COASTAL GEOMORPHOLOGY IN THE TOWNSVILLE REGION.

A study of the geomorphological evolution of the North Queensland coast between Cape Upstart and Hinchinbrook Island.

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ABSTRACT

The coastal landforms of the Townsville area indicate an evolution which can be traced back to at least the last interglacial high sea level phase. A maximum sea level of approximately 15 feet was attained during this late Pleistocene transgression. It was accompanied by a sub-humid climate in which pedimentation was a major process. This dry climate was maintained during at least the early part of the regressive phase, but became more humid during the maximum of the glacial stage. The rise in the level of the sea during the Holocene has been paralleled by a dessication of climate. The Holocene transgression in the area reached a maximum level of about 12 feet approximately 4250 years ago, leaving well-defined traces of this level on the mainland and off-shore islands. Landforms and deposits may be indentified with each of the climatic and eustatic oscillations described. A morphoclimatic influence is indentified in past and present landforms of the area.

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CONTENTS

CHAPTER 1

INTRODUCTION TO THE AREA, APPROACH AND AIMS OF THE STUDY

Detailed geomorphological investigations of tropical Queensland are few and far between. Research into the geomorphology of the North Queensland area can be divided into a number of phases. During the early part of the century a number of papers examined large areas of the Australian continent, including the tropics, but were limited almost exclusively to physiographic description, analysis of drainage patterns and vague hypotheses on general evolutionary phases in the late geological history of the area. Included amongst such work are the reports of Andrews (1902, 1910), Taylor (1911), Jensen (1911), Danes (1911, 1912), Davis (1917) and Sussmilch (1938). The general nature of these reports is comprehensible, however, when it is realised that communications on land in North Queensland in the early decades of the century were extremely poor and that observations were largely made from voyages along the coast. The improvements brought about by the building of the north coast railway in 1924 are reflected in the more intensive and localised studies which started to occur in the literature, more especially in the reports of the Great Barrier Reef Committee set up in Brisbane in 1922 under the chairmanship of Sir Matthew Nathan. Typical of these more detailed, though still descriptive studies are the works of the first full time Scientific Director, Charles Hedley (1925a, b, c, d, e, 1926) and of other officers and members of the Committee

(Stanley, 1928; Jardine, 1925a, b, c, 1928a, b). Although the original area of investigation was limited on the south by the State border, on the east by the Great Barrier Reef, on the north by the Territory of Papua and on the west by the watershed of the coastal and western streams of Queensland, examination of the later reports of the Committee indicate that detailed study was limited to the Great Barrier Reefs. This trend was emphasised by the Cambridge University Great Barrier Reef Expeditions of 1928 and 1936, as is witnessed by the scientific reports of these expeditions and by the subsequent papers based on them (Steers, 1929, 1937, 1938; Spender, 1930). Reference is made in these works to the mainland and to the high, continental islands, but it is clear that major interest was now centred on the reef. This trend has continued since the war, with the work of Fairbridge (1950, 1967; Fairbridge and Teichert, 1947, 1948), whose efforts were directed towards investigation of the morphology of reefs and reef islands.

The scant attention given to the mainland and high continental islands of North Queensland is lamentable. It is clear from the numerous scientific reports on the Great Barrier Reefs that, because of the unique nature of the reef environment, many processes were operating which were not understood by the various researchers. Nor was it possible to reconstruct a chronology of events which had affected the growth of the reef structure, largely because of both the rapid growth and destruction of at least the surface portions of the reefs. The majority of workers who investigated the problems of the Great Barrier Reefs from a geomorphological point of view moreover, had been trained in temperate areas. It is unfortunate, therefore, that they did not first turn their attention to the mainland where processes at least were similar to those with which they were familiar, even if, because of the tropical climate, their emphasis was different. A progress of study from the mainland to the high, continental islands would then have been a logical stepping stone to Great Barrier Reefs investigations for the islands, with their wide Fringing reefs, combine the terrigenous environmental features of the mainland, with the carbonate environment of the reefs.

Within the last few years new interest has arisen in the geomorphology of North Queensland (Bird, 1965, 1969; Bird and Hopley, 1969; Driscoll and Hopley, 1968; Hopley, 1968). However, it is believed that this present work constitutes the first intensive geomorphic study of a section of the North Queensland coast since such valuable aids to research as radio-carbon dating, statistical analysis and aerial photograph interpretation have become available. It is hoped that some of the findings of this work may help to update the early physiographic reports on the North Queensland coast, and provide some background to the evolution of this part of the world during the late Quaternary period which will be applicable to future studies of the Great Barrier Reefs.

The aims of the study are, therefore, to describe and analyse the morphology and nature of the deposits of a 150-mile length of North Queensland coast centred on Townsville. Particular attention is paid to the nature and morphology of coastal plain deposits and to the indications which they give to changes in environmental conditions and especially to changes in sea level and climate. Like that of many of the earlier workers in the North Queensland area, the training of the author has been in a temperate environment, but this has possibly increased the awareness

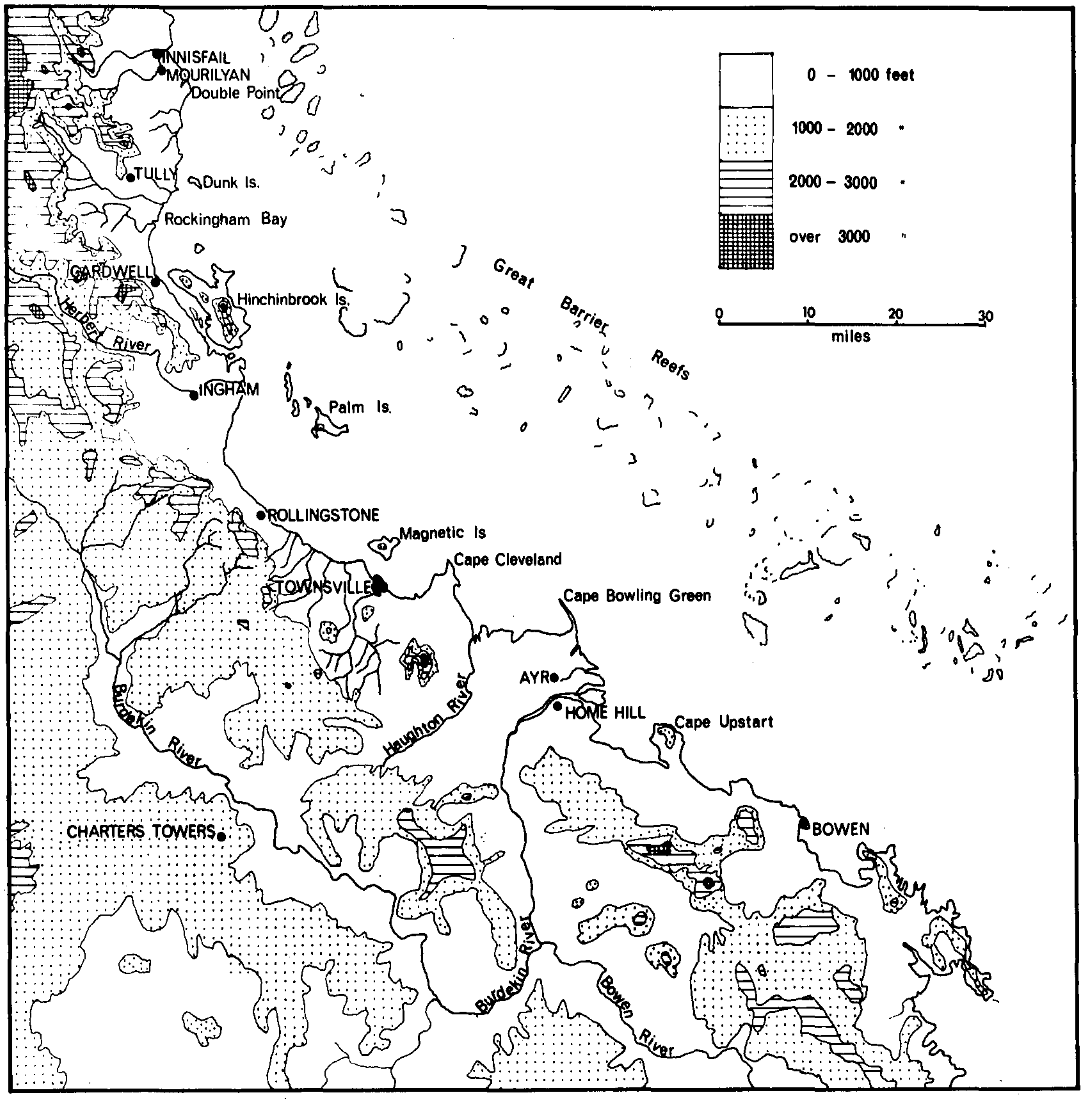

Fig. 1.1 Location, relief and drainage.

that, under tropical conditions, geomorphic processes take on different degrees of emphasis. Attempts are made therefore, to differentiate between those features which depend only on local factors such as geology or tectonic history, and those which are of morphogenic significance.

The length of coast chosen for the study extends from Cape Upstart in the south to the southern end of the Hinchinbrook Channel in the north. Essentially it is the mainland area between and including the deltas of the two largest river systems in north-east Queensland, the Burdekin and the Herbert (fig. 1.1). In addition, a number of islands in Rockingham Bay and as far north as Double Point were surveyed as they tend to emphasize, by contrast, a number of interesting features of the islands within the main research area. The southern limit of the area is an arbitrary one, though it does coincide with the limit of the area of the past and present sedimentological province of the Burdekin Delta. The northern limit may be defined climatically on the transition area from Aw to Af climates under the Köppen classification. The region thus defined coincides with the area covered by Ayr, Townsville and Ingham 1:250,000 map sheets with the northern islands extending onto the Innisfail sheet (a complete list of published topographic maps of the area is given in Appendix A).

Geological and Geomorphological History of the Area

The geology of the area is best described in the Bureau of Mineral Resources notes to accompany the 1:250,000 geological map sheets (De Keyser, 1964; De Keyser, Fardon and Cuttler, 1965; Wyatt, 1968; Paine, Gregory and Clarke, 1966). Figure 1.2 summarizes the major geological features

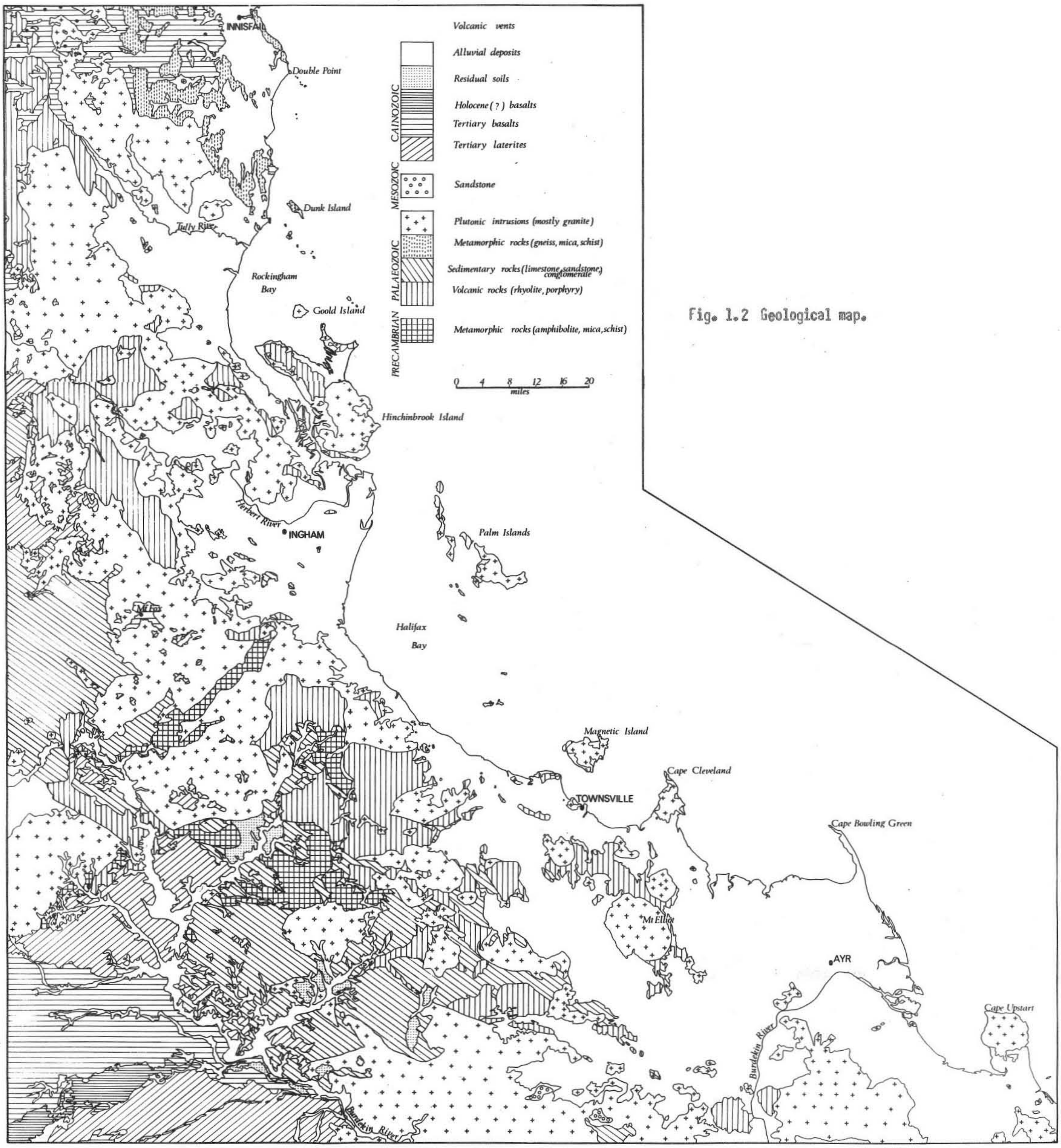

Fig. 1.2 Geological map.

of the area, which falls within the Tasman geosynclinal province.

The oldest rocks of the region are two small areas of Pre-Cambrian metamorphic rocks which appear to be remnants of pre-Tasman shield. The outcrops occur on the plateau south of Ingham and consist of amphibolites and coarse mica schists. These rocks are intruded by late Palaeozoic granite and dykes and along most of their eastern margin are faulted against the granite.

Palaeozoic rocks dominate the hard rock geology of the region. Sedimentary rocks are not extensive but indicate that numerous sedimentary basins of varying ages and environments occurred within the Tasman geosyncline. A great variety of sediments, including limestones, siltstone, greywacke, sandstone and conglomerate were deposited in these basins and range in age from Silurian to Permian. They were folded and faulted during a number of orogenies, the greatest of which took place in Carboniferous times and resulted in the metamorphism of a number of formations, especially in the north where the earlier deposits were altered to form high grade mica schists and gneisses. The orogenies were accompanied by widespread volcanic activity with the intrusion of a large variety of rocks of which rhyolite and porphyry are the most common. During the same period occurred the emplacement in several episodes of a number of plutonic igenous intrusions. The majority of these were granitic, but a number of basic intrusions occur towards the southern limits of the research area. The north-west to south-east structural trend which was impressed upon the region during this period, has been maintained through to the present day.

A small outer of sandstone south of Townsville is the only indication of deposition during the Mesozoic. Tertiary sediments are also limited to small areas of horizontal claystones, sandstones and conglomerates. The Mesozoic and Tertiary periods appear to have been a time of erosio and bevelling of the landscape. A warm, relatively humid climate appears to have existed and lateritisation was widespread.

Reconstruction of the Tertiary laterite surface suggests that it had the morphology of a pediplain with residual hills such as Mount Elliot and the Paluma Range rising above it. The main divide between east and west flowing streams is considered to have been in the region of the present coastal ranges and the proto-Burdekin and proto-Herbert river systems drained westwards (De Keyser, Fardon and Cuttler, 1965). This drainage pattern, however, was drastically disrupted by the earliest movements associated with the late Tertiary Kosciusco epeirogenic uplift which are considered to have taken place during the early Pliocene (Wyatt, 1968). These produced an upwarp 125 miles inland, initiating the present main watershed. The trough between the old divide and this new watershed was occupied by the Burdekin and Herbert Rivers, but their drainage westwards was now blocked and diversion to the east coast occurred. The disruption of the drainage pattern is also marked by lacustrine-fluviatile deposits. Uplift resulted in a new phase of erosion and series of sands and gravels were deposited over the lower pediment slopes. However, conditions suitable for the formation of laterite continued as both lacustrine deposits and fluviatile gravels are lateritised, though not to the same degree as the main plateau. Fissure eruptions occurred along the lines of weakness produced in the areas of uplift and further helped to disrupt drainage. These great outpourings of basalt continued through to the late Pleistocene or even Holocene periods.

The strongest earth movements took place during the latter part of the Pliocene and early Pleistocene. In the north the epeirogenic movements were accompanied by strong block faulting which broke up the Tertiary pediplain (De Keyser, 1964). Further south the lateritised surfaces were uplifted and tilted upwards towards the east, the areas of greatest uplift being seawards of the present coast. Vulcanism became even more widespread, with flows occupying and blocking stream valleys, damming lakes in which diatomites were deposited and generally disrupting the drainage pattern. Uplift was intermittent, allowing the formation of erosion surfaces below the laterite level. In particular it produced a surface, widespread between Charters Towers and the main escarpment, above which rise sub-surface weathering residuals. Uplift was also slow enough to allow both the Burdekin and Herbert Rivers to incise deeply, producing spectacular nick point falls and narrow gorges just above the lower reaches.

During the latter part of the Quaternary, volcanic activity has contracted. However, at Mount Fox, west of Ingham, and at Toomba, north-west of Charters Towers are flows which may belong to the Holocene period. Mount Fox, itself, is an extinct volcanic vent, but has suffered very little erosion. Similarly, in contrast to the deeply weathered older basalts the Toomba and Fox flows are very little altered and retain original flow and solidification structures.

The exact origins of the Great Barrier Reefs, which in the Townsville area lie 35 miles off-shore, is still a matter for controversy, but the evidence suggests that they were constructed largely during the Quaternary period. Fairbridge (1950, 1967) believes that the bulk of the reef has been built in the last 10,000 years. This belief has been questioned, however, and Jones (1966), for example, indicates that the three bores so far penetrated through reef material at Michaelmas Cay, Heron Island and Wreck Island tend to suggest a Pleistocene origin, with only a veneer of Holocene corals. The bores from the three islands penetrated 476 feet, 506 feet and 398 feet respectively of reef material overlying quartz sands, which at Wreck Island at least were suspected to be Pleistocene marine sediments. These in turn are considered to overlie Tertiary strata. As reef building corals do not flourish in depths greater than 120-180 feet (Jones, 1966) and, allowing for a maximum depth of 150 feet for reef construction, the additional thickness of reef material of 326 feet at Michaelmas Cay, 356 feet at Heron Island and 248 feet at Wreck Island must be explained in terms of eustatic and possibly tectonic movements. The possibility of initiation of the reefs during low Pleistocene sea levels prior to the latest cannot be overlooked. The great thickness of Tertiary (?) sands below the coralline material, which on Wreck Island extend down to 1,795 feet where they rest on volcanic tuffs, suggests that the platform has subsided, probably a movement contemporaneous with the late Tertiary upwarping of the coastal zone. A hinge line thus exists between the present coast and the Great Barrier Reefs.

Relief and Drainage

All phases of the geological history since the Tertiary period are reflected in the present landforms of the area. The major feature of the landscape is the main escarpment rising precipitously from the coastal plain to over 3,000 feet in the north but to less than 2,000 feet further south (fig. 1.1). Above the escarpment the Tertiary erosion surfaces slope imperceptibly towards the west. The oldest lateritised surfaces are limited to an area not far removed from the scarp and along the present major watershed further west. Between lies the structural trough, now occupied by the middle and upper courses of the Burdekin and Herbert Rivers, which has been further deepened by incision in response to uplift, thus removing the older erosion surfaces from this area. This same uplift was responsible for the dismemberment of the single Burdekin drainage system which occupied the trough. The rapid headward extension of a coastal stream allowed the capture of what were, until then, the headwaters of the Burdekin. The headwaters, now diverted more directly to the sea, formed the new Herbert catchment area.

Below the escarpment are the much younger coastal plains, generally less than 5 miles wide but attaining greater width where the major streams open out onto the coast and in the south in the Townsville region where a major embayment occurs. The coastal plain is a depositional area receiving material directly from the erosion of the escarpment by way of the numerous short coastal streams, and also indirectly through redistribution of material deposited in the sea. It rises gently from the littoral zone to approximately 400 feet at the base of the main escarpment. Breaking through the plain are numerous residuals of more resistant rocks. In general it is the sedimentary rocks which have been eroded during the recession of the scarp, leaving the granites and volcanic rocks as isolated hills and islands. The largest of these are composed of granite and include Hinchinbrook Island, Great Palm Island, Magnetic Island, Mount Elliot, Cape Cleveland, and Cape Upstart. The Mount Elliot massif rises to 3,914 feet and apparently rose above the general level of the reconstructed Tertiary surfaces.

The Burdekin and Herbert Rivers dominate the drainage of the region. Tributaries to these streams drain eastwards from the main watershed and westwards from the coastal escarpment, many rising only a mile or two from the escarpment itself. Coastal streams flowing directly to the sea are therefore short. The majority of streams in the area are intermittent, even the major rivers. The only exceptions are those draining the basalt areas, which, because of the water-retaining characteristics of the basalt, tend to maintain their flow during the dry winter season.

Climate

The research area lies within the *Aw* category in the Köppen classification. The transition of *Af* climates north of Ingham is rapid and some of the islands north of the Palms lie within this category.

Temperatures do not vary greatly within the research area and temperature characteristics are well illustrated by the Townsville figures (Table 1.1). Temperatures are generally high, even during winter months, and frosts are unknown along the coast though may be experienced on the plateau. Absolute minimum temperatures on the coast do not fall below 40°F. Similarly summer maximum temperatures are generally moderate though tend to be more extreme inland where temperatures of 100°F or more are not uncommon during the summer months. Whilst century readings are not unknown on the coast, they do not occur regularly or even

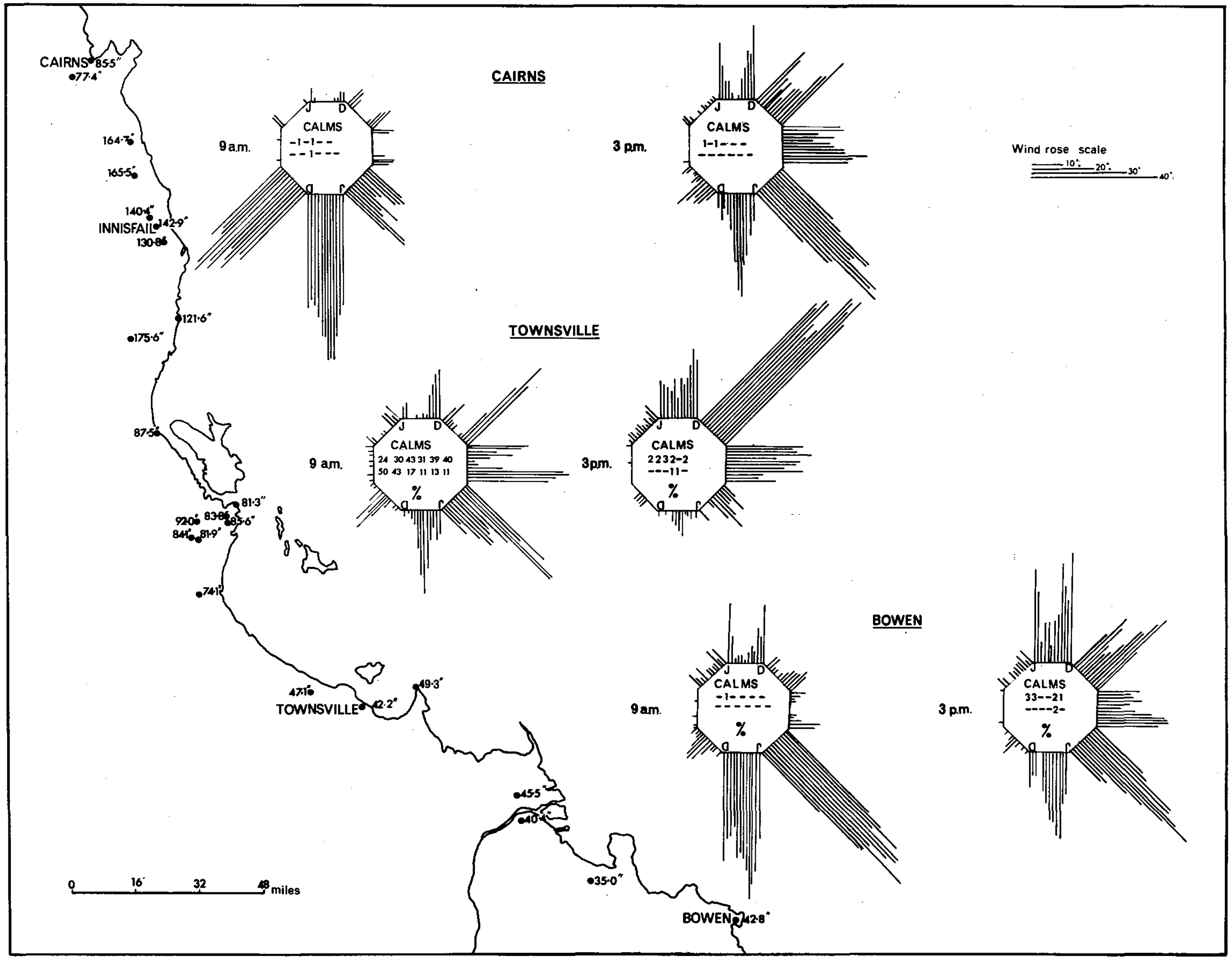

Fig. 1.3 Climatic data – rainfall figures and wind roses for 9a.m. and 3p.m.

every year. Coastal extreme high temperatures are slightly less than 110°F.

The rainfall regimes are more variable. Mean monthly totals for a number of centres are shown in Table 1.2. The steep rainfall gradient commences just south of Ingham and, within a distance of about 60 miles, the mean annual rainfall figure rises from about 40 inches to over 100 inches. Progressing southwards along the coast a number of changes occur in the rainfall regime:

i) there is the rapid decrease in total annual rainfall totals already noted in the Ingham district. A total of about 40 inches per year is maintained over a large part of the research area from north of Townsville to as far south as Bowen.

ii) there is a marked increase in rainfall variability inversely proportional to the decrease in totals. Townsville again illustrates the trend. The average rainfall is rarely experienced and extreme totals over the period 1870-1969 range from 10.53 inches in 1923 to 97.73 inches in 1894. Overall there is a 30% variability. The pattern of variability for the whole of Queensland has been discussed by Dick (1958). Variability for individual months at Townsville are shown in Table 1.3.

iii) there is an increase in the length of the winter dry season. If this is arbitrarily defined as months with less than 2 inches of rainfall, then at Innisfail there is no dry season, at Ingham it lasts for 4 months, and at Townsville, Ayr and Bowen 7 months.

A feature of the rainfall which is significant to geomorphological process is its intensity. The Townsville figures shown in Table 1.3 are typical of the region as a whole and indicate a high intensity. Jennings (1967) maps and discusses the patterns of rainfall intensity in Australia and indicates the coastal area in question to have one of the highest intensities in Australia, being surpassed only by the wetter coast to the north.

Figure 1.3 indicates rainfall figures for stations in the North Queensland area. Isohyets have not been inserted as the pattern is complex, even more complex than appears from the figures. Unpublished data indicates up to 40% variation in figures from stations less than 5 miles apart.

Wind speeds in the tropics are generally light (Jennings, 1965). The data available for the research area are in agreement with this general conclusion. Wind speeds are normally less than 10 m.p.h. They are generally highest during the winter rather than the summer months and during the afternoon rather than in the morning. Octagonal wind roses for Cairns, Townsville and Bowen are provided on figure 1.3.[1] Wind roses for both 9 a.m. and 3 p.m. are shown and indicate that, whilst the whole coast is under the influence of the south-east trades, local land and sea breezes modify the general pattern. Thus at Cairns the 9 a.m. readings indicate a prevalence of southerly or even south-westerly orientations, whilst 3 p.m. readings indicate a swing to the south-east. At Townsville the morning readings show a preference for

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1. Figures were provided by the Bureau of Meteorology, Brisbane and are based on 5 years observations.

Table 1.1

Townsville Temperature Data °F

	J	F	M	A	M	J	J	A	S	O	N	D	Annual
Mean Monthly Maximum	86.9	87.0	86.2	84.1	80.4	76.6	75.5	76.8	79.7	82.5	84.5	86.3	82.2
Mean Monthly Minimum	75.8	74.9	73.4	69.6	64.2	60.8	58.4	60.4	65.3	70.5	73.5	75.6	68.5

Table 1.2

Month Rainfall Data Inches (50 year means)

	J	F	M	A	M	J	J	A	S	O	N	D	Annual
Innisfail	22.07	25.71	27.93	17.61	10.31	7.81	5.63	4.24	3.77	3.28	6.12	8.49	142.97
Ingham	17.84	20.43	18.63	6.09	3.83	2.18	1.71	1.18	1.39	1.37	3.74	5.79	84.18
Townsville	10.74	10.17	6.74	2.24	0.96	1.08	0.67	0.50	0.86	1.18	1.90	5.16	42.20
Ayr	9.98	13.86	8.35	2.52	1.67	1.20	1.03	0.45	0.38	0.53	1.60	3.94	45.51
Bowen	9.40	12.01	7.40	2.96	1.62	1.36	1.26	0.74	0.38	0.50	1.39	3.84	42.86

Table 1.3

Monthly Rainfall Details for Townsville - Points

	J	F	M	A	M	J	J	A	S	O	N	D	Annual
Rainfall (50 yrs)	1074	1017	674	224	96	108	67	50	86	118	190	516	4220
No. of wet days	12	13	11	5	5	4	3	2	3	4	5	9	76
Rain per wet day (Points)	90	78	61	45	19	27	22	25	29	29	38	57	56
Variability (%)	56	57	67	84	92	92	117	122	125	104	93	84	30

(From Christian *et al*, 1953)

the south-easterlies or easterlies, swinging round to north-easterly in the afternoon. A similar pattern exists at Bowen, the morning south-easterlies swinging to north-easterly or northerly in the afternoon. As might be expected the trade wind influence is at its strongest during the winter months, though it remains the dominant wind system even in summer when it may be interrupted by periods of light, variable winds.

Occasionally during the summer months a tropical cyclone will affect the weather along the North Queensland coast. On an average 3 cyclones per year originate in the Coral Sea region. The majority of these track along the coast with little effect, but occasionally they swing onshore and, with winds of 100 m.p.h. or more and diurnal rainfall totals in excess of 20 inches, their effects are devastating (for example Cyclone Ada, January 1970). Geomorphologically, they can produce more changes and carry out more work in 24 hours, than can be effected by normal weather patterns in many years. However, the area affected is generally small and, at any one location, the incidence of the severe effects of cyclones is limited to one every 40 or 50 years. The morphogenic significance of cyclones is discussed in Chapter 9.

Analyses of the meteorological controls of the North Queensland weather are not available. Traditional explanations of broad climatic controls in the tropical Pacific have been shown to be inadequate (Curray and Armstrong, 1959) in the light of work such as that of Palmer (1951, 1952) and Riehl (1954) and the review of Pedelaborde (1963). However, by comparison with similar areas it is possible to outline the main controls. In particular the weather pattern of North Queensland has a close association with that of Papua-New Guinea to the north (Fitzpatrick, Hart and Brookfield, 1966; Brookfield and Hart, 1966).

The winter pattern is dominated by the semi-permanent anti-cyclonic cell of the South Pacific, periodically strengthened by the migrating high pressure systems which progress across the Australian continent during this season. Between these cells occur low pressure troughs which can bring cool southerly air as far north as Townsville, producing abnormally low winter temperatures and occasional light winter rainfall. Such influxes are rare, however. In general the North Queensland coast is dominated by the south-easterly air stream circulating around the anti-cyclonic cell. Derived from a high pressure area with stable, descending air, it is not surprising to find that during their most consistent winter period, the south-easterly trades are associated with fine weather over most of North Queensland. However, the air stream has passed over thousands of miles of ocean, and the stability of the system is at its lowest on the north-western side of the South Pacific. Periodically in winter, therefore, a weakening of the strength of the trades is accompanied by light orographic rainfall on exposed coasts. This applies particularly to the coast between Ingham and Cairns. The trend of the coast in the Townsville area is parallel to the air flow and in general is not affected.

In summer, an alternative weather pattern may exist. Following the model of Palmer (1951, 1952) the basic flow of the tropics is easterly with perturbations of the easterly wave type occurring on either or both flanks of the line considered as the Inter-Tropical Convergence zone (I.T.C.). Unstable air along and behind the I.T.C. produces the heavy rainfall of the summer months in northern Australia. However, the I.T.C. is neither continuous latitudinally nor a permanent feature of the summer weather of Australia. In north-east Queensland it appears to advance and retreat in pulsatory fashion, periods of heavy rainfall alternating with fine periods during which lighter rains fall only on the exposed coasts transverse to the south-easterly air flow which resumes between the advances of the I.T.C. The mean maximum southerly extension of the I.T.C. appears to lie in the vicinity of Ingham. To the north, therefore, summer rains are fairly reliable and on the coast as far north as Cairns the heavy rains along the I.T.C. are reinforced by orographic falls associated with the trades. To the south there is no orographic influence and the rainfall from the I.T.C. instability is by no means reliable. In some years pulsations may bring several periods of heavy rains to the Townsville area, with high annual totals resulting. In others, the effects of the I.T.C. are hardly experienced and rainfall totals well below average result. It is the unreliability of the migration of the I.T.C. which produces the high variability figures for the coast between Townsville and Bowen.

Vegetation

The vegetation of the research area is summarised by Christian *et al* (1953). It is important to geomorphic processes for the amount of protection it gives to the coastal hinterland, especially in an area where rainfall intensity is high, and for the rapidity with which it colonises new depositional areas.

A savanna woodland with a discontinuous canopy covers most of the research area. The tree storey is dominated by *Eucalyptus* spp. and especially by the Moreton Bay Ash (*E. tesselaris*), the narrow-leafed iron-bark (*E. drepanophylla*) the poplar gum (*E. alba*) and the grey bloodwood (*E. polycarpa*).

Locally, wetter, low-lying areas may be dominated by stands of Melaleuca spp. The ground storey consists of medium height grasses, generally growing in clumps and exposing considerable intervening areas of bare ground during the dry winter season. Kangaroo grass (Themeda australis) and bunch spear grass (Heteropogon contortus) are the most common species. A similar vegetation clothes the older beach ridges of the coastal zone. Young foredunes are colonised by grasses and creeping plants such as Ipomoea pes-caprae, Canavalia rosea and Spinifex hirsutus and younger, but stable ridges by trees of Casuarina equisetifolius.

In the northern part of the research area, especially on the ranges, the high rainfall results in tropical rain-forest being the dominant vegetation formation. Although covering vast areas to the north, the tropical rainforest in the research area is limited to a zone about 10 miles wide commencing on the ranges north of the Black River. The transition zone on the seaward side may consist of stands of the forest she-oak (Casuarina torulosa) and on the landward side of a wet sclerophyll forest in which the tall rose gum eucalypt, E. grandis, dominates. The rain-forests themselves have a great variety of species of Indo-Malaysian origin and have been botanically described by Francis (1951), Richards (1952) and Webb (1959). In granitic areas of moderate rainfall and with thin soils, the tree storey may be dominated by hoop pine (Araucaria cunninghamii).

Approach and Research Techniques

The current programme of research on the coastal landforms of this large region commenced in 1965. Field methods have depended greatly on aerial photographs, a list of those used being given in Appendix A. Extensive ground traverses have been undertaken and detailed survey made of critical areas. Two techniques were employed for measuring heights. In areas where accessability was limited or vegetation dense, an abney level set at zero was used in conjunction with a levelling staff. Over the short range that this method was used, accuracies to within two inches were maintained. For all detailed survey, however, an Ertel Quickset level was used. Again short traverse legs were utilised (a necessity in the North Queensland heat) and accuracies to within a fraction of an inch were maintained. Distances were measured using the Reichenbach stadia lines provided on the level which make use of the parallax technique. Elsewhere, surveying tapes and chains were used.

A major problem at the commencement of research was the choice of a suitable datum level. State datum was unsuitable, not only because it was quite unrelated to shoreline processes, but also because of the lack of any bench marks along the coast. It was finally decided to use the Mean High Water Springs (M.H.W.S.) mark of the Townsville tide gauge (which stands at 9.5 feet on the tidal gauge). This has subsequently proved to be the most useful mark, as many shoreline features are related to this level and in particular the maximum height of cementation of beach deposits. Thus surveys in the littoral zone were related to the high tide mark of the previous tide, normally in as quiet a position as possible to avoid the exaggeration of the height of the tide by swash activity. Surveyed heights were later corrected to the standard datum by reference to the height of the tide used. In most cases, it was found satisfactory to utilise published tide tables. In exceptional weather, the recorded height of the high tide in Townsville occasionally differed (generally by less than one foot) from the predicted level and it was the actual recorded height which was used in the correction.

The same datum was used over the whole research area. Maxwell (1968) has described the tides of the Great Barrier Reef Province and indicates that the moderate tidal range at Townsville of 8.1 feet between Mean High Water Springs and Mean Low Water Springs is maintained with little variation along the whole of the coast between Dunk Island and Bowen. Moreover, co-tidal lines indicate almost a synchronous flow of tides within the whole area, with less than half an hour variation in time of the turn of the tide. Heights throughout this work are therefore related to Mean High Water Springs (M.H.W.S.) at Townsville except where otherwise stated. Sources of information utilised, however, used a variety of datum levels, including the following, which have been related to M.H.W.S. (Townsville).

State Datum	4.11 feet below M.H.W.S. (Townsville)
Railway Datum (Northern Line)	90.56 feet above M.H.W.S.
Townsville City Datum	40.46 feet above M.H.W.S.

Field sampling of beach ridges and other unconsolidated deposits was extensive and carried out by use of a 4-inch post-hole auger. This generally brought up a clean sample, even in little compacted sands, though occasionally water had to be added to the borehole to allow the sample to be brought to the surface. A maximum depth of 9 feet could be sampled by this method.

Laboratory work consisted of size characteristic determination and carbonate analysis. Samples were first dried and 100 grams sieved on an automatic sieve shaker for 25 minutes. The period of 25 minutes was found by experiment to be the time by which the medium size sands being analysed had passed through the sieves and after which there was less than a 1% variation in sand weights after further sieving (up to 1 hour). Sieve sizes were related to the phi (ø) scale, individual sieves ranging in size from -4.5 ø to 0 ø (63 to 1,000 microns) in half ø sizes. Mechanical analysis of more than 400 samples was undertaken. Analysis of the results included the calculation of mean size, sorting (standard deviation), skewness and kurtosis using the methods outlined by Friedman (1961), which have the advantage of having been used by others whose work appears in the literature (e.g. Sevon, 1966). Calculations were made on the IBM 1620 computer of the University College of Townsville (James Cook University of North Queensland) using a programme provided by Dr. W.D. Sevon, but modified by Mr. I.M. Hunter. Sevon's linear discriminant functions were also calculated but were found to have no significance in the North Queensland area.

Carbonate analyses were carried out on the same samples by immersing 25 grams of material in cold, dilute hydrochloric acid (5 parts water to 1 part laboratory strength acid) and allowing to stand until reaction had ceased. This normally occurred within 24 hours. Acid solubles other than carbonates are thus included in the results, but these are considered to be too small to affect the results within the accuracy of the method.

Dating of deposits has depended to a large extent on normal stratigraphic relationships. However, considerable use has been made of radio-carbon dating techniques. Altogether, 29 radio-carbon dates are quoted for the research area of which 5 were provided by an American research team working in the Burdekin Delta (J.M. Coleman, pers. comm.), the remainder being obtained by the author. The cost of dating was borne by the University College of Townsville (21 dates) and by the Quaternary Shorelines Committee of A.N.Z.A.A.S. (3 dates). Samples were dated by Prof. K. Kigoshi of the Gakushuin University, Tokyo, using a method with an age limit of 30,000 years and an error of accuracy of less than 1%.

The combined results of the research programme are presented in the following pages. Chapters 2 to 5 presen the evidence for coastal evolution on a regional basis examining in turn the off-shore islands, the Burdekin River delta, the coastal plain around Townsville and the Herbert River delta. The emphasis in these chapters is placed on presentation of the evidence and research findings and discussion is limited to the formation of local chronologies only. Chapters 6 to 9 are a discussion of the major features which have concerned the research programme, namely beach materials, changes in the relative positions of land and sea, climatic changes and features of morphogenetic significance. In these chapters, not only are conclusions for the whole of the research area drawn together, but these conclusions are compared with results from elsewhere in Australia and from other parts of the world in an attempt to evaluate the significance of the findings in North Queensland for geomorphological research. A bibliography, in alphabetical order, is given for each chapter rather than as a single collection at the end of the volume, as this was considered to be more convenient to the reader, in view of the large number of authors quoted. It is hoped that whilst a number of important questions in the geomorphological evolution of the North Queensland coast may be answered here, the new queries which arise from this research will promote further investigations in the future.

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CHAPTER 2

THE GEOMORPHOLOGY OF THE OFF-SHORE ISLANDS

The terms "high" and "low" islands were first used by Captain Cook to differentiate the islands composed of continental and volcanic rocks from those of coral material (Fairbridge, 1968, p.568). Along the North Queensland coast between Double Point and Abbot Point the Great Barrier Reefs enclose several groups of high islands, each group continuing the structural trend of the mainland, generally in a north-north-west to south-south-east direction (fig. 2.1). Thus the Barnard Islands continue the trend of the Moresby Range near Innisfail, and Dunk Island, the Family Group and the Brooks Islands have a similar alignment to the Walter Hill Range. Further linear extensions of mainland structures are found in the Palm Islands and the isolated islands between the Palms and Townsville. South of Townsville, high islands are apparently less numerous but many isolated outcrops do occur, generally paralleling the hard rock escarpments behind the coastal plain. However, because of massive sedimentation from the Burdekin River and to a lesser extent from the Haughton and Elliot Rivers these have been incorporated within the coastal plain of the mainland. It is evident that the high islands are merely drowned extensions of mainland ranges, submerged during the late Pleistocene-early Holocene transgression.

The object of this chapter is to examine the geomorphological features of the high islands and to evaluate their contribution to the understanding of the evolution of the North Queensland coast. A basic contrast exists between the islands north of Hinchinbrooks and those to the south.

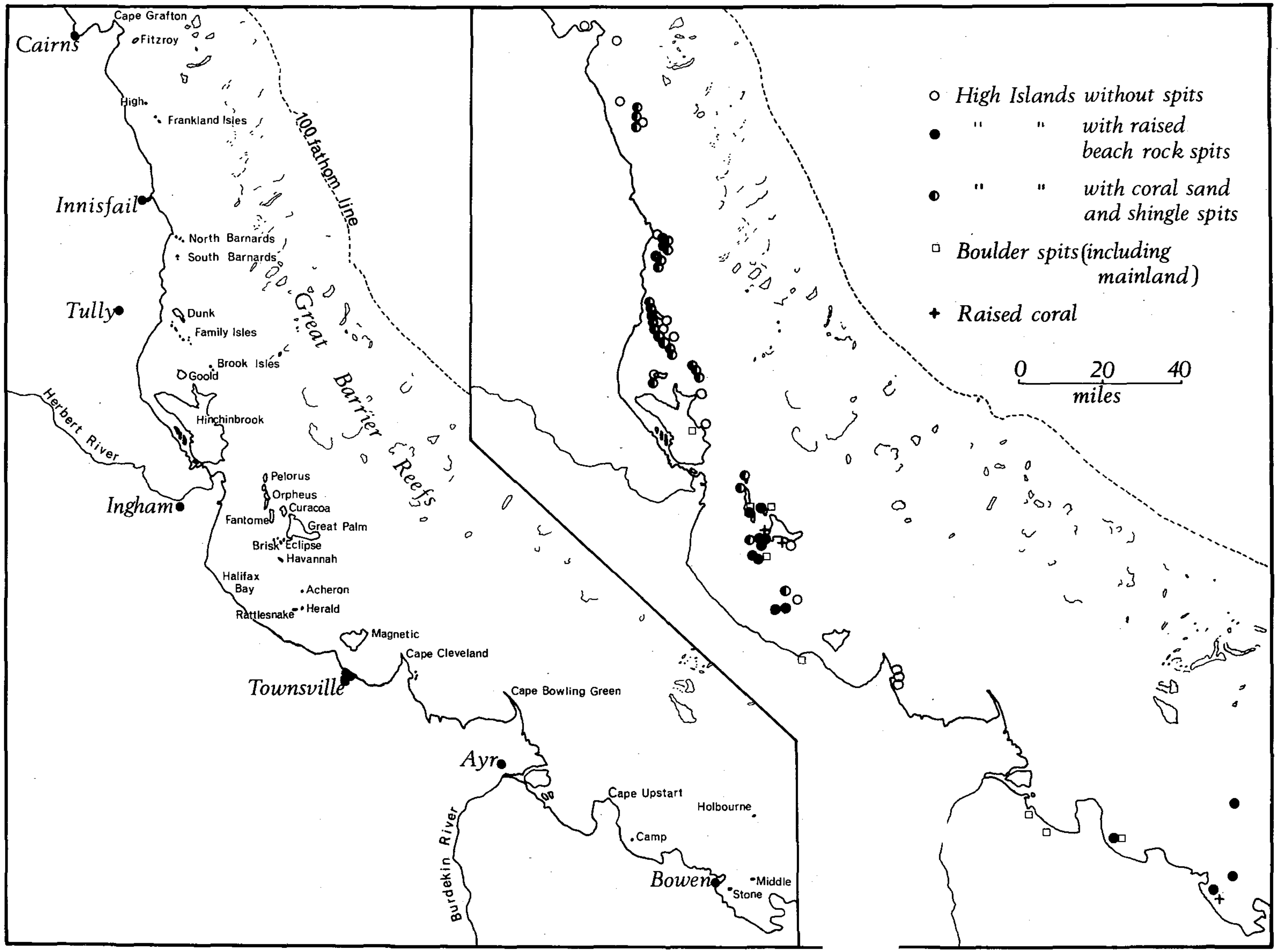


Fig. 2.1 North Queensland Islands with spit classification.

To the north, the wetter climate influences the nature of sedimentation around the islands. Contrasts in geology emphasize the climatic differences, as the northern islands consist almost entirely of metamorphic rocks whilst those of the south consist mainly of granite and of acid volcanic porphyries. The two largest islands, Hinchinbrook and Magnetic, have geomorphological features essentially the same as those of the adjacent mainland and will be considered in conjunction with the relevant area of mainland.

The islands rise fairly steeply from the shallow continental shelf which has an average depth of about 60 feet. In the wetter north, all but the steepest slopes have a thick covering of rainforest. Further south, the coastal cliffs are bare of vegetation but, except in the most exposed locations, shore platforms are not well developed and the slopes of the islands are the products of subaerial, rather than marine processes. What little steepening there is on the lower parts of the cliffs is more likely to be the result of removal by the Holocene transgression of the regolith which accumulated during the last low level stand of the sea. The cliffs can therefore be considered exhumed weathering fronts (Mabbutt, 1961).

By far the most interesting geomorphological features of the islands are those arising from deposition. Boulder foreshores extend around most islands, the boulders apparently being derived from the regolith removed by the sea. The majority of the high islands, however, have spits extending from their leeside northern or western shores and over the surrounding fringing coral reef. Great variation in morphology is displayed by these spits, but a cuspate shape is most characteristic. The smaller islands generally have the best developed features. Minor flats of unconsolidated desposits may be found elsewhere than on the north-western side, but without the cuspate shape. Examination of the spits and flats has comprised the greater part of research carried out on the islands.

The area covered by this chapter includes some 44 high islands. References to a number of these have appeared previously in geomorphological literature, but not in great detail (Andrews, 1902; Sussmilch, 1938). Short studies of single islands in the area were made in the early reports of the Great Barrier Reef Committee (Richards and Hedley, 1925; Marshall, Richards and Walkom, 1925; Hedley, 1925), with reference being made to raised coral, emerged platforms and abandoned sea caves. The only close studies made of the high islands, however, were those of Steers (1929, 1937) who discussed the origin of the island spits (1929, p.341) and concluded that, being on the leeside of the islands, the spits are the result of the refraction of the dominant south-easterly waves. These dominant waves undoubtedly play a very influential part in the moulding of the spits, but to regard these features as simple structures is misleading. This chapter illustrates the complexity of the spits and their importance in contributing to the understanding of the late Pleistocene and Holocene histories of the area.

The Materials of the Spits

The material making up the spits is a combination of terrigenous sediments derived from the high island, and biogenic material derived from the fringing reef and its marine organisms. The balance between the two sources of material is determined partly by climate, and partly by geology. The sharp climatic division in the area under study has a direct bearing on beach characteristics. The rapidity of weathering of the rocks of the wetter islands north of

Hinchinbrook, combined with the more rapid leaching of calcareous biogenic material, means that terrigenous sand deposits are generally more common on the spits of the northern islands, than on those to the south. Thus the proportion of sand of terrigenous and biogenic origins is similar. In the drier zone terrigenous deposits are generally of larger calibre and the breakdown of coral and shell fragments is slower.

Variations within this general pattern occur as a result of geology. In the wetter zone the metamorphic rock (mica schists and gneisses) of islands such as Dunk and the North Barnards, weather readily into fine grained quartzose sediments, and fine sand makes up much of the spits of these islands, often dominating over the biogenic material. Granites on Fitzroy Island and the Brook Islands also weather readily and the coarse sand and boulders resulting outweigh the shell and coral debris. The present beaches of the islands of the drier zone to the south are dominated by biogenic materials irrespective of geology. Granites and volcanic rocks make up most of the islands of this zone and at present neither produces large amounts of fine grained material, though boulders are common at the base of cliffs.

Where biogenic material is dominant it is usually in the form of coral shingle beach ridges. The angular and branching nature of the coarser coral fragments allows steep angles of rest of up to 30° to be maintained. The coral shingle of the older ridges readily acquires a black algal coating. The loosely interlocking nature of the material also allows for a certain amount of compaction and settling after weathering and decomposition.

Because of the climatic and geological conditions, sand beaches are relatively rare on the islands. Where they do occur they tend to rise moderately steeply from the calcareous mud which coats the reef flat, though the present beach and the older sand beach ridges are lower and more gently sloping than the ridges of coral shingle.

The fringing reefs of the islands are important to the spits. Not only do they supply material to the spit in the form of broken fragments, but they also form the basement over which the spit has grown. Spring tide ranges around the islands are in excess of 9 feet and low water spring tides, a reef flat up to 200 yards wide may be exposed around even the smallest island. The widest part of the fringing reefs is found on the leeside of the islands, and the reef forms the foundations for spit growth. Vigorous coral growth is limited to the outer slope of the reef. Above low water mark the reef flats display zonation. From mean low water mark to approximately 3 feet above this the reef flat consists of dead coral in situ with living corals only in deeper pools. On the weather side of the islands, algal encrustations add to the reef material in this part of the reef. This zone is apparently the current source of coral shingle during storms. The death of the coral is in part the result of fresh water flushes resulting from cyclonic rainfall on the mainland (Hedley, 1925; Rainford, 1924-6). Recovery appears to be slow. From 3 to 6 feet above L.W.M. is a zone of dead coral in situ but very much destroyed and planed down to a near level surface. Calcareous sand and mud fill many of the cavities between individual corals. The upper part of the reef flat is entirely covered by this calcareous sand and mud, though in one example at least (Eclipse Island) the reef flat emerges into an in situ raised reef above high water mark.

In such a calcareous tropical environment, it is not surprising to find that cementation of all the types of shore deposits described is common. The resulting beach rocks and beach conglomerates have given a permanence to the spits which, they would not have had as unconsolidated deposits. The cemented beach materials are found not only between tide levels on the present beach, but also off-shore to a depth of at least 25 feet below M.H.W.S. and inland on the higher parts of the spits to a height of 20 feet above M.H.W.S.

The origin of beach rock has been discussed most recently by Russell (1959, 1962, 1963, 1967) and this theme will be considered further in Chapter 6. However, it is generally agreed that cementation occurs at the water table as the result of precipitation of calcium carbonate from heavily charged ground water, the $CaCO_3$ initially being derived from the calcareous beach material itself. The maximum vertical thickness of cemented beach which can be attained is thus governed by the water table fluctuations. Within beaches and beach ridges close to the sea, especially those composed of coarse material, the fluctuations are governed by tidal changes and the thickness of beach rock reflects the tidal range. The upper level of cementation is therefore be a good indicator of high water mark at the time of formation. Cemented materials above or below the present cementation zone may indicate changes in the relative levels of land and sea. Removal of the overlying uncemented beach exposes an almost level surface which truncates the original depositional dip of the beach material. Some workers have attributed the level surface to marine abrasion, thus confusing the early interpretation of higher sea levels on the North Queensland continental islands and on nearby coral cays and low wooded islands of the Great Barrier Reefs (see for example Stanley, 1928, p.36).

Morphological Features of the Islands of the Drier Southern Area

The islands of the southern area are characterised by unvegetated coastal slopes, beaches of biogenic material, the widespread occurrence of beach rock and conglomerates, and the development of large and irregular leeside spits.

The Palm Islands (fig. 2.2)

North Palm Island, the northern end of Orpheus Island and Curacoa Island consist of volcanic porphyries probably of Upper Carboniferous age (de Keyser, Fardon and Cuttler, 1965). Tuff and breccias are reported on Orpheus Island. The remaining Palm Islands consist of granitic rocks, mostly biotite granite. Both the porphyries and the granites are intruded by swarms of dolerite dykes trending north-west to south-east.

i) North Palm Island (Pelorus)

North Palm Island is a small regularly shaped island rising to 924 feet. It has only a narrow fringing reef and spit development is limited to a small cuspate area of sand on the south-west corner.

ii) Orpheus Island

Orpheus Island consists of a long sinuous ridge about 450 feet high but reaching a maximum of 560 feet in the north. Both east and west coasts are indented and many of the small drainage lines on the east coast are graded to below present sea level, probably as tributaries to a proto-Herbert during the Pleistocene glacial low levels. Both Pioneer and Hazard Bays appear to have formed in this way, but the deepest inlet is found just north of Pioneer Bay. It is mangrove filled and partially closed by a coral shingle spit.

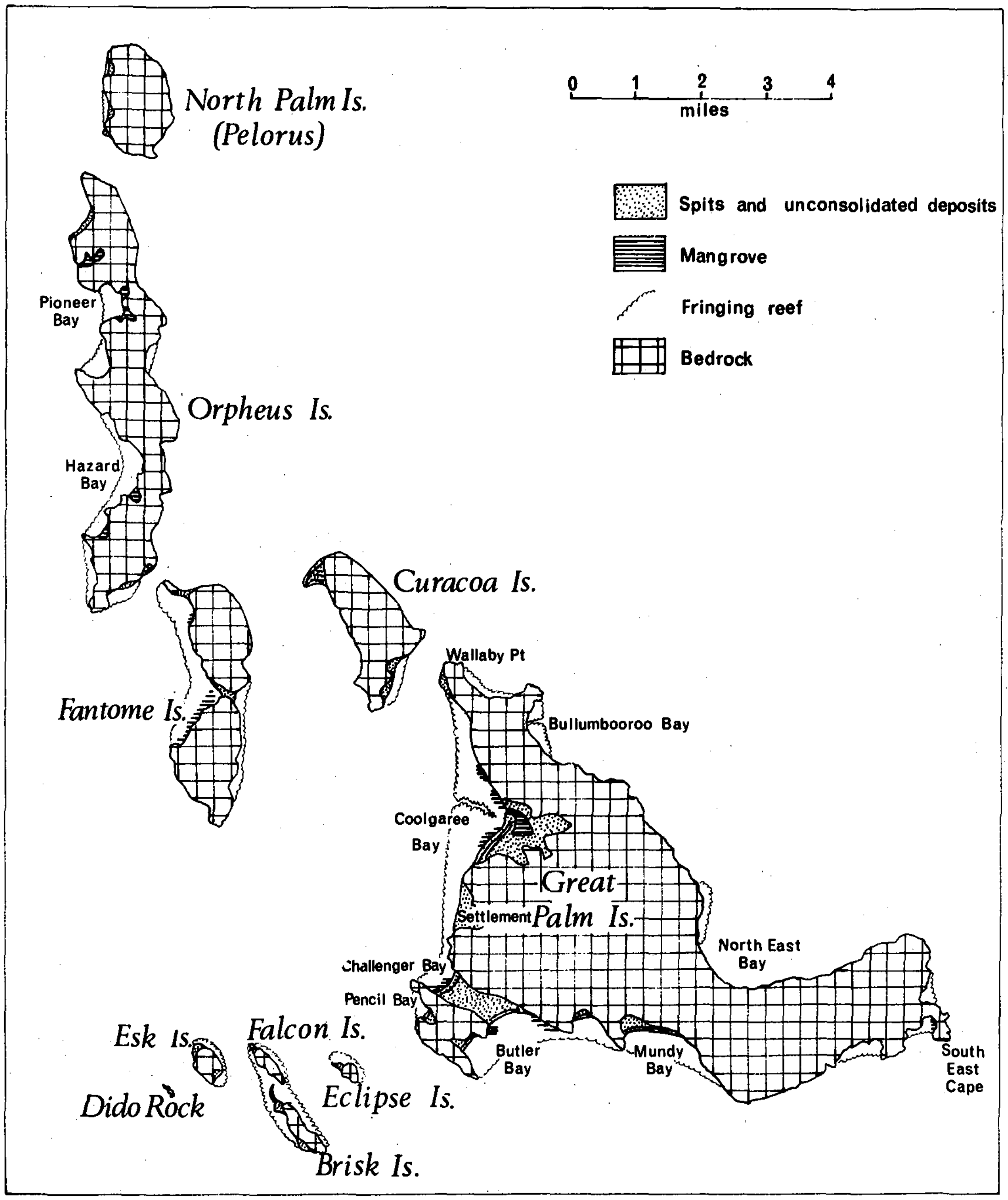


Fig. 2.2 The Palm Islands.

A narrow fringing reef occurs along the eastern side of Orpheus, widening in the bays. Bay heads of the more deeply indented bays are normally mangrove-filled; shallower bays normally have a series of sand or shingle ridges. The northern-most bay on the east coast is typical of these depositional areas (fig. 2.3). It consists of a steep coral shingle foreshore, partially cemented in the intertidal levels. The upper parts of this unvegetated ridge are made up of algae-blackened coral indicating a certain stability in the depositional environment. Behind this unvegetated ridge is a partially vegetated shingle ridge rising to 8.2 feet above M.H.W.S. and a further ridge rising to 12.7 feet which has a covering of rainforest. At the northern end of the bay this inner ridge encloses a lagoon of fresh water, the surface of which is approximately 5 feet above M.H.W.S. A rocky scree slope is found behind the lagoon. The present shingle beach rises to 4.2 feet and in view of the sheltered nature of this bay and the undoubted compaction of the shingle of the older ridges, the height of these older ridges may well indicate a higher sea level at time of deposition.

A more unique area of deposition is found on the southern end of the island (fig. 2.4). Three shallow bays exist here, each infilled with beach ridges. The southern-most beach is fairly simple, consisting of a sandy beach, with a double crested beach ridge rising to 8.0 feet. The next bay to the north has a foreshore of beach rock occurring between tide levels. Behind this is a ridge of coral sand and shingle rising to 8 feet. A small creek cuts through this ridge, exposing beach rock at its core. This does not extend above M.H.W.S., i.e. it occurs within the range of present cementation. Beach rock also floors the channel behind this ridge. A wide terrace of coral sand and shingle

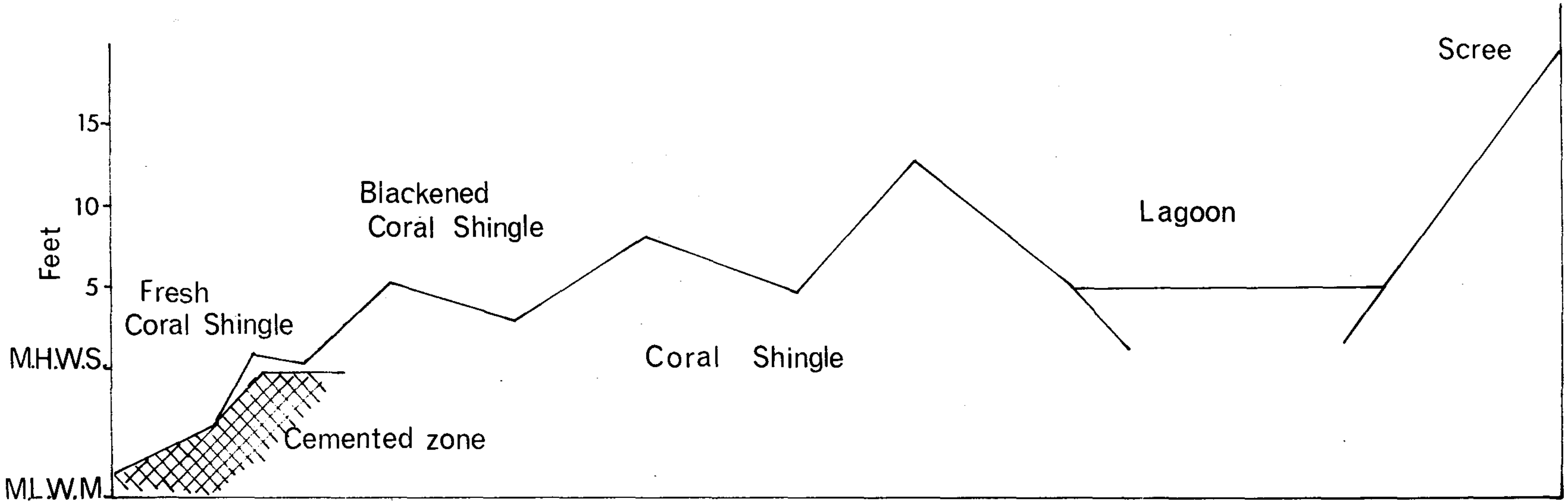


Fig. 2.3 Section, coral shingle beach ridges north Orpheus Island.

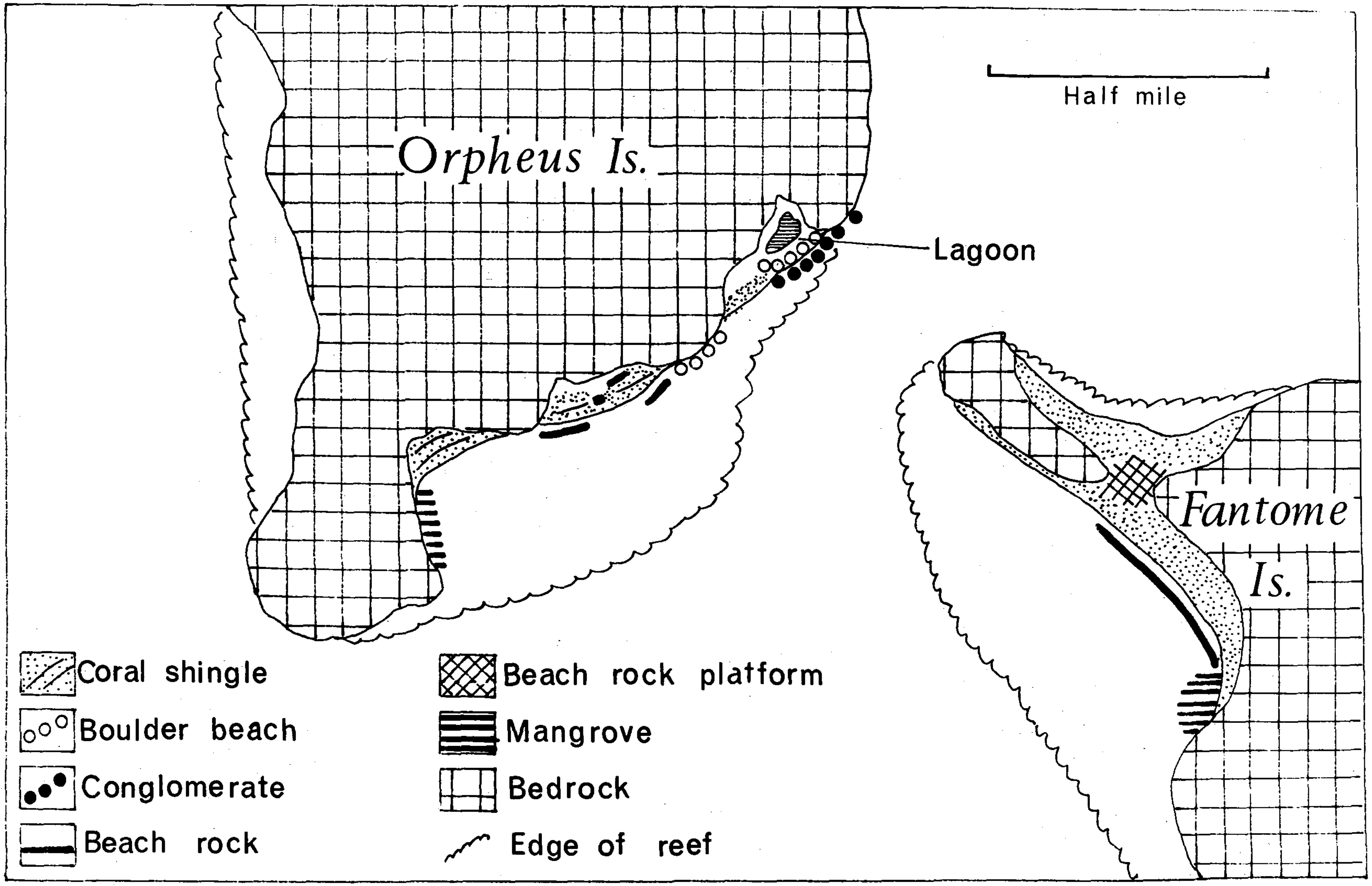


Fig. 2.4 Southern end of Orpheus Island.

is found behind the channel and rises to 10.5 feet. This in turn is separated from the scree slope at the rear by a beach rock floored channel, the height here being at least 2 feet above the present range of cementation. This strongly suggests a higher sea level at the time of formation of the rearmost beach terrace. The northern bay also provides evidence for a higher sea level. It has a boulder spit trailing from its northern side and rising to over 18 feet. Boulders of up to 2 feet in diameter are found at the northern end, grading to about 6 inches to the south. The ridge encloses a lagoon. In front of the boulder spit is an area of cemented boulders of a similar calibre and it is evident that the boulder spit is the remnant of a much larger feature. The cemented boulder foreshore is undergoing erosion, the loosened boulders being redistributed in uncemented form at the southern end of the bay. Most of the cemented boulders have thus been truncated at or just above M.H.W.S., but occasional mesas of uneroded conglomerate remain, rising to at least 4 feet above M.H.W.S., apparently the original upper limit of cementation. This is 4 feet higher than the upper limit of current cementation.

iii) Fantome Island

Fantome Island formerly consisted of three separate rocky islands, now joined together by deposition. Sand beach ridges occur at the narrow 'waist' of the island, whilst the small rocky outcrop to the north appears to be joined to the rest of the island by a raised beach rock terrace similar to that on Brisk and Falcon Islands (see below). Unfortunately Fantome is the site of a leper colony and landing is prohibited. The raised beach rock could not therefore be confirmed, though Andrews (1902) refers to an "upper beach" 12 to 15 feet above M.H.W.S. on Fantome, with beach rock apparently <u>in situ</u> occurring at the same location.

iv) Curacoa Island (fig. 2.5)

Curacoa is a smaller but extremely interesting member of the Palm Group. It rises sharply to 971 feet and has two areas of deposition, a well formed cuspate spit to the north-west and a smaller area in the south-east.

A short description of the Curacoa Island spit has recently been published (Hopley, 1968). The relative simplicity of the structure serves as a guide to the origin of more complex morphology of other islands. Essentially it consists of a boulder embankment on its north-western side with younger coral shingle beach ridges orientated towards the south. The boulder embankment is a simple spit, anchored to the main part of the island and displaying two lateral arms trailing to the south. The crest of the main ridge maintains a height of between 16 and 17 feet for the whole of its length. The boulders range from a mean diameter of approximately 2 feet at the anchor point to between 0.6 and 0.75 feet at the western end. The embankment today trends north-east to south-west but by tracing the main crest it is clear that, at the time of formation, the main axis was closer to east-north-east to west-south-west. Much of the original spit has been truncated. Basal portions of the boulder spit now outcrop along the present northern beach and show that the whole of the lower part of the boulder material is firmly cemented. A smaller area of cemented boulder conglomerate is also found on the beach along the extended line of the outer lateral ridge. Truncation may also have occurred here. Between the present shoreline and the boulder spit are several coral shingle ridges. Beneath these, the level of cementation of the boulders rises to at least 6 feet above M.H.W.S. Along the shore the conglomerate forms a platform just above H.W.M. which appears to be a wave-cut feature. On its seaward

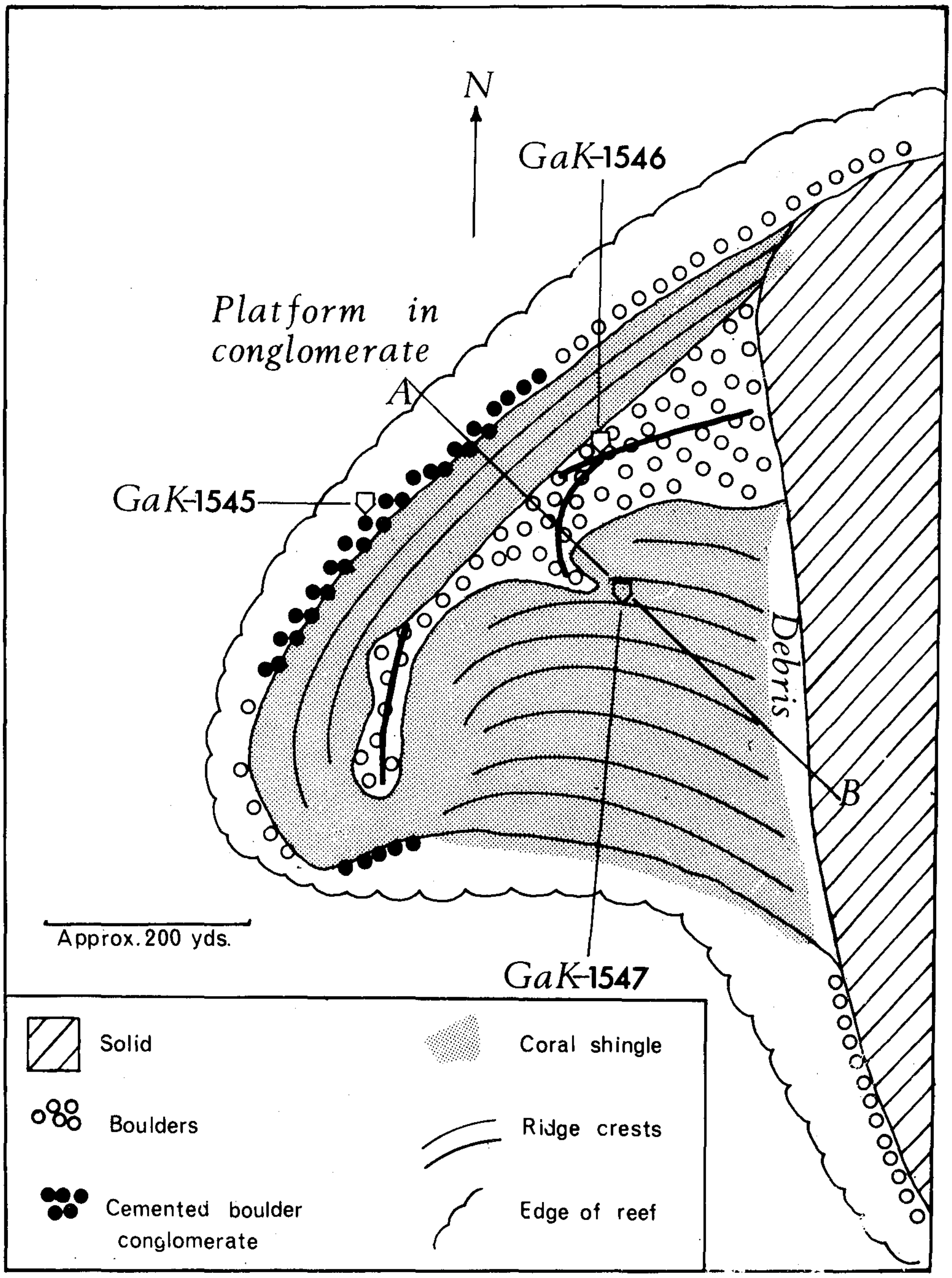


Fig. 2.5 Curacoa Island spit.

edge it drops away sharply and though it is encrusted with living coral cementation was observed to 25 feet below M.H.W.S. The coarseness of the material involved and the proximity of the present cemented deposits to the original shoreline suggest that the water table involved in the cementing process would have approximated very closely to sea level. The Curacoa exposures thus suggest a simultaneous construction of the boulder spit and cementation in the intertidal zone in response to a rising sea level, a rise which extended to at least 6 feet above M.H.W.S.

The area between the boulder spit and the main part of the island is infilled with coral shingle beach ridges. The crests of these range in height from 10 to 14.5 feet above M.H.W.S. in an irregular fashion. Compaction and settling of the coral shingle may have affected the older inner ridges. The coral shingle ridges on the outer edge of the boulder spit rise in height from 6 to 14 feet, the lower ones on the exposed platform at the level of cementation.

Radiometric dating was carried out for three samples from Curacoa, giving the following results:

i)	GaK-1545	Coral from cemented base of boulder spit 2 feet below H.W.M. - 5070 years ± 110 B.P.
ii)	GaK-1546	Coral from uncemented crest of boulder spit - 5250 years ± 100 B.P.
iii)	GaK-1547	Shell from inner coral shingle ridge - 2620 years ± 90 B.P.

The evidence suggests that the boulder spit was built by the rising Holocene sea level during which a level of approximately 6 feet above present was attained 5,000 to 6,000 years ago. Infilling with coral shingle beach ridges has occurred as sea level retreated from this mid-Holocene maximum.

I Mangrove lined ria, Orpheus Island.

II Curacoa Island spit.

The smaller depositional area on the south-east coast is less illuminating as far as the geomorphological history of the islands is concerned. It occupies two shallow indentations on the coast. The western beach has beach rock along the foreshore and a single beach ridge rising to 13.4 feet. The eastern beach has two beach ridges which have been cut through by a small stream thus exposing good sections. The outer ridge, rising to 9.7 feet, consists of coral sand overlying a cemented conglomerate rising to at least 3 feet above M.H.W.S. The outer ridge, rising to 15.9 feet, also has a core of cemented material consisting of beach rock in the upper parts and of conglomerate lower down. Cementation was observed to a height of 2 feet above H.W.M. A depositional sequence similar to that on the spit has occurred here with coarser boulder beach being deposited first, followed by later additions of biogenic beach materials (coral sand). It would appear from the observed levels of cementation that sea level was higher during or after the period of boulder beach deposition.

v) Great Palm Island

The main island of the Palm Group is triangular in shape, extending about 6 miles in a north-south direction and 8 miles east-west. Great Palm is a mountainous island, rising to 1,500 feet and much of the eastern part comprises large exfoliation sheets, which in part form the coastal cliffs of the southern and eastern coasts. It is very exposed to the south and east and a number of shore platforms can be observed from the sea, some of them beyond the reach of modern formation. However, the open aspect also made it difficult to land and surveys of the platforms were possible only around Wallaby Point and along the south coast. A wide reef is found in Coolgaree Bay and along parts of the southern coast. Elsewhere the reef occurs in patches.

Small streams entering into Coolgaree Bay and Bullumbooroo Bay have maintained narrow channels across the reef during upgrowth of the coral.

In his paper of 1902, Andrews noted the occurrence of "an interesting flat" at Challenger Bay joining two quite separate parts of the island. Young sand beach ridges occur at each end of this flat, which today is the location of the air strip for the Palms, but the plain consists essentially of sandy clay and coarse sand without shells or calcareous material. The height of this plain, 15 feet above H.W.M., and the weathered nature of the deposits, are comparable to those of the adjacent mainland which appear to be late Pleistocene in age (see Chapter 4).

Other alluvial areas on Great Palm appear to be younger. The area of the aboriginal settlement is essentially a deltaic fan with the addition of coral sand beaches. Beach rock is found along the shore. The alluvial area to the north is a partially filled lagoon dammed behind a large sand spit. Just south of Wallaby Point occurs a small cuspate sandflat, rising to 14.4 feet above M.H.W.S. and composed of fine sand, the upper parts of which may be windblown. The flat is being eroded, exposing not only current beach rock in the intertidal zone but also a much more ancient cemented deposit consisting of poorly sorted boulders up to 1.5 feet in diameter. The conglomerate extends onto Wallaby Point where it appears to be the remnants of a boulder spit extending around Wallaby Point and cemented at levels above H.W.M. It appears to be similar to those on Orpheus and Curacoa, and it seems reasonable to allocate a mid-Holocene date to this feature. This would mean that the 1.4-foot platform and the higher platforms at 3.1 and 10.7 feet into which it is cut are older, though the possibility does exist that the lower platform is contemporary to the spit. The sandflat at 14.4 feet is younger for it rests upon the eroded remnants of the boulder spit.

One further area of interest occurs on the eastern side of Great Palm. This is in the Pencil Bay area. The head of the bay has sand ridges rising to 10 feet and beach rock exposed along the foreshore. However, the area of interest is around the point at the southern side of the bay where a platform with conglomerate is found at about the high tide level, cut into a higher platform at 5.7 feet above M.H.W.S. upon which rests a storm beach of boulders and coral shingle. A little further around the point the lower platform disappears beneath a raised fringing reef exposed from 5.5 feet below to 1.5 feet above M.H.W.S. This is considered to be mid-Holocene like the nearby raised reef on Eclipse Island (see below).

The south coast has a wide fringing reef and a number of open bays orientated towards the south-west. Possibly because of this orientation the beach ridges at the heads of these bays are extremely wide, up to 100 yards across, though only about 10 feet high. The intervening headlands are in the form of granite exfoliation domes though a small amount of platform development occurs, probably again due to the open exposure. An abney level survey was carried out at a number of localities giving the following mean heights for the platforms:

i) Butler Bay - 0 feet, 3.25 feet

ii) Mundy Bay (west) - 0.25 feet, 4.6 feet

iii) Mundy Bay (east) - 2.7 feet, 7.7 feet, 11.0 feet

Well developed platforms were observed around South East Cape but survey was not possible.

vi) Eclipse Island (fig. 2.6)

Eclipse Island is one of four small islands at the

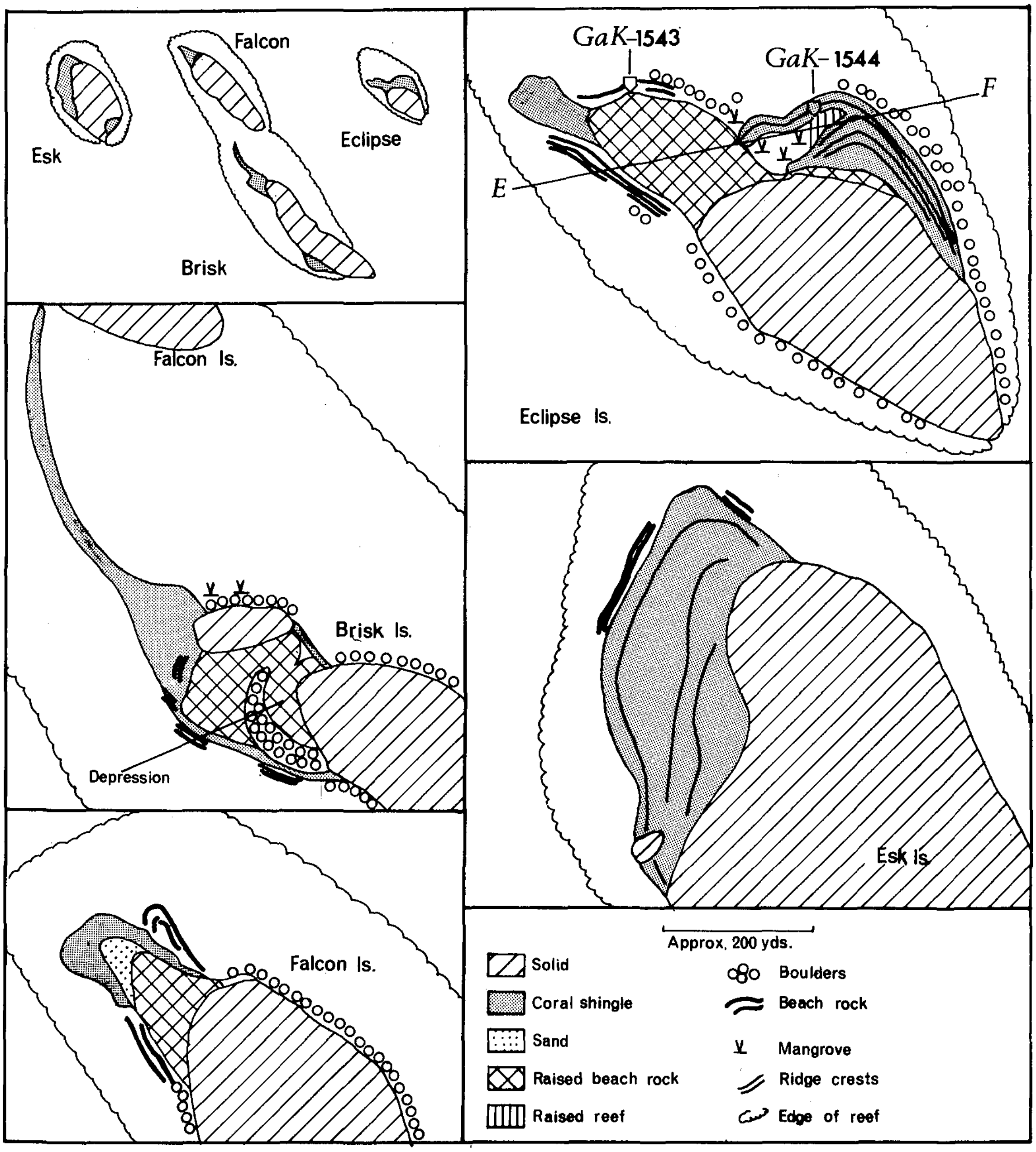


Fig. 2.6 Eclipse, Falcon, Brisk and Esk Island spits.

southern end of the Palm Group. The high, rocky section of the island is only lightly vegetated. It is cliffed, with a boulder beach at the base of the cliffs. A detailed survey was made of the spit which extends from the north-western side of the island. It is extremely irregular in shape and complex in its morphology. The spit has two separate parts, the older part consisting of a weathered beach rock platform, and a younger cuspate area of coral shingle ridges to the east. The platform consists of a cemented coral sand and shingle deposit including small amounts of shell and small stones. The maximum height of cementation observed is 9.5 feet, but the whole feature rises to a maximum of 11.5 feet above M.H.W.S., the higher areas surfaced by a dark, sandy soil containing abundant coral fragments. The whole feature is bounded by a sharp cliff, especially to the north where a marine abrasion platform of the same material extends towards the reef flat. The strike of the beach rock suggests that the original spit had a more northerly orientation. Modern beach rock outcrops along the southern shores of the platform area. A small extension, of recent origin, and composed of coral shingle surmounted by calcareous sand, is found on the tip of the spit.

The younger area of coral shingle ridges is separated from the beach rock platform by a low mangrove-filled depression. On the eastern side of this depression, and extending beneath the ridges, is an exposure of emerged reef including corals (mostly <u>Porites sp.</u>) in position of growth. The height of this raised reef is close to present M.H.W.S., approximately 8 feet above the height at which coral is growing at present. The raised reef apparently slopes down to the modern reef flat without any sharp break of slope. The shingle ridges resting on this reef rise to 9.5 feet and behind them is a small platform of cemented coral at 10.0 feet which appears to be part of the main beach rock platform. A low boulder beach is found seawards of the coral shingle ridges. This is in an active stage of accumulation from cliff erosion on the south-eastern side of the island. Radio-carbon assay of two samples from the island gave the following results:

GaK-1543 coral and shell from raised beach rock - 4,100 years ± 90 B.P.

GaK-1544 coral from raised reef - 590 years ± 70 B.P.

The origin of the raised beach rock is considered to have been a simple spit of coral shingle cemented at its base and suffering later erosion. The age is apparently mid-Holocene. The age of the coral from the reef is anomalous and points to contamination of the sample. It is suspected that the age of the raised reef is also mid-Holocene.

iv) Esk, Falcon and Brisk Islands (fig. 2.6)

These three granitic islands each have well-developed spits on their north-western sides, and smaller areas of reef flat deposits occur elsewhere. The islands are otherwise featureless.

The Esk Island spit consists of three single coral shingle ridges rising to 6.5, 10.5 and 11.5 feet above M.H.W.S. respectively. Modern beach rock outcrops on the beach. Ridges of coral sand also infill a small bay on the south-eastern side of the island. Since they are more exposed than the coral shingle ridges these ridges rise to 20 feet. Raised beach rock rises to at least 5 feet in the outer ridge, as shown on the banks of a small stream. Slabs of beach rock which may or may not be *in situ*, are found at 15 feet above M.H.W.S. between two of the ridges.

The base of the Falcon Island spit is formed from the cemented remnants of an older spit. The outer ramparts of this spit enclose a central depression. The orientation of the beach rock around the spit, which appears to have been planed down by the waves, indicates that the original orientation was in a more northerly direction. A modern addition of coral sand and shingle is found on the end of the feature.

The Brisk Island spit incorporates a former small island. Again the major part of the formation is the trimmed remnant of an older feature of which the core is a boulder embankment. Surrounding this, and partly enclosing a central depression, is the cemented base of a former beach system rising to 15 feet. The level of cementation is somewhat below this. The point of this original spit, as indicated by a beach rock exposure, was to the north-west. The modern extension, however, is further to the east and is in the form of a sinuous coral shingle spit which joins Brisk to Falcon Island at low water.

An isolated granite rock, Dido Rock, is found just west of Esk Island. It has a small fringing reef and a spit of modern coral shingle. The rock itself has prominent notching at 0.3 feet below M.H.W.S. (possibly the active notch), and a further notch with an extensive platform at 13.2 feet. The summit of Dido Rock may be a further platform at 20.5 feet.

<u>The Islands of Halifax Bay</u>

Four islands, each with a well-developed spit as their most prominent feature, are found in Halifax Bay between the Palms and Magnetic Island. In addition, there are three unvegetated rocks, only one of which, Fly Island, is noteworthy. The rock type of Fly, Havannah and Acheron Islands is again pink biotite granite. Rattlesnake and Herald are made up of massive acid porphyry. All islands are cut by dolerite dykes.

III Eclipse Island.

IV Eclipse Island spit, Falcon and Esk Islands in background.

V Falcon Island spit. Note the trend of an older spit indicated by beach rock.

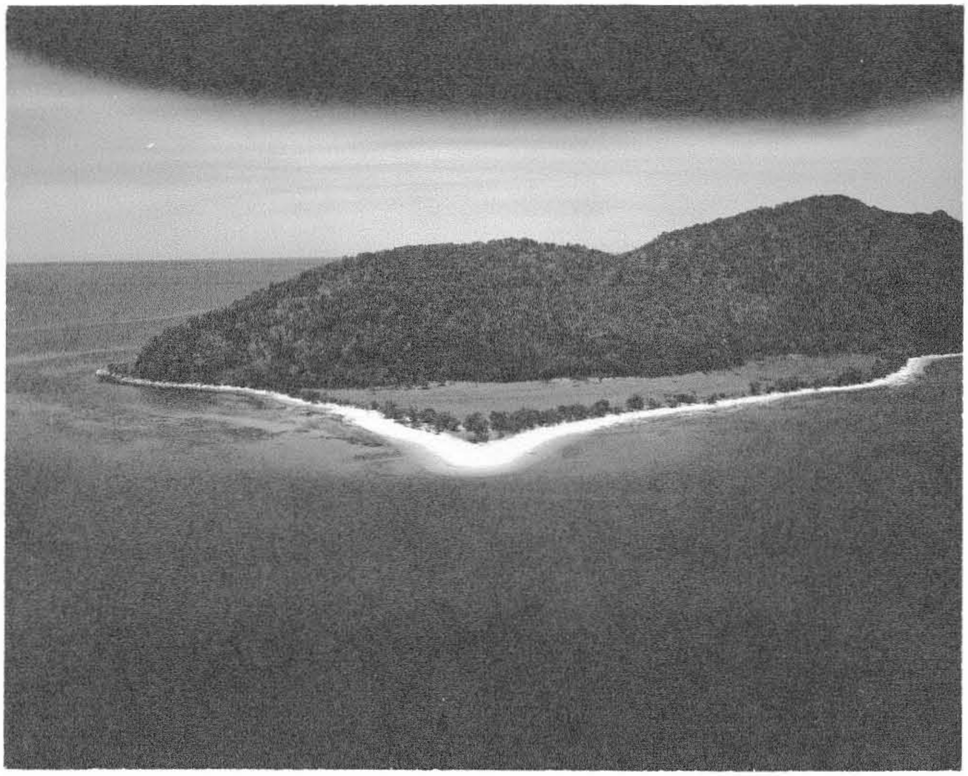
VI Brisk Island spit.

i) Havannah and Fly Islands (fig. 2.7)

The two granitic islands of Havannah and Fly have prominent spits on their north-western sides. The larger island, Havannah, has a complex spit of which the oldest part is a remnant of a conglomerate platform rising to 3.7 feet on the northern side. Large boulders up to 2 feet in diameter are found in this conglomerate and there is a general grading to a smaller size towards the west. The conglomerate appears to be the remains of a small boulder spit from which the uncemented material has been removed. Post-dating, and resting upon the conglomerate, is a beach rock plateau in which the level of cementation rises to 9.2 feet, though a low curving ridge of uncemented and weathered coral debris rests upon this platform and rises to 15 feet. This feature has a well developed black soil, though including many recognisable coral fragments. A small cuspate area of fresh coral shingle completes the apex of the spit. Modern beach rock is found between tide levels on both northern and south-western shores. To the south of the spit, and extending around much of the higher portion of the island, is a boulder beach parts of which are cemented. This beach partly lies above high water mark and is now completely stable. It apparently passes beneath the major part of the spit and may be contemporaneous with the conglomerate platform.

The Fly Island spit is similar. It consists of a boulder conglomerate platform trimmed by the waves. This again appears to be the remnant of a former boulder spit. Maximum height of the conglomerate is 7.3 feet above M.H.W at the base of the spit, where it rests upon a wave-cut platform at 4.4 feet. Coral shingle forms a modern spit lying on the conglomerate platform.

VII Fly Island and Havannah Island.



VIII Havannah Island spit.

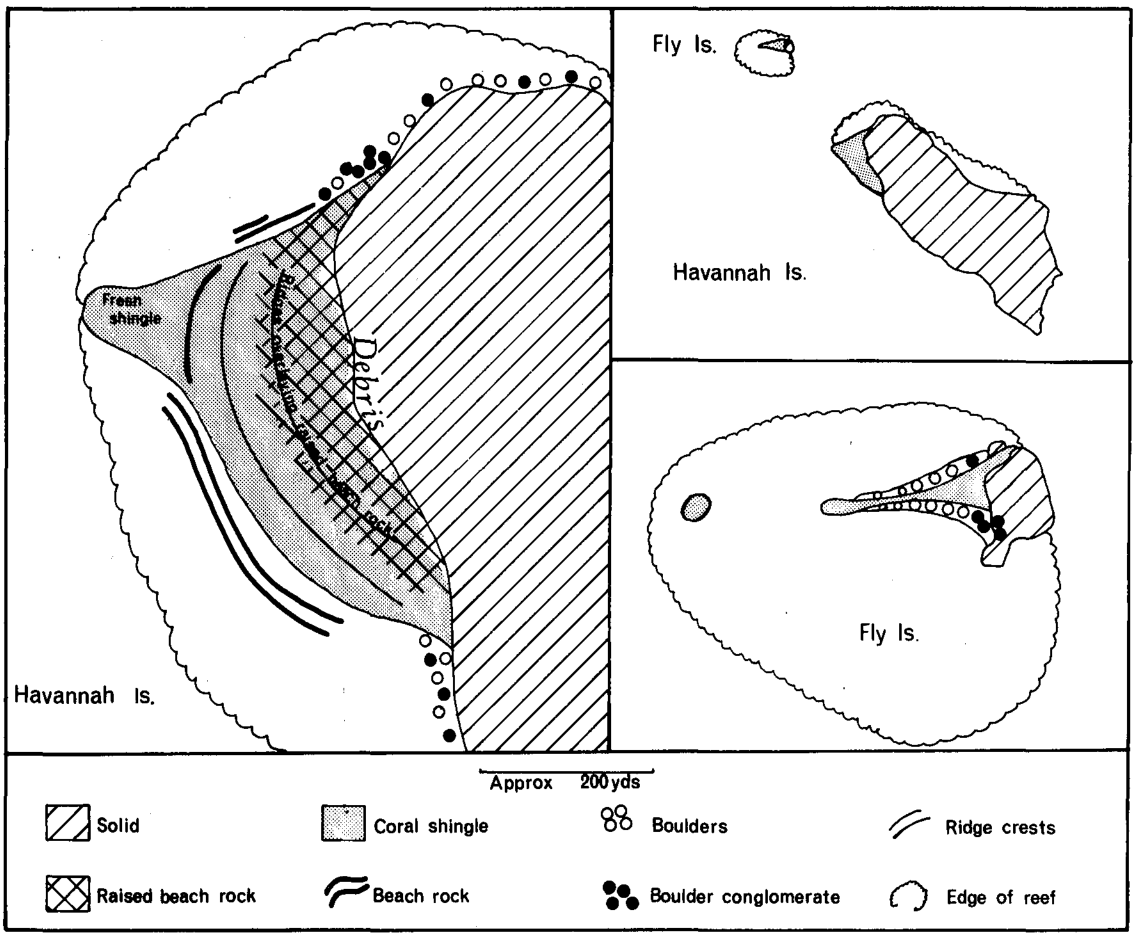


Fig. 2.7 Havannah and Fly Islands.

ii) Acheron Island (fig. 2.8)

Acheron has a small spit on its western end extending out over a wide reef flat. The feature consists of two parts, an active spit of coral shingle partially overriding an older boulder spit with a trend slightly more towards the south-west. The lower parts of the boulder spit are firmly cemented to at least 1.5 feet above H.W.M. whilst the uncemented boulders appear to have been removed from the tip of the spit. Near the island the remnants of the anchor end remain, rising to 9.0 feet. The material consists of boulders up to 3 feet in diameter together with smaller shingle and coral fragments. In places the conglomerate may be seen resting on a platform at or just above H.W.M.

iii) Rattlesnake Island (fig. 2.9)

The high parts of Rattlesnake Island and neighbouring Herald Island are composed of late Palaeozoic porphyry. Spits extend from the eastern sides of each island. The core of the Rattlesnake spit is a tombolo, mainly of boulders, joining a small rocky outcrop to the main part of the island.

Infilling of the embayments on either side of the tombolo by beach ridges of coral sand and shingle has followed. The beach ridges have been built out beyond the shelter of the embayment and erosion of the unanchored north-western ends of the ridges has occurred. The inner ridges have been cemented and beach rock is found to a height of 11.7 feet above M.H.W.S. Most of the uncemented surface material from these ridges has been removed and the inner part of the spit is a simple beach rock plateau with no surface relief apart from the incised course of a small intermittent stream. The original pattern of ridges is still discernable from the air. The deposits of the innermost ridge contain a high percentage of porphyry boulders. The resulting conglomerate

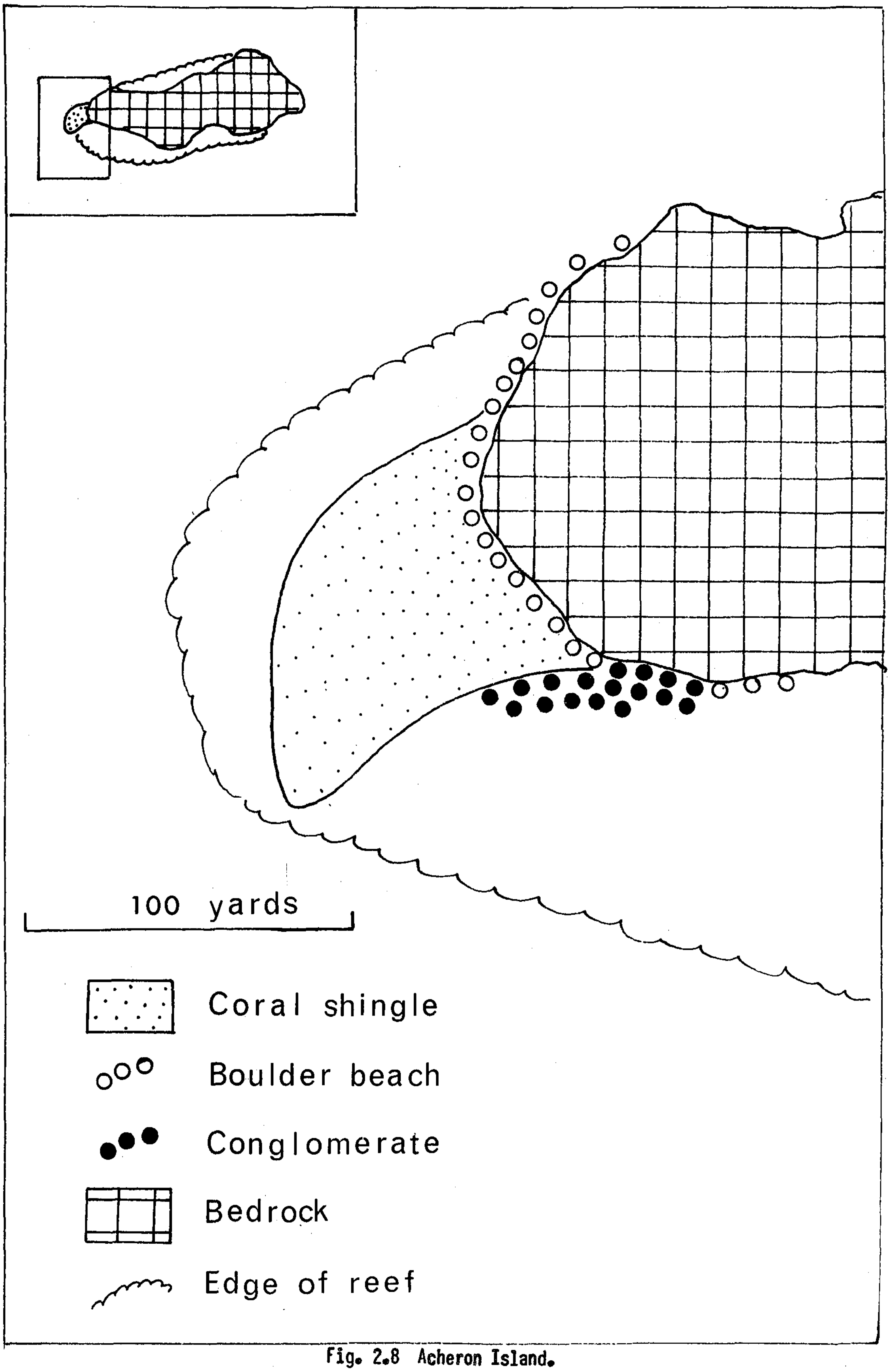


Fig. 2.8 Acheron Island.

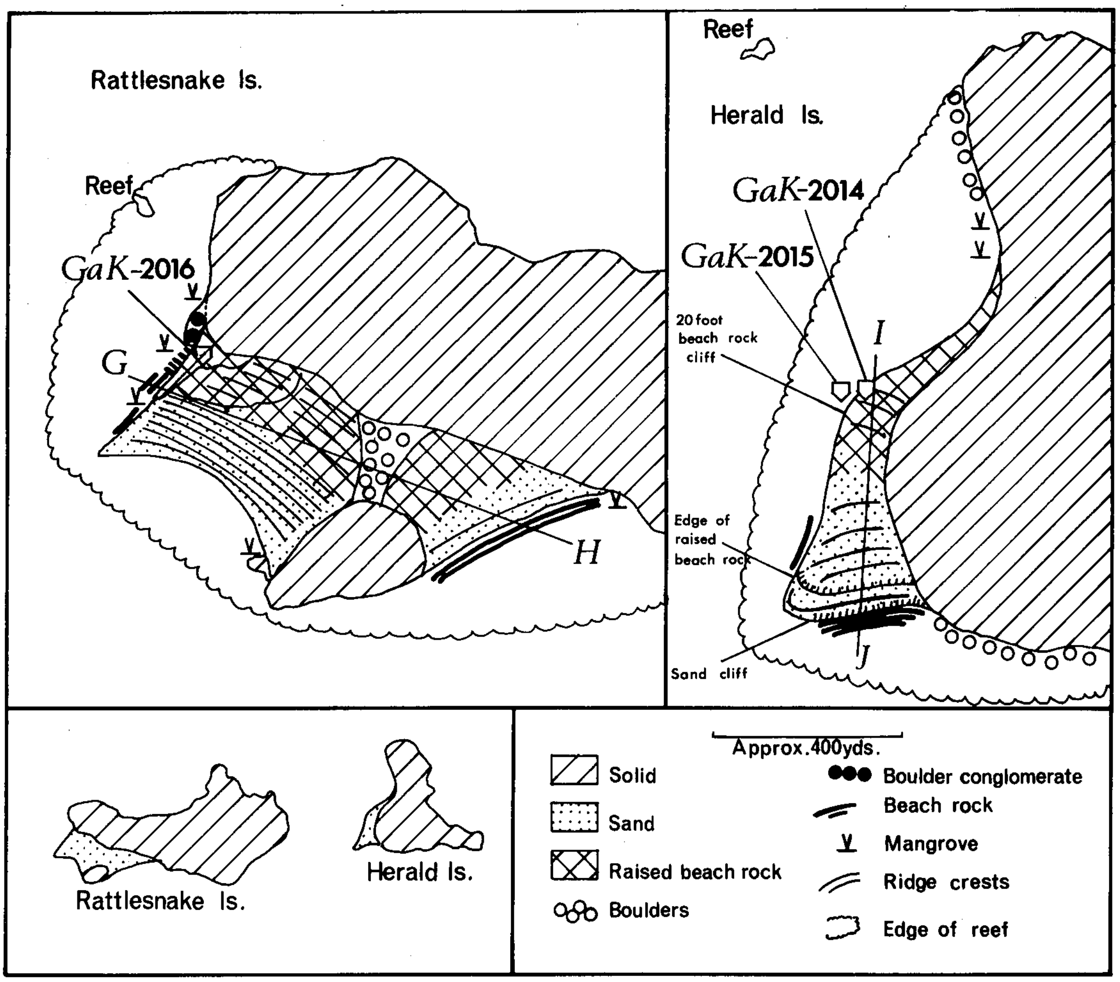


Fig. 2.9 Rattlesnake and Herald Islands.

is cemented to a rock platform with a mean height slightly above H.W.M. The outcrop of the raised beach rock on the beach nearer the point of the spit (Section G-H, fig. 2.10) is interesting. The beach rock rises to 10.7 feet in the section and the dip, towards the south-west, is consistent with the trend of the beach ridge within which it was formed. However, a lower ledge of beach rock occurs at 1.2 feet, with a dip towards the north-west. This is apparently the basal deposit of a beach which formed after the major erosional phase, but before the sea had attained its present level in relation to the land. The outer ridges of the spit are more in their original form and their surface is undulating and composed of fine coral sand. A small outcrop of beach rock nearer the apex of the spit outcrops between tide levels.

The evidence from Rattlesnake indicates the building of a spit from a beach ridge series during a fall of sea level relative to the land. A sample from the 10.7 feet section of raised beach rock gave the following radio-carbon assay:

GaK-2016 beach rock from Rattlesnake Island-
3240 years ± 100 B.P.

The age is younger than that given for the mid-Holocene transgression by the Curacoa and Eclipse Island samples, and the sample may have been slightly contaminated by material from the lower beach which has left the 1.2-foot beach rock, or by later cementation.

vi) Herald Island (fig. 2.9)

The spit on Herald Island is similar to that of Rattlesnake in that the original feature must have been much larger than the present remnant. The strike of the beach rock remaining from the early history of this spit suggests the original morphology to have been a cuspate foreland made up from a complex series of beach ridges. Like Rattlesnake, Herald has suffered greatest erosion on the north-western side and all that remains of the oldest ridges is a narrow platform of beach rock rising to 16 feet above M.H.W.S., though detached blocks of the material rise to 21 feet. The beach rock presents a steep cliff face to the sea. The material is again mostly coral sand, but containing boulders, shell (including Tridachna sp.) and coral blocks. Results of radio-carbon dating of samples from this deposit are:

GaK-2014 shell (Trochus sp.) from near top of outcrop - 4280 years ± 100 B.P.

GaK-2015 beach rock (coral debris) from base of outcrop - 3540 years ± 90 B.P.

The height to which cementation was found suggested that the deposit may been older than the lower beach rock plateau described so far. However, the morphology of the deposit suggests that the higher beach rock was originally at the rear of a wide beach ridge sequence. The water table at which the cementation took place may thus have been higher than actual sea level at that time. It would seem that proximity of the shore zone at all stages of cementation (as for example in the Curacoa boulder spit) is necessary if the cemented level is to have exact value as an indicator of past sea levels.

Further south along the spit, another outcrop of beach rock rises to 4.2 feet above M.H.W.S. This level is fairly widespread in the southern part of the spit and its southern margin is marked by a sharp break of slope. Against this is banked a sand beach ridge of recent origin. An erosional phase is indicated between the deposition of this ridge and the 4.2-foot beach rock. The sand ridge is, in turn, being eroded and is cliffed on its seaward side.

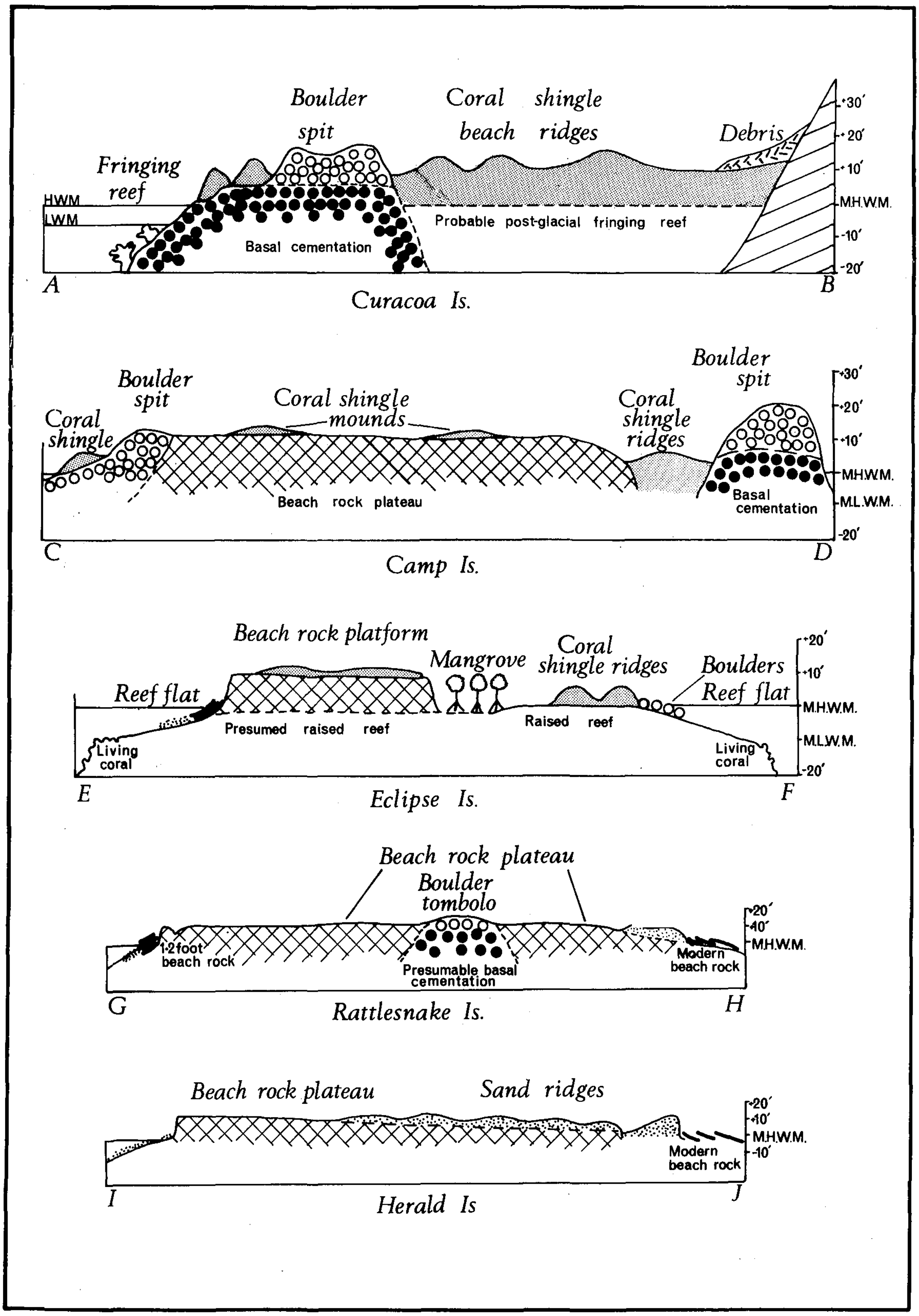


Fig. 2.10 Sections, across island spits.

An exposure of beach rock 30 yards wide and outcropping between tide levels, is found on the beach.

Camp Island, Abbot Bay (fig. 2.11)

Camp Island consists of basic plutonic rocks, mainly gabbro. It is about half a mile long and, because of wave refraction around Abbot Point, its spit extends from the south-western side. The exposed eastern side displays a series of well developed shore platforms.

A major part of the spit is made up of a plateau of beach rock consisting of extremely weathered coral fragments in a calcareous sandy matrix. The surface is flat, apart from a few low mounds of uncemented coral shingle, and averages 15.2 feet above M.H.W.S. Two boulder spits are embanked against the beach rock. The one to the south rises to 23 feet above M.H.W.S., with the lower 6.7 feet cemented. Boulders are large, ranging up to 3 feet in diameter, and are poorly sorted. The northern boulder spit is similar where it is banked against the beach rock plateau. However, several coral shingle ridges are banked against the spit and conceal any evidence of basal cementation. Beyond the plateau the spit has been extended, in a sinuous fashion across the reef flat. This appears to be a later addition, and the indications are that it has resulted from reworking of the older feature. Part of this addition has been buried beneath small irregular dunes 10 feet high, the parabolas of which are orientated to the south-east. Coral shingle embankments fill in the embayment between the end of the southern boulder spit and the beach rock plateau. Mangroves are found in the small bay to the south.

The Camp Island spit has similarities to that on Curacoa. The levels of cementation are almost identical and the evidence suggests that the Camp Island boulder spits are

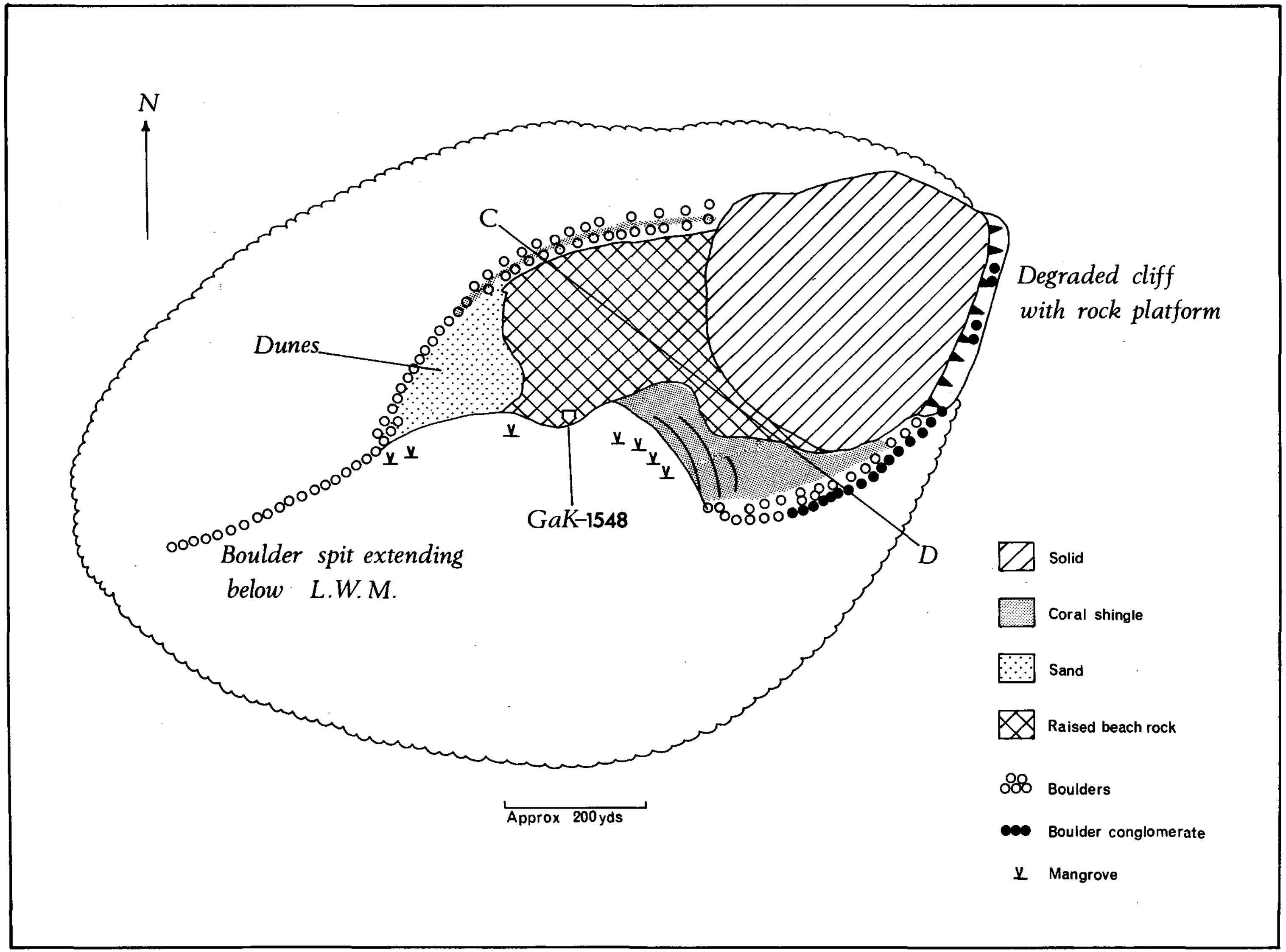


Fig. 2.11 Camp Island.

also of mid-Holocene age. Infilling of the embayment with coral shingle, extension of the boulder spits by resorting and building of the dunes are of a later date. The main difference between Curacoa and Camp Islands is the presence of an older element on Camp Island, namely the beach rock plateau. Again, a sample was taken for radiometric dating:

GaK-1548 coral fragments from near top of beach rock plateau - 20,200 years ± 600 B.P.

Contamination from the present calcareous environment is probable and the date can be regarded as minimal only. The beach rock plateau appears to be the remnant of a spit developed during a late Pleistocene interglacial or interstadial phase.

The shore platforms on the eastern side of Camp Island are better developed than on any other island examined in the southern part of the research area. These platforms were surveyed along a 150-yard section using a "Quickset" level and staff. Two levels were clearly identifiable at corrected heights of -0.3 feet (range +0.6 to -1.2 feet) and +7.4 feet (range 7.1 to 7.7 feet). An intermediate level at about 3.7 feet may also be present. The -0.3-foot level is definitely above the present zone of abrasion. It also has resting upon it the remnants of a conglomerate which may be correlated with the major boulder spit. If this is so then the lower platform is most likely of mid-Holocene age. The much more fragmentary higher level may thus be equated with the late Pleistocene beach rock. A degraded cliff is found behind the platforms. Current abrasive activity is largely limited to a level only a little above low water mark (6.5 feet below M.H.W.S. approx.).

IX Rattlesnake Island. Magnetic Island in distance.

X Camp Island.

Morphological Features of the Islands of the Wetter Northern Zone

The islands of the wetter zone north of Hinchinbrook are generally small and display contrasting features to the islands further south. These include the nature of beach material discussed earlier in this chapter and the covering with rainforest of coastal slopes right down to the foreshore which will be discussed in Chapter 9.

Again, many of the islands have leeside spits, their most interesting geomorphological feature. However, the spits of the northern islands contrast with those to the south. The most noticeable feature of these islands is the much more regular shape of the spits. Though still found predominantly on the north-western sides of the islands, the spits are outlined by long smooth beach curves in contrast to the irregular shapes of the spits on the more southerly islands such as Eclipse, Herald or Camp. The main reason for this is the lack of a core of solid raised beach rock which can maintain former orientations of the spits. Beach rock occurs on the northern islands, but only rarely above M.H.W.S. It has already been noted that, on the wetter mainland coast north of Ingham, the calcareous content of the beach sand has to be much higher to produce beach rock than it need be on the coast to the south owing to the rapidity of leaching (Bird and Hopley, 1969). On the islands, the beach deposits are sufficiently calcareous to produce beach rock, but the weathering of raised beach rock above the carbonate accumulation zone is so severe that the calcareous cement is leached to lower levels. The result is that the majority of spits in the wetter zone are composed of fine, coral sand with more recent additions of coral shingle. The refracted south-easterly waves can more easily shift this unconsolidated material to form the simpler spit morphology. Older elements on these spits are difficult to define though areas of deep soil profiles can be identified on the spits of islands such as Dunk.

Further contrasts are seen in the larger number of islands completely lacking spits and in the nature of the terrigenous deposits. In the drier zone the only islands without spits are small and rise steeply from the sea floor. Fringing reefs invariably are not present. In the wetter zone reefs may be present, but the only indication of spit development is a slight widening of the beach at the appropriate point. Another contributing factor is the rapid leaching of biogenic material and the finer nature of the terrigenous deposits as discussed above, which allows for their more immediate removal from the reef flat and into deeper water. Apart from massive blocks released by undercutting, coarser material is completely lacking and boulder spits are not known in the wetter zone. This again means that a more permanent element is missing, and is a contributory factor to the uniformity of the spits of the islands north of Hinchinbrook.

i) <u>The North Barnard Islands</u> (fig. 2.12)

The North Barnard Islands are a simple continuation of the Moresby Range and consist similarly of Barnard Metamorphics, highly altered schists and gneiss of probable Middle Palaeozoic age (Jones and Jones, 1956; de Keyser, 1964). They are steeply cliffed, and a wide and continuous platform exists at the cliff base, best developed on the eastern sides of Lindquist and Jesse Islands and around the whole of Kent Island. The platform, which has a width of 15 yards, has been described by Hedley (1925) and by Steers (1929, p.345). It rises to about 7 feet above M.H.W.S.

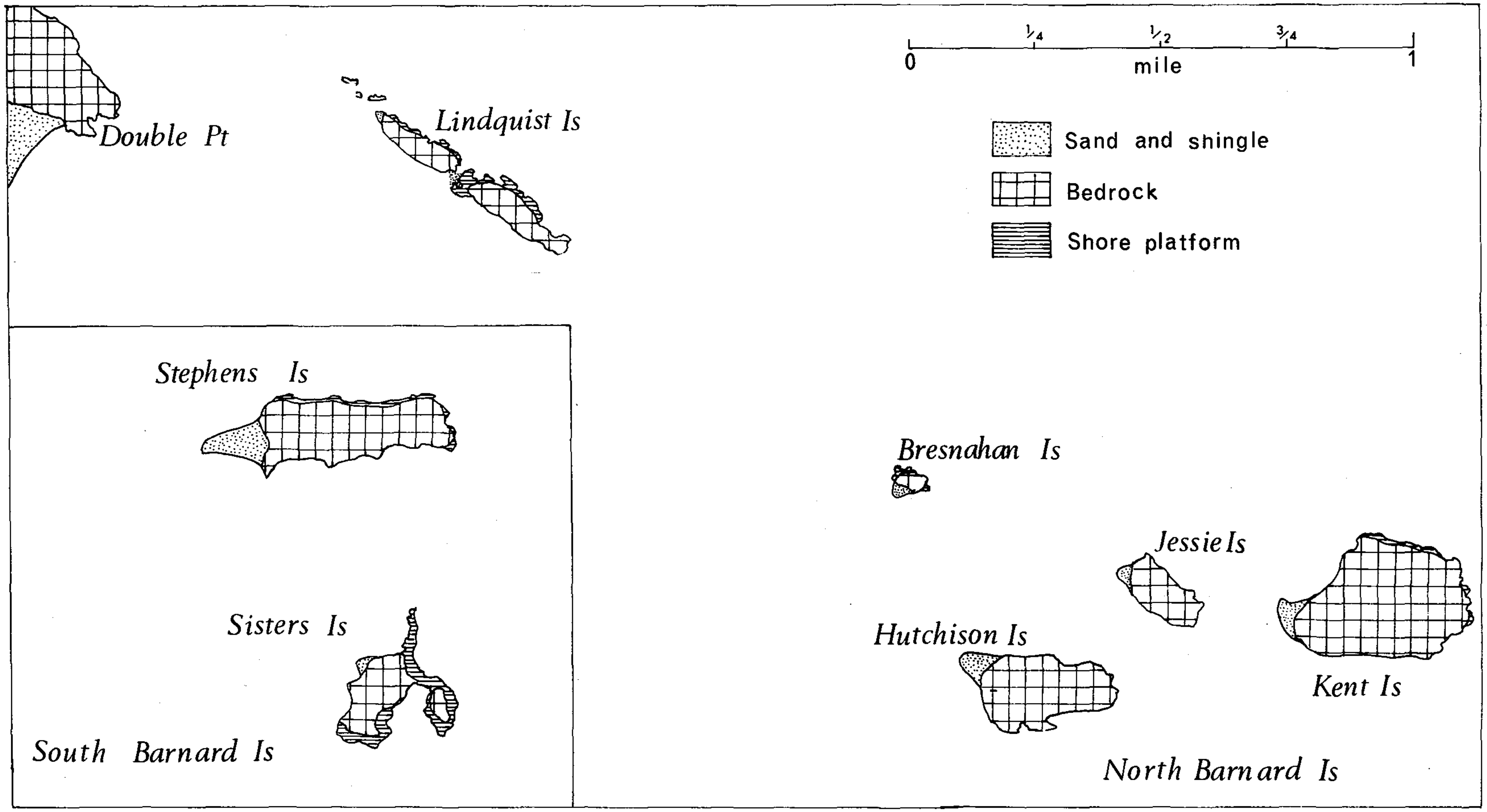


Fig. 2.12 Barnard Islands.

Small spits, consisting largely of coral shingle and sand, are found on the northern end of each island. They are simple features, without cementation and without evidence for higher sea levels.

ii) The South Barnard Islands (fig. 2.12)

Stephens and Sisters Islands consist of Cainozoic basalt and agglomerate. Both have wide platforms developed around the base of the cliffs. Again, the platform has been described by Steers (1929, p.345) who remarked on its fresh appearance and on the steepness of the cliffs behind. This bench is lower than that on the North Barnards, occurring at or slightly above the high tide level. However, it appears to be beyond the range of current bench-forming processes. Both islands have spits on their western sides, that on Stephens Island being larger and very typical of the wetter north. It is symmetrical, composed of sand (mostly biogenic) and well vegetated, but displays no signs of older portions belonging to sea levels different from the present.

iii) Dunk Island (fig. 2.13)

Dunk Island is about 3 miles long, rises to 789 feet and has the largest spit of the islands in the area surveyed, attached to its western side. The western part of the island is made up of Barron River Metamorphics (Palaeozoic slate and phyllites) whilst the eastern part is granitic. However, the whole of the higher part of the island is clothed in rainforest which descends to the shore level. No distinct platforms are observable.

The spit is a remarkable feature, very symmetrical, almost a mile long and obviously shaped in its latest episode by the refracted swells coming around the main part of the island. It has appeared in the literature earlier

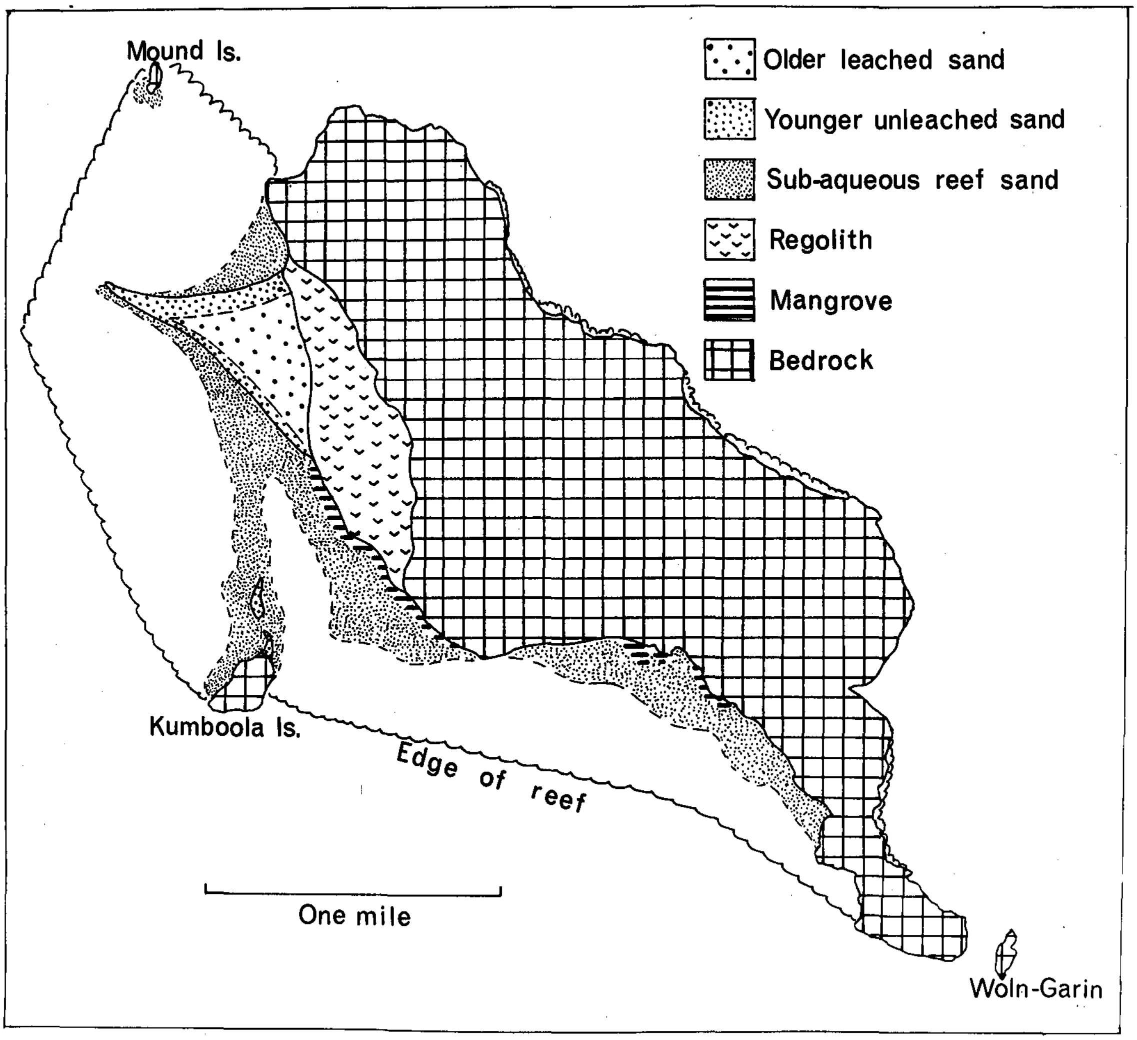


Fig. 2.13 Dunk Island.

(Andrews, 1902; Steers, 1929). Andrews examined a section close to the high part of the island and observing angular fragments and a clayey matrix, concluded that the whole spit was similar and "doubtless due to redistribution by long-shore action of matter lost to the island by marine erosion". Steers (p.342) attributed the feature to wave and current action. Neither author had opportunity to analyse the spit in detail and the present writer has examined it only on three brief visits to the island. However, it is evident that the feature is complex, for whilst the western end is made up of fresh unleached sand of biogenic and terrigenous origin in the form of lightly vegetated (mainly <u>Casuarina sp.</u>) beach ridges, the central part of the spit, rising to over 20 feet, is quite different. It consists of white leached quartz sand and lithic grains apparently overlying a humic hardpan of coffee rock and covered in rainforest. On the adjacent mainland, identical deposits have already been attributed to the late Pleistocene (Bird and Hopley, 1969) (see Chapter 8). Regolith from the slopes of the high island has slumped on top of the basal portion of the spit.

If the core of the spit is late Pleistocene, and the outer edges at the western end and northern side are Holocene, the question arises of the occurrence of deposits belonging to the mid-Holocene higher sea level as found on other islands further south. There are, however, no deposits which can be attributed to this episode. It may exist in the older Holocene ridges, but from their fresh appearance this seems unlikely. It appears that the spit is constantly being eroded and rebuilt. The southern side at present is undergoing retreat, into the Pleistocene deposits. Without the stabilising influence of beach rock, and the beach sands have far too low a carbonate content to allow this in the wet climate, the spit is open to rapid remodelling and it is likely that any mid-Holocene deposits have been removed. The original Pleistocene spit appears to have been extremely large and possibly orientated farther south than the present one. Certainly the large size of the feature today owes much to the unusual preservation of a large part of the older spit.

iv) The Family Islands (fig. 2.14)

The Family Islands are a small group of granitic knolls rising sharply out of the sea. Cliffing and benching has not occurred. All the islands display small sand spits of recent origin on their north-western sides.

v) Gould and Garden Islands (fig. 2.14)

These two islands are also granitic, though Gould has a small area of a more basic intrusive rock on its south-western side. Both have spits on their western sides, the one on Gould being about 200 yards long. It is wooded and though no exposures are visible, it is suspected that this spit may have an older core similar to that on Dunk. Inter-tidal beach rock occurs around the apex of the spit.

vi) Brook Islands (fig. 2.14)

The Brook Islands appear to be drowned granitic tors. The larger islands of the group have exfoliation domes, whilst all display block disintegration along the joints. Boulder beaches are found around most of the islands, but are especially well developed around South Island. Middle Island comprises two granitic domes, joined together by a sand spit. Each of the islands has a small spit or widening of the beach on its northern end, the one on North Island being the largest. It is also the only one with beach rock.

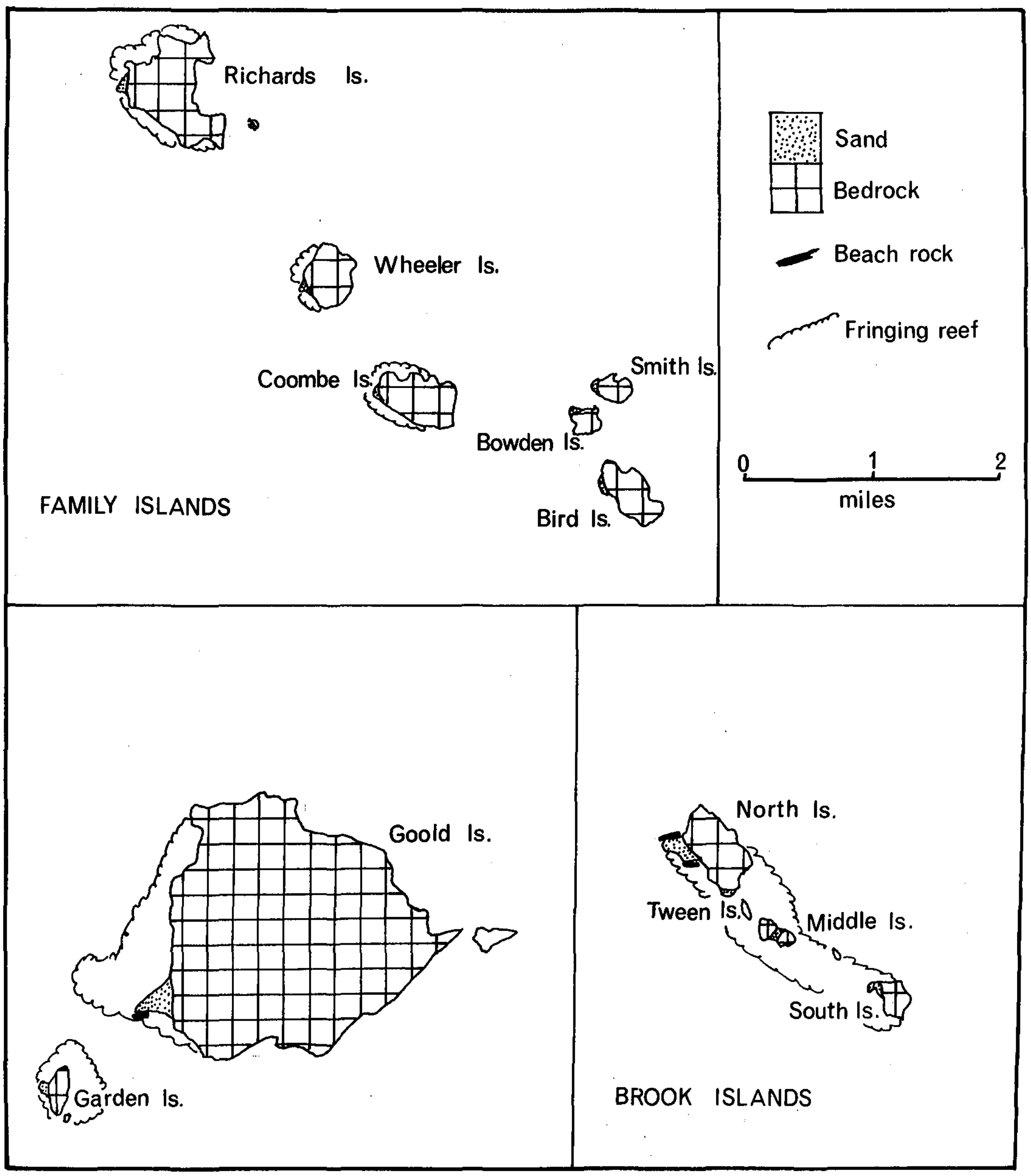


Fig. 2.14 Islands of Rockingham Bay.

XI Camp Island. Elliot River estuary on mainland.

XII Gould Island spit.

XIII Garden Island spit. Hinchinbrook Island to rear.

XIV Brook Islands. Family Islands and Dunk in distance.

Discussion and Conclusions

Evidence from the high islands sheds strong light on the late Pleistocene and Holocene evolution of the North Queensland coastline. Although the significance of these findings at both the regional and larger levels will be discussed in later chapters it is appropriate here to discuss the evidence at the local level and to summarize the conclusions.

There is much evidence that many of the island spits were at least initiated at a time when the sea stood higher in relation to the land than it does at present. Much of the evidence comes from the raised beach rock and the question arises as to the legitimacy of using water table cementation horizons as indicators of past sea levels. Russell (1967, p.137) has pointed out the dangers of relating beach rock elevation to past sea levels in areas of rapid shoreline retreat, and there are many indications of changes of spit orientation combined with erosion. Thus there are cases where the level of the beach rock surface is a doubtful indicator of the sea level at the time of formation. Herald Island is an excellent example. The high beach rock cliff has resulted from extensive erosion and the beach rock surface slopes gently down from the 16-foot level. The large size of the original spit possibly allowed a gradient to develop in the water table. Generally, however, the spits have been sufficiently small and of sufficiently coarse material to allow cementation to take place only very close to the high tide level. Beach rock provides good evidence of former sea levels where it outcrops at a constant level, and where the original morphology of the spit can be reconstructed so that it can be seen that at no stage was the beach rock sufficiently far from the sea to permit the building up of a significant water table gradient. The majority of outcrops on the spits described conform to these conditions.

The beach rock therefore indicates relatively higher sea levels. The evidence from Camp Island strongly indicates a late Pleistocene interglacial of interstadial level of approximately 15 feet. Other islands possibly contain remnants of Pleistocene spits, but the core areas of most are overgrown, often with rainforest, and the Pleistocene level is not sufficiently distinct from the maximum level of the mid-Holocene transgression to make it easily distinguishable. Steers (1929, p.346; 1937, p.21) describes and discusses two levels of beach rock cementation on Middle Island near Bowen. The higher of these corresponds well with the Camp Island example.

The mid-Holocene level is better documented. Levels of raised beach rock vary, but the more reliable examples are all within the range 6 to 11 feet. The lower levels around 6 feet come from the boulder spits and cementation is suspected slightly higher than this in the centre of these features. The evidence suggests that the mid-Holocene level in North Queensland was around 10 feet above the present. The absolute age for the attainment of this height would appear to be about 4,000 to 5,000 years B.P. The radiometric dates are considered minimal only, owing to the high risk of contamination from younger carbon in the highly calcareous environment. The evidence from Curacoa, where conglomerate is found down to at least 25 feet below M.H.W.S., indicates the rising sea level of the early Holocene.

Other evidence of higher Holocene sea levels is available. Raised reefs occur at or just above M.H.W.S. on a number of the islands under discussion (fig. 2.1).

The height relationship to the postulated mid-Holocene sea level is similar to that of living corals to present H.W.M.

Shore platforms are generally not well developed. There are a number of reasons for this, some of which have already been outlined (Driscoll and Hopley, 1968). They include:

i) the limiting of the local fetch by the Great Barrier Reefs, which largely exclude the long Pacific swells and limit wave action to the wind waves generated within the lagoon;

ii) the lithology of the rocks of the islands, and of the mainland, is not, in general, favourable to any of the processes operating to form shore platforms. The granites and volcanic rocks are especially resistant;

iii) the presence of a protective ramp of boulders around the shores of many islands. These boulder beaches appear stable at present.

For the most part, the platforms are fragmentary, poorly developed and limited to exposed headlands. However, the islands of the wetter zone in general have wider and more extensive platforms. This may be due in part to more susceptible rock types, but the presence of a bench completely around some of the Barnard Islands even in the most sheltered locations suggests that preparation of the rock by subaerial weathering prior to littoral processes may be very effective.

The presence of two clearly defined bench levels on the islands, the one at or just above M.H.W.S., the other at about 7 feet higher, agrees well with the earlier findings of Steers along the whole of the Queensland coast, (Steers, 1929, p.343-50; p.16-25). The upper platform is clearly elevated beyond the range of modern processes. The lower platform does, however, become submerged by extreme high tides, and Steers felt it necessary to prove the authenticity of the feature as evidence for emergence. (Steers, 1937, p.20-21). His evidence included an argument for the zone of maximum cutting being below mean water-level, the weathering of the inner edge of the platform and presence of a stable vegetated cliff behind it and the colonisation of the platform in some places by mangroves, which is hardly likely to happen if erosion were active.

The evidence presented in this chapter is also strongly suggestive that the lower platform just above M.H.W.S. is an emerged feature. In a number of localities conglomerate rests upon the platform and it will be argued that the majority of conglomerates are mid-Holocene in age. Thus at Wallaby Point on Great Palm Island, on Fly Island and on Acheron Island the base of the conglomerate, where it is cemented to the platform, is above the maximum level at which cementation is taking place today. This would appear to be conclusive evidence of the antiquity of the platform. It is at least mid-Holocene (approximately 4,000 years B.P.) in age. Cementation can take place rapidly (see Chapter 6) and there is nothing to prevent cementation of deposits to an erosional platform during possibly a period of fewer storms when the abrasive tools of the platform could become sufficiently stabilised.

Closely associated with the fluctuating Holocene sea levels is the varying nature of beach material on the spits. This will be discussed at greater length in Chapter 6, but the main details may be put forward here. The older beach deposits of mid-Holocene age contain much more terrigenous material than the present beaches. The Curacoa spit is an excellent example. The maximum of the transgression is marked by a boulder spit, whilst the regression from this level has resulted in a complete change in beach material, the later ridges consisting almost exclusively of coral shingle. Similarly, the oldest section of the Havannah Island spit is a boulder conglomerate, whilst the boulder spits are the oldest Holocene deposits on Camp Island and the core of the Brisk Island spit is a boulder embankment. Even where the older raised beach rocks are predominantly of biogenic material, as on Eclipse Island, it is generally true to say that they contain more terrigenous material than their modern counterparts. The tropical environment allowed a deeply weathered slope mantle to develop during the late Pleistocene low sea level. The rising Holocene sea has been able to rework these deposits and incorporate them in the spits, exposing the underlying weathering front which today forms the island cliffs unaltered in all but the most exposed positions. The boulder spits are the reworked core-stones from the regolith. The boulder ramparts around the islands though uncemented are apparently of the same origin. The best evidence for this comes from Havannah Island (fig. 2.7) where the boulder rampart passes beneath the bulk of the spit. On the northern islands of the wetter zone, where weathering was more complete and coupled with a different geology, the production of core-stones and thus of boulder ramparts, has been less common.

The regression phase from the higher Holocene sea level has exposed the fringing reefs. These have presumably been truncated by the sea not only to form the higher parts of the modern reef flats, but also to provide material for the rapid formation of beach ridges built predominantly of coral shingle or sand.

The features of the spits possibly indicate former climatic conditions. The older beach rocks preserve the original orientation which in many cases differs from that of present day growth. These changes are not consistent for all spits and, because of the changing nature of the beach materials, and of the great refraction of the waves which form the spits, it is difficult to determine accurately the exact changes involved. However, the pattern of extension of the fringing reefs during the Holocene and the effects this could have had on wave refraction, may be a factor influencing spit orientations. What is more certain is that wave activity was stronger at the time of formation of the boulder spits. These rise up to 15 feet above the postulated M.H.W.S. at time of formation. The modern equivalents, largely reworked material from the mid-Holocene boulder beaches and of smaller calibre, rarely rise above modern high water mark. Whether this is the result of greater wind strength generally, to greater cyclone activity in the summer season, or even to greater exposure to Pacific Ocean swells as the result of less protection from the Great Barrier Reefs, cannot be determined.

Summary

1. There is a strong contrast between the islands of the wetter north and those of the southern part of the study area. This is a result of both climatic and lithological contrasts.

2. The complex spits, resulting from leeside deposition on fringing reef flats, indicate significant phases in the evolution of the islands. Modern growth of these spits is continuing but the earlier portions are of mid-Holocene or even late Pleistocene age.

3. Cementation of the beach deposits has been essential in the preservation of the older elements, and indicates higher water tables and thus higher sea levels at the time of formation of portions of the spits.

4. Less favourable conditions for the formation and preservation of cemented beach deposits in the more humid sector of the North Queensland coast, combined with different lithology, has resulted in northern spits being more uniform in morphology and materials.

5. Emerged shore platforms are associated with the higher sea levels shown by cemented beach deposits.

6. Other late Quaternary environmental changes are indicated by features of weathering and coastal morphology, notably in climate and the nature of beach materials.

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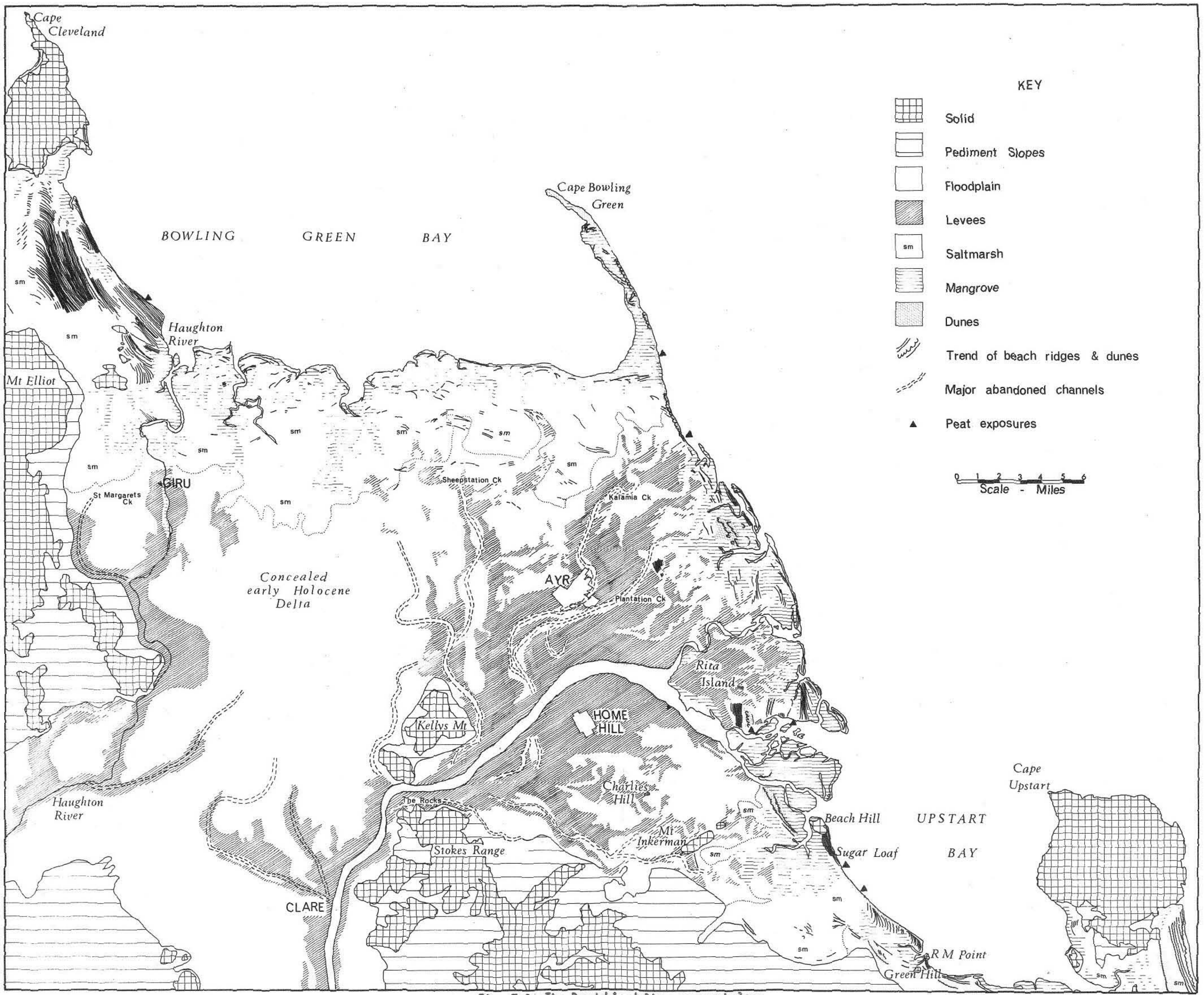

Fig. 3.1 The Burdekin delta, geomorphology.

CHAPTER 3

THE BURDEKIN DELTA REGION

The southern-most area on the mainland covered by the research programme comprised the coastline between Cape Upstart and Cape Cleveland, an area in which the coastal landforms are influenced by the distributaries of the Burdekin River (fig. 3.1). The Burdekin basin has an area of 50,618 square miles and is Australia's second largest drainage basin east of the main divide, the area being exceeded only by the Fitzroy River of Central Queensland (54,075 square miles). Conditions in the basin are ideal for a rapid sediment yield. Rainfall in the basin varies between 20 inches and 35 inches per year, a mean figure being approximately 25 inches, and with the high evaporation rates[1] and seasonality of the rainfall, conditions are thought to be close to the ideal for maximum sediment yield (Leopold, Wolman and Miller, 1964, p.48). The presence of moderate relief in the catchment, accumulation of unconsolidated weathered deposits since the Tertiary period, and the passage of the river over the Burdekin Falls at the edge of the Tertiary erosion surface only 80 river miles from the coast, all encourage a rapid supply of sediment. Thus the 200 square mile delta is the largest cuspate delta in

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1. At Mareeba, on the Atherton Tableland, north of the Burdekin Basin, the average recorded evaporation rate is 52.28 inches. Climatic conditions here are comparable to those over most of the Burdekin catchment area. (Hounam, 1961).

Australia. Deltaic deposits have a maximum recorded depth of 500 feet and it is estimated that the delta contains some 30,976 million cubic yards of sediment.

Considering the size and classic morphology of the delta, it has received surprisingly little attention. It was briefly and inaccurately described by Jardine (1928) and the geology of the area covered by the Ayr 1:250,000 map sheet is described by Paine, Gregory and Clarke (1966), though the unconsolidated deposits receive scant attention. In 1964 a team of geologists from the Coastal Studies Institute, Louisiana State University, examined the deltaic deposits but as yet no report of their findings has been published. The leader of the team, Dr. J.M. Coleman, kindly allowed the use of several C14 dates to be used by the present writer. Also during the early 1960's a geophysical survey of the delta was carried out and some tentative conclusions reached on the properties of the deposits (Wiebenga, et al 1964; Wiebenga et al 1966; Andrew and Wainwright, 1964). Methods used were entirely geophysical, based on measurements of seismic velocities, water resistivity and gravity anomalies. Some of the conclusions reached are questioned during the progress of this chapter. A C.S.I.R.O. Soil and Land-Use Report (Hubble and Thompson, 1953), maps and describes the soils of the lower Burdekin valley below Dalbeg. Although covering only the southern part of the delta, the report did prove to be a useful introduction to the contrasting alluvial deposits of the area.

In contrast to the lack of published material on the Burdekin delta, there is an abundance of unprocessed data available, largely in the form of reports of the Irrigation and Water Supply Commission of Queensland (1964a, b, 1965, 1967). Unpublished material and data has also been made available to the author through the Townsville and Brisbane offices of the Commission. The most useful material is the series of borehole logs from holes drilled by or for the Commission. Further results have been obtained from private drillers based on the delta towns of Ayr and Home Hill. The delta maintains 71,000 acres of sugar cane, irrigated largely from underground water supplies held in aquifers within the deltaic deposits. A rapid increase in acreage during the latter part of the 1950's, and a further increase following the allocation of new assignments in 1964, have apparently overstrained the aquifers and consequently are responsible for the rapid compilation of data by the I.W.S.C. during the last ten years.

The current survey has relied heavily on these drilling logs for its interpretation of the deltaic sedimentary pattern. Superficial deposits and the later history of the delta have been examined largely through a combination of field traverses and surveys, detailed inspection of the few sections exposed, a considerable amount of drilling with a hand auger and extensive use of aerial photographs.

The Solid Geology and General Physiography of the Delta Region

The geology of the delta region is outlined by Paine, Gregory and Clarke (1966). The delta and lower valley of the Burdekin occupy a basin open to the north-east and around which outcrop rocks of Palaeozoic age. These outcrops maintain the regional structural trend of north-north-west to south-south-east. The lower hills to the south of the delta and south of Mount Elliot are formed from a variety of Lower Palaeozoic rocks, including schists, phyllites and quartzite, roof pendants of early Palaeozoic low grade metasediments, which have been intruded and metamorphosed by by locally foliated granodiorite and diorite. Similar low rugged hill country is provided by late Palaeozoic volcanic and sedimentary rocks. The highest areas, including Mount Elliot (3,914 feet), Cape Cleveland (1,831 feet) and Cape Upstart (2,437 feet), comprise a series of plutonic intrusions of probably Upper Carboniferous age. These mountainous areas are generally granitic and display massive unloading features. Unvegetated exfoliation domes are typical. However, between Mount Inkerman and the southern side of the Upstart granite, occurs a series of smaller basic intrusions, mostly diorite and gabbro. These tend to weather into irregular rock outcrops with abundant screes of rounded boulders produced by differential chemical breakdown.

Major valleys in the larger intrusions tend to have common trends and have been interpreted as faults associated with cooling and settling within the masses. Two major faults occur in the region, the Woodhouse Fault south-west of the delta which extends to the north-west for 65 miles up the valley of the Reid River, and the Sugar Loaf Fault also with a north-north-west to south-south-east trend, along the coast south of the delta. Neither has much effect on the major physiography. However, probably the largest structural feature, the Inkerman Shear Zone, two miles wide and trending north-east to south-west, located just south of the delta, gives a linear trend to the topography which is across the general regional structure.

The Morphology of the Delta Basin - Bedrock Contours

The hills around the delta basin and the isolated outcrops of solid rock which protrude through the unconsolidated deposits are invariably surrounded by a pediment apron slope. These slopes are usually concave, with upper gradients of 5° to 8° easing to 1° at the lower end. The pediments are covered by sandy or gravelly deposits roughly graded downslope. The colluvial cover is generally thin and bare rock often protrudes through it. The pediments and their deposits appear to be inherited from earlier morphogenic environments. They are not actively accumulating at present and the intermittent streams which cross them are incising deeply into the bedrock. Both pediments and deposits appear to pass beneath the Holocene deltaic alluvials.

It is evident that the bedrock falls away quite steeply from the solid outcrops. Individual boreholes drilled by the Irrigation and Water Supply Commission have reached bedrock at varying depths down to 259 feet and seismic results have indicate depths down to 500 feet below the base of Cape Bowling Green. Bedrock contour maps of the delta have been previously constructed (Wiebenga _et al_, 1964, 1966). However, these maps were constructed from seismic depth probes and seismic traverses and bedrock was defined as rock with longitudinal seismic velocities equal to or greater than 6,700 feet per second. Quite apart from the errors which may result from the method itself, this definition of bedrock means that consolidated cemented and compacted sediments may appear as bedrock on the seismic plan. Also, weathered regolith lying directly upon bedrock provides problems of interpretation. Comparison of the seismic results with direct borehole logs indicates that the seismic method can give only a general idea of the depth of the solid rock, as anything up to a 10% error may be found. The detailed seismic maps (1964, 1966) are thus of limited value, and this value has been decreased by the drawing of contours from the spot heights obtained in a very questionable fashion and without regard for normal morphology.

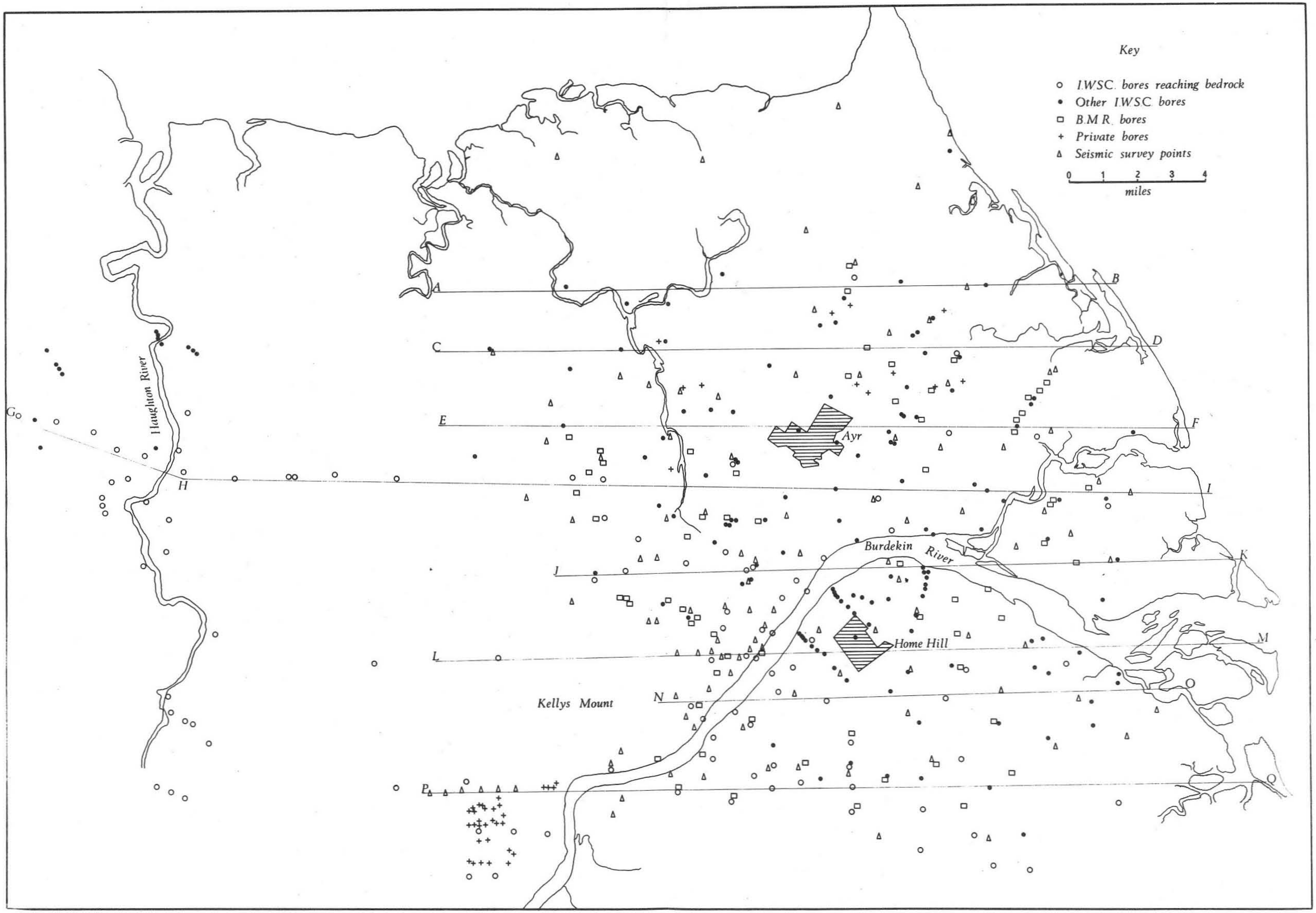


Fig. 3.2 Information points in the Burdekin delta.

Such interpretation was hampered by the scarcity of borehole data as the I.W.S.C. programme was contemporaneous with the geophysical survey and results were not readily to hand. However, in the present survey all available information, from several sources, has been compiled together to produce the bedrock contour plan of figure 3.3. Figure 3.2 shows the sources of information used for both this map and the interpretation of the deltaic deposits. The sources of points of information are as follows:

Irrigation and Water Supply Commission boreholes reaching bedrock: 100

Irrigation and Water Supply Commission boreholes not reaching bedrock: 145

Bureau of Mineral Resources boreholes: 64

Boreholes drilled by private contractors: 42

Seismic depth probes: 102

Total: 453

Greatest reliability has been put on the borehole records of the I.W.S.C. and B.M.R. Logs of boreholes drilled by private contractors without I.W.S.C. supervision are sometimes questionable, though their greatest inconsistency is in the interpretation of deposits rather than in the recording of depths. Lowest reliability has been put on the seismic results. In figure 3.3 all heights have been corrected to State Datum.

The distribution of information points on figure 3.2 also gives an indication of the reliability of figure 3.3. Greatest reliability can be given to the areas of sugar cane, namely the core of the eastern part of the delta around Ayr and Home Hill, and around the lower Haughton. It is unfortunate that the zone within about three miles of the coast has been too saline for agriculture and has therefore had scant attention in past surveys. The same can be said

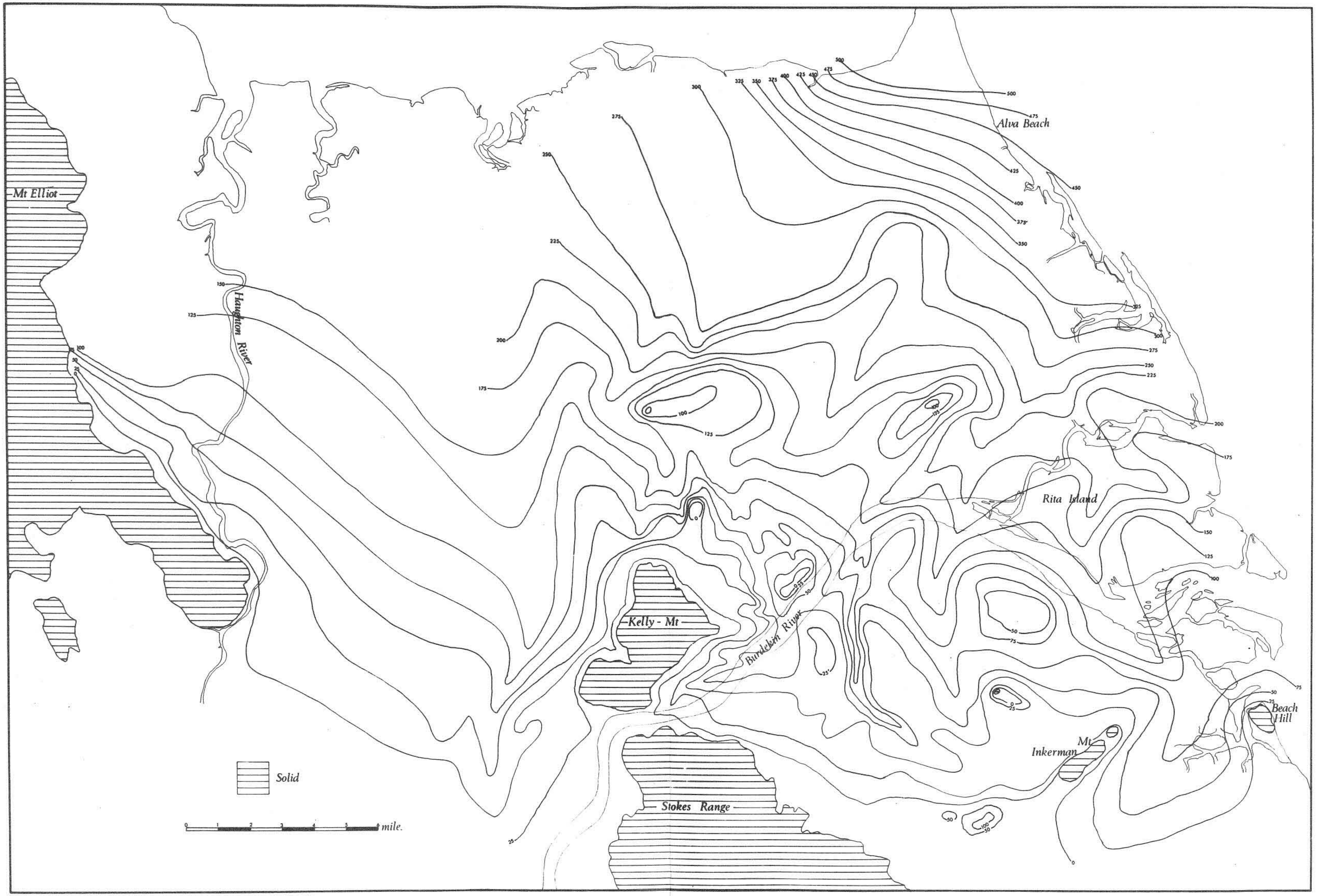


Fig. 3.3 Burdekin delta, bedrock contours.

for the country between the Burdekin and the Haughton in the area of the Barrattas Creeks where surface deposits consist of heavy clays. This appears to be a critical area for the understanding of the evolution of the delta.

Figure 3.3 is considered to be a reasonably reliable depiction of the bedrock morphology. It indicates that, as expected the pediments do extend beneath the deltaic alluvials. This is particularly noticeable to the north and east of Kelly's Mount and beyond the foot of the Stokes Range, where the low gradient slope extends two or three miles to incorporate the isolated hills of Mount Inkerman and Charlies Hill, both of which have the appearance of residual inselbergs. The gently sloping pediments do not extend much below -25 feet. Below this level the slopes drop away more sharply and are also more extensively incised. Comparison with the late Pleistocene surface of figure 3.4 (see below) suggests that the pediment is graded to this alluvial surface. Incision by smaller streams during the subsequent (Last Glacial) low sea level phase has isolated parts of the pediment apron, especially between Kelly's Mount and Mount Inkerman. The relationship of pediment to the late Pleistocene surface will be discussed in greater detail later in this chapter.

The general inclination of both pediments and the lower bedrock slopes is towards the north and north-east. Although information points are scarcest around the periphery of the delta and those which exist are least reliable, it does seem that bedrock is as deep as 500 feet at the base of Cape Bowling Green. Again, though information is scanty it appears that the bedrock drops away quite sharply below 300 feet and that below this level dissection is neglible. This is to be expected, since it is generally agreed that Pleistocene lowest sea levels were around -100 metres or

330 feet (e.g. Fairbridge, 1961, Flemming, 1968). It is evident that erosion gullies in the bedrock of the Burdekin Delta are cut down to this level.

Possibly the most remarkable feature of the bedrock morphology is the presence of a rock bar joining the Stokes Range and Kelly's Mount directly across the present course of the Burdekin. This col does not pass below current sea level and in fact, bedrock outcrops in the bed of the river, at The Rocks. It is quite evident that, with the incision of the Burdekin into the alluvial deposits at the start of any low sea level phase, the present course to the eastern part of the delta could not be maintained during any of the glacial periods of the Pleistocene. The river would be directed to the north along the western side of Kelly's Mount and into Bowling Green Bay. Bedrock contours support this theory, for a significant channel is indicated in this area. It is suspected by the present author that the underground water supply problems of the Ayr and Home Hill areas, in the form of rapid depletion of the freshwater supplies and subsequent saltwater intrusion, are closely associated with the rock bar, which diverts a high proportion of underground water directly into Bowling Green Bay. The unfortunate poverty of soils in this area means that the bulk of the underground supply cannot be exploited.

In the area of the Haughton River, there is nothing in the bedrock contours to suggest that the river maintained a seperate lower course during the low sea level phases. It would seem likely that the Haughton joined the Burdekin as a left bank tributary at about Clare, thus maintaining its west to east course south of Mount Elliot. The steep slopes of Mount Elliot are clearly maintained beneath the alluvial deposits.

Figure 3.3 indicates probable drainage lines during low sea level periods. It is not envisaged that all these were in operation during any one glacial. In fact the present bedrock morphology is a composite feature produced during all the Pleistocene eustatic low stands. Incision during one of these stillstands did not necessarily mean that the same channel would be open during the next low level stand as it may well have been buried during the aggradation phase of the intervening interglacial or interstadial. However, the strong development of a number of channels does suggest that they are the result of a number of periods of incision rather than of a single one. The best developed channel is obviously the one which carried the bulk of Burdekin waters during the glacial periods. It is quite sharply incised with an average gradient of about 15 feet per mile, though reaching 30 feet per mile immediately north of Clare. This appears to be a major nick point and it is evident that the channel would have still been actively eroding until the start of the latest aggradation phase.

Another major channel, almost gorge-like in appearance leads from the Kelly's Mount - Stokes Range col. It appears to have been the major drainage system of the eastern part of the delta. It has a number of right bank tributaries, equally deeply incised into the pediment on the north-eastern front of the Stokes Range. The headwaters of these streams today form the open gullies which drain this part of the range. They maintain a northerly course across the pediment but are diverted eastwards along abandoned Holocene channels once they emerge onto the alluvial deposits.

The presence of a major Burdekin channel into Bowling Green Bay, and of streams with only limited catchments in the eastern part of the delta, conflicts with the findings of Maxwell (1968, fig. 22C, p.52). He indicates the major channel as a continuation across the continental shelf of the present river course, with only minor drainage entering Bowling Green Bay. Such a drainage pattern appears impossible in view of the bedrock configuration described.

The Pleistocene Deltaic Deposits

A great variety of alluvial deposits has been encountered in the boreholes so far drilled in the delta, ranging from clays to large boulders. Great and rapid fluctuations in the sedimentary environments are recorded by variations in single bores. Horizontal correlation even between adjacent boreholes only a hundred yards apart is extremely difficult. The variety and mixture of deposits is the result of several factors:

i) the close relationship between littoral, marine and fluvial environments

ii) the variety in energy environments which exist in a delta at any one time, from the higher energy situations of major channels and windward shores to the minimum energy of back-swamps and mangroves

iii) the rapid changes in distributary patterns which can occur in a delta, especially during aggradation and which can reverse the energy environment pattern

iv) changes in sedimentary patterns as the result of the relative levels of land and sea

v) changes in the position of the coast as the result either of eustatic changes in sea level and/or of aggradation

vi) changes in deposits after they have been laid down owing to compaction and weathering.

The overall result is a sedimentary record which is extremely difficult to interpret on a three dimensional scale. Fluvial, littoral and marine deposits are inter-digitated in an extremely complex pattern. However, close analysis does indicate a number of features which are worthy of mention.

Immediately overlying the bedrock is a regolith of weathered and decomposed material varying in thickness from several inches to 35 feet. No clear pattern of depth of weathering exists as the original regolith appears to have been removed from many areas. Thus many logs record the deltaic deposits resting directly on unweathered rock, generally granite.

Other weathering horizons exist in the deposits though they are not always easy to identify, owing both to the condition of the horizon itself and to confusing description by the logger. At best, a weathered horizon may be described as "compact red oxidised or ferruginized clay". Elsewhere such a horizon may merely be described as "clayey sand and gravel". It is not uncommon to find several such horizons in any one borehole, indicating deposition, probably during the transgression of an interglacial/interstadial period, weathering during a subsequent low stand of the sea followed by further aggradation and weathering. However, few records indicate more than one such episode and it is clear that periods of erosion, producing unconformities in the sediments, almost certainly occurred.

Thus with one exception, it has not been possible to correlate such weathering surfaces across the delta. The exception is a level almost intact, and occurring fairly close to the present surface. It is overlain by deposits in which weathering is at a minimum, generally uncompacted and apparently of Holocene age. Although no dates are available from the base of these overlying sediments it is clear that they belong to the latest transgression and associated aggradation. The weathered surface is thus considered to be late Pleistocene in age, probably last interglacial. This surface has previously been identified, though not mapped, in the Haughton River area (I.W.S.C. 1967, Ground water Investigations, Haughton River, Appendix A). Here it commonly occurs as a distinctive spotty red clay or clayey gravel 12 to 20 feet below the present surface. The material sets hard on exposure to the atmosphere. Samples recovered from boring in the same area have been deeply oxidised and have the appearance of laterite. They have certainly been through a deep weathering sequence in a warm humid climate.

The search for similar deposits beyond the limits of the Haughton delta did not prove successful except in the area between Clare and Kelly's Mount where red oxidised clays again occur close to the surface. However, the projection of the surface from where it was clearly identifiable into adjacent areas where it was more obscure, led to the conclusion that the uppermost level where a mixture of deposits was described in borehole logs, was the same surface. Thus descriptions such as "claybound sand and gravel", "sandy clay", "clayey gravel" when seen in context generally represented this weathered surface. Environments in which clay and gravel can be deposited together are rare and it appears that such deposits result from the breakdown of material originally consisting of a coarse fraction only. Difficulties arise where the original material was clay as further breakdown could not be distinguished unless oxidation took place. Thus it was not possible to identify the surface with certainty in every borehole. The lack of oxidation and mottling in many of the boreholes may be due to a later truncation of the profile, or to the lack of a suitable environment for such processes to take place. It is notable that the surface in the area of the Haughton delta is more gently sloping and less dissected than it is in the vicinity of Ayr-Home Hill.

Thus figure 3.4 is considered to be a reliable indication of the late Pleistocene weathering surface. It represents the delta of the Burdekin River at the last interglacial stage, and to a lesser extent its extension seawards and dissection during the subsequent glacial low sea level. It can be traced from about 50 feet above sea level at Clare to 125 feet below sea level below the present eastern shoreline. The slope of the delta proper appears to have been about 6 feet per mile, which is similar to that of the present delta (fig. 3.5). It is bounded especially on the eastern side by a comparatively steep slope (up to 25 feet per mile) which represents the rapid falling away of sea level during the last glacial period, though it may also have been trimmed back by the sea at the low level. The delta flood plain appears to have been considerably smaller than the present one. Mapping has of necessity been on too coarse a scale to identify any minor flood plain features.

The regression of the sea during the Last Glacial phase caused incision of the delta streams into the alluvial deposits, though no drainage line appears to have cut down to bedrock other than at The Rocks. The pattern of incision has similarities with the pattern in the bedrock contours. A major channel, in all likelihood a main Burdekin course at the low sea level phase, is found west of Kelly's Mount, but with a left bank tributary joining it, probably the

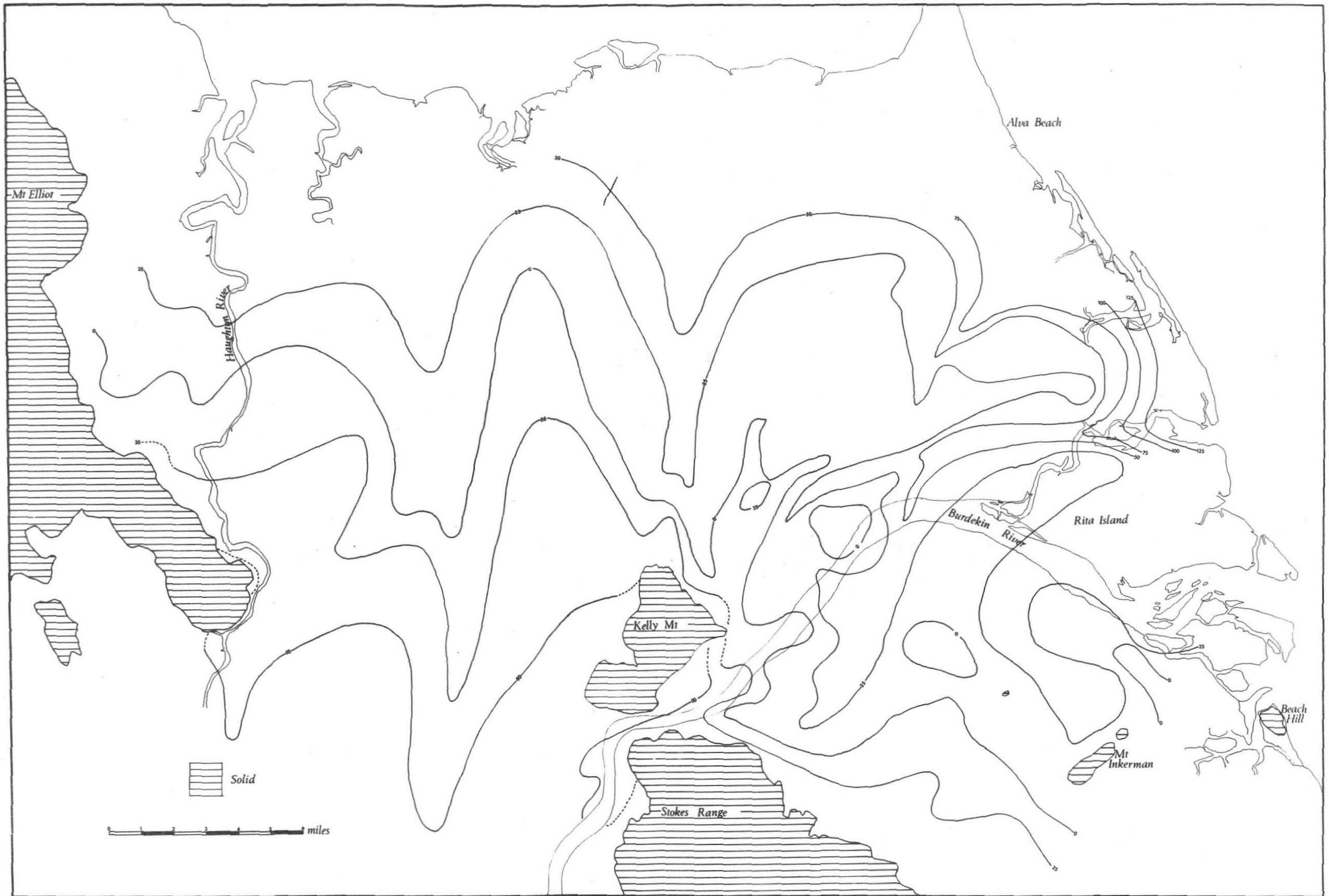


Fig. 3.4 Burdekin delta, late Pleistocene surface.

Haughton River. North and east of Kelly's Mount dissection by a number of smaller streams appears to have been rapid, probably due to the steeper slope to the edge of the delta here. One or more of these channels may have been initiated by the main Burdekin prior to its diversion to the western course. Four major channels can be identified:

i) along the line of Sheepstation Creek leading directly north into Bowling Green Bay

ii) a smaller channel south of Cape Bowling Green at the apex of the delta

iii) a deeply incised channel, with a left bank tributary, along the line of the present Burdekin and the Ana-branch

iv) a sinuous channel probably taking the drainage of the northern side of the Stokes Range.

The channel which occupies approximately the same position as the Burdekin today, was incised down to bedrock at The Rocks. Its close relationship to the major western channel suggests that it may have taken a major portion of Burdekin waters at various times even at the low sea level phase. Certainly during the Holocene transgression and the resumption of drainage more or less permanently over The Rocks the four channels of the eastern delta have had an important influence on the lines taken by Burdekin distributaries.

The Holocene Deltaic Deposits

Figure 3.5 depicts the present morphology of the Burdekin Delta. It is based largely on Irrigation and Water Supply Commission charts compiled for irrigation purposes. Comparison with figure 3.4 will give the depth of Holocene deposits. In general terms the Holocene

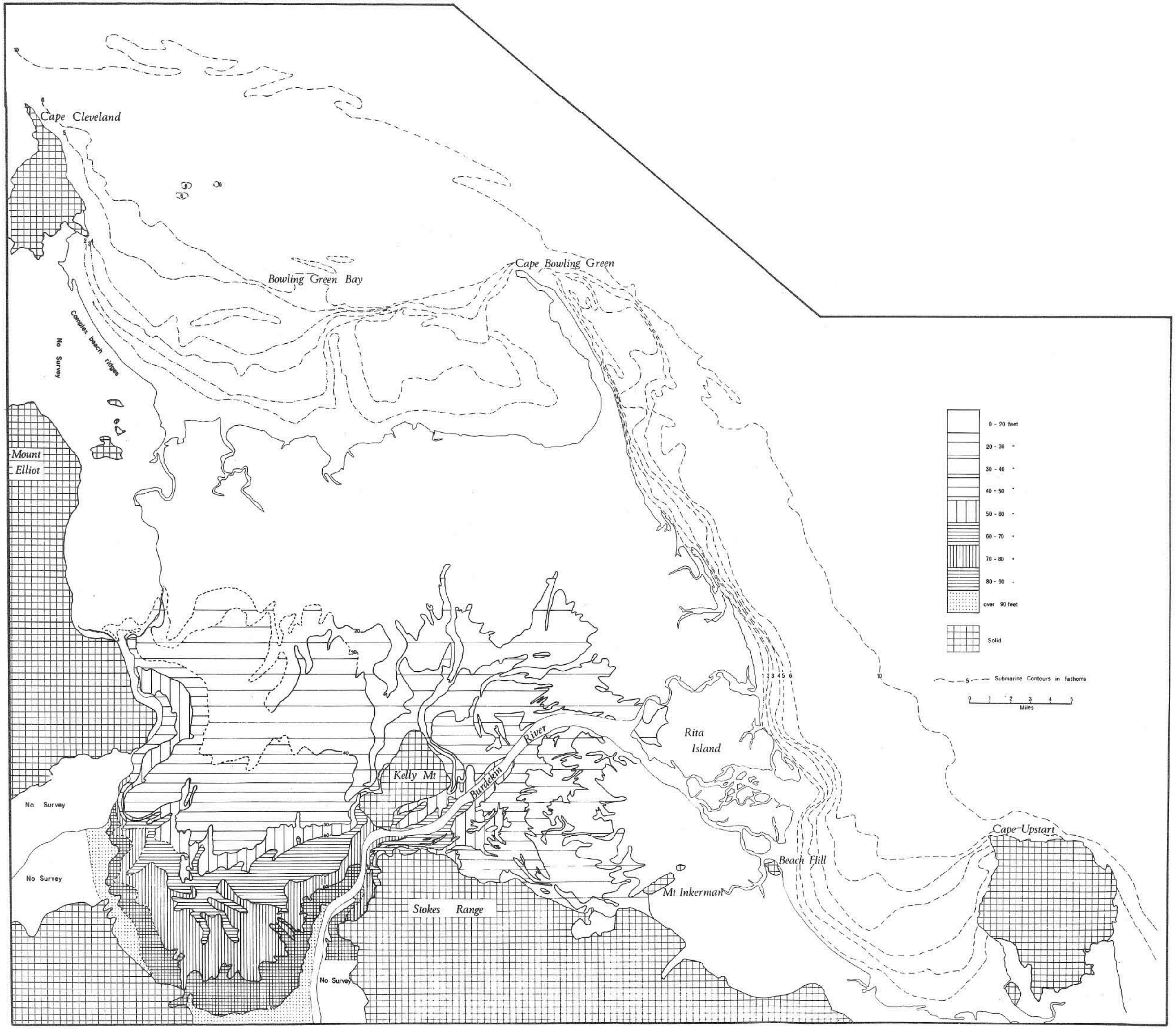


Fig. 3.5 Burdekin delta, surface and submarine contours.

deposits are wedge-shaped having a maximum thickness of over 125 feet on the eastern edge of the delta and 75 feet to the north, but thin rapidly landwards to a depth of about 20 feet or even less around the core of the delta. Deeper lenses of Holocene deposits extend up the channels incised into the late Pleistocene surface.

The Holocene alluvial deposits are little weathered and survive largely in their original condition. They are the result of accelerated aggradation during the Holocene transgression when rapid rises in sea level allowed equally rapid changes in distributary patterns and shoreline positions. The pattern of deposition strongly suggests that the Burdekin maintained its course northwards into Bowling Green Bay during the early part of the transgression, but occupied various channels in the eastern part of the delta during the latter period of the transgression.

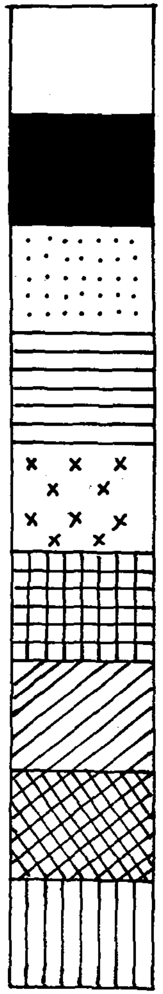
Thus the basic contrast between the eastern and northern parts of the delta, as the distributary areas of the high and low sea level periods respectively, has been emphasised. The large sediment load of the main Burdekin, flowing west of Kelly's Mount during the early Holocene, allowed rapid fluvial aggradation, so rapid that borehole evidence suggests that only during the most rapid stages of the transgression did the coastline move inland. For most of the time aggradation was able at least to maintain the position of the coast. Deposits above the Pleistocene surface are thus mainly fluvial in this part of the delta region. Littoral and estuarine deposits back from the present coastline are found mainly along the line of the channels (west of Kelly's Mount and along Sheepstation Creek).

In the eastern part of the delta aggradation during the early part of the transgression was by no means as great and the coastline migrated well inland even from its present position. Probable marine deposits are found as far inland as a line joining Ayr and Home Hill. The resulting pattern of sedimentation shows that deposits resting upon the eastern part of the late Pleistocene surface are marine rather than fluvial up to, and in some areas above, the present level of the sea. One bore log from just north of Rita Island, for example, contains 42 feet of shell grit. Only since the transference of the Burdekin across the bar of The Rocks and into the eastern delta has fluvial overcome marine deposition along the eastern seaboard. The coastline has again migrated seawards, but this is not due entirely to aggradation. A fall in sea level since the mid-Holocene period is well documented in the delta region and has helped to extend the coast not only in the eastern part of the delta but also along the shores of Bowling Green Bay.

Description of Cross Sections (fig. 3.6A-H)

Eight west to east cross-sections across the Burdekin Delta are shown in figure 3.6A-H. The position of these sections is shown on figure 3.2. Borehole information is included for holes drilled within approximately half a mile of the section line. The indicated positions of the bedrock and Pleistocene weathering surfaces are therefore only approximate to the borehole sections.

It is immediately apparent that correlation from one borehole to the next is difficult and that the complex deltaic deposits change rapidly both horizontally and vertically. However, a number of notable features may be



TOPSOIL

BEDROCK

FINE SAND AND SILT

MUDS

GRAVEL AND COARSE SAND

CEMENTED DEPOSIT

MAINLY CLAY

SHELL

WEATHERED ROCK

Key to Abbreviations

B	-	Bedrock	l	-	Loam
b	-	Boulders	Ls	-	Limestone
ba	-	Basalt	m	-	Medium
blk	-	Black	mm	-	Mangrove mud
br	-	Brown	P	-	Puggy
c	-	Clay	pe	-	Pebbles
c-b	-	Claybound	R	-	Rock
c-ba	-	Claybands	r	-	Red
cem	-	Cemented	s	-	Sand
cs	-	Course	sl	-	Shell
D	-	Decomposed rock	sm	-	Small
di	-	Diorite	si	-	Site
dir	-	Dirty	so	-	Soft
f	-	Fine	ss	-	Silty sand
fl	-	Flake	st	-	Stones
Gr	-	Granite	Tc	-	Tight clay
g	-	Gravel	Ts	-	Topsoil
gr	-	Grey	t	-	Tough
gri	-	Gritty	w	-	White

Fig. 3.6 Key to Burdekin and Herbert delta Sections.

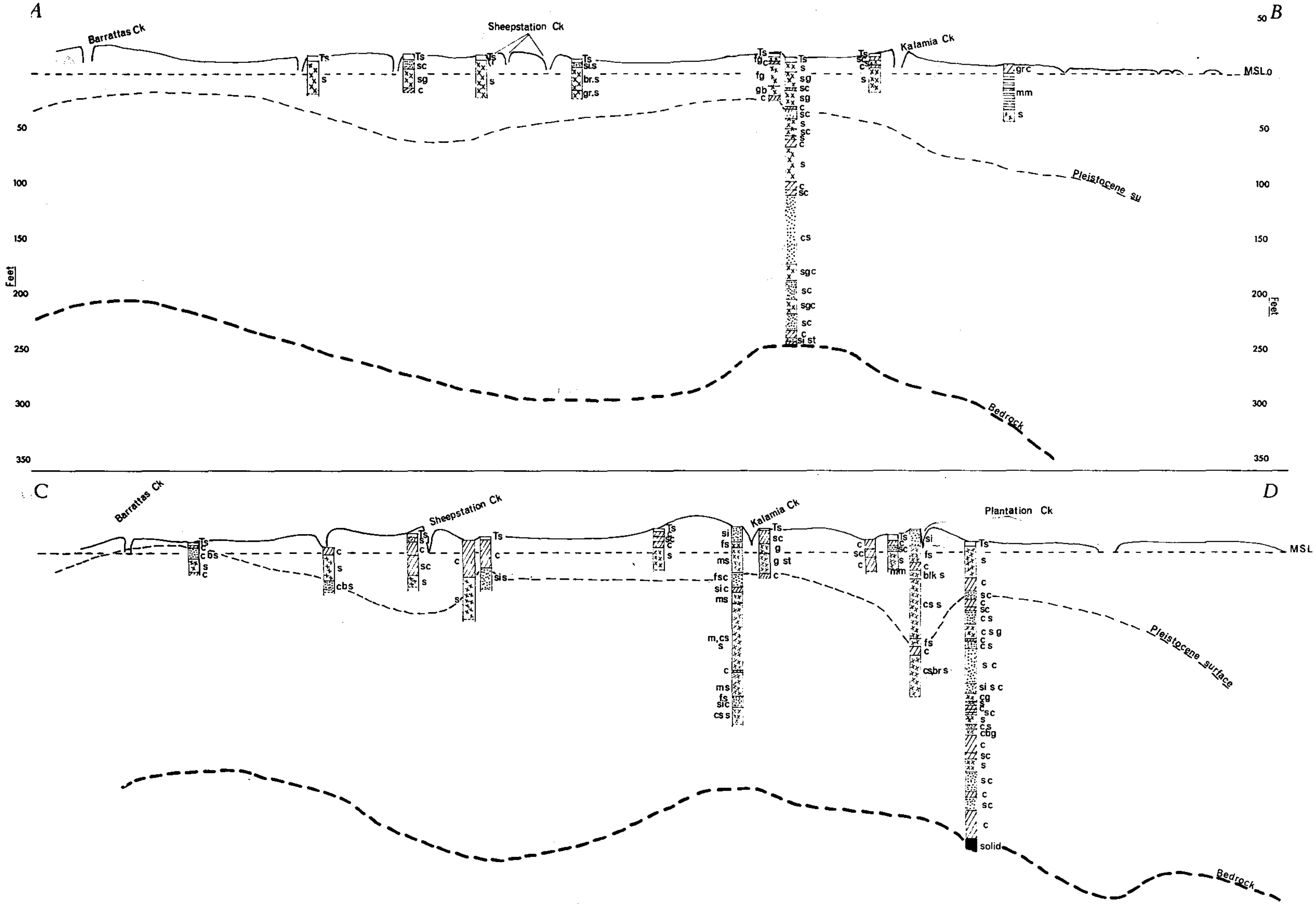


Fig. 3.6A Burdekin delta sections.

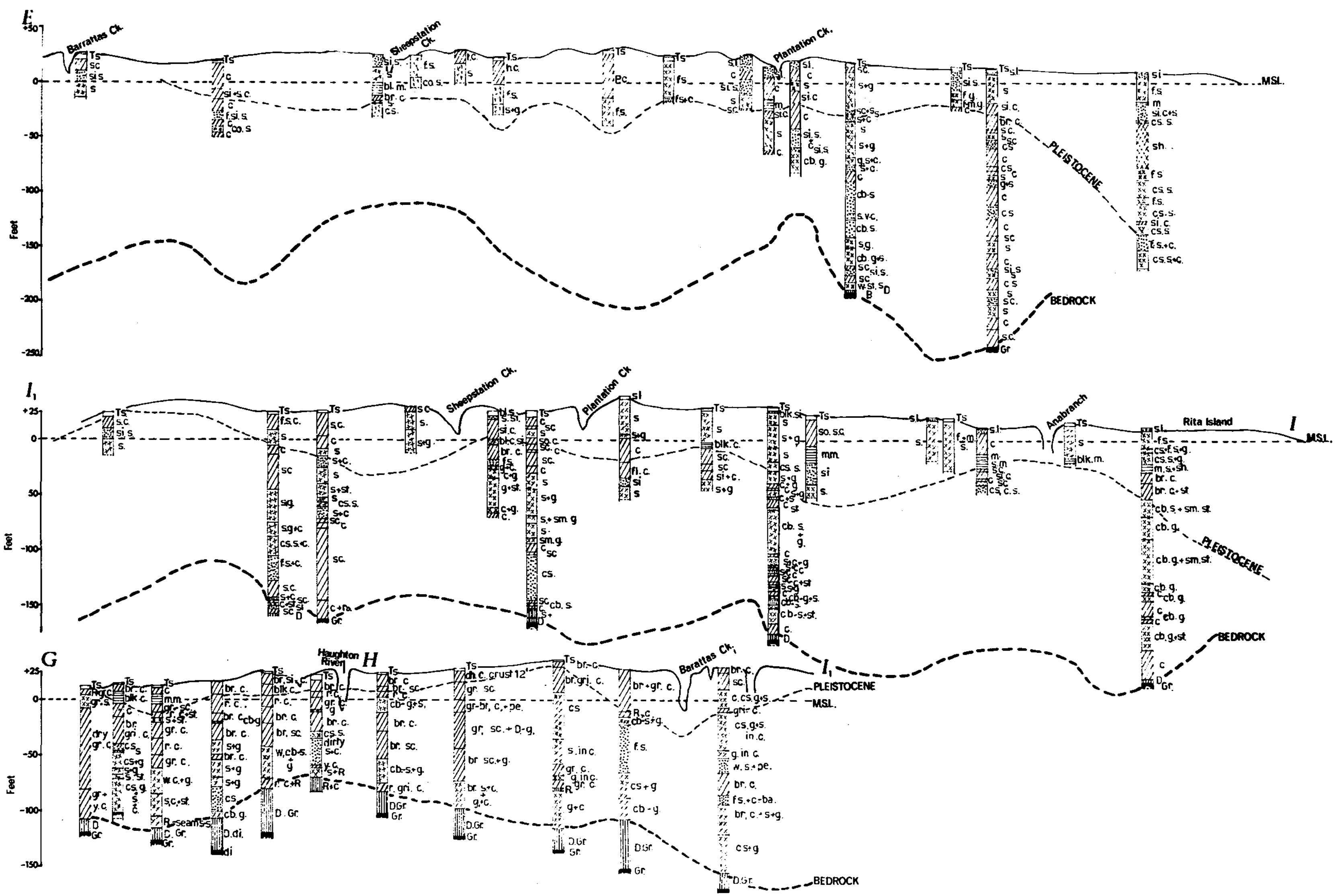


Fig. 3.6B Burdekin delta sections.

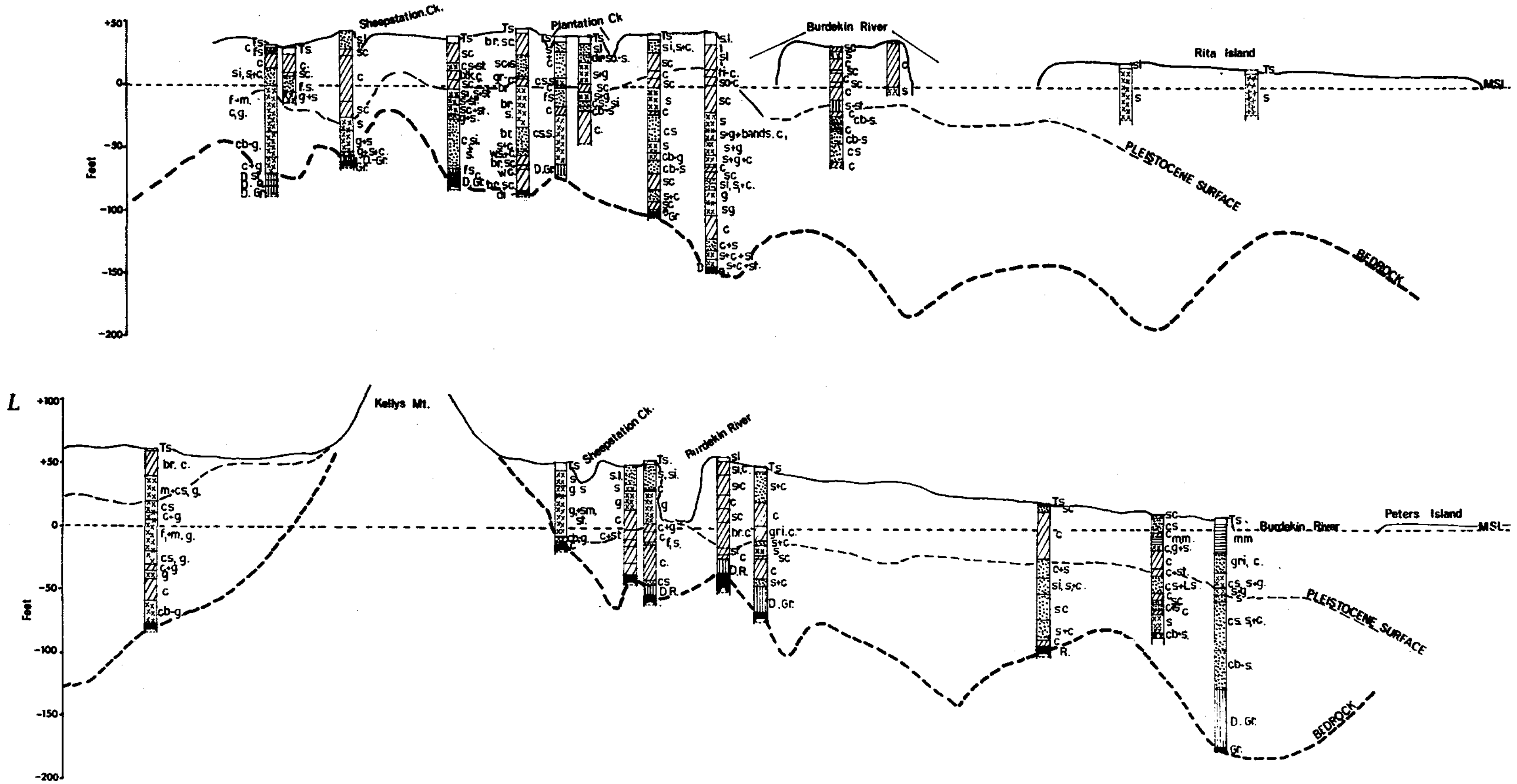


Fig. 3.6C Burdekin delta sections.

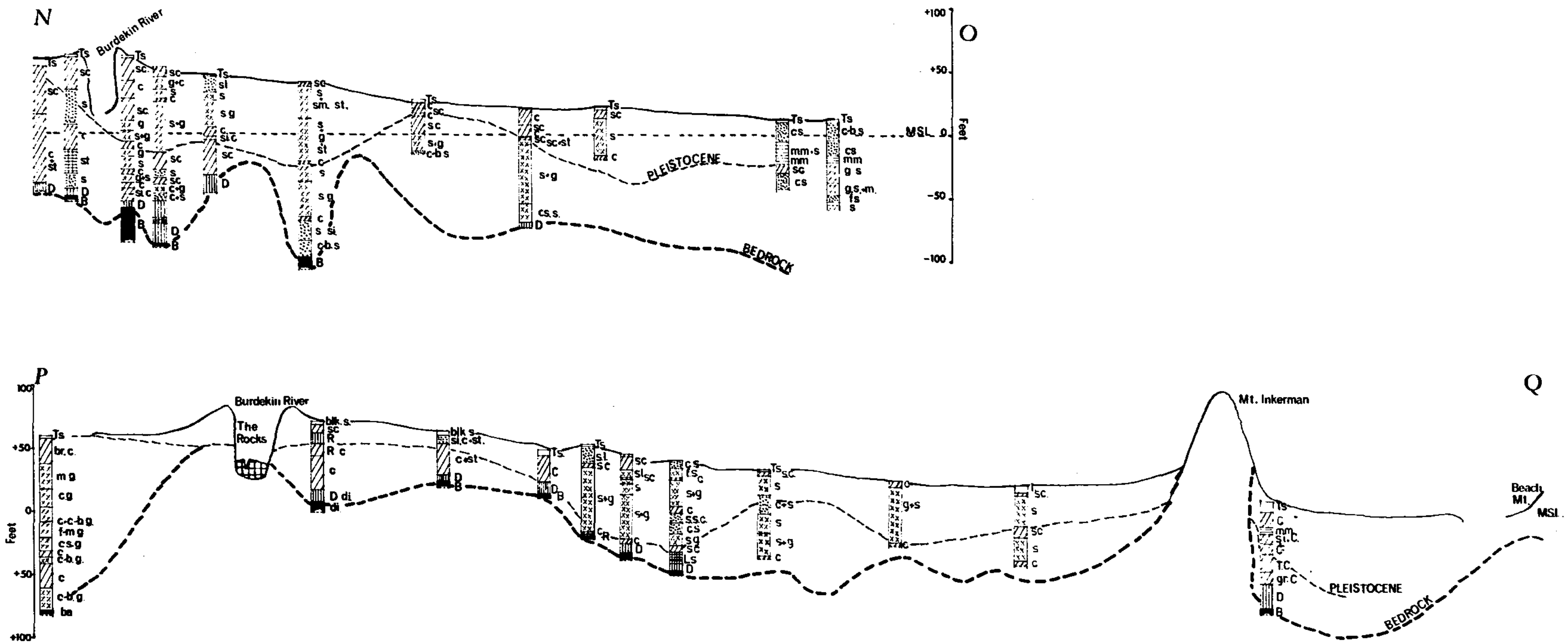


Fig. 3.6D Burdekin delta sections.

seen in each section.

i) Section A-B

This is the northern-most section across a line which probably approximates to the northern limits of the high sea level stage of the late Pleistocene Burdekin delta. Bedrock is generally more than 200 feet below sea level and dips away to greater depths to the east. No notable features occur on the bedrock surface here, though only one borehole actually reaches solid rock. The late Pleistocene surface reflects the bedrock morphology, though it is often less than 25 feet below sea level. This also dips away fairly steeply to the east. Shallow boreholes give a good indication of the nature of the Holocene deposits. They are of a surprisingly coarse nature. The present surface deposits just north of the section line are almost exclusively salt marsh, yet sands and gravels predominate in the immediate subsurface. The presence of sands and gravels together in the Sheepstation Creek and Kalamia Creek areas strongly suggests a fluvial origin for the deposits. Both these creeks have in the past served as major distributaries (see below) and this interpretation seems reasonable. In contrast, the eastern-most borehole, close to the east coast of the delta, shows 35 feet of mangrove muds extending down from present sea level, clearly indicating the littoral and estuarine deposition of the Holocene transgression in this part of the delta. The overlying clays may be fluvial.

ii) Section C-D

Again in this section from the Barrattas Creeks to the eastern shoreline, only one borehole reached bedrock. By interpolation from adjacent areas, however, it is possible to indicate an undulating bedrock surface. The late Pleistocene surface is again about 50 feet below the present surface though in the area of the Barrattas Creeks it is possibly less than 5 feet below the surface. Two well marked channels occur in the Pleistocene deposits, one in the region of Sheepstation Creek, the other corresponding to Plantation Creek. The Pleistocene surface dips away sharply to the east at the edge of the delta of that period, and to the west down to the major Burdekin channel west of Kelly's Mount.

Pleistocene deposits are varied, though in the vicinity of Sheepstation, Kalamia and Plantation Creeks they appear to be quite coarse, possibly suggesting that these drainage lines had prototypes prior to the last Pleistocene high sea level. The borehole reaching bedrock, just east of Plantation Creek, displays at least three weathering surfaces below the late Pleistocene surface. Claybound coarse alluvial deposits occur at each of these levels.

Holocene deposits are also variable, with clays generally overlying coarser alluvial material. Between the former distributary areas, clays may extend right down to the Pleistocene surface. It is considered that the sands and gravels are predominantly fluvial in origin, though the presence of mangrove muds below the Plantation Creek channel suggests that littoral or estuarine conditions may have extended up the channels during more rapid rises of the Holocene transgression.

iii) Section E-F

Section E-F passes through the town of Ayr. It is also closer to the northern slopes of Kelly's Mount and the bedrock configuration reflects this, the two high points on the bedrock section being subsurface ridges running north from this outcrop. A bedrock channel separates them. Channels also occur to the west, where the bedrock dips down towards the major western channel, and to the east where a deeply incised channel extends down to 250 feet below sea level.

The Pleistocene surface also shows moderate relief, incised by a series of north flowing streams. It lies about 50 feet below the present surface and along most of the section this puts it below present sea level. Two boreholes reach bedrock, but although only two and a half miles apart, they show little correlation in their deposits. Clays predominate in the eastern borehole, whilst the western hole contains much coarser material. It is notable that many of the coarser deposits lying below the Pleistocene surface in this section are weathered and claybound.

The Holocene deposits are more easily interpreted. Clays predominate in the interfluve areas between the Barrattas Creeks and Sheepstation Creek, and between this latter creek and the Plantation Creek channel. Coarser deposits exist along the line of Sheepstation Creek and in the channels incised into the Pleistocene surface further east. The boreholes drilled in the Plantation Creek area indicate deposits finer than might be expected. The presence of muds, probably deposited in a mangrove environment, below both Sheepstation and Plantation Creeks up to 25 feet below present sea level again suggests encroachment of estuarine conditions up pre-existing channels during the Holocene transgression. This rapid transgression is further documented on the eastern side of the delta where the Pleistocene surface drops away sharply to below -125 feet. Overlying Holocene deposits are considered to be almost entirely marine. Sands predominate in this area, though between 37 and 79 feet below present sea level is a remarkable deposit consisting of shell fragments.

iv) Section G-H-I

This is a composite section across the delta from the Haughton River to Rita Island. The undulating bedrock surface lies at depth generally around 150 feet below sea level. The major bedrock channel west of Kelly's Mount does not appear to be deeply incised owing to the change in direction of the section at the western end, where it tends to run parallel rather than transverse to the bedrock contours. The eastern part of the bedrock surface is generally more irregular. There is a notable contrast between the thin veneer of weathered rock lying on the bedrock in the east and the thick regolith around the Haughton River where the weathered mantle attains depths greater than 30 feet. Erosion and incision in the eastern part of the delta has apparently removed most of this ancient regolith here.

The Pleistocene weathering surface similarly displays greater irregularity in the eastern area, though the largest valley cut into it in the area of Barrattas Creeks is offset to the west compared to the earlier but similar feature cut in bedrock. The deposits of this area are generally coarse, reflecting its use by the Burdekin during low sea level periods. Further west, clay predominates, though sands and gravels immediately above the bedrock surface are fairly continuous, and a very early prototype of the Burdekin or Haughton may have utilised this part of the delta. The Pleistocene surface in the Haughton River area is not far beneath the present surface and may occur in the banks of some of the more deeply incised streams. Further east, this surface again comes close to the present ground level just east of the Barrattas before subsiding to 50 feet beneath the Holocene deposits of the eastern part of the delta and finally dropping away sharply beneath Rita Island. The

Pleistocene deposits east of the Barrattas generally comprise fine grained sediments in the lower sections close to bedrock, extensive sands and gravels above these, with clays predominating within 20 feet of the Pleistocene surface, though, as might be expected coarse deposits also occur in the channels incised into this surface.

The Holocene deposits consist of clays in the interfluve areas between the channels cut in the Pleistocene surface (especially west of the Barrattas), clays overlying sands and gravels in the early Holocene channels of the Barrattas and Sheepstation Creek, and coarser deposits extending to the surface in the younger channel of Plantation Creek and adjacent to the Ana-branch. The presence of mangrove muds in the sections east of Plantation Creek indicates marine, littoral and estuarine deposition here. Mangrove muds also occur in the shallow depression west of the Haughton River.

v) Section J-K

Section J-K is just north of Kelly's Mount and consequently bedrock rises to within 50 feet of the present surface. Numerous bedrock channels running north from Kelly's Mount and the Stokes Range can also be seen. The Pleistocene surface is undulating and lies close to present sea level. In this area a large amount of clay and silt is indicated and it is difficult to interpret the exact position of the weathered surface which may be more intricate than shown. Pleistocene deposits are extremely varied, though coarser deposits seem to be associated with bedrock channels. Holocene deposits are surprisingly fine grained with clays predominating even close to existing and abandoned channels. Sands, probably marine, are found beneath Rita Island.

vi) Section L-M

The major bedrock channel west of Kelly's Mount is depicted here. Other significant channels are indicated to the east. Though incision may have occurred into the bedrock since the start of accumulation of deltaic deposits, locally 15 feet or more of weathered rock remain. The regolith is mainly on interfluves in the bedrock, but 45 feet of weathered granite occurs on the floor of the eastern-most channel shown.

The late Pleistocene weathered surface dips away sharply from Kelly's Mount, though to the east the surface is undissected. Clays predominate beneath this surface to the east, but, as expected, coarser sands and gravels are associated with the channel to the west. In the same area, medium to coarse gravel of Holocene age is seen on the eastern side of the channel cut in the weathered surface. These deposits are overlain by more than 15 feet of clay deposited since the channel was abandoned. Sands and gravels are also associated with the Sheepstation Creek channel and close to the present Burdekin just east of Kelly's Mount. However, the deposits of the south side of the present delta are mostly clays until the coast is approached where an assortment of deposits is seen, including mangrove muds.

vii) Section N-O

This short section shows the south side of the present delta, an area in which the bedrock configuration is depicting the fretted edge of the Stokes Range pediment. The Pleistocene surface consists of two valleys separated by an interfluve located south of Home Hill. In the interfluve area it approaches to within 10 feet of the present surface and may actually form the current surface. A small area of scrub with soils too poor for sugar exists here as an oasis of native vegetation within the cultivated cane fields. If any Holocene deposits do exist here they are thin clays deposited in a back-swamp environment.

Both Pleistocene and Holocene deposits become progressively coarser towards the east. Extensive Holocene sand and gravel deposits east of the current Burdekin channel suggest the presence of a distributary in this area during Holocene times. The surface morphology confirms this (see below). Marine deposits, including mangrove muds exist close to the eastern shoreline, but some 20 feet below sea level.

viii) Section P-Q

The southern-most section passes between Kelly's Mount and the Stokes Range at The Rocks, skirts the southern side of the delta to Mount Inkerman and approaches the east coast at Beach Mount. The incised channel cut into bedrock west of The Rocks is even here, 75 feet below sea level. Elsewhere, bedrock approaches or breaks the surfaces. Much of it is in the form of a pediment only slightly incised.

The western valley is almost completely filled with Pleistocene deposits and the Pleistocene alluvial channel in the same region is offset approximately a mile to the west of its bedrock counterpart. East of The Rocks the Pleistocene surface is within 20 feet of the present surface though Holocene deposits in two open channels attain thicknesses of more than 60 feet.

Pleistocene deposits in the western channel are generally coarse but east of The Rocks consist of clays overlying a weathered mantle approximately 10 feet deep. Coarser Pleistocene deposits exist towards Mount Inkerman, though clays and weathered rock are found between this outcrop and Beach Mount. Holocene deposits repeat the pattern of Section N-O, with coarse sands and gravels in the channels overlapped by clays and silts, presumably reflecting the sharp change in environment after the abandonment of the Burdekin distributary across this part of the delta. West of Mount Inkerman the Holocene clays and mangrove muds suggest a sheltered environment, and evidence will be presented which indicates this to be a lagoonal area.

General Features of the Surface Deposits

The surface deposits of the Burdekin Delta region are shown in figure 3.1. Detailed analyses of these deposits will be given on a regional basis, but a number of general points may be made.

i) The beach ridges and dunes

Beach ridges and dunes are found in the delta up to six miles from the present coast. They normally occur in series, the largest of these being found south of Cape Cleveland. Materials are invariably fine to medium sands. With a few exceptions they are mainly quartzitic. Heavy minerals are present, generally in low concentration, but locally beach and dune sands may contain over 40% heavy minerals. Analysis of sand samples was made by the Bureau of Mineral Resources (Paine, Gregory and Clarke, 1966) and results indicated that ilmenite and magnetite were the dominant heavy minerals with smaller quantities of zircon, rutile, garnet and tourmaline. A commercial mining company has recently (1969) taken out a lease to dredge for gold in the old beach sands of the delta.

South and east of Cape Upstart, heavy mineral concentrations on the beaches are clearly associated with gabbro outcrops (Paine, Gregory and Clarke, 1966, Appendix 3) but in the delta the sands and associated heavy minerals have been carried to the coast by the Burdekin and Haughton Rivers. The strong littoral drift to the north and west along the whole of this coast is reflected in the major distribution of beach sands; each beach ridge and dune series is closely allied to a current or abandoned distributary to the south or east of it. In many cases, left bank levees of these channels continue without break into beach ridge series, the transported load of the river being swung along shore as soon as it comes under the influence of the littoral drift. Cape Bowling Green has originated in this way (see below).

Microscopic examination of both beach and dune-sands indicated that they are invariably poorly rounded, being mostly angular or sub-angular in the scale of roundness devised by Shepard and Young (1961). This is in keeping with the suspected origin of the sands, which have probably originated from the granites or deep weathering products resting on the granites of the middle and upper Burdekin basin. They are thus passing through their first cycle of erosion. Kuenen (1960) has indicated that a journey of a few hundred miles as is envisaged for the delta sands, need not greatly modify the original angularity of the grains.

Mechanical analysis and examination of occasional sections exposed in beach ridges indicate that a high proportion of the sand is of windblown origin with characteristic positive skewness and dune bedding and only the core was deposited by waves. Ridges are commonly 10 to 20 feet in height, the higher ones consisting almost exclusively of dune sand. Even so the ridges are symmetrical in section varying in width from 10 to 50 yards. Where closely spaced the intervening swales are normally of sand, but where the depressions are wider they may be in the form of clay pans, salt marsh or mangrove. Where ridges are extremely widely spaced, as behind Bowling Green Bay, they may be in the form of chenirs, i.e. sand ridges resting upon a clay base rather than connected sand accumulations with intervening fine grained deposition in the depressions, as seems to be more common (see Davies, 1968).

Dunes are less common. In their simplest form they are merely symmetrical ridges parallel to the shore, but the greater the exposure to the south-east, the greater the formation of blowouts and transgressive dune formations. Experience on the whole of the North Queensland coasts leads to the conclusion that coasts of comparatively large active dunes are normally eroding. In several areas in the Burdekin delta, there may be seen a sequence of construction of parallel beach ridges close to an active distributary followed by erosion and transgressive dune formation after the abandonment of that channel. This is to be expected as the rapid supply of sand during the active period of the distributary builds the coast outwards and the cutting off of the sand supply merely results in the normal process of coastal straightening with erosion of the protruding sand accumulations. In large series of beach ridges, such as south of Cape Cleveland, the presence of higher dunes in the sequence generally indicates a temporary cessation of aggradation and a period of erosion. They therefore mark the line of an unconformity in the beach ridge sequence.

ii) Mangroves

Mangroves are extensive in the Burdekin delta. On the sheltered shores of Bowling Green Bay between the Haughton and Cape Bowling Green they are found as a more or less continuous fringe as well as extending up the creek mouths, many of which originated as Burdekin distributaries (see below). On the more exposed shores orientated easterly or south-easterly, mangroves do not occur on the outer edge of the coastal zone, but are common in the estuaries and in the lagoons which occur between beach ridges. Mangroves extend several miles inland up the meandering tidal creeks.

Clear zonation of mangrove species is seen along the quieter shores. Macnae (1966, 1967) has described mangrove communities in North Queensland and his species zonation associated with varying degrees of tidal inundation in the Townsville area appears to be repeated in the delta. A seawards fringe of *Avicennia spp.* may be recognised, followed by a *Rhizophora spp.* zone, a *Bruguiera spp.* zone and a landwards fringe of *Ceriops spp.* Upstream along the creeks, species of *Rhizophora* dominate.

In distributary mouths and between the beach ridges, the zonation tends to be more complex, though possibly involving fewer species. Along the creeks and drainage channels within the mangroves *Rhizophora spp.* dominate their pattern of distribution reflecting that of a levee system. Away from the creeks, *Bruguiera spp.* are found, though running through these stands there may be clearly identifiable abandoned channels in which *Rhizophora spp.* again occur.

It has often been stated that mangroves promote rapid aggradation by trapping sediment in their entanglement of roots (e.g. Watson, 1928; Thorne, 1954; West, 1956). More recently it has been claimed that mangroves do not significantly increase the rate of seaward or lateral growth of the coast, (Scholl, 1968). Thom (1967) also considers that mangrove zonation is a reflection of geomorphic conditions rather than indicating a vegetation succession which depends on changes in the environment made by the mangroves themselves. In the Burdekin delta, the mangrove patterns appear to reflect previously existing patterns of sedimentation rather than actively to be promoting changes in sedimentation. This will be discussed in greater detail below.

iii) Salt marsh

Large areas of saline land occur around the Burdekin delta. They are restricted to sheltered environments behind mangroves or beach ridges and have been described previously by Christian et al (1953) and by Coleman, Gagliano and Smith (1966). Lower areas, covered only occasionally by spring tides, are normally unvegetated. These are extensive but tend to decrease in area northwards along the coast with increasing rainfall. They appear to be climatically controlled as excessive evaporation during a long dry season brings salt to the surface, making conditions too saline even for halophytic plants. Occasional inundation maintains the high salt content. In areas with a shorter dry season, fresh water flushes tend to maintain a salt level which can be tolerated by certain plants and such environments generally support a stunted mangrove cover.

Higher areas beyond the reach of even the highest tides may also be quite saline, maintaining a cover of halophytic vegetation in which samphires (Arthrocnemum leiostachyum, A. holocnedmoides and Salicornia australis) are dominant. Evidence will be put forward to suggest that such areas originated as unvegetated salt flats within the tidal range during a mid-Holocene higher sea level, and have been left stranded by a subsequent regression of the sea.

The lower tidal areas of salt flat are normally bounded by a salting scarp up to four feet high extending itself by sapping into the adjacent higher salt flat or into coastal alluvia. Coleman, Gagliano and Smith (1966) have described the physical disintegration, by crystal wedging, of material brought down on to the flat in this way.

iv) River Levees

The bulk of the eastern part of the Burdekin Delta below The Rocks consists of the coalescing levees of the present channel and of the many former distributaries. The gently sloping levees extend up to a mile and a half from the channels which they border and are typically 10 to 15 feet above the surrounding flood plain and between 30 and 60 feet above the adjacent riverbed. Sediments making up the levees are generally of silt size though fine sands may also be present. Sediments become finer away from the crest of the levee. All levees have well developed soils, generally light and fine-sandy in texture at the surface though becoming heavier in the sub-soil (Hubble and Thompson, 1953). They have developed over a considerable period and little aggradation is taking place now. The majority of the levees remain above water even during the largest floods. Indeed, in places, steep-sided gullies are cutting into the levees and erosion is now the dominant process. The 70,000 acres of sugar cane grown in the delta are limited to the soils of the old levees.

Figure 3.1 clearly indicates the coalescing levees of the delta. It is possible, however, to distinguish four distinct levee or distributary systems below The Rocks, each with one or more channels which may split into more complex distributary areas. They include

1. The Sheepstation Creek System, flowing into Bowling Green Bay.
2. The Kalamia Creek-Plantation Creek System, flowing towards Cape Bowling Green.
3. The Rita Island System, including the present channel and the Ana-branch.

4. The Lakes Plain-Inkerman System, flowing along the southern edge of the delta.

Minor levees and associated channels may occur between these major areas, but the four systems listed above each have well defined channels several hundred yards in width with coarse sands and fine gravels, similar to the load of the present channel, at or close to the surface of the floor of the channel. The channels still operate as floodways during periods of high river flow.

The Burdekin levees extend upstream from The Rocks. At Clare, clearly defined levee systems branch off in the direction of the Haughton and then swing directly north towards Bowling Green Bay. These levees appear to disappear beneath the finer clays of the area between the Haughton and Kelly's Mount, though fragments may be traced further north. This area will be examined in detail below. The Haughton River has similar levees. These too indicate former courses of the river.

v) The Floodplain Deposits

The low lying areas of the delta have surface deposits consisting almost entirely of clays. This is a true floodplain, being inundated during periods of high river flow occurring approximately once every ten years. Back-swamp areas with lagoons and marsh exist but generally relief is slight though gilgai micro-relief features are common. Even during floods, fresh deposition is very localised and soils of the floodplain are generally mature with a heavy surface overlying grey solonized clays containing carbonate concretions (Hubble and Thompson, 1953).

The largest area of floodplain occurs between the Burdekin and Haughton Rivers in the vicinity of the Barrattas Creeks. However, it will be shown that floodplain deposits here are thin and a more complex deltaic pattern lies just below the surface. In the eastern part of the delta, floodplain is limited to narrow marshy tracts between levees on the outer edge of the delta. The largest area is around Charlies Hill on the south side and parts of this may be a little modified remnant of the late Pleistocene surface with only a thin veneer of Holocene deposition.

REGIONAL ANALYSIS OF THE DELTA

The Cape Upstart Area

Cape Upstart is a sub-circular granitic stock with basic plutonic rocks outcropping intermittently around the margins. It is joined to the mainland by a complex area of coastal deposits about 5 miles long and 3 miles wide. Only the western side of this tombolo is within the sedimentary province of the Burdekin Delta. Refraction of the dominant south-easterly waves around Cape Upstart results in clastic sediments being washed into this corner of Upstart Bay. On the eastern side of the tombolo, sedimentation is controlled by the Elliot River, a stream with a catchment area of about 84 square miles, flowing out to sea 6 miles south of the Cape Upstart outcrop. This river has contributed a large amount of sand to the area north of its mouth (fig. 3.7).

The core of the alluvial area south of Cape Upstart is a large symmetrical dune of red oxidised sands, well compacted though not lithified. Similar dune sands a few miles further west around Green Mount (see below) have a late Pleistocene age and there is little doubt that the Upstart dune is of similar age. Half a mile to the east is a barrier system of Holocene age consisting of beach ridges

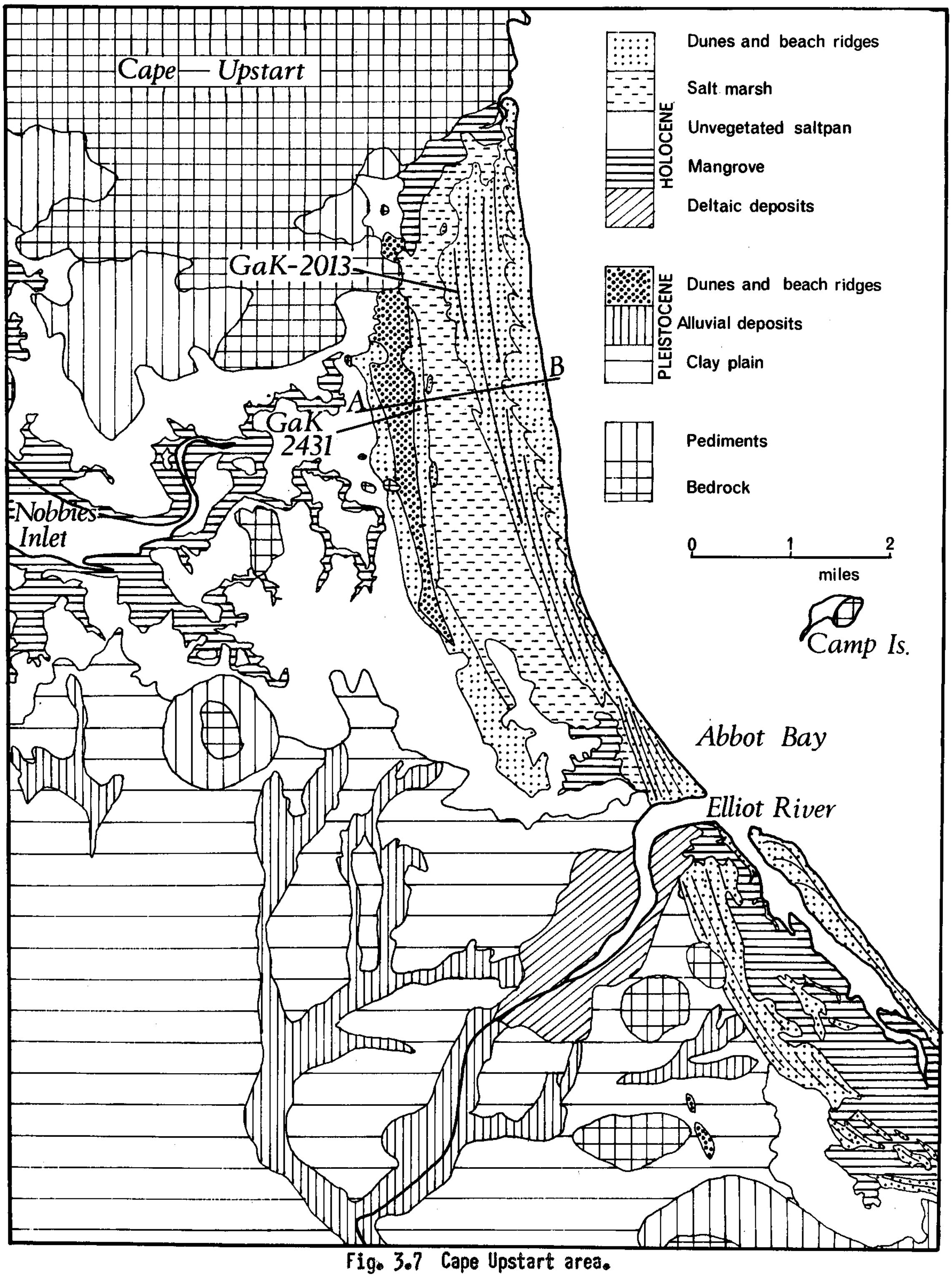


Fig. 3.7 Cape Upstart area.

and dunes, the sands of which though progressively more humus-stained towards the rear of the sequence are little leached or weathered. The outer barrier is higher towards the north as it becomes progressively more exposed to sand moving winds. At first appearance there is here a simple double barrier system identical to those described further south on the coast of eastern Australia (see for example, Hails, 1968 or Langford Smith, 1969). However, careful survey, analysis of sediments in the laboratory and in the field and the obtaining of two radiometric dates for deposits from the area have indicated a more complex evolution.

Figure 3.8 is a cross-section of the double barrier drawn from a Quickset level survey. Superimposed upon it are the results of a number of shallow boreholes. The red Pleistocene dune rises to just over 60 feet above M.H.W.S. This is about 10 feet short of its maximum height, achieved very close to the solid outcrop of Cape Upstart. Further south, towards the Elliot River, the red dune slowly descends in height until about one and a half miles from the Elliot it disappears beneath later deposits. However, the trend of the older alluvials of the Elliot River clearly indicate that this large dune ridge was initiated as a beach ridge formed from material drifted north from the early mouth of the river. Once attaining a more or less easterly orientation into the prevailing winds, dune formation became possible, and a large symmetrical dune ridge was constructed. This ridge was continued across a small embayment on the south-eastern side of Cape Upstart, and remnants, about 50 feet high remain here today.

The trend of this shoreline was particularly controlled by small outcrops of solid rock. These outcrops, formed of gabbro and diorite, have been deeply weathered but largely

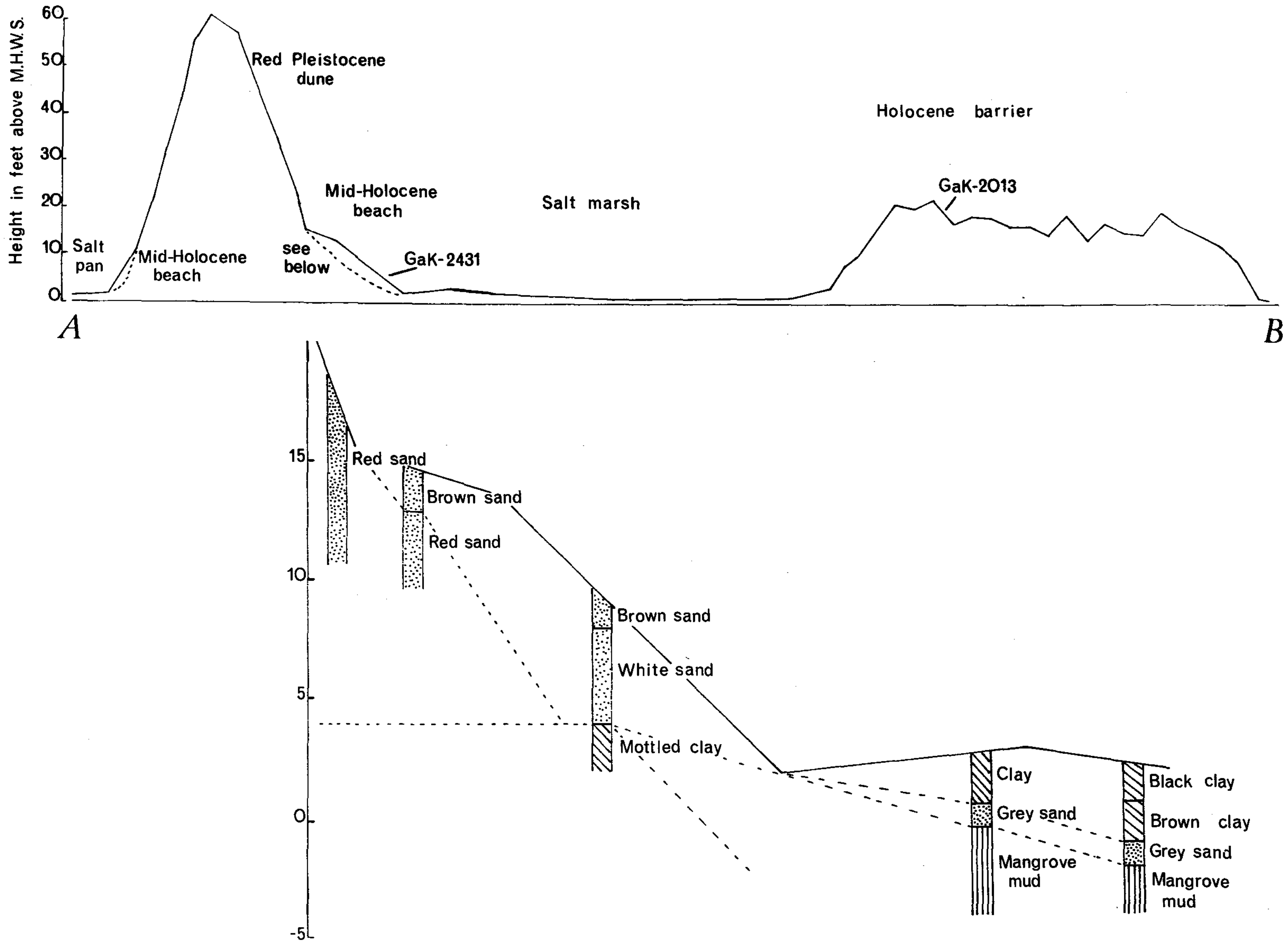


Fig. 3.8 Cross section, Cape Upstart barriers.

stripped of their characteristic red clays leaving a bouldery rubble of core-stones over the whole of each small hill. The deep weathering episode and the stripping of the finer portion of the mantle took place prior to the formation of the dune which partially engulfs one of the outcrops.

At the base of the red dune, on both eastern and western sides and extending further south towards the Elliot River, is a series of white sands, extending up to 13.87 feet above M.H.W.S. on the east and to 10.17 feet on the west. Although apparently quite well leached, these sands do contain large shells, more or less complete, but which show signs of having being rolled or washed for some time. The following species were identified in the collection that was made. The normal habitat of the species is indicated.

Telescopium telescopium - mangrove swamps, or sheltered beach.
Crassostrea sp. - estuarine sheltered beach.
Pyrazus sp. - sheltered beach.
Turritella sp. - estuarine, sheltered beach.
Anadara sp. - muddy flats or sandy sheltered beach.

Identification was made by Mr. R.P. Kenny, Dept. of Zoology, University College of Townsville. A specimen of these shells (T. telescopium) was submitted for radio-carbon assay. The result (GaK-2431) gave a date of 7530 years ± 180 B.P.

There are here two apparent anomalies. First, the shell fauna indicates quiet salt water conditions as might be expected in a lagoon with a sandy foreshore but containing mangroves. The environment of this beach with an open orientation to the east gives quite a different molluscan fauna on the present beach. However, the exact environment, as suggested by the beach fauna, is found just south of the Elliot River where a coastal lagoon draining into the Elliot estuary and filled with mangroves is found between two beach ridge systems.

The second anomaly is the date. Under any conditions, the beach on the western side of the Pleistocene dune must have been deposited under sheltered conditions and the height of the beach sands cannot be much above the height of high water at the time. Thus a sea level of approximately 10 feet higher than present is indicated by these deposits. However, dates from elsewhere in Australia and in the world of a similar nature to that obtained for the shell indicate sea levels of up to 40 feet below present. Explanation of the shells as part of an aboriginal midden is unlikely as they are too widely distributed in apparently undisturbed beach deposits, and show none of the characteristic puncture marks of shells from unquestionable midden sites in the area. A more complex explanation is necessary. Gill (1967) has claimed that coastal barriers migrate with sea level fluctuations and Bird (1961, 1967) has shown that the barriers across the lagoons of Gippsland, Victoria derived much of their material from the adjacent sea floor during the Holocene transgression. Following these models, it is possible that during the Holocene transgression in North Queensland a barrier was gradually moved onshore. At one stage, possibly 7,500 years ago a lagoon formed between this barrier and the older Pleistocene dune. Further rises in sea level breached or completely overran the outer barrier and, under the more dynamic conditions, the fauna of the lagoon were moved onshore, only the larger and more robust shells surviving. Several phases of barrier formation-destruction may have been involved. Tidal action which is strong along the mangrove creeks which drain such lagoonal areas after partial sedimentation, results in rapid erosion on the outer edge of the meander bends. Impingement of such mangrove creek meanders against the red Pleistocene dune resulted in a number of meander scars in the eastern side of the dune which pre-date the Holocene beach deposits which have partially infilled them.

Final deposition of the beach on the eastern side of the Pleistocene dune thus took place at or near to the height of the Holocene transgression, though material involved was older. Deposition took place in open water conditions with a small amount of cliffing in places in the consolidated red aeolian sands. A new dune, of fresh unoxidised sands about 20 feet high was formed in front of the beach, though most of this has been destroyed at a later date.

During the transgression the Elliot River no doubt contributed to the sediment forming the migrating barrier. At the height of the transgression when the Holocene shoreline rested against the Pleistocene dune, the remnants of the Pleistocene delta of the river would have protruded beyond the smooth curve of the shore to the north (fig. 3.7). Sediment swept northwards from the river mouth as a spit, thus formed a barrier some half mile seawards of the Pleistocene dune. A fall in sea level from the transgression's maximum may have helped to extend the width of the barrier. At the same time the lagoon has shallowed, the complex pattern seen on the aerial photographs suggesting that prior to complete drainage meandering mangrove channels occupied most of this flat. It was probably at this stage that the 20-foot dune ridge in front of the Pleistocene dune, was removed. Today the lagoon area is occupied by halophytic vegetation and salt flats with a mean height of less than 1 foot. During the higher tides of the year it becomes inundated. Erosion is today narrowing the width of the outer barrier at its southern end, though material eroded from the south is still being added to the northern end. There is no obvious reason for this erosion. It is suggested that a diminishing sand supply from the Elliot River may be responsible. Fresh movement of sand is also transgressing across the older ridges of the sequence in irregular sheets, even at the southern end. Erosion may have initiated this movement in the south but close to Cape Upstart a wide beach and an open aspect appear to be the sole influences.

Several aboriginal midden sites occur on the outer barrier. Shell from one such site located on one of the rearmost ridges of the sequence was submitted for radiocarbon assay. It was hoped that the camp site, which included hearth stones and crudely worked implements, may have been occupied when the sea was just seawards. The result of 750 years ± 80 B.P. (GaK-2013) was disappointingly young and it is suspected that much of the barrier was in existence by the time the camp site was occupied.

On the western side of the red Pleistocene dune, the suspected mid-Holocene beach is fronted by seasonally inundated salt flats drained by a few mangrove-fringed creeks. Lack of significant sediment supply to this area has produced no beach ridge or barrier formations. In places mangrove channels have left meander scars cutting into both Holocene and Pleistocene deposits but these all post date the deposition of the white Holocene sands. A salting cliff is also extending the salt marsh into the beach and dune.

The shallow borehole evidence shown in figure 3.8 tends to support the interpretation of the sequence of events. A borehole at the top of the Holocene beach showed red dune sand to at least 8 feet. Just below this at the top of the beach, 2 feet of Holocene sands overlap the red sands. In the centre of the beach a borehole indicated that below 4 feet the material became progressively heavier, probably the result of leaching of clays from the upper horizons. At a depth of approximately 7 feet, or 4 feet above M.H.W.S. is a compact layer consisting of mottled sandy clay which may be the surface on which the Pleistocene dune rests. The fourth bore was put down on the salt pan in front of the Holocene beach, but in line with the former 20-foot Holocene dune. The upper 2 feet consisted of heavy black clay, deposited under still water conditions in the lagoon. This overlies 1 foot of coarse grey sand, apparently the remnants of the eroded dune or beach ridge. The coarse sand, in turn, overlies a sandy mud containing mangrove fragments. This lay below the water table and no bottom was reached at a depth which put the deposit at slightly more than 3 feet below M.H.W.S. This deposit is apparently that of an earlier lagoon, possibly the one around which lived the shells giving a date of 7530 years B.P. This borehole would seem to confirm the idea of successive breaching and reforming of a barrier during the transgression with alternating sheltered water - open water environments.

Sands from the various formations were compared both for their size characteristics and for carbonate content. The results are given in Table 3.1. All samples have similar size characteristics, the positive skewness of all four pointing to an aeolian origin. This may be surprising for the white sands, but the sample was taken from the upper part of the beach and windblown material could easily be incorporated. The Pleistocene dune has only a very low carbonate content. It is not much higher for the Holocene sands though the older white sands have twice the carbonate content of the more recent outer barrier. This is a reflection of the origin of the sands. The white sands

Table 3.1

Analysis of Cape Upstart Sands

Sample	Mean size (ϕ)	Sorting (σ)	Skewness	Kurtosis	Carbonates (excluding whole shell)
Forward dune, outer barrier	1.6585	0.7152	0.1632	3.2563	2.4%
Inner dune, outer barrier	1.5177	0.6573	0.9582	5.8447	3.6%
White sands	2.1052	0.9356	0.2187	3.2808	6.4%
Red sands	2.2790	0.5456	0.1530	4.1512	1.2%

XV Cape Upstart. Pleistocene dune ridge with mid-Holocene beach at base.

XVI Upstart Bay near R.M. Point. Pleistocene shoreline in immediate foreground.

incorporate shell material from earlier lagoons whilst the outer barrier sands originated more exclusively from the river sands of the Elliot River. There are, however, no appreciable differences in the roundness of each of these sands, each being sub-angular to sub-round, though there is a distinct lack of heavy minerals in the older white sands. The sands of the outer barrier carry a small heavy mineral assemblage.

The Shores of Upstart Bay
(fig. 3.9)

The western shores of Upstart Bay south of Beach Mount are at present marginally within the sedimentary regime of the Burdekin delta. Refraction of south-easterly waves around Cape Upstart is sufficient to give a slight southerly drift of finer material south of Beach Mount. (fig. 3.10). However, it is clear that in the past a larger contribution has been made by the Burdekin to the sediments of this coast. In addition, a number of small streams emerge on the coast which locally have added significant amounts of sediment.

These small streams rise in the low ranges some 8 miles from the coast and are generally intermittent. They then pass over a low angle pediment with isolated outcrops, but with the overlying colluvial deposits increasing in depth seawards. The majority of these deposits are considered Pleistocene in age, with a veneer of Holocene sediments along the streams, which are deeply incised some 20 or 30 feet below the general level of the plain in their lower reaches. Recognisable beach deposits lie as much as 4 miles from the coast and traces of many old beach ridge systems can be seen, generally trending between the occasional solid outcrops which emerge through the alluvial deposits. These

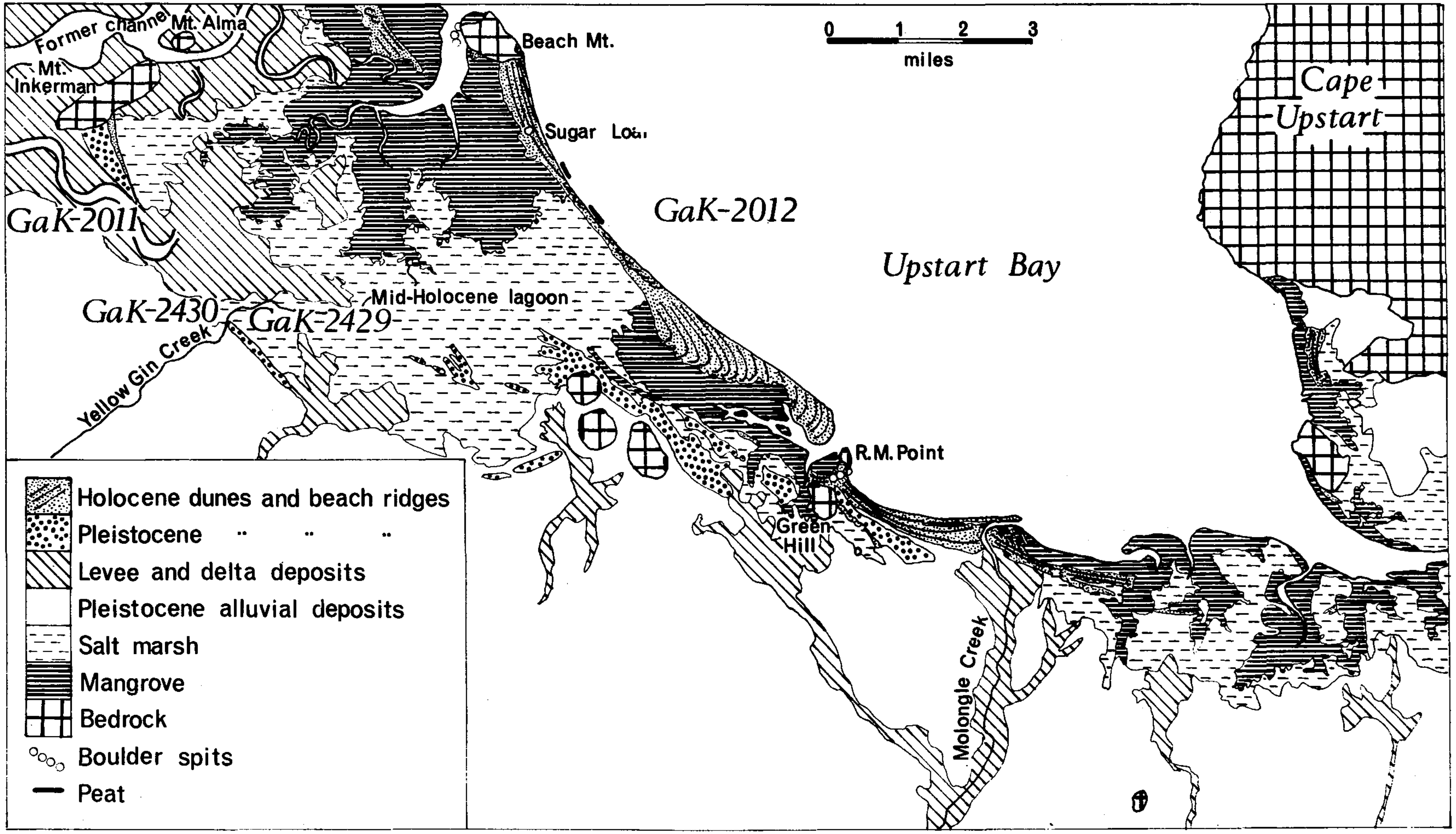


Fig. 3.9 Upstart Bay area.

outcrops in the north are mostly granitic, but in the south particularly around Green Hill, tend to be basic in composition.

The beach ridge deposits are again separable into two distinct phases as in the Cape Upstart area. The older series comprises ridges and dunes in which the material shows evidence of severe weathering. Where these shorelines have a more easterly aspect they are in the form of low symmetrical dune ridges up to 30 feet high made up of red oxidised sands similar to those of Cape Upstart. One of these dunes, south of Mount Inkerman is calcareous and reaches a height of 45 feet. Where the shoreline has a more northerly orientation, dune development has been stunted and the ridges are lower, paler in colour, but with a much higher clay content than is found in the ridges of the younger series. The younger series is comprised entirely of fine or medium sands, and though humus has been added to the upper part of the profile, little soil development has taken place.

The older shoreline is well-developed around Green Hill where it exists as a dune about 25 feet high composed of red oxidised sands which in the core of the dune are extremely well compacted. The dune trends south-east from the outcrop for about a mile where it has apparently been truncated by a former distributary of Molongle Creek. The dune was continued northwards from Green Hill in front of a series of low domes which, although having no outcrop, appear to be solid rock. The northern-most of these low hills has a complex series of clayey beach ridges attached to its northern side which trend north-westwards towards the Burdekin delta. They are truncated only half a mile from their anchor point but remnants of two further series, apparently older, occur further landwards. All three of these shoreline series are considered to belong to the same

Fig. 3.10 Wave refraction, Burdekin delta. South-easterly waves, 5 second interval, 20 wave crest spacing.

transgression, but mark different periods in the aggradational sequence of the coast or in the regression from the oldest shoreline.

This oldest shoreline can be traced in fragmentary form from the northern-most of the low hills, across Yellow Gin Creek and northwards to Mount Inkerman. South of Yellow Gin Creek the ridge is low and consists of weathered clayey sands. In the banks of Yellow Gin Creek, a section through the ridge is exposed which shows the lower portion to consist of an ancient beach rock. This is in the form of a coquinite with an 89.2% carbonate content. Small pieces of coral or calcareous pseudo-morphs of coral are also found. The beach rock, which is much more friable than any modern cemented beach deposit, has an exposure of about four and a half feet the upper level of cementation being at approximately 6 feet above M.H.W.S.

The northern end of this shoreline consists of a 45-foot dune attached to Mount Inkerman and truncated at its southern end by a former distributary of the Burdekin River. This dune, consisting of red calcareous sands, is remarkable in the occurrence of dune calcarenite which is exposed in a railway cutting through the ridge. It outcrops mainly in the frontal part of the dune, no lithification being observable in the rear section though calcarenite may occur here below the level of the railway cutting. The greater concentration on the seaward side of the ridge is considered to reflect the accumulation of coarser shell debris on this side and the consequent provision of more carbonate material for leaching to lower horizons. The dune sand has a carbonate content of only 5.6% on the surface but rapidly rises to over 25% in the interior. The calcarenite has a carbonate content of 36.9%, the remainder being sub-angular to slightly rounded quartz sand with a small heavy mineral assemblage. Details of the siz analysis of the sands are shown in Table 3.2. The surface of the calcarenite is irregular, rising at its highest point to within one foot of the surface and having a maximum exposure of about 10 feet. When unconsolidated sand is removed from around it, the calcarenite displays an extremely honeycombed and branching morphology, even at depth, apparently representing an early stage of consolidation (Jennings, 1968, p.56).

Dune calcarenites are common along the western and southern coasts of the Australian continent from Shark Bay in Western Australia to western Victoria and north-west Tasmania (Fairbridge, 1950), (Jennings, 1968), where beaches often have a carbonate content over 90% (Bird, 1963). In contrast, lithified dune sands are rare on the east coast where most sands are quartzose. No previous finds of calcarenite have been reported from tropical Queensland. The high carbonate content for the sands is consistent with other similar situations along the present coast of the study area wherever a major headland occurs. In such environments shelly organisms abound and shell debris is constantly supplied to the adjacent beaches. This will be discussed in greater detail in Chapter 6.

A sample of calcarenite was submitted for radio-carbon dating. Although the cementing $CaCO_3$ is derived from the original biogenic sand of the dune, cementation involves solution and precipitation which will introduce fresh CO_2. Thus the resulting date (GaK-2011) of 25,150 years ± 1050 B.P. may be considered minimal. However, a date of 26,900 years ± 900 B.P. was obtained for cemented shell material from the beach rock exposed in the banks of Yellow Gin Creek by a research team from the Coastal Studies Institute, Louisiana State University (J.M. Coleman, pers. comm.). The importance of these dates to the chronology of late Pleistocene shorelines warranted the obtaining of a check date on this beach rock. The result (GaK-2429) of 28,900 years $^{+\ 2,800}_{-\ 1,700}$ B.P. is interesting. The compatability of the three dates may be coincidental and their significance will be discussed in Chapter 7. For the moment it suffices to say that the older shoreline in the area is definitely late Pleistocene.

At the base of the Inkerman dune is a bank of sand resembling a narrow beach and composed of brownish sands (fig. 3.11a). Though weathered and humic stained, these sands appear different from the red dune sands. Mechanical analysis (Table 3.2) confirms this for whilst the dune sands have a slight negative skewness (which nonetheless would still diagnose the deposit as dune according to Friedman, 1961, fig. 1), the lower sands have a much stronger negative skew which suggests a beach origin. These sands are not oxidised and experience of the analogous situation at Cape Upstart possibly indicates a Holocene age for the deposit. A comparable deposit occurs at the base of the Pleistocene dune trending south from Green Hill. However, remnants of a beach of white sand are also found on the landward side of this dune and the presence of salt marsh here suggests the impounding of a small lagoon, draining through the Pleistocene dune immediately west of Green Hill at some stage during the Holocene.

Certain features in the Inkerman area suggest that the possible Holocene deposits here were also the beach of a lagoon rather than an open water beach. The outer veneer of Pleistocene sands around the calcarenite is completely unconsolidated and would easily be eroded in anything but a quiet water environment, yet there is no sign of cliffing at the base of this dune. Furthermore, a borehole put down through the salt marsh deposits fronting the dune indicates the following succession

Table 3.2

Characteristics of sands from the Inkerman-Green Hill area

Sample	Mean size (ϕ)	Sorting (σ)	Skewness	Kurtosis	Carbonates
Green Hill, red dune	2.2152	0.7909	0.0298	3.4962	15.0%
Green Hill, white sands	1.8432	0.7945	0.3722	3.6848	3.6%
Green Hill, Holocene ridge	1.5852	0.6696	0.7267	4.0126	4.8%
Yellow Gin Creek, modern	0.8930	0.7883	0.3379	3.2432	10.4%
Inkerman, red dune	2.7960	0.5183	-0.2509	4.9955	5.6%
Inkerman, lower sands	2.8905	0.6756	-1.1779	6.4828	7.6%

Topsoil	0 to 8 feet	
Clay	8 to 20 feet	
Mangrove mud	20 to 25 feet	
Silty clay	25 to 33 feet	
Clay	33 to 40 feet	
Tight clay	40 to 55 feet	
Hard grey clay	55 to 65 feet	
Decomposed granite	below 65 feet	(I.W.S.C. bore J10).

No high or medium energy deposits are seen in the column. Clays and mangrove muds suggest a lagoonal environment, especially when compared with the Pleistocene beach deposits (shell grits at Yellow Gin Creek area) and the coarse to medium sands of the present Beach Hill beach of the same area. The height of the salt marsh surface is 2 feet above M.H.W.S. The beach deposits at the base of the dune range in height from 4 to 14 feet. This is strongly suggestive of a higher sea level at the time of the lagoon. Two former distributaries of the Burdekin entered the lagoon. Their position in the Holocene chronology will be discussed in the next section of this chapter. One entered the lagoon through the gap between Mount Inkerman and Mount Alma a feat which could only have been accomplished during a higher sea level for the bedrock col between the two outcrops lies above present sea level. The other distributary flowed behind the Inkerman dune and cut through it to the lagoon about a mile south of Mount Inkerman. Both deltas built by these distributaries appear to have been of the digitate type, confirming the low energy environment of the lagoon.

The presence of a lagoon in this area indicates the formation of a coastal barrier to seawards. A barrier does exist today, trending south from Beach Mount and Sugar Loaf. There is no firm evidence to suggest that this was built to

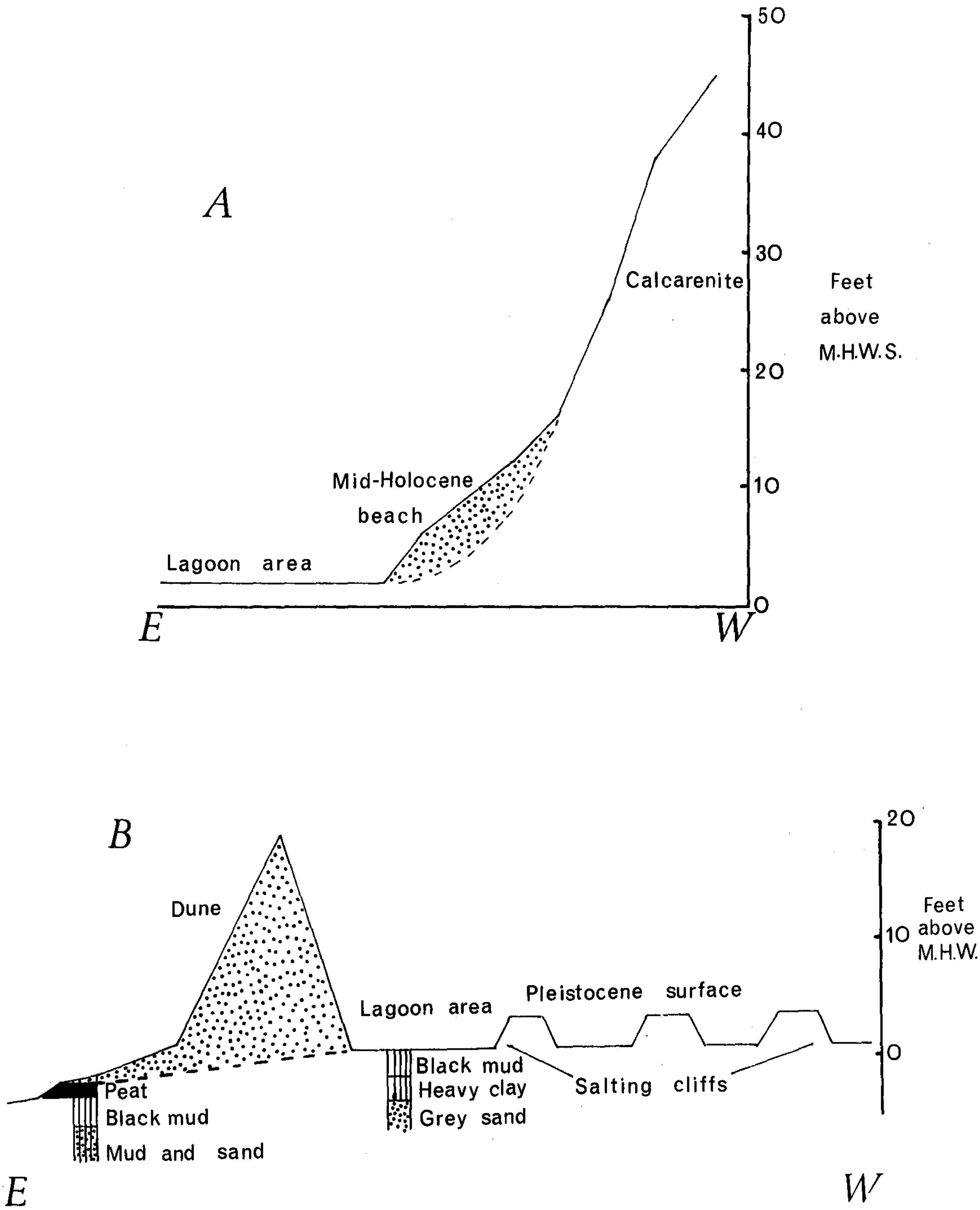


Fig. 3.11 Sections. A, Inkerman dune; B, Beach Mount Beach.

a higher sea level, but it is a complex feature indicating at least two phases of construction and at present undergoing erosion. At its northern end, around Sugar Loaf the barrier consists of two distinct ridge systems, the older one being truncated by the line of the present beach. The southern end of the barrier, just north of R.M. Point consists of the isolated recurved ends of a series of spits, probably the remains of the older beach ridge system further north. Although fresh dune sand has been added to the summits of these ridges beach erosion has exposed older soil profiles in the truncated sections of the ridges. Unfortunately no good section is observable, but it is possible that this series of spits was the barrier which enclosed the Inkerman lagoon.

The outer ridges are much younger, but these too are suffering erosion and in the centre of the beach, both older and younger systems have been completely removed, and only a narrow active dune remains. Boulders of beach rock are sometimes washed up from off-shore, probably from the cemented basal portion of the eroded barrier. Complete removal of the barrier systems in the centre of the beach means that erosion has eaten into the deposits of the former lagoon. Thus mangrove peats with root stumps up to 1 foot across occur along the whole of this part of the beach from about the mid-tide level to within a foot of M.H.W.S. Although mangroves grow within this range today, stands with trees of the size indicated are generally limited to the shallow but permanently inundated areas. The evidence though not confirming the postulated higher sea level at the time of the lagoon, certainly does nothing to deny it.

A sample of root stump from the mangrove peat was submitted for radio-carbon assay, giving a result (GaK-2012) of 3,680 years ± 90 B.P. The barrier must certainly have existed to the seawards of the present beach by this date. The height of the sheltered water beach deposits at Mount Inkerman suggest a higher sea level of at least 10 feet above present, as it is not envisaged that beach deposits could be thrown more than 4 feet above high water in the enclosed waters of the lagoon. The peat deposits may indicate a sea level slightly higher than today, though not 10 feet higher, and the date of 3,680 years probably belongs to the regressive phase from the highest level reached.

The extent of the lagoon is indicated in figure 3.9. The major distributary of the Burdekin at the time the older ridge series of the outer barrier was built, was close to the present mouth (see below). The southern edge of the lagoon was irregular, extending up some of the small creeks. A shell deposit occurring at the maximum height of present tides in Yellow Gin Creek just behind the Pleistocene ridge was thought to be a deposit from this period. It contains small shells of <u>Cerithium</u> sp. and <u>Turritella</u> sp. of marine mud flat environments. However, a radiometric date (GaK-2430) indicated the deposit to be modern (0 $\pm$ 100 years B.P.). Between this point and the coast, the edge of the lagoon is difficult to trace exactly. It was formed by the alluvial surface on which the Pleistocene ridges sit, and has subsequently retreated by sapping of the salting cliff which marks the limits of the present salt marsh. This has isolated small "islands" of the Pleistocene surface which stand consistently 4 feet above the salt marsh level. Figure 3.11b shows a surveyed section across this area from the Beach Mount beach. The flat immediately behind the modern dune was part of the lagoon. Further inland are remnants of the Pleistocene surface, isolated by extension of the salting cliff as described by Coleman <u>et al</u> (1966). Augering down to 6 feet below the surface in the present beach and just behind the dune indicated mangrove muds with interbedded fine sands.

South and east of R.M. Point the outer Holocene barrier is more continuous. It is strongly influenced by the present and former deltaic areas of the small streams of the coast. These become fewer and smaller towards the head of Upstart Bay and here mud flats, saltpan and mangrove predominate with a few discontinuous cheniers close to the occasional stream.

It is evident that Beach Mount, Sugar Loaf and R.M. Point were islands prior to the formation of the outer barrier, and each has a small spit on its leeside reminiscent of those described on the islands in Chapter 2. Beach Mount has an extensive sand flat on its south-western side and a coarse boulder spit rising to about 10 feet trailing from its north-western point. A number of shore platforms are developed on the seaward side of Beach Mount. These will be discussed further in Chapter 7. Sugar Loaf has a small sand flat on its landward side. R.M. Point has a 15-foot high boulder spit trailing to the south and onto which the Holocene barrier is attached. The origin of these spits is considered to be the same as that described in Chapter 2. The height of the boulder spits strongly suggests construction during a higher sea level.

The Burdekin Delta in the Ayr Region

The area covered in this section is that of the four levee systems of Sheepstation Creek, Kalamia and Plantation Creeks, Rita Island and the Lakes Plain-Inkerman area, and of the coastal deposits to seawards of them. Essentially the area consists of coalescing levees of former distributaries of the Burdekin with intervening narrow marshy

XVII Burdekin River and delta looking downstream from The Rocks.

XVIII Burdekin delta, mouth of the Anabranch.

tracts of fine grained floodplain deposits and a larger area in the southern part of the delta south of Home Hill which is apparently a little modified part of the late Pleistocene surface (see above). Seawards of the levee banks, marine deposits predominate and have depths of over 100 feet along the east coast. The surface configuration and deposits of this eastern sector of the Burdekin delta here, belong to the period since the Burdekin has passed through the narrow gap at The Rocks.

During the latest low stand of the sea in the late Pleistocene, the Burdekin flowed west of Kelly's Mount, though the form of the late Pleistocene and bedrock surfaces (fig. 3.3, 3.4) suggests that a small but deeply incised stream flowed eastwards from the Kelly's Mount - Stokes Range col. The Holocene transgression appears to have resulted in rapid aggradation of the delta west of Kelly's Mount, which maintained the coastline not much farther inland than it is now, even during the most rapid phases of the transgression (see above). In contrast, the smaller streams of the eastern delta could not aggrade at a sufficient rate to prevent the migration of the coast landwards. It has already been indicated that marine deposits are found as far inland as a line joining Ayr and Home Hill.

The height of the gap at The Rocks is 20 feet above M.H.W.S. (reduced level from I.W.S.C. delta). Thus, as the early Holocene Burdekin infilled its former channel in the Pleistocene surface it slowly raised itself to a level at which, during flooding it could be diverted through The Rocks. The gradient of the lower Burdekin of this time as suggested by the gradient of the old levee crests was about 3 feet per mile. There is strong evidence to suggest that the Bowling Green Bay coastline at the time of diversion was approximately 10 miles north of The Rocks. With the given gradient, and a direct course being taken to the coast, when the bed of the Burdekin first stood at the level of The Rocks gap, the shoreline could have been some 30 feet lower. Thus from these calculations the diversion would have been possible once sea level had attained a height above 10 feet below present. However, it is not certain that the incised stream which headed eastwards from the diversion area, prior to its capture of the main Burdekin, had actually cut down to bedrock and the original col may have stood slightly higher than the present gap. Also, the chances of the diversion occurring immediately the Burdekin had aggraded to a suitable level are remote, but the chances would increase rapidly towards the maximum of the transgression. However, the early Holocene delta of the Barratta Creeks area has been buried beneath what in places appear to be partly marine deposits. Thus it is considered that the diversion through The Rocks took place prior to the attainment of the Holocene maximum sea level. As evidence from the delta and adjacent areas indicates that this was about 10 feet above present, it is tentatively suggested that sea level at this time stood close to its present position, but still rising.

Once the course between Kelly's Mount and the Stokes Range had been taken, the shorter passage to the sea and resulting steeper gradient (as much as twice the steepness of the western channel) resulted in a new, though short-lived, period of incision, an incision which would have given some permanence to what otherwise appears to be a highly unlikely course.

Subsequently, the Burdekin has held a number of different courses in the Ayr region. There is a marked contrast in the morphology of the distributary areas which have flowed eastwards to those which flow northwards into Bowling Green Bay. The eastern part of the delta is directly open to the east and, with refraction around Cape Upstart, can receive the south-easterly waves generated by the trades in a medium energy form (fig. 3.10). In contrast, the northern coast, even allowing for the absence of Cape Bowling Green in the earlier history of the area, is one of low energy. The effects are seen in the morphology of the levee systems. Those flowing northwards, mainly the Sheepstation Creek system, appear to have built outwards as jetty or digitate deltas, with only small amounts of material being trailed westwards by longshore drift to form beach ridges. The eastward flowing systems, however, do not appear to have been able to build outwards at the same rate and their sediment load has been rapidly drifted northwards in the form of beach ridges and spits, the largest and most spectacular of which is Cape Bowling Green itself. Details of this eastern coast are seen in figure 3.12.

Close study of the beach ridge systems of the present and past distributaries confirms that major series of ridges on the eastern coast have always built up northwards of the major distributaries. This helps in the reconstruction of delta chronology. Only south of Beach Mount does there appear to have ever been an appreciable southwards movement of material (see Upstart Bay section above). However, it is also apparent that at times of flood, abandoned channels and distributaries may come into temporary operation again and minor shorelines can be constructed after the abandonment of a distributary as a major channel. There is nothing to suggest that at any one time the Burdekin was utilising more than one major distributary system, though several minor distributaries belonging to the one levee system may have operated together.

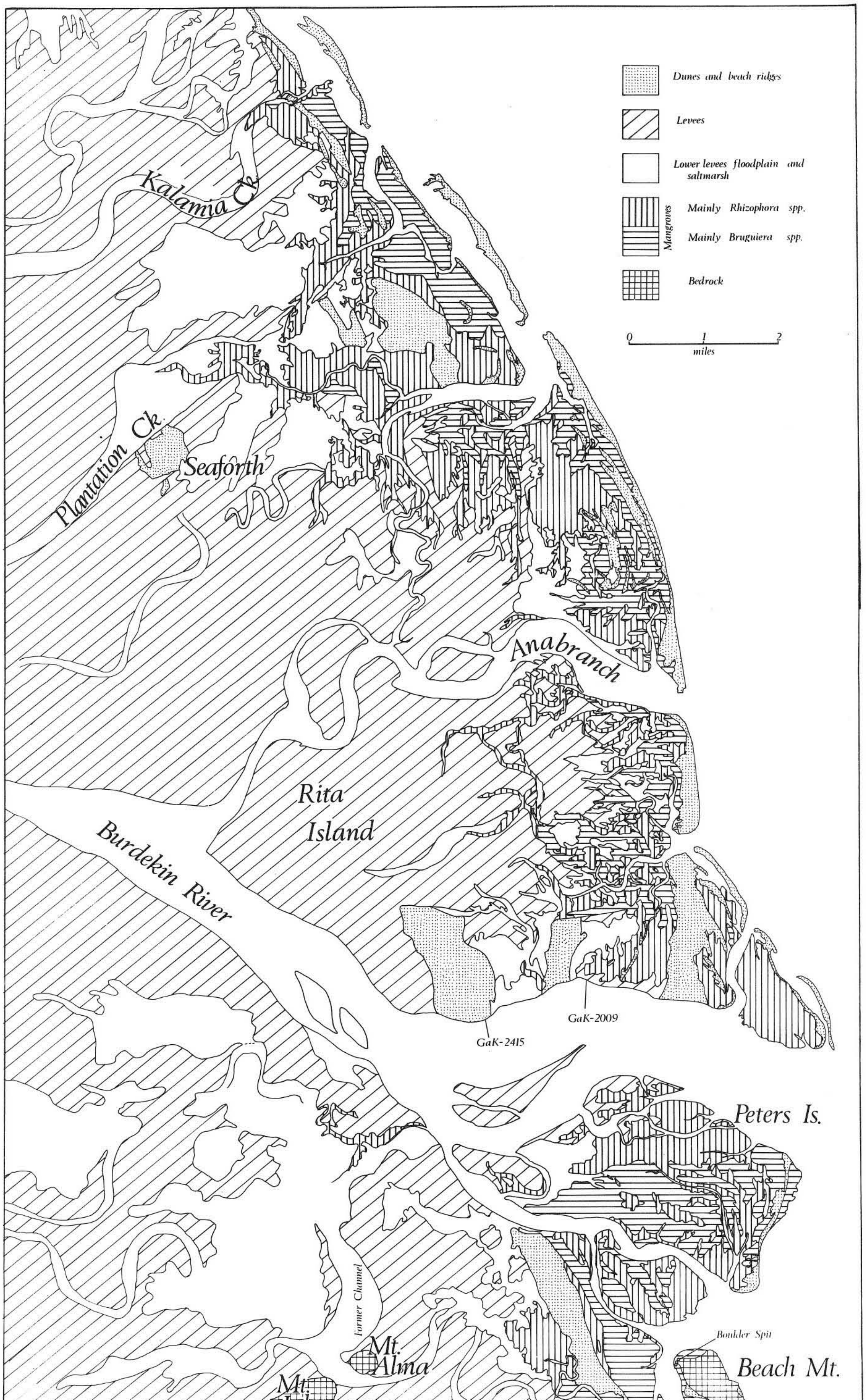


Fig. 3.12 The east coast of the Burdekin delta.

In places, the levee systems are superimposed over one another, or the beach ridges of one system are so orientated that they could not possibly have been constructed if an adjacent levee system had been present. Careful observation, especially on aerial photographs, but with ground checks, has made it possible to put the levee systems into sequence and to interpret the chronology of the area in the second half of the Holocene period. Radio-carbon dating confirms this chronology.

The oldest distributary system, by coincidence appears to be close to the present mouth. Evidence will be given to show that the levee systems of the delta, and especially those close to the present channel above Rita Island are features of an older period of deposition. The levee pattern of figures 3.1, 3.12 is centred on the western part of Rita Island, with arms extending both to north and south. This would have been the logical course for the Burdekin to take immediately after diversion over The Rocks for it is the incised course of the stream which effectively captured the major Burdekin River. The southern-most arm of this distributary system built up a beach ridge sequence, remnants of which on the southern edge of Rita Island, though eroded, are still half a mile wide. A continuation of either the same ridge series or of a contemporary series trailing north from another distributary, is seen near Seaforth just south of Plantation Creek. It is also considered that the barrier which enclosed the Inkerman lagoon was built up from sediment drifted south from the southern-most of these distributaries. If this is so then further light may be shed on the height of sea level at the time of formation of this barrier.

The ridges themselves are low with intervening sandy swales only 3 feet below the crests. Erosion has eaten into the seaward sides of both the Rita Island and the Seaforth series and dunes are found up to 70 feet high on Rita Island. Soil profiles are beginning to develop on the ridges and humus staining extends to below 2 feet beneath the surface. Erosion of the bank along the southern part of Rita Island especially during the floods of February 1968, has exposed an excellent 400-yard section in these ridges, exposing the following sequence:

Top	Fine sands 12.0 to 18.0 feet
	Coarser sands with pumice 6.5 to 12.0 feet
	Coarse grits with current bedding 1.5 to 6.5 feet
Base	Fine to medium sands 0 to 1.5 feet

The base of the section is at M.H.W.S. Results of mechanical analysis and carbonate content of these sediments is seen in Table 3.3.

By comparison with Friedman's (1961) data the upper fine sands, with a negative skewness, may be diagnosed as beach sands and there would appear to be little aeolian capping on the ridges. The sands with pumice beneath, although having a slight positive skew, lie within the area difficult to diagnose between dune and beach, though by using the parameters kurtosis against skewness they clearly lie outside the range of river sands. However, the presence of rounded pieces of pumice up to 6 inches in diameter suggests a beach origin for these sands. There is little doubt about the origin of the current bedded grits as a fluvial deposit. Although the lower sands have a similar almost non-existent carbonate content, their strong negative skewness again indicates a probable beach origin.

The interpretation of the section is that the lower beach sands belong to the Holocene transgression with a

Table 3.3

Analysis of Rita Island Sediments

Sample	Mean size (ϕ)	Sorting (σ)	Skewness	Kurtosis	Carbonates
Dune sands	2.7115	0.4504	-0.7180	6.2648	2.4%
Coarser sands	2.0180	0.6366	0.0153	3.2789	1.6%
Current bedded grits	0.7267	1.0217	0.7415	2.4665	0.1%
Lower sands	1.9785	0.7521	-1.1727	4.5730	0.1%

rising sea level, that these have been buried beneath fluvial deposits possibly graded to a sea level higher than present, and that these in turn have been capped by a beach ridge sequence graded to a sea level at least 6.5 feet above present. This sequence fits the postulated pattern of diversion of the Burdekin into the eastern part of the delta. The fluvial grits are thought to indicate the first incursion of Burdekin sediments into this area in the Holocene and the overlying beach ridges to be a later part of the same sequence. The relationship of the Rita Island section to the deposits to the seawards is seen in figure 3.13. The later deposits and chronology will be discussed below.

The next levee system to be constructed was that in the south of the delta. This clearly post-dates the Rita Island system, as the digitate type delta without trailing shorelines clearly necessitated the building of the outer barrier and formation of the lagoon, which as we have seen, depended upon the Rita Island distributaries. There is a possibility that both distributary systems operated contemporaneously. However, the height of the Holocene shoreline on the Inkerman dune indicates that the lagoon's highest level was about 10 feet, or slightly higher than the level indicated by the Rita Island ridges. This again supports the idea that the first diversion through The Rocks occurred prior to the culmination of the Holocene transgression. The rising sea level towards the maximum and the period at the highest level prior to the regression facilitated the overtopping of levees and rapid changes in course within the delta. The subsequent regression has resulted in incision and a greater permanence to the river channels.

The levees of the Inkerman system are not extensive and it is probable that this course was not held for long. It can be shown that the Sheepstation Creek system has been superimposed over the Inkerman system, and that this in turn is older than the Kalamia-Plantation Creek channels. Thus the formation of the Sheepstation Creek deltaic area has been followed by a migration of the distributaries eastward and southward around the delta region. This was to be expected, for formation of beach ridge systems to west and north of each distributary, following the dominant littoral drift, would allow for easy change of course only in the opposite direction, once the levee system was over extended and breaching occurred.

The Sheepstation Creek distributaries appear to have been quite complex, and to have extended the delta outwards at least six miles from the coastline formed prior to the Burdekin's diversion. Shorelines associated with these mouths are relatively few, largely because most sediment was used in building the levee systems outward. However, the few which are found appear to be perched on the surrounding plain with a level of about 10 feet above M.H.W.S. Because of inaccessibility and lack of datum points it has been impossible to confirm this height.

Certainly this height seems to have been maintained when migration of the delta brought into formation the Kalamia Creek system. This set of distributaries came out at the apex of the delta and the sediment they carried was quickly swept northwards as an extension of the left bank levee. It was at this stage that Cape Bowling Green was initiated. As one of the longest protruding sand spits in Australia, it will be examined in more detail below. However, this too appears to have been built to a sea level higher than present, for at Alva Beach a cliff has been cut into interbedded deltaic sands and muds lying about 10 feet above the present level of accumulation of these deposits. A radio-carbon date was obtained by the Bureau of Mineral Resources (Paine, Gregory and Clarke, 1966) for carbonised wood embedded in sand near the top of this sequence. The date of 3,870 years ± 50 B.P. apparently sets a maximum age limit on the Kalamia Creek distributary, and on Cape Bowling Green.

Migration of the Burdekin to the Plantation Creek channel and then, via a number of smaller distributaries, to the Ana-branch and finally to the present mouth has initiated a series of smaller but similarly trending spits down the east coast, each one extending the delta a little further eastwards. These spits are seen to be only the latest in a long series since the delta flowed out to sea in this area, for remnants of older spits can be traced up to 3 miles inland. It is evident that the old distributaries down the east coast north of Rita Island have been in intermittent use, probably during floods, ever since they were first initiated. During large floods they are still used today and sediment is being added to the spits. Each spit has isolated an area of lagoon between itself and the levees or the older shorelines. Sedimentation in these lagoons has been rapid and the forms of deposition, as subaqueous levee banks or deltas are clearly picked out by the mangrove patterns, the Rhizophora species generally indicating the areas of deposition, Bruguiera sp. occupying parts of the lagoons (fig. 3.12). Infilling of the older lagoons inland and to the north and the transformation of mangrove into salt flat lying above high tide level, is thought to have been aided by the regression of the sea from the mid-Holocene high level.

The final migration of the delta's major distributaries to the Ana-branch and to the present channel has brought it back to approximately the same position that it occupied when first diverted through The Rocks. Modifications to the original morphology of this area appear to have taken place in the intervening period. The sedimentary history of the area is indicated by the deposits exposed in the Burdekin's banks along the southern shore of Rita Island and indicated in figure 3.13. Initially the migration of the active delta away from this area and the subsequent cessation of sedimentation resulted in erosion of the beach ridge series formerly built up. Further south, erosion seems completely to have removed any ridges of the earlier sedimentation period, though the dune which remains in this area appears to overlie older sediments. Unfortunately no clear section is available. On Rita Island dune formation appears to have accompanied coastal recession, as it has in other areas. However, the phase of recession appears to have been more complex for beneath the dunes there are mangrove muds including stumps in situ. Unfortunately the section in this part of the bank is not clear due to the continual slumping of overlying dune sands but it is highly unlikely that mangroves, normally requiring a quiet environment, could have existed on an actively retreating shore. The mangrove deposits rise to approximately 1.5 feet above M.H.W.S. and although this lies just within the range of present mangrove growth, the situation is thought to be analogous to that of the mangrove peats on the beach south of Beach Mount (see above) and that the nature of the mangrove remains suggests a slightly higher sea level than present, but lower than at the time of the beach ridges into which the mangrove surface is cut. A sample of mangrove stump has been submitted for carbon dating. The result of 3,200 years ± 110 B.P. (GaK-2415) gives a date similar to that for the Beach Mount peat. The mangrove muds are overlain by coarse sands including

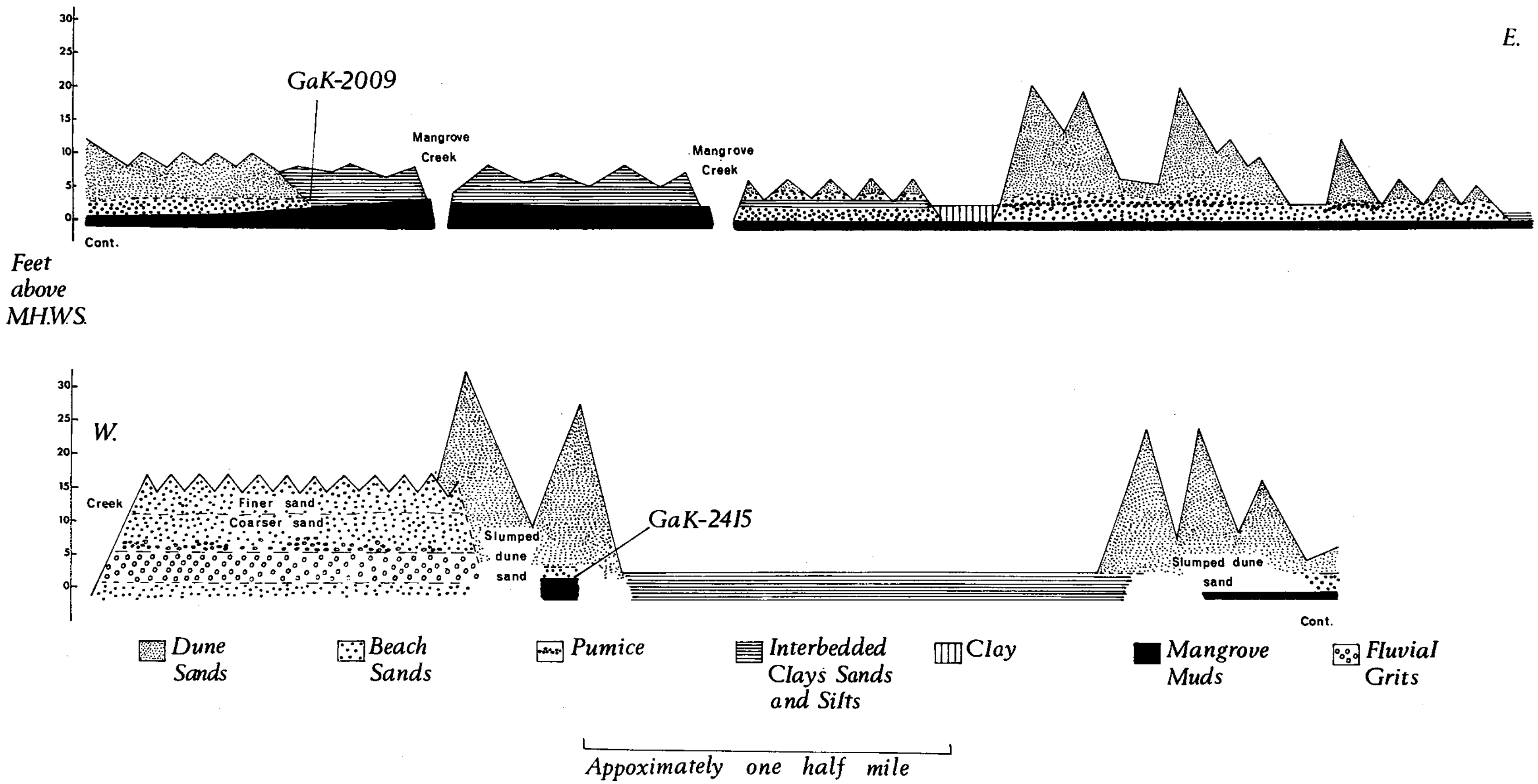


Fig. 3.13 Section along the southern shores of Rita Island.

pumice, which are in turn overlain by the dune sands. The suggested sequence for this area after the Burdekin first migrated from it is:

1. Erosion of the ridges during or after a regression of sea level.
2. Formation of an outer barrier enclosing mangroves. This outer barrier formation may well have been aided by the fall in sea level.
3. Migration of the outer barrier landwards and dune formation, the dunes partially overtopping the older ridges.

In front of the dunes is an area of interbedded silts, sands and clays rising to 3 feet above M.H.W.S. apparently indicating quiet water deltaic sedimentation when the Burdekin distributaries were some distance away. Seawards of this flat is a series of dunes and beach ridges, the dunes occurring at the rear of the sequence and rising to about 30 feet. This whole sequence rests upon a shelf of mangrove muds rising to about M.H.W.S. Seawards of the ridges the mangrove muds disappear and a variety of deltaic sediments are exposed in the bank, mostly consisting of fine sands, in places overlain by silts where the river has overtopped its banks. Beyond a small mangrove-lined creek, the mangrove muds again reappear rising to about 1.5 feet and overlain by irregular mounds of sand which appear to have been deposited as levees. A beach ridge trends northwards from this sandy area. A probable interpretation of these deposits is that they were laid down under generally quiet conditions some distance from the main Burdekin mouth which probably lay some miles to the north. However, the presence of dunes and beach ridges towards the rear of the sequence, and levee banks further seawards strongly suggests that intermittently during

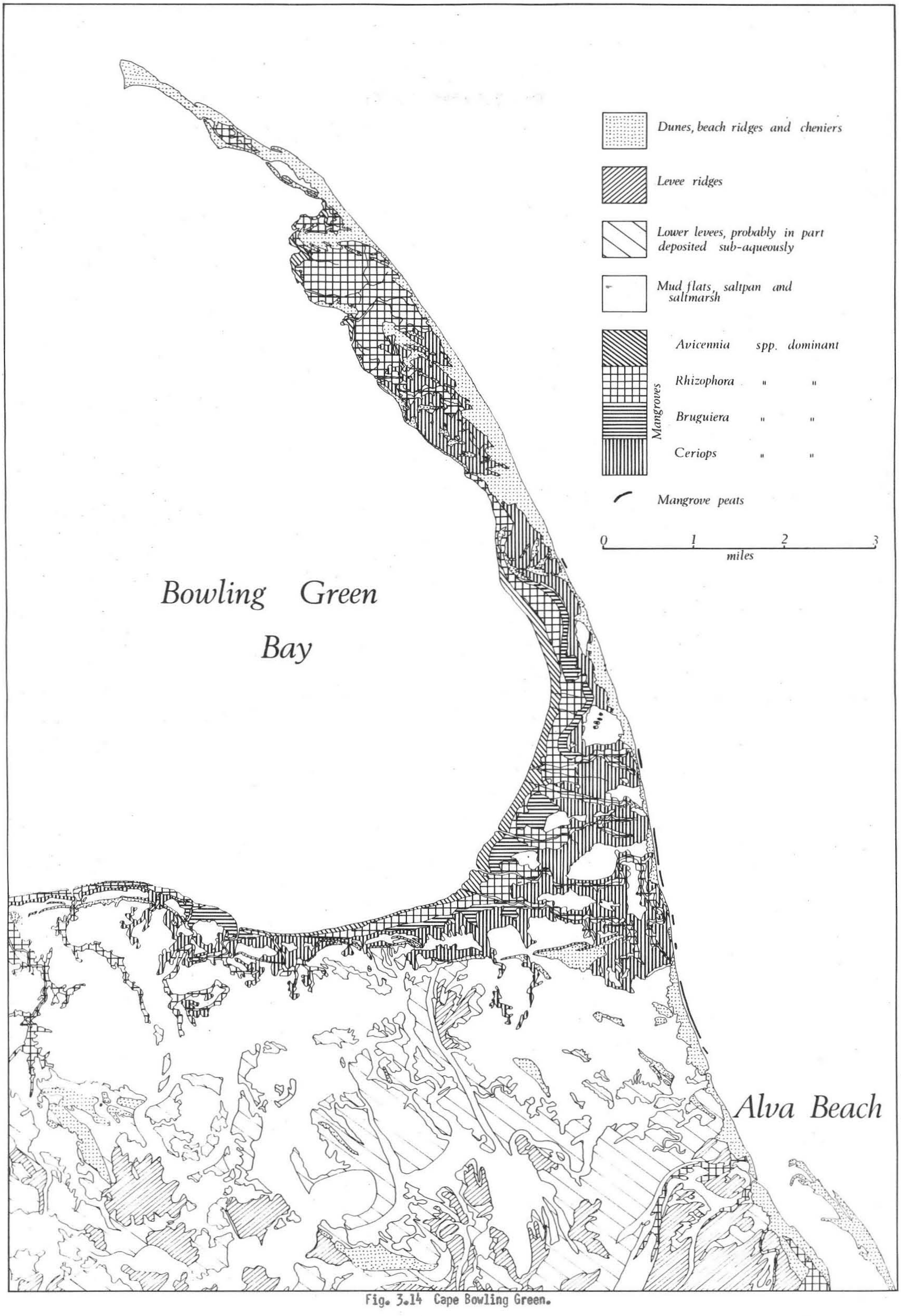


Fig. 3.14 Cape Bowling Green.

floods a flood channel operated in this part of the delta. There is no firm evidence of a higher level of the sea than present, though mangrove mud exposures are generally a little above M.H.W.S. Certainly seawards of the levee deposits the mangrove muds do not extend above 1 foot below M.H.W.S. The sequence may thus represent a regression in the order of 2 feet.

The levee area is fronted by a series of dunes and beach ridges rising to 20 feet and about 1,200 yards wide. Beach sands underlie aeolian deposits in these ridges. They represent the deposits of the Burdekin since its return to the present channel. Although this is the end of the section exposed in the Burdekin's banks, further beach ridges and spits, with intervening mangrove are found to seawards.

The rate of progradation of the delta appears to be rapid though intermittent. Shell from the deltaic sediments which front the seaward series of major dunes gave a date of 480 years ± 80 B.P. (GaK-2009). This deposit lies three miles from the present outer edge of the delta where a similar ridge is actively accumulating today. This represents an outgrowth in the order of 11 yards per year, though it is clear that within the fairly recent past the delta has extended itself about 1 mile by forming a bar behind which there has been rapid colonisation by mangrove.

Cape Bowling Green
(fig. 3.14)

Cape Bowling Green is a classic example of a sand spit with recurved lateral arms. From its base at Alva Beach to the growing tip of the spit is a distance of a little more than 13 miles. At no point away from the base is the spit more than a mile and a half wide, including the extensive mangroves which have accumulated behind the wave-constructed sand ridges. A radio-carbon date of 3,870 years ± 50 B.P. (Paine, Gregory and Clarke, 1966) has already been quoted for the deltaic deposits at the base of Cape Bowling Green and if, as seems likely, this represents the date of the start of construction of the spit, then it represents a mean annual extension of 6.03 yards per year. It is quite evident from the extension of fresh sand ridges at the northern end of the spit, that it is still growing. Comparison of the aerial photographs taken in 1961 with oblique aerial photographs taken by the writer in 1968 indicates an extension of about 150 yards, an average rate of growth of 21.4 yards per year or more than three times the estimated average.

It is evident that Cape Bowling Green was initiated as an extension of the left bank levee of the major Kalamia Creek distributary. Although the meandering of many former tidal creeks has eroded much of the former shore morphology from the base of the spit, traces of former shorelines may still be seen. They indicate that as the distributary system prograded, the sediments it was transporting became more and more under the influence of the strong drift northwards which is found along the east coast of the delta. Initially the shorelines which were forming from this distributary system were sheltered from this drift, and refraction around what would still have been the apex of the delta gave a strong east to west drift. Shorelines thus trended in an east-south-east to west-north-west direction from the distributaries. However, with outward growth, a more northerly component was introduced into the littoral drift and shorelines trended first south-east to north-west and finally south-south-east to north-north-west. At this stage the distributary sediments were directly under the influence of the refracted south-easterly waves and the higher energy environment combined with the strong longshore drift to the north to prevent any further progradation of the distributary system. The result was that all sediments were now contributing not principally to the building of a levee system as in the quieter environment to the west, but to the construction of the major spit which is now Cape Bowling Green. It is clear that since the early development of Cape Bowling Green and prior to the final abandoning of the Kalamia Creek-Plantation Creek system, a distributary did return to the area to the west. That Cape Bowling Green was in existence at this time is clear from the fact that most longshore drift and spit formation was from west to east, a situation which could not have existed if shelter had not been given from the refracted south-easterly waves. Thus in the quiet conditions behind the early Cape Bowling Green, a fine digitate delta was developed. The emergence of these shorelines and of the salt flats and mangrove swamps around them is partly the result of clastic sedimentation but, as raised deltaic deposits are visible in the cliffs of Alva Beach, it is considered that the regression of the sea from the mid-Holocene high level is also involved.

Supply of sand to the spit has been by longshore drifting. The original source of sand however, would have terminated with the migration of the major distributary area southwards down the east coast. Although the northward drift of material continued and has developed a number of new spits parallel to the shore, little of this material has reached Cape Bowling Green. Nevertheless,

XIX Cape Bowling Green.

the spit has continued to grow and another source of sand has obviously been found. It is considered that this new supply has come from the erosion of the southern anchor end of the spit and of a considerable portion of the former delta system. There is much evidence to support this. Firstly, the Kalamia Creek levees are obviously truncated on their seaward side thus exposing the sequences of deltaic deposit in the cliffs at Alva Beach. Next, for 6 miles north of Alva Beach, almost the entire length of foreshore of the spit has peat deposits exposed between tide levels. These are mangrove peats, obviously formed when the outer barrier of the spit was much further eastwards. A date of 2,060 years ± 115 B.P. was obtained for wood from this peat at low tide level at Alva Beach (J.M. Coleman, pers. comm.). Thirdly, the shoreline in the vicinity of Alva Beach is concave, whilst those of the more recent distributary areas further south are convex. Examination of submarine contours however indicates a convex area, probably marking the limits of the original delta in the Alva Beach area. (fig. 3.5). Finally, there is historical evidence (though unfortunately not quantitative) of serious erosion of the foreshore and dunes of the Alva Beach area. Thus, along the southern end of Cape Bowling Green all the original spit features have been eroded. Although the foreshore on the east coast may be wide, behind it is only a narrow dune of recent origin migrating westwards over the mangroves. It is obvious that shoreline recession along this coast is rapid for it has truncated the mangrove channels in several areas. Extrapolation of shoreline trends on the northern part of Cape Bowling Green, and of levee systems at the base, suggests a shoreline retreat at the base of the spit in the order of one and a half miles.

The reason for the erosion is related to the general coastal dynamics of a delta area. A strong supply of sediment to the area of active distributaries tends to extend that part of the delta outwards so that it protrudes as a kind of foreland beyond the general outline. When the distributaries are abandoned, sedimentation no longer exceeds the rate of removal of material. Erosion is a natural consequence, part of the normal process of coastal straightening. The deltaic coast to the south of Alva Beach has not suffered erosion to the same degree, for each distributary area has been close enough to its successor for the spit, which has trailed northwards from the mouth of each new distributary, to give it protection. Thus each spit in turn is protecting its predecessor from erosion at its vulnerable southern end, but lack of erosion has also meant that these spits have ceased growing rapidly immediately the distributary with which they are associated, has been abandoned. Subsequent growth has been limited to the odd occasion when the distributary has become operative again intermittently during floods.

As a result of erosion, recurved lateral arms are found only along the northern half of Cape Bowling Green. The more complete nature of the northern part of the spit allows an appreciation of the constructive wave elements. Sediment supply is controlled by the south-easterly waves but the general orientation of this northern end of the spit is towards the north-east, and waves from this direction are the major alignment controls. Subsidiary orientations play an important part in the morphology of the lateral arms. These appear to be initiated by refraction around the tip of the spit. However, many of the lateral arms have what are effectively secondary spits trailing from their tips to both north and south. Examination of the actively accumulating northern end of Cape Bowling Green

XX Cape Bowling Green. Note darker patches of peat on beach.

XXI Northern end of the Cape Cleveland beach ridge sequence.

indicates that this type of development, which has resulted in sandy shores on parts of the leeside of the Cape, occurs when further extension of the major spit gives protection to the lateral. This allows minor waves developing over the restricted fetch to the south-west, west and north-west, to redistribute the material of the distal ends of the laterials, giving them the appearance of winged headlands. Waves approaching from the north-west appear to be the most effective, for many of the beaches of the leeside of Cape Bowling Green are orientated in this direction, which gives them a fetch within the lagoon of the Great Barrier Reefs of more than 85 miles.

In spite of this redistribution of material the leeside of Cape Bowling Green is essentially a low energy environment, and one in which colonization by mangroves is rapid. Figure 3.14 shows the classic mangrove zonation which this area displays. The outer fringe of Avicennia marina is typically 100 to 120 yards wide, much greater than that described by Macnae (1966, 1967) for other areas of the North Queensland coast. At the southern end of the spit Avicennia, where not succeeded by a wide zone of Rhizophora and Bruguiera, may extend even further back to the edge of the bare unvegetated mud flats. The Avicennia mangrove is extending outwards as young mangroves are colonizing the shallow mud flats to the west. The Avicennia fringe is best developed at the southern end of Cape Bowling Green. It narrows and disappears almost completely about half way along the spit.

The mangrove zone behind the Avicennia zone is one of predominantly Rhizophora stylosa, a narrow zone of closely spaced trees. This in turn is succeeded by a Bruguiera zone constituting the area of highest trees. It is apparently Rhizophora which takes over as the seaward fringe north of the point where the *Avicennia* fringe disappears. Landwards the *Bruguiera* zone gives way to thickets of *Ceriops* (generally *C. Tagal*) growing densely together though normally not more than 15 feet high. Within the *Ceriops* zone are large areas of salt flat. The hypersaline conditions of these flats appear unsuitable for mangroves. They occur in greatest area towards the base of Cape Bowling Green and as this is the earliest part of the spit, constructed in a sea level higher than present, emergence is considered to have played a part in the formation of the flats.

Some Geomorphological Features of the Lower Burdekin Valley

There is good evidence in the delta of the Burdekin River for a higher Holocene sea level. The main response of the river itself to the fall in level over the last 4,000 years, has been incision, so that it now lies anything up to 50 feet below its levee crests. There is, however, no sign of any lateral erosion and no terrace development. Sixty miles upstream, at Dalbeg, the much narrower Burdekin valley has a well developed terrace. The floodplain here is narrow and the bed of the Burdekin lies approximately 50 feet below the floodplain. Looked at in isolation, the floodplain both in the delta and at Dalbeg appears to be identical, which would mean that the Dalbeg terrace was in all probability older than the Holocene transgression, the delta floodplain being suspected of having been deposited in relation to the higher level. However, close analysis of the levels of river floodplain, levees and terraces along the whole length of the lower Burdekin below the falls throws light on both the terrace and the delta floodplain

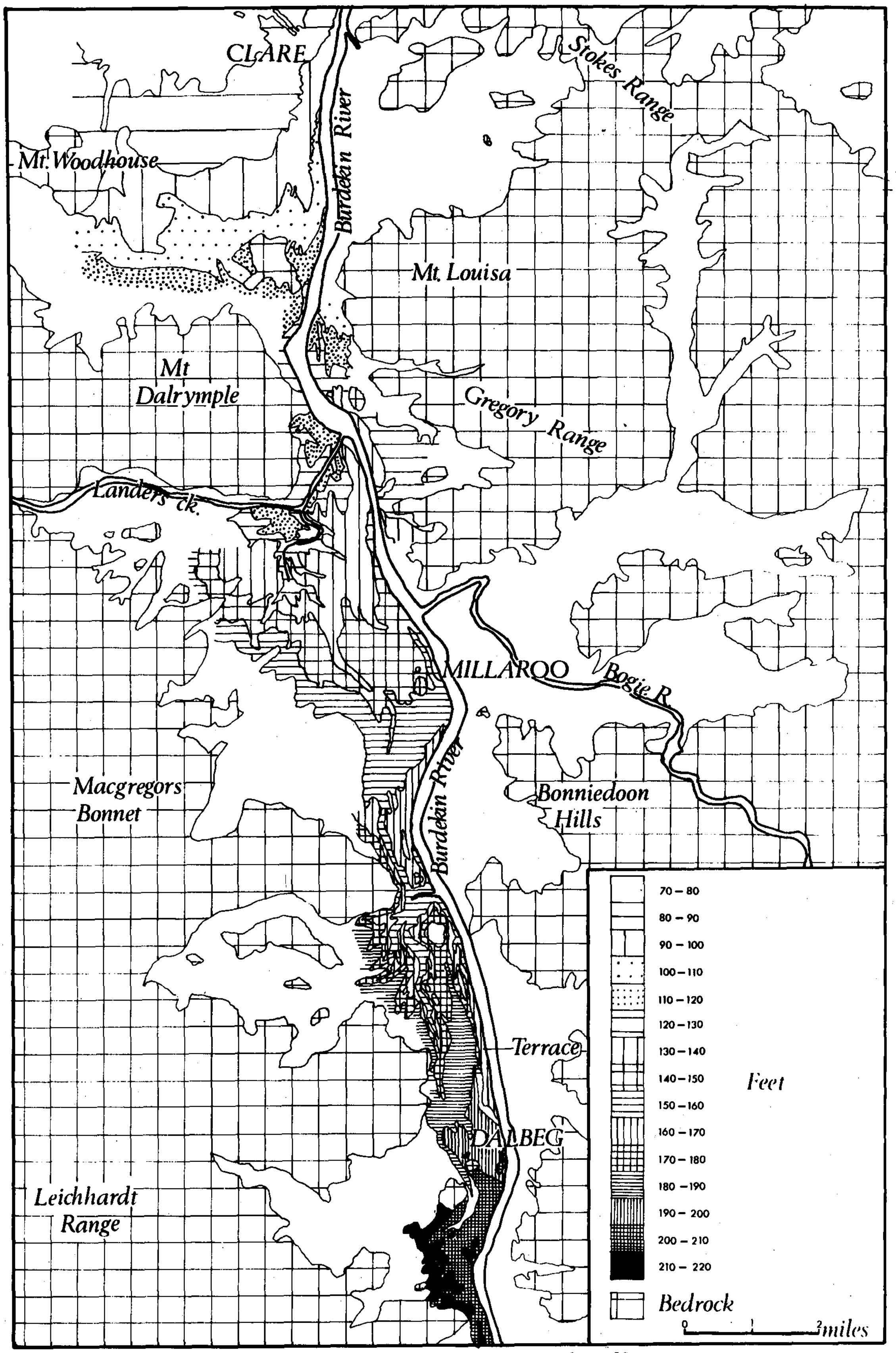


Fig. 3.15 The lower Burdekin valley.

(fig. 3.16). Data for this analysis was provided from a large number of surveys carried out by the Irrigation and Water Supply Commission.

The lower Burdekin commences at the base of the Burdekin Falls (fig. 3.15). Above the falls the valley follows a wide structural trough trending towards the south-east between the upwarp of the present Main Dividing Range, the result of early Tertiary earth movements reinforced by Tertiary and Quaternary vulcanism, and the coastal ranges formed by Pliocene earth movements (Stewart et al, 1953). At the falls, however, the river changes course to flow directly northwards across the structural alignment. The lower valley therefore alternates between open basin sections, as at Dalbeg, Millaroo and Clare, and narrow gorge-like reaches where more resistant rocks are crossed.

Figure 3.16 indicates the relationship of river bed, levee bank, floodplain and terrace levels. The degree of incision of the Burdekin into its deposits can be clearly seen. The most important point of this figure however, is the indication that the terrace at Dalbeg and not the present floodplain there, is the continuation of the delta floodplain surface. The floodplain is thus considered to be a relict feature, undergoing erosion. The reason for valley widening and the formation of a new floodplain only around Dalbeg is not clear. It is obvious that in the delta region the response to the recent fall in sea level has been simply in incision of the river into its deposits, without any valley widening but it could well be that the formation of the Dalbeg terrace has been the result of changes in hydrologic regimen (Leopold, Wolman and Miller, 1964, p.453). An increase in precipitation over the whole catchment, with increased run-off for example, would

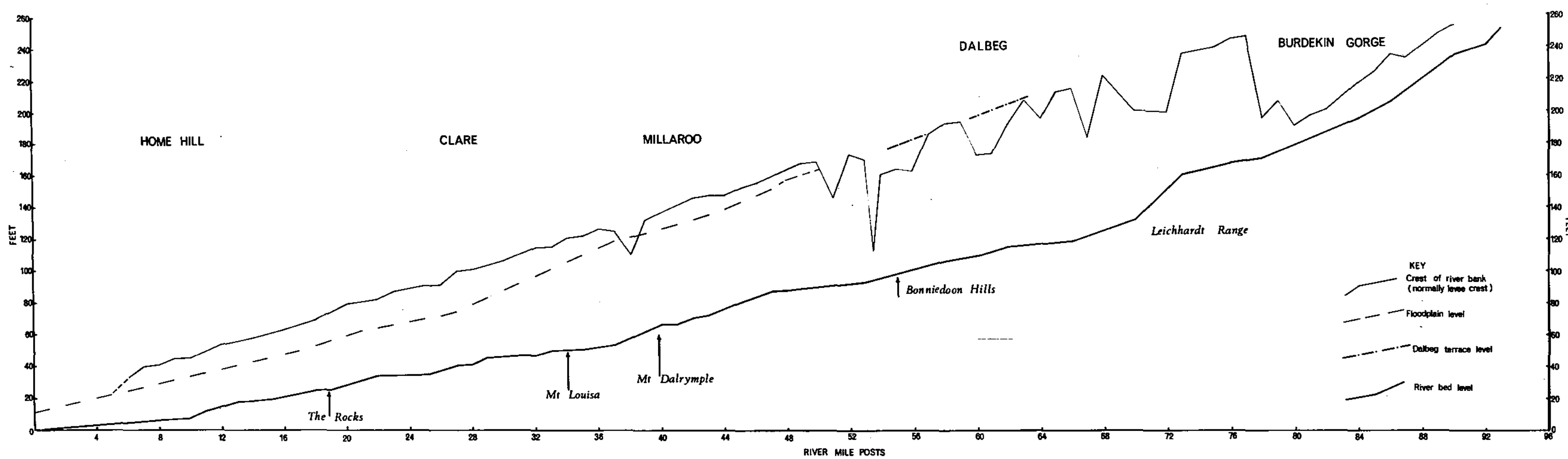


Fig. 3.16 Longitudinal profile of the Lower Burdekin valley.

result in degradation and production of a new floodplain. However, recent laboratory experiments have shown that the rate of the falling of base level can determine whether a river degrades with or without lateral erosion (Yoxall, 1969). Rapid falls will result in incision, a slower fall in lateral erosion. If these results in the laboratory were pertinent to conditions in the field then the incision in the lower Burdekin may be the result of a rapid fall in sea level, whilst the lateral erosion of the Dalbeg area results from the effects of the falling base level being felt more slowly in this higher part of the valley. This could be due to both the greater distance from the sea and also to the cushioning effect of the rock bars which occur between the delta and Dalbeg, which would tend to slow down the upstream migration of nick points. Extrapolation downstream of the new Dalbeg floodplain level finds it meeting the higher floodplain level of the delta in the region of Mount Louisa and Mount Dalrymple i.e. that above this point lateral erosion would possibly produce a new floodplain as at Dalbeg. This may be significant, for rock outcrops occurnin the river bed and in the banks at this point. Whatever the reason for the terrace formation at Dalbeg it is clear that conditions which produced the delta and lower valley floodplain and levee system, were different from those existing today.

The Barrattas Deltaic Area
(fig. 3.17)

From the evidence presented so far, it is clear that the area between Kelly's Mount and the Haughton was the major deltaic area until the diversion of the Burdekin through The Rocks. This is, therefore, a very important area for the understanding of the geomorphology of the delta.

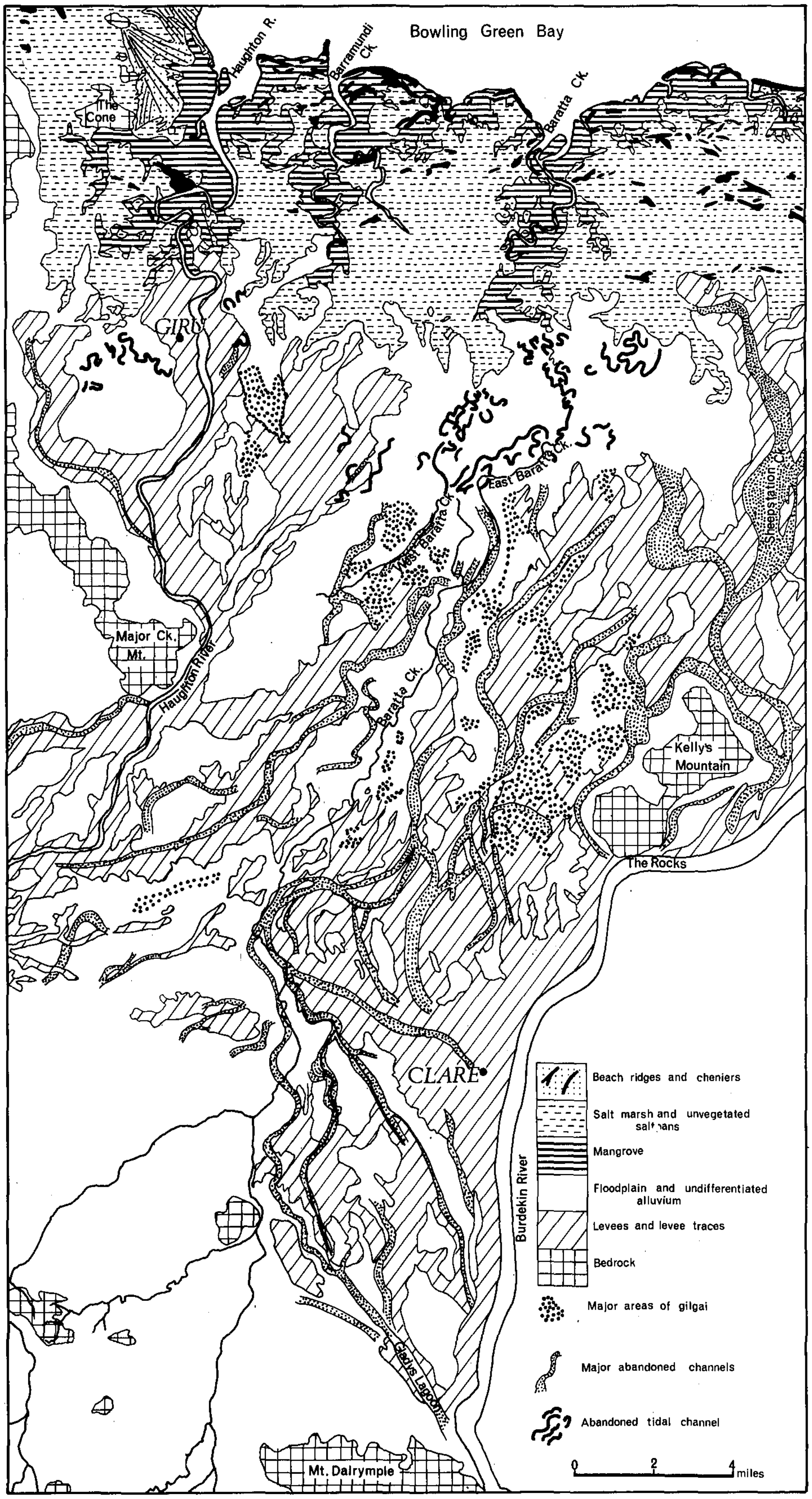


Fig. 3.17 Geomorphology of the Barrattas area.

Unfortunately since it is largely uncultivated and likely to remain so because of the heavy clay soils, it is also the area of poorest borehole records, fewest surveyed levels and greatest inaccessibility. On the ground, the general plain level is interrupted only by the occasional lagoons and shallow channels, the deeply incised courses of the East, Middle and West Barratta Creeks and by the micro-relief features such as gilgais. Except for a small number of low sandy areas, clay soils predominate throughout. From the air the monotonous impression of the morphology gained from the ground gains a new dimension. Lagoons and shallow channels emerge as a logical pattern of meandering and anastomosing courses typical of a major deltaic area, though the present day drainage pattern of the Barrattas takes little heed of the former deltaic system. On the ground this anomaly in the drainage is reinforced by two further anomalous features. First, there is such a general lack of relief in the greater proportion of the Barrattas area that normal deltaic features such as channels and levees do not stand out to anywhere near the same degree as in the present delta area. Secondly, there is a lack of contrast in the surface deposits which are normally clay, without the usual sand and gravel deposits of channel beds or the finer sands and silts of levees. This area has its deltaic morphology buried, at shallow depth, by a later clay deposit. Only occasionally do silty levees protrude through the clay cover (near the main Townsville-Ayr road these are well picked out by small patches of cultivation of sugar cane or sorghum). Channels are normally infilled though small rises do exist occasionally in the region of the former banks, especially where the old course is still in use as a Burdekin floodway. It is clear that the differentiation possible from the air is largely the result of tonal gradations in the vegetation cover, itself dependent upon the much more variable sub-soil conditions.

Evidence from boreholes strongly supports this interpretation for, in the few records available, those which appear to occur in channel or levee areas generally have coarse sands and gravels within 25 feet of the surface. Permeation of the overlying clays into the coarser deposits has in some cases made the identification of the Pleistocene surface difficult in this area. The nature of the area means that exposures of the deposits are rare. However, a mile south of the main road, and two miles east of the Haughton River is an old quarry which has been excavated through the overlying clays into the sands and gravels. The clays here are approximately 10 feet deep and more than 20 feet of sands and gravels are exposed. The pattern on the aerial photographs suggests this area to be part of a deltaic distributary system (see below).

The Barrattas area tends to zone itself into east to west strips in which the morphology is reasonably similar. In the south, around Clare, the former levee and floodplain features of the old Burdekin system are intact and occur on the surface with modifications only in the freshness of the features. The major surface channel is undoubtedly that which branches off the present Burdekin at Clare and bends towards the north close to the Barratta Creek. It appears superimposed over an older, though still little modified, levee system immediately north of Clare, though the present Burdekin levees truncate the upper end of both abandoned systems. The morphology strongly suggests that the branch at Clare is the course of the Burdekin immediately prior to the diversion through The Rocks. Within the same zone, a levee system from the Haughton following approximately the same line as the proto-Haughton incised into the Pleistocene surface described above, extends eastwards apparently to join the Clare branch of the Burdekin. Even older, and thus less well-defined Burdekin channels branch off towards the Barrattas area just north of Mount Dalrymple (through Gladys Lagoon) and between this point and Clare. The general height of this area is between 60 and 80 feet.

To the north these levee systems tend to become less well-defined and by about the latitude of Kelly's Mount, as far as ground level survey is concerned, have disappeared almost completely beneath a layer of clay, presumably the finer grained sediments which could be carried over the top of the levees of both Burdekin and Haughton Rivers during flood. This is the zone however, in which channel traces are clearly definable from the air, though levee systems except where they protrude through the clay cover, are less easily identified. Maximum gilgai development tends to occur on the clay infill of a number of the apparent channels. Possibly two separate deltaic areas may be present, a western one occurring about a mile east of the Haughton River and extending to about the latitude of Giru, and an eastern one in the area of the Barrattas drainage area extending not so far north. Part of the Sheepstation Creek distributary system is superimposed over and across the eastern-most deltaic area.

This second zone extends down to an altitude of below 20 feet just north of the main Townsville to Ayr road. It is succeeded northwards by a narrow and irregular fringe, best developed between the two presumed deltaic systems, which consists of gently sloping partly saline country scarred by numerous abandoned channels of a highly meandering drainage system. The great sinuosity of these channels is matched in the area only by tidal creeks with mangrove fringes. The origins of such meanders have been discussed by Whitehouse (1944) and Twidale (1966) in the Gulf of Carpentaria. Although there is little altitudinal data available, it appears that these abandoned creeks lie between 5 and 15 feet above the range of similar features today. The pattern is certainly unrelated to the major drainage pattern of the deltaic areas and in places has eroded the older traces. The present drainage pattern, in particular that of the Barrattas Creeks, is partially influenced by the older tidal creek pattern. It has already been suggested that the Burdekin's diversion occurred prior to the attainment of the maximum level of the sea during the Holocene transgression. If this is so, then the further rise subsequent to diversion would have resulted in a transgression into, and partly over, the older deltaic areas of the Barrattas, and in particular between the two postulated distributaries. This would have been a low energy area, receiving little coarse sediment, ideally suited to the development of mud flats and tidal creeks. Regression of the sea from the maximum level has stranded these creeks, though the extension of the coastal salt flats through both sedimentation and the fall in sea level, has extended the permanent drainage system into the area of the abandoned creeks, some of which have been utilised.

The wide area of salt flats with meandering tidal creeks and mangrove fringed shore, comprises the northernmost zone of the Barrattas area. Remnants of a few beach ridges or cheniers trend westwards from the Sheepstation Creek distributaries. The present coastline is largely mangrove fringed though apparently some of the small creeks are contributing some coarser sediment to the coast for they have small spits extending westwards from their mouths.

XXII Part of the Barrattas deltaic area. Burdekin River bottom right.
Scale about 1:80,000.

The most remarkable features of this coastline are the deep mangrove filled indentations now occupied by the estuaries of the Barratta Creek, Barramundi Creek and the Haughton River. Whilst the Haughton estuary, as the outlet of a moderate sized river system is explainable, both the Barramundi and Barrattas estuaries are anomalous to the size of catchment involved. Their relationship with the channel systems further south suggests that these are partially infilled channels of the former Burdekin River prior to the reaching of the maximum level of the Holocene transgression. This is strongly supported by the off-shore morphology, the soundings indicating a cuspate deltaic area (fig. 3.5). Extending from the Barrattas estuary is a shoal suggestive of a drowned levee. East to west trending shoals near the 5 fathom and 10 fathom marks have the appearance of drowned shoreline features, though they apparently trend west to east from the suspected distributaries in the opposite direction to the present littoral drift.

The morphology of the Barrattas area is suggestive of the following chronology:

1. During the early Holocene transgression the Burdekin occupied a channel incised within the late Pleistocene surface during the glacial low sea level phase. As sea level rose, at least the upper reaches of this channel were infilled by aggradation.
2. Aggradation lifted the Burdekin levee system above the level of the confining limits of the previously existing incised channel, allowing it to spread over a wider area of the Barrattas region. At this stage the Haughton joined the Burdekin as a left bank tributary close to its distributary area.

3. Prior to the maximum level of the Holocene transgression, the Burdekin was diverted through The Rocks. The Haughton now became a separate system.
4. The Barrattas delta was partially obliterated by floodplain sedimentation of the Burdekin in its new course, and by the Haughton River. At the height of the transgression, the sea may also have truncated the lower end of the former deltaic area.
5. Regression, combined with the accumulation of fine grained sediments in a low energy environment, has resulted in a wide area of salt marsh along the shores of Bowling Green Bay.

The Cape Cleveland Beach Ridge System
(fig. 3.18)

The dominant south-east to north-west littoral drift means that, unlike the south-eastern fringe of the Burdekin Delta Region, the north-western edges of the delta are very much within the Burdekin's sedimentary province. Between the Haughton River estuary and the granitic outcrop of Cape Cleveland is a series of beach ridges many of which appear to have evolved as spits trending towards Cape Cleveland, for, although the ridges are generally orientated towards the north-east, the majority have quite sharply recurved ends. Altogether there are almost 100 ridges in the sequence, apparently growing as an assymmetrical cuspate foreland typing Cape Cleveland and a number of isolated outcrops to the mainland.

The weathered appearance of some of the rear-most ridges suggests that they are Pleistocene in age, and it is evident that the ridges indicate a long period of deposition. Because of this it was decided that the series warranted a

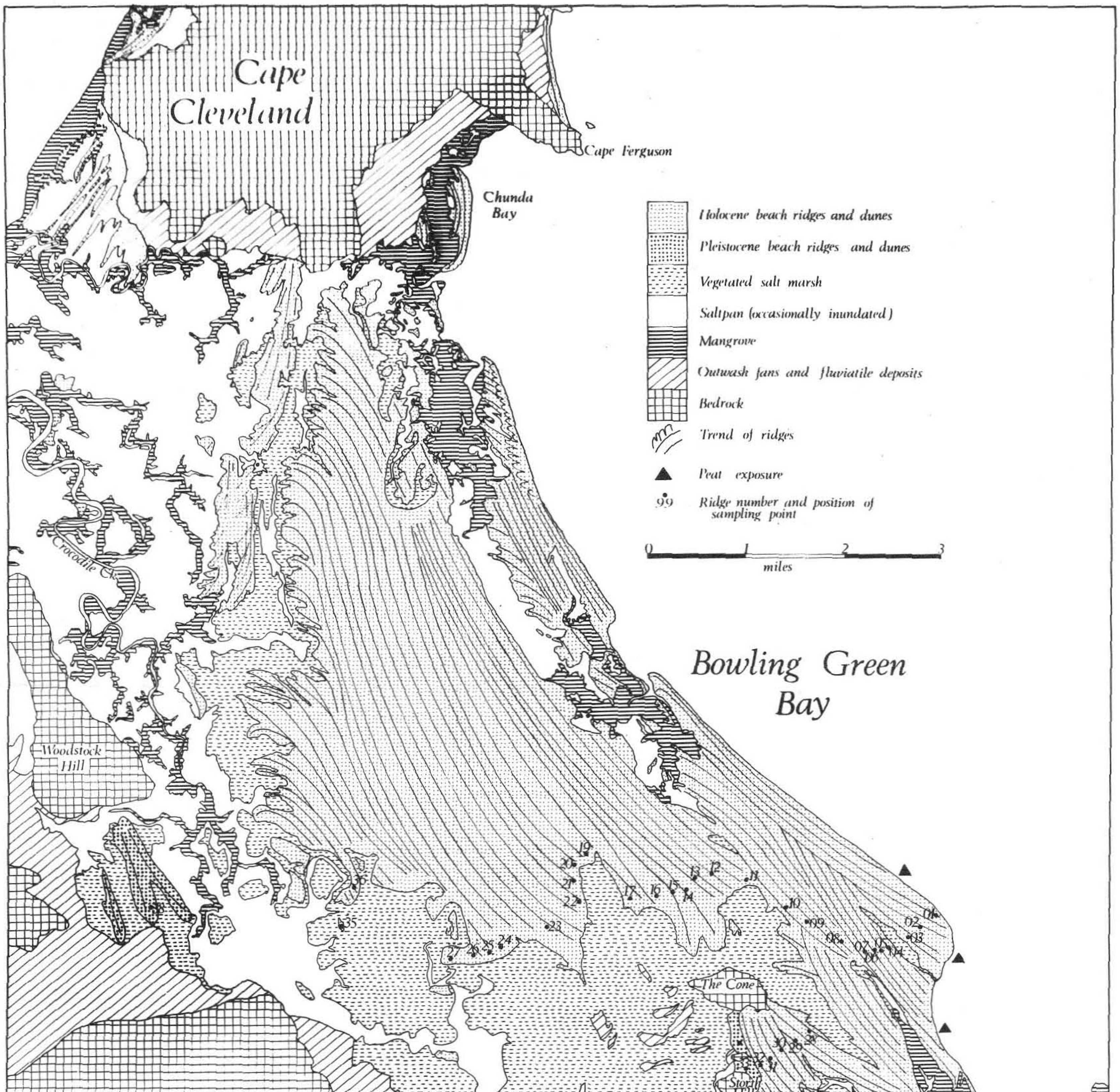


Fig. 3.18 Cape Cleveland beach ridge area.

detailed investigation. This took the form of:

i) Quickset level traverse of six and a half miles from the beach across the sequence to the rear-most ridges. The traverse had a number of legs due to the necessity of keeping close to a four wheel drive track. A separate leg was taken between The Cone and Storth Hill. Checking against tidal levels at the start and finish of the traverse indicated an accuracy to within 1 inch.

ii) Sampling of the sand from the crest of every third or fourth ridge down to a depth of 8 feet, samples being taken at one-foot intervals.

iii) Mechanical analysis of the samples, with calculation, using an I.B.M. 1620 computer, of mean size, sorting (standard deviation), skewness and kurtosis coefficients. Phi (ø) units were used throughout.

iv) Laboratory analysis to indicate the carbonate fraction of each sample.

Altogether, 36 ridges in the sequence were sampled together with the present beach, foredune and main dune a total of 324 individual sand samples. Details of field and laboratory methods used are given in Chapter 1. Results are shown in graph form in figure 3.20 and in detail in Appendix B. The numbers given to the sampled ridges are those given in the field and are not necessarily consecutive. The aims of the investigation were to attempt an amplification of the history of the Burdekin Delta, and in particular to detail the changes of sea level, and the sources of beach ridge sand.

Analysis of Results

1. Heights of Ridges and Swales

The heights of the ridges ranged from 8 to 21 feet (all heights related to M.H.W.S.), though the main dune behind the beach rises to 31 feet. Altogether the composite section (fig. 3.19) shows 72 ridges, some minor ridge crests not being indicated and also a number of ridges along this section line have been removed by erosion. Saline flats of black clay soils or salt pan with sticky black muds indicate these areas of erosion.

On a height basis alone the ridges divide themselves into a number of sections, each section having ridges of fairly uniform height and width and the different sections usually being separated by a higher ridge. The higher ridges sometimes show signs of spilling onto the adjacent ridges behind, and occasionally have blow outs and parabolic forms. Their morphology strongly suggests that they are dunes similar to the main dune behind the present beach. On the aerial photographs it is also evident that the dunes mark the outermost ridge of different sequences with slightly different orientations. This implies that horizontal unconformities occur in the series, with erosion predominating at times. The occurrence of peat on the present beach indicates that erosion is taking place now. The association of erosion and dune building has been mentioned earlier. The process has not been examined in detail but would appear to result from two factors: first, the undermining of a stabilising vegetation cover on the outermost ridge; and secondly, the widening of the beach as it is cut back into the ridges. Whatever the reasons, erosion may be accompanied by dune construction especially where the orientation of the beach is towards the east or

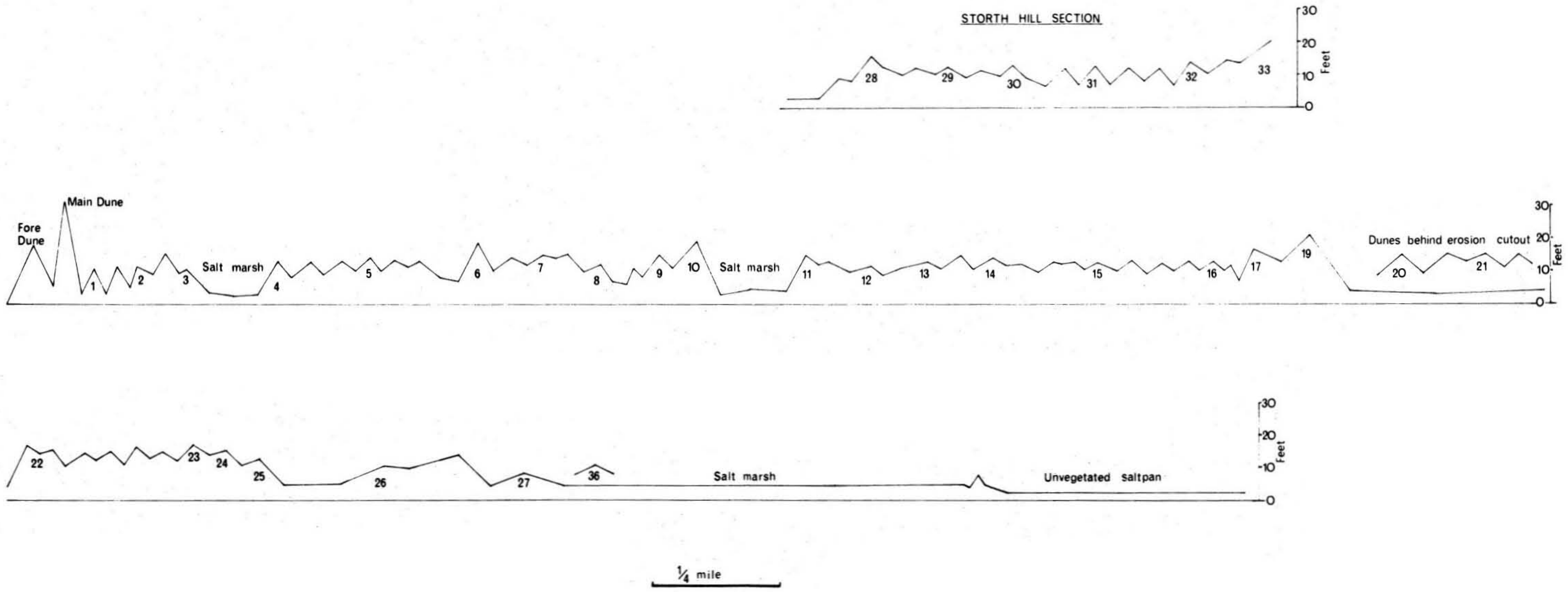


Fig. 3.19 Survey section across Cape Cleveland beach ridges indicating sampling points.

south-east. Thus the higher ridges would appear to indicate erosional phases in the history of the area.

The smaller sequences within the whole series are as follows:

i) an active foredune (18 feet) and main dune (31 feet);
ii) a narrow sequence of 3 ridges, mean height 11.47 feet;
iii) a higher dune ridge (15.45 feet);
iv) a wider sequence of 7 ridges, mean height 13.13 feet, but containing an erosional depression;
v) a higher dune ridge (19.08 feet);
vi) a series of 6 ridges mean height 14.03 feet;
vii) a higher dune ridge (19.61 feet);
viii) a very wide sequence of 15 ridges, mean height 13.10 feet;
ix) 2 higher dune ridges (16.92 and 20.47 feet);
x) another wide series of 13 ridges with a mean height of 15.41 feet, but lowering towards the rear of the sequence;
xi) 4 wide, low, ridges (heights of 11.78, 14.56, 8.70, 11.00 feet);
xii) a single ridge remnant surrounded by salt flats 8.64 feet;
xiii) a sequence of weathered ridges, mean height approximately 10 feet;

The Storth Hill section shows an outer dune of 16.11 feet, followed by a 10 ridge series with a mean height of 12.99 feet, backed by a higher ridge of red sands rising to 22.4 feet at the surveyed point, but possibly having a maximum elevation about 8 feet higher.

The mean heights of the ridge series of 11.47, 13.13, 14.03, 13.10, 15.41 and the lower ridges at the rear of the sequence may reflect changing sea level conditions. However, beach ridge heights are notoriously unreliable as an indicator of sea level due to variation in thickness of dune capping (see for example, Hails, 1969). Unfortunately the swales cannot give complementary evidence as the close spacing of the ridges means that they are banked up against each other, completely burying the basal surface upon which they rest.

2. Mean Size of Sands

The overall mean size of all samples analysed was 2.5799 ϕ which indicates that the sediments lie within the fine sand category. Ranges of mean size were from 1.2965 ϕ down to 3.2470 ϕ for individual samples. However individual beach ridges show a remarkable conformity of sediment size throughout their upper 8 feet (see fig. 3.20). The overall mean size for all samples from each ridge is seen in figure 3.21. A certain amount of correlation is detected between the trend in mean size and the smaller sequences of ridges indicated by height analysis. This is not great in the seaward ridges. However, there is a tendency for the mean sand size to become smaller in the widest ridge sequence of 15 ridges (ridge 11 to 16), though the two dune ridges behind show a rapid rise in overall mean size. The sands of the succeeding sequence of ridges (20 to 25) have a mean size larger than that for all other ridges whilst the rear-most ridge shows a further reduction in mean size. This was expected as this ridge appears to have suffered much weathering. The sands of the outer ridges of the Storth Hill section show a degree of uniformity. A rapid rise in overall mean size is seen for

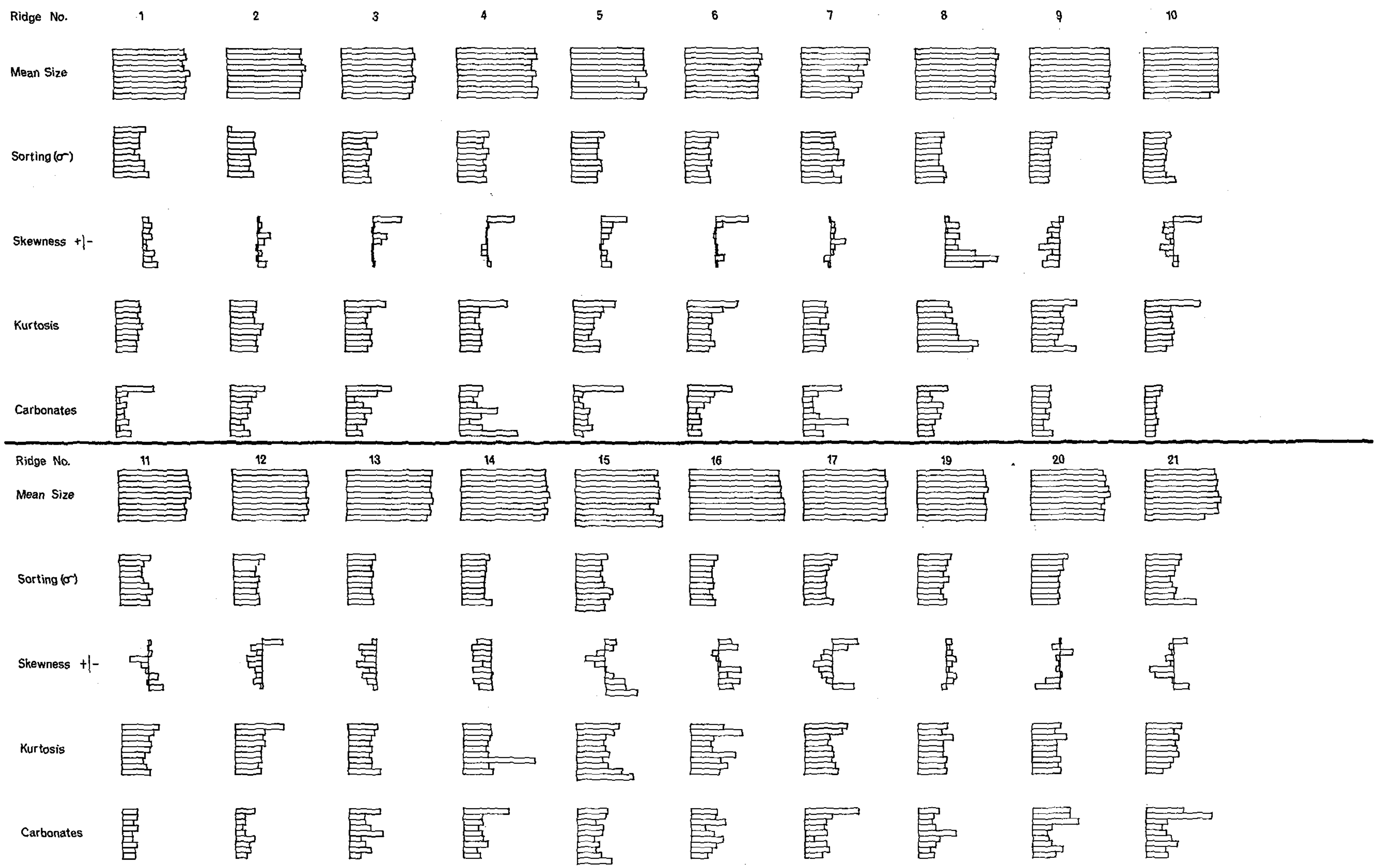


Fig. 3.20 Characteristics of Cape Cleveland beach ridge Sands. Columns show characteristics from surface to 8 feet.

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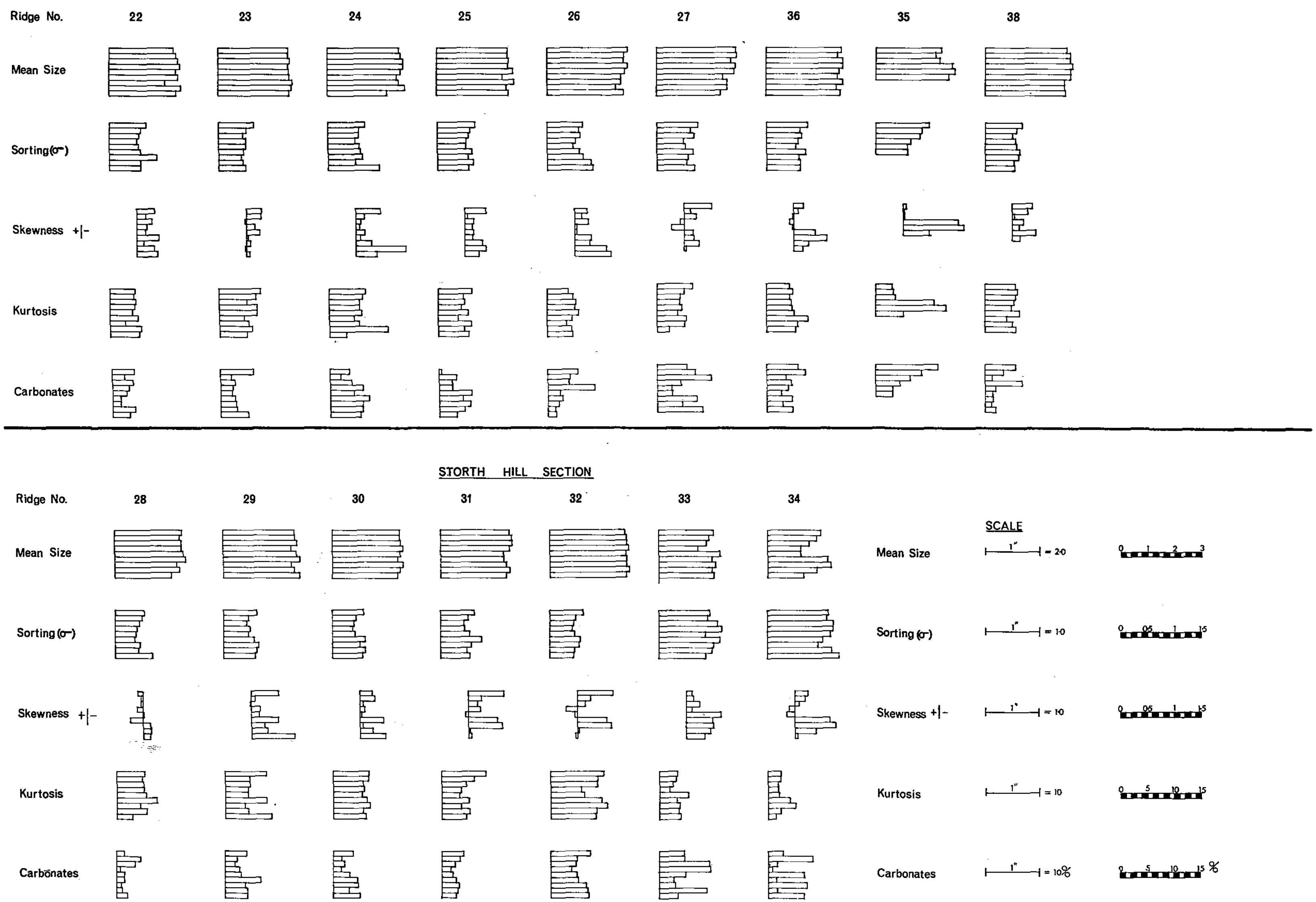

Fig. 3.20 Cont. Characteristics of Cape Cleveland beach ridge sands.

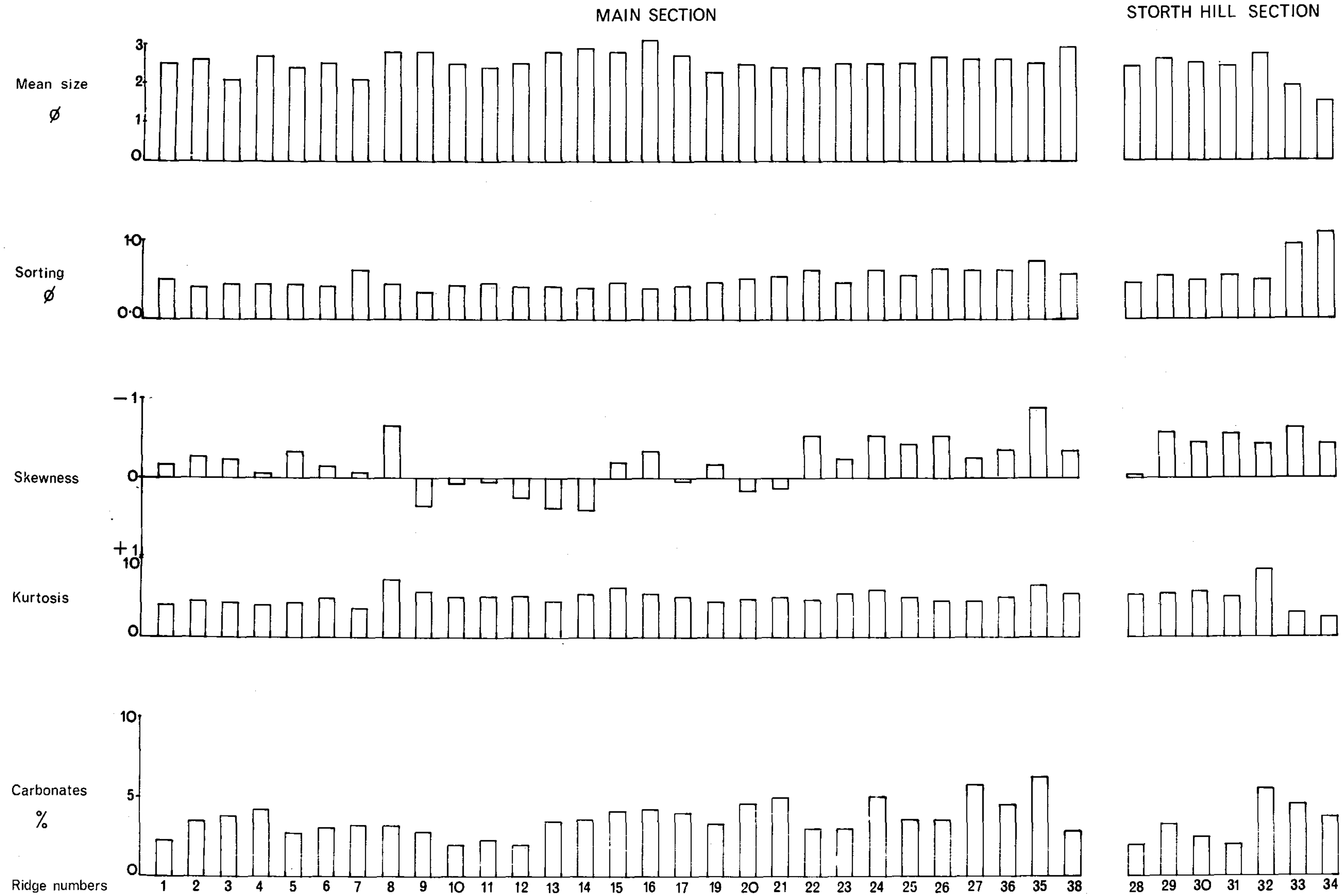

Fig. 3.21 Characteristics of Cape Cleveland beach ridge sands - mean values for each ridge.

the two ridges lying between Storth Hill and The Cone.

The mean size of the modern beach sands is 2.4380 ϕ, of the foredune 2.6085 ϕ and of the main dune 2.4643 ϕ. The mean size of sands of the present littoral zone thus shows no major departure from that of the ridges.

3. Sorting

The overall mean standard deviation for all samples was 0.5394 ϕ. The verbal scale to describe sorting devised by Folk and Ward (1957) though designed for their own sorting measure (Inclusive Graphic Standard Deviation) can be applied owing to the close value of their measure to the mathematically determined standard deviation. Applying this scale, the beach ridge sands may be described as moderately sorted. The modern beach has a standard deviation of 0.6000 ϕ, the foredune 0.3946 ϕ and the main dune 0.4516. Thus in general the sands sampled lie within the range of standard deviations of the modern beach and dune. The standard deviations of individual samples ranged from 0.3270 ϕ to 1.3129 ϕ. Within individual ridges there was again a remarkable uniformity. The mean standard deviations for individual ridges (fig. 3.21) ranged from 0.3671 ϕ to 1.1243 ϕ. No correlation could be seen between ridge series and degrees of sorting, though in general the sands of the older ridges are less well sorted. The two rear-most ridges of the Storth Hill section are again outstanding in the poor sorting of their sands.

4. Skewness

Skewness values ranged from -2.2396 to +0.8322: values for the modern beach, foredune and main dune are -0.4133, -0.9427 and -0.8235 respectively. It is generally regarded that skewness is the best indicator of the environment in which a sediment has been deposited and that this measure is especially useful in the differentation of dune and beach sands (see for example King, 1966, p.287; Friedman, 1961; Sevon, 1966; Chappell, 1967). Generally beach sands are negatively skewed, dune sands positively skewed, though a certain amount of overlap occurs as is well illustrated by the modern beach and dune sands of the Cape Cleveland area. Thus whilst the majority of samples from the beach ridges had a negative skewness this does not necessarily indicate a beach origin.

The mean skewness value for individual beach ridges is of limited value as any single ridge may be expected to contain both dune and beach sands. However, a strong negative skewness may indicate predominantly beach sands, a strong positive skewness predominantly dune. The overall pattern is shown in figure 3.21. A slight mean negative skewness is seen for ridges 1 to 7. The sands of ridge 8 are much more strongly negatively skewed. Positive skewness is recorded as a mean value for the sands of ridges 9 to 14 and 17, 20 and 21. Sands of ridges 15,16 and 18 have a slight negative skew. Ridges 22 to 38 are more strongly negatively skewed, a maximum mean value of -0.8999 being recorded for ridge 35. In the Storth Hill section all ridges show a fairly high mean negative skewness, with the exception of ridge 28.

These results are interesting for they suggest that, even taking into account the variation in ridge heights, the height of beach sands tends to vary within the ridges with corresponding variation in thickness of the aeolian capping. However, the skewness of individual samples has to be taken into consideration and these related to variation in heights of ridges before any conclusions can be reached about variation in absolute height of beach sands.

The major problem however, is the confident differentiation of beach and dune sands. Friedman (1961) did this by using mean size and skewness as parameters, but the variation in skewness between beach and dune sands in all mean size grades which he used tended to be constant (see Friedman, 1961, fig. 1). This was especially so for the mean size values obtained for the Cleveland samples. Sevon (1966) calculated linear discriminant functions to discriminate between New Zealand dune, beach and river sands, using the values of mean size, sorting, skewness and kurtosis. His formulae were applied to the samples from the Cape Cleveland ridges but the values obtained ranged beyond those obtained in New Zealand and it was clear that the linear discriminant functions were valid only for the environment in which they were evolved.

With this in mind, a pilot programme was drawn up to compare skewness values of sands from dunes and beaches in the Townsville area. Eighteen beach sand samples were used, together with 10 dune samples. All samples had a mean size value lying within the range of the Cape Cleveland ridge samples (1.2965 ϕ to 3.2470 ϕ). The mean skewness value of beach sands was -1.0943 and of dune sands +0.0449, but a certain amount of overlap occurred. Thus the standard deviation from the mean was calculated for each set of values. The result for dune sands was 0.5667 and for beach sands, 0.7599[1]. Statistically, assuming a normal

1. Using Sevons (1966) data, similar figures result. The mean skewness value for beach sands is -0.40 with a standard deviation of 0.40. The mean skewness value for dune sands is +0.05 with a standard deviation of 0.28.

distribution, 68.3% of dune sands should lie within one standard deviation of the mean (i.e. within the range -0.5218 to +0.6116) and a similar proportion of beach sands should lie with one standard deviation of the appropriate mean (i.e. within a range -1.8542 to -0.3344). Again, there is a small overlap, but there would be a fair chance of samples with a skewness value of -0.5218 or less (i.e. beyond one standard deviation from the mean of dune sands) being beach sands. The possibility would be even greater if skewness values beyond two standard deviations of the mean of dune sands (covering 95.45% of occurrences) were taken to define beach sands. This would give a value of -1.0885 or less.

These figures have been used to interpret the sands of the Cleveland ridges. Results are shown in figure 3.22. Each column represents a ridge drawn to scale. Interpretation of samples is as follows:

Skewness values -1.0885 or less: almost certainly beach sands
" " -1.0884 to -0.5218: probably beach sands
" " -0.5217 to -0.3344: indeterminate
" " -0.3343 or more: probably dune sands

Two areas within single ridges have strong negative skewness normally indicative of beach sands. One, at the base of the sections of the ridges sampled is to be expected, and samples with such a skewness in this position are interpreted as beach sands. The other area is in the upper one or two feet of the profiles. A capping of beach sand is highly improbable and it is thought that this is the result of normal soil forming processes with the leaching of the finest sands and small silt fraction from the upper horizon, thus removing the finer tail which gives a dune

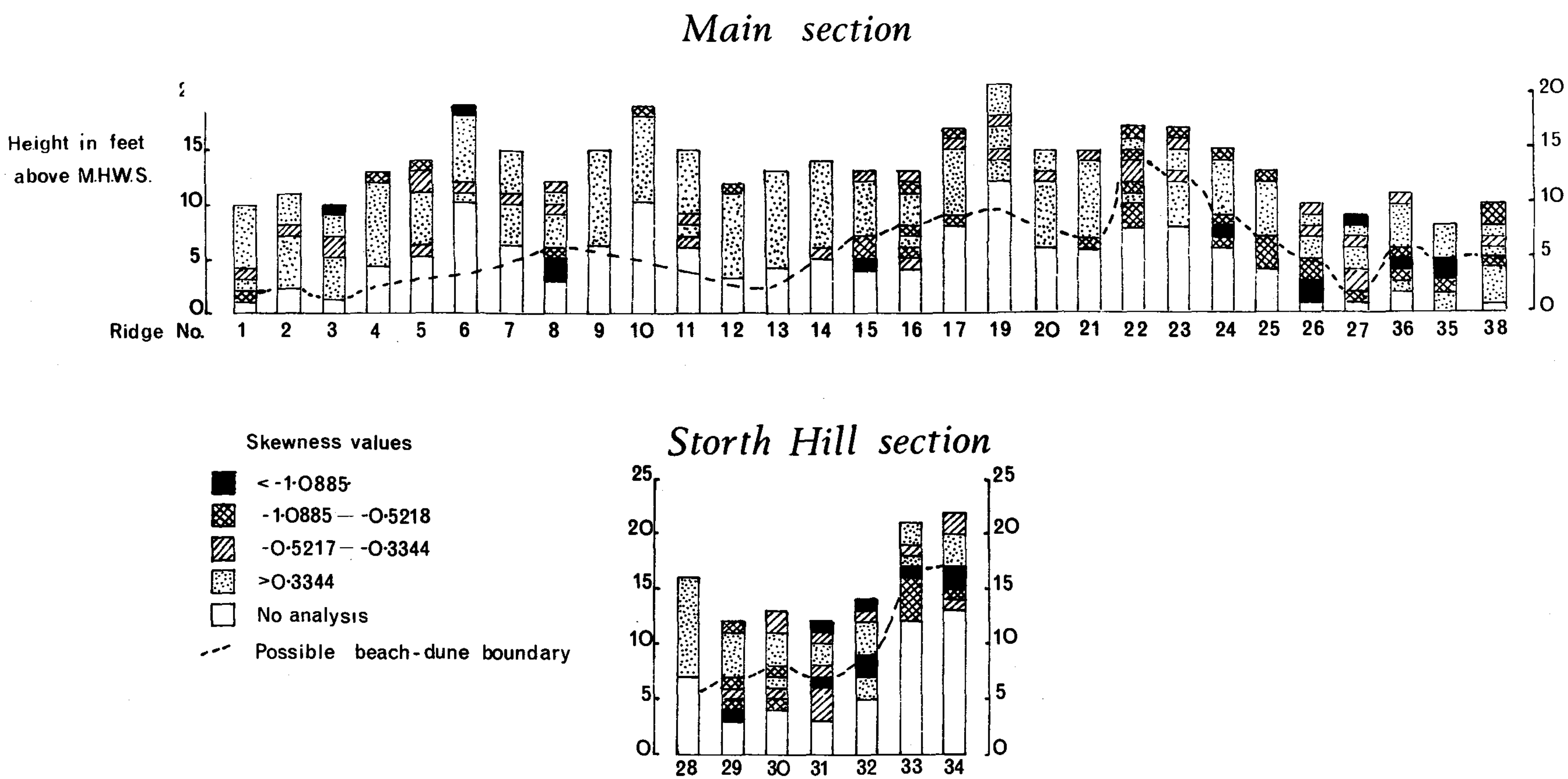

Fig. 3.22 Interpretation of Cape Cleveland beach ridge samples.

sand its positive skew.

Results are interesting, for the absolute height ot beach sands closely parallels the height of the ridges themselves, implying a near constant thickness to the aeolian capping. The problem is to relate the probable height of beach sand to the level of the sea at time of deposition. Study of the present beach indicates little evidence of swash activity more than 2 feet above M.H.W.S. This would appear to be confirmed by ridge 1 which has probable beach sand to this level. It may be tentatively assumed that sea level was approximately 2 feet below the highest level of recorded beach sands. Compaction of the sands since deposition may, of course, reduce this interpreted sea level. More importantly, the higher level of beach sands in some ridges may be the result of greater storm activity or exposure in the past. However, in the absence of evidence to support this and with the evidence of other parts of the Burdekin Delta strongly suggesting that higher Holocene levels have existed, it may be assumed that the pattern of change indicated by the beach ridges is a competent one.

The first ridge with an indication of a higher sea level is ridge 8 where a height of +4 feet is suggested. Landwards of this, the next ridges to have elevated beach sands are 15, 16 and 17, indicating sea levels of 5, 6 and 7 feet above present. Between these and ridge 8, sea level may well have been little different from that of today for no suggestion of beach sand is seen at the base of either ridge 12 or 13 at levels of 3 and 4 feet respectively. Ridge 21 suggests a level of +4 feet, and ridge 22 a level of + 9 feet. There may well be an unconformity between these two ridges. From ridge 22 a steady lowering of sea level is indicated, ridge 27 suggesting a level close to that of present. Ridge 36 and 35 may indicate a slightly higher level of +4 and +3 feet. Ridge 38 is difficult to interpret though a level of about +3 feet is indicated. In the Storth Hill section the outer ridge 28 is apparently composed of aeolian sand throughout the upper 8 feet. The slightly lower earlier ridges indicate heights of +5, +6, +5 and +7 feet and apparently correspond to ridges 15, 16 and 17 of the main sequence. The two rear-most ridges, suspected as Pleistocene. indicate heights of +15 feet.

5. Kurtosis

Kurtosis values are generally high ranging from 1.4662 to 12.7493. Mean kurtosis values for each ridge show little variation, with the exception of ridges 8 and 32 which have values higher than normal. Variation in values occurs within any one ridge. In a number, notably ridges 8, 15, 16, 24, 36 and 35, a higher kurtosis value is recorded for the lower sands indicated as beach sands by skewness. Similarly, the uppermost sample from each ridge may also have a higher kurtosis, probably for the same reasons as outlined above. However, there appears to be no overall consistency in the trends of Kurtosis values.

King (1966, p.285) considers that sediments with abnormally high kurtosis values are generally bimodal with a complex history. The generally high values of the Cape Cleveland ridge samples supports this view as the sands are considered to have originated as river sands, to have been transported along the sea floor, sorted as beach sands and, because of the fine nature of the original beach sand, to have been further sorted as dune, but without a great deal of selection. (see below).

6. Carbonates

The sands are generally very low in carbonates, a mean carbonate content of 3.5% being recorded within a range of 0.8% to 11.6%. Present beach, foredune and main dune content is 9.2%, 2.0% and 2.4% respectively. Variation exists both in individual ridges and within the series as a whole. In general, the older ridges may have a slightly higher carbonate content than the younger ones. Slightly higher values for the surface layer of many ridges may be due to the leaching of humic material from what is essentially the A horizon of a young soil.

7. Other Criteria

The following features of the ridges and sand samples were noted in less detail:

i) Composition of grains

The sand grains were predominantly quartz throughout the ridge series. However, close to the solid outcrops of Storth Hill and The Cone, small lithic fragments were present in the coarser fraction and feldspar became more common. A small heavy mineral assemblage was noted in the majority of samples.

ii) Shape of grains

Microscopic examination indicated the grains to be entirely sub-angular or angular. Again, close to the solid outcrops of Storth Hill and The Cone, the angularity tended to increase.

iii) Depth of Humus Staining

The development of a soil profile obviously increased with age. Outer ridges had only a thin litter layer, without humic staining. By about ridge 12, a humic stained layer, dark brown in colour extended down to about 15 inches. This gradually increased to reach a maximum of about 2 feet towards the rear of the sequence. The changes were not always constant in the one direction and deeper humic stained layers may be found to weawards in any part of the sequence. It is obvious that age alone is not responsible for the depth of humus staining. The red colour of ridges 33 and 34 and the yellow to orange colours of 38 at depth are also considered to be the joint product of weathering and soil development. These three ridges are obviously older than the rest.

iv) Water table mottling

Mottling as the result of a periodic rise in the water table was observed in some ridges. It was seen at a depth of 7 feet in ridge 15, 5 to 6 feet in ridge 16, 6 feet in ridge 30 and 6 feet in ridge 31, and may have been present in other ridges. The ridges appear to be quite freely drained today and the water table, even in the wet season, lies below the depth to which augering was possible. However, the ridges with mottling are included amongst those deposited during suspected higher sea levels. Mottling occurs at or just above the postulated sea level for each of these ridges and may thus be a fossil feature of a higher water table related to this higher sea level.

Evolution of the Cape Cleveland Area

The oldest beach deposits of the Cape Cleveland area are the ridges between Woodstock Hill and Mount Elliot and the ridges joining The Cone, Storth Hill and adjacent outcrops. These deposits are weathered and oxidised in much the same way as those of the ridges which are demonstratably Pleistocene in the southern part of the delta. It is considered that The Cone-Storth Hill outcrops were islands or a single island during the late Pleistocene transgression. The sea level indicated by the deposits of ridges joining these outcrops is in the order of 15 feet (see above), probably belonging to the height of the transgression. The level indicated by the Woodstock Hill ridges is only 3 feet, probably an indication of the regressive stage. If this is so, then it seems improbable that Storth Hill and adjacent outcrops could have been joined to the mainland at any time during the height of the transgression. Moreover, the deposits of the Storth Hill ridges suggest a local origin, possibly the reworking of a regolith overlying the local granite. Unless wind conditions were vastly different from those of present, it would be expected that longshore drift to this area would have carried sediment from the Burdekin distributaries to Storth Hill had it been part of the mainland. Even assuming the Burdekin had been flowing via The Rocks gap to the eastern part of the delta at the height of the transgression, it would have contributed a heavy sediment load to Bowling Green Bay both before and after the maximum sea level stage. The Cone-Storth Hill area appears to have been isolated from a mainland source of sediment throughout.

In contrast to the relatively small amount of sedimentation in the northern part of the Burdekin Delta during the late Pleistocene transgression, the area has received massive amounts of material during the Holocene. The question arises as to the origin of this material. It is certainly not immediately local as some of the late

Pleistocene sands are. If it had been local, a much greater variation in characteristics would have been expected. Although variation in the characteristics has been demonstrated, these are relatively minor and it is suspected that the entire sand complex has had a common source.

The most obvious immediate source for the sands is the Haughton River. The major part of the beach ridge series is in the form of spits trending towards the north from the Haughton estuary. Strengthening this idea is the fact that the beach ridges appear to have started accumulating prior to the maximum of the Holocene transgression at about the same time as the Burdekin was diverted eastwards and the Haughton occupied approximately its present position for the first time. However, it is very evident that the Haughton is contributing little to the present beach which is showing signs of erosion. Also, the rear section of the beach ridge complex, which although partly eroded still indicates massive and rapid sedimentation, is effectively cut-off from the Haughton by The Cone, Storth Hill and Feltham Cone. No doubt the Haughton has contributed some material to the complex, but it has not been the major source.

The Burdekin as a direct source via longshore drifting is also highly unlikely. Whilst a former mouth of the Burdekin is situated less than 10 miles from the southern end of the Cleveland ridges there is no evidence of former transport of massive amounts of sediment across the intervening area which lacks beach ridges almost completely. Erosion of an entire series is unlikely. The possibility that the ridges started to accumulate about the same time as the Burdekin's diversion away from Bowling Green Bay is also a point against it being the direct source of beach ridge sands.

However, in Bowling Green Bay there is a large accumulation of sediment deposited by the Burdekin during the late Pleistocene and early Holocene. The ridges are orientated towards the north-east, in a similar direction to Cape Bowling Green and the major sand accumulations along the east coast of the delta, and if major sand moving waves are approaching from this direction, they would pass over the former delta area, reworking, and carrying shorewards massive quantities of sand especially to the southern end of the beach ridge area. Such shoreward drifting of fluvial sand deposited on the sea floor during the low sea level phase is considered to have taken place in the east Gippsland coast of Victoria and the south coast of New South Wales during the Holocene transgression (Bird, 1961, 1967). Even the dominant south-easterly waves would tend to approach the coast from the north-east, as the result of the refraction around the apex of the delta and more recently around Cape Bowling Green (fig. 3.10). Longshore drifting of the deposits is evident in the recurved ends of the ridges, but this cannot be a strong movement for it is clear that at no time has it been sufficient to completely close off the small creeks draining the northern end of the beach ridge area. Longshore drifting is thus considered to be the result of very local wind waves generated by the prevailing south-easterlies entirely within Bowling Green Bay. Bird (1967) considers that a low feldspar content in coastal sands of New South Wales is indicative of selective abrasion favouring the persistence of the more resistant quartz grains, in a sand which has been repeatedly reworked over a long period by wave action. Certainly the Cleveland sands have a much lower feldspar content than the sands of either the Haughton or Burdekin Rivers. Fuller (1962) studying sands from shallow water with depths between 6 and 12 feet, showed that sediments from this environment were often deficient in about the 2.0 ø grade and suggests that sand of this size is most easily transported onshore. Large areas of Bowling Green Bay are approximately this depth and it may be significant that the majority of Cleveland sands have a mean size of 2.5799 ø.

The early growth pattern of the beach ridges also tends to support this hypothesis. A partially eroded series is attached to Cape Cleveland, the recurved ends indicating movement southwards from the Cape as well as northwards from The Cone. Thus up to about the construction of ridge 23 of the sampled section, the pattern of sand movement was towards the centre of the bay near Woodstock Hill. After this time the movement of sand northwards appears to have become stronger and the southern ridges are the only ones to have grown, extending themselves in front of the earlier series. However, a gap between the two series appears to have been maintained throughout, probably by Crocodile Creek which entered the sea between the two series apparently until fairly recently. The exact reason for the sudden change in the pattern of ridge accumulation is not known, but it may be significant that ridge 23 and adjacent ridges are the ones which appear to have been constructed at or about the time of the maximum level of the Holocene transgression. Not only would the changes in sea level cause modifications to the patterns of sediment yield and movement, but also contemporaneously, other changes were taking place in the area which may have influenced the Cleveland beach ridges. These included the migration of the Burdekin distributary area out of Bowling Green Bay to the Kalamia Creek-Plantation Creek system, and the initiation of Cape Bowling

Green which would seriously modify the wave refraction pattern in the area.

One further problem of the Cape Cleveland area is the amount of erosional 'cut-outs' in the beach ridge areas. In particular a great deal of the rear of the beach ridge series has been removed, especially adjacent to The Cone and Storth Hill. The agent of erosion is not difficult to find, though the details are more obscure. The Haughton River has a former distributary to the west of its present course which has occasionally diverted the floodwaters of the river northwards between Feltham Cone and Mount Elliot. Two courses were then open, either behind the ridge sequence and along the line of Crocodile Creek (its former course through the ridges) or alternatively through the ridge sequence near The Cone in a more direct line to the sea. Both courses have been used and old meander scars are visible on the aerial photographs in both areas. It is considered that the Crocodile Creek course was the first to be used, possibly at a higher sea level phase when much of the area which is salt marsh today would have been an estuary or lagoon. Also, the ridges at the rear of the sequence, possibly built to a sea level not much different from the present, are lower than the ridges to seaward and would not create a difficult barrier for the Haughton's floodwaters to overcome.

The pattern of erosional scars in the ridges near The Cone suggests at least two periods when floodwaters broke through in this region, one prior to the construction of ridge 19 and the other to ridge 10, both of which seem to have closed off floodway breaches. The analysis of sands of the ridges suggests that sea level was below the maximum of the Holocene transgression at the time which may have influenced the closing of the former Crocodile Creek course and the emergence of the earlier lagoon or estuary into which the floodwaters flowed. The point where the floodwaters broke through is logical, as the majority of the rear-most ridges were tied at their southern ends to The Cone, and the barrier would therefore be narrowest close to this outcrop. It would also have been lowest as dunes and beach ridges tend to gain height towards the northern end of any bay where they came under the more direct influence of the dominant south-easterlies.

Further linear breaks in the beach ridges closer to the coast occur. These appear to have resulted when, following upon a short erosional phase, a new sequence of ridges has been constructed at an angle to the erosional coast, thus leaving a small lagoon or tidal flat between the older and newer ridges. It is to be expected that, if erosion and aggradation are the result of slight changes in wind patterns, either directly (through greater or lesser storm activity) or indirectly (through the slowing down of sediment supply from the off-shore zone) then different orientations would exist for erosional and aggradational beaches. Similar sequences, related to changes in wind patterns have been identified in northern New South Wales (Hopley, 1967). Subsequent drainage by tidal creeks of these inter-ridge areas has eroded meander scars into ridges both to landward and to seaward.

The general lack of biogenic material in the Cape Cleveland ridges has prevented the drawing up of any firm chronology of events by radiometric dating. The American research team mentioned earlier did acquire 3 dates for the area but they do little to clarify the situation (J.M. Coleman, pers. comm.). A marine shell layer near the mouth of the Haughton River at low tide level gave a date of 3,460 years ± 110 B.P. However, shell banks are common throughout Bowling Green Bay and the date without further details does not appear to relate to any specific event in the evolution of the area. Woody material from one of the beach ridges gave a date of 1,370 years ± 100 B.P. The ridge was not identified with any precision but could have been approximately ridge 23. Again, as the wood could have been introduced at any stage after the formation, and the description suggests it may well have been part of a former root, the date can only be considered minimal for the ridge. Woody material on a ridge just landward of the present beach was too young to date.

Discussion

Deltas display enormous variety in their size, shape, structure composition and genesis (Van Straaten, 1960). This is not altogether surprising because of the wide differences existing in geologic setting, climate, basin characteristics, tidal conditions, off-shore conditions and other influencing factors. All deltas therefore display unique characteristics though it is normally possible to fit them to one of the major classifications such as that of Samojlov (1956) or Volker (1966). The Burdekin however, probably has more unique features than most deltas which have appeared in the literature. Hydrologically the Burdekin appears to have affinities with deltas of other tropical areas with a prolonged dry season, such as the major deltaic areas of mainland South-east Asia, and salt-water intrusion is similarly a major problem during the latter part of the winter and spring. However it is difficult to equate it with other deltas on morphological grounds alone. Essentially it has only a single river branch, but does not fit any of the sub-types within this major section in Samojlov's classification (1956). If the division of the channel by mangrove muds can be considered as branching into several distributaries, then the Burdekin fits best into section III (b) of the classification and is comparable to the Lena, Yukon, Zambezi and Niger deltas. Examination of the literature suggests, however, that there is a much more even distribution of waters throughout the deltaic areas of these rivers than there is, or ever has been, in the Burdekin. Nevertheless the Burdekin has certain parallels with these rivers, and on a smaller scale with the Niger in particular. Although no single distributary of the Niger carries more than 29% of the waters, the overall morphology and depositional environments appear similar (see Allen, 1966). Precipitation is higher within the immediate confines of the Niger delta, but both rivers are draining sub-humid catchments in which river sediments are derived mainly from a crystalline basement complex or its weathering residues. Both rivers have similar tidal ranges, 7.2 feet at the mouth of the Niger (Coleman, 1968) and 7.6 feet at Groper Creek in the Burdekin Delta (Queensland Tidal Tables).

The most detailed deltaic studies have been carried out at the mouth of the Mississippi River (e.g. Russell, 1936, 1939, 1940, 1967, Fisk, 1944, 1952, Fisk and McFarlan, 1955, Gould and McFarlan, 1959). However, the Mississippi and Burdekin, quite apart from size, have few comparable features. Identification of a weathered Pleistocene alluvial surface is common to both, but the environments of both the erosional and depositional basins differ considerably. In particular the sediments of the Burdekin tend to be considerably coarser than those of the Mississippi and many of the features of the latter river appear due to subsidence of the deltaic basin on a geosynclinal scale. Subsidence due to compaction of sediments and to isostatic adjustment to the loading factor is a fairly common feature of most deltas (Bird, 1968). One of the more obvious results of subsidence is the common occurrence of lakes and lagoons within the deltaic area. However, the almost complete lack of these features and the general evidence for emergence in the Burdekin delta is apparently a divergence from the usual deltaic morphology. There is no evidence for subsidence in any part of the delta. The compaction factor may be small due to the high proportion of coarse sediments, but the loading factor may have been expected to have had some influence. The nature of the higher sea levels indicated in the delta, and their relationship to eustatic and tectonic features will be discussed further in Chapter 7. For the moment, it suffices to indicate that evidence of emergence of any kind is unusual in deltaic areas, and appears responsible for the general preservation of the older distributary areas which are now separated from the sea by wide zones of salt marsh and mangrove. The tendency of the Burdekin to concentrate into single distributaries, or highly localised distributary areas, also appears to result at least partly from incision following emergence with consequent concentration rather than spreading of waters. However, the clearly identifiable separate distributary systems of the Burdekin have certain similarities with the sub-deltas or crevasses of the modern Mississippi (Coleman and Gagliano, 1964) though are better preserved due to isolation from the coast and to emergence.

Probably the most outstanding feature of the Burdekin is the complete separation of the deltas of high and low sea level phases. The morphology of the late Pleistocene surface suggests that this is not a feature only of the

Holocene. It has led to completely different sedimentary cycles in the northern part of the delta as compared to the eastern sector, a contrast which has been emphasised by the differences in exposure between northern and eastern coasts. Thus whilst the smooth cuspate shape of the delta is broken only by Cape Bowling Green, the reasons for the smoothness differ on the contrasting coastal sections. The north coast is essentially that of an abandoned series of digitate deltas straightened by emergence of the sub-aqueous deltaic clays. The eastern coast has been regularised by more vigorous wave activity and the sealing of inter-distributary areas by a succession of sand spits trailing northwards from southward migrating distributaries.

Summary Evolution of the Burdekin Delta

Analysis of the deposits and morphology of the Burdekin Delta region suggests the following evolution:

1. The coastal embayment into which the Burdekin flowed was initiated with the start of infilling, probably during late Tertiary-early Quaternary times.

2. Continued accumulation occurred during the middle and latter part of the Pleistocene, influenced to a large extent by eustatic changes in sea level. The sequence consisted of emergence of deltaic deposits with subsequent weathering and incision during regressive phases, and general outgrowth of the delta and submergence and rapid aggradation during transgressions.

3. The latest complete cycle began in the late Pleistocene when a delta considerably smaller than that of present was formed. Maximum height of sea level indicated in

the delta region during this phase was approximately 15 feet above present. Shorelines of the regressive period indicate sea levels below the maximum. Dunes up to 60 feet high were constructed and where locally calcareous, dune calcarenite has formed either during or since the late Pleistocene high sea level period.

4. The climate of this period is considered to have been more arid than at present. Pediments around the hills of the delta region are graded to the late Pleistocene delta level, though below the height of the maximum level of the sea at this time, suggesting that arid conditions continued during the regressive phase.

5. During the latest low sea level period, the Burdekin flowed into Bowling Green Bay, a course it had taken at every previous low sea level phase. Incision of the higher delta deposits occurred.

6. The start of the Holocene transgression initiated the selective shore movement of sediments laid down under fluvial conditions far out on the continental shelf. Migration of these deposits has contributed to the formation of the younger beach ridge barriers of the present coastline.

7. The Burdekin, still flowing into Bowling Green Bay, formed a large cuspate delta between the present Cape Cleveland and Cape Bowling Green.

8. More rapid rises in sea level during the later stages of the Holocene transgression saw a migration inland of the deltaic shores which came under the lee of the Pleistocene delta and isolated rock outcrops, and in the sheltered conditions a generally digitate form delta developed.

9. Prior to the maximum of the transgression when sea level was at or just above its present position, the Burdekin was diverted through The Rocks, a more direct course to the sea with resulting incision.

10. The major distributary system of the Burdekin has subsequently migrated from its initial position in the vicinity of Rita Island, to a position near Mount Inkerman and from there back to Bowling Green Bay via the Sheepstation Creek system. Migration has then moved the major outlets around to the east coast with Kalamia Creek, Plantation Creek, the Ana-branch and the present mouth successively taking on the role of major distributary. The maximum of the Holocene transgression, about 10 feet above present sea level, probably occurred when the Burdekin occupied the Kalamia Creek system, about 4,000 years ago. Regression has caused incision of the Burdekin into its older mid-Holocene deposits.

11. The Burdekin east coast distributaries contributed large amounts of sand for coastal barrier formation in the form of spits. The oldest and largest of these is Cape Bowling Green, also initiated at about the maximum of the mid-Holocene transgression.

12. During and since the transgression, the deposits of the drowned Bowling Green Bay delta have been moved selectively onshore to form the wide beach ridge system south of Cape Cleveland.

13. The present delta distributary is prograding the coastline at a rate of approximately 11 yards per year. Elsewhere erosion is taking place. This may be due to variations in wind patterns or even to a slight rise in sea level, but major areas of erosion

are considered to be those where rapid progradation in the past has occurred. Subsequent reduction of sediment supply with migration of the Burdekin's mouth has exposed these coasts to erosion by way of coastal straightening.

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CHAPTER 4

THE TOWNSVILLE COASTAL PLAIN

The Townsville coastal plain, bordering Halifax and Cleveland Bays, consists of three distinct parts. In the south, fringing the Muntalunga Range and extending between the mouth of the Ross River and Cape Cleveland, is a narrow chenier plain. West of Townsville the coastal plain widens into a large embayment in which the coastal plain rises to 400 feet. The main escarpment here is 15 miles from the sea. The embayment comprises the combined drainage basins of the Black, Bohle and Ross Rivers. Beyond the headwaters of the Ross a coastal "corridor" (Sussmilch, 1938) extends behind Mount Elliot through to the Haughton River. The watershed between the two catchments is poorly defined and less than 200 feet high. North of the Black River as far as the Herbert delta, the coastal plain narrows to a width of less than three miles in places. A steep escarpment leading up to the Tertiary erosion surface overlooks the coastal plain and materials produced by retreat of the scarp have contributed to the deposits of the plain. The escarpment in the north rises to over 3,000 feet in the Paluma Ranges, but falls to less than 2,000 feet in the Harvey Range further south. The isolated Mount Elliot massif forms the eastern boundary of the region.

Numerous outcrops interrupt the level surface of this coastal plain. Both these outcrops and the main escarpment are comprised largely of rhyolitic and andesitic flows of late Palaeozoic age into which a series of granitic rocks has been intruded (Wyatt, 1968). It is the granites which generally form the larger outcrops such as Mount Elliot, Magnetic Island and the bulk of the Mount Stuart Range. The Frederick's Peak plateau is an isolated part of the Tertiary erosion surface, the spectacular pinnacle of Frederick's Peak itself being part of a dacitic ring dyke. The majority of the smaller hills are craggy outcrops of volcanic rocks with small exposures of conglomerate, sandstone and sedimentary rocks.

Previous investigations into the geomorphology of the area have been made, though on either a purely descriptive basis or on a general scale only. Physiographic descriptions of the area occur in the early reports of the Great Barrier Reef Committee. Hedley (1925) describes the Townsville plain explaining the higher parts and stranded beach ridges in terms of tectonic uplift. This report is valuable however, as a description of the lower Ross area prior to building development. A more complete and accurate description is provided by Jardine (1928). A shorter description of the area is found in Sussmilch's (1938) analysis of the geomorphology of eastern Queensland. Most recently the coastal plain deposits have been broken down into 'land systems' which correspond on a general level with the actual distribution described in this chapter. Christian et al (1953) ascribe the upper pediment and fan deposits to the Millaroo land system, the finer textured alluvials to the Rocky Ponds system, the clay plain away from the major streams to the Northcote system and the coastal environments to the Bowling Green and Littoral systems. A geomorphological reconnaissance of the coast area covered by this chapter was made by Driscoll and Hopley (1968). A number of revisions are made to the conclusions of this paper. The Bureau of Mineral Resources mapping of the area, though clarifying the solid geology adds little to the knowledge of the coastal plain alluvials (Wyatt, 1968). Russell (1967), and Russell and McIntire (1965, 1966) have referred briefly to beach rock occurences in the region and to the beaches of the Rollingstone area. Macnae (1966, 1967) describes the mangroves of the Townsville area. Thus, although a certain amount of literature is available for the Townsville region it generally lacks detail and no attempt has previously been made to define a chronology for the coastal plain deposits. A survey of the soils of the Townsville plain currently being carried out by the C.S.I.R.O. has greatly aided the compilation of this chapter (see below).

The Muntalunga Chenier Plain

The Muntalunga chenier plain is a small region comprising widely spaced cheniers of surprisingly varied lithologies and heights and resting on salt marsh or clay plain deposits. Although this type of morphology is restricted in the area covered in this research programme (analogous areas are found in Bowling Green Bay and near the mouth of the Bohle River), comparison with areas along awwider sector of the North Queensland coast suggests that this is typical of areas of low to moderate wave energy but capable of receiving high storm waves at widely spaced intervals (probably during cyclones) and where a direct source of supply of coastal sands from either off-shore or from an adjacent river mouth, is not available.

The major features of the geomorphology of the region are shown on figure 4.1. The proximity of the area to the extensive beach ridge series south of Cape Cleveland and the obvious contrast in beach materials promoted the same detailed examination of the Muntalunga cheniers. The

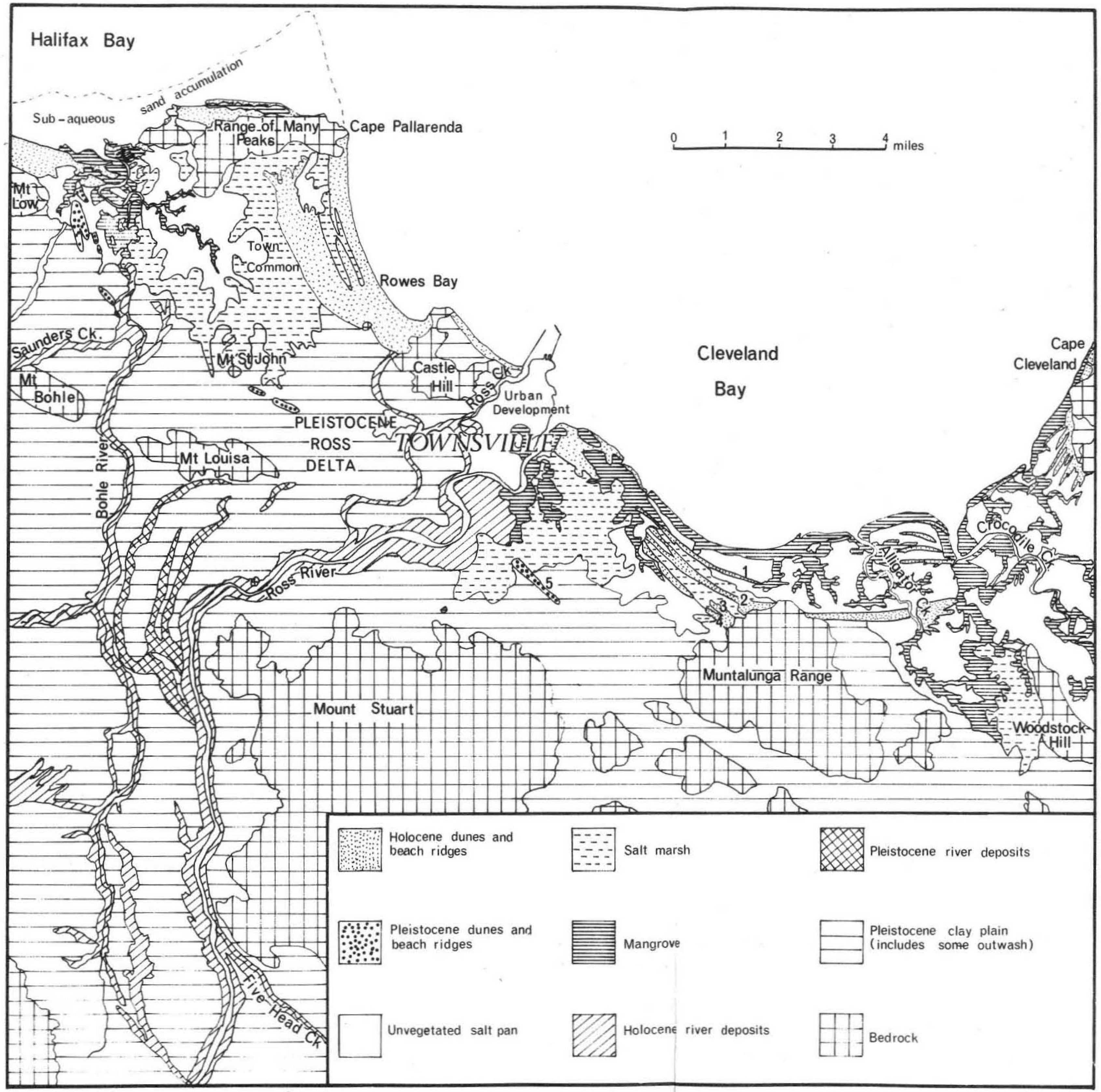


Fig. 4.1 Geomorphology of the Townsville area. Numbers refer to sampled cheniers.

results are seen in Appendix C and in graphic form in figure 4.2. Discussion of the results and comparison with the Cleveland ridges in terms of beach materials will be made in Chapter 6. The location of the five cheniers analysed is shown in figure 4.1.

The major ridge of the series is the one winging the Muntalunga Range (Ridge 2), a chenier with a thick aeolian cap rising to between 25 and 30 feet to the west of the range and to 15 to 20 feet to the east. In front of it is an expanse of tidal flat, periodically inundated by the highest tides but bare of all vegetation. Macnae (1966) has indicated that such areas are wetted by fewer than 117 tides per year. Behind the main dune ridge the cheniers rest upon a clay plain just beyond the reach of high tides (at about 3 feet above M.H.W.S.). Augering has indicated heavy black muds underlying this clay plain which are similar in all respects to those of the salt pans. The area is colonised by Sporobolus virginicus and by halophytes (Arthrocnemum leiostachyum, A. halecnemoides, Salicornia australis) which become more common towards the edge of the salt pans. Unvegetated salt pans also extend behind this higher area, the junction between the two levels often occurring as a low salting cliff.

Mangroves are extensive, occurring along the outer edge of the coast, between the cheniers near Ross River and along all the minor creeks draining the area. Avicennia spp. make up the outer edge of the littoral zone, with a Rhizophora spp. zone behind. Discontinuous Ceriops spp. thickets occur on the landwards side. Between the cheniers the lower wetter areas are colonised by forests of Rhizophora and Bruguiera, the higher areas by Ceriops. The creeks are fringed by either Rhizophora or Avicennia.

Landwards of these Holocene coastal deposits is a slightly higher area, its seaward margin marked by a low salting cliff, but gently sloping up towards the solid outcrops of the Muntalunga Range and Mount Stuart. Whilst the higher areas fringing the Ross River are undoubtedly Holocene river levee deposits, the remainder of this high coastal plain has solodic soils identical to those north of Townsville which will be given a late Pleistocene age (see below). The inner-most of the chenier ridges of the Muntalunga sequence rests upon this surface. The Ross River's levee and floodplain deposits are not extensive. Changes in river course discussed below indicate that the Ross has not long occupied its present position.

The cheniers are the most interesting of the features of this area. The detailed analysis tabulated in Appendix C was made of the cheniers to the west of the Muntalunga outcrop where the sequence is most complete.

a) Chenier 1

The outer-most ridge rises sharply from the surrounding salt pan to a height of 10 feet. Complete analysis was made of only the upper six samples as the lower part of the ridge, below 5 feet was composed almost completely of coarse shell grit. The overlying sands, the mean characteristics of which are indicated in Table 4.1, show an increase in carbonate content with depth and shell fragments make up the coarser fraction throughout. Mean size of these sands is comparatively coarse, within the range 1.2335 ϕ to 1.5585 ϕ. Sorting is only moderate throughout and the negative skewness of all but the surface sample suggests that an aeolian cap is lacking, though only the sample from 3 feet suggests a beach origin with any certainty. Kurtosis values are generally lower than those

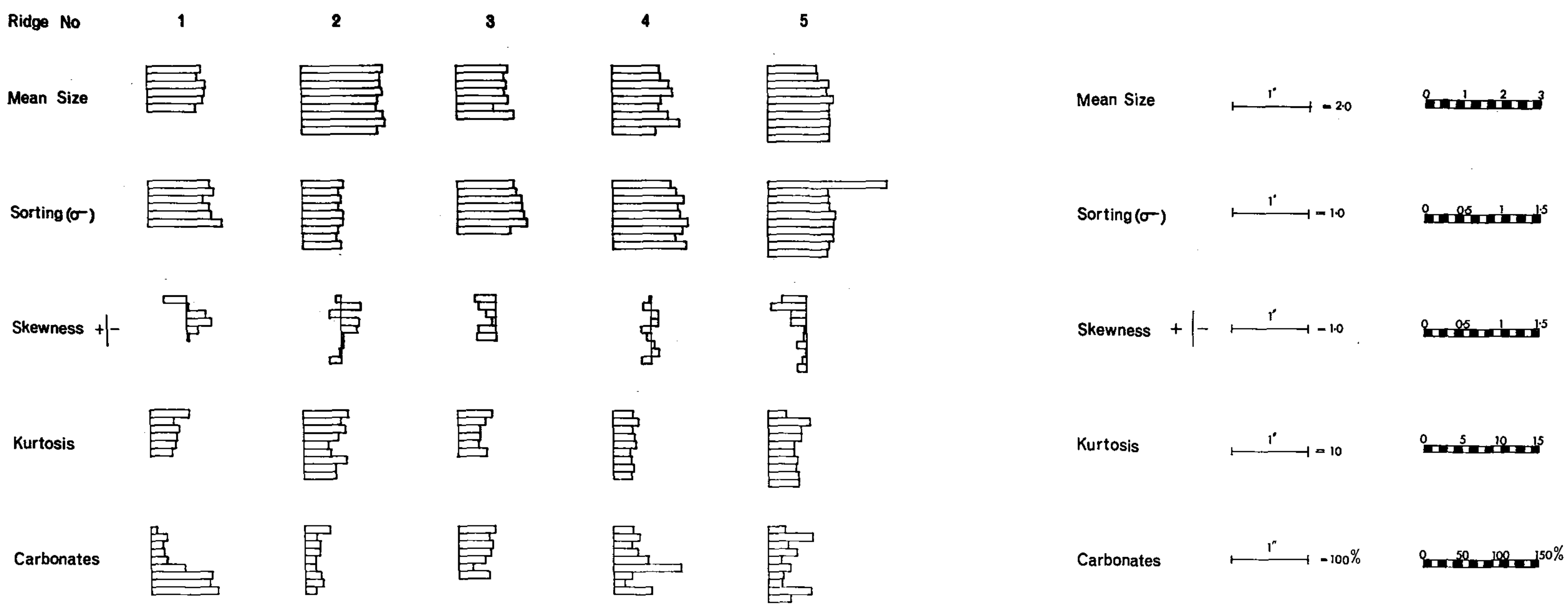


Fig. 4.2 Characteristics of Muntalunga chenier deposits.

Table 4.1

Mean size, sorting, skewness, kurtosis and carbonate average values for each ridge

Ridge No.	Mean size (ϕ)	Sorting (σ)	Skewness	Kurtosis	Carbonates %
1	1.3973	0.8213	-0.1475	3.6361	42.0
2	2.0552	0.4829	-0.0756	4.7004	2.0
3	1.2872	0.8196	0.4831	3.7093	3.9
4	1.3771	0.8776	0.0527	2.7295	3.8
5	1.5080	0.8740	0.3500	3.7539	3.0

recorded for the Cleveland ridges.

The upper sands consist of angular quartz and feldspar grains. These become coarser at depth and form the non-calcareous fraction in the lower shell grits. This material is considered to be of local origin and is similar to the coarse granite sands being shed by both the Cape Cleveland and Muntalunga outcrops.

b) Chenier 2

This is the high dune ridge and has completely contrasting characteristics to the outer ridge. The aeolian origin of the sands is indicated by a smaller mean size (2.0552 ϕ), by better sorting and by a positive or only small negative skew. Kurtosis values are again moderate. Very low carbonate contents are recorded, giving a mean $CaCO_3$ value of 2.0%. A thick aeolian capping is undoubtedly found on this ridge. Only the upper 18 inches are humus stained, which is indicative of the young age of the ridge.

c) Chenier 3

The third chenier is just within the lee of the Muntalunga Range and rises to only 10 feet. Beach rock was struck at between 6 and 7 feet, at a height of about 3 feet above M.H.W.S. This may indicate a higher sea level at the time of formation of the beach rock. Unfortunately no large samples suitable for dating could be brought to the surface. The chenier is undoubtedly older than those to the seaward with humus staining down to 3.5 feet.

The sands are positively skewed throughout this chenier though the small fragments of beach rock from 6 feet contained coarser shell grit suggestive of a beach origin at this depth. The mean size of material is higher than that of the dune ridge and sorting is again only moderate.

Comparatively low Kurtosis values are recorded. Carbonate values are again low, but still twice those of the dune ridge. The conclusion reached is that Chenier 3 has a core of beach sands overlain by a 6-foot capping of aeolian sands. The nature of the dune sands is again suggestive of a local origin, probably material washed from the slopes of the Muntalunga Range.

d) Chenier 4

This feature is very similar to Chenier 3, though about 2 feet higher along the line of transect. All properties are similar to those of the ridge to seawards. Although beach rock was not found in this ridge, carbonate values increase with depth. However, the material is apparently aeolian throughout the depth examined.

e) Chenier 5

The most landward of the cheniers again displays a remarkable change in appearance. Resting upon coastal deposits which are interpreted as Pleistocene the ridge, not surprisingly, displays a profile of red oxidised sands throughout. It is also much wider than the ridges to seaward. However, its other characteristics are very similar to those of the two cheniers to seawards and it is evident that, although Pleistocene in age, and rising to 20 feet, the ridge has evolved in much the same way as the Holocene cheniers. The positive skewness throughout is suggestive of a dune origin for the sands. The gritty appearance of the coarser fraction suggests that this material too originated as slope wash from the Muntalunga Range.

The Bohle - Ross Plain

A large part of this area lies within the boundaries of the city of Townsville and reclamation and urban development have obliterated much of the original morphology, especially along the lower Ross River. Hedley (1925), for example, describes beach ridges on Ross Island between the Ross River and Ross Creek, but no sign of these features remains today as the whole area has been infilled and reclaimed. Extension of the harbour area has obliterated ridges at the mouth of the Ross River, though these are visible on the 1961 aerial photographs. Essentially this is a low lying deltaic area, much of it salt marsh less than 5 feet above M.H.W.S., across which the Bohle and Ross Rivers have migrated. Higher areas are provided by beach ridge sequences, Ross River levees and by the older Pleistocene deposits. The general morphology of the area has been controlled by the solid outcrops of Castle Hill, Mount Louisa and the Many Peaks Range.

The close proximity of the upper Ross and upper Bohle Rivers, which for a distance of 10 miles flow in parallel courses only a mile apart, is at first sight puzzling. However, detailed mapping of the levee deposits of both streams (fig. 4.1) indicates how this anomalous situation has come about. The oldest surface deposits indicating the former course of the Ross-Bohle system are found south of Mount Louisa where channel deposits trend east to west and are joined by a number of similar channels trending north from the present Ross River. They lead into a deltaic fan area extending from Mount Louisa northwards to Castle Hill. The beach ridge south-east of Mount St. John appears to have been deposited during an early stage of the delta's construction. However, this ridge is regarded as a continuation of the shoreline found on the west bank of the Bohle estuary and which is definitely late Pleistocene in age (see below). The soils of the delta and channel deposits are much more highly developed than those of any clearly Holocene features of a similar type. The soils are solodics and, by comparison with the deposits of the coastal plain to the north, may be allocated a late Pleistocene age. The late Pleistocene Ross-Bohle Rivers thus appear to have flowed into a bay which now forms the Town Common.

In comparison to the solodic soils of the Pleistocene channels, the Holocene deposits display soils of a much earlier stage of formation, mainly red earths and red podsolics. The oldest of the Holocene river courses is that which branches from the present Ross near its confluence with Five Head Creek to join the Bohle. As there are no indications of a Holocene diversion around the southern side of Mount Louisa it is assumed that this system flowed over the col between Mount Louisa and Mount Bohle. As bedrock outcrops in the stream at this point it is highly unlikely that this course could have been maintained at a low sea level stage and it seems likely that the joint Bohle-Ross flowed here during the latter part of the Holocene transgression. Evidence of a low sea level stage has been obliterated but it is assumed that the Ross and Bohle were quite separate systems during this stage.

North of the Mount Louisa-Mount Bohle col, the joint rivers were joined by Saunders Creek and appear to have incised themselves into the earlier Pleistocene deposits, breaking through the Pleistocene beach ridges and continuing northwards. As much of the Town Common is at a height which would put it below sea level during the postulated maximum of the Holocene transgression, the lack of a Holocene delta in this region and the incision of the rivers into the Pleistocene deposits is suggestive of an age for this joint Bohle-Ross system prior to the maximum of the transgression. There is also no direct evidence of shoreline development associated with this stage. However, the large beach ridge series west of the present Bohle's mouth appears to indicate a sediment supply much greater than that of the Bohle River alone. The ridges themselves are young but appear to be fed from a large sub-aqueous sand accumulation north of the Bohle estuary and the Range of Many Peaks. It is suggested that this accumulation is the deltaic area of the joint Bohle and Ross Rivers.

Evidence from the upper catchment of the Ross River suggests that at the time when the Ross joined the Bohle, some of the major headwaters of the Ross, including Landsdowne Creek, joined the Major Creek drainage catchment which, in turn, joins the Haughton River. The watershed between the two systems is poorly defined today and the soil pattern of the C.S.I.R.O. pastoral research station at Landsdowne certainly indicates the truncation of Ross River headwaters (G.G. Murtha, pers. comm.). The eventual acquisition of new headwaters, combined with the Holocene transgression, may well have been the factors influencing the Ross River's abandonment of its course across to the Bohle and around the north-western corner of Mount Stuart. Subsequent courses have been as follows.

1. The Ross flowed north of a small isolated outcrop, meandered through what are now the western suburbs of Townsville and around the southern and eastern edge of the older Pleistocene delta, across to Castle Hill and out to sea in Rowes Bay. Most of the beach ridges trending north to the Range of Many Peaks were constructed at this time, the Town Common

forming a lagoon or marsh between the Ross and Bohle systems.

2. Meander migrations finally caused the Ross River to abandon the Rowes Bay mouth and to enter the sea at Ross Creek.
3. The latest change has been a migration south to the present Ross estuary.

The latter part of this sequence was accompanied by incision of the river into its levee deposits, probably as a result of downward movement of the sea level over the last 3,000 years demonstrated by evidence from adjacent areas. However, the Ross during floods can still utilise all its former courses. Hedley (1925) records that the Ross can still revert to a course which flows out to sea at Rowes Bay. Sedimentation and marine regression have combined to produce the salt marsh of the Town Common and to connect the Range of Many Peaks to the mainland by more than the Rowes Bay beach ridge sequence.

Remnants of a Pleistocene beach ridge sequence are found on the western side of the Bohle and also just east of Mount St. John. These will be discussed with the deposits of the coastal plain to the north.

The evidence suggests that the Range of Many Peaks was an island during mid-Holocene times. The area is shown in figure 4.3. Even the southern side of the range has under-cut slopes and small undercut stacks. The northern side of the range has a series of moderately developed shore platforms at varying heights (see Chapter 7) together with some shallow caves partially concealed beneath the sand ridges which rest against the solid outcrop. On the western end of the former island (or pair of islands) is a stable vegetated boulder spit rising to nearly 15 feet. The boulders

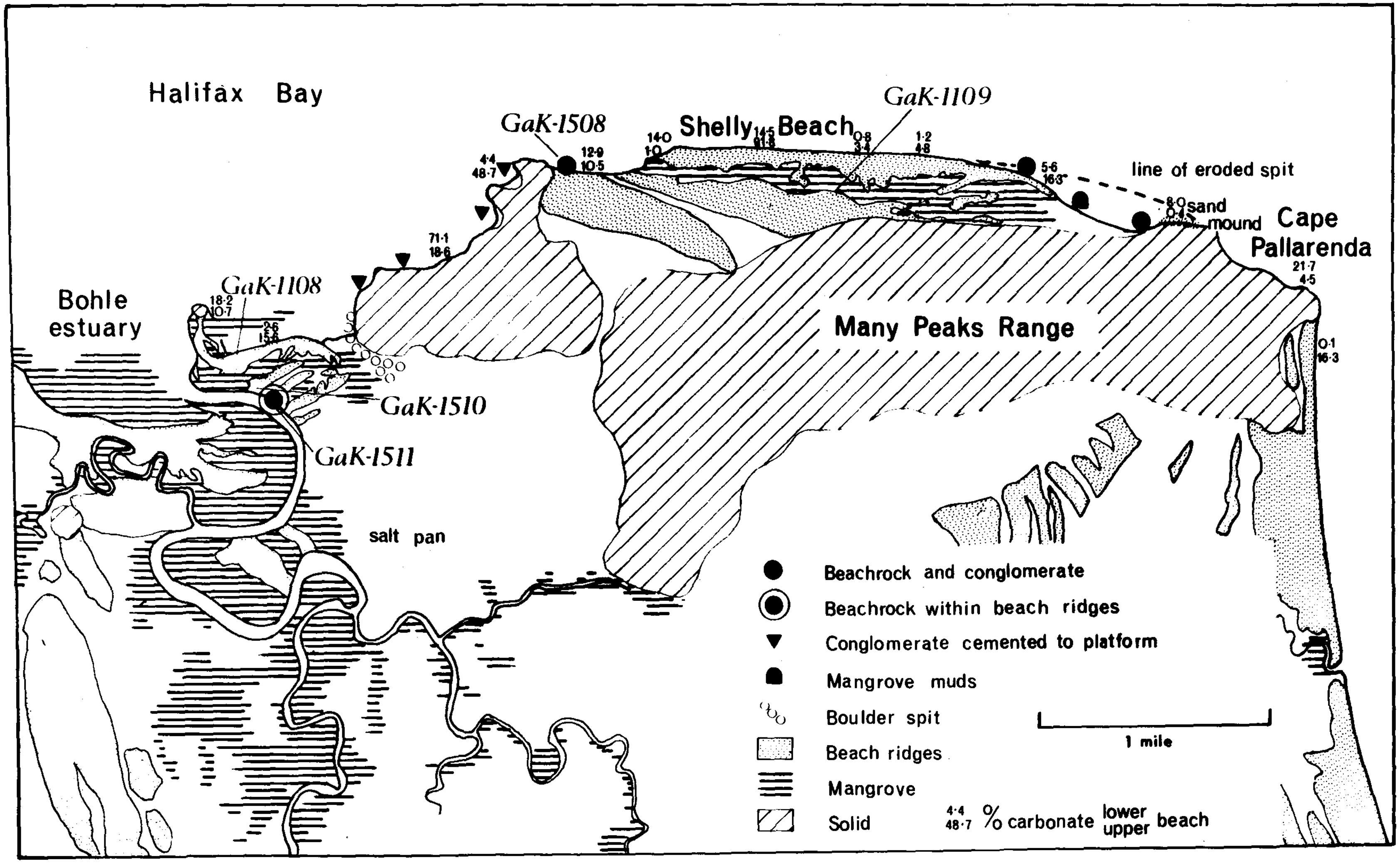


Fig. 4.3 Range of Many Peaks area.

are roughly graded along the spit, having a diameter of up to 2 feet at the anchor point to less than 1 foot at the tip of the spit. The southern end is buried beneath coarse sand deposits, but drilling has confirmed the present of boulders 2 to 3 feet beneath the sand along the entire length of the feature. The close resemblance of the boulder spit to similar features on the off-shore islands which have been shown to be mid-Holocene in age may indicate a mid-Holocene age for the Many Peaks spit.

Large beach ridges are found around the Range of Many Peaks. South of Cape Pallarenda is a dune 20 feet high which is a continuation of the Rowes Bay ridges. Behind this, however, is a higher dune 25 feet high. Although humus staining in this inner dune extends to 3 feet, the sands are not weathered in any way and appear quite fresh at depth. The ridge is considered Holocene, possibly mid-Holocene in age.

A contrasting series of ridges is found on the northern side of the range behind Shelly Beach. The inner ridges are simple dunes, infilling a small embayment. The outer-most ridge, however, is more complex. It grew in the form of a spit with many curved laterals from an anchor point at the eastern end of the Many Peaks Range. The western end is still extending but the spit has been broken by erosion in the anchor point section and the mangrove depression behind is now exposed on the present beach. East of the break, a sand mound is the only sign of the former spit. Just west of the point where mangrove muds and roots are exposed on the beach, is a complete section through the ridge and in this area a small patch of beach rock is exposed in a position which would put it in the centre of the former ridge. This material is friable and only lightly cemented but the strike of the deposit follows the line of the spit, not that of the present beach. The height of this outer ridge is 10.5 feet.

The second ridge rises to a maximum of 19.8 feet, but has a general height of between 11 and 12 feet. It has been fretted along its northern edge by the mangrove creek between it and the outer spit and this has revealed some good sections through the ridge. Shell grits form the lower 5.25 feet and these are overlain by dune sands which still appear to be accumulating. An aboriginal midden site, complete with charcoal, heat-shattered rocks and punctured shells was found in one section 2 feet below the surface. Radio-carbon dating of the charcoal gave a result of 840 years ± 80 B.P. (GaK-1109). Thus 2 feet of dune sand has accumulated since this date. As the location of such camp sites is normally close to the beach it is suspected that the outer spit may have been constructed since this date. The second ridge is older. Its alignment is continued in the west by a band of firmly cemented inter-tidal beach rock, though the ridge itself has been truncated by the present beach. It is not surprising to find beach rock at the base of this ridge considering the shelly nature of the basal material. Shell from the beach rock gave a radio-carbon age of 2,460 years ± 80 B.P. (GaK-1508).

The inner-most ridge is an extremely broad one having a maximum width of nearly 200 yards. It has several crests, the outer one, the highest, reaching 27.5 feet, though the general level is not much more than 15 feet. This is an older ridge resembling the inner dune at Cape Pallarenda. Beach rock was encountered in two auger holes at 3 feet and 7 feet. Unfortunately exact heights of this cemented deposit could not be taken, but it is estimated to occur at approximately 12 feet above M.H.W.S. This is strongly suggestive of a mid-Holocene age.

The Bohle River enters the sea less than half a mile west of the Range of Many Peaks. A complex history is indicated for this area. A wide series of beach ridges is found on the western side of the Bohle north of the Mount Low Range. These are comprised of dominantly quartzose sand throughout. A 10-foot section exposed in the west bank of the Bohle at the rear of the sequence indicates 8 feet of dune bedded quartz sands overlying coarse grits. The whole sequence rests upon a heavy clay base rising to M.H.W.S. which suggests that the feature is better described as a chenier than a beach ridge. In contrast to the western ridge sequence a small series of ridges is found on the east bank widely separated by mangroves and salt flat. These all rest upon a similar clay base of constant height but their materials are quite different from those on the opposite bank. From the seawards side inland the sections exposed in the ridges are as follows:

	Depth	Description	Mean size (ϕ)
Ridge 1	0 - 4.4 feet	Shell grit	-
	4.4 down	Heavy clay	-

This ridge is found behind mangroves and curves as a spit to a small granitic outcrop near the Bohle's mouth.

Ridge 2	0 - 0.25 feet	Humic stained calcareous sand	0.7625
	0.25 - 1.0	Sand and shell slightly stained	1.2046
	1.0 - 2.0	Fine shell grit	0.4908
	2.0 - 2.5	Coarser shell grit	0.2243
	2.5 - 5.0	Coarse shell grit	-0.6190
	5.0 down	Heavy clay	-

	Depth	Description	Mean size (ϕ)
Ridge 3	0 - 0.4 feet	Humic stained sand with shell	0.6258
	0.4 - 0.75	Sand and shell grit	0.7393
	0.75 - 1.8	Fine shell grit	1.0176
	1.8 - 6.3	Shell grit lightly cemented at base	-0.2290
	6.3 down	Heavy clay	-
Ridge 4	0 - 1.2 feet	Humic stained sand and shell	0.8821
	1.2 - 4.25	Shell grit	0.8408
	4.25 down	Heavy clay	-
Ridge 5	0 - 6 feet	Brown quartz sand	2.5270

This is a higher ridge rising to nearly 10 feet. No base to the sand was reached at 6 feet.

Behind ridge 5 is another area of low sand ridges of similar material. The contrast between these ridges and those to seaward is remarkable. However, ridge 5 and associated remnants appear to be an extension of the similar though higher ridges to the west on the opposite bank. Their lower altitude appears to be the result of their position in the lee of the Range of Many Peaks. Meander traces indicated on the aerial photographs suggest that the Bohle formerly flowed further east close up against the boulder spit on the end of the Many Peaks Range. Examination of the area indicates that shell grit material originates around the rocky shores of the Range moving westward to the Bohle's mouth. The depth of the Bohle estuary, however, does not allow coarse shell grit to pass across it. Thus, when the Bohle flowed further east, the ridges to which it was contributing material received only the quartzose sands of the Bohle itself. Since the river has migrated west and breached the beach ridge or chenier barrier, the coarser shell grit has been transported further west to form the shell grit cheniers of the eastern bank (see fig. 4.3). The migration of the river mouth also led to the construction of a new set of beach ridge-cheniers to the west with a slightly different orientation to the older ones which they truncate.

Three radio-carbon dates from the outer shell grit cheniers give an indication of both the rate of chenier construction (where the material is almost completely biogenic) and also of the date when the Bohle took up its present position. Charcoal within a narrow pumice layer in the outer ridge gave a date of 1780 years ± 90 B.P. (GaK-1108); shell from the second ridge dated at 1320 years ± 70 B.P. (GaK-5110); and shell from the third ridge at 2350 years ± 90 B.P. (GaK-1511). The first date is probably too old, the ridge accumulating driftwood of much greater age. It is obvious that growth of cheniers in this situation is extremely slow and each one is possibly dependent upon a catastrophic event such as the passage of a tropical cyclone. The Bohle probably took up its position about 2,400 years ago. The indications are that sea level at this time was not much different from that at present and has varied little in the intervening period.

The Coastal Plain North of Townsville

This region includes the large embayment around the headwaters of the Black River and the narrower coastal plain to the north. It is an area of extremely complex deposits which, in general, form massive coalescing alluvial fans and distributary systems radiating out from the base of the coastal escarpment and from the isolated coastal

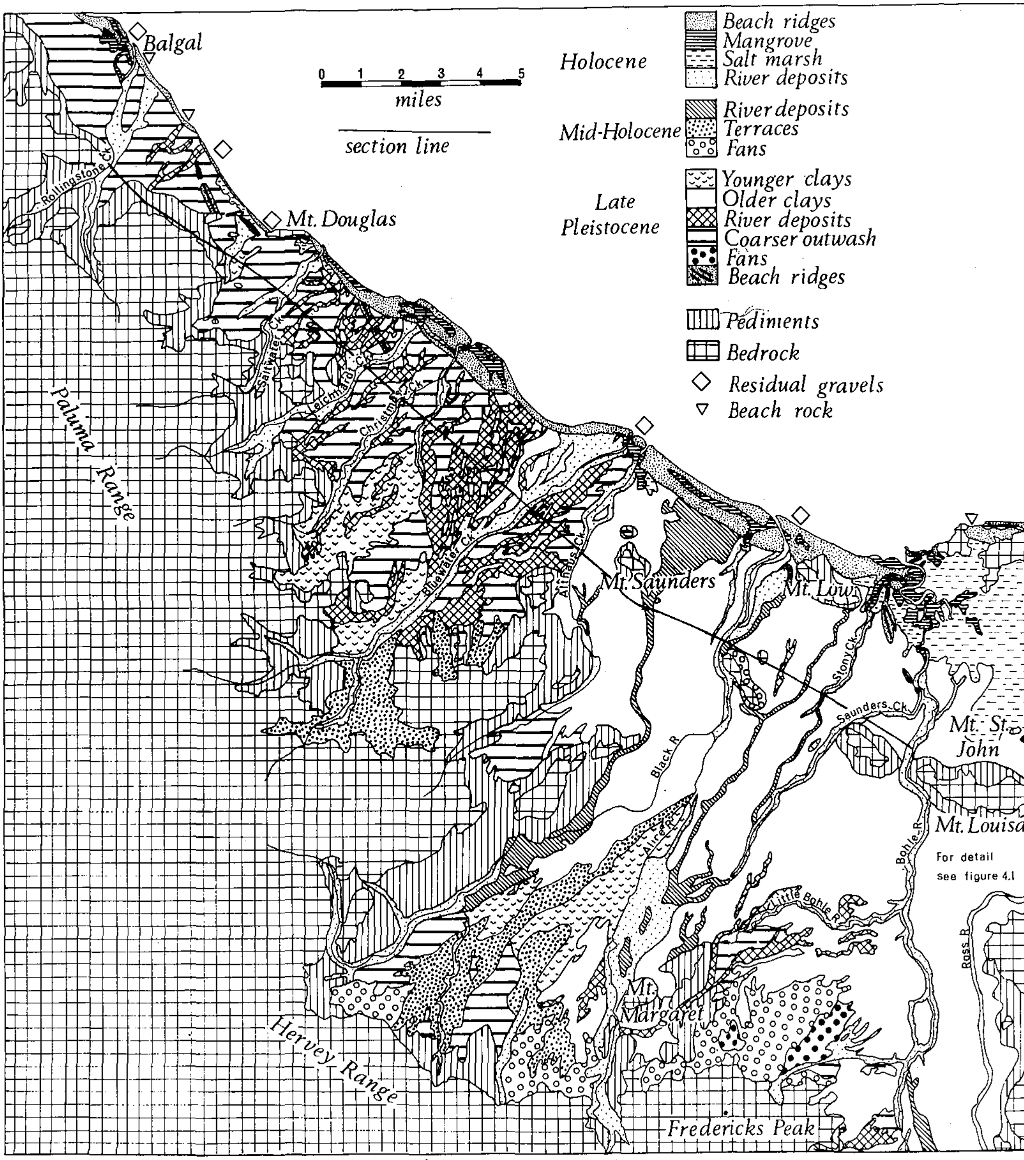


Fig. 4.4 Coastal plain deposits.

hills. However, the pattern of simple grading of deposits from coarse to fine towards the coast is complicated by the presence of fans and alluvial deposits of varying ages. Also, the accumulation of deposits during fluctuations of sea level has resulted in alternate phases of incision and aggradation, at least in the zone within a few miles of the present coast. Fluctuations in the climatic pattern between sub-humid and humid with corresponding fluctuations in geomorphic processes further adds to the complexity of the deposits.

This section of the chapter attempts to unravel the changes mentioned. Interpretation has been greatly helped by a soil survey of the same area by the C.S.I.R.O. (Mr. G.G. Murtha, Soils Division, Townsville) and it is largely with the co-operation of C.S.I.R.O. that the map of deposits (fig. 4.4) has been drawn. Thus the interpretation is based not only on geomorphological data but also on a description of soil and weathering profiles. Figure 4.4 indicates fourteen separate types of deposits apart from the solid outcrops. These fall naturally into two divisions, an older, apparently Pleistocene series and a younger, Holocene series, though age differentiations can be made within these two broad catagories.

Pleistocene Deposits

1. Solid Outcrops and Pediments

All solid outcrops are ringed by a pediment slope of varying width and inclination, with one exception, the Range of Many Peaks, where any former pediments have been trimmed backmback by the sea or are found beneath the surrounding coastal deposits. Only one other outcrop occurs on the coast, Mount Douglas, and though pediment destruction by marine processes is taking place here, the exposures are probably the most significant in the whole area. Elsewhere the pediments extend up to one and a half miles from the sharply defined pediment angle and have a slope of up to 15°. Bedrock protrudes through the pediment deposits in many places, and the veneer, away from the major fans, is relatively thin, of the order of 5 to 10 feet. These deposits have great variety and appear to be a composite cover of several periods. In places they may be seen to consist of boulders and sandy loams with only slight signs of leaching and are of apparently Holocene age. They overlie, with an abrupt transition, heavy clays which grade into sands, gravels and boulders of probably Pleistocene age.

The occurrence of clays within the pediment deposits is indicative of a break in the process of pedimentation. Indeed, it is doubtful whether the pediments are extending themselves at present, for the majority of streams, though flowing only seasonally, are incised into the deposits and into the pediment itself. However, there are indications that pediment deposits in the form of fans have accumulated during the Holocene (see below). There appears to have been no continuity in the development of pediments and deposits between the earliest examples of Pleistocene age, and the later Holocene features. Thus Pleistocene river deposits indicating channel flow, as opposed to the laminar flow required for pedimentation, also cross the pediments. The best example of this is found in the headwater of the Alice River below Frederick's Peak where a linear deposit of weathered fluvial sediments crosses the pediment between the main escarpment and Mount Margaret. Complete stabilization and cementation of the older pediment and fan deposits has also occurred and they have in general not become mobile again during the more recent period of similar accumulation.

Sections in the pediment deposits are rare and the exposures at Mount Douglas on the coast are thus of great interest. Mount Douglas is a narrow ridge of volcanic rocks about 1,200 yards in length and 250 yards wide which rises to 157 feet (fig. 4.5). It is the only rock outcrop in the mainland littoral between the granite tor at the mouth of the Bohle River and Tam O'Shanter Point near Tully some 120 miles to the north. As a guide to the nature of pediment deposits and the weathering processes which have operated in this part of North Queensland, the sections exposed along the shore are invaluable. The Mount Douglas site gains further significance as it lies on the climatic boundary between the Aw climates to the south and wetter Af and Am climates to the north. Although no records are available for the Mount Douglas area, it is estimated that the average annual rainfall here is in the range of 50 to 55 inches.

The geology of the area is complex. Mount Douglas is the last of a line of similar hills trending east-south-eastwards across the coastal plains from the main escarpment (fig. 4.4). It is composed of late Palaeozoic volcanic rocks which on the landward side are mainly tuffs, but which along the coast are fluidal and spherulitic rhyolites. The crest of the ridge to the west is determined by an intrusion of massive porphyritic rhyolite about 20 feet wide and smaller intrusions of similar material outcrop intermittently along the coast. Sand beach ridges trend northwards and southwards from the headland. Behind these and extending right to the base of the ridge is a coastal plain about 15 feet above M.H.W.S.

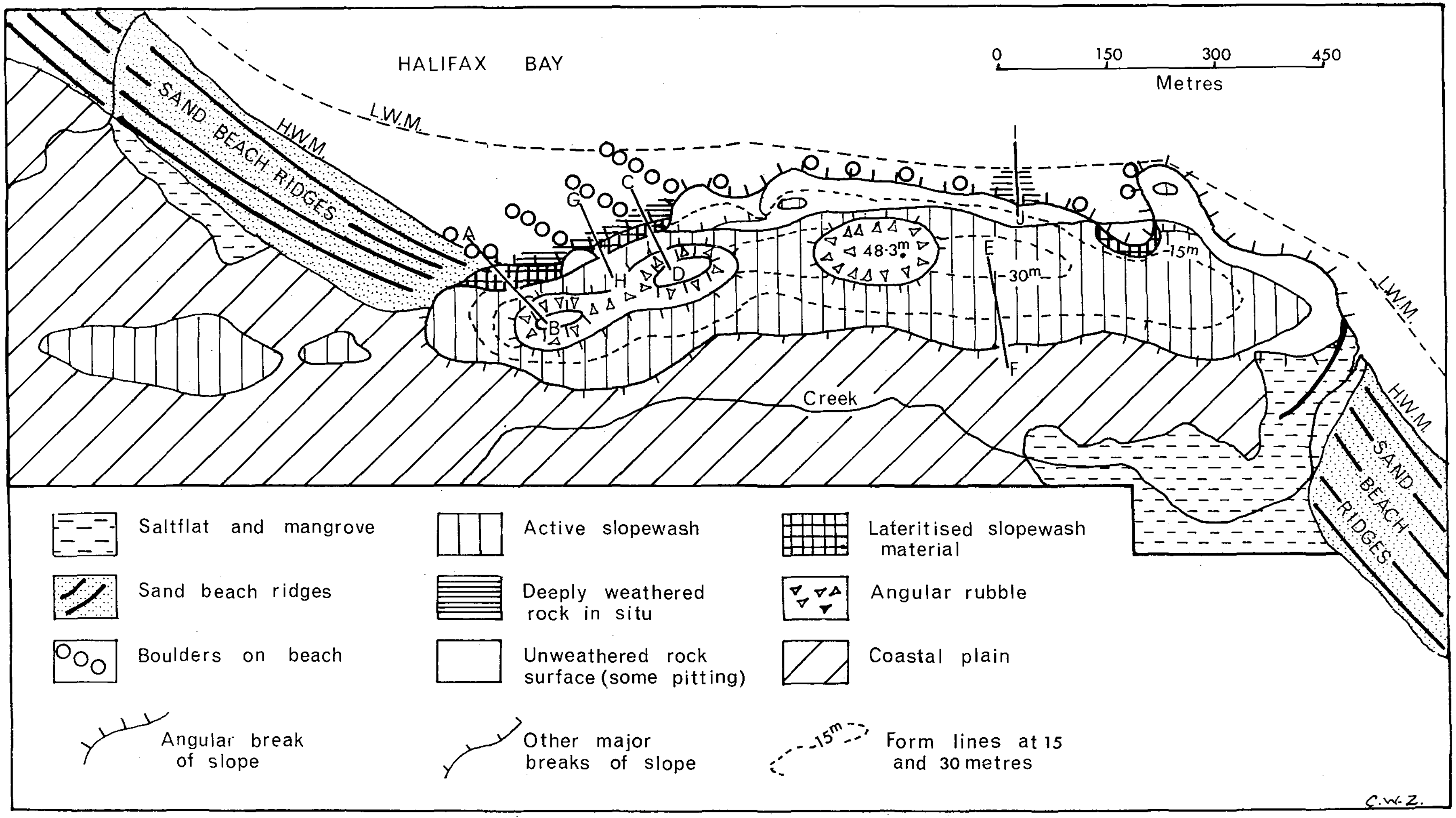


Fig. 4.5 Mount Douglas. Section lines are indicated.

Appreciation of the sections on Mount Douglas cannot be made without a consideration of the current processes of rock disintegration. A contrast in general weathering processes is observed in the area within and outside the rainforest which clothes the coastal escarpment behind Mount Douglas. Slope deposits in the rainforest appear to be quite stable even on 20° slopes. Occasional cuttings along the roads in the ranges display up to 30 feet of deeply weathered material predominantly red kaolinitic clays, overlying a partially decomposed granite _in situ_. The boundary between the two levels is sharp. The lighter vegetation cover of the lower rainfall areas appears to be the main influence on the greater instability of slope deposits here. During the dry winter season there is comparatively rapid mechanical breakdown of the rocks, of a granular type on granites and by fracture along joint and flow lines on volcanics. The torrential downpours of the wet season allow for a rapid downslope movement of these materials.

Mount Douglas is typical of these less humid coastal hills. Its open woodland vegetation consisting, of a tree storey dominated by _Eucalyptus tessellaris_, _E. polycarpa_ and _E. drepanophylla_ and a medium height herbaceous layer (mainly _Heteropogon contortus_), leaves much bare ground especially towards the end of the dry season. The angular regolith which clothes most of the ridge is susceptible to rapid soil creep and debris slides during the wet season.

Under normal sub-aerial weathering, the tuffs and rhyolites generally break down into angular rubble. However, the porphyritic rhyolites along the crest are more resistant and produce tor-like forms surrounded by large boulders. Both tors and boulders are subject to spherulitic weathering, individual spherules being about half an inch in diameter giving the rock surface the appearance of a conglomerate. Within the spray zone the rhyolites are subjected to wetting and drying and/or exsudation. Here, the porphyritic rhyolites decompose quickly and become kalinised. Rapid decomposition is also experienced by the spherulitic rhyolites but the fluidal rhyolites take on a polished, highly resistant surface, and it is these rocks which form the small promontories around the headland.

Rock outcrops along the crest of the ridge, in the form of tors at the western end and as a dome partially buried byaangular rubble in the centre of the ridge. The whole of the landward slopes are covered with active slopewash rubble. Two small excavations near the base indicate at least 4 feet of this material.

The seaward side of Mount Douglas is of greater significance. For the most part the littoral zone consists of convex cliffs slightly steepened at their bases and with a few poorly developed shore platforms which have been described previously (Driscoll and Hopley, 1968). However, at the western end and in a small cove to the east (fig. 4.5) are the remains of a former weathering profile, consisting of lateritized slopewash material which is now being subjected to cavernous weathering.

The western exposures are by far the best, and here the full profile of approximately 8 feet can be seen. The material is a stabilised slope deposit consisting of angular debris with individual boulders up to 3 feet in diameter. This closely resembles the active slopewash deposits, especially close to the summit of the ridge, where the calibre of the material is larger. Following stabilisation the deposits suffered a period of deep weathering and lateritisation. Sesqui-oxides are concentrated in the upper one and a half feet of the profile in sufficient quantity to produce a cap-rock effect. However, the iron concentration is by no means as high as that observed in the laterite of the uplifted late Tertiary surfaces behind the coastal escarpment. Below this upper horizon is a mottled zone about three and a half feet deep, followed by a kaolinised pallid zone of about 3 feet. In all three horizons the original boulders of the slopewash deposits are clearly seen, but individual boulders are completely rotted. The full profile is not seen over the complete exposure and in places it is only the kaolinised material which remains. Where this occurs, this lower part of the profile is silicified.

The morphology of the outcrop can be seen in the sections of figure 4.6. The indurated material emerges from beneath active slope deposits about 20 feet above mean high water mark and with a slope of about 18°. In only one place can the horizon be traced higher (on the headland near profile G-H) and here it rapidly thins as the slope increases. The main outcrop is cliffed with cavernous weathering extending the work of marine agencies so that the sharp break of slope is retreating in a parallel fashion from the shoreline. In front of the cliffed exposure is a shore platform actively being extended though the remains of another platform some 4 feet higher may be present and may be the line from which the erosional scarp is retreating. If the slope and depth of the lateritic material were constant from the main outcrop, one would expect the maximum width of the shore platform to be only 25 feet, with a progression upwards through the profile so that the lateritic material would be outer-most on the platform. However, a decrease in slope is suspected for the platform has a width of up to 90 feet, with the entire extent being cut into the mottled and pallid

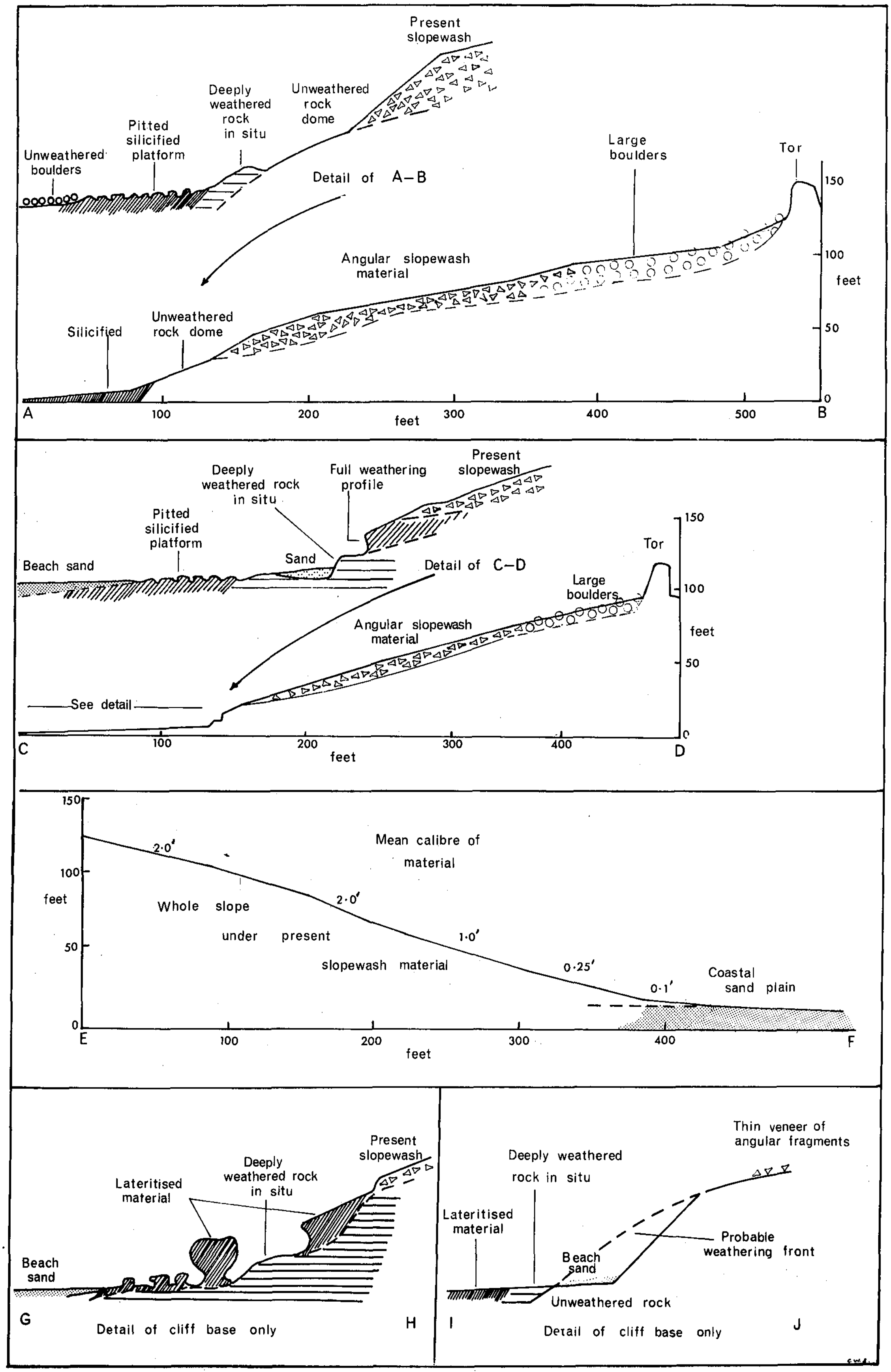


Fig. 4.6 Mount Douglas sections.

zones. In places the ancient weathering front, in the form of much weathered rock in situ, outcrops on the surface. This can also be seen in places along the main exposure. Both the rotted rock and the lateritic-silicified material within the inter-tidal zone are deeply pitted. At about mean high water mark, remnants of the silicified zone are found as pedestal rocks.

The smaller outcrop to the east is very similar, though the low cliff with its cavernous weathering is found behind a beach berm which completely masks any extensions of the deposits as platforms. However, 100 yards to the west is a small platform cut across deeply weathered rock in situ (Section I-J). Unweathered rock forms the cliff behind, but the relationships here suggest that whilst marine erosion is responsible for the lower and steeper portion of the cliffs of Mount Douglas, the bare upper convex slopes of some of the lower headlands are exhumed weathering fronts.

The ancient weathering profile clearly extends below present sea level suggesting a late Pleistocene agedduring the latest low level stand of the sea. The material subjected to deep weathering, and the deep weathering episode belong to contrasting climatic conditions. The angular nature of the material and its position at what appears to be a pediment angle suggest the origin of the material as an unstable piedmont fan extending over a pediment with a slope of about 3^{o}. The nearest location on the coast where similar landforms are active today is in the granite area behind Bowen 120 miles to the south, though even here there is evidence that the pediments and deposits at least originated in the late Pleistocene as they slope beneath Holocene alluvial deposits. On and around Mount Douglas similar slopewash materials are active today, though of a smaller calibre and without obvious signs of pedimentation.

The original climate for the assembling of the weathered deposits is suggested to be one slightly drier than today with a rainfall possibly in the order 30 to 35 inches and probably extremely seasonal.

The stabilisation of the deposits and subsequent severe weathering suggests a trend of the climate in a more humid direction. This could be attained by a southward movement of the tropical disturbances which bring the heavy, extended rains to the coast north of Ingham. Similar deposits are reported in the Herbert River Delta near Ingham (De Keyser, Fardon and Cuttler, 1965) and these are commonly mottled and cemented.

The latest trend has been towards dessication allowing the induration of lateritized material and initiating slopewash activity. The ancient pediment junction and its deposits are being covered by small angular material. The rising Holocene sea level has initiated the parallel retreat of the lateritic horizon. The steeper slopes of Mount Douglas probably never allowed a deeply weathered mantle to form over the whole ridge. However, parallel retreat is as much responsible for the removal of the cover from the lower slopes (including the present headlands) as marine erosion.

The original Holocene shorelines were seawards of these exposures. East of the main exposure are three lines of boulders marking the trends of three former shorelines (lag gravels of Driscoll and Hopley, 1968, see below). The beach ridges behind the present beach are all extremely young and it is evident that the shoreline has been in a position to expose the lateritic material in this area for only a short period of time. Similarly, lines of boulders across the mouth of the small cove in which the other exposure is found also suggest a protective barrier here.

2. Pleistocene Outwash Fans

Around the base of Frederick's Peak, the piedmont deposits tend to take on the morphology of true outwash fans. A Holocene fan series is found here (see below) but beneath and beyond this is an older outwash deposit interpreted as Pleistocene. Closer to the scarp foot it tends to rise above the younger fan, possibly indicating an originally steeper slope to the Pleistocene deposits. The materials are composed of bleached sands overlying waterworn gravels. The main feature distinguishing the Pleistocene deposits from the later fans is the presence of ironstone nodules and iron impregnated gravel throughout the section. The lower gravel may be cemented in places.

3. Pleistocene River Deposits

Sandy deposits overlying coarse sands and water-worn gravels at depths of 5 to 6 feet, occur as linear extensions over various parts of the coastal plain. The majority of present coastal streams have steep levee banks rising above the surrounding plains and the morphology of the Pleistocene deposits suggests a similar formation as they form low rises, though they may only be detected as such by detailed survey. The deposits are strongly leached, though there may be a concentration of ferro-manganese nodules at a depth of 3 to 4 feet.

The most extensive area of these deposits is in the north across the narrower part of the coastal plain. The closely spaced pattern reflects that of the present streams, but the current drainage lines are unrelated to the Pleistocene deposits. The drainage lines are particularly close around Bluewater Creek where they form a large fan-type distributary system, probably indicating the sphere of migration of the proto-Bluewater during late

Pleistocene times. Further south the channel deposits are limited to the upper parts of the Black River embayment. They tend to form fan like aprons of closely spaced channels just beyond the pediments but on morphological grounds appear younger than the Pleistocene outwash fans and tend to be more restricted to true channels. A particularly prominent drainage line trending west to east in the headwaters of the Alice River appears to anticipate the Little Bohle River.

4. Pleistocene Sandy Outwash Plains

Surrounding the clearly delineated river deposits are areas of weathered sandy alluvials which appear to be the old floodplains of the Pleistocene river system. Aerial photographs indicate signs of channelled flow within these areas but in general they appear to be lower than the highest parts of the channel deposits. They may have formed the lower parts of the levee system.

These deposits are generally strongly leached coarse sands on the surface becoming mottled and clayey at depth. Coarser fine gravels may be encountered at depth and especially within the Black River embayment. At between 4 and 5 feet siliceous or ferruginous nodule pans are encountered. Concentrations of silica or ferro-manganese nodules at depth appears to be diagnostic of the Pleistocene deposits (see below).

5. Older Pleistocene Clay Plains

By far the largest area of the coastal plains is taken up by clay deposits forming solodic soils with a very even surface, sloping imperceptibly down to the sea. The deposits are of a duplex nature consisting of silt size or even sand size material in the upper one or two feet but invariably overlying heavy clays. They generally occur on the interfluve areas and indicate low energy environment depositional conditions. Some of the deposits may have originated under marine or littoral conditions and may be older than the last interglacial.

Like many of the other deposits of Pleistocene age, the clay plains contain ferro-manganese nodules, sometimes throughout the soil profile, more commonly in the lower layers. Concentration of these sesqui-oxides in the profile is the result of seasonal fluctuations in the water table, impregnation following the lines of least resistance where water can circulate (Maignien, 1966). Current research being carried out by C.S.I.R.O. in Townsville has indicated that even in the wettest years in the area at present, such fluctuations are limited to the upper 3 feet of the heavier deposits. Accumulation of sesqui-oxide nodules is thus limited to the upper few feet, a much more restricted area than that found in the Pleistocene clays. It is considered that wetter conditions, though still with a strong seasonal rhythm, were required to form the bulk of ferro-manganese accumulation.

Nodules of calcium carbonate up to half an inch in diameter are also found in the profiles, from about 12 inches down. It is difficult to envisage conditions which would promote the precipitation of both sesqui-oxide and carbonate nodules together, and with the leaching factor of $CaCO_3$ being up to 75 times more rapid than that of iron (Miller, 1961) the carbonate nodules are considered to belong to a drier phase occurring between the period of ferro-manganese accumulation and the present. A radio-carbon date on one carbonate nodule suggests that there was a period of carbonate accumulation approximately 15,000 years ago (see below, Pleistocene Shorelines).

6. Younger Pleistocene Clay Plains

The older Pleistocene clay plains are limited to the seawards end of the coastal plain system, generally below 100 feet. Above this level the clay plains become more restricted, inter-digitating between the coarser fluvial and fan deposits. These higher clay areas appear to be younger than those of the coastal zone. In particular, ferro-manganese nodules, though occurring, are by no means as common. The relationship of these plains with the younger drainage lines indicates that they definitely pre-date the Holocene drainage pattern. The interpretation which is offered is that the lower clay plains were deposited during the last interglacial with a high sea level. During the subsequent glacial period, the lowered sea level produced incision by the coastal streams, thus isolating the clay interfluves from further deposition. In the headwaters of the coastal streams, however, there was isolation from the eustatic changes in sea level for a longer period and deposition continued well into the low sea level phase. Such isolation of a headwater sector from eustatic changes in sea level, with consequences for soil development have been described by Walker (1962a, b), and Butler (1967) in the Nowra district of New South Wales.

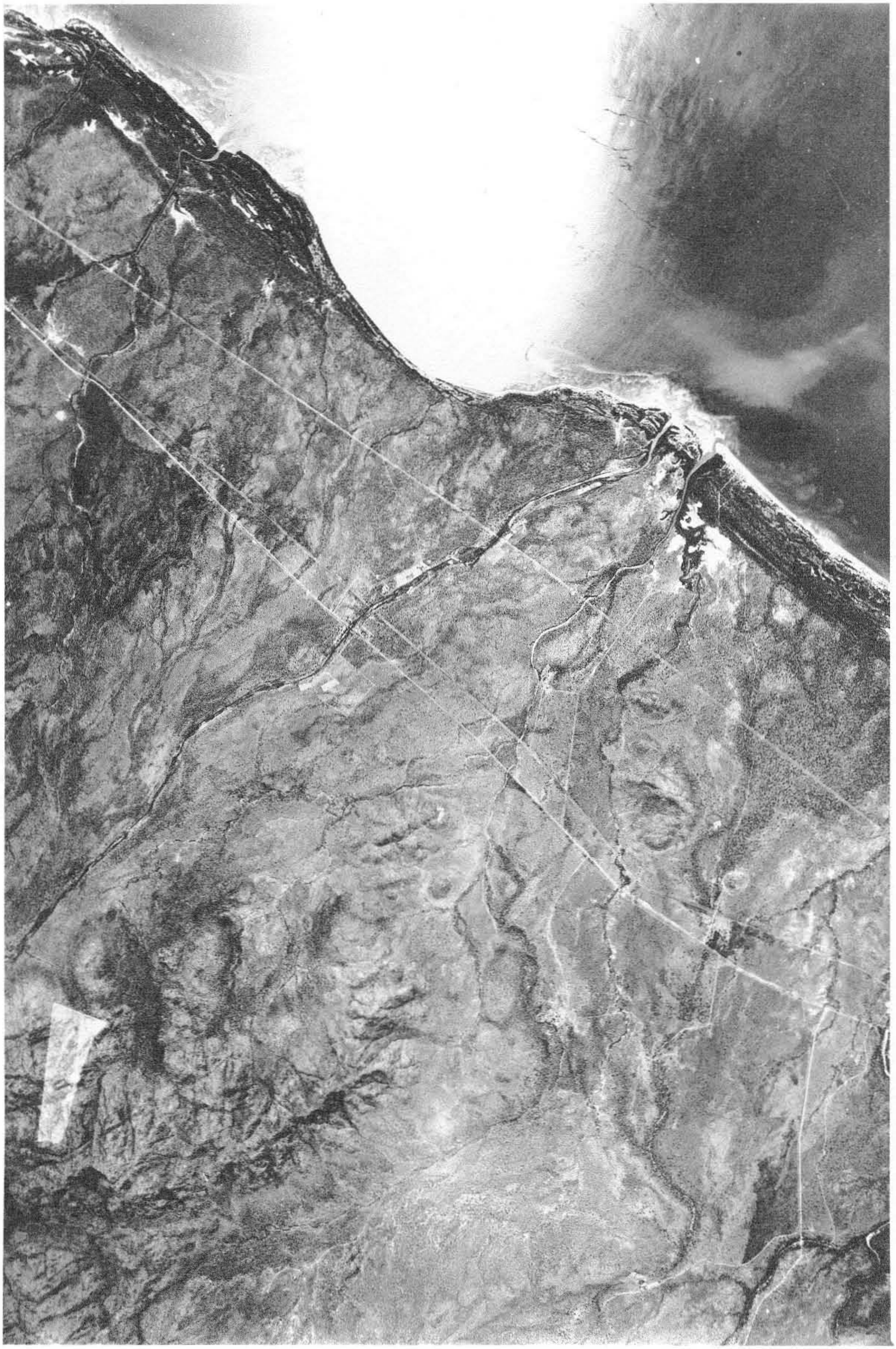
In the Black embayment especially, the younger clays overlie fine quartz gravels and weathered granite fragments more consistent with the higher fans. Changing climatic conditions may be indicated by the changing patterns of sedimentation (see Chapter 8).

7. Pleistocene Shorelines

Pleistocene shorelines in the form of weathered beach ridges are rare in the area and the upper limit of the late Pleistocene transgression appears to have been seawards of much of the present coast. This is also suggested by the Pleistocene drainage pattern. Two low sandy rises occur north of Mount Douglas attached to an outcrop of bedrock. North of Leichhardt Creek is another similar ridge. Extension of the drainage pattern seawards during the regressive stage has cut a number of gaps through this ridge.

The best documented of the Pleistocene shorelines is found near the lower Bohle River. A small outcrop of granite occurs inland from the present shoreline and trending south from this are the remnants of at least three wide sandy ridges. One of the ridges continues south to cross the Bohle 3 miles upstream. It apparently continued in a south-easterly direction to join Mount St. John. East of this small outcrop are interrupted remnants of the same ridge, probably trending towards Castle Hill. The Bohle and Ross Rivers have jointly obliterated much of this shoreline. However, a fine section is seen through the ridge and adjacent Pleistocene clay sediments in the west bank of the Bohle. The ridge is composed of coarse sands throughout, bleached white or grey in the upper 2 feet but becoming yellow or brown at depth. The most surprising feature is the presence of a firmly cemented calcareous and jointed sandstone in the core of the ridge. This is exposed as a ledge for 30 yards along the Bohle's banks. Its level surface, which rises to 8 feet above M.H.W.S., is similar to that of the beach rock plateaux of the off-shore islands, and there seems little doubt that the sandstone originated as beach rock. If so, then a late Pleistocene sea level of about 8 feet higher than present is indicated.

Above the cemented horizon in the forward part of the ridge are carbonate nodules about a half an inch in diameter. Examination of sections through these nodules showed no sign of "onion" skins indicating periodic or intermittent growth



XXIII The coastal plain around Bluewater Creek. The mid-Holocene deltaic fan of the Black River is seen to the east.

and a sample was submitted for radio-carbon assay. The result (GaK-2010) of 14,680 years ± 310 B.P. confirms the ridge as Pleistocene, and possibly indicates a period of carbonate nodule formation.

Holocene Deposits

1. Holocene Outwash Fans

The Holocene outwash fans are composed of leached white sands overlying coarse waterworn gravels. The deposits are uncemented and overlie or enclose the older Pleistocene fan deposits. They occur at the base of Frederick's Peak and have a remarkably similar distribution to their older counterparts. They are not active today and are being incised by the small streams flowing from the Frederick's Peak scarp.

2. Holocene Terraces

In the upper Black River and upper Bluewater Creek catchments are terraces up to 25 feet above the present streams. The materials consist of coarse sands overlying waterworn gravels at depth. The upper parts of these terraces, especially in the upper Bluewater area appear to merge into outwash fans. They have not been differentiated in figure 4.4. The presence of these deposits in the upper areas of the catchments suggests that the terraces are related to climatic and not eustatic fluctuations.

3. Mid-Holocene River Deposits

A number of sandy rises similar to those described as Pleistocene river deposits, but not as weathered and much more pronounced, occur in the southern part of the coastal plain. These linear deposits are independent of the present drainage lines but it is obvious that part of the present drainage pattern is inherited from the older mid-Holocene pattern. Thus the upper parts of the present Saunders Creek and the lower course of Stony Creek are joined by a low sinuous ridge of mid-Holocene fluvial deposits. Similar relationships can be found in the upper part of Saunders Creek and between the Bohle and Ross Rivers. The most continuous of the mid-Holocene courses is that of the Black River which flowed to the north and west of its present course, branching into an extensive distributary area in its lower section just behind the present beach ridges.

The deposits, which consist of red podsolised sands, are considered mid-Holocene because of the stage of development of their soils (but without ferro-manganese nodules). They are also perched on the clay plain above the present river courses which have been incised up to 20 feet into the plain probably as a result of the late Holocene regression. The soils and texture of the deposits resemble the low sandy rises which protrude through the clays of the Barrattas area in the Burdekin region. These were also regarded as mid-Holocene (see Chapter 3). The abandoned Black River course passes between Mount Saunders and another small outcrop of solid in much the same way as the Burdekin flows over the rock bar at The Rocks and the similar passages of the Bohle and Ross Rivers described above. As the example of the Black River occurs close to the shore and not far above sea level, it is considered that such a course would be possible only during a phase of rapid aggradation, probably close to the mid-Holocene maximum sea level.

4. Holocene River Deposits

Sands and gravels are found along all the present watercourses, as narrow floodplains or levees. On the lower parts of the coastal plain the streams have incised into these deposits and the levees have been stranded on the upper banks. Where this has occurred the deposits may be mid-Holocene and have developed red earth soils. Bluewater and Leichhardt Creeks have small deltaic areas of recent origin, though both appear to have been trimmed back by the waves and are fronted by very fresh beach ridges. A number of minor stream diversions are indicated by the Holocene river deposits.

5. Holocene Shorelines

Beach ridges have built up along the entire coast, many of them showing distinct signs of developing as spits under the influence of a strong south to north littoral drift. The ridges are generally closely spaced and overlie a variety of deposits including little modified Pleistocene clay plain, mangrove muds, beach rock and unconsolidated gravels. Beach recession appears to be taking place along much of this coast and the present shoreline truncates the trend of the older ridges. This is especially so just north of Rollingstone Creek where excellent sections in the ridges are exposed in a low cliff. The outer ridges have a core of shingle and coral fragments with a dune capping of about 3 feet. The inner ridges rest upon a platform of mangrove muds with stumps in situ rising 1.8 feet above M.H.W.S., generally above the level of growth of close stands of large mangroves as indicated by the deposit. The rear-most ridges may thus have formed during the higher mid-Holocene sea level. The evidence from the Cleveland ridges of a fairly constant thickness to the dune cap may be applicable along part of this coast as the inner ridges are usually higher than the outer. Thus a series north of Rollingstone Creek has heights of 5.3, 8.3, 6.3, 12.8 and 16.3 feet above M.H.W.S. However, factors other than a higher sea level could be involved.

6. Mangroves and Salt marsh

Mangroves and salt marsh are not extensive along the coast. Mangroves are limited to the small creeks draining the beach ridge areas. Of the major streams, only the Bohle has extensive mangroves at its mouth. Salt marsh and salt pan are found behind the beach ridges in areas of formerly impounded tidal drainage. Some areas may have originated as small lagoons.

Detailed contouring of the whole of the coastal plain is not available, but a section line is contoured between the Bohle River and Rollingstone Creek which shows the relationships of the different deposits. This was surveyed along the line of the north coast railway prior to its construction in the early part of the century. The section and deposits found along it are shown in figure 4.7. The near constant level of the Pleistocene clay plain is interrupted only by minor gullies and by the extensive levee systems of present, mid-Holocene and Pleistocene streams. In particular the mid-Holocene deltaic system of the Black River rises some 20 feet above the general level. The degree of incision of the streams into their Holocene deposits is striking. Towards the northern end of the section line, the ground surfacr rises as the coastal plain narrows and the main escarpment approaches the line of the railway.

Cemented Deposits of the Townsville Plain

Cementation of deposits other than the fan gravels of the piedmont zone occurs throughout the coast plain area, and in particular along the stream courses and on the coast. Cementation of river sediments occurs in the banks of many streams to within a foot or two of the surface. These deposits, variously described as "creek rock", "stream rock"

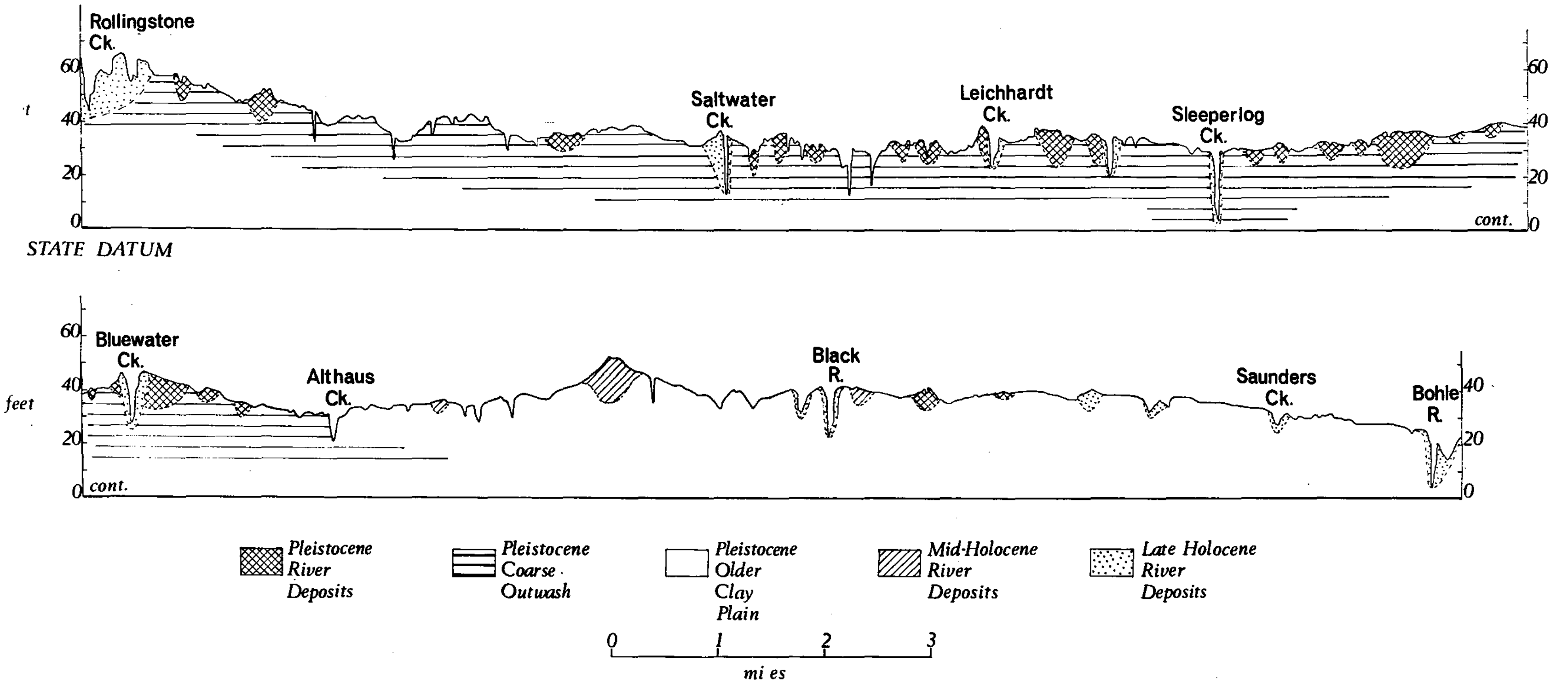


Fig. 4.7 Section across the lower part of the Townsville coastal plain.

or "water table rock" have been described by Russell and McIntire (1965) and Russell (1967) and attributed to accumulation of the cementing agent along the stream banks by fluctuations in water table level. These fluctuations are much greater adjacent to the streams than in the coast plain deposits generally and up to 15 feet of cemented deposits may occur alongside the streams, often forming a ledge with a more or less horizontal surface. The level of cementation along many streams, especially close to the coast, appears to be well above the level of present water table fluctuation. In some examples the cemented deposits are underlain by uncemented materials and are almost certainly fossil features related to a higher water table produced either by a wetter climate or by a higher sea level or by a combination of both. Drilling has indicated that the cemented horizon does not extend horizontally for any distance away from the stream banks, which seems to confirm Russell's hypothesis that complete lithification occurs only with exposure to the atmosphere. The cementing agent in most examples examined appeared to be silica, but iron and calcareous cements were observed and occasionally induration appears due to the illuviation of clay particles in a particular horizon.

Beach rock occurs along the coast but exposures are not widespread. However, augering in many of the beach ridges immediately behind the present beach and examination of sections exposed where small creeks have cut through the ridges or where coastal retreat has occurred, show that incipient beach rock, only lightly cemented is found in many ridges, especially where coarser materials form the basal deposits. Well cemented deposits consisting of large boulders and blocks of coral up to 2 feet across in the basal portion occur at Balgal and within the outer-most beach ridge to the south where it is exposed at creek exits. This exposure has been described by Russell and McIntire, (1965, 1966) and Russell (1967) though the upper level of beach rock (which occurs almost exactly at M.H.W.S.) above the lower beach was over-estimated by these authors. Coarse shingle extends out into the lower beach flat with detached or displaced patches of beach rock and conglomerate, and apparently indicates the former extent of cemented deposits. Other areas of coarse gravels occur along the coast on the lower beach (the lag gravels of Driscoll and Hopley, 1968). They appear stable with crusts of oysters and other marine organisms. There is no evidence that these were cemented but they do seem to indicate the position or positions of the former coastline. The example at Mount Douglas has already been described. North of Rollingstone Creek where the present coast truncates the beach ridges, the line of these ridges is continued on the lower beach by similar trending exposures of these coarse gravels, which also form the basal portion of the ridges.

The coastal streams are not supplying material of this calibre to the beach at present. The shingle and boulders appear to havebbeen incorporated in the Holocene beaches through erosion of the coastal plain and dislodgement of late Pleistocene and mid-Holocene perched fluvial gravels. However, the presence of blocks of coral in the conglomerates of a larger size than is generally encountered on the beach today, may indicate stormier conditions, or alternatively more rapid erosion of off-shore reefs exposed to erosion by a falling sea level. Shell from the Balgal conglomerate gave a radio-carbon date of 2,180 years ± 80 B.P. (GaK-1509).

Summary Evolution of the Townsville Coastal Plain

1. A late Pleistocene high sea level is indicated in the area with a maximum height of 8 feet above present. The climate of this period may have been wetter than present as widespread clay plains were found at this time. Alternatively the clay plains may have been inherited from an earlier phase.

2. Towards the end of the high sea level phase the climate became drier allowing the construction of coarse alluvial fans and the formation of pediments. This drier climate continued when sea level fell below that of present.

3. At the low sea level phase a more humid climate, probably wetter on a seasonal basis, set in, causing deep weathering of the earlier deposits, especially the coarser ones which allowed a deeper penetration of water and the formation of ferruginous pans. Ferro-manganese nodules formed in the deposits of the clay plains, which now extended into the headwater reaches of the Black River, over the earlier coarse deposits.

4. Towards the end of the Pleistocene, probably by 15,000 years ago, the climate became considerably drier, a position which possibly continued into the Holocene period. The climate was probably drier than that of present. New alluvial fans of coarse material developed, and streams courses were clogged with coarser deposits.

5. At the mid-Holocene stage, sea level in the area may have been higher than that of present and with rapid aggradation, the streams had many changes in course.

6. A slight change towards a wetter climate has accompanied the regression from the mid-Holocene level. Stabilization of the fans with subsequent incision into these and the pediments and their deposits has occurred. The streams generally carry finer calibre material, sands overlying the older gravels. Streams have became incised, as a result of the falling sea level close to the coast, and as a result of a lowering of the coarse fraction of the transported load in the headwater reaches. In the sheltered environments of the south, chenier development has continued through this period. In the north, the latest event on the coast has been one of shoreline retreat.

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CHAPTER 5

THE HERBERT RIVER DELTA

At the northern end of Halifax Bay the narrow coastal plain widens into the extensive deltaic plain of the Herbert River. The Herbert, with a catchment area of 3,400 square miles and a mean annual flow of 2.878 million acre feet, is a much smaller river system than the Burdekin and its delta is only about one third the size. However, though the rainfall of the delta area is approximately 80 inches per year, or twice that of the Burdekin, the climate, geology and physiography of the catchment of these two major rivers, are very similar. Unfortunately, a detailed analysis of the morphology and evolution of the Herbert delta is not possible for a number of reasons. First, although this delta supports a vigorous sugar cane industry, with agriculture limited to the higher levee soils as in the Burdekin, there is a belt approximately 5 miles wide of mangroves and freshwater swamps along the coast which is almost completely inaccessible, except along three roads. Secondly, because of the higher rainfall, irrigation of the sugar cane is not necessary and there has not been the same intensity of drilling in the Herbert delta as in the Burdekin. The higher rainfall also means that the Herbert delta is much wetter than the Burdekin with large areas of swamp behind the levees, even back from the coast, and this too hinders access. For the same reason, vegetation is much more luxuriant and where uncleared is difficult to traverse on the ground, overgrows any stream bank sections and generally makes interpretation from the air more difficult.

Nevertheless, probably because of the simplicity of the Herbert delta, a satisfactory resume may be made of the more recent evolution of the morphology of the area. The lower Herbert is much more restricted than the lower Burdekin and occupies a funnel shaped embayment opening towards the south-east between the Cardwell Range to the north and the Seaview Range to the south. Both ranges are part of a Permo-Carboniferous igneous complex comprising porphyritic volcanics, various granitoid rocks and acid and basic dykes (De Keyser, Fardon and Cuttler, 1965). These rocks have a strong south-west to south-east trend and are cut by the major Palmerville fault which has a similar trend and is thought to underlie the Herbert delta. The Hinchinbrook Island massif further restricts the deltaic area to the north. Although the coast of the delta has an orientation south of east, this is not as open a coast as might be expected as considerable protection is given by the Palm Islands, 12 miles off-shore and by the smaller islands of Halifax Bay. Nevertheless, a strong south to north littoral drift exists which has swept material northwards from all the former distributaries of the Herbert.

Previous geomorphological work in the area has been sparse. The Cainozoic deposits are briefly described by De Keyser, Fardon and Cuttler (1965). Information of geomorphological interest is also contained in a number of local and State Government reports (Hinchinbrook Shire Council, undated Report on Stream Improvements; Report on Flooding in the Ingham District, 1967; Calvert, 1959). The report by Calvert on groundwater investigations of the Herbert River delta contains the only reliable borehole data. Unfortunately only 27 boreholes are recorded of which 11 reached bedrock. Macnae (1966, 1967) has described the mangrove ecology of the northern part of the delta at the southern end of the Hinchinbrook Channel.

Bedrock Morphology

The few borehole records available are limited in the area they cover and restrict the reliability of the map of bedrock morphology drawn from them (fig. 5.1). There are numerous rock outcrops in the lower delta which suggest that deltaic deposits are shallow to the north of the present course of the Herbert and also along the southern edge of the plain. The borehole evidence confirms this and also indicates the extension of a subsurface ridge northwards towards Trebonne. The gap between this ridge and the Mount Leach Range is narrow, less than 2 miles wide.

It is in this gap that the main bedrock channel is cut. Near Trebonne the bedrock channel apparently coincides closely with the present course of the Herbert, but whereas the present river swings north-eastwards at Ingham, the older bedrock channel continues towards the east probably crossing the coast just north of Allingham. The channel is surprisingly deep and gorge-like, having a depth greater than 250 feet below sea level beneath Ingham and in all probability greater than 300 feet before it crosses the coast. Two and a half miles north of Mount Mercer a bore reached 288 feet below sea level without finding bedrock. Even near Trebonne a borehole reached bedrock at 121 feet below sea level and it is likely that the channel here is over 150 feet deep.

South-west of Trebonne, bedrock was not reached at 106 feet. Apparently the Stone River also has a deeply incised channel which is a tributary to the main Herbert. Further east is another tributary channel trending north from the Seaview Range, this may be connected with the Stone River south of the northern-most outcrop which breaks the surface.

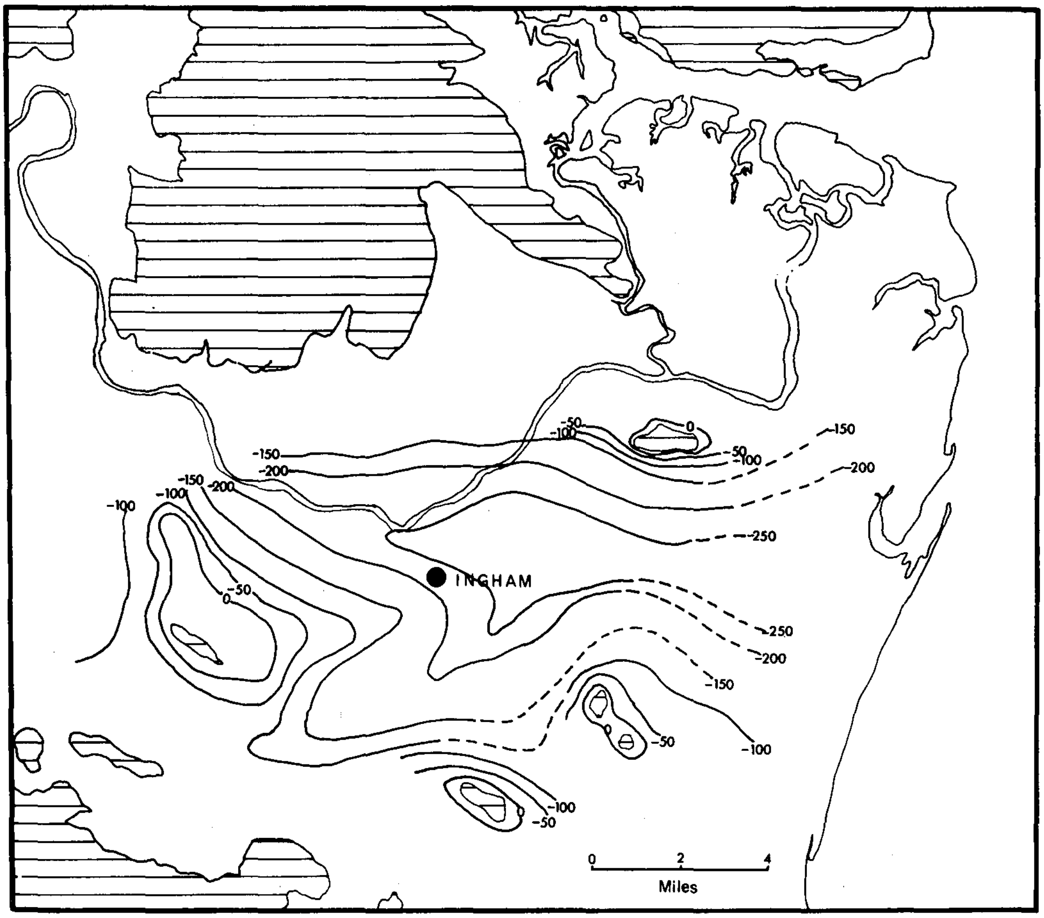

Fig. 5.1 Herbert River delta, bedrock contours.

Extension eastwards of the main channel brings it into the vicinity of the Palm Islands. Admiralty charts suggest three passages for the Herbert during Pleistocene low sea level phases. The most obvious is a channel between Brisk and Havanna Island, passing south of Great Palm Island. However, another channel leads northwards just west of Orpheus Island, whilst the deepest channel of all, meanders between the Palm Islands, passing out to sea between Fantome and Curacoa Islands.

The Deltaic Deposits

The deltaic deposits reach a maximum thickness of more than 315 feet in the Palm Creek area. Examination of borehole records indicates a complexity equivalent to that in the Burdekin delta. Two sections, figure 5.2 and 5.3, derived from Calvert (1959) are shown and serve to illustrate the salient features of the deposits. As in the Burdekin delta, weathering horizons may be recognised in the sequence as oxidised red or brown clays sometimes overlying or being replaced by cemented deposits. Several such horizons may be recognised in any one core, but only the uppermost appears to have any continuity. Following the analogy of the Burdekin delta, this is interpreted as the late Pleistocene deltaic surface (fig. 5.4). Owing to the paucity of records no details of this surface can be detected but the major channel of the Burdekin at the time appears to have followed a remarkably similar course to that of the bedrock channel, crossing the present coast just north of Allingham after closely paralleling the present river between Trebonne and Ingham.

Because the Herbert has apparently maintained more or less the same channel throughout the latter part of the

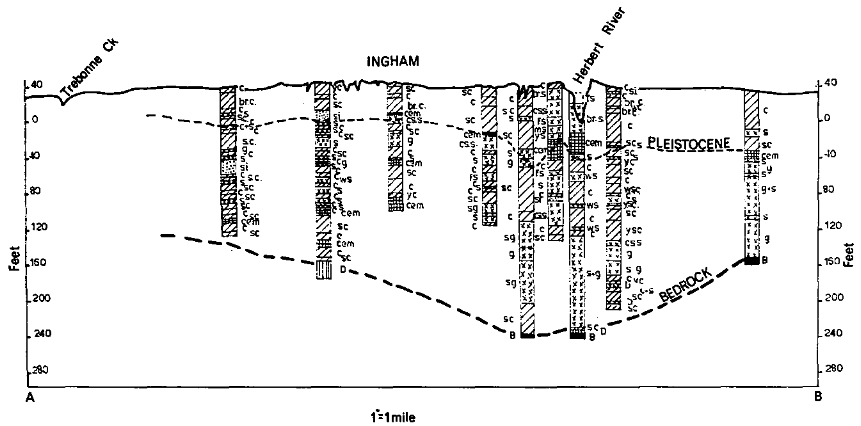

Fig. 5.2 Herbert River delta, north-south section at Ingham.

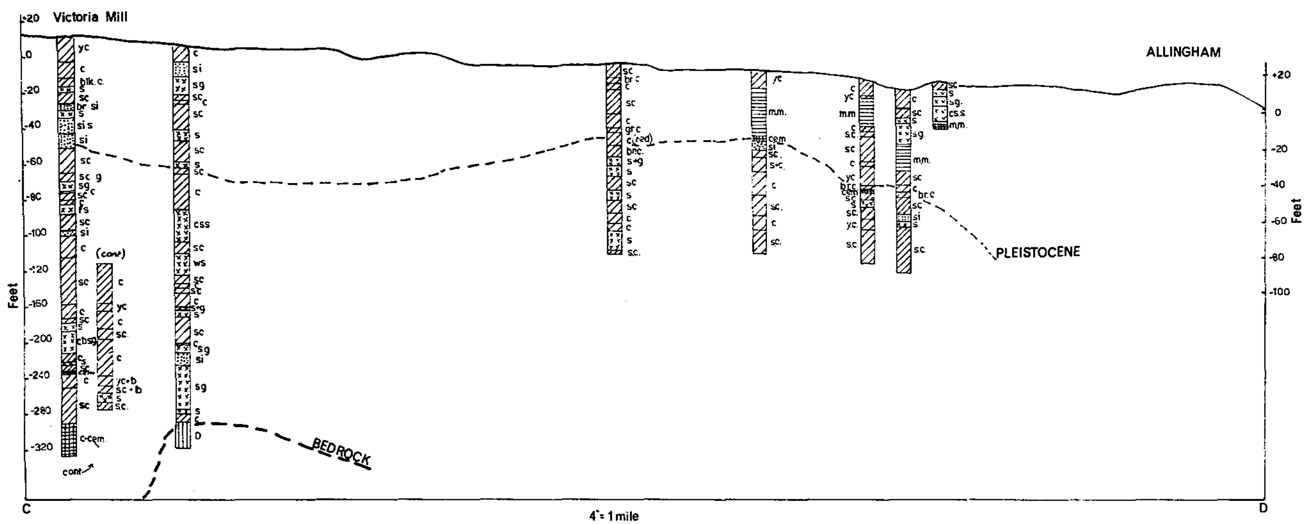

Fig. 5.3 Herbert River delta, east-west section at Allingham.

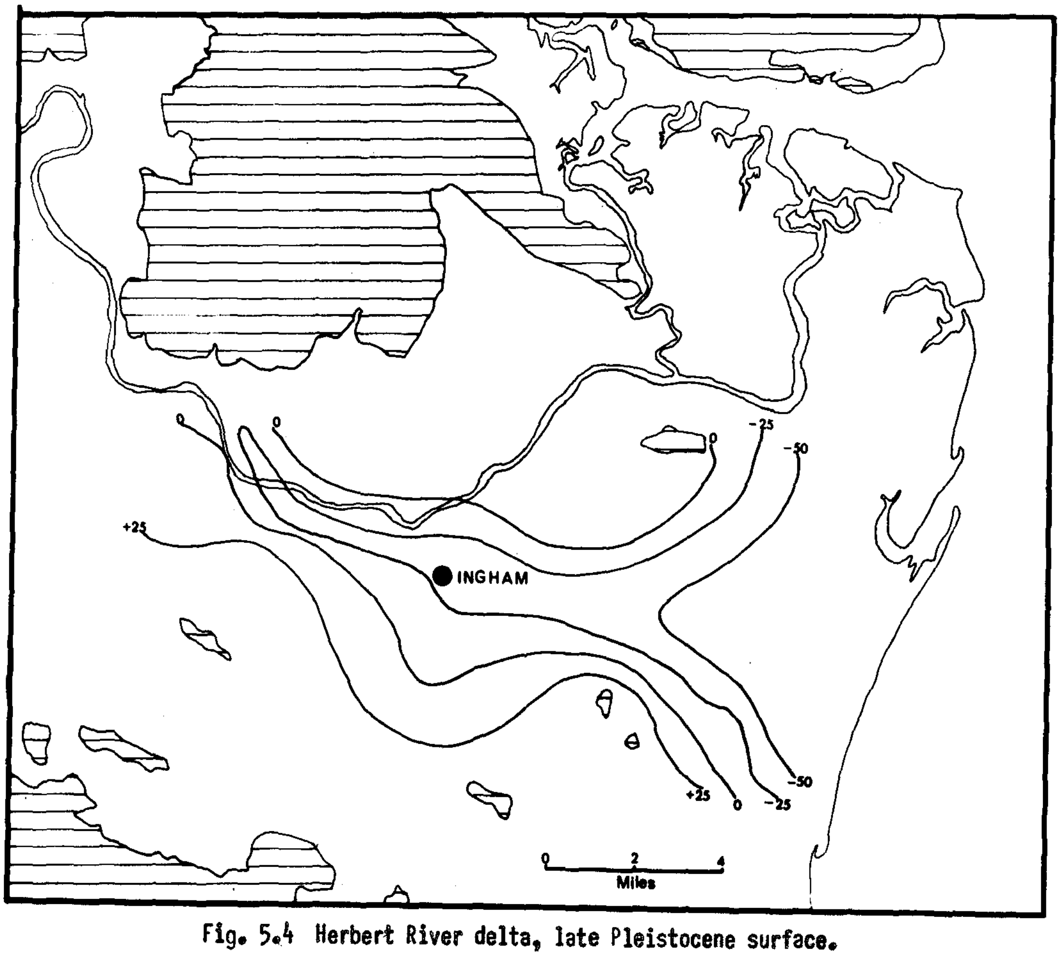

Fig. 5.4 Herbert River delta, late Pleistocene surface.

Quaternary, the coarser river deposits consisting of sands and gravels have been constrained to the one narrow belt. This is well seen in figure 5.2 where sands and gravels dominate beneath the present river and for about a mile to the south, within the late Pleistocene and bedrock channels. Outside these channels the quieter environments have experienced mainly fine grained sedimentation with coarse alluvials occuring only in lenses. The thick sand and gravel deposits occuring at the base of the northern-most bore of figure 5.2 are thought to belong to the streams issuing from the Cardwell Range, rather than to the main course of the Herbert. The widespread levee deposits north-east of Ingham in the present deltaic region are considered to be a comparatively thin veneer of recent date.

Figure 5.3 is an east-west section between Victoria Mill and Allingham. The Pleistocene surface here is between 20 and 30 feet below sea level, though dropping away fairly sharply about a mile inland from the coast. The transect is on the southern edge of the bedrock and late Pleistocene channels and clays tend to dominate the deposits. The latter part of the Holocene transgression is recorded in the deposits up to 2 miles inland. Mangrove muds containing roots and wood are found up to 35 feet below sea level and extend to 9 feet above this level. These figures relate to State Datum. Corresponding levels related to M.H.W.S. would be -38.6 to +5.4 feet. The higher level is generally beyond the range of mangrove habitats at present. It may indicate a higher Holocene sea level.

Surface Deposits and Morphology

The Herbert River enters the sea through an asymmetrical delta, the bulk of recent deposition being towards the northern edge of the delta. Although still partially confined within the bedrock walls of the lower valley the characteristic cuspate shape is maintained in part by the strong tidal scour which keeps open the Hinchinbrook channel. There is one major distributary but the lower delta contains a network of minor branching channels. The Seymour River, the lower course of which is a former major distributary, is connected with the main Herbert channel, and still carries part of the Herbert River flow.

Figure 5.5 depicts the surface morphology of the deltaic plain and lower valley below Herbert Vale. The map has been based largely on aerial photograph interpretation with ground checking in the more accessible parts of the delta. It is evident from the map that the Herbert in the past has occupied a number of channels to the south of the current distributary area. Two major distributary systems are apparent: one on the southern edge of the delta of which Trebonne and Cattle Creeks are the major channels, Trebonne Creek below the township of Trebonne being the former lower course of the Herbert; and between the southern deltaic area and the active delta, a system in which Palm and Victoria Creeks were the main channels and which branched off from the present Herbert in the vicinity of Ingham. Minor abandoned channels tend to interlock the levee distributary system though it is thought that each has operated more or less independently of the others. During floods the Herbert's flow may still be diverted through the old channels. Subaqueous deltaic sedimentation has occured opposite the mouths of each of the old distributaries.

The relationship of river, levees and floodplain is much the same as in the Burdekin. The Herbert is incised up to 50 feet into its levee deposits which range in height along the present banks from about 60 feet near Trebonne to 50 feet immediately north of Ingham and 30 feet near Halifax.

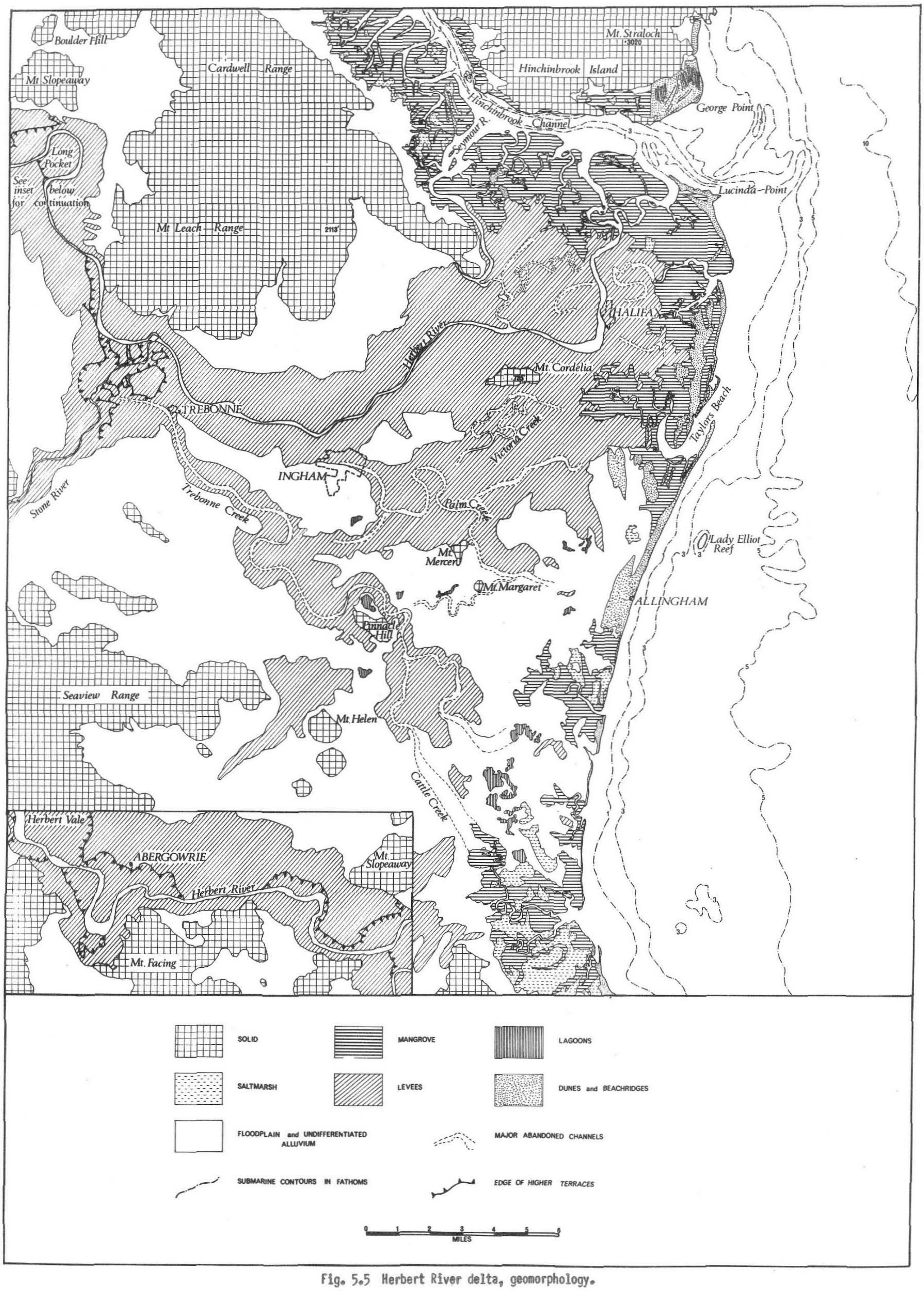

Fig. 5.5 Herbert River delta, geomorphology.

The heights of the levees of the abandoned channels have a similar range. The levees of Trebonne Creek a mile south of Trebonne are fractionally higher than along the adjacent parts of the Herbert River, and maintain their height to within a mile or two of the sea. Those of Palm and Victoria Creeks are slightly lower and are of a similar height to those of the present distributaries. The floodplain is generally some 20 feet lower than the levees and, except where artifically drained, is very swampy. It grades gently into the colluvial deposits of the delta's confining ranges.

In the more confined valley upstream from Trebonne the morphology of the valley floor is very reminiscent of that of the Burdekin near Dalbeg with a lower floodplain terrace generally less than a mile wide, overlooked by a terrace about 20 feet higher. The higher terrace merges imperceptibly into the slopewash deposits of the surrounding hills. The lowest area along the river where the two levels may be seen is around Trebonne where the old Trebonne Creek channel branches from the main Herbert. Unfortunately the morphology in this region is complicated by the confluence of the Stone River, a major right bank tributary, which also has at least one terrace higher than its present floodplain. However it would appear that the higher terrace level is the partially eroded levee system of the Trebonne Creek distributary system. The 1967 report on flooding indicates the river is currently widening its floodplain at the expense of the higher terrace above Trebonne. The relationship of the two terrace levels and of the levee system, together with the higher level of the Trebonne Creek-Cattle Creek levees close to the sea, may suggest a higher sea level at the time of this deposition. Unfortunately no sections have been observed in the deposits which could confirm this.

The relationship of the three distributary systems strongly suggests that the earliest deltaic area was the Trebonne-Cattle Creeks system and that the Herbert has subsequently migrated northwards. The relatively sheltered position of the delta has resulted in vigorous outgrowth of levee systems, with only moderate amounts of material being directed to shoreline development. Beach ridges have developed north of each of the distributaries under the influence of the south to north littoral drift. However, the northward migration of the Herbert together with the vigorous outward growth has meant that earlier beach ridge systems have generally been engulfed or at least fragmented by the later levees. The utilisation of the older channels during flood has maintained a narrow beach along the southern delta shores. The present distributary area, sheltered by Hinchinbrook Island has only a minimal development of sand ridges.

Development of sand ridges, largely in the form of recurved spits has not been as widespread as in the Burdekin delta. Much of the material which has been swept out to sea has been carried northwards, congesting the southern end of the Hinchinbrook Channel which is kept open by the strong tidal scour. The sand deposits making up the cuspate foreland of George Point on Hinchinbrook have been derived from the Herbert.

The sand spits have enclosed inter-tidal lagoons which have been readily colonised by mangroves. Macnae (1966, 1967) has described the mangrove sequences near Lucinda. Bruguiera forests are the most extensive, with B. parviflora and B. gymnohiza dominating and with scattered traces of Xylocarpus australasicum. Old channels and fringes of present channels are occupied by Rhizophora stylosa. Ceriops tagal occurs in higher areas, specially adjacent to the older sand ridges which occur within the mangroves.

Around the present distributary area of the Herbert, and up the Hinchinbrook Channel the extensive mangroves have colonised the area enclosed by sand ridges and extend as fingers inland between the levee systems. A different location is noted for the older deltaic area of Trebonne and Cattle Creeks, where the mangroves tend to extend inland only up the abandoned channels. Inter-distributary areas are above the range of most tides and are occupied by salt marsh or freshwater swamp. Whilst the higher level of these areas in the south may be due to sedimentation, an emergence factor may have to be taken into consideration. It is notable that salt marsh increases rapidly in area in the south, occupying much of the environment colonised by mangroves further north. The effect of the lower rainfall will be discussed in Chapter 9.

Comparison with the Burdekin Delta

The Herbert River delta is considered a much less complex depositional area than that of the Burdekin River. This is due to a large extent to the confined nature of the lower Herbert basin which has restricted the river throughout most of its traceable history to more or less the same course. High and low sea level phases therefore have been similar in the Herbert, though the rapid progradation during the Holocene transgression has allowed the river to migrate from the confines of the low sea level incised course.

In many ways the Herbert delta has similarities with the eastern side of the Burdekin Delta, south of Cape Bowling Green. The orientation of both areas is identical though the Herbert delta appears to be in the lee of the

Palm Islands. It is not surprising, therefore, to find that both deltas have spits trending northwards from their former and present distributaries. However the more sheltered environment of the Herbert delta has produced generally smaller and narrower sand ridge barriers. Further similarities are found in the "crevasse" system of separately functioning distributary areas, and in the rapidly tapering wedge of Holocene sediments thinning towards the west.

There is great contrast in the more recent history of the two deltaic areas for, in spite of similar orientations and similar directions of longshore drifting, whilst the Burdekin has migrated steadily southwards during the last few thousand years, the Herbert over the same period has migrated northwards. The southerly migration of the Burdekin was determined by the blocking of all northerly exits by the vigorous development of spits creating long wide barriers, the height of which was reinforced by dune development. In contrast the more sheltered Herbert delta has experienced greater progradation than lateral movement of sediments. Barriers have been narrower, lower and shorter and each migration has merely moved the mouth northwards beyond the point of the then active spit. Moreover, the wetter climate has prohibited the development of dunes (see Chapter 9) and there has been little in the way of an aeolian cap to reinforce the ridges against a break through by the river. Migration northwards has therefore received no great opposition. The position of the present distributary area of the Herbert is in many ways analogous to that of the Burdekin at the stages of the systems of Sheepstation Creek or Kalamia Creek (prior to it coming under the full influence of the northerly drift of the east coast). Vigorous progradation is matched by weak development of shorelines; those which do occur within the mangroves are narrow, widely separated and apparently cheniers resting upon a clay or

XXIV Part of the Herbert River delta.

mud base.

Summary Evolution of the Herbert Delta

1. The former Upper Burdekin was diverted to a more direct course to the sea to become the Herbert River system (see Chapter 1).

2. A narrow funnel shaped embayment formed the Herbert estuary, with the main channel to the south of the present river.

3. Incision occurred during Pleistocene low sea level phases to about 300 feet below sea level.

4. Aggradation occurred during high sea level phases of the Pleistocene, though even by the last inter-glacial, infilling of the embayment was not complete and the Herbert flowed out to sea by way of a partly filled estuary.

5. Aggradation and progradation have been rapid during the Holocene period, with migration of the shoreline at least two miles landwards of its present position.

6. Evidence in the Herbert delta suggests, though does not prove, a higher Holocene sea level, by the maximum of which the Herbert had over-topped the confines of the estuarine channel and occupied the Trebonne Creek-Cattle Creek delta.

7. Gradual migration northwards of the distributary area by way of the Victoria Creek-Palm Creek delta, to the present delta centered on Lucinda, has been the latest phase of development.

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CHAPTER 6

SOME CHARACTERISTICS OF BEACH MATERIALS

The coast within the research area is predominantly a depositional one. Great variety, however, is found in the beach environments and in the types of beach deposit. Variations also seem to occur with time. This chapter summarises the nature of the beach material and comments on the characteristics of distribution, and the processes of cementation.

Nature and Distribution of Beach Materials

Contrasts in beach materials occur between the following environments:

i) in close proximity to and away from river mouths which contribute sediments to the mainland coasts.

ii) in close proximity to and away from outcrops of solid rock on the mainland coast.

iii) with an open orientation to the south-east or east, and with orientation towards these directions restricted.

iv) between the mainland and island beaches in general.

Close to, and especially to the west or north of the river mouths, sand beaches of material contributed by the river predominate. The nature of the geology of the hinterland may determine the exact mineralogy of the beach sands, particularly in the heavy mineral assemblages, but the widespread occurrences of granitic rocks and acid volcanics means that quartzose sands dominate, with minor contributions of feldspars. Estuaries of these streams provide limited environments for molluscan fauna and, with few nearshore coral reefs, the biogenic contribution to the beaches of these environments is low. Carbonate content of the beach sands is consequently small, generally less than 10% and often less than 5%.

Away from the river mouths, the amount of sand in the littoral zone decreases, indicating the predominance of fluvially transported terrigenous beach materials on the mainland littoral. The apparent response to these conditions is illustrated by the coastal deposits in front of the Muntalunga Range (fig. 4.1) and across to Cape Cleveland. Generally fine grained sedimentation will predominate in such an environment provided only low or medium energy conditions exist. Sorting occurs between the dominant clastic sediments of probable terrigenous origin and the small proportion of coarser fragments which are congregated together to form widely spaced cheniers. The origin of these coarser fragments is diverse. In front of the Muntalunga Range many are shell fragments (more than 80%, Appendix C). In general along this coast, the most favourable environment for a flourishing molluscan fauna is a rocky one. The presence of the Muntalunga outcrop not far removed from the present beach may indicate outcrops further out to sea which could contribute shell material to the present beach. The remaining 20% or less of the coarser beach materials is made up of angular quartz and feldspar fragments. These too may have originated from off-shore rock reefs, from occasional longshore drifting in a direction different from the normal or from sub-aqueous deposits which may not have been transported on-shore during the Holocene transgression. The calcareous nature of the cheniers seawards of the Muntalunga Range may be misleading. The total amount of shell material on this coast may be no greater than on other fluvially dominated beaches, but the absence of other coarse material and the concentration of the coarser fraction into a few cheniers give these beaches their calcareous characteristics.

In general, however, beaches of fluvially derived sands predominate. The reasons for this are twofold. First, the coastal streams, though small and intermittent, are quite closely spaced; secondly, along most of the coast, a strong littoral drift occurs, strong enough to transport sediments along the shore between adjacent river mouths.

The importance of solid rock outcrops to the biogenic fraction of beach materials has already been indicated. High carbonate readings are generally found on the beaches of the headlands, though figures as high as 80% such as were recorded on the cheniers north of the Muntalunga Range, are rare, for though the total production of biogenic material may be considerably greater, it is combined with terrigenous material or sediments washed up from the sea floor, which lowers the carbonate reading in individual samples. However, beyond the headlands, in the direction of longshore drift, high carbonate readings may again occur as the lighter shell fragments are more readily transported. The best illustration is provided by the Range of Many Peaks area. Figure 4.3 indicates the carbonate content of the sands of the upper and lower beach around the headland[1]. The overall average carbonate content of all samples is 15.75%, much higher than on any beach fed primarily by fluvial sands. Great

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1. Collection and analysis of the samples was carried out by Mr. G.L. Dalton, third year honours student, University College of Townsville, under the supervision of the author.

variation in carbonate content occurs, within the range 0.1% to 91.8%, with a tendency for the higher readings towards the western end of the headland (longshore drift is from east to west).

Although the carbonate content of the present beach just east of the mouth of the Bohle is only modest, the cheniers behind are composed of almost pure shell grit, indicating the nourishment from the headland. A reading of 84.3% carbonate, with a residue of quartz grit was recorded for the first ridge. The reason for the lower content in the present beach is not known. However, the importance of the nourishment of the calcareous beaches from the headland is indicated by the change in nature of the present beach and the beach ridges in the west bank of the Bohle, where the sands have a carbonate content below 5.0%.

An interesting feature of the headland beaches is the contrast between the upper and lower beach relationships along rocky and sandy sectors of the shore. Where the present beach backs onto rock it is the lower beach which generally has the higher carbonate reading. Where beach ridges have accumulated, it is the upper beach which is more calcareous. The upper beach is invariably coarser than the lower beach owing to the strong action of the swash and weaker action of the backwash as a result of percolation (Bird, 1968, p.83). On the rocky shore the non-calcareous materials are normally of coarse sand calibre, larger than the shell fragments. on the sandy shores the shell fragments appear about the same size but the non-calcareous sands are finer apparently owing to transport along or onto the shore.

The logical pattern of beach sediments indicated by the Range of Many Peaks is not obviously repeated by the Muntalunga Range cheniers. Apart from the outer ridge, beyond the solid outcrop, carbonate values are low, and whilst the boreholes may not consistently have gone deep enough to encounter beach sands, even for aeolian sediments the values are low. However, the environment of salt marsh with widely spaced ridges, which existed even when hard rock outcropped on the coast (as indicated by the older cheniers), is not conducive to a dense molluscan fauna. The sheltered habitat, in the lee of Cape Cleveland appears to have been the dominant factor, However, on other open beaches adjacent to solid rock, a proportion of broken shell is incorporated in the beach sands and carbonate values above 10% occur.

The importance of orientation towards the south-east or east i.e. towards an open aspect, is also related to the nourishment of beaches from off-shore sources. The only three areas where there is evidence to suggest the on-shore movement of barriers with a rising sea level or of previously deposited fluvial or deltaic sands are west of the Bohle estuary, south of Cape Cleveland in Bowling Green Bay, and between Cape Upstart and the Elliot River. All these areas have an open aspect with vigorous wave activity which has allowed the on-shore movement of sea floor sediments. More detailed analysis is needed to determine the full implications for the beach sands, but microscopic examination indicates that these sands have a much higher proportion of quartz sand, to the exclusion of biogenic material and more delicate minerals including feldspars, than do beaches fed more directly by fluvial sources and longshore drifting. Only the more resistant quartz appears to survive the constant abrasion which occurs during the long period of transportation. The rapid build up of beach ridges north of river mouths indicates that sands moving longshore, are probably subject to the abrasive activity of the breaker zone for a relatively short period, before becoming stabilized within a beach ridge, hence the survival of more fragile beach elements.

The greatest contrast in beach materials is between the beaches of the mainland and those of the off-shore islands. Although high carbonate values may be recorded occasionally in the mainland beaches, they are the exception and the majority of beaches have values of 10% or less. The islands, however, consistently have high carbonate contents in their beaches derived from the erosion of the fringing reefs, and from an environment in which a dense molluscan fauna flourishes. In comparison, there are few stream courses, apart from incipient gullies, and provision of terrigenous material is dependent upon the erosion of the island cliffs. This is considered to be slow. Sediment yield from the sea floor is prevented by the steep front of the fringing reefs. The majority of samples analysed had carbonate values in the range 80% to 90% for both sand and fine coral shingle beaches. Typical are the values from the southern side of Curacoa spit (fig. 2.5) where the upper fine shingle beach of coral fragments had a value of 81.6%, the residue consisting of small lithic fragments, and the lower beach of coarse sand a value of 92.0%, the residue this time consisting almost entirely of quartz grains. The only island examined which had consistently lower values than those quoted was Great Palm Island, which has a few small streams supplying sand to the littoral zone. Carbonate values of 50% to 60% were common, the lowest value encountered being 33.2% just south of Wallaby Point (fig. 2.2). Even this value is much higher than is normally encountered on the mainland.

Comparison of Pleistocene, Mid-Holocene and Present Beach and Dune Materials

The common occurrence of stabilized boulder embankments on many of the off-shore islands has already been noted (Chapter 2). Boulder spits or beaches form the oldest identifiable Holocene features on Curacoa, Brisk, Havanna, Fly, Rattlesnake and Camp Islands, around or onto which the later deposits are laid. The boulder beaches at the base of the island cliffs also appear to be fossil features. On the mainland, a small number of similar boulder spits occurs on outcrops which, at the mid-Holocene stage, were undoubtedly islands. These include R.M. Point, Beach Mount and the Range of Many Peaks. Later sand beach ridges are attached to these features. In general the boulder embankments indicate a sea level as high as or higher than present and are all of mid-Holocene age.

Boulder beaches are not forming today, except in the few areas where older boulder deposits are being reworked, as on Camp Island. On the islands in particular, there is a great contrast between the boulder embankments and the biogenic sands and shingles of the present beaches. On the mainland the present sand beaches provide a similar contrast. Table 6.1 shows the carbonate values for deposits of different ages from several areas. Examination of beach rock samples from many of the islands indicates that though these are mainly calcareous the mid-Holocene deposits contain rock fragments, stones and boulders. Carbonate analysis was carried out on samples weighing between 25 and 50 grams, generally too small to include the larger lithic fragments. The values given therefore are generally only for the finer matrix. The Wallaby Point conglomerate is a good example, for the boulders here are estimated to form up to 90% of

Table 6.1

Carbonate Values of Pleistocene and Holocene Beach and Dune Materials and Beach Rocks

Location	Sample	Age	Carbonate
Muntalunga cheniers	Ridge 1, base	Late Holocene	88.8%
Muntalunga cheniers	Ridge 4, base	Mid-Holocene (?)	5.0%
Muntalunga cheniers	Ridge 5, base	Pleistocene	2.8%
Cape Upstart	Present dune	Present	2.4%
Cape Upstart	Rear of outer barrier	Mid- to late Holocene	3.6%
Cape Upstart	Beach at base of red dune	Mid-Holocene	6.4%
Cape Upstart	Red dune sands	Pleistocene	1.2%
Green Mount (Upstart Bay)	Present dune	Present	4.8%
Green Mount	Mid-Holocene beach	Mid-Holocene	3.6%
Green Mount	Pleistocene dune	Pleistocene	15.0%
Curacoa Island	Beach rock	Present	87.2%
Curacoa Island	Conglomerate	Mid-Holocene	10.0% (estimated)
Eclipse Island	Beach rock	Present	86.9%
Eclipse Island	Beach rock	Mid Holocene	88.8% +lithic fragments
Herald Island	Beach rock	Present	91.0%

Continued.

Table 6.1 (cont.)

Location	Sample	Age	Carbonate
Herald Island	Beach rock	Mid-Holocene	94.5% +lithic fragments
Rattlesnake Island	Beach rock	Present	92.1%
Rattlesnake Island	Beach rock	Mid-Holocene	95.9% +lithic fragments
Camp Island	Beach rock	Mid-Holocene	91.0%
Camp Island	Beach rock	Pleistocene	94.7%
Wallaby Point, Palm Island	Beach rock	Present	65.5%
Wallaby Point,	Conglomerate	Mid-Holocene	10.0% (estimated) [or 85.2% for finer matrix only]

the material. The intervening matrix, however, has a 85.2% carbonate content, mostly fine shell grit and coral sand. In general, the carbonate values of the present beach rocks are similar to those of the cementing matrix of the mid-Holocene deposits.

On the mainland, there is not the same contrast between the older and recent Holocene sands. Carbonate values are generally too low even in the present beaches for significant differences to stand out. Beach deposits of all ages appear to be dominated by sands from fluvial sources. There is, however, the presence of the boulder beaches, in a few localities which leads one to suspect that they may be found beneath sand ridges in many other places close to solid rock outcrops. Evidence from the research area as a whole does little to invalidate the conclusions drawn from the islands that the rising Holocene sea level has reworked the regolith formed during the late Pleistocene low sea level phase, during which there is evidence for a period with a climate suitable for deep weathering (see Chapter 8). Investigations from elsewhere (for example Russell, 1967, p.104-106) have pointed out the reduction in sand volume of present beaches compared to those formed during the Holocene transgression. During the controversial period since the mid-Holocene, the stillstand or regression of sea has led to a diminishing sand supply. Erosion has occured on beaches where the source of sand had been predominantly from the sea or from the weathered deposits of the old coastal plain upon which it encroached. In the area under consideration, the mainland beaches have been, and are, supplied with sand from fluvial sources and differences cannot be noted, and, on the off-shore islands, the rapid production of local biogenic material has always been great. Indeed, the late Holocene regression has exposed fringing reefs to wave attack and increased the amount of beach material available.

Little can be concluded from the small number of Pleistocene samples analysed. In general terms they are comparable to present beach and dune samples, but exact comparisons are difficult as it is not always possible to determine if the Pleistocene feature belongs to the transgressive or regressive phase of the higher sea level. Presumably calcareous materials would increase in proportion (if not in actual amount) during the regressive phase. This probably explains the high carbonate content of the Inkerman and Green Hill ridges (see p.108).

Beach Rock and Conglomerate

There is a very extensive literature on descriptions and analyses of beach rock and hypothesis of formation, which, nevertheless, remains a controversial issue. In spite of observations dating back to Moresby (1835), Jukes (1847) and Dana (1852, 1853), discussion still centres around the origin and nature of the cementing carbonate.

One hypothesis for the origin of the carbonate is that it is precipitated from heavily charged groundwater which has acquired its carbonate by percolating through beach deposits with a high shell or other biogenic content. This hypothesis has been most recently proposed by Russell (1959, 1962, 1963, 1967) who indicates that the precipitation occurs at the water table, which, close to the beach approximates to sea level. Tidal fluctuations in sea level give the range over which precipitation will take place and determine the thickness of the beach rock. Numerous other authors (for example, Jukes, 1847; David, 1904; Field, 1920; Umbrove, 1928; Gardiner, 1930; Yonge, 1930; Sewell, 1932;

Trichet, 1965; Bloch and Trichet, 1966) agree that the carbonate is precipitated from groundwater, but at the junction of freshwater and sea water below the water table. There is strong evidence to support both views but, as Stoddart and Cann (1965) have pointed out, well-developed beach rock occurs in arid areas such as the Red Sea where percolating groundwater can hardly have played a part in formation, and also on islands and atolls too small to support a permanent lens of freshwater, the evidence from the atolls of the Northern Marshall Islands suggesting that a freshwater lens does not develop where rainfall is less than 45 inches per annum.

A second hypothesis involves the precipitation in the pores of the beach sands of calcium carbonate from sea-water which in the tropics is normally supersaturated in carbonates (Daly, 1924; Kuenen, 1933; Merrin, 1955; Ginsburg, 1953; McKee, 1956; Revelle and Fairbridge, 1957; Emery, 1962). Precipitation is promoted by an increase in temperature and evaporation, or by a decrease in hydro-static pressure or a combination of these factors. Again, there is strong evidence against this hypothesis, one of the major arguments being the patchy and discontinuous distribution of the beach rock which is difficult to explain in any one region if the cementing agent is derived from the uniform mass of sea water.

Another major school invokes biochemical activity (Cloud, 1952; Nesteroff, 1954; Ranson, 1955a, b; Kaye, 1959; Maxwell, 1961). Cementation is caused either by precipitation under the promotion of micro organisms such as bacteria, which are abundant in the area of the water table, or, as Maxwell (1961) claims, through algal encrustation, green and blue-green algae flourishing within the littoral zone. However, confirmed reports of such encrustations are not widespread and whilst lithification may be aided by biological agents, the major cementation process does not appear to be biochemical (Krauss and Galloway, 1960).

Conflicting reports from different environments in different climates and on different lithologies of cemented deposits and cogent objections to virtually all general theories of origin so far proposed may well indicate that beach rock can be formed by a number of processes, the importance of which tend to vary in different environments. This conclusion has also been reached by Kaye (1959), Guilcher (1961) and Stoddart and Cann (1965).

The exact nature of the cementing matrix also tends to lead to this conclusion. Aragonite, calcite and amorphous carbonate have been variously described as the cementing agent. Nesteroff (1954) showed that in the Red Sea beach rocks, the cementing agent changed its form with age. Earliest lithification was by amorphous calcium carbonate, but crystallisation then occurred in the form of aragonite needles and re-crystallisation into rhombohedrons of calcite. Geochemical analysis has indicated that salinity or degree of supersaturation may determine whether calcite or aragonite is precipitated (Higgins, 1968).

Detailed study of beach rock is outside the scope of the present research programme. Interest in lithified beach deposits has been mainly in the information which they can supply of past environments and present processes. However, a number of observations have been made which may confirm and add to the known facts on lithified beach sediments.

The rapidity of cementation described by many authors is confirmed in the Townsville region. A report by local residents indicates that a layer of beach rock formed over a boat ramp on the northern side of Magnetic Island only six months after it had been completed. The beach sands involved were coarse shell grits. The amount of carbonate in the original beach deposit appears to be a strong influence on the rate of formation of beach rock. Whilst it is common on the islands where biogenic sands predominate, it is relatively rare on the mainland. Moreover, whilst the island beach rocks appear to form rapidly, even on recently formed and constantly shifting extensions of the lee side spits, on the mainland the few known beach rock locations are associated with older beach ridges and apparently rapid coastal retreat. Stabilization of the beach deposits long enough for the cementing matrix to build up appears essential. On the mainland this stabilization has to occur within vegetated beach ridges (with possibly humic acids helping to leach the carbonates down to the underlying water table). On the islands, in the much more calcareous environment, beach rock was forming not only in the ridges behind the present beach but apparently within the upper beach itself.

Exposed mainland beach rock is limited because it needs a high carbonate content in the original beach sand, combined with stabilization over a long period to allow cementation to take place, followed by a period of coastal erosion to expose the resulting lithified deposit. However, high carbonate content is found only around headlands and general observations indicate that beaches are most stable close to their anchoring points. Short term oscillations are not likely. Thus it is not surprising to find that beach rock is exposed in such situations only with a major beach recession and that the exposed beach rocks are comparatively old. At Balgal an age of 2,180 years ± 80 B.P. (GaK-1509) was indicated and at Shelly Beach, Range of Many Peaks an age of 2,460 years ± 80 B.P. (GaK-1508). Just to the south of the research area at Dingo Beach near Bowen a similar age of 1,660 years ± 300 B.P. was obtained by the Bureau of Mineral Resources (Paine, Gregory and Clarke, 1966). The similarity in age of these deposits indicates that the erosion, which appears so widespread along the coast of North Queensland, has retrograded the littoral zone to its most landward position for 2,000 years.

The actual carbonate content of beach rocks is illustrated by a number of results given in Table 6.1. In general the beach rocks of the islands have carbonate values around 90%, not far removed from the values for the adjacent beach. In contrast, the Shelly Beach sample had only 46.1% carbonate, a reflection of the generally lower values of the mainland beaches. However, the adjacent beach, although calcareous, has only a 10% carbonate content, indicating the degree of enrichment during cementation. The known occurrences of beach rock on the mainland all appear to have a similarly low carbonate content, except for the example in the Pleistocene beach ridge trending south from Mount Inkerman (Chapter 3) and exposed in the bank of Yellow Gin Creek. This had a carbonate content of 89.2%, but this beach ridge is highly calcareous throughout: further north it contains the Inkerman calcarenite.

Exact carbonate values for beach rocks elsewhere are not indicated in the literature. However, general descriptions indicate that the majority of beach rocks in other areas though containing boulders and mineral sands, have a higher calcareous content than those on the Townsville region mainland. Russell and McIntire (1965) have attempted to set temperature limits on beach rock formation. Rainfall is considered to be another important factor. If it is too low, then leaching of carbonates in groundwater may be slow and require a high carbonate content in the original material. Whilst beach rock may still form through other processes, it is considered that downward movement of carbonates is the most rapid type of formation. If the rainfall factor is high then the leaching factor may also be high, with unsaturated and still aggressive groundwater reaching the inter-tidal zone during low water, and preventing cementation from taking place. As seen from the island spits, a higher rainfall certainly prevents the preservation of raised beach rock. From observations in North Queensland and in eastern Papua-New Guinea (Hopley, in press) a much higher carbonate content is required in beach sands for cementation to take place in the wetter tropics than is needed in tropical areas with a long dry season. In general in areas with a rainfall of 80 inches or more per annum, only coral island beaches have a sufficiently high carbonate content to become cemented. Even beaches consisting of 80% or more coral sand, if combined with terrigenous sediments, may show no evidence of lithification taking place. The climate of the Townsville area may well be close to the optimum for beach rock formation.

Beach rock as an indicator of sea level at the time of formation has been one of the major interests in lithified deposits in the current research programme. In general, the literature on the subject is in agreement that beach rock is an inter-tidal feature, though Russell does suggest that the cemented surface may rise inland with a rising water table. However, in all the examples examined in North Queensland the apparently modern beach rock is most definitely found between tide levels, the upper level being at or just below M.H.W.S. Where beach rock higher than this is found inland, the water table does not show a corresponding gradient and the beach rock is interpreted as fossil. Indeed, on the off-shore island spits, there is apparently no permanent freshwater (Ghyben-Herzberg) lens and in the coarser materials involved the water table is closely related to sea level.

The upper surface of beach rock is thus horizontal, truncating the bedding of the sands. The lower surface of the cemented zone is also reported as being equally abrupt and level (Kuenen, 1933). The thickness of beach rock should reflect the local tidal range. The older beach rocks of the off-shore islands display thicknesses of up to 16 feet, much greater than the present tidal range. However, the regression of the sea from the mid-Holocene maximum level would have transferred the zone of cementation downwards and, whilst the materials in the beach rocks may belong to the mid-Holocene period, their cementation in the lower portions, may be younger. This may well explain why a younger date was obtained for the beach rock at the base of the Herald Island outcrop compared to the date from near the top (Chapter 2). Whereas a single shell was submitted for dating from the top, the lower sample contained some of the cementing matrix.

Once removed from the cementation zone, by either a change in water table level or by exposure on the beach, the beach rock undergoes erosion. This may be through wave attack, biological activity (McLean, 1967a, b), freshwater run-off corrasion (McLean, 1967c) or, most extensively, through solutional effects (Reville and Emery, 1957). All forms of erosion have been observed in North Queensland. The opening of joints in the beach rock appeared to facilitate the disintegration. Most rapid erosion appeared to be in the inter-tidal zone where all methods of attack are operating. Raised beach rock however, seems to be eroded only slowly, mainly through corrosion. The porosity of the material appears to retard most solutional processes and may explain the survival in a comparatively fresh state, of mid-Holocene and even late Pleistocene beach rocks.

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CHAPTER 7

DISCUSSION OF THE EVIDENCE FOR SEA LEVEL CHANGE

Former shorelines some of which indicate sea levels higher than that of present, have been described from all parts of the research area. It is intended here to correlate the evidence from the region as a whole and to give an absolute chronology for the sequence of sea level changes in North Queensland. In addition, the question of the tectonic stability of the coast will be discussed in relation to possible warping of shorelines. The significance of the results and their correlation with those obtained from elsewhere in Australia and other parts of the world will be indicated.

Late Pleistocene Shorelines

A shoreline marked by dunes and beach ridges composed of weathered and oxidised sands and by older, emerged, beach rocks has been described from the whole of the research area. Only one of the off-shore islands, Camp Island, contains a feature which can definitely be ascribed to the Pleistocene. Here, a beach rock plateau composed of cemented coral fragments rises to 15.2 feet above M.H.W.S. and a radiometric date of 20,200 years ± 600 B.P. was obtained for this. On the mainland, interrupted shorelines can be traced from Cape Upstart in the south, to Rollingstone Creek in the north. This shoreline is much less continuous than the Holocene outer barrier of dunes and beach ridges behind which it is found. However, it is sufficiently well preserved for it to be compared to the inner barrier of the coast of south-eastern Australia (see for example, Hails, 1968). South of Cape Upstart this shoreline consists of a 60-foot high dune of red oxidised sands, resting on a mottled clay surface 4 feet above M.H.W.S. Between Cape Upstart and the southern edge of the Burdekin delta, the Pleistocene shoreline can be traced as a series of ridges associated with which is a similar clay surface separated from the lower salt flats by a salting cliff. This surface also rises to 4 feet above M.H.W.S. South of Mount Inkerman, one of the ridges contains dune calcarenite, dated at 25,150 years ± 1,050 B.P. and beach rock rising to 6 feet above M.H.W.S. and giving dates of 26,900 years ± 900 B.P. and 28,900 years $^{+2,800}_{-1,700}$ B.P. In the Burdekin delta, the indications are that the inner barrier has been buried beneath Holocene deltaic sediments. South of Cape Cleveland, the older ridges reappear, sediments with characteristics diagnostic of beach sands rise to 17 feet in one of the ridges near Storth Hill. This is thought to indicate a sea level of approximately 15 feet above present. The inner barrier can be traced in the Townsville area from south of the Ross River to the mouth of the Bohle River. A section in the bank of the Bohle River indicated beach rock rising to 8 feet above M.H.W.S. Carbonate nodules from above this gave an age of 14,680 years ± 310 B.P. North of Townsville only isolated remnants of the Pleistocene shoreline remain. However, the inner barrier has been recognised further north in the Tully area (Bird and Hopley, 1969).

The evidence suggests that the Pleistocene sea level stood at between 4 and 15 feet higher than that of present. The possibility of tectonic warping being the only reason for this discrepancy must be dismissed as both 4-foot and 15-foot levels occur within close proximity of each other.

For example, the Camp Island beach rock is located only 3 miles from the Cape Upstart dune. There is no evidence to suggest such a highly unlikely pattern of local warping. Two further possibilities exist: that the two levels represent two completely different shorelines, one of approximately 15 feet the other of 4 to 8 feet; or that the remnants of the Pleistocene shoreline all belong to more or less the same period, the higher remnants belonging to the maximum of the transgression, the lower ones to the regression phase from this level.

The possibility of two separate transgressions must be given serious consideration as a casual examination of the deposits involved apparently indicate two series, one oxidised and red in colour the other weathered, clayey and bleached. However, a detailed analysis indicates that these variations are related to the nature of the original beach and dune materials rather than age. What is almost certainly the same shoreline south of the Burdekin delta, is composed of red sands near Green Mount and of bleached deposits further north. Similarly, in the Townsville area the Pleistocene shoreline near the mouth of the Bohle is composed of white sands, but changes to brown sands near Mount St. John and to red oxidised sands in what is considered to be the same feature south of the Ross River. The absence of the higher level can be explained by erosion which can take place even during the regressive phase (Bird, 1968, p.101). It is unfortunate that the full range of levels of the Pleistocene shoreline is not available in any one sequence. However, the ridge south of Mount Inkerman appears to indicate a 6-foot level, those further seawards a 4-foot level and no obvious discontinuity is indicated between them. The conclusion to be drawn from this evidence is that the Pleistocene shorelines all belong to the one higher sea level phase, both the maximum and regressive stages being indicated.

The age of the Pleistocene shoreline is controversial. The morphology of the area indicates that without doubt it belongs to the latest high level stage prior to the Holocene transgression. The radio-carbon assay results are spread over a wide range from 14,680 years ± 310 B.P. to 28,900 $^{+\,2,800}_{-\,1,700}$ B.P. However, the younger date is for secondary carbonate and gives a minimal figure only. One other date, that of 25,150 years ± 1,050 B.P. from the dune calcarenite is also from secondary carbonate and again can be considered as minimal. Of necessity the samples had to be taken from a highly calcareous environment and contamination from younger carbonates is very likely. The date from the raised beach rock on Camp Island (20,200 years ± 600 B.P.) is certainly too young. There remains the two dates from the beach rock at Yellow Gin Creek which are compatable at 26,900 years ± 900 B.P. and 28,900 years $^{+\,2,800}_{-\,1,700}$ B.P. It is also interesting to note that the secondary carbonate of dune calcarenite was dated at about 2,000 years younger.

Although there is little published information on the rates of formation of dune calcarenite, Jennings (1968) has indicated that the whole series of the extensive calcarenites of southern Australia reach well back into the Pleistocene. Veeh (1966) and Teichert (1967) give a radiometric Th 230 age of 100,000 years ± 20,000 B.P. for coral underlying calcarenite in Western Australia. Gill (1967) quotes an ionium date of 125,000 years for the younger of two calcarenites in Western Victoria. Blackburn (1966) quotes radio-carbon ages of 24,950 years ± 300 B.P. and 30,600 years ± 450 B.P. and two dates beyond the range of carbon dating for materials overlying concretionary layers only 6 inches thick.

The stage of accumulation indicated by the 25,150 year old date is obviously not known, though the sample dated came from almost the centre of the exposure and it would not be unreasonable to expect that the secondary carbonate accumulation was well developed by this stage. The radiocarbon dates thus suggest that considerable accumulation of calcarenite had occurred in approximately 2,000 to 3,000 years, but this does not appear compatable with the rates of formation intimated from the southern Australian calcarenites. Whilst it is quite possible that, under the different climatic conditions of north Queensland, formation of calcarenite is much more rapid, the contrast in rates would appear to be too great. Another possibility must therefore be considered, that of contamination of the Yellow Gin Creek beach rock samples, and the compatability of the two dates being coincidental.

The maximum age measurable by the Gakushuin University (Tokyo) radio-carbon laboratory, using the method by which the samples submitted were assayed, is 30,000 years B.P. The dates of the Pleistocene beach rock are thus close to the maximum possible. It would require only a minute amount of modern carbon contamination to produce a date of 25,000 years to 28,000 years (as quoted) for material which was actually beyond the range of dating. Contamination of the order of 1% would probably be sufficient. Although great care was taken in the collection of the sample, there can be no guarantee that the sample was as sterile as is needed for dates of the magnitude obtained. The calcarenite date may possibly suggest that an age of about 28,000 years B.P. is much too young.

The problem reflects the controversy found in the literature dealing with the ages of late Pleistocene shorelines. The point of issue lies in the possibility of an interstadial sea level as high as, or higher than, present during the Würm, the alternative being that the latest high sea level phase prior to the Holocene occurred during the Riss-Würm interglacial (Eemian or Sangamon). The main evidence in the controversy has been recently summarised by Guilcher (1969), who concludes that a high intra-Würm sea level is possible but points out that large differences in the figures found for the age of the supposed interstadial (ranging from 20,000 to 35,000 years B.P. or more) are an additional difficulty against its acceptance. Nevertheless, a number of authors appear firmly convinced that a high sea level existed approximately 30,000 years ago and correlate it with the Gottweig or Paudorf inter-stades. The greatest support for this date comes from Milliman and Emery (1968) whose evidence comes mainly from the Atlantic coast of the U.S.A. However, similar conclusions have been reached by others from widely separated areas, for example Shephard (1963) at Oahu, Hawaii and Hoyt (1967) from Georgia and West Africa.

Although a number of dates older than 25,000 years B.P. have been obtained for shoreline deposits in Australia (Gill, 1956-7, 1961), they have generally been accepted only with caution. Walker (1962), however, indicates a date of 29,000 years B.P. for the beginning of pedogenisis on a terrace associated with a 20 to 25-foot sea level, but the attitude of Jennings (1961) to a date of 37,500 years ± 1,900 B.P. for driftwood from an older shoreline is possibly more typical of Australian attitudes to the controversial interstadial:

> "..... and it is impossible to infer no more than that the Old Shorelines belong either to the last (Sangamon) interglacial or to a subsequent inter-

stadial older than all the Wisconsin glacial drift of North America".

More recently Dury (1968), has doubted the existence of a high interstadial level during the Würm, placing the Würm I/Würm II interstadial at no more than 50,000 years ago and indicating that even during this period of glacier recession, temperatures were still below those of the present day.

Palaeo-climatic evidence does suggest that a warmer phase may have existed 28,000 to 35,000 years ago (Karlstrom, 1966). From an examination of trace elements in cave soils from various parts of the tropical Pacific, Sabels (1966) indicates that a warmer phase existed about 35,000 years ago. Radio-carbon dates occurred in sequences and were related to rates of accumulation and there seems little doubt as to the validity of these older dates here. However, a warmer phase need not necessarily have been warm enough, or warm for a long enough period, for a glacio-eustatic rise in sea level to above that of present. In Senegal and Mauretania, Faure and Elouard (1967) describe deposits in the range 2 to 7 metres and date them at around 31,000 years B.P. However, they indicate that tectonic uplift of the land is probable and estimate that the higher sea level reached only 10m. below the present level. This agrees well with Curray's (1961, 1965) findings in Texas where he places an interstadial sea level a few metres below present at around 30,000 years B.P.

These estimates for the interstadial are more in keeping with the palaeo-climatic data of Emiliani (1955), Maarleveld and Van der Hammen (1959) and Van der Hammen <u>et al</u> (1967) and reported by Guilcher (1969). Their information indicates that no large variation in climate existed 30,000 years ago sufficient to cause a higher sea level than present, though possibly a 5°C rise in temperature is indicated (in the Netherlands). However, a 15°C rise was necessary to produce the Holocene transgression.

The balance of the evidence would seem to weigh against a high interstadial sea level within the range of radio-carbon dating, suggesting that where such evidence is forthcoming, contamination of the samples dated is very probable. More recent use of radio-active isotopes other than carbon 14 almost certainly supports this view. Newell (1961) compares the dates obtained on dune calcarenites in the Caribbean using radio-carbon compared to those obtained from uranium and ionium isotopes. Material dated at between 20,000 and 30,000 years B.P. by radio-carbon gave ages of 70,000 to 160,000 years using the greater ranging isotopes. More recently, similar results have been recorded in Australia. For example Veeh (1966) and Teichert (1967) discuss Th^{230}/U^{238} and U^{234}/U^{238} ages of 100,000 and 140,000 years for raised corals associated with a 15-foot emergence in Western Australia. In Victoria, shell from calcarenite gave an ionium dating of 125,000 years (Gill, 1967).

Russell (1964) has shown that a shoreline immediately preceding the late Pleistocene lowering of sea level, is a feature found in most parts of the world, at about 15 feet (5m). The late Pleistocene shoreline in North Queensland corresponds well with this feature elsewhere, and a last interglacial age is indicated. Although a radio-carbon age of around 28,000 years B.P. is indicated, the possibly anomalous compatability of the age from the secondary carbonate of the aeolianite together with the consensus of opinion in the literature would favour an age in the order of 80,000 years B.P. The North Queensland shoreline may thus correlate with the Lower Normannian deposits of Western Europe, the Hoxnian deposits of Britain, the Princess Anne shoreline in eastern U.S.A. and the Epi-Monastirian of the Mediterranean, all of Eemian or Sangamon age.

The Low Sea Level Phase

Little is known of the last glacial low sea level phase in North Queensland. The major streams became incised and the coastline was certainly far east of its present position. Maxwell (1968a, b) has recognised strand lines at 16 fathoms (96 feet), 22 fathoms (132 feet) and 32 fathoms (192 feet) along the whole of the Great Barrier Reefs province. The rise of sea level during the latter part of the Pleistocene and the early Holocene is documented elsewhere in Australia, particularly in Victoria (Gill, 1968). In North Queensland it is indicated probably by the sub-aqueous delta of the Burdekin River in Bowling Green Bay, the onshore movement of coastal sand barriers, especially south of Cape Upstart, and by cemented deposits which lie below present sea level. Those of Curacoa Island have already been noted (Chapter 2) but others occur, as indicated by the washing up of beach rock fragments on the beaches apparently from submerged outcrops. Only one has been located with any certainty and this lies near the dredged channel into Townsville harbour at a depth between 32 and 35 feet below L.W.M.

The Mid-Holocene Transgression

Although the early stages of the Holocene transgression are not well documented in North Queensland the maximum of the transgression is very clearly recorded. On the off-shore islands of the Palm Group, in Halifax Bay and in the southern part of the research area at Camp Island, cemented beach rocks and conglomerates indicate a higher sea level between

6 and 16 feet higher than present within a range of 3,900 to 5,250 years B.P. On the mainland the evidence is equally convincing. South of Cape Upstart and near Green Mount in Upstart Bay are sheltered environment beaches indicating Holocene sea levels 10 feet higher than present. At Beach Mount Beach and on Rita Island in the Burdekin Delta, mangrove peats possibly formed when sea level stood 4 to 5 feet higher than present, give radio-carbon dates of 3,200 and 3,680 years B.P. Sections in the Burdekin delta display inter-tidal deltaic deposits 10 feet above M.H.W.S. giving a radio-carbon date of 3,820 years B.P. In the same area Holocene beach sands rest on fluvial grits 6.5 feet above M.H.W.S. South of Cape Cleveland beach sands rise to 9 feet above their present maximum level of accumulation. In the Townsville area beach rock occurs in older dune ridges about 12 feet above M.H.W.S.

In contrast, beach rocks and peat which appear related to present sea level give radio-carbon ages no greater than 2,460 years B.P. The radio-carbon dates obtained for the research area and quoted in Chapters 2 to 5 which can be related to sea level, are plotted on figure 7.1. Those derived from beach rocks can be related very closely to sea level, but those from peats can be shown only approximately. A number of other dates shown in the graph may need correction factors as indicated. These are:

i) the date for shell dredged from an older barrier and deposited in the 10-foot beach south of Cape Upstart;

ii) the date for the beach rock summit on Herald Island which may indicate a level related to a water table above the sea level of the period;

iii) the date for beach rock from Rattlesnake Island which is probably too young due to incorporation

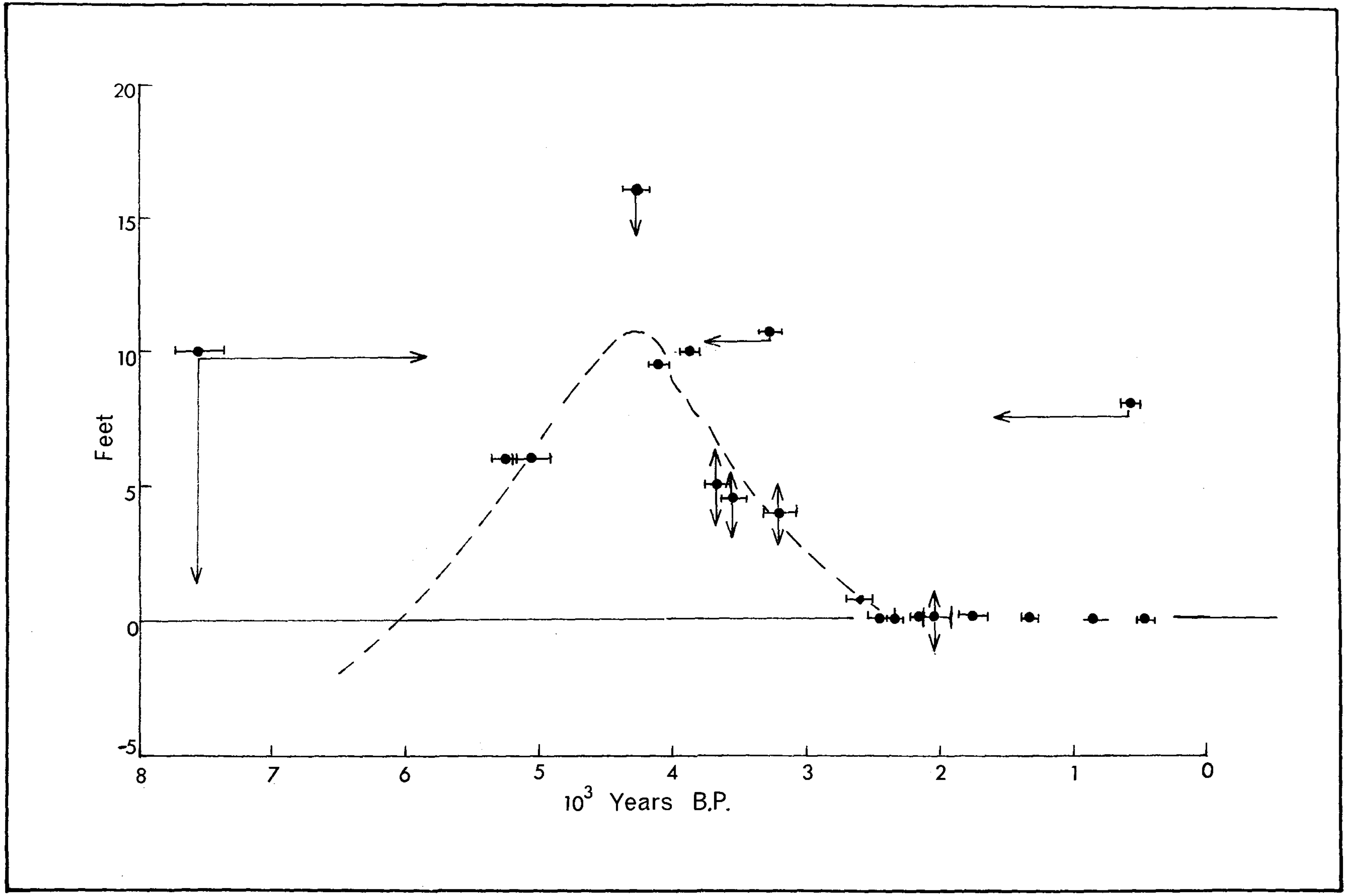

Fig. 7.1 Radio-carbon dates related to sea level changes in the research area.

of younger calcareous cement;

iv) the anomalous date for raised coral reef from Eclipse Island, probably contaminated from overlying coral shingle of a younger age.

However, a fairly lucid picture of the mid-Holocene transgression and the late Holocene regression is indicated. Sea level 5,000 years ago was about 6 feet higher than present and still rising, reaching a maximum of 10 or 11 feet about 4,200 years ago. The maximum level was not maintained for long. By 3,500 years ago, a level of about 5 feet above present is indicated, the present land-sea relationships being reached about 2,500 years ago. Since then there appears to have been little variation in level.

The postulated variations in sea level have a close fitting relationship with all the evidence of higher sea levels presented in the research area. Three other carbon dates are known for coastal deposits in North Queensland. At Byrne's Creek near Babinda, 85 miles to the north of the Herbert River delta, a mangrove log in marine mud 9 feet above present mangrove level gave a radio-carbon date of 3,720 years ± 85 B.P. (Grant-Taylor and Rafter, 1962) and in the same area, a mangrove peat a few feet above H.W.M. dated at 6,270 years ± 120 B.P. (Fergusson and Rafter, 1959). Both these dates would deviate little from the postulated curve of figure 7.1. Further north at Karumba on the Gulf of Carpentaria, Twidale (1966) quotes a date of 3,320 years ± 125 B.P. for beach rock 70 feet thick with an upper surface lying at about 20 feet. The datum to which this level is related is not indicated but a higher level may be expected on this coast as tidal ranges are greater than at Townsville.

The question of a higher Holocene sea level is one of the most controversial issues of Quaternary studies today.

In spite of a wealth of material available, including numerous radio-carbon dates, there is no general agreement on the changes in sea level over approximately the last 6,000 years. Results may be deformed by movements of the land during the period studied, but many authors claim that their research area is a stable one (for example, Thom, Hails and Martin, 1969; Scholl and Stuiver, 1967; Shepard et al 1967) or that they are able to take into account a geo-synclinal or loading isostatic depression factor (e.g. Jelgersma, 1961; Coleman and Smith, 1964) or a glacial isostatic unloading factor (e.g. Morner, 1969a, b). Nevertheless, disagreement still exists.

The numerous hypotheses on Holocene eustatic shorelines have been discussed by Jelgersma (1966), Guilcher (1969) and at the INQUA meeting in Paris 1969 where data from all parts of the world were presented (Jelgersma, 1969; Davis, 1969; Fujii, 1969; Richards, 1969; Hopley, 1969). Basically the hypotheses fall into three groups:

i) The Holocene transgression is marked by many oscillations in sea level, some of which may have taken sea level above that of present. The best known of these hypotheses is probably that of Fairbridge (1961) who indicates rapid oscillations in the Holocene with higher levels at 6,000 to 4,600 B.P. (Older Peron 10 to 15 feet), 4,000 to 3,400 B.P. (Younger Peron, 10 feet), 2,600 to 2,100 B.P. (Abrolhos, 5 to 6 feet) and 1,600 to 1,000 B.P. (Rottnest, 2 to 3 feet). However, Fairbridge's data were taken from many different environments and from many different parts of the world and errors may have been incorporated not only from the radio-carbon technique but from the use of contrasting materials and datum. More recently Morner (1969a, b) has presented evidence of similar though not identical oscillations from Scandinavia, claiming to have taken into account the glacial isostatic uplift factor. Several of his oscillations reach or just exceed present sea level, the maximum of 0.4m (1.25 feet) occuring 3,600 to 3,350 years B.P.

ii) The Holocene transgression is marked by a steady rise in sea level 5,000 to 3,000 years B.P. by which time it had reached that of present and since which it has remained steady. Evidence for this hypothesis comes mostly from the Gulf Coast region of the U.S.A. (Fisk, 1951; Gould McFarlan, 1959; Le Blanc and Bernard, 1954; McFarlan, 1961; Coleman and Smith, 1964). However, these findings are paralleled by those of Godwin, Suggate and Willis, (1968).

iii) The Holocene transgression is marked by a steady rise of sea level continuing right up to the present day. This concept was first conceived by Shepard and developed by Shepard and other authors (Shepard and Suess, 1956; Shepard, 1960, 1961, 1963, 1964; Shepard and Curray, 1965).

The problem is epitomised by the Australian region. Figure 7.2 shows the level of the sea in relation to radio-carbon dates available in the literature. Great variations exist in the evidence, and its interpretation, from state to state and even within the one region. Thus in the Perth area of Western Australia high sea levels of about 16 feet are indicated from about 5,500 to 3,800 B.P. (Fairbridge,

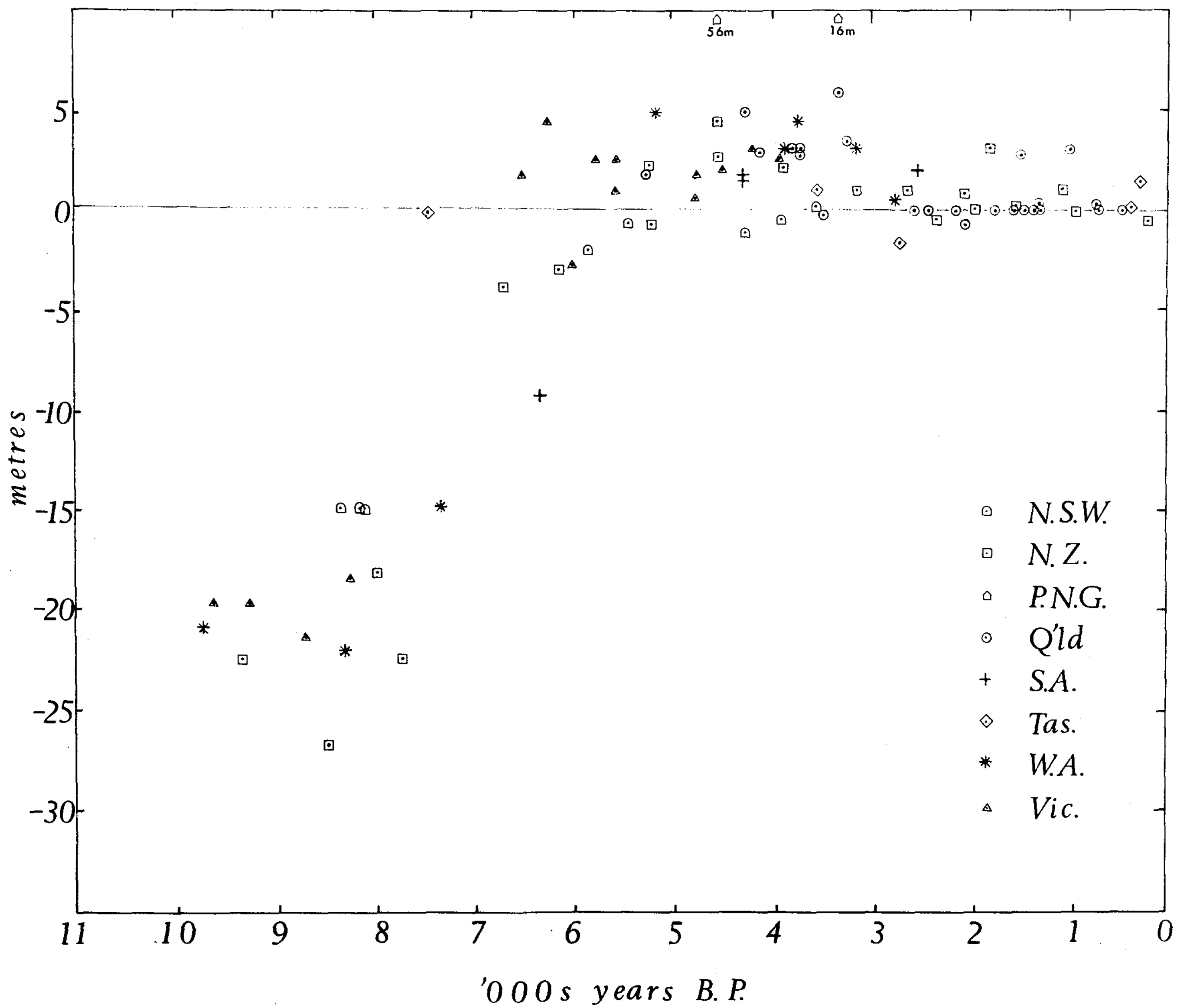

Fig. 7.2 Radio-carbon dates related to sea level in the last 11,000 years in Australasia.

1961) though at least part of this evidence has been questioned by Russell (1964). 450 miles to the north, at Shark Bay, emergent marine strata formerly considered to belong to the Holocene have now been allocated to the late Pleistocene (Logan, 1967) but shelly marine beds including articulated pelecypods indicating a higher sea level to about 4 feet, have been dated at between 4,000 and 5,000 years B.P. (Logan, 1968).

Although Holocene tectonic activity is suspected in South Australia higher Holocene sea levels have been interpreted as eustatic. A 6-foot level was dated at 4,330 years in Holocene sand ridges apparently unwarped near Robe and a 7-foot level is quoted for emerged shell beds at Port Germain (Blackburn, 1966).

The structurally complex coast of Victoria, consisting of a series of horts and grabens, provides convincing evidence of a higher Holocene level. Concentrating research on undisturbed still water marine facies over the whole length of coastline, Gill (in press) has indicated that a higher sea level of 6 to 10 feet existed along the whole coast within the age bracket 4,000 to 6,500 years B.P. The importance of these results is their constancy over 500 miles of coast and across 5 major tectonic provinces which have been active during the early Quaternary. If earth movements are considered as influencing the emergence of these shell beds then the movement has been similar over the whole coast and has taken no account of recently active structural weaknesses. Moreover, the rate of movement will have been almost 200 times more rapid than the average rate of movement calculated since the beginning of the Oligocene. An upward movement would also be envisaged for areas in which the Tertiary movements have undoubtedly been downward.

In contrast to Victoria, it is surprising to find that in New South Wales, no convincing evidence of higher Holocene sea levels incorporating radio-carbon dates has been reported. In the Shoalhaven delta, marine deposits of about present sea level date at 4,470 years ± 150 (Langford-Smith, 1968) and are overlain by freshwater fluvial deposits. Similarly in the Macleay delta, on the north coast, marine deposits do not extend above sea level (Hails, 1968). Hails (1965) has summarised the evidence on sea level changes in eastern Australia, though his conclusion that no high Holocene sea levels exist in eastern Australia should be restricted to the N.S.W. coast. Thom, Hails and Martin (1969) discuss further the absence of higher Holocene levels though their definition of eastern Australia, might be more accurately termed N.S.W. Rather surprisingly in view of the evidence presented in Chapter 2, they quote evidence which suggests that sea level has not risen above the present during the Holocene in the Burdekin delta, though they do suggest that the nature of evidence from northern Queensland requires further study.

It may be significant that, in N.S.W. where the higher level has not been found, gentle down-warping of the continental shelf in at least the central coast area around Sydney, has been postulated in the Quaternary (Phipps, 1967) and it has been suggested that the Lapstone monocline, which forms the front of the Blue Mountains west of Sydney, attained its present form during movements which post-date the middle Pleistocene (Brown, Campbell and Crook, 1968).

The evidence from North Queensland very strongly indicates that a higher Holocene sea level has existed <u>in the area studied</u>. The heights and dates quoted agree well with those from elsewhere in Australia, and though there is no firm evidence of any great oscillations in the sea level movements, there are suggestions of such oscillations in the variations in height of beach sands in the Cape Cleveland beach ridges. Although the hypothesis of Bloom (1967) allows for the co-ordination of the hypotheses of a continuing rise of sea level to the present and of present sea level being reached several thousand years ago, by introducing a water loading isostatic factor on the continental shelf, which will vary with the width of the continental shelf, it can do nothing to help in the explanation of evidence for higher Holocene sea levels.

It is proposed that the evidence presented here is significant in that beach rock heights as indicators of former sea level are possibly more exact than shore platforms, peat levels or unconsolidated deposits. However, the writer must agree with the conclusions of Kuenen (1955) that:

> "It must be admitted that the problems connected with sea level as datum are not yet in a satisfactory stage of development. Random observations will not bring much advancement. What is needed are accurate altitude measurements of well dated terraces in widely separated localities madebby observers realising the difficulties involved. Only this will be possible to distinguish between glacial-eustatic and general eustatic movements and to assess the role played by coastal warping".

The examination of the coastal area between North Queensland where higher Holocene sea levels are found, and northern New South Wales where possibly they are not, may well help to solve the problem at least in Australia. In particular, extension of the research on raised beach rock terraces would seem to be indicated.

The Question of Warping in Study Areas

Beach rock is an ideal agent for indicating the heights of past sea levels, but the rapidity with which cementation can take place means that even minor oscillations may have beach rock indicators. As indicators of warping, therefore, beach rock levels are not ideal. Thus a level of 10 feet at one place and of 12 feet at another may give similar radio-carbon dates and suggest warping. However, the two samples may each have error dates of the order of ± 200 years which could easily place them 400 years apart. It is suggested that beach rock may be too fine an indicator of sea levels in relation to the error of the age to allow for interpretation of warping trends.

Shore platforms on the other hand are formed much more slowly and may indicate only major stillstands. Thus platforms cut at different eustatic sea levels but in similar climates and lithologies should remain the same vertical distance apart, assuming that no tectonic movements take place. The question as to what height the platforms are cut in relation to sea level and lithology (see Bird and Dent, 1966; Gill, 1967) should not enter the problem. Slight variations in exposure in response to a different sea level may not be experienced evenly over the whole area being examined and could give small anomalies in the height differences of platforms, but these are considered too small drastically to affect the results.

Mention has been made in the regional chapters of platforms occurring at various levels in the research area. A partial analysis of these was made by Driscoll and Hopley (1968) who concluded that platform notches occurred at mean heights of 0.2 feet, 4.8 feet and 14.8 feet (their heights have been related to M.H.W.S.). The upper platforms is fragmentary and not found in all localities and interest in this study has centred on the two lower platforms. That at 0.2 feet is well within the reach of modern wave activity and shore platform processes in general but cemented conglomerate occurs on this platform in places and in a number of localities (for example Havannah Island, Wallaby Point on Great Palm Island and Camp Island) the conglomerate is almost certainly of mid-Holocene age. Moreover, this platform at or just above M.H.W.S. in many places appears to be suffering erosion, being consumed by a lower notch not much above L.W.M. The platform is therefore interpreted as mid-Holocene, though it may be a composite feature cut during both the transgressive and regressive phases of the Holocene high sea level as the indications are that the actual maximum level was of too short duration to allow a significant platform to develop. The higher 4.8-foot platform is older and more weathered and being destroyed at present by solution pitting within the spray zone. It appears to be the next oldest of the platforms and is therefore allocated a late Pleistocene age. The relationship between the mean heights of platforms and assumed maximum sea levels at time of formation are remarkably similar. The 0.2-foot platform is associated with an 11-foot sea level (10.8-foot difference), the 4.8-foot platform with a 15-foot sea level (10.2-foot difference). Variations of at least this magnitude may be explained in terms of local irregularities in platform heights which limit the accuracy of the survey method.

Using the data published by Driscoll and Hopley (1968) and extending the platform survey over a much greater area of the research region, an attempt has been made to indicate the degree or lack of warping in the coastal zone in the last 100,000 years. The areas surveyed include from north to south:

i) Palm Island, composite figures from Great Palm, Fly and Havannah Islands.

ii) Mount Douglas.

iii) Range of Many Peaks.

iv) Muntalunga Range.

v) Beach Mount, Burdekin delta.

vi) Camp Island.

All the platforms were poorly developed, the majority being cut in granite, the remainder in rhyolite or gabbro. Examination of current processes suggested that the platforms were cut at about the same level in all lithologies. Table 7.1 shows the mean heights and height relationships of the twomplatforms in the different localities. Variation at each level appears due to variations in exposure.

The height differences range from 4.4 feet to 8.4 feet. The range appears great and possibly indicates warping though it may also reflect the difficulty of identifying the notch at the rear of the higher platform. In Table 7.1 there appears to be no logical pattern to the differences in spacing of the platforms.

The amount of data is too small for the use of statistical techniques to identify any significant pattern. However, of necessity, the information points are located in linear fashion along the coast in a direction which parallels the regional structure and in particular the line of main Tertiary uplift from north-west to south-east. Figures 7.3a and 7.3b show regression lines for the height differences plotted against distance along a base line, in figure 7.3a the base line being parallel to the regional structural trend (i.e. parallel to the coast), in figure 7.3b it being transverse to the regional structural trend. The results indicate a degree of warping upwards from north-

Table 7.1

Mean heights of shore platforms in the Townsville area

Location	Mean height lower platform	Mean height higher platform	Height difference
Palm Islands	0.8 feet	7.3 feet	6.5 feet
Mount Douglas	-1.3 "	3.2 "	4.5 "
Range of Many Peaks	2.0 "	6.4 "	4.4 "
Muntalunga Range	2.3 "	7.9 "	5.6 "
Beach Mount	5.2 "	13.6 "	8.4 "
Camp Island	-0.3 "	6.2 "	6.5 "

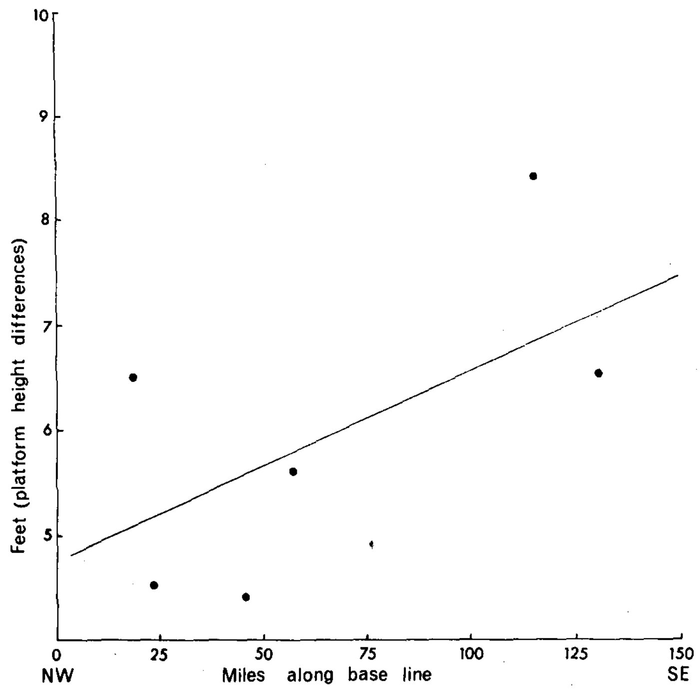

Fig. 7.3A Regression line indicating warping parallel to the coast.

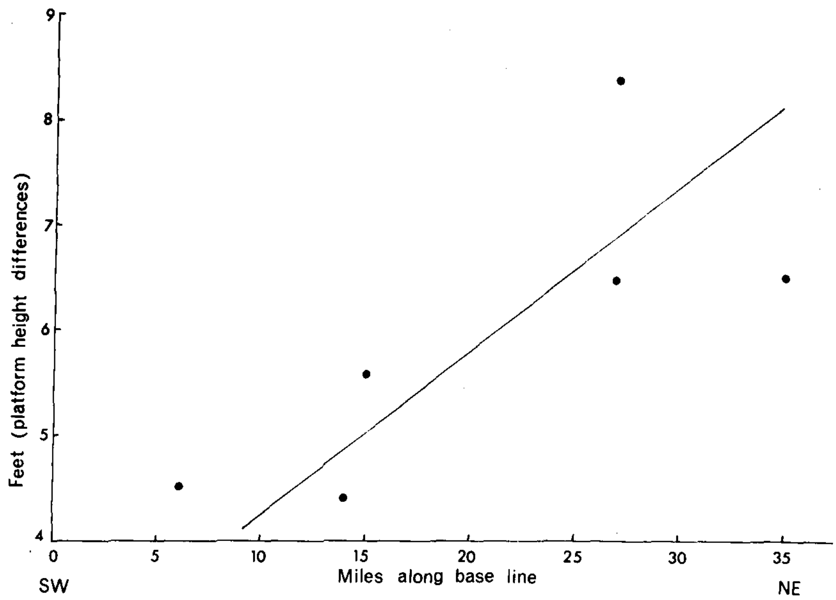

Fig. 7.3B Regression line indicating warping transverse to the coast.

west to south-east at a rate of 1 foot in 58 miles. This is not considered significant in view of the small amount of data available and the difficulties and possible errors involved in its collection. The other graph (7.3b) indicates a much greater degree of warping, as would be expected across the regional structural trend. A rate of warping upwards from the coast of 1 foot in 6.5 miles is indicated. This appears more significant but in view of the same difficulties must be treated with caution. Nevertheless it is possible that warping along the coastal zone has continued into the late Pleistocene.

The amount of warping indicated is not great but it may have accompanied vertical movements of much greater magnitude. Thus the significance of the results to the late Pleistocene and mid-Holocene shorelines cannot be judged. The figures indicate warping in the time span between these two shorelines, at rates which if continued since the mid-Holocene period, would not noticeably affect the mid-Holocene level. The degree of vertical movement and the influence such a movement has had on these emerged shorelines cannot be gauged, though it is suggested that, in the absence of further evidence, the mid-Holocene level must be considered as eustatic rather than tectonic. The general agreement between the level of the late Pleistocene 15-foot shoreline in North Queensland and probably the same feature from other presumably stable areas in Australia and elsewhere in the world, would suggest that the amount of vertical movement over the region as a whole has been neglible in the last 100,000 years.

Assuming that the conclusions reached from figure 7.3b are correct and that the tilting is continuing the same trends as the major late Tertiary movements, then the axis of tilting in the Townsville area is shown to be seawards of the present coastline.

Conclusions from North Queensland on Sea Level Changes

1. The oldest identifiable littoral deposits in the research area belong to a transgression with a maximum sea level height of 15 feet occurring in the late Pleistocene. A last interglacial age of 80,000 years or greater is allocated to this transgression in preference to a Wurm interstadial. The results from North Queensland closely agree with those obtained elsewhere in Australia and in other areas.

2. Little information is available on the Wurm low sea level phase, though shorelines identified 96 feet, 132 feet and 192 feet below sea level many indicate stillstands during the late Pleistocene.

3. Submerged beach rocks possibly 30 to 35 feet below M.H.W.S. may correlate with a stillstand during the Holocene transgression.

4. The mid-Holocene transgression culminated at about 4,250 years B.P. with a maximum sea level of approximately 11 feet. Close agreement is found between these results and from elsewhere in Australia, though not from New South Wales.

5. The maximum level was not held for long. By 2,500 years B.P. sea level had fallen to approximately its present position and has remained at about this level ever since.

6. Analysis of mid-Holocene and late Pleistocene shore platforms suggests that a tectonic factor may be

involved. The rate of tilting could well affect the Eemian deposits but it is not considered strong enough to affect the mid-Holocene shorelines. Tilting in an upwards direction seawards at a rate of 1 foot per six miles per 100,000 years (approx.) is indicated. The amount of vertical movement involved is not known, but again is not considered drastically to have affected the mid-Holocene shoreline.

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CHAPTER 8

DISCUSSION OF THE GEOMORPHOLOGICAL EVIDENCE FOR CLIMATIC CHANGE

The development of a morphogenetic approach to geomorphology (Peltier, 1950; Tanner, 1961; Büdel, 1963; Leopold, Wolman and Miller, 1964; Tricart and Cailleux, 1965; Wilson, 1968; Stoddart, 1969) has permitted the interpretation of past climates from the fossilised, non-active landforms of the present landscape. By far the greatest attention has been centred on Pleistocene climates and the pattern of cold, glacial climates with intervening warm interglacials of higher latitudes has been paralleled by an apparently synchronous pattern of pluvial and arid phases in tropical and sub-tropical latitudes. Variations in temperatures are also indicated in tropical areas during the Pleistocene with decreases during glacial periods of the order of 7°F (c.4°C.) compared to todays climate and increases during interglacials of about 3°F (c.2°C.) (Flohn, 1952; Emiliani, 1955; Fairbridge, 1961a). Little data is available from the Australian region to confirm the amplitude of these variations, though oxygen isotope palaeotemperatures determined by Dorman and Gill (1959a, b) suggest a late Pleistocene rise of temperature in southern Australia similar to that elsewhere.

These variations in temperature have possibly not been acknowledged sufficiently in previous climatic reconstructions in the Australian region (e.g. Whitehouse, 1940; Browne, 1945; Crocker, 1959) though more recently, Watkins (1967) did take into account the lower temperature factor in his study of the relationship between climate and development of landforms in the Cainozoic of Queensland. It is suggested that the water balance approach is fundamental to climatic geomorphology. Evidence has been presented in Chapters 2 to 5 for both wetter and drier phases in the past climate of the research region. It is intended that these terms "wetter" and "drier" be used with caution and that they refer not simply to periods of higher or lower rainfall, but to times when the availability of water for geomorphic processes was either greater or less than it is at present. Such variations could result from simple fluctuations in annual rainfall totals, but they could be produced by alterations in the rainfall regime, with a greater or lesser proportion of the annual total falling in the cooler winter months when evaporation is less, or alternatively by lower or higher temperatures, with similar effects on precipitation effectiveness through evaporation.

In view of the evidence for temperature fluctuations during the Pleistocene, an analysis of the water balance of the Townsville area was considered an essential pre-requisite for a discussion on climatic change. Figure 8.1 shows the water balance assessment based on Townsville figures for

a) the present, using mean monthly temperature and precipitation figures.
b) the Pleistocene glacial phases, assuming a similar precipitation pattern as today, but a depression of each month's mean temperature by 7°F.
c) the Pleistocene interglacial phases, assuming a similar precipitation pattern as today, but an increase in each month's mean temperature by 3°F.

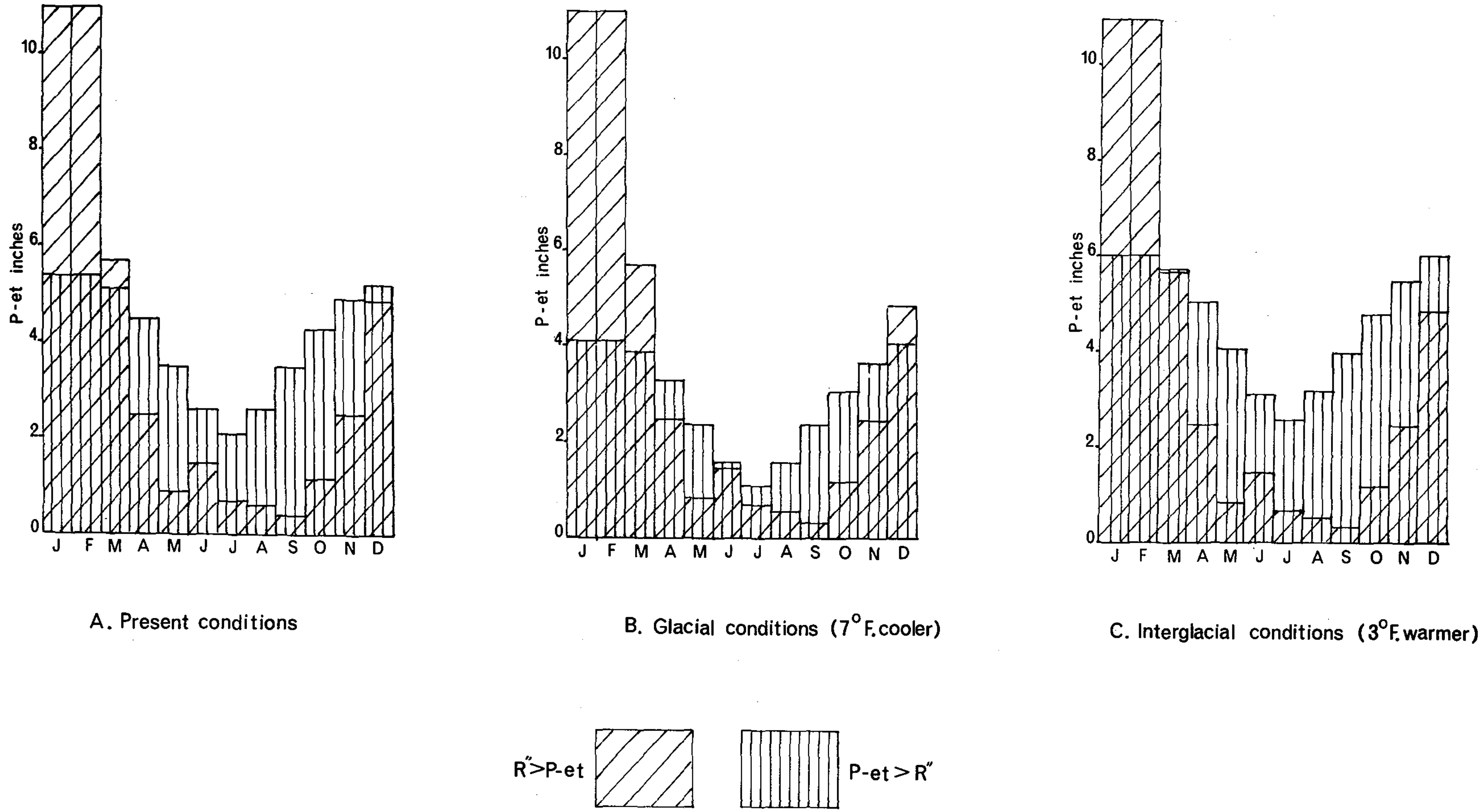

Fig. 8.1 Potential evapo-transpiration water balance graphs for Townsville.

Potential evapo-transpiration figures were computed using the Thornthwaite (1948) formulae based on temperature[1]. These formulae when applied to North Queensland, have a very close approximation to the considered figure based on evaporation measurements of 0.674 of the Australian Standard Evaporation Tank figure (Hounam, 1961).

At present the Townsville area receives an average of 42.7 inches of rain per annum. The total potential evapo-transpiration figure for the year is 49.68 inches, a deficit balance of 6.98 inches. Taking only the months when rainfall exceeds potential evapo-transpiration, it is calculated that there are 11.47 inches available for geomorphic processes (other than those which take place during the evaporation). There are 3 months when the rainfall figure is the greater. During the cooler Pleistocene phases it is estimated that the total potential evapo-transpiration figure would be 35.98 inches, an excess balance of 6.79 inches, and taking only the months when rainfall would have exceeded potential evapo-transpiration, which number 4, there is a total of 16.00 inches available for geomorphic processes. The calculations for a warmer interglacial phase show a total potential evapo-transpiration figure of 56.37 inches, a deficit of 13.67 inches. with rainfall being the greater

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1. The formulae used are:

$$P.E.(\text{inches}) = \frac{T+0.04T.(T-65)+T-m}{25.4}$$

when T-m is positive

$$\text{and } P.E.(\text{inches}) = \frac{T+0.04T.(T-65)-2(m-T)}{25.4}$$

when T-m is negative.

T = mean monthly temperature ^oF, and m = mean annual T^o ^oF.

figure in only 2 months and producing only 9.78 inches for geomorphic process.

Although a number of assumptions are made in this analysis, including the assumption that the Pleistocene rainfall distribution was similar to that of present, and that the mean annual temperature variations calculated from elsewhere, were distributed evenly over the whole year, the results are considered valid. They indicate that a difference of over 20 inches existed in the water balance figures for glacial and interglacial phases, that the wet season was effectively twice as long and that the amount of water available after evapo-transpiration during the cooler periods was almost twice that for the interglacials. Although insufficient data are available to evaluate the effects on geomorphological processes, it is suggested that the temperature variations alone may have been sufficient to produce the observed fossil landforms in the research area. Moreover, the reductions and increases in temperature inferred though sufficient to produce effective changes in the water balance, but would not have greatly altered the general tropical nature of the environment.

Climatic Conditions and Geomorphic Processes

Under the present climatic regime, the hillslopes of the research area are shedding small angular debris which is apparently further broken down at the slope foot as the rivers generally carry a heavy load of sand size material. Alteration to clays is not taking place rapidly except in the most stable situations on flat or gently sloping terrain. Soil processes reflect the alternation of wet and dry seasons, but water table fluctuations are not great and accumulation of sesqui-oxides is limited the upper three feet (see

Chapter 4, p.202). The dessication of the environment is considered to result in an increase in the size and amount of slope debris as a result of a reduction in the vegetation cover and an increase in mechanical weathering processes (Langbein and Schumm, 1958), though Dury (1967) questions the increase in yield. Accumulation of fans would result at the foot of hillslopes and pedimentation would become the major process. Streams, which would flow on a seasonal basis to an even greater extent than they do now, would carry a heavier and coarser load. It is thought that the restricted mobility of sesqui-oxides which occurs in the soils today, would cease and carbonate accumulation would occur. Alternatively, if the environment were to become more humid, even on a seasonal basis only, there would be an increase in the water table fluctuations and an increase in sesqui-oxide accumulation over a greater depth of the unconsolidated deposits, and given sufficient time, lateritisation would become the major process. A denser vegetation cover would restrict weathering process and mobility of slope debris and help to increase the importance of chemical weathering. Sediment yield would trend towards finer materials and especially clays. Channelled flow would be found in the piedmont area with incision into any previous pediments.

The Pattern of Climatic Change in North Queensland

Assuming the changes outlined, it is possible to reconstruct the past water balance conditions in the North Queensland area. The earliest period examined is the last interglacial. The widespread occurrence of clay plains during this period may imply that an earlier phase existed which had moister conditions than the present. Moister conditions producing deep weathering are indicated in the Cape Upstart area, where they produced large rounded core-stones on the slopes of the small basic igneous outcrops found here. The large Pleistocene dune of this area is attached to and partly covers these outcrops thus giving a minimum age for this deep weathering episode, which may, however, date back to the previous glacial phase, possible the Riss. However, by the end of the interglacial period, dessication had occurred accompanied by the regression of the sea from the interglacial high level. The early part of this sequence is possibly recorded by the dunes of late Pleistocene age, for the ones associated with a 4-foot sea level and interpreted as belonging to the regressive phase are the largest. Though the highest example is that to the south of Cape Upstart, the Inkerman beach ridge-dune provides the best contrast. The dune ridge at its northern end, where the calcarenite is found, rises to 45 feet but declines rapidly in height as a northern orientation is attained. In contrast, the dune at Green Hill, which has a similar orientation to the lower parts of the Inkerman ridge, is almost twice the height. Although this evidence is far from conclusive, the general increase in height of the Pleistocene ridges with the regressive phase is possible an indication of dessication.

That pedimentation and accumulation of angular fragments in the piedmont zone occurred at a lower sea level phase is best illustrated by Mount Douglas (Chapter 4, p.193). Here, the pediment on the seaward side of the outcrop and associated piedmont angular gravels slope beneath present sea level. The relationship of the late Pleistocene surface and the pediments of the Burdekin delta also suggest pedimentation during the early part of the last glacial low sea level. The pediments in the interior of the delta are graded to this alluvial surface, apparently prior to its incision, but nearer the coast it is evident that the pediments also grade down to at least 25 feet below sea level. Again, it appears that the drier conditions were initiated in the interglacial and continued into the early part of the glacial phase.

Further deposits almost certainly belonging to the late Pleistocene arid conditions are found in the piedmont zone and on the coastal plain north of Townsville. Large angular fan gravels rest on pediment surfaces along almost the entire length of the foot of the coastal escarpment. Fan gravels are especially prevalent in the Frederick's Peak area where they are cemented, contain iron-stone nodules and occur beneath younger fan deposits. It would seem that the pediments of the research area are almost entirely fossil features belonging not to the most recent drier phase, but to that occurring in the late Pleistocene period. The streams deposits north of Townsville allocated to this period are extremely coarse in their lower sections, the younger, upper deposits grading into sands possibly indicating the change to moister conditions at a later date.

That moister conditions prevailed during the low sea level phase is certain. The most interesting evidence comes from the Mount Douglas sections again where the old pediment deposits become deeply weathered and lateritised, with the development of a sesqui-oxide accumulation horizon of about 1.5 feet overlying mottled and pallid zones. The whole sequence passes beneath present sea level. It is suggested that the piedmont area of Mount Douglas with its coarse gravels was a favourable location for moisture accumulation and water table fluctuations, which explains the more complete deep weathering which occurred here in comparison to the clay deposits of the coastal plain. Even here, however, accumulation of ferro-manganese pisolites took place to a much greater depth than is occurring today. Similarly, the late Pleistocene fluvial deposits become weathered with accumulation of sesqui-oxides. In the scarp-foot zone, the coarser fan gravels suffered deep weathering to a similar extent as the Mount Douglas pediment deposits, probably for the same reasons. The moister phase is also marked by incision of the pediments and by the deposition of younger Pleistocene clays even in the piedmont area where they overlie the coarse gravels of the interglacial stage.

Possibly because the Burdekin delta region also contained alluvial deposits coarser than clays, which allowed water table fluctuations, explains why the interglacial deltaic surface became deeply weathered and oxidised here. Although this surface can be recognised over the whole delta, the borehole deposits which most closely resemble laterite, with a red cemented upper surface and underlying pallid zone, are those developed on coarser materials. Similarly, the red cemented deposits exposed at the surface in the Haughton River area were originally coarse gravels. Elswhere in the delta, where clays appear to have been the predominant late Pleistocene surface deposits, accumulation of sesqui-oxides has been less general and limited to nodular or pisolitic forms. Although borehole evidence is less detailed in the Herbert River delta, a similar pattern seems to be found there.

The question as to whether the deep weathering which took place was the result of an altered water balance sequential upon the lowered temperatures, or whether it followed an increase in precipitation as well, is an interesting one. Certainly the weathering occurred over a wide area, and, considering the comparatively short time span it appears to have been a rapid process. If lower temperatures alone were responsible for greater availability of moisture it might be expected that, with a similar rainfall regime as today, the effects would be felt along the entire length of what is the present dry sector of the north Queensland coast (from south of Ingham almost to Mackay). There are doubts concerning this for south of Cape Upstart, outside the research area, the landscape certainly changes. This may be a reflection of geological conditions, as massive granites become the only rock type found in the coastal zone, but pediments are more extensive, fresher in appearance and, apart from angular fan deposits, have no extensive colluvial cover as in the Townsville area. Research into the nature of the late Pleistocene alluvial surface of the Don River delta may determine the extent and nature of weathering, but certainly the general appearance of the landscape suggests that drier conditions existed here much more permanently than further north. Again, it may be significant that the only known occurrence of late Pleistocene raised beach rock is on Camp Island, at the southern limit of the research area. It has already been noted in Chapter 2 that on the wetter islands north of Hinchinbrook, raised beach rock of even mid-Holocene age does not survive. The wetter conditions of the last glacial may well be responsible for the erosion of raised beach rocks of interglacial age from the Palm Islands and the islands of Halifax Bay. The Camp Island raised beach rock may thus owe its survival to the absence of much wetter conditions during the latter part of the Pleistocene. It is interesting to note that two levels of raised beach rock, the upper one possibly of late Pleistocene age, are described on islands in the Bowen area, as for example, Middle Island (Stanley, 1928, p.36; Steers, 1929, p.346, 1937, p.21). That conditions should alter so rapidly between the Burdekin delta and Bowen, a distance of 60 miles, is not surprising in view of the fact that today the average annual rainfall of Townsville is half that of Ingham, a similar distance to the north. The evidence thus suggests that the glacial phase climate was wetter as well as cooler than present.

The wetter conditions did not survive the end of the Pleistocene period. Dessication of the environment is indicated by the cessation of ferro-manganese accumulation in the soils of the coast plain and the initiation of a carbonate accumulation phase. Radio-carbon dating suggests that the drier conditions were effective by 15,000 years B.P. New fan accumulation in the piedmont zone and resumption of pedimentation are also allocated to this period. Massive waste deposits formed in the upper reaches of the streams. The present streams have incised themselves into these, leaving the arid phase deposits as stranded climatic terraces. It would seem that the drier phase extended at least until the mid-Holocene maximum sea level stage, as stream courses apparently graded to this higher level contain coarser deposits than those carried by streams at present. The widespread accumulation of levee deposits, which also appears to date from this period may also reflect the greater sediment yield produced under drier conditions.

The reversion to the moister climate of the present has stabilised the fans, caused incision of the streams into the coarse deposits of their headwaters, produced a sediment yield of smaller calibre and started a new though restricted accumulation of ferro-manganese nodules in the soils of the area. However, the variability of rainfall appears to produce an alternation between conditions favourable to fan accumulation and pedimentation, with those associated with stabilization of fans and channelled flow in the piedmont zone, the latter conditions being the more common. It is suggested that the balance between the two is delicate.

Discussion

The pattern of climate indicated is one of conditions as dry as or drier than present existing during the warmer interglacial periods and wetter than present during the glacial period, though the dry climate appears to have extended into the early part of the low sea level stage of the glacial and to have resumed well in advance of the eustatic recovery of sea level. The climatic anticipation of the rise in sea level is understandable and parallels Fairbridge's (1961a) melt retardation hypothesis which suggests that climatic warming proceeds the melting of the temperate ice masses by at least 4,000 years and that the eustatic rise is at least 10,000 years behind the radiation oscillation which initiates the melting. Both Fairbridge (1961b) and Shepard (1961) agree that by 17,000 years B.P. the eustatic rise in sea level had started. In temperate latitudes the presence of massive areas ofice, even though in ablation, would tend to retard the recovery of temperature to a greater extent than in the tropics where there would be nothing to prevent an earlier recovery of temperature and reversion to the interglacial conditions. It is, therefore, not altogether surprising to find that the drier, supposedly interglacial conditions, existed by 15,000 years B.P. in north Queensland.

Why the interglacial conditions should prevail during the eustatic lowering of sea level of the last interglacial, is more difficult to understand if it is accepted that temperate and tropical climatic changes were in phase during the Pleistocene. It may well be that whilst the conditions which trigger off a melting of the ice sheets will automatically produce climatic changes in tropical latitudes, the conditions which produce the start of a glaciation have less effect and tropical glacial stage conditions are more dependent upon the changes in circulation produced by the ice sheets themselves. This could explain the retardation of climatic change in north Queensland at the end of the last interglacial.

The present wet season, and the great variability of rainfall in the research area are a reflection of the not completely reliable extension of the Inter-tropical Convergence (I.T.C.) this far south during the summer months. It may be assumed that the wetter phase saw not only an improved water balance position as a result of lowered temperatures, but also a more reliable wet season, conditions possibly regularly resembling those of the wetter wet seasons now experienced only occasionally. Townsville for example over the last 100 years, has experienced a "wet" year of over 60 inches rainfall a total of 18 times, and over 50 inches a total of 38 times. These wet years generally indicate the seasons when the I.T.C. clearly extends south of Townsville. The great variability of Townsville's rainfall also indicates it's dependence on the progress southwards of the I.T.C. Ingham's rainfall is much less variable because the passage of the I.T.C. is more dependable. Years when Townsville has less than 35 inches of rainfall see no great departure from the mean at Ingham. It is thus suggested that the glacial period saw the mean summer position of the I.T.C. over the coast of north Queensland 60 miles further south than it is today. The Bowen area could therefore be still in the zone of unpredictable summer rains, with a restriction in the deep weathering processes. In a recent paper, Bird and Hopley (1969) suggest a migration or expansion and contraction of the climatic zones during the Pleistocene, with wetter conditions extending north of the present Af climatic area, as well as to the south of it. This too may be associated with the migration of the I.T.C. further south and its delayed return northwards out of the Australian region. Disturbances associated with the I.T.C. would thus be experienced in northern Australia for a longer period, producing wetter conditions, though probably still seasonal

These conclusions are not altogether in accord with the changes postulated for the tropics in the literature. Fairbridge (1961a, 1968) considers that the glacial periods were ones of reduced rainfall as a result of less evaporation. He has illustrated his ideas in North Africa (1964) where he relates the pluvial phases of the Sahara with the period of post-glacial climatic optimum (10,000 to 4,000 years B.P.). In a figure reproduced in each of the papers to which reference has been made, Fairbridge does, however, indicate an expansion of the warm equatorial zone during the glacials, though stressing that the equatorial latitudes as a whole were drier.

Fairbridge's views are opposed to those of Büdel (1951) who shows a migration polewards of 3° for the humid savanna and tropical rainforest zone during the Wurm glacial. This would be quite sufficient to give the Townsville area the higher rainfall postulated for the late Pleistocene.

In Australia the only detailed studies of climatic change during the Quaternary have been carried out in the south-eastern portion of the continent where they have been related to glacial and periglacial activity (e.g. Galloway, 1965; Derbyshire, 1969). Galloway, in particular, from evidence of cold, dry, windy conditions in south-eastern Australia, postulates that there was an extension of the high pressure arid belt during the glaciation, explaining certain "pluvial" features in terms of reduced evaporation. His findings are, however, opposed by Dury (1967).

Anumber of early studies of Australian climatic changes (e.g. Whitehouse, 1940; Crocker, 1959) also indicated that, contrary to Galloway's conclusions, the Pleistocene glacials were periods of higher rainfall, and interglacials periods of desert expansion. Gentilli (1961) claims that the narrowing and intensification of the climatic zones during the Pleistocene glacials would increase the rainfall along the equatorial convergence, between intensified tropical easterlies. He also extends the humid glacial climate to at least 7,000 years B.P. his "Great Aridity" occurring only at the mid-Holocene stage. The conclusions reached in north Queensland may confirm his views on the activity along the I.T.C. but it would appear that in coastal tropical Queensland, at least, the arid period may have to be extended further back.

Extending the conclusions of Gentilli, Coaldrake (1968) has more recently assumed generally moister conditions over the whole of north-east Australia during the Würm. He also considers that the interglacial climate, though drier in the interior with an expansion of the central arid zone, would not be altered to any great extent along the coast. This may be an overgeneralization.

Walker (1966), indicates that botanical data is as yet insufficient to use reliably to reconstruct climatic change, at least over the last 8,000 years. However, in a very comprehensive survey of phytogeographical elements in the Australian region, Burbidge (1960) makes a number of comments which are relevant to the evidence for climatic variations in north Queensland. Although primarily recognising only a general Pleistocene pluvial period in Australia and a more recent "Great Aridity" along the lines of Crocker and Wood (1947) she does allow for several climatic oscillations during the Pleistocene. North-east Queensland is seen as an important entry and exit point for plants, which linked Australia with New Guinea, New Caledonia and New Zealand. Burbidge concludes that migration of Indo-Malaysian elements into Australia during the Pleistocene could only have occurred during the low sea level phases, and that for migration of rainforest species to have taken place, the climate must have been wet. This relates closely to the findings presented in this chapter, for in the years when the I.T.C. migrates further south than Townsville the areas to the north normally have higher than average rains as the return northwards of the I.T.C. is delayed, and convectional instability in the moist air behind the I.T.C. is experienced over a longer period. Thus, not only do higher rainfalls occur, but the wet season becomes prolonged and there is a contraction in the length of the dry season, which has a greater influence on the distribution of rainforest than rainfall totals alone. These conditions are envisaged consistently for the last glacial low sea level and, with the improved water balance resulting from lowered temperatures, there would be no climatic barrier to the migration of Indo-Malaysian flora at least as far south as Townsville. Burbidge indicates that a number of apparently recent floristic arrivals have not dispersed out of north Queensland. Although a time factor may be involved here, the indication of a dry zone south of the Burdekin delta may also have prevented dispersal further south.

A further point made by Burbidge, is that migration of <u>Eucalyptus</u> sp. from Australia to New Guinea must also have taken place during a Pleistocene low sea level and that the presence of Australian elements in dry monsoon climates of Malaysia may similarly be explained. She provides three possible explanations for the apparently anomalous position of high rainfall Indo-Malaysian species moving south across a land bridge at the same time as low rainfall Australian species were moving north:

i) that the climate was not consistently pluvial during the Pleistocene low sea levels

ii) that there was a gradation east to west of climates across the land bridge

iii) that the migration took place earlier than the Pleistocene when a land bridge existed at the time of an arid climate.

Although Burbidge favours the latter explanation, especially for the presence of Australian elements in Malaysia, problems still remain. The evidence presented in this chapter may at least give more weight to the first alternative to explain the migration of eucalypts into New Guinea. It has been indicated that the dry conditions of the last interglacial extended into the low sea level phase, possibly long enough for these to coincide with the formation of the Australian-New Guinea land bridge.

Conclusions

The conslusions reached on climatic change in north Queensland based on geomorphological evidence are summarised below. They are far from being in complete agreement with hypotheses concerning climatic changes for the whole of Australia which have been published. However, this is not altogether surprising considering the size of the Australian continent and the fact that Pleistocene climatic changes in the tropics have generally been interpolated from evidence in the southern or interior portions of the continent.

The changes envisaged are not great and can generally be explained in terms of the more common occurrence in the past of what are now exceptional climatic years. The relatively small changes which are considered to have taken place in the atmospheric circulation in north Queensland during the late Quaternary have probably been magnified by variations in water balance conditions resulting from temperature fluctuations. The changes which have occurred are:

1. At some period prior to the regression phase of the last interglacial period, a wetter climate existed. This may have been contemporaneous with the penultimate glacial period.
2. The latter part of the last interglacial experienced a climate drier than present. The conditions could have been produced simply by higher temperatures, rather than decreased rainfall. The dry conditions continued into the low sea level phase.
3. During the last glacial period, a wetter climate existed which was produced not only by improved water balance conditions with lowered temperatures, but also by an extension of the mean position of the Inter-tropical Convergence 60 miles further south than its present mean position during the summer months.
4. Dry conditions again prevailed from the latter part of the Pleistocene (at least 15,000 years B.P.), to the mid-Holocene period 4,000 to 5,000 years B.P. The higher temperatures of this period may again have been influential.

5. The present climatic pattern is intermediate between the two extremes, though more closely allied to the drier phases. A slight lowering of temperature may have occurred since mid-Holocene times.

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CHAPTER 9

MORPHOGENIC FEATURES OF A TROPICAL WET AND DRY COAST

The conclusions from the previous chapter indicate that though the research area may have experienced a wetter climate during the Pleistocene, the seasonality of the rainfall persisted. The consistency of the climate during the period when the coastal landforms of the North Queensland area were evolving results in many of the present features of the coast being attributable directly or indirectly to the one morphogenic system. Whilst a climatic approach is commonly adopted in general geomorphological studies (see references in Chapter 8), its application to coastal studies has been restricted, though Davies (1964) has proposed a morphogenic approach which acknowledges the existence of "climatic factors of morphogenic significance affecting such things as beach regimes and materials, cliff and platform weathering, and the regional formation of coral reefs, salt marshes and coastal dunes". Modes of coastal evolution in contrasted climates have been discussed by Tricart and Cailleux (1965a), with emphasis on the features of humid tropical zone coasts, notably in Brazil and West Africa. More recently Bird and Hopley (1969) have considered how far the coastal features in the humid tropical sector of north-east Queensland conform with those described elsewhere in similar climates.

However, the treatment of the tropical wet and dry area as a separate coastal morphogenic zone has not apparently occurred previously, though Tricart and Cailleux (1965a) indicate that some of the features they describe are more common in the wet and dry tropics, than the continuously wet zone. It may be argued that the wet and dry tropics constitute only a transitional zone between the tropical wet and the desert climates. Alternatively, in view of the greater temperature extremes experienced by the wet and dry tropics, they may be transitional between the tropical wet system and temperate areas. However, a savanna morphogenetic region is recognised in the systems of both Peltier (1950) and Tricart and Cailleux (1965b). It is argued in this chapter that such a morphogenetic region may be recognised in the coastal zone.

The wet and dry tropical zone into which the research region fits is basically the Aw type in the Köppen classification. Such climates are limited by the precipitation of the driest month falling below 2.4 inches, and the temperature of the coolest month not falling below 64.4°F. A large proportion of the Australian coast lies within this system. The Australian tropical coasts are climatically related to those of parts of India, East Africa, parts of West Africa and north-east Brazil.

The nature of landforms on any coast is dependent on the processes operating in three interrelated zones. First, the processes working in the coastal hinterland, i.e. in the basins of the rivers flowing to the coast, have an important influence on the type of sediment being supplied to the littoral zone. Secondly, there are processes operating within the littoral zone itself, where the interplay between sub-aerial and marine activities may be less directly dependent upon climate, but where, nevertheless, indirect influences are morphologically important. Finally there is the off-shore zone, where another source of beach sediments may be found in the form of either fluvially deposited or sub-aerially weathered material belonging to low sea level phases of the Pleistocene or material of biogenic origin. Water temperatures and wave and swell characteristics are also important off-shore influences on the littoral zone which may be dependent upon climate. The contribution of these three zones in the research area is examined below.

Sediment Supply from the Hinterland

The geology and physiography of the hinterland of the research area is favourable to a rapid supply of sediment to the coastal zone. The presence of a deeply weathered fossil regolith in the upper reaches of the major catchments and the occurrence of large areas of granite, the rapid granular decomposition of which appears to produce a steady supply of sand size material, are factors which mean that coastal streams invariably carry a large load to the coast. The process of sediment supply is undoubtedly helped by the sub-humid climate of the catchments. As has been mentioned earlier, following the conclusions of Langbein and Schumm (1958) and Leopold, Wolman and Miller (1964), the rainfall of the basins of the rivers of the research area is close to that which will result in the maximum sediment yield. However, these conclusions are questioned by Dury (1967) and evidence from North Queensland presented by Douglas (1965) tends to support Fournier's (1960) conclusions that in general, erosion is a function of the amount of rainfall and the intensity with which it falls. In his study of four catchment areas on the Atherton Tableland, Douglas indicates the maximum sediment yield to come from the river which drains the highest rainfall area (Behana Creek) but that the figure for the lowest rainfall area (based on observations of the

Wild River) is not significantly lower. Certainly per unit volume of water, the lower rainfall area, with a mean annual precipitation of 40 inches, has the greater potential for sediment yield. Douglas noted that when rain does fall in this area, it falls with great intensity and too rapidly to infiltrate and make up the soil moisture deficit. Surface run-off, picking up loose soil particles, quickly reaches the stream channels. The discontinuous vegetation cover does little to interfere with the rapid run-off.

The question of rainfall intensity is an important one. Jennings (1967) mapped rainfall intensities in Australia and indicates the highest crude intensities to be in the tropics. The Aw climate areas, with the exception of a narrow corridor in the Ord River area of Western Australia, all have rainfall intensities greater than 50 points of rain per rain day. The highest intensities occur within the research area with intensities greater than 65 points per rain day over the whole area, and the highest intensity in the whole of Australia occurring at Reid River, 34 miles south of Townsville with 98.9 points per rain day. It is not the purpose of this chapter to enter into the discussion on the relationship of precipitation and sediment yield (for a discussion of results, see Stoddart, 1969). It is sufficient to note that, even if absolute yields of sediment in rivers in Aw climates do not exceed those of rivers of the wetter Af and Am climates, their yield per unit volume of run-off is likely to be high. Moreover, with intense chemical decomposition restricted to a short wet season, it seems reasonable to assume that the sediment yield will include a lower proportion of clays and soluble minerals and an increase in sand size and larger calibre materials. This is important to coastal processes, for whilst finer material delivered to the coast may be carried far from the littoral zone, to be eventually deposited on the continental shelf and beyond, the larger material is unloaded in the near shore zone, where given suitable wave conditions, it may be transported onshore at a later date. It may be significant that Maxwell (1968), even though suggesting that the supply of fluvial sediments to the continental shelf behind the Great Barrier Reefs is low, indicates that mud facies are dominant in the inshore zone of the high rainfall area near Innisfail (fig. 144B). His figure 138B shows that sediments are highly terrigenous (less than 20% carbonates) in the area between Cape Upstart and the Black River. His figures 138A-D indicate that terrigenous materials in the near shore zone of the continental shelf, may be correlated not only with major river mouths, but also with lower rainfall areas.

No figures are available to indicate the size of river loads in the research area. All streams are choked with sand and fine gravel and flow is restricted to a few months of the year for all except the major Burdekin and Herbert Rivers. In a recent mining company report, Sutherland (1970) indicates that the 100 year flood discharge of the Burdekin River at Ayr is 1.3 million cusecs, of which 0.915 cusecs would flow in the main channel. He suggests that during particularly heavy flooding there is potentially a 30 to 40 feet depth of mobile sand in the river bed. The general indication is, therefore, that fluvial sediment supply is particularly heavy along the coast of the research area, and that the bulk of this material is sand.

The Littoral Zone - Cliffed Coasts

Actively receding cliffs are very limited in the research area. Solid rock outcrops on the mainland are rare and even where rock does occur both here and on the islands, it is doubtful whether much erosion is taking place. It has already been noted that the cliffs of the off-shore islands and of Mount Douglas are essentially little modified exhumed weathering fronts. Wave attack is generally less vigorous than further south on the Australian coast, partly because of the exclusion of the high energy ocean swells by the Great Barrier Reefs, but also because of the comparative rarity of strong winds in the tropics (Jennings, 1965). The absence of rock types such as sandstone, mudstone or limestone which might have more readily yielded cliff forms, and the ubiquity of resistant granites and volcanic rocks has been a further factor in the absence or slow rate of cliff recession. Shore platforms are also poorly developed, the foreshore topography generally being rugged and irregular similar to that of the wetter zone to the north (Bird and Hopley, 1969). However, possibly owing to the presence of more easily eroded metamorphic rocks in the wetter zone, a high tide notch is much better developed than in the drier south. Certainly lithology is an influencing factor here. However, the present writer has noted that in New Guinea (Louisiade Archipelago) the formation of wide shore platforms also in metamorphic rocks (schists and phyllites) and behind a barrier reef, is aided by subaerial chemical decomposition of the rock down to the intertidal level (Hopley, in press). A similar process has been suggested for the platforms of the Barnard Islands (see Chapter 2). Such a process could not be a significant factor in the research area, whatever the lithology. Although deep weathering appears to have produced a regolith during the late Pleistocene, providing core stones for the construction of Holocene boulder spits, there is clearly little weathering preparation of the foreshore occurring today. Minor weathering forms, such as spray pitting and tafoni, occur where lithologies are suitable but these appear to be similar to those of both the wetter coast to the north and the cooler coast to the south (see Bird and Hopley, 1969; Bird and Dent, 1966).

A major difference between the rocky shores of the wetter coastal zone to the north and the research area, is the presence of a vegetation cover almost down to high tide level in the wetter area. Cliff slopes may thus retain their weathering mantle and differ little from the wholly subaerial slopes of the hinterland. Such slopes are typical of the off-shore islands as far south as Hinchinbrook and the transition to still convex, but bare rock forms in the Palm Islands is sharp. A similar transition occurs on the mainland.

Headlands both in the wetter and drier coastal areas provide suitable environments for molluscan fauna and adjacent beaches consistently have a higher than normal carbonate content. Sediment yield direct from the rock outcrops is not great. In the wetter zone the material delivered to the beach is generally of clay size in all but the most sheltered environments, is transported away from the littoral zone. The yield from outcrops in the drier research area is mostly in the form of grits or coarse sands which combine with shell fragments to form the coarser fraction of the local beaches. The lithological contrast of mica-schists, phyllites and gneisses with some basalt in the wetter zone and granites and volcanic rocks further south contributes to this contrast in beach materials.

The Littoral Zone - Depositional Coasts

The large sediment load of predominantly sand size material which is brought down to the coast by the rivers and the low yield from cliff erosion and, on the mainland away from headlands, from biogenic sources, results in depositional features being dominated by sands of fluvial origin. Indeed, so massive is the sediment yield that depositional landforms are the typical morphological features of the coast in question. Broad barrier systems of parallel beach ridges are typical of all exposed coasts and are replaced by mangrove and salt marsh only at the southern ends of embayments sheltered by the dominant south-easterly waves by prominent headlands as in Cleveland, Bowling Green and Upstart Bays. This indicates that a sand supply is available to a high proportion of the coast, partly the result of the close spacing of coastal streams and of the fact that even the smallest carry an abundant sand load, and partly the result of the nature of the material supplied by the rivers. Since it is largely sand size it is quickly deposited by the rivers as they enter the sea. However, a large proportion of the load appears to lie within the range 2.0 to 2.5 ϕ which has been shown to be that most easily transported by waves onshore and along shore (Fuller, 1962). Thus the material is of sufficient size to prevent it being carried far onto the continental shelf, but not large enough to prevent it being carried onshore again.

With the larger rivers, sediment supply is more rapid than sediment movement and rapid progradation is taking place close to the river mouths. However, the rapid growth of off-shore barriers and spits (as in the Burdekin region) and the width of the near level marine and littoral plain, allow for rapid changes in river courses within the zone close to the coast. Thus an area of rapid progradation and formation of deltaic cuspate forelands, may suddenly lose its sediment supply with resulting erosion as coastal straightening takes place. Although the nature of dunes on the North Queensland coast is discussed below, it may be indicated that coastal erosion is characteristically accompanied by dune formation where an open orientation between east and south is available. As alternations between progradation and erosion appear to be ultimately related to the rapid fluvial sediment supplv, it seems reasonable to regard them as morphogenic features.

The construction of multiple beach ridges may also be considered as related to climatic influences for their formation has been shown to be correlated with coasts where beach face angles appropriate to the beach material and most significant wave type are steeper than the overall shore profile (Savage, 1959). As beach faces are steeper with coarser material and lower waves, ridge building is favoured by either of these conditions (Davies, 1968). Continual shallowing of the off-shore profile, usually because of abundant sediment supply, according to Johnson (1919), will result in multiple beach ridges. All these characteristics are found in the coast between Cape Upstart and the Herbert River delta. The rapid supply of coarser material and the general low wave height (owing both to generally low wind velocities and to exclusion of ocean swells by the Great Barrier Reefs) may be considered as being indirectly dependent upon climatic factors.

In spite of a long dry season, stabilization of beach ridges by vegetation is rapid. The dune creepers _Ipomoea pes-caprae_ and _Canavalia rosea_ are particularly rapid colonisers. Weathering and soil formation on the ridges and dunes is closely dependent upon climate. Holocene ridges have rapidly acquired a profile stained in its upper few feet by humic material. However, the severe leaching which is evident on even the Holocene ridges of the wetter coast further north, is lacking in the ridges of the Townsville area. The formation of beach rock by the accumulation of calcium carbonate at the water table within the ridges, is a feature of beach ridge weathering restricted to the drier zone (see below). Contrasts also exist between the weathering of Pleistocene ridges on the wet and on the seasonally wet and dry tropical coasts. In the research area, weathering of the older deposits is not severe, a certain amount of breakdown to clay occurring in some ridges, but with oxidation of sands, producing a typically red colour, being the usual form of weathering. In contrast, podsolisation of the sands appears characteristic of wetter areas both to north and south. Bird and Hopley (1969), describe alluvial ferruginous sand rock near Kurrimine (Innisfail area) and this is overlain by severely leached, white, quartzose sands. Similar materials are also described from southern Queensland and northern New South Wales (Coaldrake, 1955; McGarity, 1956). These, too, appear to be Pleistocene in age (Langford-Smith and Thom, in press). The survival of beach rock and even dune calcarenite of Pleistocene age, is also an indication of the less severe nature of leaching of coastal deposits in the drier tropics.

In the review on beach rock formation in Chapter 6, it was noted that conditions for cementation of beach deposits may well be at their optimimum in the tropical wet and dry morphogenic region. However, the restricted occurrence of beach rock on the mainland coast is an anomalous feature which may be explained only by reference to the nature of beach materials as fluvially derived sands of extremely low carbonate content. Even under ideal conditions it is suggested that a minimum carbonate content of at least 30% is necessary for cementation. Such conditions are met on the mainland only around headlands, and so rapid is coastal progradation that these appear to be quickly engulfed within beach ridge systems thus limiting the calcareous material to a comparatively small number of ridges. On the islands, however, the high biogenic content of beach materials combines with the climatic factors to allow rapid cementation of a wide range of beach materials on almost every beach. It is the importance of beach rock as a stabilizing agency, its rapidity of formation and its slow rate of erosion in the tropical wet and dry climate which make the irregular island spits of the research region features of morphogenic significance. To the north, beach rock forms less readily, and apparently, when it does form and becomes emerged, is quickly consumed by weathering. Thus island spits to the north are nearly all of Holocene age and more regular in shape (see Chapter 2). Further south, outside the tropics, both the lack of fringing coral reefs as a basement for spit development and the slower rates of formation or even complete absence of beach rock, are factors which prevent significant spit development. Although Russell and McIntire (1965) report beach rock on the Queensland coast only as far south as Sarina near Mackay, there are reports of it further south around Shoalwater Bay (Jardine, 1928) and it occurs commonly on the coral cays of the southern limits of the Great Barrier Reefs (extensively, for example, on Heron Island). The present author has also observed cemented beach deposits of beach rock type exposed during coastal recession at Byron Bay in New South Wales. However, it is evident that towards the southern Queensland coast, even given highly calcareous beach materials, cementation occurs much less readily.

The absence or poor development of dunes in areas of tropical wet climates has been discussed at length in numerous papers (Nossin, 1961; Jennings, 1964, 1965; Bird, 1965; Bird and Hopley, 1969). It appears that beach sands become windborne far less readily than on coasts in cooler and drier environments. In a discussion of the factors involved Bird and Hopley (1969) dismiss the suggestion of Morton (1957) whondescribed the inhibition of beach sand deflation on the Gold Coast (West Africa) in terms of protective surface coasts of salt-cemented sands by evaporation of beach moisture in dry weather, as such a process has not been generally observed in the tropics. The idea that dune development is impeded by rapid invasion and stabilization of backshore sands by luxuriant vegetation is not tenable as the presence of such vegetation would aid rather than prevent dune building if sand were being blown from the beach. The suggestion that beach sands are generally too wet to be removed by wind action is not entirely satisfactory, for strong winds can deflate wet sands, but the comparative rarity of strong winds in the humid tropics and the fact that when they do occur, they are often accompanied by heavy soaking rains (Jennings, 1965; Tricart and Cailleux, 1965) seems to go far towards explaining the poverty of coastal dune development in this environment.

Although these remarks are directed toward dune development in wet tropical climates, the comparative rarity of dunes in the research area would seem to suggest that similar restrictions are operating here. However, the restriction in orientation is by no means as strict as it is on the wetter coast further north (Bird and Hopley, 1969). The rarity of dunes is surprising in view of the large amounts of sand delivered to the coastal zone. Certainly, salt-cemented crusts have not been observed and whilst colonisation of beach ridges is relatively rapid, it appears that this is not a significant influence. The conclusion that strong winds are generally rare in the tropics is a characteristic which is shared by both wet and seasonally wet and dry tropical climates. The contention that when strong winds do occur, they are accompanied by heavy rains is not altogether appropriate however, as with the exception of weather associated with tropical cyclones (discussed below), the strongest winds occur during the winter months when rainfall of any kind is rare. The dunes are invariably limited to locations open to the prevailing south-easterly winds, which is normally towards the northern ends of major embayments. However, the general trends of the coast line in the research area tend to restrict the proportion of coast with an aspect suitable for dune development. The implication of the distribution of dunes is that wind action has been strong enough only to move sand from the beach to the backshore on the most exposed sectors of the coast. This is readily understood when wind roses for wind speeds greater than Beaufort Scale 3 are studied (i.e. at velocities sufficient for deflation). Figure 9.1 indicates wind roses of this type for Cairns, Townsville and Mackay. The importance of a south-easterly orientation in the wet zone at Cairns, where 88.2% of sand moving winds come from the south-east is obvious. Further south at Townsville and Mackay, the importance of a single direction is not as great, though more than 75% of sand moving winds still blow from a single quadrant. At Mackay this is again the south-eastern quadrant but at Townsville is the north-easterly direction. The apparently anomalous situation at Townsville may be explained in terms of turbulent distortion of the regional wind pattern by the location of the wind gauge in the lee of Castle Hill. The slightly wider are of dune forming winds in the area south of the wet tropics, may be a factor in the small increase in dune occurrence.

Although coarse deposits predominate, the southern ends of many of the major bays are sheltered from the larger waves approaching from a south-easterly, easterly or north-easterly direction. The lower wave energy in these environ-

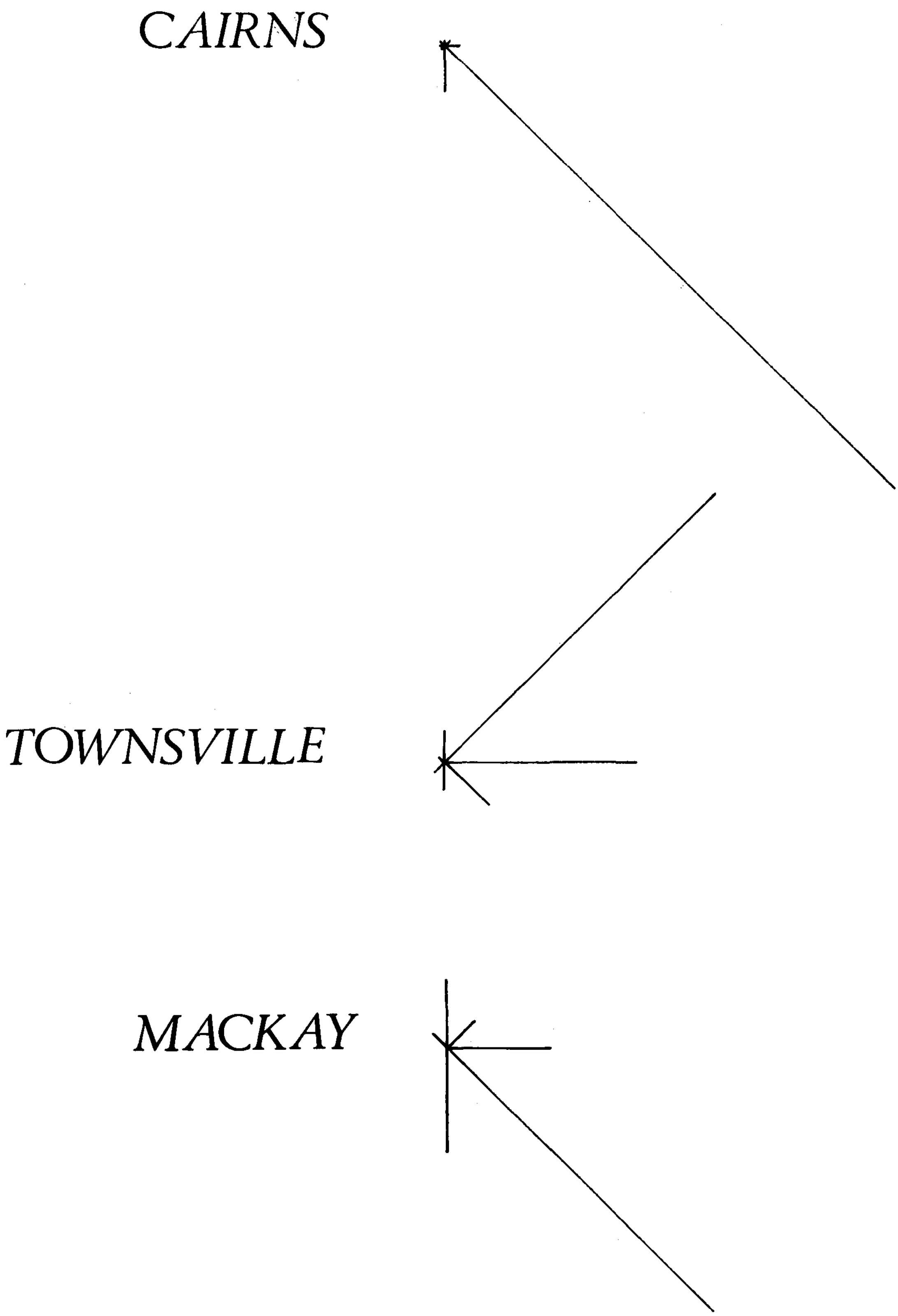

Fig. 9.1 Wind roses for wind speed Beaufort Force 3 and above.

ments allows only finer sediments to be delivered. Further north in the high rainfall areas, similar environments are almost exclusively colonised by mangroves. In temperate areas salt marsh would fill this ecological niche. In the research area, and possibly in other similar climatic regions, these areas appear to be intermediate between the tropical wet and temperate forms. Mangroves are extensive but by no means the only type of environment found. In comparison to the wetter areas they are much more restricted to the immediate vicinity of creeks and to sheltered seaward margins where inundation occurs frequently. In the slightly higher areas, where tides may wash less than 117 times a year (Macnae, 1967) there is an abrupt transition to bare, unvegetated mud flats with salt encrustations. It would appear that in areas without a good circulation water, the combination of high evaporation and seasonal rainfall causes salinity rates too high for the successful establishment of mangrove or any other vegetation.

Bare unvegetated mud flats are extensive in the Townsville area and in parts of Cleveland, Bowling Green and Upstart Bays form the dominant morphological unit. High salinity. causes not only a general lack of vegetation, but an intensity of chemical weathering which is matched by few other environments (Coleman et al, 1966). Plants which can tolerate pure sea water are not able to develop adaptions to the augmented salt concentration brought about by evaporation over much longer periods than daily or half daily fluctuations. Fosberg (1961) has noted the occurrence of such flats along the Queensland coast and elsewhere in the tropics where a long dry season exists, though his observation that such areas also have large tidal ranges does not apply to the Townsville region. In the wetter tropics, high salt accumulations are prevented by fresh water flushing during intense downpours which can occur throughout the year. Further south on the eastern Australian coast (probably south of Gladstone), not only is the rainfall distribution more even, but lower temperatures, at least during the winter months, restrict the amount of evaporation. Mangroves, however, do not colonise such areas. Instead, a cover of salt tolerant grasses, in particular Sporobolus virginicus, is characteristic of such areas.

Salt marsh vegetation does exist in the tropical wet and dry climate of the research area. However, it does not fill the same ecological position as it does further south. In general its distribution is limited to low clay plains of apparently marine origin which are rarely, if ever, inundated by even the highest spring tides. In the research region, such areas appear to have evolved from former mangrove and mud flat environments elevated above the tidal limits by the late Holocene regression. The salt marsh of the research area appears to have as much in common with the salt pans of interior Australia as with the coastal marshes further south. Evaporation brings the salt of the clay deposits to the surface only slowly, and though conditions are saline enough to maintain a halophytic vegetation cover (including Arthrocnemum leiostachyum, A. halecnemoides, Salicornia australis and Suaeda australis), the summer wet season allows the flushing of surface accumulations before they reach toxic levels. In more humid tropical areas, removal of the salt from similar deposits appears to be accomplished quickly and rainforest appears to have accomplished a rapid colonisation.

Thus climatic conditions apparently determine that acceleration of normal intertidal deposition in quiet water conditions by the aid of vegetation, either in the form of mangroves, as in the wetter north, or by salt marsh, as in the cooler and wetter south, is not a widespread feature of the coast of the Townsville area. Indeed, the fine grained coastal deposits suffer erosion and planation to a level not far above M.H.W.S. by the extension of low salting cliffs. Thus in spite of only a moderate tidal range, large areas of the salt flats may be inundated by the highest tides.

The Off-shore Zone

There is, in the tropics, a considerable uniformity in physical and chemical conditions of tropical waters (Orr, 1933). Theoretically, therefore it may be expected that off-shore conditions will be similar in all tropical morphogenic systems. However, the off-shore zone itself is affected by morphogenic characteristics of the land itself and thus, indirectly the influence of this zone may have morphogenic significance.

During low Pleistocene sea levels much of this continental shelf was exposed and, whilst climatic conditions may not have been identical to those of present, the geomorphic processes were essentially subaerial and dependent upon climatic conditions. The evidence put forward in Chapter 8 suggests that though wetter, the latest low sea level climatic phase was still essentially one with a significant dry season. Processes may be assumed to have been similar to those operating today. Reference has already been made to Maxwell's (1968) work which indicates predominantly sandy deposits of terrigenous origin along the coast under discussion. Accumulation of these may be attributed to fluvial activity similar to that on todays coasts, during the period of low sea level.

The most important feature of the off-shore zone is the growth of coral reefs. In general terms coral formations are a morphogenic feature of all tropical areas and the variations in form of the outer barrier (Fairbridge, 1950, 1967) are related to non-climatic features. However, there do appear to be certain features in the distribution of coral reefs which are related to the seasonal rainfall pattern of the research area. Fairbridge (1967) has noted that suspended sediment in turbid waters may be tolerated by the corals but that they are intolerant of salinity changes. The concentration of precipitation to a comparatively few days of the year means that, in the near shore zone at least, and especially in the vicinity of major rivers, salinity fluctuations are sufficient to prevent the growth of fringing and near shore reefs. These are restricted to headlands such as Cape Upstart, which are remote from major rivers and which in many ways are similar to the off-shore islands which have wide fringing reefs. The poor development of mainland reefs compared with, for example, the coast of Papua-New Guinea may be related to the high incidence of torrential downpours and greater intensity of rainfall even on the North Queensland wet coast. Douglas (1967a, b, 1969) concluded that the nature of rainfall in North Queensland was sufficiently different (more intense) compared to that of Malaysia, to be responsible for significant differences in channel forms. It may well be that these same characteristics prevent a greater development of fringing reefs on any part of the mainland coast of the research area.

The Effects of Tropical Cyclones

The geomorphic implications of the seasonality of rainfall outlined above are even further emphasised by the effects of tropical cyclones. Intense rainfall, with 24-hour totals in excess of 20 inches, high winds and heavy seas even in relatively sheltered waters, and the temporary raising of sea level all have far reaching geomorphic effects.

Coral reefs in particular are susceptible to the passage of a cyclone. At Stone Island near Bowen a flourishing fringing reef (Saville-Kent, 1893) was largely destroyed by the coincidence of a low spring tide and heavy rainfall from the 1918 cyclone in which 19 inches fell in 3 days (Hedley, 1925; Steers, 1937). Flourishing coral reefs around the Palm Islands photographed by Saville-Kent (1893) also appear to have been destroyed by the same agency. As tropical cyclone genesis occurs in the tropics more than 5° away from the equator, their effects in general are experienced in Af climates only at their poleward extremities and it is the Aw and Am climates in which the cyclones cause greatest changes. The fact that the Innisfail is at the southern limit of Af climates and may experience tropical cyclonic activity, with rainfall intensity sufficient to reduce salinity at least in the near-shore zone may well be an influence in the paucity of mainland fringing reefs here, compared to the New Guinea coast, which, though an area of cyclone formation, does not normally experience the full force of activity.

There are no figures to indicate the amount of geomorphological work carried out by cyclones. Douglas's (1965) work in the tropical wet area of the Atherton Tableland suggests that even in years without cyclonic activity 50% of the sediment load is carried by flows occurring less than 37% of the time, and for the Wild River which has a regime approaching that of the streams of the study area, 50% of the load was carried by flows occurring only 1.4% of the time. In the drier climate of the research area, the occasional passage of a cyclone may result in more geomorphological work being carried out within 24 hours than is accomplished under normal conditions over several years.

Rainfall of cyclonic intensity is required to cause flooding in the Burdekin Delta, and thus to set in motion the full depth of transitory bed sediments. Evidence from the delta mouth suggests periods of extremely rapid build up correlated with high rainfall periods, the most intense of which are cyclonic in origin. Similarly, reports from local inhabitants of the Don River Delta near Bowen indicate that changes in the course of the Lower Don occur during the passage of each cyclone, which in this area has a mean periodicity of about once every 10 years. It is suggested that some of the major changes in course which have taken place in the Burdekin Delta may have been related to periods of cyclonic rainfall.

The abnormally high amounts of energy available for geomorphic work is not limited only to the effects of heavy rainfall. The high wind speeds associated with the passage of a cyclone may bring about both constructional and erosional activity. Preliminary reports from the Proserpine area indicate that the passage of cyclone Ada (January, 1970) produced a great deal of coastal erosion on the mainland, but on the islands the major process was one of construction, with the formation of new coral shingle beach ridges. There is here, the implication of a truncation of the fringing reefs by the heavy seas. On many of the islands described in Chapter 2, coral shingle beach ridges rising to 8 or more feet above M.H.W.S. immediately behind the beach occur in what must be considered sheltered environments during normal conditions. The fact that the winds accompanying a cyclone may come from any point of the compass is considered an important factor in producing high energy constructional features in areas normally not subjected to such activity i.e. in areas not open to the east or south-east. On the mainland, the formation of cheniers in the sheltered southern and eastern corners of embayments may also be associated with abnormal conditions. On the Gulf coast of Louisiana, Russell (1967) considers that cheniers are constructed during periods of coastal retreat when waves transport the coarsest sediments available to them landward to form beaches. Intervening clay and mud deposits form during periods of coastal advance, the alternation between advance and retreat being associated with Mississippi River migrations. In the research area, the cheniers of eastern Upstart Bay, Bowling Green Bay, Cleveland Bay and the Bohle estuary show no evidence of being associated with periodic advance and retreat of the coast, and with the exception of those at the mouth of the Bohle River, do not appear to be in a location which could be affected by changes in river mouths. They apparently indicate progradation of the coast, possibly aided by a falling sea level, but in normally quiet water environments with occasional incursions of higher energy when coarser material is swept in from the adjacent sea floor. The high wave energy produced by a tropical cyclone is suggested as the major factor in chenier construction in sheltered environments.

A Comparison of the Coastal Landforms of the Research Area with these of Coasts with Similar Climates

The features of the coast of the Townsville area which appear to have morphogenic significance have been outlined. Fundamentally, the coast is a depositional one with rapid supply of sand size material and formation of multiple beach ridges. Dune development, however, is limited. Climatic conditions for cementation of beach deposits are ideal, but normally the carbonate content in the beach is insufficient. Mangroves are not as extensive as in wetter climates except in areas of good water circulations. Large areas of bare intertidal mud and salt flats appear to be typical of this coast. Wave energy is generally low, a result of both the normally low wind speeds and the protection given by off-shore reefs. However, along the mainland coast, fringing reefs are limited. Cliffed coasts are rare and normally consist of bare rock slopes which may be exhumed weathering fronts rather than true sea cliffs. Short and intensive periods of geomorphic activity may take place at widely separated and irregular intervals associated with the passage of tropical cyclones.

A large proportion of the Australian coast belongs to the same climatic region. C.S.I.R.O. Land Research Series reports allow a comparison to be made between the research area and a large part of the tropical coast (Christian and Stewart, 1952; Christian et al, 1952; Speck et al, 1960; Speck et al, 1964; Perry et al, 1964; Twidale, 1966; Speck et al, 1968; Story et al, 1969). The areas covered by these reports include parts of the Gulf of Carpentaria, the Northern Territory and northern Western Australia. A remarkable similarity exists between these coasts and that of the research area. Locally beach ridges may be widely spaced and the supply of sand to the beach may not be as great but this is considered a reflection of the nature of the hinter-land which is generally low, and composed of non-arenaceous rocks. In such conditions, the salt flats tend to increase in area. Bare unvegetated flats appear the most ubiquitous and characteristic feature of the coasts of the Aw climatic zone in Australia with mangroves limited to estuaries and lower intertidal areas. Dunes are generally low, no major dune sequence being described in any of the reports. The large dune fields which occur on the eastern coast of Cape York Peninsula are evidently related more to the availability of a sand supply derived from Pleistocene sands and Jurassic sandstones combined with locally easterly or south-easterly coastal orientations, than to any contrast in the morphogenic processes.

The question of beach rock as a morphogenic feature in Australia is debatable, largely because of the lack of data on its exact distributional limits. The observations made by Russell and McIntyre (1965) indicate that lithification of beach materials does extend outside the limits of the Aw climatic zone, recurving as far south as Rottnest Island near Perth in Western Australia. It may be significant, however, that these authors note that south of Onslow, beach rock outcrops are poor. The west coast of Cape York Peninsula described by Valentin (1959, 1961) appears to be morphologically similar to that of the research area. Beaches with shelly facies are limited however, to the area between Karumba and Aurukun Mission. Elsewhere the carbonate content of beaches is low (R.F. Isbell, pers. comm.). Within this shelly zone beach rock occurs widely, but whereas the exposures are firmly cemented in the south, they became much more friable further north, in spite of an almost pure shell-grit content. It is interesting to note that within this region rainfall increases from about 38 inches in the south, to 64 inches near Aurukun, which is high for an Aw station.

It is unfortunate that detailed descriptions of coastal landforms in many parts of the tropics are not available. Tricart and Cailleux (1965a), in a 38-page section of their book, examine features of tropical coasts, taking examples from Brazil and West Africa. Though concentrating their attention on thewwet tropics they do note that fluvio-marine deposition is a characteristic feature of all the tropics. Significantly, they observe that the Senegal River is depositing in its delta an enormous load of sand with a median diameter of about 2.0 ϕ. The hinterland is similar to that of the Burdekin and the sediment yield appears to have the same characteristics. The change from argillaceous to arenaceous sedimentation from the tropical wet to sub-humid tropical climates is also noted by Stoddart (1969) who quotes figures for the proportion of sand making up known bottom sediments on the inner continental shelf in rainy tropical climates (31.4%), sub-humid tropical (38.4%) and warm semi-arid climates (59.5%). The figures for mud distribution show a corresponding decrease (48.5%, 37.0% and 24.0% respectively). It is not surprising therefore to find that sand beach ridges are the characteristic coastal morphology of coasts within the Aw climatic zone, as shown, for example, by Fairbridge (1967b), and Fairbridge and Richards (1969) in Brazil, Battistini (1969) in Madagascar and Curray and Moore (1963) in Mexico. It is evident that the climate of the hinterland is an important factor. Coastal zones with Af or Am climates, if drained by rivers which have flowed through areas with a sub-humid tropical climate, may be dominated by a massive sand sediment yield, providing that the lithology favours a sand yield, as for example the Niger in West Africa (Allen, 1963). Alternatively if the rivers in an Aw climatic zone are draining a wetter catchment, then swamps and mangroves may dominate over the sand ridges. The point is well illustrated by the drier sector of the Papuan coast near Port Moresby, which though fringed by beach ridges, has a much higher proportion of swamp land then appears typical of Aw coasts. However, even here, the drier climate tends to increase salinity rates in the higher intertidal areas and bare tidal flats are a feature of the coastal zone (Mabbutt et al, 1965).

Mangroves are common to all tropical coasts (Scholl, 1968) and it is clear from the comments of Macnae (1966, 1967) that the reduction in distribution noted in the Townsville area compared to the wetter coast further north is a feature common to all the sub-humid tropical coasts. He notes that along desert coasts only one or two of the most hardy mangroves survive. With the decrease in mangroves, the increase of bare areas appears to be a common factor. Fosberg (1961) in particular notes their occurrence in southern Ecuador and north-west Nicaragua, both areas with Aw climates.

Certain characteristics of the distribution of beach rock have been noted in Chapter 6. From an overall appreciation of the references given in that chapter it is clear that though beach rock may extend out of the tropics, its greatest development occurs within the tropical zone. It is also evident that the incidence of beach rock decreases with increasing rainfall. Tricart and Cailleux (1965a) note that beach rock is essentially a feature of the drier climates. The literature in general indicates that most rapid cementation apparently takes place in Aw climates (see for example Russell's 1959 comments on the Caribbean area). However, it is also evident that beach rock may have greater exposure in even drier tropical climates, for whilst its formation may be slower, the availability of beach materials with an originally high calcareous content may be the dominant factor. However, if sands of the Aw zone do have a high calcareous content, perhaps as the result of the onshore movement of biogenic material from the inshore continental shelf, then beach rock may be found in abundance. Branner (1904), for example, describes beach rock outcropping intermittently for 1,000 miles along the north-east Brazilian coast.

Reference to the geomorphic effects of tropical cyclones is limited. In Mauritius, McIntire and Walker (1964) found that cliff abrasion, the cutting of platforms above calm weather sea level, and the modification of beach profiles and beach ridge topography all took place in brief episodes of storm wave activity during tropical cyclones. In British Honduras, Stoddart (1962, 1965) describes the effects of a hurricane noting the disappearance of up to 90% of reef corals in some areas, the destruction of vegetation, marginal beach erosion, local construction of fresh coral shingle and rubble ridges and the disappearance of seven cays. Resurvey of the area four years later indicated only slow recovery of the reefs. Stoddart's conclusions, that geomorphic changes at and above sea level appear to be permanent at least until modified by later hurricane action, agree with the observations made on the North Queensland coast on the importance of the abnormal conditions to local geomorphology.

The indications are that the North Queensland coast around Townsville has many morphogenic counterparts. Many of the major features may be attributed directly or indirectly to the tropical wet and dry climate. Whether these features may be allocated to a quite separate morphogenic system or not is perhaps debatable. If transitional, then Aw coasts would appear to lie between tropical wet (Af) and desert (BS, BW) coasts rather than the tropical and temperate systems. From the evidence of continental shelf sediments (Stoddart, 1969), there is an increase in the importance of sand away from the wet tropics towards both the drier and cooler climates but the supply of sand to the coast is intermittent and more closely resembles the sediment yield characteristics of the drier climates. Moreover, the changes noted in mangrove ecology tend to be changes which continue steadily towards the drier tropical climates, rather than towards the temperate area, where mangroves tend to be replaced by salt marsh. The occurrence of unvegetated salt pans is another feature which indicates a progression towards the drier, rather than cooler climates. Tropical cyclone activity in the area is an important morphogenic feature, but even this may extend beyond the limits of the Aw climatic area to affect drier regions (for example, Western Australia) or cooler regions (such as the Gulf coast of the U.S.A.). However, though it may be convenient to regard the research area as being transitional between other tropical and sub-tropical morphogenic systems, the combination of landforms present appear to be found elsewhere in similar climatic areas. Transitional though the area may be, the geomorphic processes and resulting landforms in the coastal zone are sufficiently distinct to allow the recognition of a separate morphogenic system in seasonally wet tropical climates.

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APPENDIX A

List of Topographic Maps and Aerial Photographs in the Research Area to which Reference has been made.

A. Topographic Maps

Scale 1:250,000

Innisfail	SE55 - 6
Ingham	SE55 - 10
Townsville	SE55 - 14
Ayr	SE55 - 15
Bowen	SF55 - 3

Scale 1:100,000

Rollingstone	8159
Townsville	8259
Mingela	8258
Bowling Green	8359
Ayr	8358
Cape Upstart	8458
Abbot Point	8558

Scale 1:50,000

Innisfail	8162 - IV
Clump Point	8162 - III
Halifax Bay	8160 - III
Rollingstone	8159 - I
Mount Stuart Special	

APPENDIX A (Cont.)

B. Aerial Photographs

Name	Date	Height (A.S.L.)	Lens	Runs
Innisfail	7.6.60	25,000	88.09mm	10
Ingham	18.6.61	25,000	88.09mm	9
Townsville	18.6.61	25,000	88.09mm	9
Ayr	12.6.61	25,000	88.09mm	9
Bowen	4.6.60	25,000	88.09mm	9
Cardwell	2.6.56	28,000	152.63mm	7
Kirrama - Rockingham	21.7.56	28,000	152.63mm	7
Ayr	15.6.59	12,500	153.50mm	9
Bowling Green	25.8.61	12,000	152.09mm	8
Townsville	11.8.61	12,000	152.09mm	9
Burdekin Delta (I.W.S.C.)	4.7.64	6,100	152.46mm	18
Barnard and Frankland Is. (Q.A.S.C.O.)	22.6.68	5,000	152.01mm	2
Townsville (Townsville City Council)	1.7.65	2,500	152.11mm	32

APPENDIX B

Characteristics of Cape Cleveland Beach Ridge Sands. Phi Values. Samples at 1-foot Intervals, Surface Downwards.

Sample	Mean size	Sorting	Skewness	Kurtosis	Carbonates %
Beach	2.3480	.6000	-.4133	2.6761	9.2
Foredune	2.6085	.3946	-.9427	6.4136	2.0
Main dune	2.4632	.4516	-.8235	6.5814	2.4
01-A	2.4380	.5710	-.2098	3.9880	6.8
01-B	2.5485	.4417	-.2866	4.5392	2.0
01-C	2.4057	.4514	-.2506	3.8362	0.8
01-D	2.4432	.4703	-.3111	4.1627	2.0
01-E	2.6612	.3978	-.1185	4.7685	1.6
01-F	2.5257	.4738	-.1177	3.6472	1.6
01-G	2.4842	.5355	-.4065	3.9412	2.4
01-H	2.5127	.5377	-.3094	3.7383	0.8
01-I	2.4835	.6283	-.5441	3.7604	2.8
02-A	2.6092	.4862	-.0611	4.5603	6.0
02-B	2.6555	.4363	-.1339	4.5689	4.4
02-C	2.5785	.4680	-.0696	4.0818	3.6
02-D	2.5940	.4931	-.4516	4.1221	3.0
02-E	2.7092	.3611	-.2345	5.7528	3.2
02-F	2.6507	.3636	.0157	5.4364	2.8
02-G	2.6365	.3948	-.1964	4.7432	1.6
02-H	2.6360	.3787	.0345	4.5704	2.4
02-I	2.5667	.4400	-.2969	4.7576	3.2
03-A	2.4505	.6087	-1.1640	7.2722	8.0
03-B	2.5327	.4221	-.1043	4.5947	5.6
03-C	2.5152	.4385	.0057	3.9638	1.6
03-D	2.4685	.4949	-.5207	3.5678	3.0

APPENDIX B (Cont.)

Sample	Mean size	Sorting	Skewness	Kurtosis	Carbonates %
03-E	2.4100	.4787	-.3539	3.7510	4.4
03-F	2.4980	.4241	.0510	4.6155	3.2
03-G	2.4022	.4315	.1983	4.1791	3.4
03-H	2.4187	.4461	.0073	4.4817	2.0
03-I	2.3592	.4866	-.1182	3.7206	2.8
04-A	2.7920	.5334	-.9691	8.6023	4.0
04-B	2.8455	.4505	-.0952	3.5834	3.2
04-C	2.6522	.4335	.1101	3.3297	2.4
04-D	2.6155	.5212	.0453	2.6569	2.8
04-E	2.7192	.4809	.0873	3.4917	6.4
04-F	2.6682	.4535	.2544	3.9734	3.6
04-G	2.6502	.4808	.2377	3.6485	1.6
04-H	2.8417	.4528	-.0366	3.9006	4.0
04-I	2.8827	.4991	-.1500	3.4243	10.0
05-A	2.5120	.5521	-.9392	7.4356	8.4
05-B	2.5155	.4513	-.4039	5.2454	1.6
05-C	2.5202	.4765	-.3784	4.7522	1.2
05-D	2.4937	.4565	-.2451	3.5568	1.6
05-E	2.6112	.4546	-.0942	3.5765	2.8
05-F	2.2665	.5280	.0207	3.2147	2.4
05-G	2.2977	.5256	-.2830	2.8142	2.4
05-H	2.5997	.4425	-.2927	4.4149	3.2
05-I	2.5305	.4451	-.3849	4.4208	1.6
06-A	2.5532	.5579	-1.1087	8.9167	7.6
06-B	2.6750	.4351	-.1968	6.3564	4.4
06-C	2.6220	.4091	.0524	4.0325	4.0
06-D	2.5080	.4231	.2155	4.1161	2.8
06-E	2.4492	.4049	.0370	3.5899	1.6
06-F	2.4945	.4316	-.0328	4.0266	2.0

APPENDIX B (Cont.)

Sample	Mean size	Sorting	Skewness	Kurtosis	Carbonates %
06-G	2.5292	.3919	-.0444	4.0070	2.4
06-H	2.4952	.4169	-.3824	4.5002	0.8
06-I	2.5267	.4309	-.0896	3.7606	2.4
07-A	2.3765	.6267	.0362	3.8394	6.8
07-B	2.4312	.5403	-.1742	4.2000	2.4
07-C	2.3617	.5604	-.1870	3.7976	1.6
07-D	2.0370	.6506	-.1361	2.8985	1.6
07-E	2.2500	.6358	-.4566	4.2532	1.6
07-F	1.7660	.7461	-.1883	3.0952	2.6
07-G	2.1092	.5509	-.0045	3.7927	7.8
07-H	2.0137	.5700	.2506	3.9117	2.0
07-I	1.8625	.6992	.0757	3.4033	3.2
08-A	2.8145	.4844	-.1595	5.5927	5.2
08-B	2.9222	.4519	-.4457	6.0826	2.0
08-C	2.9392	.4247	-.0585	4.9775	2.4
08-D	2.8822	.4538	-.4547	6.0625	4.4
08-E	2.8895	.4009	-.3820	6.9296	3.2
08-F	2.8500	.4133	-.4136	7.1085	4.0
08-G	27130	.4974	-1.0383	7.1533	3.0
08-H	2.6587	.5276	-1.8172	10.4868	2.4
08-I	2.8150	.4917	-1.3031	9.7319	2.8
09-A	2.8607	,4476	-.1244	7.8799	3.2
09-B	2.8155	.3930	.2930	5.5506	3.0
09-C	2.8352	.3769	.4154	5.0465	3.0
09-D	2.7917	.3319	.3223	5.5532	3.2
09-E	2.8132	.3348	.4641	5.3274	2.4
09-F	2.8400	.3487	.7636	5.3567	3.0
09-G	2.7800	.3591	.2637	4.7097	2.0
09-H	2.7167	.3852	.4152	3.9872	2.0

APPENDIX B (Cont.)

Sample	Mean size	Sorting	Skewness	Kurtosis	Carbonates %
09-I	2.8087	.3270	.5968	7.6350	3.6
10-A	2.5755	.4576	-.9839	9.4661	3.0
10-B	2.6015	.4087	.3565	4.3748	2.4
10-C	2.6597	.3860	.4020	4.6243	2.0
10-D	2.6165	.3978	.2751	4.3770	2.0
10-E	2.5785	.3866	.1237	4.5611	1.6
10-F	2.6320	.3522	.4454	4.9093	1.8
10-G	2.6082	.3555	.2393	4.6670	2.0
10-H	2.5660	.4156	-.1410	4.6782	1.6
10-I	2.2960	.5559	-.1909	3.6263	1.6
11-A	2.4130	.5622	-.1247	6.7812	2.8
11-B	2.4445	.4429	-.0023	5.8299	2.8
11-C	2.4987	.4161	.1540	4.8431	2.0
11-D	2.5520	.4173	.6118	5.3645	2.8
11-E	2.5195	.4318	.2597	5.1463	2.0
11-F	2.3622	.5208	.0910	4.4786	2.0
11-G	2.2775	.5830	-.3756	3.9227	2.8
11-H	2.3582	.4824	.0205	4.7085	2.4
11-I	2.3260	.5276	-.4937	5.3310	2.4
12-A	2.5795	.5342	-.6884	8.5871	3.2
12-B	2.6075	.4393	.4526	5.3058	1.6
12-C	2.6300	.3900	.2130	4.8414	1.6
12-D	2.5805	.3861	.5933	5.3235	1.2
12-E	2.5627	.4564	.5396	4.4507	1.6
12-F	2.6130	.4128	.2835	4.6252	3.2
12-G	2.5505	.4072	.2711	4.6815	2.4
12-H	2.6065	.4341	.3711	4.2637	2.6
12-I	2.5077	.4374	.1068	4.5938	2.0
13-A	2.9667	.4842	.0971	5.0348	5.4

APPENDIX B (Cont.)

Sample	Mean size	Sorting	Skewness	Kurtosis	Carbonates %
13-B	2.8907	.4292	.6035	4.6474	2.8
13-C	2.8980	.4155	.5238	3.9931	2.8
13-D	2.8607	.4299	.4014	3.7763	3.6
13-E	2.9397	.4109	.6755	4.0975	6.0
13-F	2.9635	.4151	.2119	3.7679	2.0
13-G	2.8747	.4026	.5324	4.1764	2.8
13-H	2.8825	.4146	.3840	4.0295	4.0
13-I	2.7992	.4420	.1388	5.7277	2.0
14-A	2.9080	.4598	.5445	4.8584	8.0
14-B	2.8860	.4167	.7031	4.8315	3.2
14-C	2.9202	.4073	.6595	4.6363	3.2
14-D	2.9880	.4036	.6538	4.1126	2.4
14-E	3.0467	.3913	.3177	3.8003	3.2
14-F	2.9907	.3922	.6296	4.0298	3.2
14-G	2.8620	.3910	-.0106	12.6189	4.0
14-H	2.9710	.3928	.6180	4.1129	2.4
14-I	2.8440	.5105	-.4430	5.3813	2.8
15-A	2.8145	.5293	-.3902	7.3286	5.2
15-B	2.7362	.4256	-.2546	6.3940	5.0
15-C	2.8572	.4364	.3366	4.9093	3.2
15-D	2.8972	.4281	.7153	4.6830	4.4
15-E	2.8922	.4305	.3935	4.9469	4.4
15-F	2.8350	.4727	-.0126	5.5821	2.8
15-G	2.5985	.6025	-.2889	4.4508	3.8
15-H	2.6820	.5855	-.6910	5.4149	3.2
15-I	3.0525	.4665	-.7047	8.1001	4.2
15-J	3.0505	.4761	-1.1423	9.8117	6.0
16-A	3.0482	.4768	-.4074	5.8469	4.4
16-B	3.0712	.4253	-.6216	8.9728	4.2

APPENDIX B (Cont.)

Sample	Mean size	Sorting	Skewness	Kurtosis	Carbonates %
16-C	3.1012	.3889	.2250	3.8683	6.0
16-D	3.1442	.3923	.1136	3.6376	2.4
16-E	3.1692	.3914	-.0339	3.7416	4.0
16-F	3.2230	.4100	-.7934	7.7847	5.6
16-G	3.2470	.3564	-.3003	5.0679	4.4
16-H	3.2050	.3985	-.7487	6.4376	3.6
16-I	3.1920	.4291	-.4472	5.0187	2.8
17-A	2.8440	.5715	-.8821	7.3391	9.2
17-B	2.8325	.4774	-.5132	6.7893	4.6
17-C	2.9087	.4070	.3784	4.1273	3.6
17-D	2.8890	.3875	.4285	3.9339	3.2
17-E	2.8760	.3673	.7229	4.6172	3.6
17-F	2.7270	.3687	.5636	4.8397	1.2
17-G	2.6225	.3586	.4608	4.7275	3.6
17-H	2.7730	.3968	.2780	5.0772	4.0
17-I	2.5805	.5124	-.7399	5.5823	2.8
19-A	2.2692	.5712	-.2131	5.4737	3.6
19-B	2.3107	.5114	-.1283	4.9816	2.6
19-C	2.3650	.4732	-.2084	4.2913	2.4
19-D	2.4037	.4571	-.3731	4.0548	3.0
19-E	2.2650	.5203	-.1982	3.4787	6.8
19-F	2.3160	.4473	-.1023	3.8455	3.6
19-G	2.3750	.4192	-.3361	3.9973	3.2
19-H	2.3727	.4311	-.2733	4.3805	2.0
19-I	2.3745	.4816	.1801	4.5963	2.8
20-A	2.4520	.6141	-.0467	5.1430	6.4
20-B	2.5610	.5466	.2841	4.0764	6.4
20-C	2.5632	.5542	-.4087	6.2097	8.0
20-D	2.6455	.4901	.1445	4.4156	3.2

APPENDIX B (Cont.)

Sample	Mean size	Sorting	Skewness	Kurtosis	Carbonates %
20-E	2.7262	.4669	.0863	4.3997	2.6
20-F	2.5790	.4683	.1964	4.4642	2.8
20-G	2.4872	.4927	-.0123	4.9499	3.2
20-H	2.5587	.4933	.5636	4.8179	5.2
20-I	2.5375	.4691	.8412	5.0888	4.0
21-A	2.4277	.6088	-.4338	6.3291	6.4
21-B	2.4435	.5656	.1786	4.9677	11.6
21-C	2.5075	.5032	.0908	5.8915	3.8
21-D	2.4995	.4723	.3248	5.1128	2.8
21-E	2.5745	.4440	.1327	5.3252	3.6
21-F	2.6292	.4584	.8322	5.7780	4.4
21-G	2.5470	.5274	.6859	4.7636	5.4
21-H	2.5172	.5144	.0611	4.1476	3.5
21-I	2.0735	.8876	-.5354	2.9206	3.8
22-A	2.3920	.6754	-.6678	4.7865	4.2
22-B	2.4742	.5964	-.3271	4.5283	2.4
22-C	2.5245	.5683	-.5830	4.8267	4.0
22-D	2.6227	.5228	-.3846	4.7760	3.2
22-E	2.4460	.5305	-.3597	4.1053	2.8
22-F	2.5655	.5855	-.8102	5.0776	1.8
22-G	2.0837	.8782	-.2932	2.7435	1.8
22-H	2.6525	.5801	-.6621	5.8541	4.4
22-I	2.4872	.5838	-.7709	5.3868	3.2
23-A	2.5457	.6156	-.5708	7.1918	6.0
23-B	2.5155	.4787	-.5167	6.5533	2.0
23-C	2.5837	.4489	.1044	4.8107	2.4
23-D	2.5392	.4823	-.2757	5.7150	2.0
23-E	2.5662	.4711	-.4758	5.9532	2.0
23-F	2.5747	.4477	-.0176	4.4943	2.4

APPENDIX B (Cont.)

Sample	Mean size	Sorting	Skewness	Kurtosis	Carbonates %
23-G	2.6642	.4091	-.1220	5.2613	2.8
23-H	2.6270	.4188	.0439	5.8653	3.0
23-I	2.5650	.4920	-.1157	4.9520	5.2
24-A	2.5942	.6730	-.8380	6.5989	3.6
24-B	2.6185	.5476	-.2831	6.0202	2.0
24-C	2.6987	.5416	-.1362	5.5191	4.0
24-D	2.6930	.4967	-.1192	5.4133	6.0
24-E	2.6250	.5572	-.2916	5.9513	4.4
24-F	2.5027	.5830	-.1856	4.6422	7.2
24-G	2.5532	.6118	-.5511	5.4436	6.0
24-H	2.7867	.5994	-1.8088	10.6903	6.0
24-I	2.1432	.9241	-.7130	3.0671	5.6
25-A	2.5720	.6854	-.7231	6.2558	0.4
25-B	2.5790	.5936	-.0451	4.6520	3.2
25-C	2.5965	.5510	-.3086	4.9265	2.4
25-D	2.5505	.5280	-.2517	4.2874	2.4
25-E	2.7610	.5211	-.2875	5.3015	6.0
25-F	2.3712	.6338	-.2554	3.5556	4.4
25-G	2.7790	.5475	-.6066	6.0028	6.0
25-H	2.4860	.6432	-.7766	4.9224	4.8
25-I	2.5685	.5576	-.5345	5.5914	3.2
26-A	2.9640	.6440	-.4350	3.9381	5.6
26-B	2.8020	.5783	-.2300	4.6405	4.0
26-C	2.7855	.5929	-.4883	5.2230	4.0
26-D	2.9275	.5323	-.0407	4.9993	8.6
26-E	2.8075	.4847	-.0403	5.7827	2.2
26-F	2.6687	.5793	-.6035	4.3773	2.8
26-G	2.6785	.6577	-.5471	3.4091	2.0
26-H	2.5117	.8063	-1.1629	4.4576	1.6

APPENDIX B (Cont.)

Sample	Mean size	Sorting	Skewness	Kurtosis	Carbonates %
26-I	2.7950	.8289	-1.2990	4.4917	1.6
27-A	2.8547	.7434	-1.0594	6.5348	5.6
27-B	2.8702	.6037	-.2634	4.9789	7.2
27-C	2.6562	.6793	-.4624	4.4248	10.0
27-D	2.8350	.4975	.1583	4.3928	4.4
27-E	2.8155	.5095	.4967	4.6930	2.8
27-F	2.3820	.6622	-.3493	3.8343	2.8
27-G	2.5270	.5749	-.3719	5.4520	7.2
27-H	2.5350	.5583	-.5570	5.0692	4.8
27-I	2.2927	.6952	-.0645	2.3722	8.4
28-A	2.5655	.5374	.1999	5.3805	1.6
28-B	2.4765	.5107	.0377	5.0036	4.8
28-C	2.5272	.4692	.0279	5.1056	3.6
28-D	2.5287	.4135	.2045	5.3191	0.8
28-E	2.5460	.4033	-.0554	5.4184	1.6
28-F	2.6687	.3732	.4346	7.6989	1.6
28-G	2.3962	.4917	-.3030	4.5925	1.0
28-H	2.4147	.4741	-.3286	5.7666	1.2
28-I	2.1822	.7123	-.3166	3.0253	2.0
29-A	2.6160	.6178	-.9997	7.4734	4.0
29-B	2.6610	.4607	-.1034	4.5725	2.0
29-C	2.7135	.4259	.025	4.6400	1.6
29-D	2.5765	.4851	-.2899	4.2251	2.4
29-E	2.7145	.4548	-.2787	4.3790	2.8
29-F	2.8012	.5624	-.9947	7.6823	6.4
29-G	2.5987	.6642	-.4880	3.6922	3.6
29-H	2.6437	.6113	-.5725	4.3284	4.0
29-I	2.8880	.6057	-1.5893	8.5066	4.0
30-A	2.5122	.5431	-.4345	6.5641	3.4

APPENDIX B (Cont.)

Sample	Mean size	Sorting	Skewness	Kurtosis	Carbonates %
30-B	2.5222	.4562	-.5202	6.5401	1.4
30-C	2.5747	.3976	-.1508	5.5598	2.0
30-D	2.6140	.3735	-.1884	5.6823	1.2
30-E	2.5600	.4033	-.0969	5.2041	2.8
30-F	2.4197	.6193	-.8653	6.0456	4.4
30-G	2.6552	.5237	-.1342	6.7233	4.4
30-H	2.5330	.6062	-.4750	5.4013	2.8
30-I	2.4697	.5627	-.9353	5.8179	4.6
31-A	2.5642	.6159	-1.3756	8.2827	4.0
31-B	2.6467	.4805	-.5068	6.0370	3.2
31-C	2.6652	.4236	-.1291	4.7505	2.2
31-D	2.5097	.4394	-.0863	3.6394	1.6
31-E	2.3312	.5392	-.3608	3.3915	2.0
31-F	2.3007	.7458	-1.2049	5.0280	2.6
31-G	2.4470	.5670	-.4087	3.6021	3.0
31-H	2.5920	.4692	-.3403	5.0781	2.8
31-I	2.2902	.5427	-.4824	4.6279	2.4
32-A	2.7627	.6054	-1.3016	9.9880	7.2
32-B	2.8860	.4790	-.4493	8.4734	4.8
32-C	2.8762	.4370	-.3126	8.4818	4.5
32-D	2.9305	.4024	.4061	5.6671	3.6
32-E	2.8822	.4452	.1005	6.1192	4.8
32-F	2.8742	.5512	-1.0630	9.1851	5.0
32-G	2.8865	.5388	-1.2177	10.1556	6.4
32-H	2.9052	.4478	-.0117	8.4133	6.8
32-I	2.8465	.4454	.0879	8.3489	7.0
33-A	2.0927	.9297	-.2019	3.2998	4.4
33-B	1.8580	.8832	-.0290	3.0910	4.4
33-C	1.7030	1.0804	-.4560	2.2503	9.2

APPENDIX B (Cont.)

Sample	Mean size	Sorting	Skewness	Kurtosis	Carbonates %
33-D	1.4567	1.1481	-.1996	1.8238	9.2
33-E	2.2482	.8241	-1.2448	5.0594	4.8
33-F	1.9892	1.1017	-.9242	3.0350	2.4
33-G	2.0435	.9869	-.9583	3.6622	2.8
33-H	1.9297	.9649	-.8427	3.3873	8.4
33-I	2.0252	.8368	-.6579	3.8973	3.2
34-A	1.9475	1.1000	-.4529	2.5007	2.8
34-B	1.8230	1.0700	-.3863	2.3512	8.2
34-C	1.5322	1.2063	-.1376	1.7303	1.6
34-D	1.2965	1.1958	.2482	1.7930	0.8
34-E	1.2017	1.1475	.3321	1.9513	6.8
34-F	2.2267	.9947	-1.2722	4.0183	1.6
34-G	2.3622	.9018	-1.4727	5.1478	7.2
34-H	1.8537	1.1897	-.7484	2.3129	1.6
34-I	1.3850	1.3129	-.0322	1.4662	6.4
35-A	2.4042	.9967	-.1580	3.1828	11.6
35-B	2.1802	.8508	-.0247	3.2966	8.4
35-C	2.3660	.8228	-.0236	3.5458	6.4
35-D	2.7855	.6398	-2.0090	10.7756	4.4
35-E	2.8275	.5951	-2.2396	12.7493	3.2
35-F	2.6662	.5941	-.9448	5.3626	3.2
36-A	2.7052	.7643	-.3666	4.2843	6.0
36-B	2.5932	.6267	-.1993	4.8418	7.2
36-C	2.7790	.6478	.0058	4.2827	3.6
36-D	2.7600	.5788	.1820	4.4733	4.6
36-E	2.6567	.5460	.0193	4.5849	4.0
36-F	2.5420	.7142	-.7863	5.0075	2.8
36-G	2.7717	.5946	-1.2135	7.6774	4.8
36-H	2.5282	.6008	-.5426	5.8909	3.0

APPENDIX B (Cont.)

Sample	Mean size	Sorting	Skewness	Kurtosis	Carbonates %
36-I	2.6665	.6013	-.3452	5.3876	4.8
38-A	2.9630	.6771	-.7291	5.6541	5.6
38-B	3.0737	.5801	-.5948	6.0826	3.2
38-C	3.0642	.5044	-.0835	5.6154	1.2
38-D	3.1575	.5601	-.4166	5.4556	6.8
38-E	3.0457	.5772	-.2157	4.9057	2.0
38-F	3.0417	.6388	-.8387	6.4596	1.6
38-G	2.8775	.6108	-.2751	4.0101	1.6
38-H	2.8492	.5489	.0305	5.1022	1.2
38-I	2.8642	.5461	.0070	5.5870	2.0

APPENDIX C

Characteristics of Muntalunga Chenier Sands. Phi Values. Samples at 1-foot Intervals, Surface Downwards.

Sample	Mean size	Sorting	Skewness	Kurtosis	Carbonates %
01-A	1.3937	.8012	.6634	5.2005	8.0
01-B	1.2427	.8597	-.0828	3.1178	22.0
01-C	1.5585	.6983	-.4997	3.9843	16.4
01-D	1.5317	.7913	-.6187	3.4414	18.4
01-E	1.4242	.8267	-.2941	3.3157	21.2
01-F	1.2335	.9507	-.0535	2.7574	44.4
02-A	2.1112	.5330	.1316	5.9881	3.2
02-B	2.0952	.4732	-.5197	4.8636	1.6
02-C	2.0267	.4901	.2988	5.4265	2.0
02-D	2.0730	.4745	-.4645	4.6876	2.0
02-E	1.9847	.5042	-.4032	3.3470	1.6
02-F	1.9610	.5016	-.0362	3.6938	1.6
02-G	2.1157	.4532	-.0422	5.8974	2.0
02-H	2.1537	.4316	.0391	4.3244	2.4
02-I	1.9762	.4852	.3155	4.0755	1.6
03-A	1.3872	.7556	1.0302	5.1859	4.8
03-B	1.2575	.7792	.5839	4.4687	4.0
03-C	1.2910	.8549	.4574	3.7467	4.5
03-D	1.2657	.8544	.2847	2.9975	4.4
03-E	1.3307	.8731	.1274	2.9824	3.6
03-F	.9915	.9140	.4233	2.8795	2.0
03-G	1.4870	.7064	.4751	3.7048	4.0
04-A	1.2290	.7746	.1313	2.8762	2.8
04-B	1.2525	.8120	.2717	3.3331	3.6
04-C	1.5200	.9117	-.1040	2.5619	2.4

APPENDIX C (Cont.)

Sample	Mean size	Sorting	Skewness	Kurtosis	Carbonates %
04-D	1.5890	.8570	-.1525	2.8004	3.2
04-E	1.2862	.8780	.3094	3.0155	4.8
04-F	1.2005	.9781	.2022	2.2814	8.8
04-G	1.4297	.9163	-.0184	2.4948	2.4
04-H	1.7260	.8183	-.1647	2.7114	1.6
04-I	1.1615	.9529	.3093	2.4910	5.0
05-A	1.2290	1.5355	.6990	2.1577	2.0
05-B	1.2645	.7561	.9550	5.1163	5.6
05-C	1.5762	.7725	.4231	4.1076	2.4
05-D	1.5225	.7932	.4342	4.0983	3.6
05-E	1.6292	.8530	.0967	3.4746	1.6
05-F	1.5580	.8497	.1291	3.4189	2.8
05-G	1.5672	.8405	.2809	3.6499	2.0
05-H	1.5900	.8021	.0303	3.6502	1.6
05-I	1.5665	.7746	.1762	3.8889	5.2
05-J	1.5770	.7628	.2763	3.9767	2.8