in the total number of samples analyzed. For example, andalusite has been found in 38 of the 100 Pearl Beach barrier samples.

Mineral	Pearl Beach Barrier (100 samples)		Patonga Barrier Spit (217 samples)	Patonga Offshore (70 samples)
Monazite	31		18	27
Garnet	10		8	6
Apatite	-		1	-
Staurolite	2	less than	1	-
Epidote Group	17		30	54
Amphiboles (chiefly Hornblende)	21		20	54
Andalusite	38		44	51
Topaz	-		4	7
Sphene	1		-	1
Pyroxenes (chiefly Augite)	2		9	11
Hypersthene	6		3	4
Enstatite	-		1	-
- - -

TABLE 8.4

Average percentage occurrence (by number) of heavy minerals in south coast barrier samples. Percentage taken to nearest whole number.

Mineral	Eden Barrier Spit (Twofold Bay)	Boyd Town Barrier Beach Ridge System (Twofold Bay)	Pambula Barrier Spit
Opaques (Magnetite, Ilmenite, Leucoxene, Heamatite, Limonite)	50	23	46
Zircon	3	0*	0*
Tourmaline	30	5	24
Rutile	0*	0*	0*
Andalusite	5	0*	6
Amphiboles (chiefly Hornblende)	3	41	10
Pyroxenes (chiefly Titan-augite and Augite)	3	11	0*
Epidote	3	17	11
Others	3	3	3

* Included in 'Others' as percentage occurrence in samples is less than 3 per cent.

TABLE 8.5A

Specific gravity and hardness values of heavy minerals identified in cliff-top dunes. Hardness values on Mohs scale.

Mineral	Specific Gravity	Hardness
Andalusite	3.16-3.20	7.5
Epidote	3.25-3.50	6-7
Ilmenite	4.50-5.00	5-6
Leucoxene	3.50-4.50	-
Magnetite	5.17-5.18	5.5-6.5
Piedmontite	3.45-3.50	6.5
Rutile	4.18-4.25	6.0-6.5
Staurolite	3.65-3.77	7.0-7.5
Topaz	3.51-3.61	8.0
Tourmaline	2.98-3.20	7.0-7.5
Zircon	4.20-4.86	7.5

TABLE 8.5B

Order of Persistence of heavy minerals in the geologic column. (Least persistent minerals are listed first. Minerals marked * occur in cliff-top dunes). Tables based on that of Pettijohn (1941). Read down columns.

Olivine	Topaz*	Apatite
Actinolite	Andalusite*	Biotite
Diopside	Hornblende	Garnet
Hypersthene	Epidote*	Monazite
Sillimanite	Kyanite	Tourmaline*
Augite	Staurolite*	Zircon*
Zoisite* (Epidote Group)	Magnetite*	Rutile
Sphene	Ilmenite*	Anatase

TABLE 8.6

Range and average percentage concentration by weight of heavy minerals in Pleistocene and Holocene sediments.

Area/Location	Environment	Age	Heavy Mineral concentration	
			Range	Average Percentage
TWOFOLD BAY				
Eden	Barrier spit	Holocene	0.1-1.2	0.25
Boyd Town	Barrier beach ridges	Holocene	0.4-14.0	2.70
Whale Beach	Barrier spit	Holocene	0.2-8.0	4.06
SOUTH COAST				
Pambula	Barrier spit	Holocene	0.2-4.6	0.96
BROKEN BAY				
Pearl Beach	Barrier beach	Holocene	0.1-44.0	8.37
Umina-Woy Woy	Barrier beach ridges	Holocene	0.1-14.6	3.45
		(?)Pleistocene	0.6-22.0	2.74
Patonga Beach	Barrier spit	Holocene		
	(ridges)		0.1-7.0	0.28
	(swales)		0.1-3.0	0.23
	(foredune)		0.2-1.8	0.49
	(random bores)		0.1-56.0	6.81
	Grand Total		0.1-56.0	1.45
Patonga Offshore	Neritic	Holocene	0.1-2.0	0.44
MID-NORTH COAST				
Delicate Nobby	Barrier ridges	Holocene on Pleistocene	0.2-13.0	2.05
Back Beach	Inner Barrier	Pleistocene	0.4-6.6	2.30
Killick Creek	Inner Barrier	Pleistocene	0.2-15.0	4.13
Front Beach	Outer Barrier	Holocene	0.1-7.6	1.14
Hat Head	Outer Barrier	Holocene	0.2-2.0	0.58
Hat Head	Inner Barrier	Pleistocene	0.1-5.2	0.76
Hat Head	Cliff-Top Dunes	Pleistocene	0.4-2.4	1.50
Smoky Cape	Cliff-Top Dunes	Pleistocene	0.8-7.8	3.56
Front Beach	Transgressive Dunes	Pleistocene	0.2-1.4	0.91
Clybucca Shoreline	Beach ridges	Pleistocene	18-50.6	32.62

Figure 8.1 Locality map of the Mid-North Coast showing location of samples collected for heavy mineral analysis.

Geology based on work of Voisey (1934b).

Figure 8.1

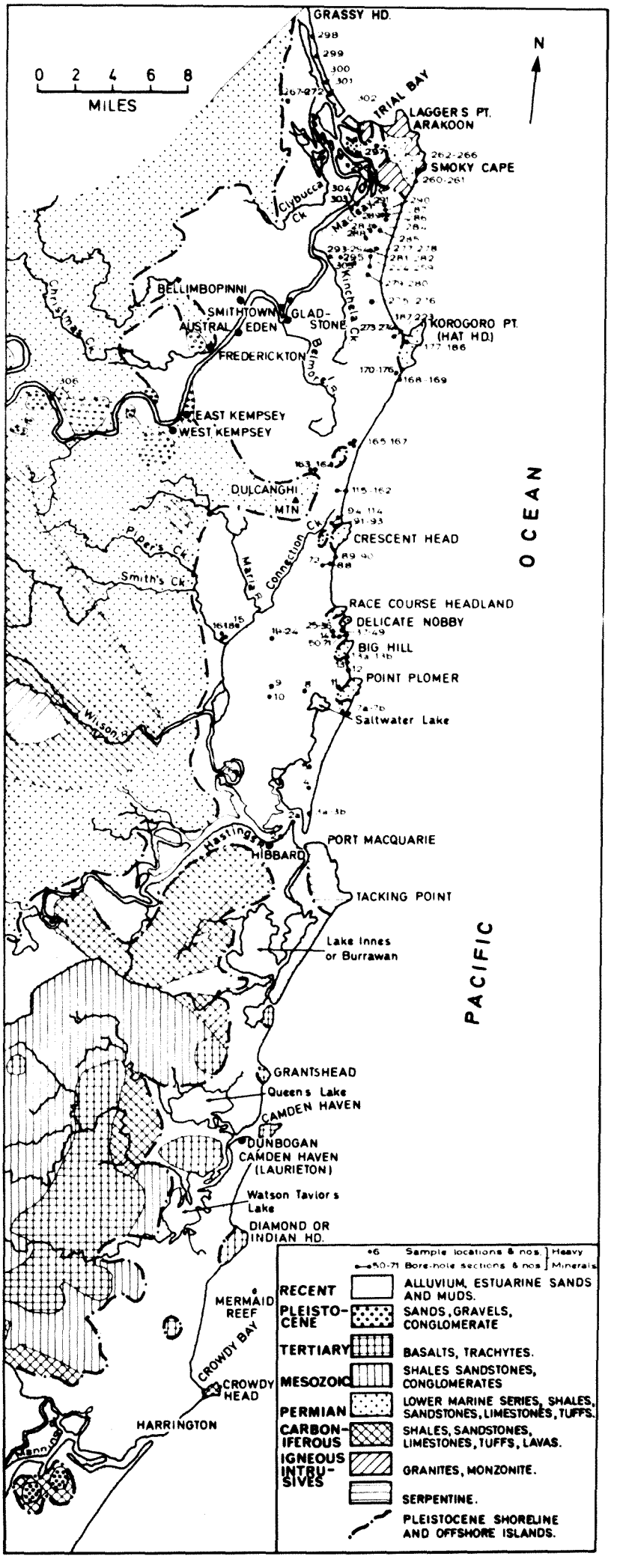
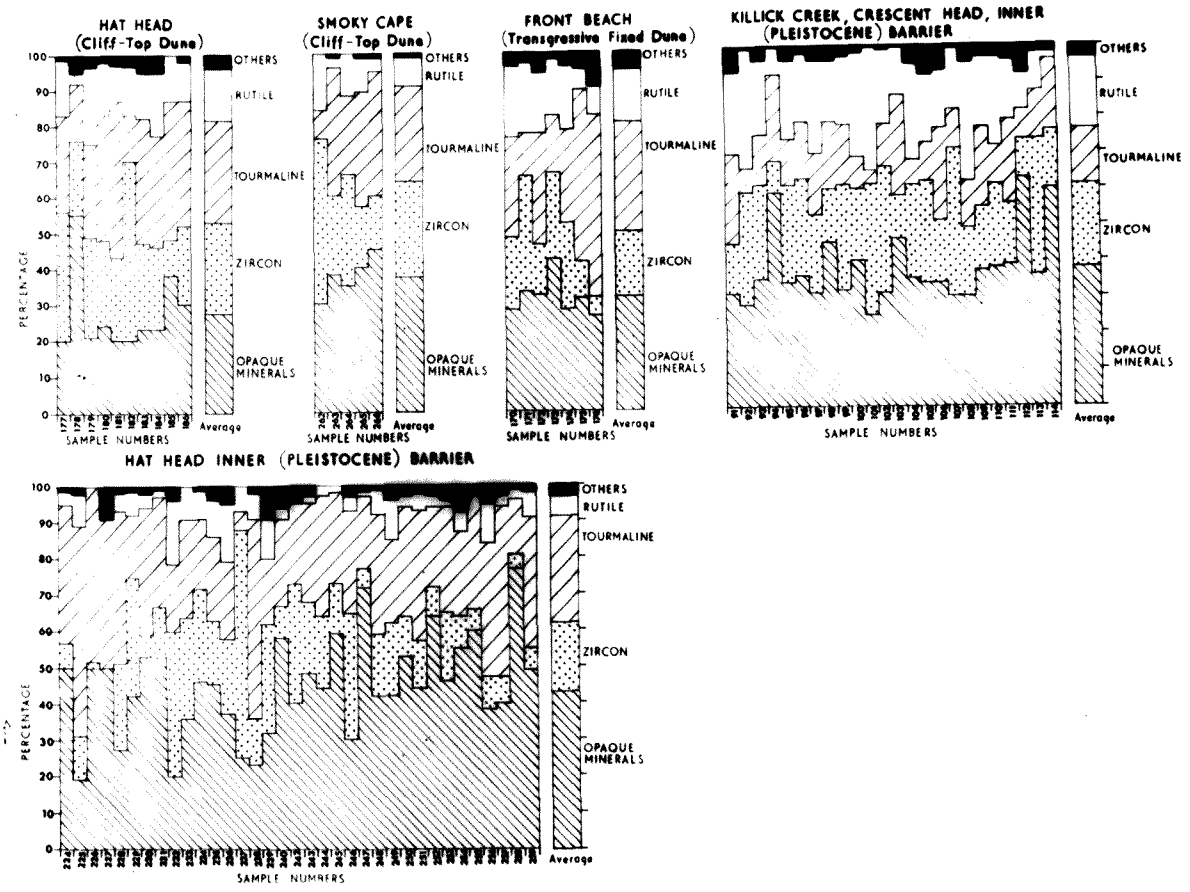

GRASSY HD.
0 2 4 6 8
MILES
N
TRIAL BAY
LAGGERS PT.
ARAKOON
SMOKY CAPE
Clybucca Ck
Macleay R.
BELLIMBOPINNI
SMITHTOWN
AUSTRAL
EDEN
GLADSTONE
Kinchela Ck
KOROGORO PT.
(HAT HD.)
Christmas Cr.
FREDERICKTON
Belmore R.
EAST KEMPSEY
WEST KEMPSEY
DULCANGHI
MTN.
Piper's Ck.
Smith's Ck.
Maria R.
Connection Ck.
CRESCENT HEAD
OCEAN
RACE COURSE HEADLAND
DELICATE NOBBY
BIG HILL
POINT PLOMER
Saltwater Lake
Wilson R.
Hastings R.
HIBBARD
PORT MACQUARIE
TACKING POINT
Lake Innes
or Burrawan
PACIFIC
GRANTSHEAD
Queens Lake
CAMDEN HAVEN
DUNBOGAN
CAMDEN HAVEN
(LAURIETON)
Watson Taylors
Lake
DIAMOND OR
INDIAN HD.
MERMAID
REEF
CROWDY BAY
CROWDY
HEAD
HARRINGTON
Hennings
•6 Sample locations & nos.] Heavy
•—•50-71 Bore-hole sections & nos.] Minerals
RECENT
ALLUVIUM, ESTUARINE SANDS AND MUDS.
PLEISTOCENE
SANDS, GRAVELS, CONGLOMERATE
TERTIARY
BASALTS, TRACHYTES.
MESOZOIC
SHALES SANDSTONES, CONGLOMERATES
PERMIAN
LOWER MARINE SERIES, SHALES, SANDSTONES, LIMESTONES, TUFFS.
CARBONIFEROUS
SHALES, SANDSTONES, LIMESTONES, TUFFS, LAVAS.
IGNEOUS INTRUSIVES
GRANITES, MONZONITE.
SERPENTINE.
PLEISTOCENE SHORELINE AND OFFSHORE ISLANDS.

Figure 8.2 The percentage occurrence (by number) of heavy minerals identified in Mid-North Coast barrier and dune samples.

Figure 8.2


HAT HEAD
(Cliff-Top Dune)
SMOKY CAPE
(Cliff-Top Dune)
FRONT BEACH
(Transgressive Fixed Dune)
KILLICK CREEK, CRESCENT HEAD, INNER
(PLEISTOCENE) BARRIER
HAT HEAD INNER (PLEISTOCENE) BARRIER
OTHERS
RUTILE
TOURMALINE
ZIRCON
OPAQUE MINERALS
PERCENTAGE
SAMPLE NUMBERS
Average

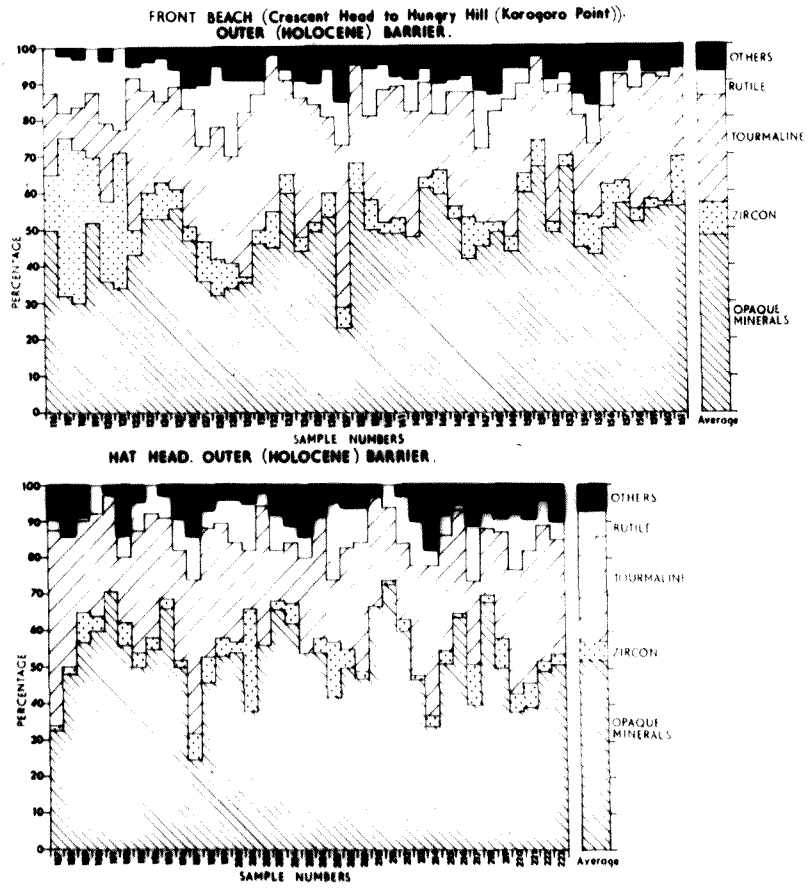

FRONT BEACH (Crescent Head to Hungry Hill (Korogoro Point)).
OUTER (HOLOCENE) BARRIER.
HAT HEAD. OUTER (HOLOCENE) BARRIER.
OTHERS
RUTILE
TOURMALINE
ZIRCON
OPAQUE MINERALS
PERCENTAGE
SAMPLE NUMBERS
Average

Figure 8.3 Non-opaque heavy mineral composition of some barrier and dune samples collected on the Mid-North Coast.

Figure 8.3

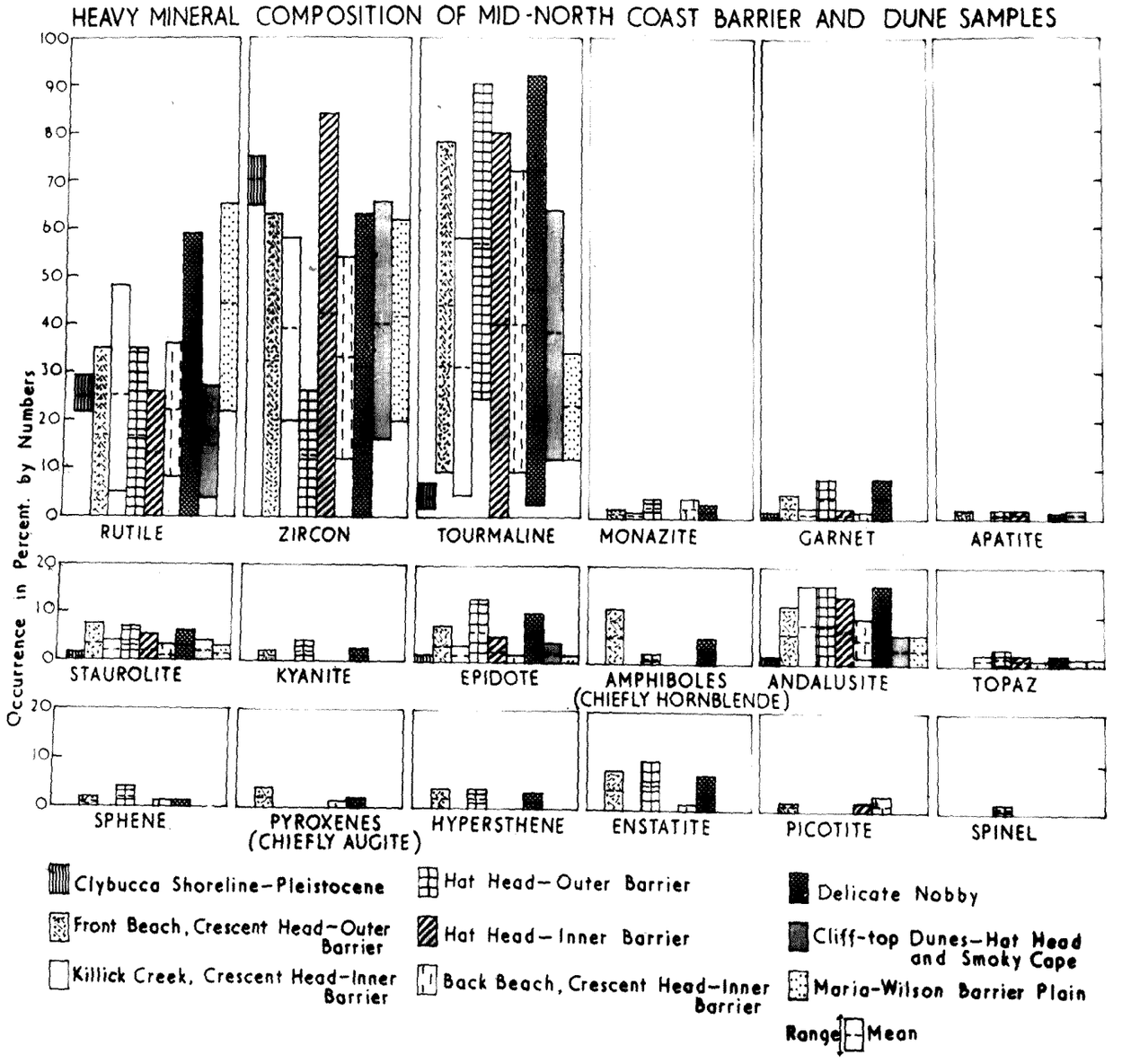

HEAVY MINERAL COMPOSITION OF MID-NORTH COAST BARRIER AND DUNE SAMPLES
Occurrence in Percent. by Numbers
RUTILE
ZIRCON
TOURMALINE
MONAZITE
GARNET
APATITE
STAUROLITE
KYANITE
EPIDOTE
AMPHIBOLES (CHIEFLY HORNBLENDE)
ANDALUSITE
TOPAZ
SPHENE
PYROXENES (CHIEFLY AUGITE)
HYPERSTHENE
ENSTATITE
PICOTITE
SPINEL
Clybucca Shoreline–Pleistocene
Front Beach, Crescent Head–Outer Barrier
Killick Creek, Crescent Head–Inner Barrier
Hat Head–Outer Barrier
Hat Head–Inner Barrier
Back Beach, Crescent Head–Inner Barrier
Delicate Nobby
Cliff-top Dunes–Hat Head and Smoky Cape
Maria-Wilson Barrier Plain
Range
Mean

Figure 8.4 The percentage occurrence (by number) of heavy minerals identified in Broken Bay barrier samples. The average composition is also shown.

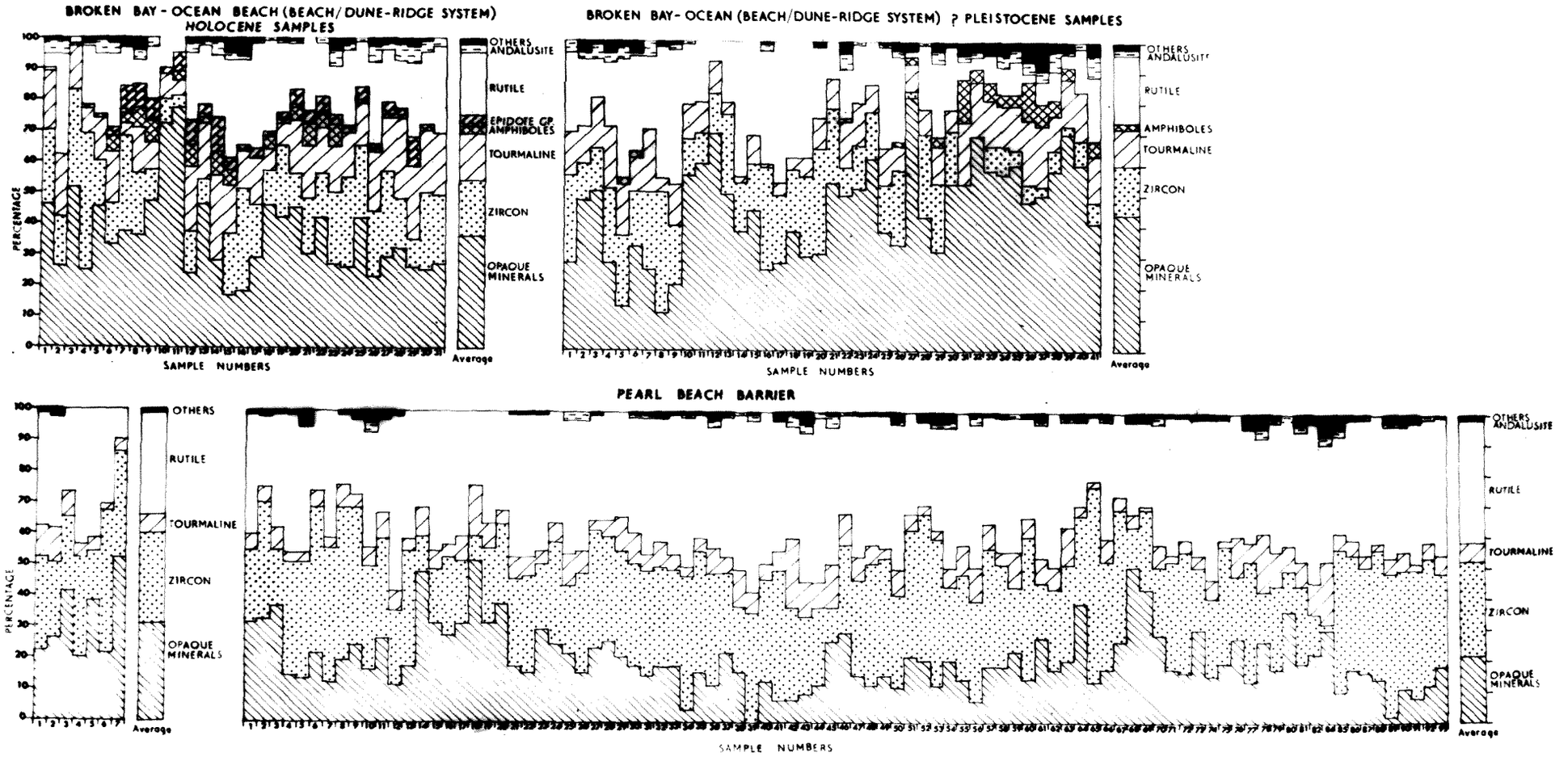
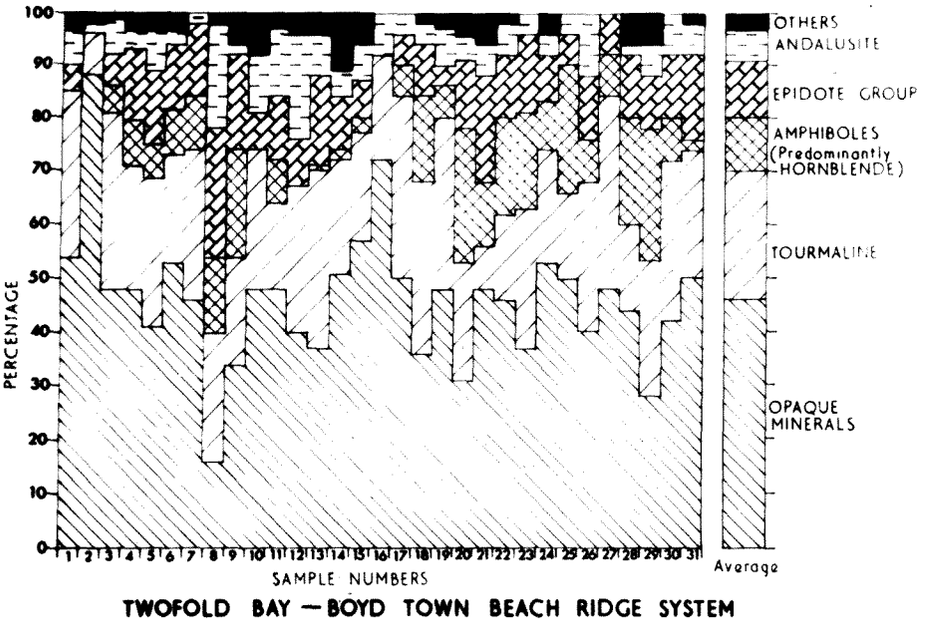

BROKEN BAY - OCEAN BEACH (BEACH/DUNE-RIDGE SYSTEM)
HOLOCENE SAMPLES
BROKEN BAY- OCEAN (BEACH/DUNE-RIDGE SYSTEM) ? PLEISTOCENE SAMPLES
PEARL BEACH BARRIER
PERCENTAGE
SAMPLE NUMBERS
Average
OTHERS
ANDALUSITE
RUTILE
EPIDOTE GP.
AMPHIBOLES
TOURMALINE
ZIRCON
OPAQUE MINERALS

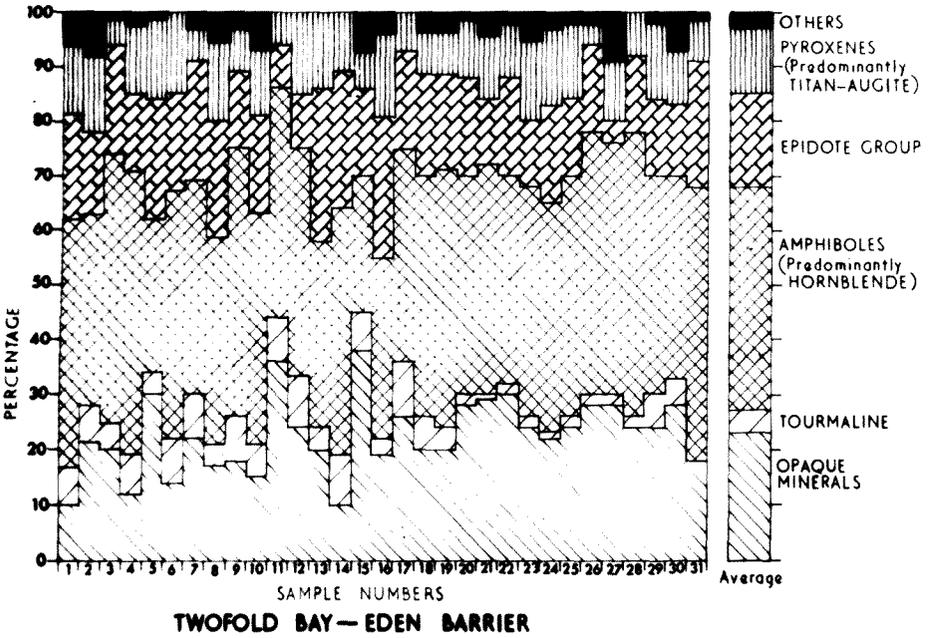
Figure 8.4

Figure 8.5 The percentage occurrence (by number) of heavy minerals identified in south coast barrier samples. The average composition is also shown.

PAMBULA BARRIER



TWOFOLD BAY — BOYD TOWN BEACH RIDGE SYSTEM



TWOFOLD BAY — EDEN BARRIER

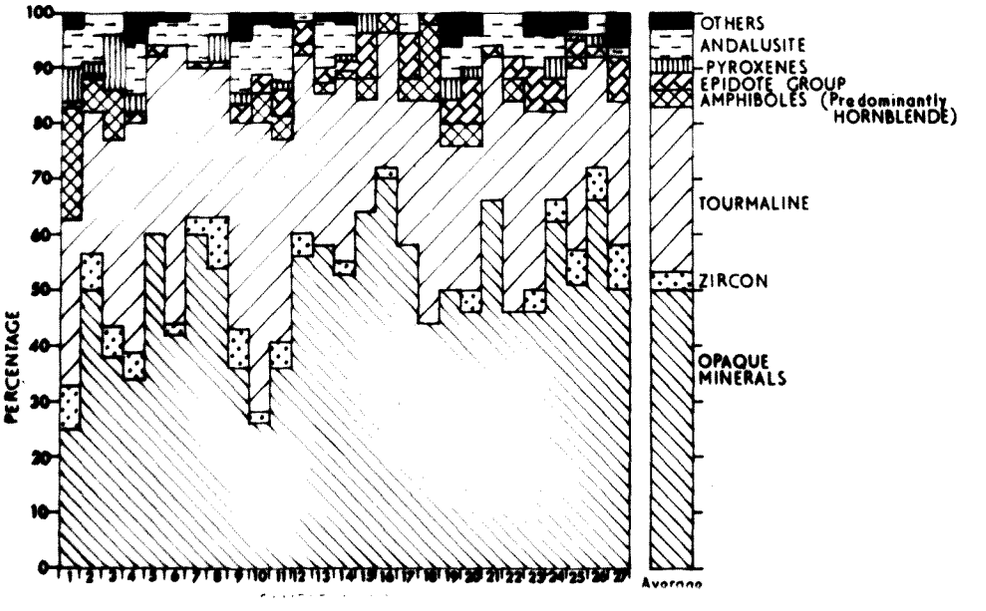


Figure 8.6 Possible sources of heavy minerals in the Mid-North Coast study area.

Erratum: Localised longshore drift within zeta-curved bays resulting from refraction of swell waves should read ..... caused by southeasterly swell waves arriving at an angle to the shore.

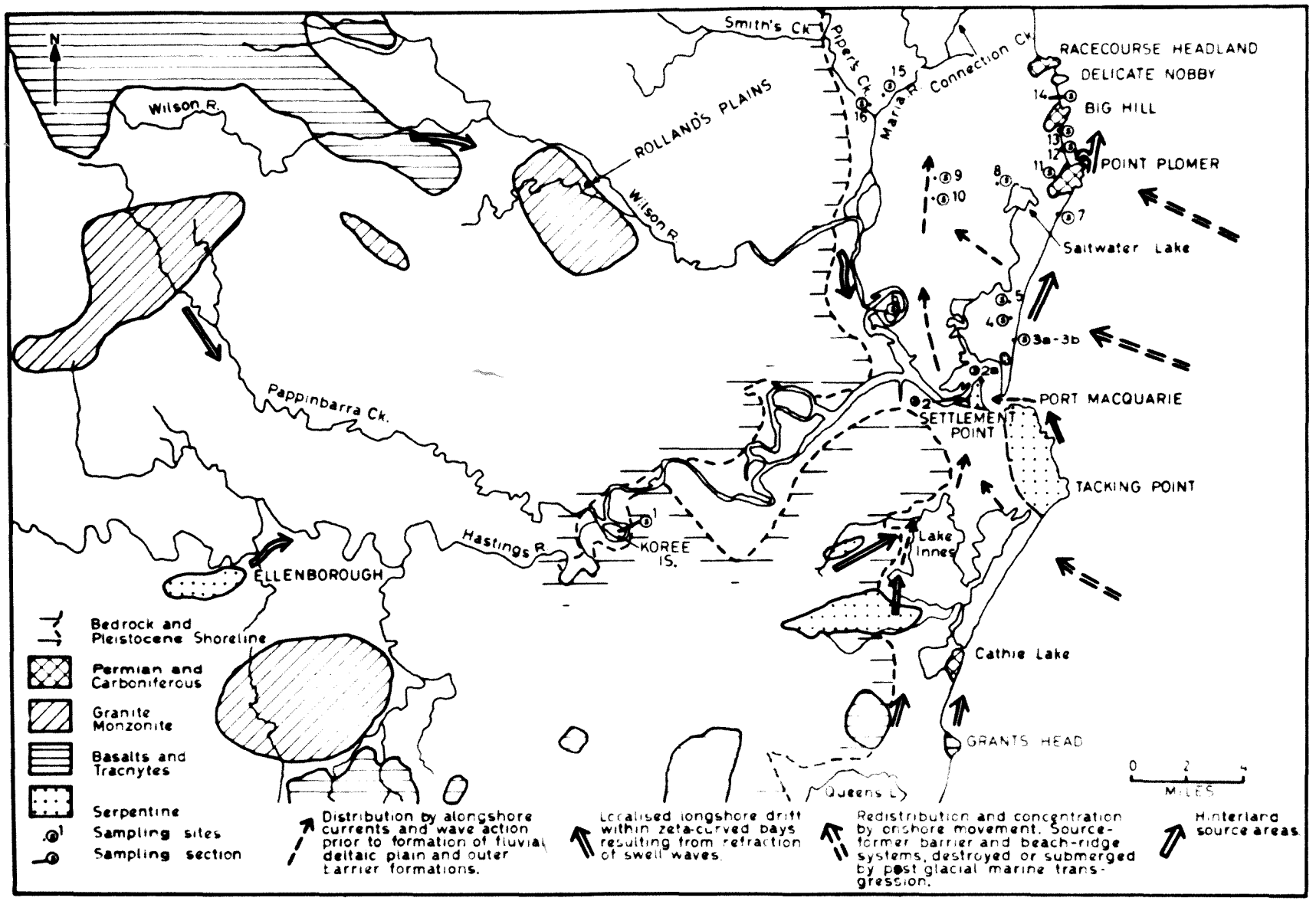

N
Wilson R.
Smith's Ck
Piper's Ck
Maria R.
Connection Ck
RACECOURSE HEADLAND
DELICATE NOBBY
BIG HILL
POINT PLOMER
ROLLAND'S PLAINS
Wilson R.
Saltwater Lake
Pappinbarra Ck.
PORT MACQUARIE
SETTLEMENT POINT
TACKING POINT
Hastings R.
KOREE IS.
Lake Innes
ELLENBOROUGH
Cathie Lake
GRANTS HEAD
Queens L.
0 2 4
MILES
Bedrock and Pleistocene Shoreline
Permian and Carboniferous
Granite Monzonite
Basalts and Tracnytes
Serpentine
Sampling sites
Sampling section
Distribution by alongshore currents and wave action prior to formation of fluvial deltaic plain and outer barrier formations.
Localised longshore drift within zeta-curved bays resulting from refraction of swell waves.
Redistribution and concentration by onshore movement. Source-former barrier and beach-ridge systems, destroyed or submerged by post glacial marine transgression.
Hinterland source areas.

Figure 8.6

Figure 8.7 Some of the heavy minerals identified in Mid-North Coast samples.

A. Hat Head cliff-top dune samples (x 58).

B. Smoky Cape cliff-top dune samples (x 36).

C. Front Beach transgressive dune samples (x 36).

1. Piedmontite
2. Zircon
3. Rutile
4. Tourmaline
5. Leucoxene
6. Magnetite
7. Andalusite
8. Ilmenite

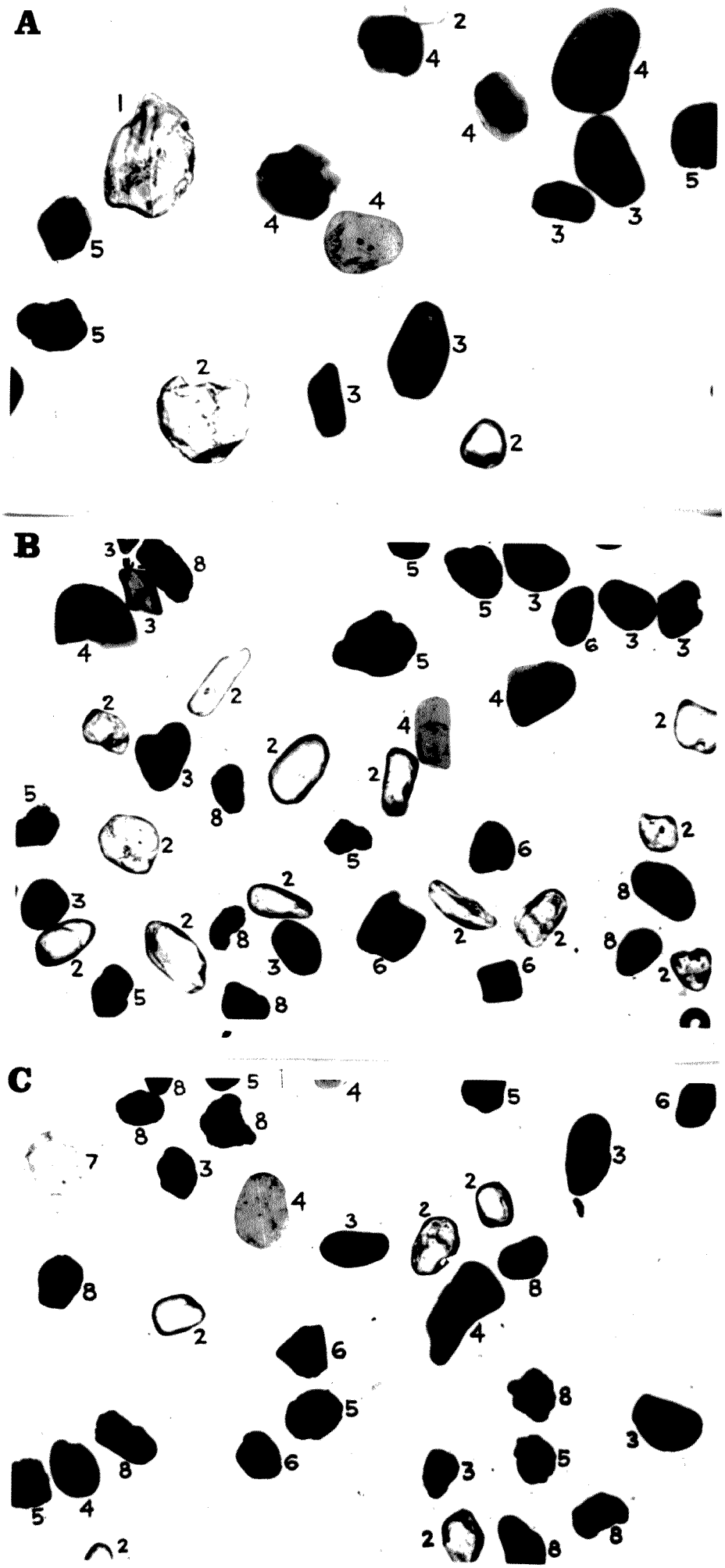

A
B
C

Figure 8.7 continued Some of the heavy minerals identified in samples from the three study areas.

D. Boyd Town beach ridge system (x 36)

x A - Amphibole
E - Epidote
H - Hornblende
T/Aug - Titan-augite
P - Pyroxene

E. Whale Beach barrier (x 36)

M - Magnetite

F. Pambula barrier spit (x 58)

G. Number 3a-3b, Figure 8.1, North of Port Macquarie.

An - Andalusite
T - Tourmaline

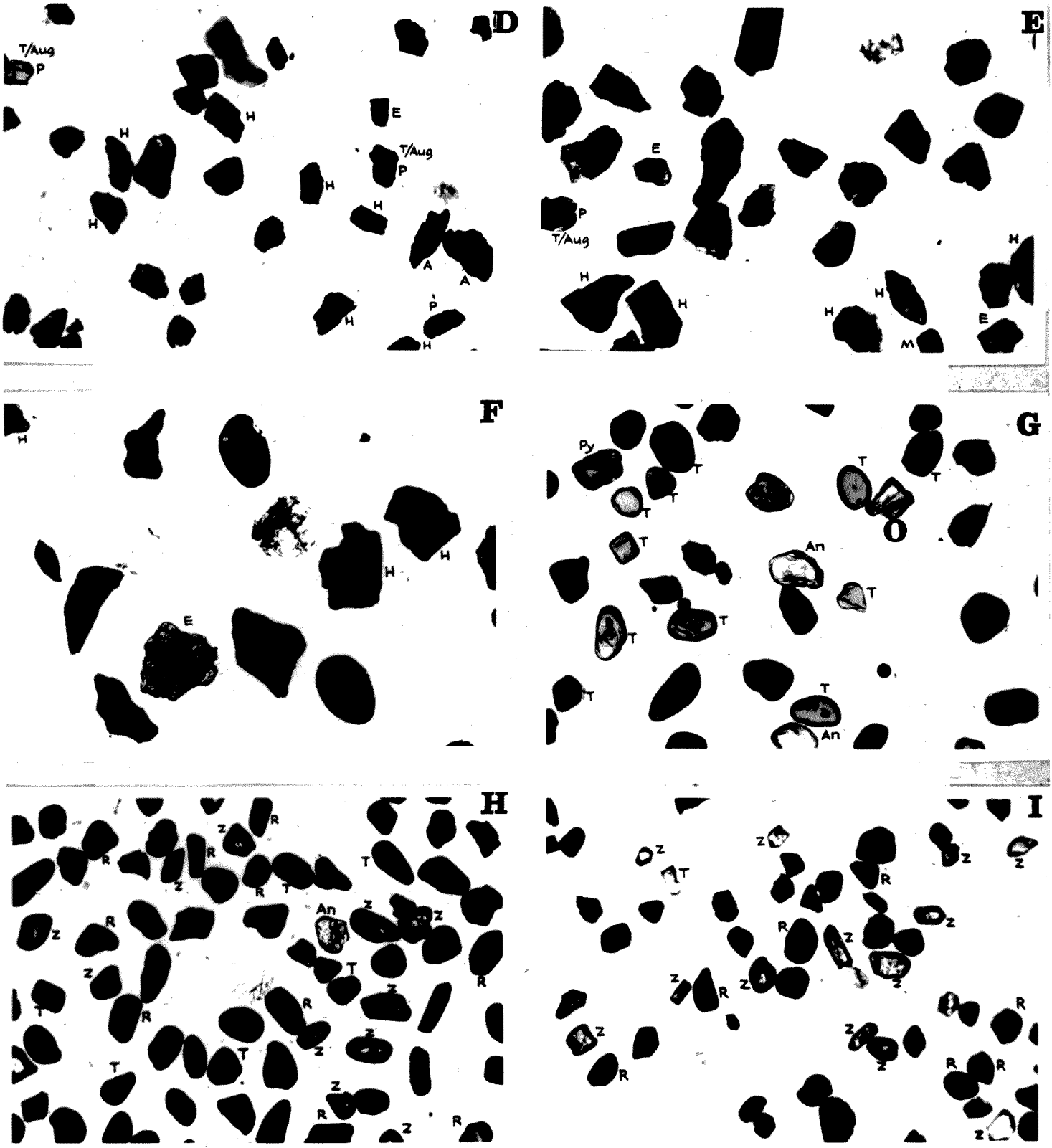
H. Patonga barrier spit (x 36)

R - Rutile
Z - Zircon

'I'.Macleay River- Sherwood Bridge (x 36)

T - Topaz

x Same symbols for D - 'I' unless shown otherwise.


D
T/Aug
P
H
E
T/Aug
P
H
H
H
A
A
P
H
H
E
E
P
T/Aug
H
H
H
H
M
E
F
H
H
H
E
G
Py
T
T
T
T
T
T
T
T
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R

CHAPTER 9

EUSTATIC CHANGES OF SEA LEVEL IN EASTERN AUSTRALIA WITH PARTICULAR REFERENCE TO THE STUDY AREAS

Introduction: Although in recent years considerable attention has been devoted to eustatic changes of sea level, few geologists and geomorphologists are in agreement about changes in the relative level of land and sea in Australia, especially during the Holocene epoch. This divergence of opinion has aroused the interest of some overseas authorities including Flint (1957), Russell (1963) and Shepard (1963a, 1963b).

There are three main criticisms from overseas of some Australian coastal studies. The first is that much evidence is believed to be of questionable value because it is based on the misinterpretation of contemporary and Pleistocene coastal features (Russell, op. cit.). Second, some dated shell samples have probably been collected from aboriginal kitchen-middens left on older terraces (Shepard, 1961). The third criticism is that many of the seemingly anomalous carbon-14 dates for stranded coastlines could well be derived from inadequately cleaned samples (Russell, op. cit.).

It is difficult to establish precisely the elevation of former higher stillstands of the sea in eastern Australia because of a lack of fossiliferous marine deposits more than 20-25 feet above present sea level, and consequently it is difficult to separate tectonic movements and eustatic changes of sea level. On a few relatively stable barrier coasts outside the continent the heights of former sea levels can be determined from the upper limit of preserved lagoonal-salt marsh sediments, and from the upper limit of fossil burrows of the marine decapod Callianassa (Hoyt and Hails, 1967).

Callianassa australiensis, one of the 70-odd living species of Callianassa, is present along the east Australian coast between the Low Isles in northern Queensland and Port Phillip in Victoria, but according to Hailstone (1962) it is found exclusively in inter-tidal estuarine sandflats, or the lower reaches of coastal rivers. Apparently, it is most abundant on sand banks or gently sloping sandflats composed of fine-grained sand mixed with lesser proportions of mud. However, preserved littoral sediments of a similar composition have not been found above present sea level in the study areas, and Callianassa australiensis has not been reported in Pleistocene barrier sands.

Another problem is how to determine accurately the heights of stranded coastal features, such as marine beaches and terraces, because there are no accurate datum points in many areas. This problem has been summarized adequately by Bauer (1961): 'Meaningful study of the traces left by former stands of sea level against the land must be based on accurate measurements of the differences in elevation between those features and present sea level. It is doubtful if this vital data has been obtained to an accuracy of ±5 feet for more than two score of the many features described in the literature. Yet the fault does not lie with the observers; it is an unpleasant fact of life for the Australian geomorphologist that very few levelling surveys have been done in coastal areas, and that most of them extend no more than 100 feet above sea level....This lack of accurately determined points of known elevation above present sea level puts serious limits on nearly all phases of terrace study.'

According to David (ed. W.R. Browne, 1950) there is evidence of Pleistocene fluctuations of sea level up to at least 150 feet on various

sectors of the Australian coast, and in New South Wales terraces have been recorded at several intervals between 5 and 200 feet. But as already mentioned no marine fossils have been recorded above about 25 feet.

Here it is proposed to evaluate the evidence for possible higher sea levels in the study areas provided by both erosional and depositional features, including abandoned wave-cut platforms or marine benches backed by degraded sea-cliffs, sea-caves, and relict boulder beaches, and to examine the significance of carbon-14 dates, and pollen and macro-plant studies, in determining changes in sea level during late Holocene time. Since probably no coastal area is stable sensu stricto, no attempts have been made to correlate the evidence with similar data from other areas. Correlating between and within regions, based on elevations and terrace sequences, is highly suspect because coastlines may be warped or displaced by local or regional tectonism. Nevertheless, world-wide correlations, on the basis of comparative elevations, have been attempted in order to establish a sequence of Pleistocene sea level changes (Zeuner, 1959; Woldstedt, 1961; Ward, 1965).

EVIDENCE FOR HIGHER STANDS OF THE SEA

Mid-North Coast: Abandoned erosional marine features, like contemporary wave-cut platforms, are not strikingly well developed on the Mid-North Coast because the headlands are particularly resistant to wave attack. In fact there are only two abandoned wave-cut platforms or marine benches. One is a narrow bench truncating fairly steeply dipping Lower Palaeozoic metasediments on the north side of Grassy Head (Plate 9.1F). The inner edge of the bench is backed by degraded sea-cliffs, and stands about 20 feet above present sea level. Most of the bench is covered with vegetation

and there is little evidence to suggest that it is washed by waves even during storms accompanied by onshore northeasterly winds. The seaward edge of the bench is separated from a lower contemporary wave-cut platform by a steep break of slope(Plate 9.1G).

In contrast, there is a much wider abandoned 20-ft bench, cut in sedimentary rock, at the back of Delicate Nobby headland (Plate 9.1'I'). It seems most likely, because of its position, that this bench was probably cut during a high stand of the sea before the formation of the Inner Barrier when Delicate Nobby was an island.

The possibility cannot be discounted that other wave-cut platforms may be buried beneath the transgressive dunes piled against the exposed side of the headlands on the Mid-North Coast.

An abandoned sea-cave, cut in claystone, mudstone and tuffaceous sandstone but characterized by dripstone and flowstone formations, has been located at Big Hill headland. However, some caution is necessary in interpreting the evidence this cave may afford about changes in sea level because it may be the product of more than one period of marine erosion. One of the problems the writer has encountered is how to determine precisely the height at which the sea formerly stood when the cave floor is almost completely buried beneath an enormous heap of rubble which has collapsed from the cave roof. At least survey aneroid traverses showed that the floor at the back of this cave stands between 25 and 30 feet above present sea level.

The anomalous occurrence of dripstone/flowstone formations in this cave demands a brief comment. As far as the writer is aware, the only comparable anomalous occurrence of such formations in Australia has been reported on King Island by Jennings (1956). Big Hill headland is partly

mantled with vegetated podzolized dune sand of Pleistocene age (Plate 3.3E), and it can therefore only be assumed that during podzolization some calcium carbonate, in solution, percolated through planes of weakness in the bedrock.

Apart from the relict boulder beaches between 80 and 100 feet above present sea level on the north coast of New South Wales outside the Mid-North region (Langford-Smith and Hails, 1966), the writer has found similar deposits at 40-45 and 20-25 feet at Delicate Nobby headland in the study area. Possible relict boulder beaches, now partly buried beneath deeply podzolized sand, have been located along the periphery of some of the isolated bedrock masses (former offshore islands) to the north of the Maria-Wilson barrier plain (Figure 3.7). Exfoliation features are clearly recognizable on several boulders and although most of them are well rounded the absence of fossiliferous material makes it difficult to confirm whether or not the boulders are definitely abandoned shoreline deposits.

Again, some care is needed in determining the height of former sea levels from the location of boulder beach relics because storm waves can deposit pebbles many feet above high-water mark; the crests of some of the modern storm-wave boulder beaches average about 10 feet above HWM. By inference, therefore, the boulder beaches at 20-25 feet may have been deposited during the 15-ft high stand of the sea which witnessed the establishment of the Inner Barrier. Other relict boulder beaches at comparable heights with those on the Mid-North Coast, have been located at Forster-Tuncurry(18-25 feet) by Langford-Smith and Hails (see Gill, 1964), and reported at Boat Harbour, Port Stephens (Sussmilch and Clark, 1928).

Reference has already been made (Chapter 3) to an ancient Pleistocene coastline which extends throughout the length of the Mid-North region and

marks the landward limit of the fluvial-deltaic plains. It is characterized by low degraded cliffs, some of which are masked in places by colluvium and dense vegetation. To the north of Clybucca Creek, the cliffs are fronted by a series of relict beach ridges - this part of the Pleistocene coastline has been designated the Clybucca shoreline by the writer in order to distinguish it from the Inner Barrier (Figure 3.4). Survey aneroid traverses show that the crest of the cliff-line is generally between 40 and 50 feet above mean sea level, but along the southern margin of Belmore Swamp it is distinctly bevelled and only stands 20-25 feet above the level of the swamp. The absence of beach deposits on this bench can be explained by its partly sheltered position inside a former embayment.

Voisey (1934a) reported mollusc shells 10 feet above high-water mark at the base of the coastline between Frederickton and Grassy Head(cf. Plate 3.3D). The shells, which include Ostrea cucullata, and Arca(Anadara) trapezia, were broken at the posterior margin and contained artefacts. As Voisey correctly stated, the shells are not stranded beach deposits but aboriginal kitchen-midden material.

Broken Bay: The writer found no erosional marine features or beach deposits in Broken Bay which could be taken as reliable evidence of former higher stands of the sea. There are a few narrow ledges and notches above present sea level near the base of some of the cliffs in the bay but these features are not reliable indicators of higher sea levels because they owe their origin to mechanical and, to a lesser degree, chemical weathering which have been guided by the lithology of the bedrock.

One cave was found about 100 feet above sea level on the ancient bedrock coastline behind the Umina-Woy Woy beach ridge system. Its floor was partly covered with debris that had collapsed from the roof, and

weathered material including broken shells and charcoal - substantial evidence of an aboriginal kitchen-midden. However, this particular feature is not considered to be a stranded sea-cave but one of the several 'rock shelters' that have been eroded along the strike of the massively-bedded Hawkesbury sandstone in this region.

South Coast: The writer found shells (but no charcoal) on a very narrow bench, which truncates Tertiary(?) deposits overlying steeply dipping Devonian strata, about 90 feet above present sea level near Toallo Point on the south coast. The shells that have been identified are listed in Table 9.1. Although the majority of them are not diagnostic, and may only be kitchen-midden material, the occurrence of Notospisula may have some significance because this specimen was not collected for food by the aborigines. On the other hand the possibility cannot be discounted that the Notospisula shells may have been carried accidentally with other beach material by the aborigines to the site where they were found.

Another bench, comparable in height to the one at Toallo Point, was located at Merimbula Point, but at this locality the evidence is too inconclusive to indicate its origin.

A cave occurs below the lighthouse at Eden in Twofold Bay, and another near the jetty on Merimbula Point. The entrance to the former is about 20 feet above sea level but again, as the writer experienced on the Mid-North Coast, a large pile of roof debris made it difficult to establish accurately the height of the cave floor above present sea level. No shells or beach sand were found in the cave which has been cut along a contact between Devonian rhyolite and an intraformational conglomerate. The cave at Merimbula Point, which has been cut in Devonian red shales,

resembles very closely some of the rock shelters cut in the Triassic sandstone on the central coast of New South Wales in the Broken Bay region. It stands approximately 15-20 feet above sea level but its floor is covered with boulders and other rubble.

Perhaps the only significant fact to record here about the possible evidence for higher stands of the sea is that the heights of the three caves, the abandoned marine benches on the Mid-North Coast and the relict 20-25ft boulder beach at Delicate Nobby are comparable even if they are widely distributed along the coast, over a distance of some 600 miles.

The Significance of Carbon-14 Dates, and Pollen and Macro-Plant Studies

At this point it is apposite to refer briefly to the divergent views on changes in sea level during late Holocene time. One view, supported by Shepard and Suess (1956), Shepard (1960,1964) and Scholl (1964), is that the sea has risen slowly and continuously to its present level since about 5000 years B.P. But Fisk (1944), LeBlanc and Bernard (1954), Gould and McFarlan (1959), McFarlan (1961), Redfield and Rubin (1962), McIntire and Morgan (1962), Russell (1964) and Coleman and Smith (1964) are of the opinion that there has been a relative stillstand for the past 3000 to 5000 years; the evidence discussed by these workers supports the stillstand theory although it must be admitted, at the same time, that details of sea level changes during the last 4000 years are still far from conclusive. Then there are those who claim that the sea has been fluctuating above and below its present level; Fairbridge (1961) is the leading proponent of this theory, although a possible 10-ft Recent (Holocene) higher sea level in Australia has been attributed by Gill (1955, 1961) to a postglacial climatic optimum about 4-6000 years B.P. Strong arguments for a Holocene

high stand of the sea, in areas widely scattered around Australia, have been put forward by several workers (Teichert and Fairbridge, 1952; Davies, 1959; Jennings, 1959a, 1961; Ward, 1965), but so far no conclusive evidence of this postulated higher sea level has been found in New South Wales (Hails, 1965b; Thom, 1965; Langford-Smith and Thom, 1969 in press).

This section is essentially an evaluation of radiocarbon dates relevant to the controversial problem of a possible Holocene higher sea level in eastern Australia. Particular emphasis is placed on a recently dated group of eight peat samples from the Mid-North Coast, and other areas. The similarity in site, age, and environment of deposition of the peats is also considered to be significant.

It was mentioned briefly in Chapter 3 that the retreat of the Outer Barrier (and in some cases the Inner Barrier) has exposed peat beds and humate in many localities on the New South Wales coast. Both the peats and humate outcrop in the backshore zone of the beaches and generally range in thickness from about 1 to 6 feet. In a few areas they extend as a continuous outcrop from a few feet to several miles parallel to the beach, and except where small streams drain into the sea they are covered on the landward side by many feet of dune sand. On the beaches to the north and south of Evans Head humate extends below present sea level, and work by Langford-Smith and Hails (1963, unpublished) has shown that it occurs intermittently for some miles along the shore of a huge compound embayment between Iluka and Ballina and is often exposed as vertical sea cliffs and overlain by deeply podzolized sand.

On the Mid-North Coast peat beds have been located at Front Beach north of Crescent Head, at Back Beach just north of Race Course Headland,

to the north of Delicate Nobby headland and south of Big Hill and Port Macquarie. The peat bed at Back Beach is situated about 1 foot above high-water mark, intercalated between two boulder beaches and overlain by residual Outer Barrier sand knolls. As mentioned earlier, the peat at Front Beach, which extends well below present sea level low-water mark, was exposed when the beach was cut back by floodwater in 1963. The peat bed north of Delicate Nobby headland is located about 20 feet below the crest of the Outer Barrier, just about at high-water mark. Boreholes sunk to 12 feet below sea level located the peat under the Outer Barrier south of Big Hill leadland. Although the actual extent of this bed has not been determined precisely it is known to extend inland from the beach for at least 200 feet.

Pollen and macro-plant analyses show that the peats have formed under a variety of plant communities. Actually, all these communities can be matched with the existing types of coastal vegetation occupying dune depressions, inter-barrier lagoons, and waterlogged beach-ridge swales. These are essentially paludal or terrestrial freshwater environments. The pollen and macro-plant analyses of the peat collected immediately north of Delicate Nobby show that Cyperaceae (and possibly reed) dominated, with adjacent Paperbark or Tea-tree and fringing Casuarina woodland. The identification of Nothofagus pollen seems to indicate that some grains were transported over a considerably long distance from a temperate rain forest, although the other tree pollens have been derived from a dry sclerophyll forest of local origin. Some of the ecological properties have been summarized in Tables 9.2 and 9.3.

The ages of the peats are listed in Table 9.4. These dates, together with samples from other environments relevant to the problem of sea level changes during the Holocene are plotted as a depth-time association in Figure 9.1A. This relationship, as already shown by Coleman and Smith (1964), includes changes of level resulting from both subsidence and eustatic movements and thus cannot be used to represent the actual position of sea level unless the sampled areas are known to be stable. Because of the limitations of radiometric techniques in dating humate, only one humate sample has been shown in Figure 9.1A.

In order to evaluate the significance of the peats outcropping on the beach from the point of view of eustatic changes of sea level, two assumptions have been made. First, contamination by younger or older carbon-rich material has not significantly affected the dates. All samples have been buried by accumulations of siliceous dune sand, which implies that root contamination is insignificant, since the peats were buried by landward migrating dunes. The second assumption is that the Mid-North Coast and adjacent areas are relatively stable and that regional subsidence or uplift has had minimal effect on the elevation of the peat beds (see also the following discussion on coastal stability). Within the broad embayments formed in bedrock of Palaeozoic or Mesozoic age the peat and fine-textured inorganic sediments constitute only a small fraction of embayment fill, and it is unlikely that local subsidence is of much importance. The effects of compaction must be considered as a factor in the variability of the dates since the samples were not always collected at the base of the peat horizons. However, the total amount of compaction is probably very small, considering the thickness of the peat beds.

The major contribution that the dates, which have an average age of 3,625 years and a range of 1,500 years, in Table 9.4 make to our knowledge of eustatic sea level fluctuations is that the sea could not have been higher than its present level (excluding the effects of compaction) during the formation of the peats. Since these are freshwater organic deposits formed in coastal localities, it is therefore interpreted that mean sea level must have been at or slightly below its present position during the period 2000-4500 years B.P. This view is also supported by the conclusion of Jelgersma (1961), based on data from the Netherlands: 'Though peat may have been formed several metres above sea level, it can hardly be assumed that peat was formed many metres below sea level during Fairbridge's high stages.'

An Evaluation of Coastal Stability

Voisey (1934a) has invoked uplift of the Mid-North Coast region to account for the elevated position of the high-level ridge gravels in the upper Macleay Valley and the shore platforms above present high-water mark in areas adjacent to the study region. He also suggested that deposition in the lower Macleay valley was later supplemented by uplift which caused much of the swampy land to be drained. But detailed surveys (Chapter 6) show that parts of the swamps are still at, or below, mean sea level. It is difficult to generalize about the formation of wave-cut platforms, or about the duration of stillstands and local conditions when they are supposedly cut, because of the several inter-related factors that control their development. However, it is possible that some of the contemporary abrasion platforms were initially cut during a stillstand of the sea immediately preceding the late-Wisconsinan regression, and that the sea is now within a few feet of its former level during that stillstand

(see also Hails and Hoyt, 1968).

Maze (1933) has postulated a 20-ft uplift of the land in Broken Bay, based on the evidence of pot-holes at Green Point. The pot-holes are deeply grooved, contain soil, stand 18.5 feet above high-water mark, and are very similar to those found in stream beds, and on the modern coast. However, such features are known to be produced by normal weathering processes and it seems likely, in the absence of contrary evidence, that the pot-holes at Green Point illustrate the effects and complexities of sub-aerial weathering on sandstone in coastal areas rather than evidence of uplift.

Although only a very few areas in New South Wales have been studied in detail there is as yet little evidence to support differential tectonic activity along the coast. Recently, attention has been drawn by Higgins (1965) and Bloom (1964,1967) to the possibility that some coastal areas may be isostatically warped by the load of water added to the continental margins by the postglacial rise of sea level. According to Crittenden's (1963) study of glacial Lake Bonneville, maximum vertical movement is likely to occur along a narrow, steep continental shelf. The most recent of several studies undertaken by Phipps (1966) has shown that there has been Pleistocene warping of the outer continental shelf of central and southern New South Wales. Although the evidence is still inconclusive, there is some indication that the warping may represent a deep seated weakness of the continental margin rather than the effects of continuously varying water loads on the continental shelf. Nevertheless, if coastal deformation, or tilting by local crustal movements, has also occurred in northern New South Wales it is difficult to detect because the Holocene

fluvial-deltaic plains have a fairly uniform elevation over many miles. Furthermore, there is no evidence to suggest that the Inner and Outer Barriers have been tilted transversely (to the coast), either by uplift or subsidence.

Unfortunately, there are practically no tide-gauges on the New South Wales coast, and none in the study areas, so it is impossible to determine any recent change of sea level from tide-gauge records. Since no geophysical work has been undertaken so far on the coast, the final solution to the problem of coastal stability may remain obscure until detailed projects are carried out on the well-preserved river terraces in the study areas. In fact, the writer thinks it possible that such a study may show that the tectonic movements at the end of the Tertiary period which were responsible for the plateaux of the Sydney region and the incision of river valleys on the north and south coast of New South Wales, may have continued much longer into the Pleistocene epoch then has hitherto been supposed.

Conclusions: There is no conclusive evidence in the study areas to indicate a higher sea level during Holocene time. Even if one accepts the hypothesis of a Recent (Holocene) climatic optimum, it by no means establishes that the relative short phase of higher temperatures would have had any significant effect on a change of sea level. Wave-cut notches at the base of sea-cliffs, sea-caves, boulder beaches and even wave-cut platforms along a coast at different levels to about 10 feet above high-water mark are well within the limits of contemporary storm wave action. Therefore, they do not necessarily afford evidence of higher stands of the sea during Holocene (and possibly Pleistocene) times, but rather exemplify the different levels at which shoreline features can be found on tidal and exposed coasts (Hails, 1965b).

The lack of fossiliferous marine deposits has already been noted, and therefore the problem of distinguishing between tectonic movements and eustatic changes of sea level during the Pleistocene will not be resolved until more sophisticated techniques are employed in the field. The writer claims that correlations between widely scattered areas of the continent cannot be attempted in the light of the evidence available at present. The three main criticisms of Australian studies cited at the beginning of this chapter illustrate the questionable value of some of the reported evidence.

In conclusion, the writer is aware that the radiocarbon dates reported here do not necessarily provide a final solution to the problem of a Holocene high stand of the sea. Field evidence indicates that the Mid-North Coast has been relatively stable during late Quaternary time even if the evidence from Broken Bay and the south coast is less conclusive at present. Therefore until more evidence is available the following points are mainly a tentative chronological summary of sea level changes in New South Wales as reported in this and preceding chapters.

Summary: 1. A shoreline (presumably early Pleistocene)at 80-100 feet is the highest recorded so far. No barrier deposits have been associated with this higher sea level, although some of the lowest cliff-top dunes may have been emplaced during this high stillstand.

2. The bedrock margin of the fluvial-deltaic plains was probably planed during a 40-50-ft high stand of the sea.

3. A 20-25-ft high stand of the sea preceded a 15-ft higher sea level during which the Inner Barrier was probably established.

4. During a late-Wisconsinan low stand of the sea the coastal rivers entrenched their courses and entered the sea probably several miles east of the modern coast.

5. During the Holocene marine transgression since about 18,000 years B.P., sea level rose rapidly until approximately 7000 years B.P. Since then there has been either a slow continuous rise of sea level, or a stillstand since 3-5000 years B.P. Evidence along the New South Wales coast indicates a fairly stable sea level during this time. The pronounced barrier erosion may be attributed to the effects of an interruption in shoreline equilibrium.

6. The Outer Barrier formed sometime after 7000 years B.P.

7. There is no evidence in the areas studied by the writer to support a higher sea level during the Hypsithermal period 4000-6000 years B.P. During this period the fluvial-deltaic plains were constructed landward of the barriers.

8. Erosional and depositional shoreline features that occur at levels up to 10 feet above mean sea level can be related to present sea level and storm wave activity, and do not necessarily afford evidence of higher Holocene stands of the sea.

TABLE 9.1

Shells found on the marine bench near Toallo Point.

1.	*Cellana tramoserica*(?)	Fam.	Patellidae
2.	*Dicathais orbita*	Fam.	Thaisidae
3.	*Patelloida altcostata*	Fam.	Patelloididae
4.	*Cymatilesta spengleri*	Fam.	Cymatiidae
5.	*Melanerita atramentosa*	Fam.	Neritidae
6.	*Subninella undulata*	Fam.	Turbinidae
7.	*Patellanax peronii*	Fam.	Patelloididae

TABLE 9.2

Pollen analysis of Delicate Nobby peat sample collected at about high-water mark approximately a quarter of a mile north of the headland. Dated 3600±120 B.P.

		Number of Pollen Grains	
Aquatics + Gramineae	Cyperaceae (general)	52	
	Cyperaceae (Machaerina-Gymnoschoenus type)	17	
	Gramineae	47	+ epidemal cells and stomata
	* Typha	1	
	* Triglochin (Potamogetonacea)	24	
Tree pollen	* Eucalyptus (Various)	9	
	* Eucalyptus (Crebra type)	4	
	* Angophora type	1	
	* Melaleuca (quinqenervia type)	8	
	* Leptospermum type	11	
	* Casuarina	31	
	* Nothofagus (moorei type)	2	
	* Banksia cf. serrata	1	
	Callitris	1	
	Restionaceae	3	
	Compositae	1	
	Leguminosae	1	
	Doryanthes type (monocot 1- sulcate grain)	1	
	Urticaceae	1	
	Portulacaceae	1	
	Unidentified Dicotyledons	4	
	Monolete fern spores	4	
	Schizaea type	2	
	Trilete fern spores (various)	3	

* Described in the text in association with modern swamps and Pleistocene and Holocene Barriers.

The Gramineae are high in percentage content. The high number of Cyperaceae and Triglochin show that conditions were aquatic or nearly so. There is a paucity of wet heath types such as Banksia, Callistemon, Epacridaceae, Restionaceae, Boronia and so forth. See also Table 9.3.

TABLE 9.3

Palynological analyses of peat samples from Delicate Nobby, and Front Beach to the north of Crescent Head. (Percentage composition is abbreviated since there are 89 different entries in the full analyses).

	DELICATE NOBBY I	DELICATE NOBBY II	FRONT BEACH
Background Pollen:			
Eucalyptus/Angophora	17.5	17.3	24.0
Melaleuca quinquenevia type	9.3	2.5	4.0
Leptospermoideae type etc.	15.1	8.6	13.0
Callistemon		3.7	4.0
Casuarina	38.4	27.8	27.0
Callitris	1.2	13.6	7.0
Monotoca		1.9	4.0
Other woody plants	4.1	12.3	5.0
Compositae	2.4	2.5	1.0
Chenopodiaceae		2.5	1.0
Other herbaceous plants	3.6	6.2	11.0
Locally Produced Pollens:			
Triglochin/Potamogeton	36.0	21.0	24.5
Typha	1.2		
Restionaceae	3.5	1.2	165.0
Eriocaulon			25.0
Philydrum			
Cyperaceae (general)	50.0	82.7	34.0
" (polyforate))	19.8	130.9	15.0
" (Schoenus-Cladium type)	15.1	22.2	13.0

* Total "Background" pollen is taken as pollen sum of 100% for each sample.

_____ Most significant.

TABLE 9.3 continued

	DELICATE NOBBY I	DELICATE NOBBY II	FRONT BEACH
Locally Produced Pollen cont'd:			
Gramineae	59.3	26.5	51.0
Other Monocots	1.2	?	5.0
Haloragidaceae		1.9	2.0
Brasenia			
Nymphoides			
Other Dicotyledons		2.5	2.0
Fern Spores (all types)	11.6	1.8	10.0
Selaginella uliginosa			78.0
Lycopodium laterale			
Hystrichospheres		2.5	
Dinoflagellates			
Pediastrum			
Desmids			
Chara			

TABLE 9.4

Radiocarbon dates of peats, shells, humate and stumps collected on the New South Wales Coast and plotted in Figure 9.1A.

Sample Number	Laboratory Number	Location	Latitude-Longitude	Sample Description	Elevation in feet above HWM	Age (Years B.P.)
1	O-2177	Delicate Nobby	31°15'S, 152°58'E	Peat	0	3600±120
2	O-2164	Back Beach Crescent Hd.	31°14'S, 152°57E	Peat	+1	4600±130
3	Gak508	As Above	As Above	Peat	+1	3600±110
4	O-2174	Front Beach Crescent Hd.	31°6'30"S, 153°1'E	Peat	0	3600±120
5	O-2176	As Above	As Above	Peat	0	3100±115
6	O-2178	Killick Ck.	31°10'S, 152°58'E.	Humate	-3 to -4	5450±140
7	Gak-834	Clybucca Ck. Anderson's Inlet	30°56'S. 152°59'E.	Shells (see Chapter 6)	-5 to -6	4220±90
8	Gak-835	Little Cooperabung (Nr. Kempsey)	31°16'S 152°50'E	Wood	0	8240±140
9	Lj-451	Long Reef, Sydney	34°45'S 151°19'E	Peat	+1	3980±150
10	O-2157	Fingal Bay Port Stephens	32°45'S 152°12'E	Peat	+1	3150±115
11	O-1844	Eskdale Swamp Hunter Valley	32°40'S 151°44'E	Shell	-5	5900±145
12	V-32	Captain Cook Dock, Sydney	33°52' 151°13'E	Stump (*Eucalyptus gummifera*)	-50	8360±110

TABLE 9.4 Cont'd.

Radiocarbon dates of peats, shells, humate and stumps collected on the New South Wales Coast and plotted in Figure 9.1A.

Sample Number	Laboratory Number	Location	Latitude-Longitude	Sample Description	Elevation in feet above HWM	Age (Years B.P.)
13	0-1849	Belmont	33°02'S 151°42'E	Peat and Charcoal	-48	8075±175
14	0-1855	Tomago Hunter Valley	32°45'S, 151°50E	Humate	+15	3050±115
15	0-1860	Upper Myall River, Myall Lakes	32°29'S 152°15'E	Humate	+6	3630±120
16	0-1856	Lower Myall River, Myall Lakes	32°37'S, 152°14'E	Humate	+4	4550±130

Samples 1, 4, 5 and 6 were collected by the writer.

Samples 2, 3, 7 and 8 were collected by the writer and T. Langford-Smith.

Sample 9 collected by T. Langford-Smith and F. P. Shepard.

Samples 10, 11, 14-16 collected by B. G. Thom.

Sample 12 collected by E. D. Gill.

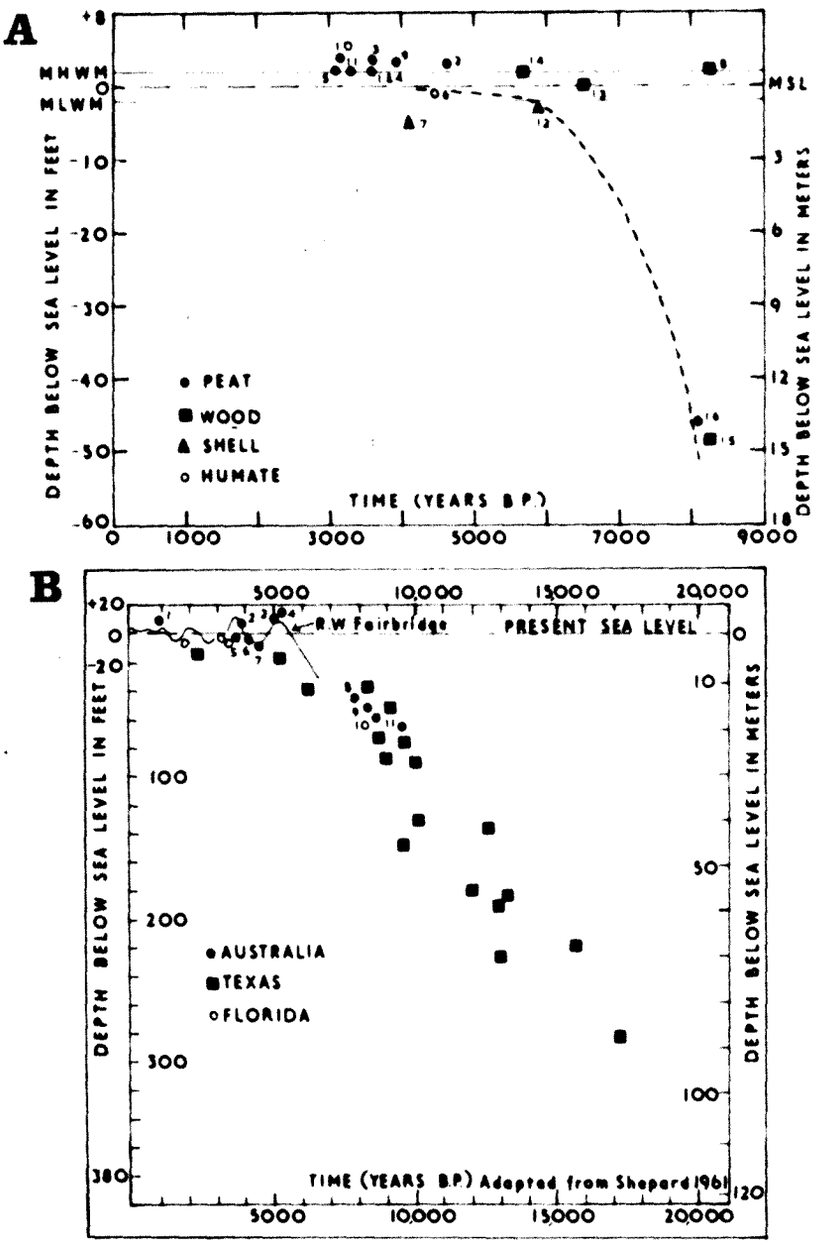
Sample 13 collected by B. G. Thom and A. R. H. Martin.

Figures 9.1A and 9.1B

9.1A Plot to show the approximate rise of sea level since 8000 B.P. Based on Carbon-14 dates of peats, shells, wood and humate samples.

9.1B Rise of sea level indicated by Carbon-14 dates from Australia, Texas and Florida. Postulated Holocene higher sea levels are also indicated.

Figures 9.1A - 9.1B



Plates 9.1A - 9.1E

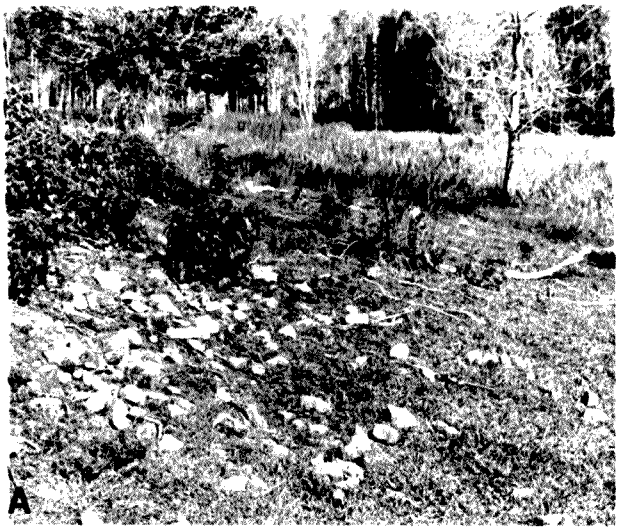
9.1A Boulder beach, Delicate Nobby.
This is a short distance west of that in 9.1B.

9.1B Boulder beach near base of marine bench
(cf. Plate 9.1'I'), Delicate Nobby.

9.1C - 9.1E

Contemporary boulder beaches, Crescent Head. In 'C', the headland is linked with the mainland by a tombolo-like boulder beach shown in 'E'. Note concentration of boulders by northeasterly and southeasterly waves refracted around the headland. 'D' is a view looking northeast.

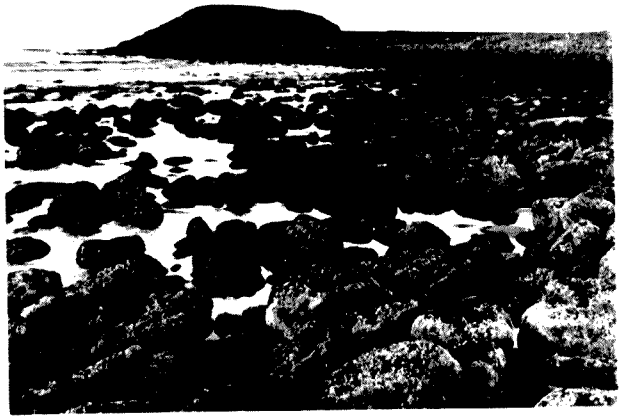
A



B



C



D



E



Plates 9.1F - 9.1'I'

9.1F Stranded marine bench, backed by degraded cliffs, at Grassy Head.

9.1G Stranded marine bench at Grassy Head terminated by steep break of slope which grades into a lower wave-cut platform.

9.1H View of part of Big Hill headland, showing steep cliffs and lack of wave-cut platforms because of resistant bedrock.

9.1'I' Marine bench on western side of Delicate Nobby headland.

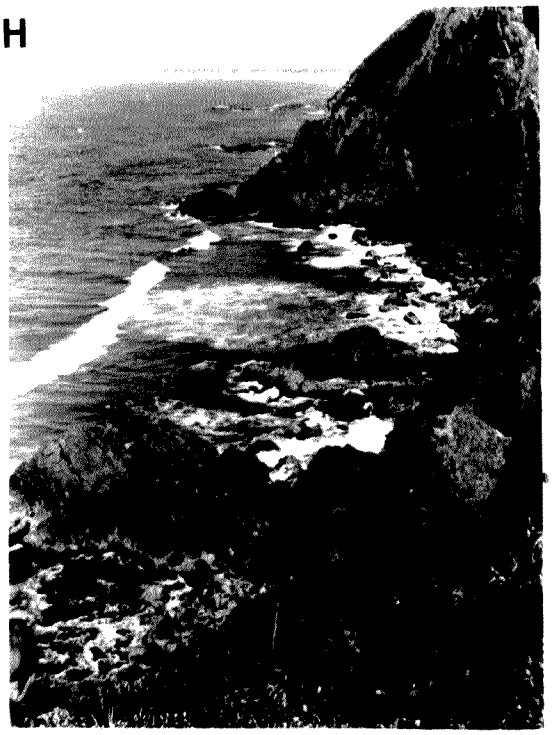
F



G



H



I



CHAPTER 10

GENERAL SUMMARY AND CONCLUSIONS

Although summaries and conclusions have been given at the end of most chapters, it is pertinent to review briefly here some of the more important findings and problems that have come to light in this study.

The writer experimented by correlating sedimentology with other aspects of geomorphology in an attempt to define Pleistocene and Holocene depositional environments more accurately. It has been shown that Pleistocene and Holocene sedimentary environments can be distinguished by the use of statistical parameters. A correlation appears to exist between grain-size analysis and depositional environments, and graphical and moment measures of polygenetic sediments show that skewness is basically an environmentally-sensitive parameter. However, the use of roundness analysis to distinguish between dune, barrier and beach sands is rather tenuous, particularly when coastal sands are regarded as polygenetic. The writer's work supports the contention that it is perfectly valid to use statistical parameters to supplement empirical geological and geomorphological data, and they can be usefully employed in future studies of depositional environments.

The petrological study of heavy minerals provided valuable clues on the source of some sediments, and also on the movement of material in Twofold Bay, but also brought to light some intriguing problems that may be resolved by more exacting investigations than the writer has been able to conduct during his study of three areas.

Evidence in the study areas strongly supports the view that barriers are built during marine transgressions and not during a fall in sea level.

By studying three areas which are quite different physiographically and geologically, it has been shown that the size of coastal sand barriers is dependent upon the amount of sediment delivered to the coast and continental shelf during lower stands of the sea, which is later reworked and moved shoreward by wave action and eventually incorporated in the barriers during and subsequent to a series of marine transgressions. It has also been demonstrated that although barriers are common practically everywhere on the New South Wales Coast, they are generally less well-developed on rugged sectors which are drained by coastal streams with small catchments. This may explain the absence of an Inner Barrier from the south coast study area.

Although the Inner and Outer Barrier systems can be distinguished by their respective soil profiles and vegetative cover, the major problem still awaiting solution is the precise age of the Inner Barrier, since there is a lack of fossil evidence and material suitable for radiocarbon dating. Although it has been suggested that the Inner Barrier was probably built during an interglacial period, the possibility cannot be dismissed that it may have been built during a high stand of the sea more than 25,000 years ago corresponding to an interstadial in late Wisconsinan time. The few available radiocarbon dates of predominantly freshwater peats, referred to in this study, suggest that the Outer Barrier was built sometime after 7000 years B.P., when the rate of the postglacial rise of sea level is reported to have slowed down considerably, and probably when the sea stood only a few feet below its present level.

As mentioned already, there is an urgent need for quantitative studies of sediment movement in the nearshore zone, and of the fluvial-deltaic plains in order to establish whether or not these plains were

partly built during a Recent (Holocene) pluvial period.

The problems confronting coastal geomorphologists, such as a lack of large-scale contour maps and datum points from which accurate measurements can be made, have been outlined. There is room for projects planned on a long-term basis to solve the problem of changes in the relative level of the land and sea during the Pleistocene epoch. For example, practically nothing is known about the origin of the Hawkesbury and Macleay river terraces, or for that matter the origin of most other river terraces on the New South Wales coast.

The recent discovery of relict boulder-beaches between 80 and 100 feet above mean sea level in northern New South Wales accentuates the need for detailed investigations of other headlands and of the high cliff-top dunes. Since no geophysical work has been undertaken to evaluate coastal stability, any correlation between areas on the coast must inevitably be tentative. The possibility of neotectonism on sectors of the New South Wales coast cannot be overlooked. Evidence on the Mid-North Coast at least suggests that there has been no movement in that region since the formation of the Inner Barrier.

Thus, there can only be speculation about some of the problems this study has realized until more evidence comes to light; but it may take several decades to amass this evidence and to answer the questions being asked by overseas researchers about changes of sea level during the Quaternary period in Australia.

APPENDIX 3.1

WAVE REFRACTION DIAGRAMS

Figures A3.1 - A3.3 are refraction diagrams for southeasterly swell waves of 12 seconds period in each study area. The diagrams have been constructed in order to show the relationship between the swell wave pattern and the offshore profile. Figures A3.1 and A3.2 show the effects of refraction as waves advance into shallow water in Twofold Bay and Broken Bay and their velocity and length decrease. The orthogonals in these diagrams (which would be parallel in deep water) are bent, and where they diverge the level of wave energy is lower than where the orthogonals converge.

Wave crests fit the outline of the barrier beaches particularly well in Twofold Bay. Figure A3.1 shows that the level of wave energy (lowest refraction coefficients) in Twofold Bay is lowest at Boyd Town, and at the northern end of Whale Beach barrier immediately south of Mowtree Headland. The level of wave energy (highest refraction coefficients) is highest along Eden barrier spit which is relatively more exposed to southeasterly swell. Lagoon entrances and river outlets are generally at a point where the level of wave energy is lowest.

The rivers on the Mid-North Coast enter the ocean at a point where the level of wave energy is lowest, generally near the headlands bordering the arcuate bays.

APPENDIX 3.2

TIDAL PLANES AND PRINCIPAL COMPONENTS

(Based on information supplied by the Department of Harbors and Rivers, Sydney)

Tidal planes in feet and decimals above zero of local ridge gauge.

	SYDNEY (Fort Denison)	COFF'S HARBOUR (Mid-North Coast)	EDEN (Twofold Bay)
Mean Spring Range	4.32	4.42	3.64
Mean Neap Range	2.60	2.50	2.36
Mean Range	3.46	3.46	3.00
Range H.H.W.(S.S.) to I.S.L.W.	6.24	6.58	5.87
H.H.W.(S.S.)	6.24	6.28	5.48
I.S.L.W.	0.00	-0.30	-0.39
M.S.L.	2.96	2.81	2.36
M.H.W.	4.69	4.54	3.86
M.L.W.	1.23	1.08	0.86
M.H.W.S.	5.13	5.02	4.16
M.L.W.S.	0.80	0.60	0.54
M.H.W.N.	4.26	4.06	3.54
M.L.W.N.	1.66	1.56	1.18
Time Comparison H.W. with Sydney L.W.	0 min.	-15 mins. -15 mins.	-8 mins. 0 min.

Key:
- M.H.W.S. and M.L.W.S. = Mean High and Low Water Springs.
- M.H.W.N. and M.L.W.N. = Mean High and Low Water Neaps.
- M.H.W. and M.L.W. = Mean of all high and low tides (including springs).
- M.S.L. = Mean sea level.
- I.S.L.W. = Indian Spring Low Water which has been adopted by the Royal Australian Navy, Maritime Service Board, and Department of Harbours and Rivers as the datum for soundings on all charts.
- H.H.W.(S.S.) = Higher High Water of Spring Solstices: a high tidal plane.

N.B. The above tidal planes have been used in the writer's publications. The datum level at Fort Denison, Sydney, is zero. Thus, mean sea level is 2.96 feet above Hydrographic Datum (N.S.W.) at Sydney.

APPENDIX 3.3

Pearl Beach borehole records.

Borehole locations are shown in Figure 3.8

Depths in feet and inches.

Borehole No. 1	0 -	1-0	Dark, organic A_1 horizon
	1-0 -	3-3	Becoming lighter in colour with depth
	3-3 -	4-0	Leached A_2 horizon
	4-0 -	5-0	Dark, sandy incipient B horizon (humate); slightly plastic
	5-0 -	5-3	Leached sand.
Borehole No. 2	0 -	1-0	Sand with comminuted shell fragments
	1-0 -	2-0	Coarse sand; organically stained
	2-6 -	3-9	Distinct organic horizon
	3-9 -	5-9	Iron stained horizon - reddish-brown
	5-9 -	7-3	Intercalated grey and orange-brown sand.
Borehole No. 3	0 -	1-0	Sandy topsoil (A_1)
	1-0 -	2-6	Light-coloured (leached) A_2 horizon.
Borehole No. 4	0 -	1-0	Organically-stained, sandy topsoil
	1-0 -	3-0	Grading into leached A_2 horizon with depth
	3-0 -	3-6	Incipient B horizon
Borehole No. 5	0 -	1-0	Organically-stained A_1 horizon; dark in colour
	1-0 -	2-9	Leached A_2 horizon
	2-9 -	3-9	Yellowish-brown in colour at about 3-6.

APPENDIX 3.3 continued...

Borehole No. 6	0 - 1-0	As for Numbers 4 and 5 above
	1-0 - 2-9	Leached A_2 horizon
	2-9 - 4-0	Becoming brownish in colour at 4-ft.
	4-0 - 5-6	Grading into humate (incipient)
	5-6 - 7-0	Horizon continuing, but grading into a yellowish-brown colour. Rounded quartz pebbles at 7-ft (2mm x 5 mm and smaller)
	7-0 - 8-0	Horizon continued.
Borehole No. 7	0 - 0-9	Dark-coloured organic horizon
	0-9 - 2-0	Leached, grey-white sand (Grey horizon below sand along creek).
Borehole No. 8	0 - 1-0	Organically-stained A_1 horizon
	1-0 - 6-0	Leached fine-grained sand continuing to 6-ft.
Borehole No. 9	0 - 0-6	Organic horizon
	0-6 - 4-0	Leached A_2 horizon, grading into humate at 4-ft.
	5-0 - 12-0	Clay - varying from white to red in colour
	12-0 - 20-0	Sand.
Borehole No. 10 (Foredune Section)	0 - 1-0	Buff to yellow coloured sand continuing to 4-ft
	4-0 - 12-9	Slight organic staining at 10-6" and 12-ft.
	12-9 - 17-0	Sudden change to leached grey sand - fine-grained and well-sorted - at 13-ft. Horizon continuing to 18-ft.

APPENDIX 3.3 continued.

Borehole No. 11	0 - 1-0	Fresh sand, becoming stained at 2-ft
	2-6 - 3-0	Organic horizon
	3-0 - 3-6	Fairly coarse sand comprising the organic horizon which continues to 6-ft.
Borehole No. 12	0 - 2-6	Dark, organically-stained sand comprising A_1 horizon
	2-6 - 8-0	Grading into yellow sand - slightly iron-stained in places - at 2-6"; almost pure sand continuing to 5-ft with some coarse grains
	8-0 - 9-0	Intercalated layers of leached sand at 8-ft, becoming coarser with depth (some grains greater than 2mm). Iron-staining pronounced at 9-ft and continuing to 11 feet. However, no marked change in profile until 9 feet.
Borehole No. 13	0 - 3-9	Dark coloured organic horizon
	3-9 - 4-0	Transition to iron-stained sand; continuing to 5 feet.
Borehole No. 14	0 - 4-0	A_1 horizon as in Nos. 12 and 13.
	4-0 - 4-3	Transition to leached sand which continues to 5-6".
Borehole No. 15 (Foredune Section)	0 - 5-0	Fresh, yellow sand increasing slightly in grain size with depth; some comminuted shell fragments, and slight staining
	5-0 - 12-0	Continuation of above horizon. Complete shells recovered at 12 feet. Sand fairly well rounded.

APPENDIX 3.3 continued

Borehole No. 16	0 - 1-6	Organically-stained sand grading into leached, white sand
	1-6 - 5-0	A_2 horizon continuing to 5-6".
Borehole No. 17	0 - 4-0	Predominantly light grey leached sand
	4-0 - 5-0	Iron-staining quite pronounced - humate and angular quartz pebbles
	5-0 - 6-3	Horizon becoming distinctly coarser; sandy clay; pebbles $\frac{3}{4}$-inch in diameter and iron-stained. A few incipient concretions of sesquioxides.
	6-3 - 6-6	Light-brown sand, slightly mottled reddish-brown at irregular intervals
	6-6 - 9-6	Mottled red and light-brown clayey sand. Clay content increasing with depth; almost a hardpan at 8-3"; quartz pebbles ($\frac{1}{2}$-inch in diameter).
	9-6 - 11-6	Rounded iron concretions and mottled orange-brown horizon continuing. Clay becoming more pronounced with depth, although sand content still high.
	11-6 - 14-0	Orange-brown and grey horizon with concretions and rounded quartz pebbles. Mottling increasing with depth. No bedrock encountered at 17 feet when boring stopped.

The heavy mineral assemblages of 7 samples collected from this borehole are shown separately in Figure 8.4

Figure A3.1 Wave Refraction Diagram: Southeasterly swell waves of 12-seconds period, Twofold Bay. Note position of lagoon entrances and river outlets generally at a point where the level of wave energy is lowest. The lowest level of wave energy in Twofold Bay is at Boyd Town, and at the northern end of Whale Beach barrier immediately south of Mowtree Headland. Wave energy is much higher along Eden barrier spit which is relatively more exposed to southeasterly swell.

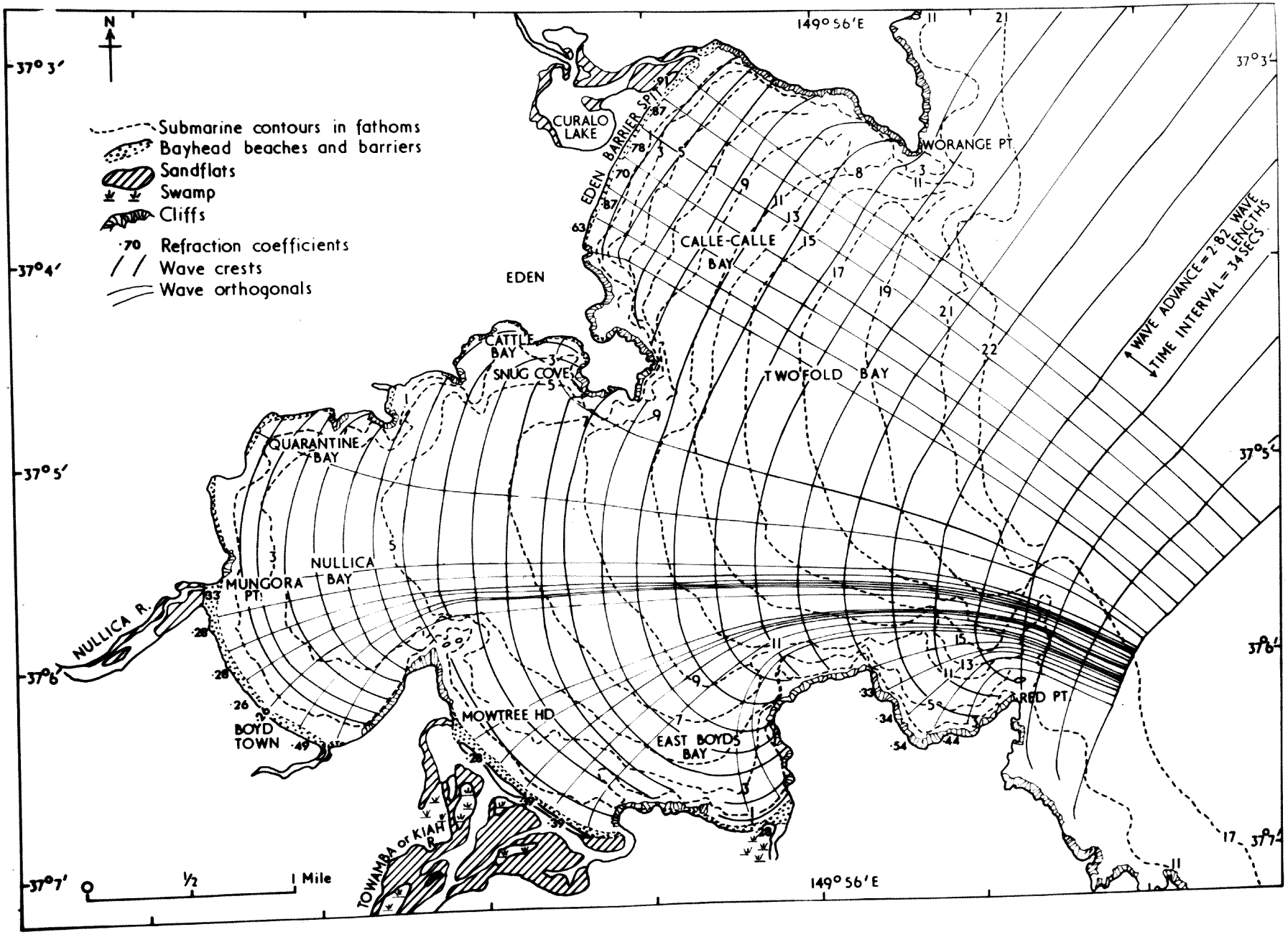

N
Submarine contours in fathoms
Bayhead beaches and barriers
Sandflats
Swamp
Cliffs
70 Refraction coefficients
Wave crests
Wave orthogonals
WAVE ADVANCE = 2.82 WAVE LENGTHS
TIME INTERVAL = 34 SECS
149° 56' E
37° 3'
37° 4'
37° 5'
37° 6'
37° 7'
CURALO LAKE
EDEN BARRIER SPIT
WORANGE PT
CALLE-CALLE BAY
EDEN
CATTLE BAY
SNUG COVE
TWOFOLD BAY
QUARANTINE BAY
NULLICA BAY
MUNGORA PT
NULLICA R.
BOYD TOWN
MOWTREE HD
EAST BOYDS BAY
RED PT
TOWAMBA or KIAH R.
½
1 Mile

Figure A3.1

Figure A3.2 Wave Refraction Diagram: Southeasterly swell waves of 12-seconds period, Broken Bay.

Figure A3.2

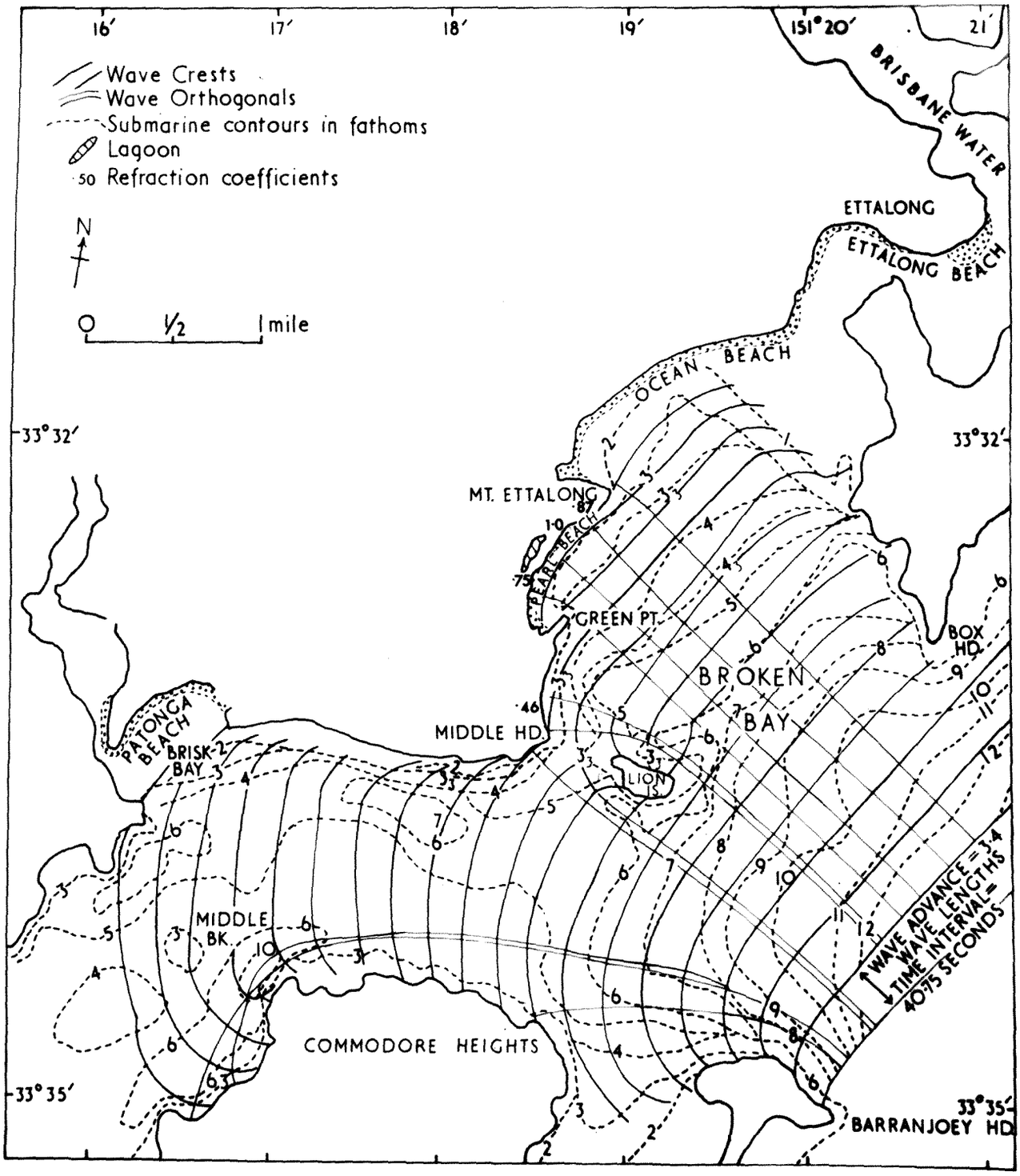
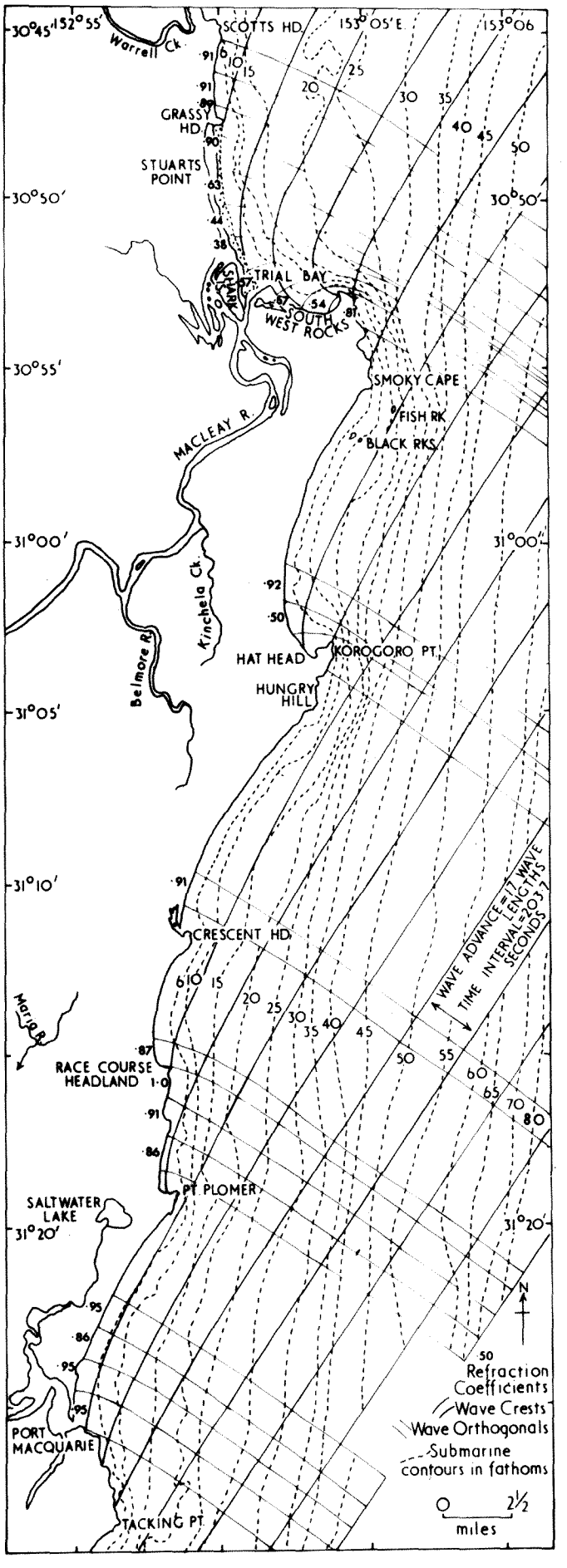

16′
17′
18′
19′
151°20′
21′
Wave Crests
Wave Orthogonals
Submarine contours in fathoms
Lagoon
so Refraction coefficients
N
0 1/2 1 mile
BRISBANE WATER
ETTALONG
ETTALONG BEACH
OCEAN BEACH
33°32′
MT. ETTALONG
PEARL BEACH
GREEN PT.
BOX HD.
BROKEN BAY
PATONGA BEACH
BRISK BAY
MIDDLE HD.
LION I.
MIDDLE BK.
COMMODORE HEIGHTS
WAVE ADVANCE = 3.4
WAVE LENGTHS
TIME INTERVAL =
40·75 SECONDS
33°35′
BARRANJOEY HD.

Figure A3.3 Wave Refraction Diagram: Southeasterly swell waves of 12-seconds period, Mid-North Coast. The rivers on the Mid-North Coast enter the ocean at a point where the level of wave energy is lowest, generally near the headlands flanking the arcuate bays.

Figure A3.3


30°45'
152°55'
Warrell Ck
SCOTTS HD
153°05'E
153°06
GRASSY HD
STUARTS POINT
30°50'
TRIAL BAY
SOUTH WEST ROCKS
30°55'
SMOKY CAPE
FISH RK
BLACK RKS
MACLEAY R.
31°00'
Kinchela Ck
Belmore R.
HAT HEAD
KOROGORO PT
HUNGRY HILL
31°05'
31°10'
CRESCENT HD
Maria R.
RACE COURSE HEADLAND
PT PLOMER
SALTWATER LAKE
31°20'
PORT MACQUARIE
TACKING PT
WAVE ADVANCE=17 WAVE LENGTHS
TIME INTERVAL=203.7 SECONDS
N
Refraction Coefficients
Wave Crests
Wave Orthogonals
Submarine contours in fathoms
0
2½
miles

APPENDIX 4.1

WIND RESULTANTS

The wind resultants shown in Figure 4.1A were obtained by constructing vector diagrams following the Landsberg-Bagnold method, modified by Jennings (1957). The vector is calculated accordingly:

$$b = s \sum_{j=3}^{12} n_j (v_j - V_t)^3$$

where s is a scaling factor of 10^{-3}; j is the summation of the Beaufort speed numbers between 3 and 12; n is the wind frequency in a given direction with speed v in m.p.h.; V_t is the speed of 10 m.p.h., corresponding to Beaufort Scale number 3, which is the threshold speed for sand drifting.

APPENDIX 6.1

METHODS USED FOR MECHANICAL AND CHEMICAL ANALYSES OF SOILS

1. Mechanical Analysis (Bouyoucos Method) of Swamp and Fluvial-Deltaic Plain Soils.

Samples were oven dried and particles larger than 2mm. were removed. 30gm. of oven-dry soil were added to 25cc. of 5% Calgon solution (brought to pH 8.5 with Na_2CO_3) and 275 ml. distilled water in a 600 ml. beaker. After stirring, the contents were transferred to a metal beaker and stirred with a milk-shake mixer for 10 minutes. The contents were then washed into a 500cc. graduated cylinder and the temperature recorded. Hydrometer readings were taken after shaking vigorously for one minute. The time the shaking ceased was recorded, and the hydrometer was read at intervals of 5 minutes, 1 hour and 2 hours. On completion of the readings the supernatant suspension was poured away from the cylinder and the sediment containing the coarser fractions was washed into a 600 ml. beaker. The contents were stirred and allowed to settle for 4 minutes 48 seconds. After repeated decantations, the sand remaining in the beaker was dried and separated, using a 0.2mm. sieve, into coarse and fine sand fractions. These were weighed, and calculations were made of the clay, silt and sand content of each sample.

2. Total Water-Soluble Salts - Conductometric.

Standard apparatus was used. A pipette electrode was rinsed and filled with filtered soil-water extract, prepared by shaking 20gm. of soil in 100ml. of water for 30 minutes. The variable resistance of a Wheatstone bridge was adjusted until the point of minimum sound was



reached. As the null point was approached the variable condenser was adjusted to assist in obtaining a sharp balance at the null point. The electrode was rinsed with water between determinations. The resistance of the standard potassium chloride solution was measured before and after each series of determinations. The electrodes were carefully rinsed with two quantities of the solution.

Calculation of Results: The specific conductivity (in reciprocal ohms or mhos.) of 1:5 soil suspension at 20°C is given by the expression:

$$\frac{R_{(KCl)}}{R_{(suspension)}} \times K$$

where $R_{(KCl)}$ = Observed resistance of 0.005N potassium chloride

$R_{(suspension)}$ = Observed resistance of the soil suspension

and K = Specific conductivity of 0.005N potassium chloride at 20°C = 0.65 millimhos.

Approximation of the total soluble salts can be obtained by multiplying the values for specific conductivity by 375*, a value derived from actual correlations of the specific conductivities with the amounts of total soluble salts determined gravimetrically in a large number of Australian soils. The correlation is only approximate as it is largely influenced by the composition of the salts, particularly in soils of low salt content.

* K in mhos x 375 gm. salt/100 gm. soil in 1:5 suspensions.

3. Soluble Chloride - Volumetric:

50cc. of the 1:5 water extract were titrated with N/100 $AgNO_3$, and 3 to 4 drops of potassium chromate solution were used as indicator. For soils low in salt content N/100 $AgNO_3$ diluted from N/10 was used, and

for soils high in salt content, N/10 $AgNO_3$ was used.

4. Total Nitrogen (Kjeldahl):

The standard Kjeldahl method was employed. The procedure consisted of digesting the soil with concentrated sulphuric acid to oxidize the carbon to CO_2 and to leave the nitrogen as ammonium sulphate. In this experiment, anhydrous sodium or potassium sulphates are added to raise the temperature, and a catalyst used to speed the oxidation.

10 gm. of finely ground soil were transferred to a Kjeldahl digestion flask. 25ml. of water were added, followed by 20-25ml. of concentrated sulphuric acid. The mixture was heated gently until most of the water had boiled off. After cooling for a few minutes, 10gm. sodium sulphate and one crystal of copper sulphate were added.

Digestion took about 40 minutes in a fume cupboard, until the liquid was clear. (Further concentrated acid was added if the soil contained a large amount of organic matter). 100ml. of water were added after the flask was completely cooled. The liquid was transferred to a litre distilling flask. The solid in the digestion flask was washed, and the 'washings' decanted into a flask by using 3 or 4 lots of 50ml. water.

120ml. 40 per cent sodium hydroxide were carefully added down the side of the distilling flask, so that the alkali formed a layer below the acid solution. Further sodium hydroxide was added until a turbid brown (or green) layer formed at the bottom of the flask.

The flask was attached to a distillation apparatus, agitated to mix the two layers and distilled into a receiving flask containing 50ml. of 4 per cent boric acid solution, until no ammonia could be detected in

the issuing vapours. The distillate in the receiving flask was cooled sufficiently to prevent a rise in temperature of the boric acid solution, otherwise ammonia would have been lost owing to thermal breakdown of the ammonium borate complex. Since boric acid is a weak acid, the ammonia could be titrated directly with N/10 HCl. Screened methyl red indicator was mixed with the boric acid ready for use. The end point change was from dark-green to red. The percentage nitrogen in the soil was then calculated.

5. Organic Carbon (Tinsley's Method):

Sufficient finely ground, air-dry 2mm. soil was weighed so that it contained at least 10-25mgm. of carbon (about 0.5gm. for surface soils and 2.0gm. for sub-soils). The soil was transferred to a 250ml. conical flask and 25ml. of the acid dichromate mixture (0.4N, dichromate) were added. The flask was fitted onto a cold thimble condenser on a sand bath and allowed to simmer for 2 hours.

The digest was titrated with 0.4N ferrous sulphate, after 5 drops of the tri-orthophenanthroline ferrous sulphate internal indicator were added. The colour changed rapidly from blue-green to grey or reddish-grey at the end point. From the equation

$$2\ Cr_2O_7 - - + 3C + 16H^{+} \longrightarrow 4\ Cr^{+++} + 8\ H_2O + 3\ Co_2$$

1ml. N dichromate = 3mg. carbon

The percentage organic carbon in the soil, the percentage organic matter, and the C/N ratio were calculated.

Reference: Tinsley, J. 1950: Proc. 4th Int. Conf. Soil Sci., I.

Soil Science Practical Manual, Faculties of Agriculture and Science, University of Sydney.

APPENDIX 7.1

Methods of processing of data

An electronic computer (KDF 9) was used in order to determine graphic and statistical moment measures from grain size analyses.

The programmes were adapted from those employed by Collias, Rona, McManus and Creager (1963).

Two programmes were used:

1. Sediment Description Programme - to determine order statistics which include the graphic measures (percentile estimates) of Trask (Krumbein and Pettijohn, 1938), Inman (1952), and Folk and Ward (1957).

2. Moment Measures Programme.

The results of sieving for individual samples were punched on detail cards. An example of Output from the Sediment Description and Moment Measures Programmes is given:

SAMPLE 1209 Patonga Offshore - 3A3 - October 1964.

Phi Size	Fraction Per cent.	Accum. Per cent.
-1.00	0.00	0.00
-0.75	0.00	0.00
-0.50	0.25	0.25
-0.25	0.10	0.35
0.00	0.30	0.65
0.25	0.58	1.23
0.50	1.20	2.43
0.75	2.22	4.65
1.00	3.71	8.36
1.25	5.30	13.66
1.50	14.62	28.28
1.75	14.34	42.62
2.00	30.10	72.72
2.25	14.45	87.17
2.50	12.11	99.28
2.75	0.60	99.88
3.00	0.09	99.97
3.25	0.01	99.98
3.50	0.00	99.98
3.75	0.00	99.98
99.99	0.00	99.98

% Level:	5	16	25	50	75	84	95
Phi:	0.78	1.31	1.46	1.83	2.03	2.18	2.36

Trask Values	Q1	Q2	Q3	SO LOG	So	SKG
	0.364	0.282	0.245	1.221	0.087	1.06

Inman Values	MEDIAN	MEAN	DEV.	SKEW.	SKEW 2	KURT.
	1.83	1.75	0.44	-0.18	-0.58	0.81

Folk and Ward Values

	MEAN	DEV.	TYPE	SKEW.	TYPE	KURT.	TYPE
	1.77	0.46	2	-0.25	2	1.13	2

MOMENTS	MEAN	DEV.	SKEW.	KURT.
DATA	1.721	0.495	-1.089	4.995
EXT. DATA	1.721	0.495	-1.089	4.995
CORR. EXT. DATA	1.721	0.494	-1.091	5.000

The Sediment Description Programme provides phi size at selected percentile levels - 5, 16, 25, 50, 75, 84 and 95 - and the percentile measures referred to as Trask values, Inman values, and Folk and Ward values. Sediment Description Programme: Trask, Inman, and Folk and Ward values are computed in this programme.

Trask values (Krumbein and Pettijohn, 1938) are computed for the first, second and third quartiles (Q1, Q2 and Q3) expressed in millimetres, and the sorting deviation or the geometric quartile deviation (So), the log quartile deviation (Log SO) and quartile skewness (SKG). These values are shown by the following equations:

$$Q_1 = e^{-\phi 25 \log_e 2} \quad \ldots\ldots\ldots\ldots (1)$$

$$Q_2 = e^{-\phi 50 \log_e 2} \quad \ldots\ldots\ldots\ldots (2)$$

$$Q_3 = e^{-\phi 75 \log_e 2} \quad \ldots\ldots\ldots\ldots (3)$$

$$So = \sqrt{\frac{Q_1}{Q_3}} \quad \ldots\ldots\ldots\ldots (4)$$

$$SKG = \sqrt{\frac{Q_1 \cdot Q_3}{Q_2^2}} \quad \ldots\ldots\ldots\ldots (5)$$

$$\text{Log SO} = \log_{10} So \quad \ldots\ldots\ldots\ldots (6)$$

where ϕ_{25}, ϕ_{50} and ϕ_{75} are the phi-sizes at the 25, 50 and 75 percentile levels.

Inman Values: The Inman statistics (Inman, 1952) computed are the median($Md\phi$), mean($M\phi$), deviation or sorting($\sigma\phi$), and skewness($\alpha\phi$). The second skewness($\alpha 2\phi$) and kurtosis($\beta\phi$) are also computed if the penultimate accumulated percentage is greater than 92. The equations are as follows:

$$Md\ \phi = \phi\ 50 \quad \ldots\ldots\ldots\ldots (7)$$

$$M\ \phi = 1/2(\phi_{16}+84) \ldots\ldots\ldots (8)$$

$$\sigma\ \phi = 1/2 \cdot (\phi_{84} - \phi_{16}) \ldots (9)$$

$$\alpha\ \phi = \frac{M\phi - Md\phi}{\sigma\phi} \quad \ldots\ldots\ldots (10)$$

$$\alpha 2\phi = \frac{\left[1/2 \cdot (\phi_5 + \phi_{95})\right] - Md\ \phi}{\sigma\ \phi} \quad (11)$$

$$\beta\ \phi = \frac{\left[1/2 \cdot (\phi_{95} - \phi 5)\right] - \sigma\ \phi}{\sigma\ \phi} \quad ..(12)$$

where $\phi 5$, $\phi 16$, $\phi 50$, $\phi 84$ and $\phi 95$ are the phi-values at percentile levels of 5, 16, 50, 84 and 95.

Folk and Ward Values: The Folk and Ward statistics (Folk and Ward, 1957) computed are the mean(Mz), the inclusive graphic standard deviation ($\sigma 1$), skewness(Sk) and kurtosis(Kg) from the following equations:

$$Mz = (\phi_{16} + \phi_{50} + \phi_{84}) \div 3 \quad ..(13)$$

$$\sigma 1 = \frac{\phi_{84} - \phi_{16}}{4} + \frac{\phi_{95} - \phi_{5}}{6.6} \quad ..(14)$$

$$Sk = \frac{\phi_{16} + \phi_{84} - 2\phi_{50}}{2(\phi_{84} - \phi_{16})} + \frac{\phi_{5} + \phi_{95} - 2\phi_{50}}{2(\phi_{95} - \phi_{5})} \quad .... (15)$$

$$Kg = \frac{\phi_{95} - \phi_{5}}{2.44(\phi_{75} - \phi_{25})} \quad ..... (16)$$

After each of these values, except the mean, was computed, a type number was given as listed in the following Tables.

TABLE 7.1A

FOLK AND WARD CODE FOR STANDARD DEVIATION

Code	Range of Standard Deviations		Verbal Scale
	From	To	
1	0.00	0.34	very well sorted
2	0.35	0.50	well sorted
3	0.51	1.00	moderately sorted
4	1.01	2.00	poorly sorted
5	2.01	4.00	very poorly sorted
6	over 4.00		extremely poorly sorted

TABLE 7.1B

FOLK AND WARD CODE FOR SKEWNESS

Code	Range of Skewness		Verbal Scale
	From	To	
1	-1.00	-0.30	very negative-skewed
2	-0.30	-0.10	negative-skewed
3	-0.10	0.10	nearly symmetrical
4	0.10	0.30	positively-skewed
5	0.30	1.00	very positive-skewed

TABLE 7.1C

FOLK AND WARD CODE FOR KURTOSIS

Code	Range of Kurtosis From	To	Verbal Scale
1	0.65	0.90	platykurtic
2	0.91	1.11	mesokurtic
3	1.12	1.50	leptokurtic
4	1.51	3.00	very leptokurtic
5	over 3.00		extremely leptokurtic

Moment Measures Programme: The moment measures for this programme are defined as (1) Mean, or the first moment about the origin

$$\bar{X} = {}^{1}/_{100} \sum fX_i \quad \ldots\ldots\ldots\ldots \quad (1)$$

(2) Standard Deviation

$$\sigma = \sqrt{\sum f(X_i - \bar{X})^2}\Big/100 \quad \ldots\ldots\ldots \quad (2)$$

(3) Skewness

$$\alpha_3 = {}^{1}/_{100\sigma^{-3}} \sum f(Xi - \bar{X})^3 \ldots\ldots \quad (3)$$

(4) Kurtosis

$$\alpha_4 = {}^{1}/_{100\sigma^{-4}} \sum f(X_i - \bar{X})^4 \ldots\ldots \quad (4)$$

where X_i is the midpoint value of the size class and f is the fraction percentage for that class.

APPENDIX 8.1

A brief description of the heavy minerals identified in the barrier, beach and dune sands, (cf. Figures 8.7A - 'I').

Andalusite: Characteristically colourless to pale-rose pleochroism distinguishes this mineral. Grains are generally subrounded to subangular; some well rounded grains have also been identified.

Apatite: Mostly rounded colourless grains present in the samples.

Epidote: Yellowish-green grains are common in all samples, although some dark green grains have been seen. Colourless to pale green grains of clinozoisite and zoisite have been identified in some samples. These minerals are members of the epidote group. Piedmontite (see Figure 8.7A) has been identified in a Hat Head cliff-top dune sample. It is red-lilac in colour and strongly pleochroic. Most epidote grains are subangular in South Coast samples.

Garnet: Pale pink, green and colourless varieties have been identified, especially in the Broken Bay and Mid-North Coast samples. Most grains are well rounded although a few are fairly angular. A conchoidal fracture has also been identified.

Hornblende and Amphiboles: Hornblende grains in South Coast samples are angular in appearance, pale green to yellow brown in colour, and slightly pleochroic. Some dark green to brown varieties have been identified. Many grains are prismatic. Green and yellowish actinolite has been identified, and a few grains of tremolite in South Coast samples.

Kyanite: Tabular, angular grains are quite common in all samples. These are colourless.

Monazite: Generally occurs as very well rounded, pale yellow grains; almost colourless grains are also prominent. Very weak pleochroism has been noticed in a few samples.

Opaque Minerals: The majority of the magnetite, ilmenite and leucoxene grains are well rounded, although some of the dune samples contain subrounded to subangular grains (Figure 8.7A-C). Magnetite is dark steel-grey to black, and ilmenite bluish-black under reflected light. Leucoxene grains are often white or brown.

Picotite: Grains are identified by their conchoidal fracture and vitreous lustre. Most grains are dark brown (characteristic "coffee' colour), although brown on the edges, and isotropic under crossed nicols. The majority of the grains are fairly well rounded.

Pyroxenes: Titan-augite and diopsidic augite are common in Twofold Bay samples. Hypersthene and enstatite are the orthorhombic pyroxenes, although they have been separated from the other pyroxenes in the Figures and Tables. Hypersthene has been distinguished by its pleochroism - pink to light green. Some grains are ragged and subangular. Enstatite is usually grey to pale yellow in colour and irregular in shape; some grains are prismatic. No pleochroic grains have been identified.

Rutile: Grains vary from yellow, through reddish-brown to almost opaque. Yellow grains are prismatic and fairly common in Mid-North Coast samples. A few grains are slightly pleochroic. Well rounded grains were observed in most samples from the three study areas, although a few have angular corners.

Sphene: Irregularly and diamond-shaped, pale-yellow grains have usually been seen in the samples.

Spinel: Only the green variety has been identified in the samples. Grains are rounded, have a vitreous lustre, and are isotropic under crossed nicols.

Staurolite: Straw-yellow and brownish-yellow grains are common in all samples; most of these are pleochroic, and some contain inclusions. Grains are subrounded to subangular in shape, although well rounded grains have been identified.

Topaz: Colourless, and one or two yellow grains have been identified. Most grains are fairly well rounded. A few glassy grains have been seen in Mid-North Coast samples. Subangular grains have been identified in Macleay River samples (Figure 8.7'I').

Tourmaline: Brown, green, yellow and blue varieties have been identified. The shape of the grains varies between well rounded to angular. Practically all the grains are strongly pleochroic, especially the greenish-brown grains.

Zircon: Most grains are colourless although several contain inclusions. The shape varies from rounded (highly in some cases) to almost perfectly shaped tetragonal crystals. Pyramidal terminations can also be seen.

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