SUBMERGED DUNES OF NORTHEASTERN EYRE PENINSULA

An investigation into the age, origin and palaeoclimatic implications of relict aeolian landforms.

Wilhelmus J. Van Deur, B.A. (Hons.) Dip. Ed.

Submitted for the degree of Master of Arts

Department of Geography,
University of Adelaide.

1983

DECLARATION

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

W. J. Van Deur

SUMMARY

The presence of what are apparently longitudinal dunes submerged off the coast of northeastern Eyre Peninsula, South Australia, poses a number of problems that are investigated in this thesis.

These submarine features are located adjacent to the Utera Plain, which supports a series of northwest to southeast trending seif dunes. The Utera dunes are relict features, but when were they formed, from what sediment source and by what process? If these landforms are indeed dunes, how do they relate to the sand ridges of the Utera Plain, and, considering that dunes are commonly consolidated and subject to rapid erosion by marine activity, how have they survived submergence?

The relict longitudinal dunes deposited on the semi-arid Utera Plain attest to a period of former aridity. Further, the results obtained in this investigation indicate that the submerged landforms are dunes, and are related to the Utera dunes. Thus the dunes were drowned by the post-glacial rise of sea level during the Holocene. Radiometric dating of shell and other organic material superimposed stratigraphically over the dunes indicates that the dunes are pre-Holocene in age, while the results from a calcrete layer developed pedogenically within the dune, together with other evidence, suggests that the dunes were deposited at some time between 12,000 and 24,000 years B.P., that is, during the last-glacial maximum.

The concept that glacials were arid rather than pluvial, as was previously believed, is now accepted widely. This study has extended this theory to the eastern part of Eyre Peninsula, and contradicts the only major previous survey which concluded that the dunes were deposited during the last Interglacial.

CHAPTER

TABLE OF CONTENTS

ACKNOWLEDGEMENTS

I wish to extend my thanks to Mr T. Griffin, Chairman of the Department of Geography for the provision of facilities, and to those staff members who assisted in their use.

To the staff of the CSIRO Division of Soils, I would like to express my thanks for the use of equipment, in particular pneumatic coring equipment.

To my supervisor, Dr C. R. Twidale, I extend my gratitude for the assistance he has provided throughout the course of the study.

CHAPTER ONE

INTRODUCTION

'While the effects of Pleistocene climatic changes have been exceedingly well documented from glaciated regions, the impact of the same changes on the desert regions of the world is now only beginning to be understood.' (Bowler, 1976, p. 283)

During the Quaternary, climatic fluctuations of considerable magnitude resulted in the growth and retreat of ice sheets (Hollin, 1962, 1965, 1969; Mercer, 1973), oscillations of sea level (Fairbridge, 1960; McFarlan, 1961; Curray, 1961; Veeh and Chappell, 1970; Bloom et al., 1974; Bloom 1979), the migration of climatic zones (Lamb, 1972; Rognon and Williams, 1977) and the extinction of numerous biota (Butzer, 1972).

In Australia and elsewhere, changes in atmospheric circulation during the Quaternary resulted in some present semi-arid areas located marginally to truly arid zones experiencing aridity. Such aridity found expression in the development of aeolian landforms, and in particular of active dunes. These relict dunefields, currently stabilized by vegetation, have been described from Australia (Madigan, 1936, 1946; Marshall, 1948; King, 1956, 1960; Wopfner and Twidale, 1967; Mabbutt and Sullivan, 1968; Twidale, 1972; Bowler, 1971, 1973, 1976, 1977, 1979; Bowler et al., 1976; Sprigg, 1965, 1979), from Africa (Grove and Warren, 1968; Butzer, 1972; Fairbridge, 1961, 1964) and from the U.S.A. (Smith, 1965).

Relict dunefields extend below sea level in Senegal (Tricart, et at., 1957, 1961), north-western Australia (Fairbridge, 1961, 1964; Jennings, 1975) and near the mouth of the Hunter River (Galloway, 1965). The relict Utera dunes, aligned from north-west to south-east, are developed on the Utera Plain (Twidale et al., 1976) between Franklin Harbour and Murninnie, eastern Eyre Peninsula, South Australia (Fig. 1.1, 1.2), and appear to plunge beneath the waters of Spencer Gulf (Fig. 1.3, 1.4, 1.5).

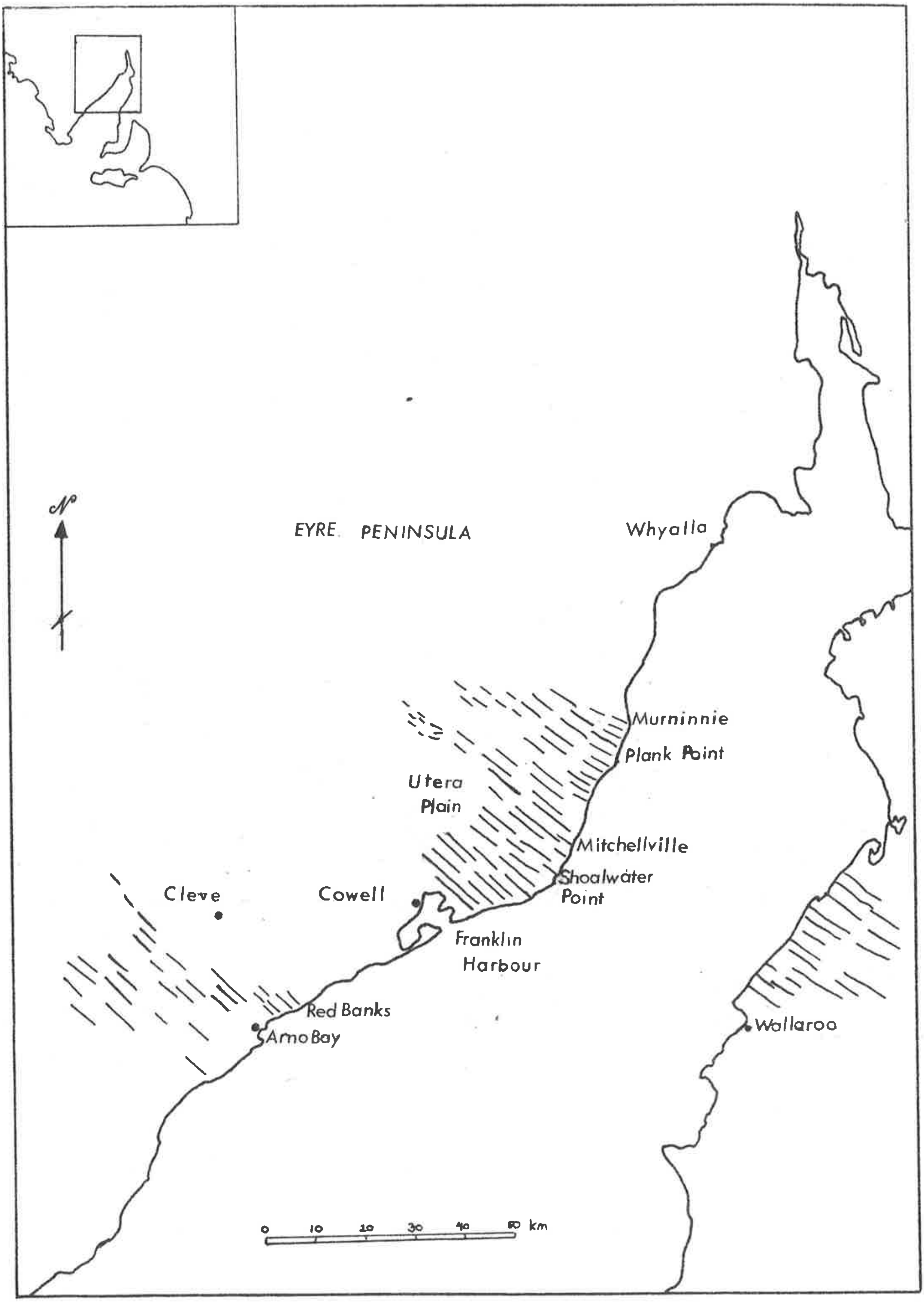


Fig. 1.1 Location map of study area.

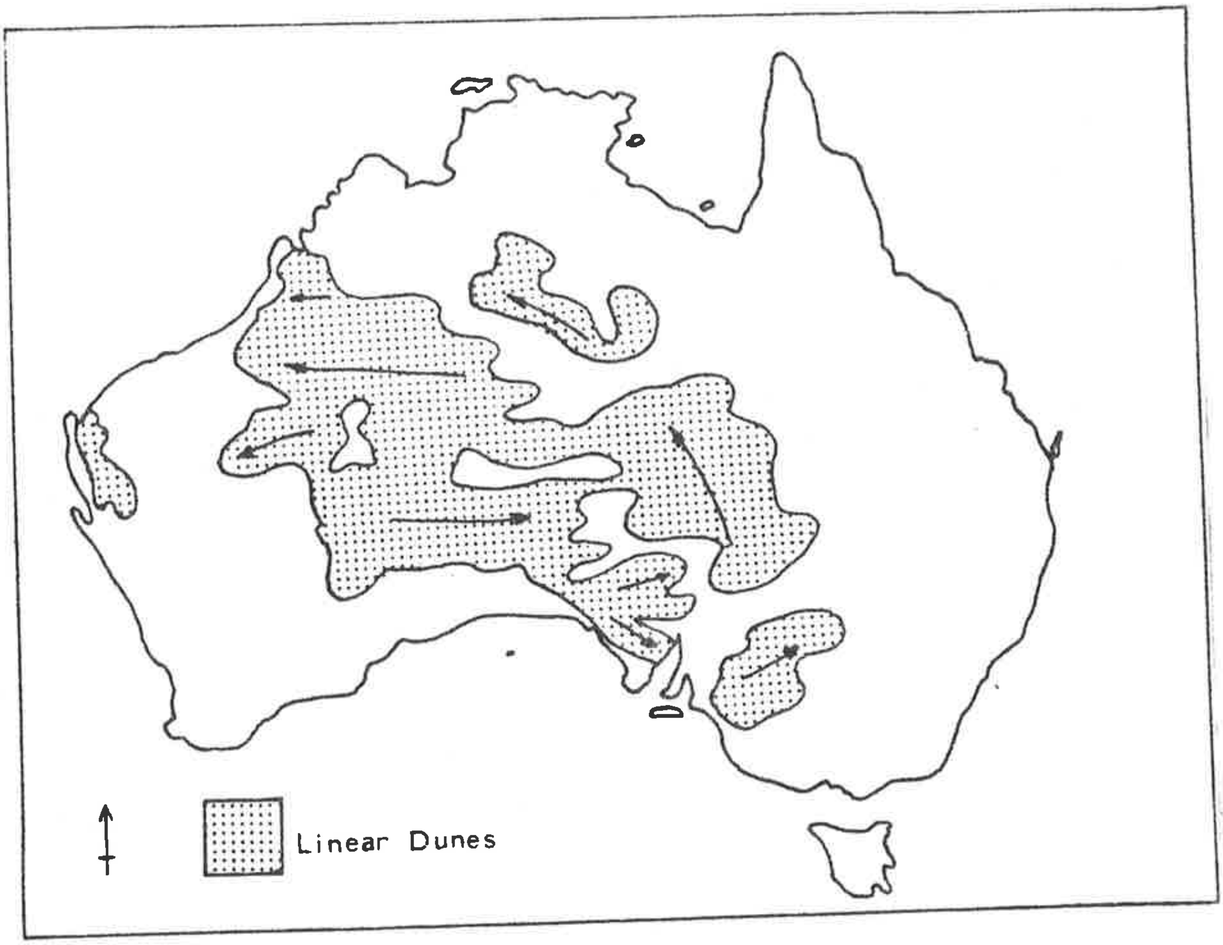


Fig. 1.2 Distribution of Australian relict dunes (after Jennings, 1975)

Fig. 1.3 Utera Plain and dunes. Note, Cleve Hills in background, Franklin Harbour to left, Lucky Bay in centre and embayed dune swales (a).

Fig. 1.4 Relict Utera dunes and submerged dune cores (a). Note Holocene beach ridges attached to seif dune ends (b) and embayed swales (c).

Fig. 1.5 Relict Utera dunes and submerged dune cores.

Jessup (1968, a & b) stated that the relict seif dunes situated on Yorke Peninsula (Fig. 1.1) extend into Spencer Gulf, and, by correlating the formation of a number of paleosols of this region with glacio-eustatic movements, suggested that the seif dunes were deposited during two phases of lower sea level; one during the late Pleistocene and the other during the Holocene.

The initial purpose of this investigation is to ascertain whether the submerged landforms off eastern Eyre Peninsula are in fact sand dunes, and if so, how they relate to the relict Utera dunefield. The salient sedimentary characteristics (grain size, shape, surface features, etc.) of both the submerged landforms and the Utera dunes must therefore be calculated and compared. If it can be demonstrated that the features in question are indeed drowned sections of the Utera dunefield, their survival needs to be explained, for under normal circumstances unconsolidated aeolian deposits are readily eroded. Furthermore, the question arises as to the cause of submergence. Were the dunes drowned by the partial subsidence of the Utera Plain, or were they formed during a period of low sea level and subsequently inundated?

If tectonism can be discounted, dune formation must have occurred during a period of time when sea level stood below its present position. Previous interpretations of Pleistocene climates held that glacial phases, when sea levels were lower, were synchronous with pluvials, and that interglacials were arid. Jessup, in his study of the dunes of northern Yorke Peninsula, applied this association and stated that the dunes had formed during interglacial periods, but before sea level had risen from its glacial low position, thereby explaining their partial submergence.

Sufficient evidence has been brought forward over the past two decades to seriously question this association, and in fact, it is now generally held that glacials were arid rather than pluvial periods, and that dune formation occurred during these phases. To date, evidence to this effect has been presented for a number of areas of Australia. This thesis intends to add to the growing body of data that supports the concept of glacial aridity, and in particular to extend the concept of glacial aridity to the Eyre Peninsula area of South Australia.

In order to do so, it is first necessary to establish the age of the dunes developed on the Utera Plain. Absolute dating by radiometric means would allow the correlation of the time of dune formation with existing glacial chronology, in particular, glacial-interglacial cycles determined from foraminiferal evidence recovered in deep oceanic cores (Emiliani, 1955, 1958, 1966; Shackleton and Opdyke, 1973, 1976), and from reinterpreted terrestrial sequences in Europe (Kukla, 1977). The determination of the absolute age of the Utera dunes and their submerged counterparts thus constitutes a vital aspect of this investigation. To this end, as the relict Utera dunes were acted upon by marine processes, it is possible to employ marine deposits associated stratigraphically with the dunes, in order to define more precisely the time of dune formation.

CHAPTER TWO

THE UTERA DUNEFIELD

2.1 Demarcation and description of the study area.

Using monochromatic and coloured aerial photographs, aerial reconnaissance and ground-truth survey, the geographical boundaries of the study area were defined. Demarcation was based on the distribution of fossil dunes and upon the presence of landforms believed to be drowned seif dunes. Effectively, the study area corresponds with the Utera and Cowell Plains, but as the latter is of limited areal extent, the name Utera Plain and Utera dunefield shall include the Cowell Plain and dunes. A series of maps showing the distribution of the Utera dunes was produced from coloured aerial photographs at a scale of 1:10000, and subsequently reduced photographically (Appendix I).

Franklin Harbour (Fig. 1.1) is the southern limit of the area under consideration, for although relict dunes are found farther south near Arno Bay, none of these dunes evidently extends into Spencer Gulf. The major northern boundary lies in the vicinity of Murninnie, 80 km to the north of Franklin Harbour, where the Utera dunefield ends. Seif dunes are present farther north in the region of Lake Torrens, and in many instances are partially active (Williams, 1973), but are excluded from consideration in this investigation because they are beyond the range of inundation by the waters of Spencer Gulf.

The Utera Plain, upon which the dunes are deposited, is gently undulating, of variable width, being at a maximum between Cowell and Murninnie, and rises from Spencer Gulf in the east, to an elevation of between 100-150 m on its western boundary. This boundary consists of two main components; the Lincoln Fault System and the Cleve Hills. The Lincoln Fault System (Fenner, 1930), is an *en echelon* series of faults extending from Port Lincoln in the south to Port Augusta in the north (Fig. 2.1). These faults reflect the underlying Proterozoic lineaments, with reactivation of movement along these lineaments occurring during the late Cretaceous and early Tertiary resulting in the formation of St Vincent and Spencer Gulfs. This faulting disrupted the comparative stability that had prevailed since the Proterozoic, over which time denudation had produced a number of surfaces of low relief (Twidale et al., 1976). Minor seismic activity continues to the present (Sutton and White, 1968). The faults (Fig. 2.2, 2.3) find expression as low, unconsolidated sediment rises termed 'dirt scarps' (Miles, 1952). Movement along these faults is limited, with a maximum throw of the order of 25 m and an average displacement of only 15 m (Miles, 1952).

The Cleve Hills, immediately west of Cowell, are constructed of highly folded Proterozoic metasediments in which structure has determined the contemporary ridge and valley topography (Tilley, 1920; Johns, 1961; Thomson, 1969, 1980; Parker, 1980). Generally, the hogback and homoclinal ridges are underlain by quartzite or gneiss with more readily erodible schists beneath the valleys.

The Utera Plain is constructed of Tertiary fluvial and colluvial sediments (described below) derived from the Cleve Hills and deposited as a series of coalesced alluvial fans adjacent to the uplands, in the shallow graben that is Spencer Gulf (Miles, 1952; Ludbrook, 1955; Linsay, 1970; J. Parker, pers. comm.). These sediments are capped by a calcrete duricrust.

Calcrete is ubiquitous in the area and, as it is an important factor in both the preservation of the submerged dunes and the dating of the time of dune formation, needs further description. The calcrete consists of either powder, nodular, honeycomb, cemented nodular or massive sheet hardpans (Netterberg, 1967). The thickness of the calcrete layer thins towards the Cleve Hills where the

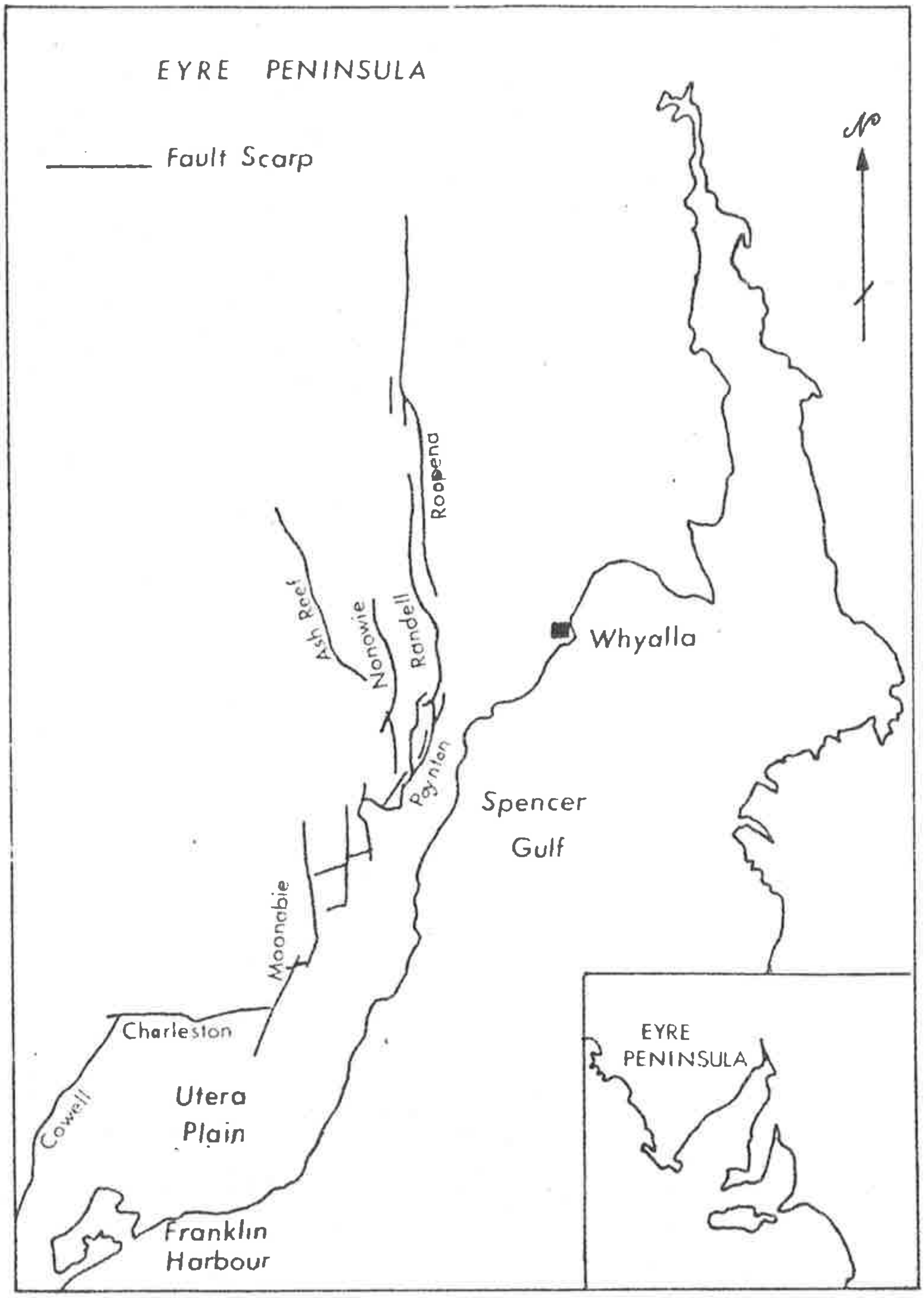


Fig. 2·1 Fault scarps, eastern Eyre Peninsula.

Fig. 2.2 Cowell scarp showing stream dissection.

Fig. 2.3 Charleston scarp.

slope of the alluvial fans approaches 7-8^{o}, with stream cuttings on the Cowell dirt scarp showing little, if any, carbonate accumulation. Individual colluvial fragments are veneered by a thin layer of carbonate in many instances, but on being broken, reveal a core of rock derived from the Cleve Metamorphics. Calcrete nodules are present and show concretionary growth bands, but these are of no great extent near the scarp, certainly not sufficient to be cemented into a hardpan.

Although the precise mode of calcrete formation is controversial (Goudie, 1973), and it is beyond the province of this discussion, it is possible to account for the thinning of calcrete towards the uplands. Such thinning is, in all probability, the result of the slope of the alluvial fans. These are of the order of 7-8^{o} which allow the transport of carbonates by groundwater drainage, thereby inhibiting calcrete formation.

Along the coast, the calcrete that underlies the Utera Plain finds expression as a broad, flat, intertidal platform developed between Franklin Harbour and Murninnie. The platform itself is the result of the breakdown of calcrete through a number of stages (Figs. 2.4, 2.5, 2.6). The original massive calcrete is fretted by weathering, and undermined by marine solution and erosion which eventually leads to the collapse of large blocks. Further weathering and erosion of these blocks produces cobble-size clasts which are deposited, in ramp form, at the base of the massive calcrete layer. Seaward, this ramp grades into an almost horizontal platform veneered by cobble to gravel-size clasts of calcrete derived from the larger shingle by attrition. These clasts are constructed of either cemented masses of nodular calcrete, or of rounded, laminar calcrete. Individual clasts of both laminar and nodular calcrete have, at a number of locations, been cemented into a massive hardpan.

In the intertidal zone the surface of this layer takes a

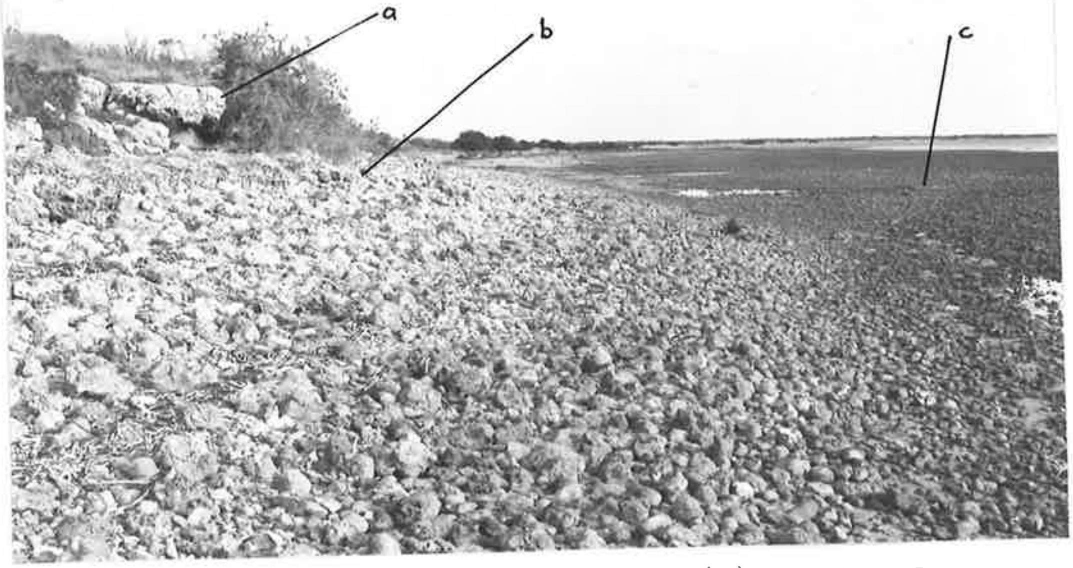


Fig. 2.4 Breakdown of massive calcrete (a) to shingle ramp (b) and planate surface veneered by small clasts (c).

Fig. 2.5 Massive calcrete layer undermined by marine solution and erosion. Note shingle at base of nodular calcrete.

Fig. 2.6 Intertidal platform. Note roundea rete clasts distributed over surface.

number of forms. In some instances it appears as a laminar, smooth-surfaced mass, often with botryoidal undergrowths. More commonly however, the surface of the calcrete is displayed as a jagged, fretted platform analogous to coastal lapies developed on aeolianite. Calcrete in this form is more prominent along the open coast than within the confines of Franklin Harbour, where shingle commonly overlies the indurated calcrete. Within these lapiés, at low tide, pools of water collect, leading to further weathering by solution, salt crystallization and biogenic processes. Such processes operate to remove the calcite cement binding the sediment grains, resulting in further breakdown.

Overall, calcrete imitates the general trend of the land surface. However, in the area occupied by dunes, and especially towards the coast, there exists a pronounced undulating surface with the troughs corresponding with the swales and the rises with the dune crests. Auger and core samples show the calcrete layer rising beneath the dunes and continuing onto the next swale (Fig. 2.7). The calcrete within the dune has developed in situ, rather than the dunes being deposited upon a pre-existing, undulating calcrete layer, as cross-bedded aeolian sediments are located beneath the calcrete horizon in some instances. More often however, it would appear that the calcrete layer is massive enough and is sufficiently deep to cement the entire dune core and part of the underlying alluvial sediments.

Where clearing of vegetation is pronounced, aeolian activity has resulted in deflation stripping the dune crests down to the duricrust surface. On aerial photographs, these denuded seif dunes appear as dune 'ghosts'. However, where such lowering has occurred, removal of sand has not always been halted by this major calcrete layer. At a number of sites, an horizon of powder calcrete, no more than a zone of carbonate deposition, has prevented further

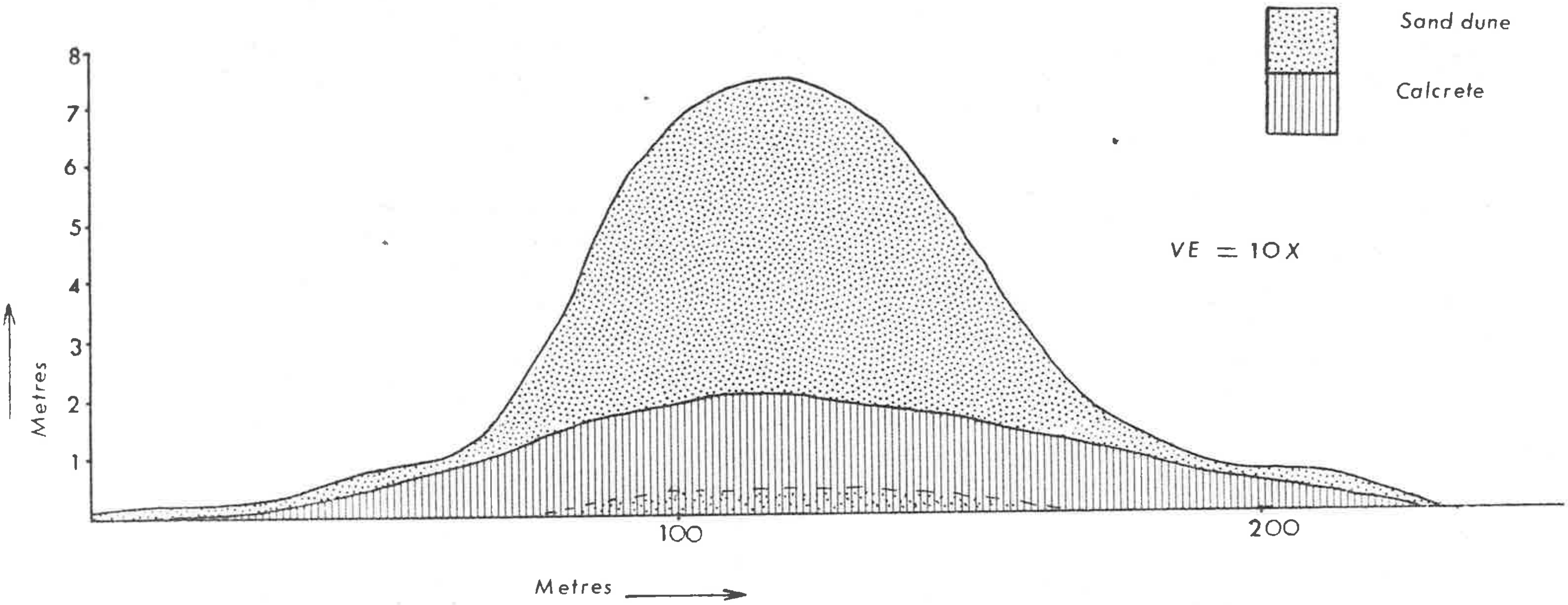


Fig. 2.7 Lenticular calcrete developed in dune profile

downcutting. Augering has revealed such a zone in many of the dunes developed to varying degrees, while in others the layer is largely absent. This layer of powder carbonate implies a period of carbonate movement in the recent past or possibly, even at present. Jessup (1968, a & b) noted a similar deposit developed in the Yorke Peninsula dunes and suggested that this powder carbonate was Holocene in age. Whether the source of the carbonate is the underlying calcrete layer, atmospheric carbonate or combinations of both, is not known.

2.2 Description of the Relict Utera Dunes

2.2.1 Morphology

The Utera dunes stand at an elevation of between three and ten metres above the adjacent corridors and have an average interdune spacing of 360 m. Interdune spacing increases slightly towards the northern margins of the dunefield and is accompanied by a minor, commensurate increase in dune height, supporting the inverse relationship observed between dune height and horizontal spacing which, to date, has not been explained adequately (Madigan, 1936; Bagnold, 1953; Wopfner and Twidale, 1967; Glennie, 1970; Twidale, 1972).

In cross-section the flanks of the Utera dunes are, in the main, symmetrical, in contrast to the dunes of, for example, the western Simpson Desert where asymmetry is pronounced (Mabbutt, 1968). It is entirely possible that the dunes were asymmetrical at the time of deposition, but this asymmetry has been reduced as a consequence of the modification of the flanks over time. Evidence for the degradation of the dune flanks is found in close proximity to the present coast where Holocene marine deposits interfinger with dune sands on the lower edges of the dune flanks (Fig. 2.8). Such degradation is the direct result of a number of exogenetic

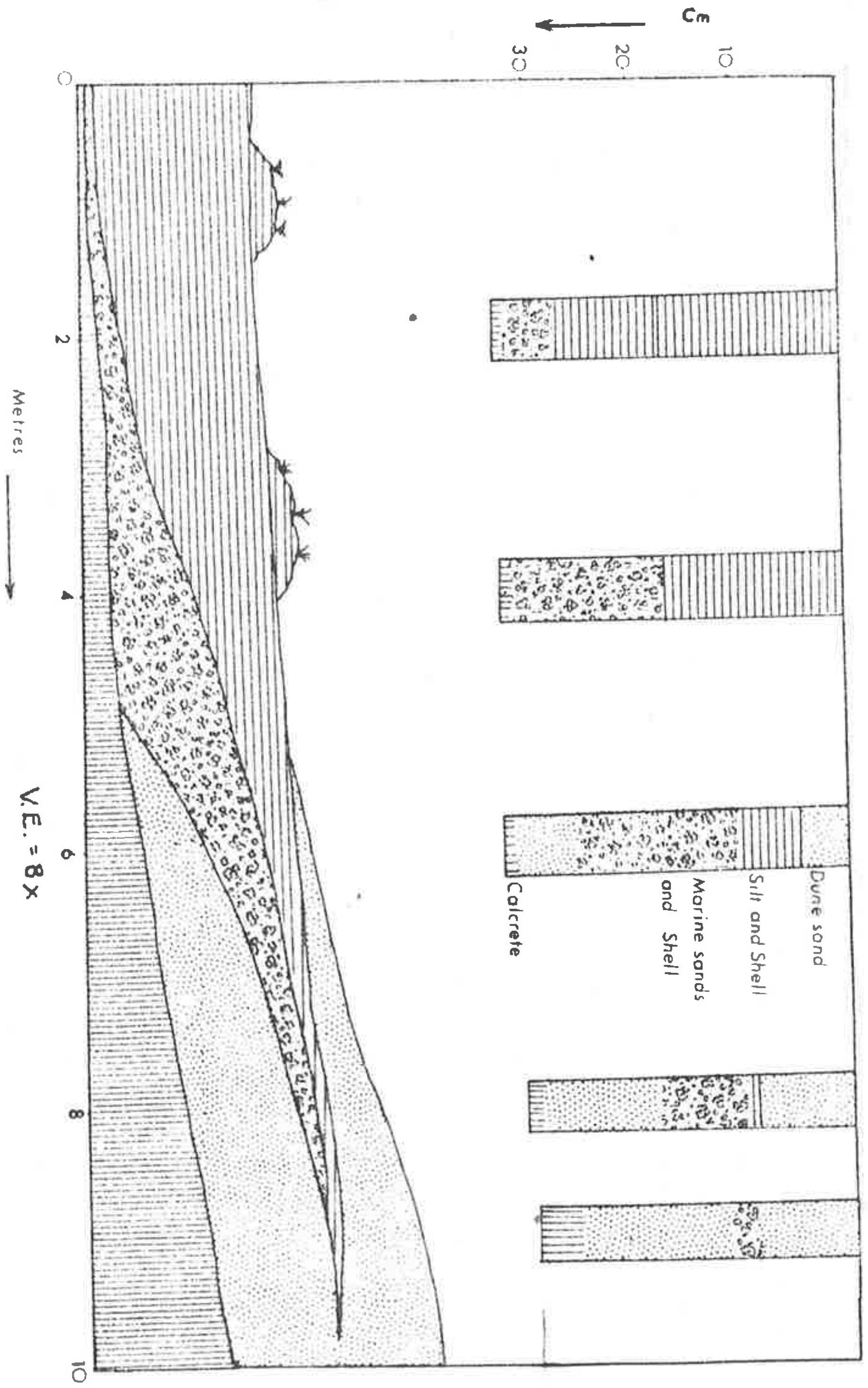


Fig. 2.8 Cross section normal to Utera dune, showing the interfingering of dune sand and Holocene marine deposits.

processes operating upon the dune flanks including rain splash, surface creep and the percolation of dew (Cornish, 1897; Smith, 1963; Flint and Bond, 1968; Grove, 1969). However, not all longitudinal dunes are asymmetrical, while the processes producing asymmetry are far from certain (Mabbutt et al., 1969; Clark and Priestly, 1970), thus it is equally possible, on the basis of the available evidence, to suggest the dunes were originally symmetrical.

The Utera dunes are classified as longitudinal or seif dunes rather than transverse dunes on the basis of internal sedimentary structure. Cross-bedding within the dune consists of high-angle avalanche foresets on both flanks of the dune rather than the low-angle topset and high-angle lee slope cross-beds associated with transverse dunes (McKee, 1966; McKee and Tibbetts, 1964; McKee and Douglass, 1971; McKee and Moiola, 1975).

Tuning fork, or Y-junctions (Madigan, 1936, 1946; King, 1956, 1960; Wopfner and Twidale, 1967; Folk, 1971; Mabbutt and Sullivan, 1968; Mabbutt, 1977), are a common feature of the Utera dunes, with the two limbs of the coalescing seifs open to the northwest.

Excluding active coastal foredunes and areas cleared for agriculture, the dunes of northeastern Eyre Peninsula are stabilized by mallee on both crests and flanks. On the Utera Plain, red mallee (E.socialis-E. gracilis complex), fruit ridge mallee (E. incrassata) and broombush (Melaleuca uncinata) are present. Towards the coast where the Utera dunes interdigitate with marine sediments and landforms, coastal mallee (E. diversifolia) is found in conjunction with samphire saline flats and, farther seaward, mangrove colonies (Avicennia marina var. resinifera) (Figs. 2.9, 2.10, 2.11,2.12, 2.13). The degree of vegetation cover produces stability of both the crests and flanks of the dunes, unlike the Simpson dunes that are stabilized on the flanks only. Further, many of the dunes of arid central Australia are actively being

Fig. 2.9 Mallee vegetation, Utera Plain.

Fig. 2.10 Utera dune stabilized by mallee scrub.

Fig. 2.11 Vegetation cover developed on relict Utera dune (a) and beach ridge attached to dune (b).

Fig. 2.12 Mangrove colony, Franklin Harbour.

Fig. 2.13 Samphire and mangrove vegetation, Franklin Harbour.

extended in length or, in some cases, are being formed from debris mounds located on the lee-side of playa lakes (Twidale, 1972). In comparison to the latter dunes therefore, the Utera dunes are considered to be relict features formed at a time of increased aridity.

2.2.2 Dune Alignment

Dune trend is developed in response to the resultant wind direction prevailing at the time of dune formation (Bagnold, 1941, 1953; Landsberg, 1956), but in many instances is discordant with contemporary sand drift or dune alignment (Smith, 1965).

The orientation of the Utera dunes was calculated from aerial photographs aligned to topographic maps, by measuring the bearing of the major dune axis from true north. The trend of the Utera dunefield was thus established as N 298° ($\sigma = 1.9^{\circ}$), aligning the dunes with those of central Eyre Peninsula (Bourne, et al., 1974), and in turn, with the predominantly anti-clockwise ellipse of dunes that extends from King Sound in northern Australia to northeastern Tasmania in the south (Marshall, 1948; Bowler, 1976, 1979; Sprigg, 1979).

From Australia, the data comparing contemporary and palaeowind regimes (using indicators such as dunes) is limited (Sprigg, 1965, 1979; Brookfield, 1970; Bowler, 1975, 1976, 1979). Consequently, wind roses were constructed for Cleve, Whyalla and Port Lincoln (Fig. 2.14) for the months of January and July at 0900 and 1500 hours. Only sand-moving winds of greater than 10 knots were considered.

Resultant wind directions were calculated for Cleve, the recording station nearest to the Utera dunefield, for 0900 and 1500 hours for January and July. Vectors for the eight main compass points were calculated using;

$$b = s \sum_{j=3}^{12} nj \ (v_j - V_t)^3 \qquad \text{(Landsberg, 1956)}$$

where b is the individual vector;
s is a scaling factor of 10^{-3};
n is the frequency of the wind in a given direction;
v is speed in m.p.h.;
V_t is the speed of 10 m.p.h., the threshold for sand-moving winds;
j is the Beaufort speed number.

The resultant winds are presented in Table 1.

TABLE 1 Resultant winds Cleve

Month	Time	Resultant Direction	Deviation from dune trend
Jan.	0900	N 329°	31°
Jan.	1500	N 192°	106°
July	0900	N 319°	21°
July	1500	N 294°	4°

The alignment of the Utera dunes deviates by as much as 106° from the resultant wind direction at 1500 hours in January. However, such a southerly component is explicable in terms of afternoon sea breezes blowing off Spencer Gulf and the importance of this component can only be assessed after the time of dune formation is established. If the dunes were deposited during a glacial phase, when sea level was lower than at present, then Spencer Gulf would have been an exposed sea floor and no afternoon sea breeze could have prevailed.

The resultants for 0900 hours for both January and July deviate by 31° and 21° respectively from the alignment of the dunes whereas the 1500 hours resultant is as little removed from the dune trend as 4°. The detailed implications of such variation shall be discussed below when considering palaeoclimates. However, the Utera dunes show a similar deviation, between current

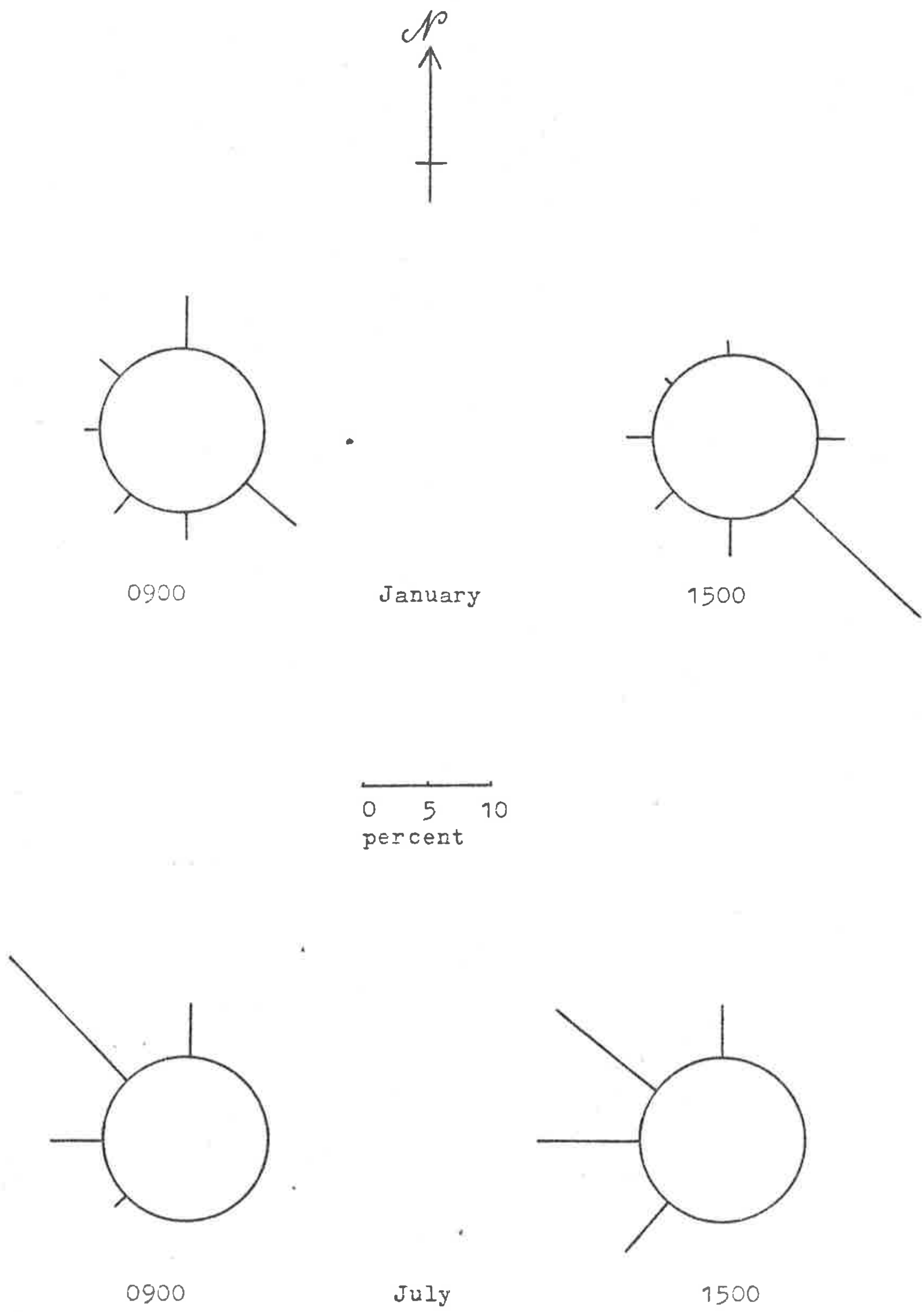


Fig. 2·14 (a) Wind roses for Cleve, northeastern Eyre Peninsula, showing percentage of sand-moving winds (over 10 knots).

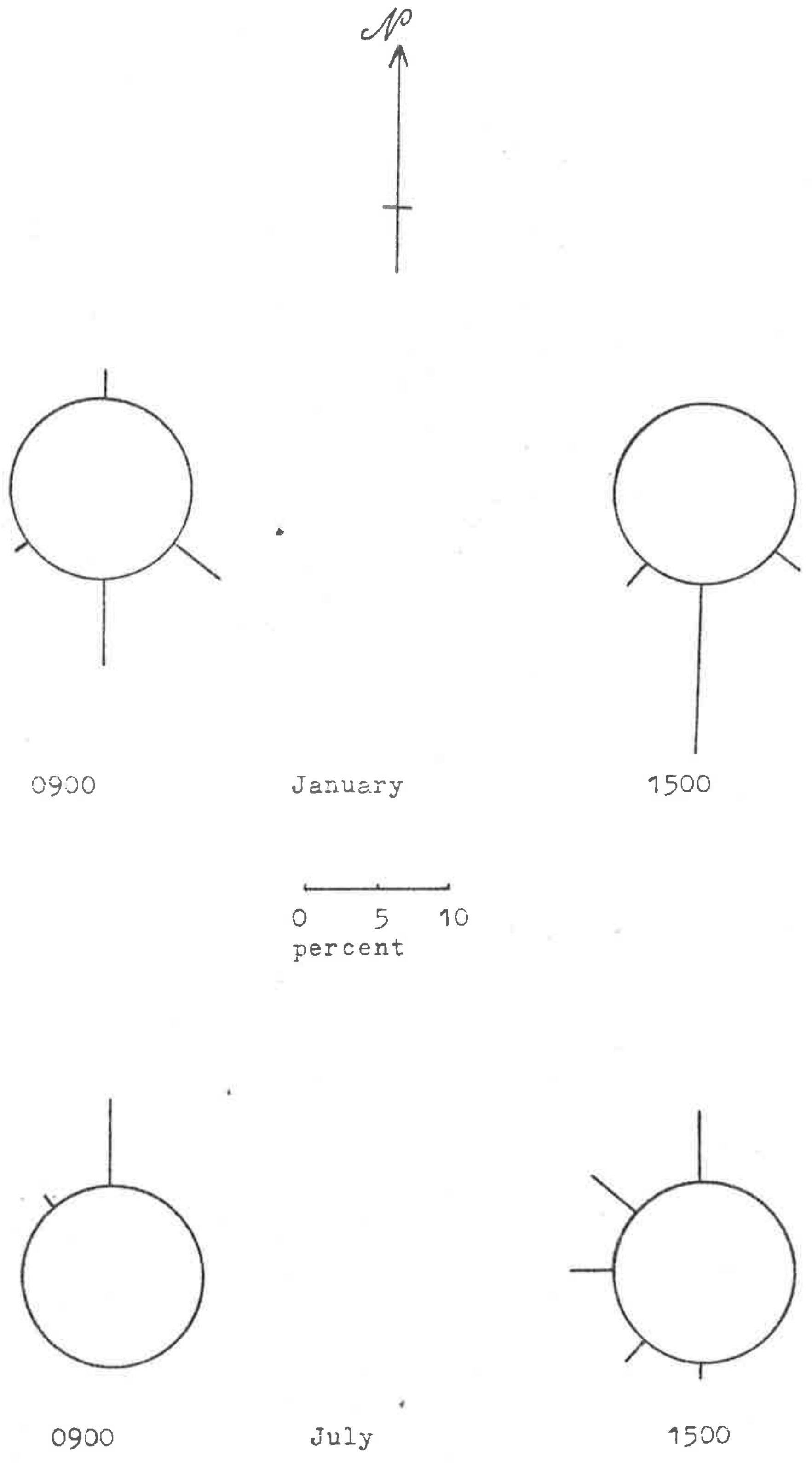


Fig. 2·14 (b) Wind roses for Whyalla, northeastern Eyre Peninsula, showing percentage of sand-moving winds (over 10 knots).

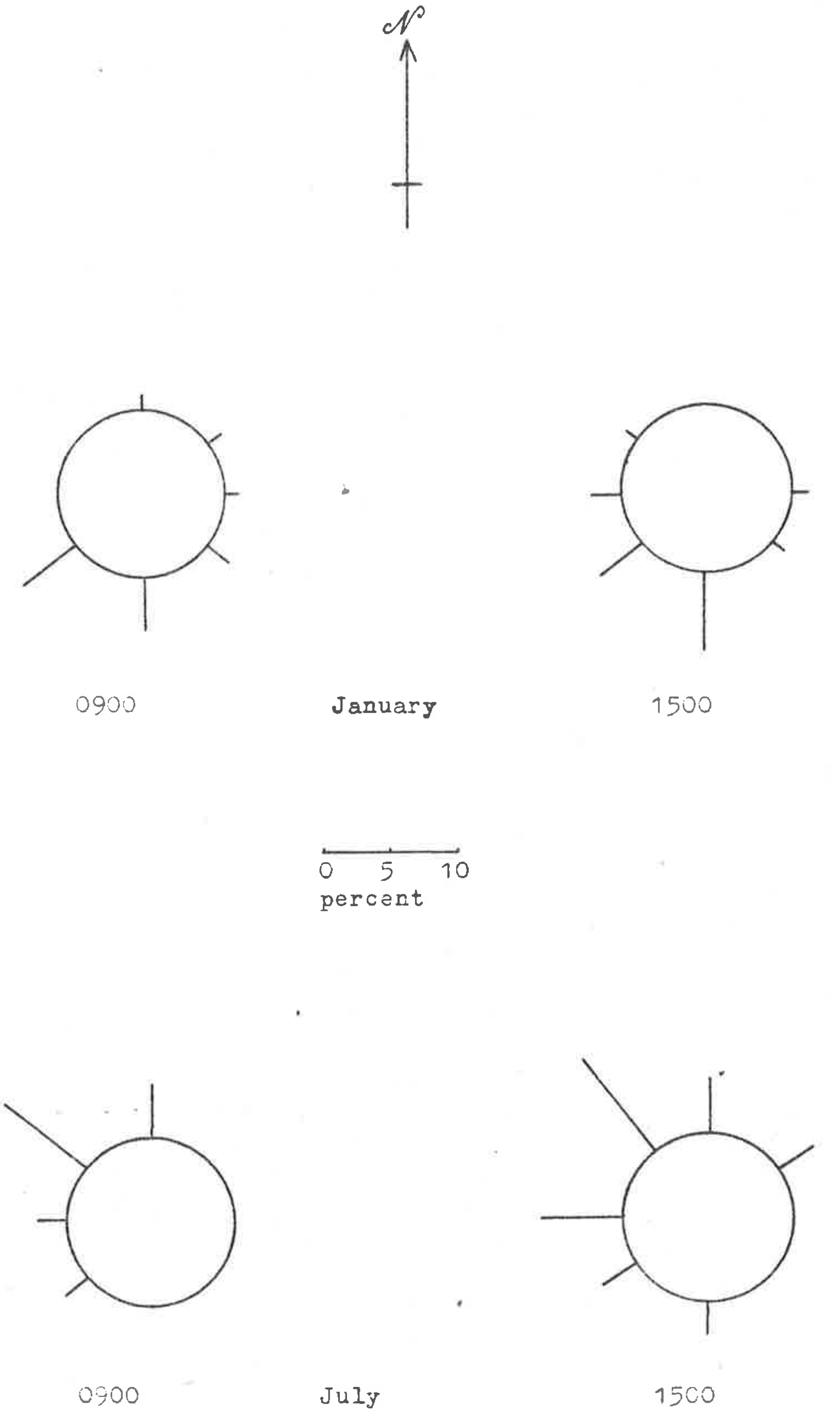


Fig. 2·14 (c) Wind roses for Port Lincoln, southeastern Eyre Peninsula, showing percentage of sand-moving winds (over 10 knots).

and formative wind resultants, as do the central Eyre Peninsula dunes (Bourne et al., 1974). Non-alignment between dunes and wind resultants also occurs on Kangaroo Island (Bowler, 1975, 1979), while Sprigg (1965, 1979) cites non-alignment between dunes and contempory sand drifts of up to 70° in the Murray Mallee. In contrast, Brookfield (1970) found little variation between dunes and resultant winds in the Simpson Desert, thus sustaining the hypothesis that in central Australia little alteration in wind direction has occurred. The greatest deviation between current and palaeowind resultants therefore, are to be found on the southern and northern margins of the continent (Jennings, 1975).

2.2.3 Mineralogy

The sedimentary characteristics of the Utera dunes were established by analysing samples collected at varying depths within the dunes and from different locations upon the dune, in particular, from either the crests or the flanks of the dunes. The majority of samples were extracted by sand auger. Samples were also collected by driving metal tubes into the dune with a portable pneumatic hammer. Such sampling was limited however, as the tubes proved difficult to extract with the portable tripod used. It was found that the small amount of lateral movement produced during the extraction of the tube caused sand to roll down between the tube and the wall of the hole which, in effect, tended to bind the tube in tightly.

The Utera dunes are constructed largely of sand-size grains of quartz, with lesser amounts of feldspar and accessory darker minerals. These sand grains are predominantly subangular to subround in shape (Powers, 1953), though there exists variation from this within certain size ranges. For example, grains finer than 3 Ø display a noticeable degree of rounding.

The surficial appearance of sand grains before treatment by dilute hydrochloric acid was disguised by a surface veneer. Folk (1978) labelled the silica precipitate on sand grains found in the Simpson Desert a 'turtle skin', thereby accounting for the 'greasy' lustre of these dune sediments. In contrast, the grains in the Utera dunes often possess a dull lustre due to the precipitation of calcium carbonate upon the grain subsequent to deposition. This dull, white lustre is most pronounced in an horizon some 100 cm below the dune crest, where a layer of powder calcium carbonate has formed and, in all probability, is still forming. In the surface horizon, sand grains are humic stained, while reddening of grains occurs lower in the profile. Treatment in dilute hydrochloric acid removes the surface patina of calcium carbonate, revealing the pre-depositional surface of the grain. In appearance, these grains range from polished to slightly frosted.

The sedimentary parameters of dune sands were calculated by analysing samples that were treated in dilute hydrochloric acid to remove any calcareous cement; dispersed in a calgon solution; wet sieved through a 4 Ø screen; dried (under 4 Ø) and disaggregated, and dry sieved through screen at a 0.5 Ø interval using a mechanical shaker. Pipette analysis was used to determine the percentage of silt and clay (greater than 4 Ø) in each sample. Employing the results of this analysis, the statistical parameters of mean, skew, sorting and kurtosis were calculated using the graphic method proposed by Folk (1974) and are presented in Table 2 and Figures 2.15 and 2.16.

Examination of Table 2 indicates that the Utera dunes are, overall, moderately to moderately well sorted, near symmetrical and slightly mesokurtic. The mean grain size of all samples is 2.24 Ø (σ = 0.16 Ø). However, this overall value fails to discriminate between particle sizes deposited upon the dune crests

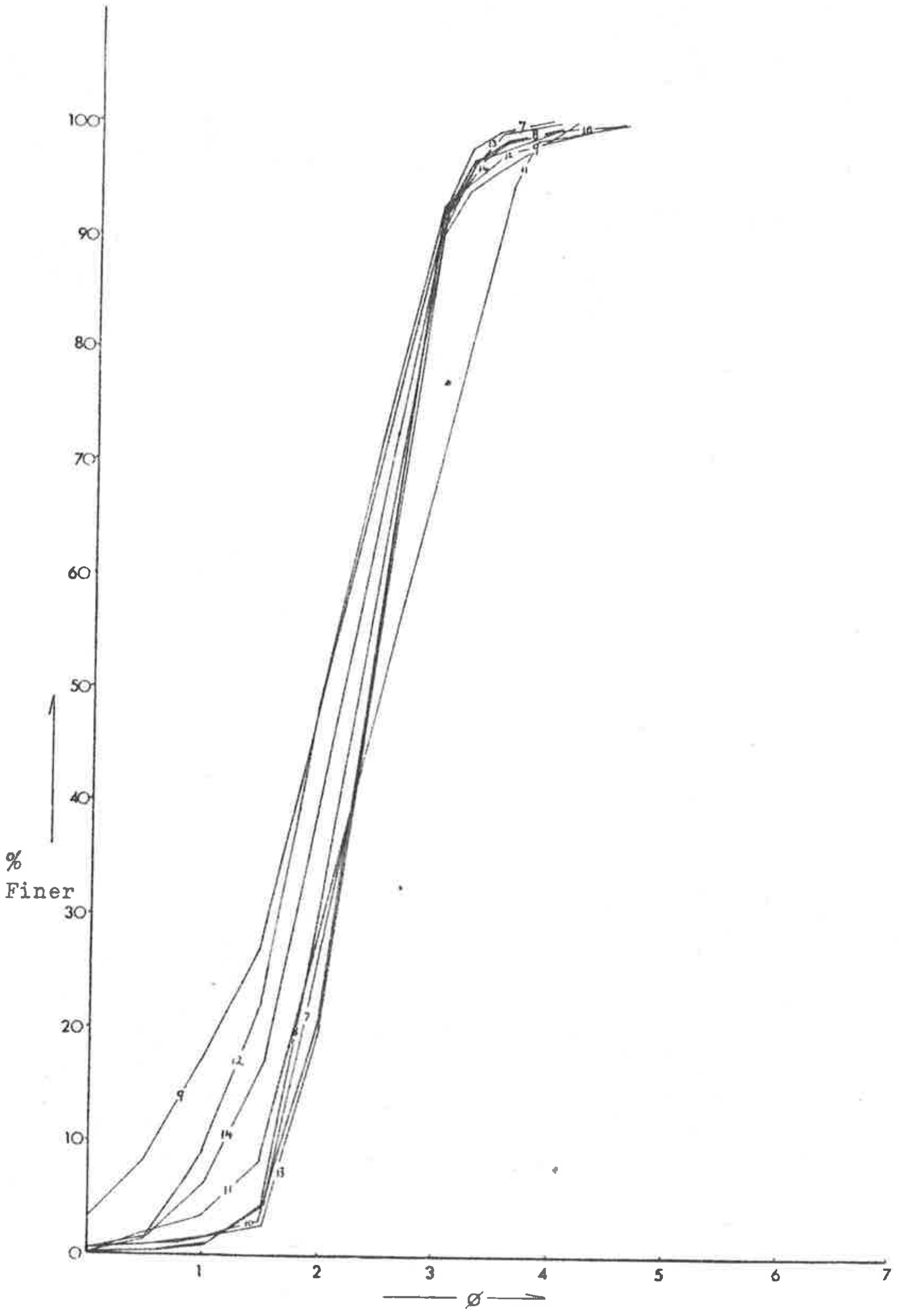


Fig. 2.15 Cumulative frequency graph, dune crests.

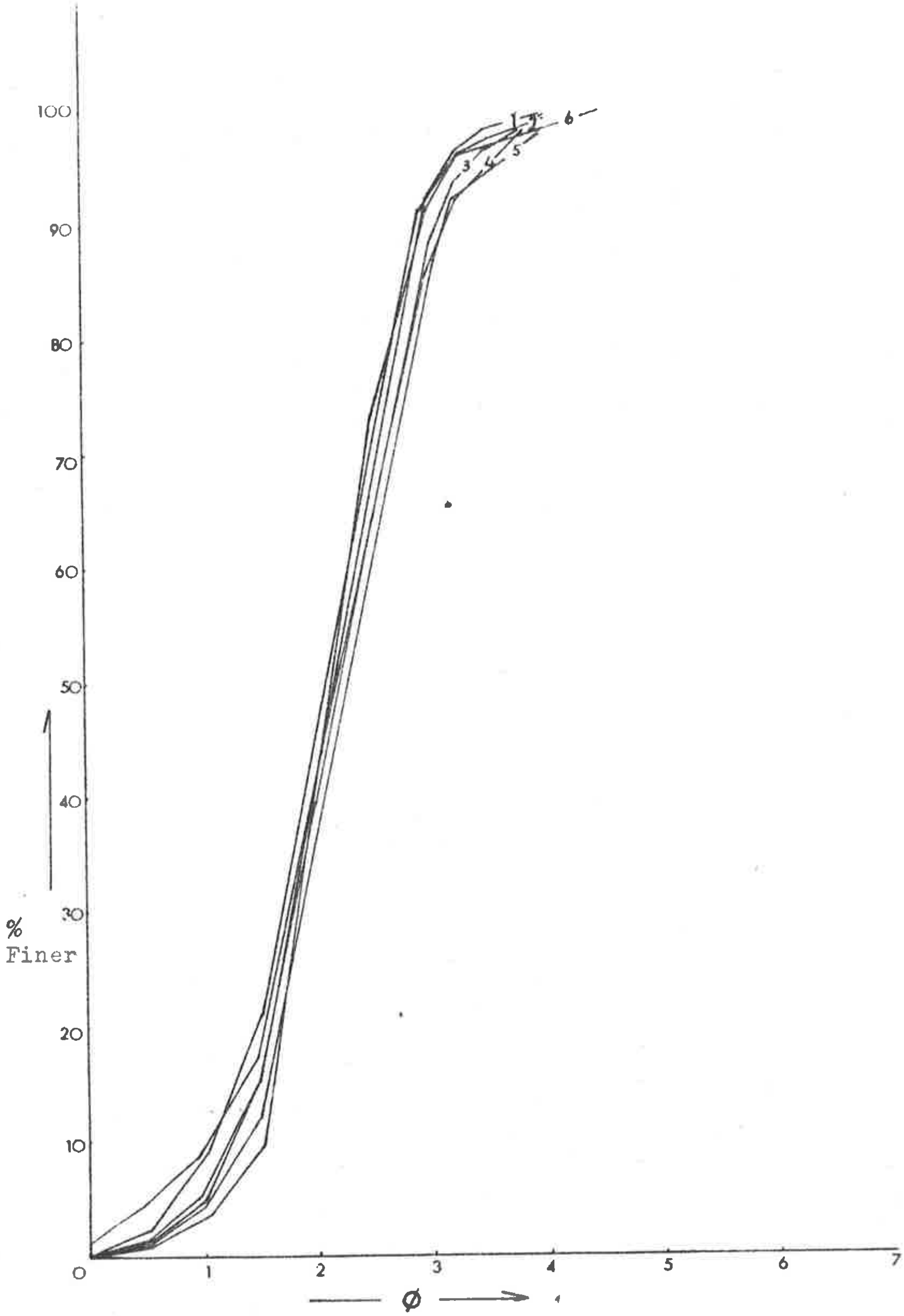


Fig. 2.16 Cumulative frequency graph, dune flanks.

TABLE 2

SEDIMENTARY PARAMETERS OF RELICT DUNES

SAMPLE	DEPTH (CM)	MEAN	SORTING	SKEW	KURTOSIS
Dune flank					
1	60	2.16Ø	0.67Ø moderately well	0.00 symmetrical	0.966 slightly meso-kurtic
2	130	2.05Ø	0.71Ø moderately well	0.095 near symmetrical	0.94 mesokurtic
3	190	2.18Ø	0.71Ø moderately well	-0.05 near symmetrical	1.05 mesokurtic
Dune Crest					
4	10	2.21Ø	0.83Ø moderate	0.14 near symmetrical	1.12 leptokurtic
5	160	2.28Ø	0.71Ø moderately	0.03 near symmetrical	1.01 mesokurtic
6	50	2.18Ø	0.62Ø moderately well	0.06 near symmetrical	1.02 mesokurtic
7	60	2.32Ø	0.49Ø well	0.14 coarse skewed	0.92 mesokurtic
8	180	2.28Ø	0.53Ø well	0.072 near symmetrical	0.84 slightly platy-kurtic
9		1.93Ø	0.96Ø moderate	0.118 near symmetrical	1.09 mesokurtic
10		2.38Ø	0.51Ø moderately well	0.007 symmetrical	0.97 mesokurtic
11	100	2.21Ø	0.56Ø moderately well	0.03 near symmetrical	0.95 mesokurtic
12	40	2.04Ø	0.74Ø moderate	0.04 near symmetrical	1.01 mesokurtic
13	50	2.39Ø	0.51Ø moderately well	-0.02 near symmetrical	0.96 mesokurtic
14	50	2.14Ø	0.69Ø moderately	0.0.079 near symmetrical	0.94 mesokurtic
Sample G_1	250	0.06Ø	2.77Ø very poor	0.17 fine	1.89 leptokurtic
G_2	10-200	3.4Ø	3.95Ø very poor	0.59 strong fine	1.30 mesokurtic

and those located upon the dune flanks. Dune crests are well sorted, near symmetrical and mesokurtic, with a mean grain size of 2.21 Ø (σ = 0.15 Ø). Although dune flanks have similar sedimentary parameters overall, grain size is, on average, slightly coarser than the crests (2.26 Ø, σ = 0.18 Ø). Such variation is in contrast with the Simpson Desert dunes where the crests are marginally coarser than the flanks (Folk, 1971).

2.3 Origin of Dune Sediments

The degree of rounding, surface appearance and sedimentary parameters of dune sands are, in part, determined by the sedimentary characteristics of the material from which the dune sands are derived. The origin of the dune sands must therefore be established. Two main sources of sediment need to be considered; that the sands are derived from the sediments immediately underlying the Utera Plain, or that dune sands were transported from another source outside the study area. Further, it is also possible that the sediments are polygenetic in origin, being derived both from local sand deposits and from outside sources. Howsoever it may be, a local source, the Utera Plain, will be examined initially.

To date, little detailed information is available concerning the age, origin or composition of sediments underlying the Utera Plain, the greater part of geological research being confined to the analysis of the Cleve metamorphics, or to water resource surveys (South Australian Department of Mines and Energy). By utilizing bore log data from the latter surveys, which have been drilled at a number of sites between Franklin Harbour and the Cowell and Charleston scarps, it is possible to describe the Utera sediments in broad detail.

The depth of overburden these bores penetrated before striking bedrock ranged from 40 to 90 m. These deposits are post-

Miocene in age if calcareous deposits located at some depth are the equivalent of the Melton limestone (J. Parker, per. comm.). Though minor variations exist in detail, the overall stratigraphic profiles obtained at a number of sites are similar. At or near the surface of the Utera Plain a calcareous duricrust is reported from all cores logged. This ubiquitous calcrete layer is underlain by red-brown and blue-grey mottled clays, sandy clays, clayey sands and silty clays. Grits and gravels, described in bore logs as 'waterworn', thereby implying a fluvial mode of deposition, are interbedded with these finer sediments.

The information obtained from these bore logs allows a general description of the Utera sediments but is insufficiently detailed to permit a direct comparison with dune materials. Hence, it is not possible to establish whether or not the Utera sediments were the source of the dune sands. In order to do so, a detailed investigation of the Utera sediments was undertaken.

Core samples were extracted to an average depth of 2.5 m using a portable pneumatic hammer and tripod extracter loaned by Soils Division, C.S.I.R.O. While problems of compaction of the sample in the core tube is known to occur, the error produced at the scale of investigation undertaken is not significant. To supplement the data obtained from the core tubes, numerous stratigraphic sequences were established by using a 12 cm auger with extension sections to 5 m. Because the auger cannot penetrate either massive or nodular calcrete, it was necessary to find locations where the calcrete duricrust was broken, either naturally or in man-made cuttings such as dam sites which had not yet been filled.

As few streams dissect the area, there are limited natural exposures to be found, especially towards the coast where the hard-pan is at its thickest. However, in some interdune corridors the calcrete was broken and auger samples were taken. In order to ascertain the degree of alteration of the sub-calcrete sediments between areas where the calcrete was broken either naturally or artificially, and sediments beneath massive calcrete, percussion tubes were driven through the calcrete where possible. In all cases the degree of disturbance was limited to the uppermost 5-10 cm of the sample.

For example, core G (field identification label) was extracted by percussion tube hammered through the calcrete layer in a swale and compared with sediments obtained by auger. Field and laboratory inspection of the subcalcrete sediments suggests that, in the main, they are poorly sorted, fluvial gravels, sands and clays. Two representative samples from core G (G_1 and G_2, Fig. 2.17) were analysed. G_1 consisted of material collected at a depth of 2.5 m beneath the swale surface, while G_2 consisted of sediments from 10, 70, 150 and 200 cm.

Both samples were poorly sorted and fine skewed, but differed in that G_2 was mesokurtic whereas G_1 was very leptokurtic, indicating that the central portion of the latters distribution is better sorted than the tails. Compared to G_2 where only 10% of the sample is coarser than 0 ∅, G_1 consists of 50% coarser than 0 ∅ of which 28% is less than -1 ∅. On the other hand, G_2 contained 28% of material finer than 4 ∅, compared to 8.5% for sample G_1. After dispersion, sample G_2, when stirred and allowed to settle, displayed a large percentage of material in suspension after a period of two weeks, indicating that the proportion of clay finer than 11 ∅ is considerable. The variation in the distribution of sediment size between samples is reflected in the mean values, G_1 having a mean of 0.06 ∅ compared to 3.4 ∅ for G_2.

Variation in the ratio of clay, sand and gravel was noted in samples taken by auger both between sites and at different depths within a core. However, although sections of individual depositional beds had been noted in a newly excavated dam, detailed

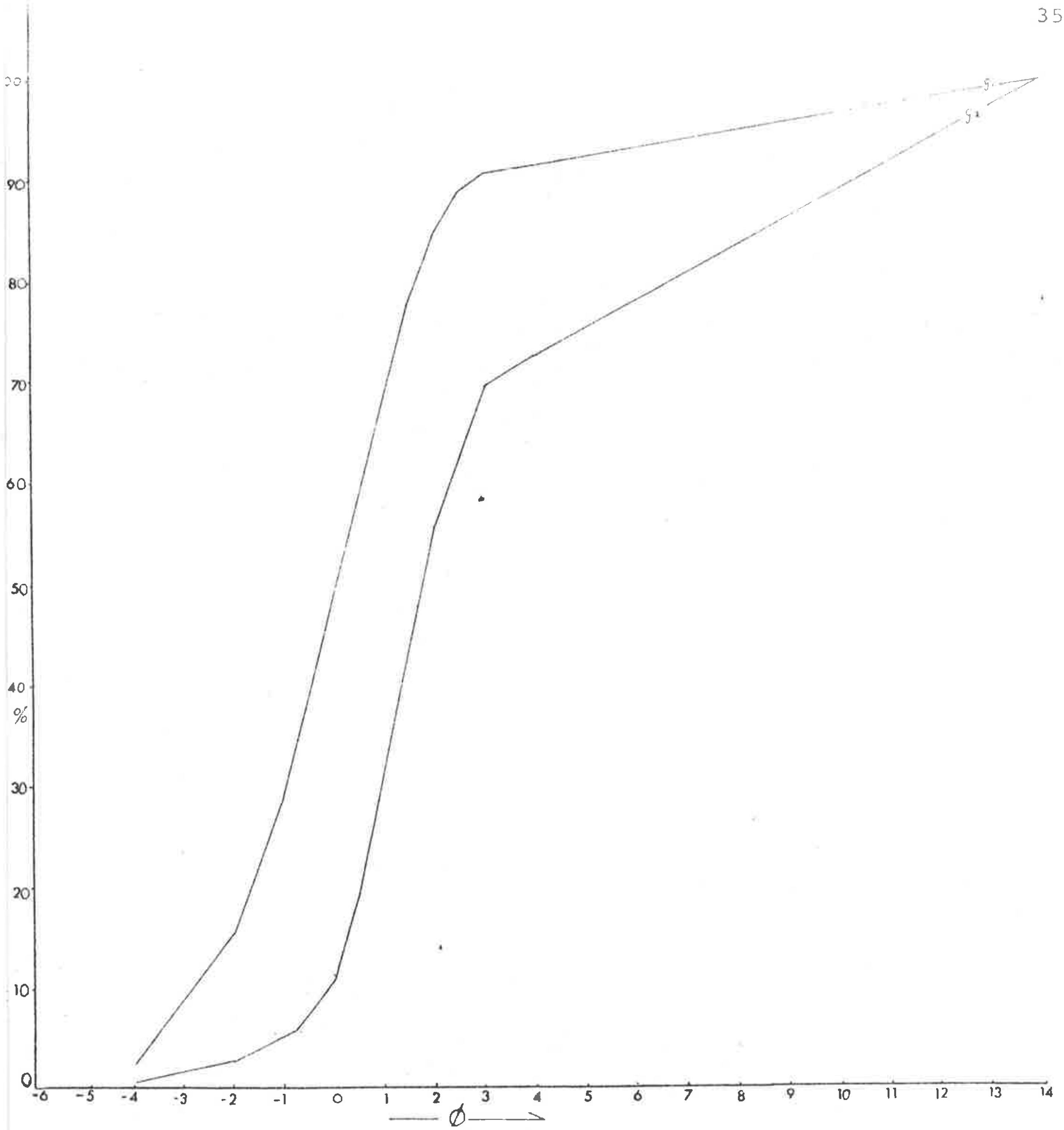


Fig. 2.17 Cumulative frequency graphs, sub-calcrete deposits, Utera Plain.

stratigraphic boundaries could not be established beyond this area. For example, clay lenses are present in the core profiles, but the spatial extent of such lenses could not be determined due to the calcrete layer which prevented the drilling of a number of close-spaced cores. It was because of this factor that it was decided to analyse a sample mixed from sediments collected at varying depths. If the dunes were indeed built out of the sediments of the Utera Plain, then the whole range of available grain sizes needs to be considered. Alternatively, because there are clay-rich layers within the profile, sample G_2 can be misleading if the high clay content is assumed to be equally distributed through the profile. If this were the case, deflation would be more difficult. In fact, as sample G_1 indicates, much of the material is coarser than 0 Ø. A more important aspect in determining the origin of the Utera dune sands is therefore the amount and the characteristics of the sand-size fraction contained within the total sample.

In samples analysed, both in the laboratory and the field, some 60% of the sediments underlying the Utera Plain consists of material between -1 Ø and 4 Ø in size (very coarse to very fine sand). Quartz is the dominant mineral in these fluvial deposits, while minor quantities of feldspars and darker minerals are present. Sand grains are subround to subangular in the main, with only a small percentage of rounded grains present in all size ranges. The source of these sediments is the Cleve Hills to the west, a belt of Precambrian metasediments in which the Warrow Quartzite is a major member. Grains of sand derived from this source were rounded to varying degrees during transportation, though angularity may have been increased by weathering subsequent to deposition.

The question remains as to whether the dune sands were derived from the fluvial and colluvial deposits of the Utera Plain.

Certainly quartz grains in the sand-size fraction are present in sufficient quantities to account for the supply of dune sediment. Further, sand grains in both the dunes and the subcalcrete deposits are subround to subangular, but differ, albeit only slightly, in that the dune sands are marginally more polished than the dull to frosted fluvial deposits. However, though aeolian activity has been cited as a factor in both the polishing and frosting of sand grains, there is considerable debate as to the effects of agents of erosion and transportation in relation to post-depositional modification of the grain surface (Sorby, 1880; Galloway, 1919; Kuenen, 1959 a & b; Kuenen and Perdok, 1961, 1962.)

In toto, the characteristics of the dune and subcalcrete sand-size sediments are sufficiently similar to support the conclusion that the Utera dunes were developed from sediment underlying the Utera Plain. This conclusion is sustained when considering the mode of dune formation.

2.4 Dune development

The nature of the cross-bedding within the Utera dunes, as described above, indicates that they are longitudinal rather than transverse dunes, but how were they formed? In explanation, a number of different hypotheses have been postulated. Some state that longitudinal dunes are entirely depositional, whereas others believe they result from a combination of erosion and deposition (Frere, 1870.) It has also been suggested that this dune type is due entirely to erosion (Blanford, 1879; Frere, 1911; Melton, 1940; King, 1956, 1960.) Melton (1940) introduced the term 'windrift' to describe the residual, linear ridges left in relief when largely unidirectional winds furrow deep, usually alluvial, sand deposits, and such a process must be considered in explanation of the Utera dunes.

Y-junctions described from the Simpson Desert by Madigan

(1936, 1946) were believed by King (1956, 1960) to constitute evidence in support of a windrift process of formation. Such Y-junctions, with their limbs open to the northwest, are present on the Utera dunefield, suggesting therefore, that they are windrift. However, a number of factors argue against this proposal. In the first instance, Mabbutt (Mabbutt and Sullivan, 1968; Mabbutt, 1977) refuted King's interpretation of the Simpson dunes, and in particular that Y-junctions are windrift features. As evidence, he cites the stage development of Y-junctions at Hale River and Andado station. Further, the throats of these junctions are areas of sand accumulation, whereas, if they were windrift, they would be zones of deflation.

Dunes formed by windrifting should, according to theory, be alluvially cored, evidence to this effect being noted by King (1956, 1960) in the Simpson. In fact, King's analysis has been shown to be incorrect (Wopfner and Twidale, 1967; Mabbutt and Sullivan, 1968; Twidale, 1972) since it is based only on the dunes near Lake Eyre. Twidale (1972) has shown that these dunes are extending downwind from lunette-type mounds situated on the lee shores of playa lakes, and have, in many instances, developed over Holocene alluvial sediments. The migration of these dunes excludes a windrift origin, while Y-junctions cannot, on the above grounds, be accepted as evidence for windrifting.

The arguments against an erosional origin can equally be applied to the Utera dunes. In particular, two lines of evidence can be cited. Windrift dunes should be cored by non-aeolian sediments but, in fact, the Utera dunes are not, consisting of sand-size grains only, and are separated from the alluvial deposits by a layer of calcrete that continues across the swale floor. Further, in windrift dunes, ridges are left as residuals above the swales, and therefore the lower sections of such ridges should not display the cross-bedding found in aeolian, depositional landforms. At a number of locations (eg, road cuttings) where the base of the Utera dunes are exposed, aeolian cross-bedding is discernible. In conclusion, the available evidence indicates that the Utera dunes are constructional rather than windrift. How then did they form?

For the Utera dunefield to have formed, a period of aridity, combined with a low water table, must have prevailed. The scarcity or absence of vegetation would have allowed predominantly north-westerly winds to act upon the deep, alluvial deposits of the Utera Plain, which, as described above, contain up to 60% sand-size grains. It is possible that helicoidal air flow (Bagnold, 1953; Hanna, 1969) in conjunction with bi-directional wind regimes selectively picked up grains of between -1 and 4 Ø and deposited these grains as longitudinal dunes.

It is also possible that sand was transported to the Utera Plain from the northwest, the Y-junctions indicating that the dunes developed from that direction. However, for this to occur, sand would need to be carried over the Cleve Hills. Bourne[1] has reported that Salt Creek, that flows out of the Cleve Hills, is an anomalous stream and, in part, accounts for this feature in terms of stream piracy but also suggests that diversion of the river is due to dune encroachment. However, if the Utera dunes had developed from the northwest then it would be anticipated that some of these dunes should either be present on the scarp face, or at least in close proximity. In fact, there exists a distinct area, running parallel to the scarp face, that is free of dune development. It is possible that this absence is due to the separation of airflow over an obstacle and that the Utera sediments are scoured only when this flow is re-established. The Utera dunes

1. J. A. Bourne, 'Denudation Chronology of Northern Eyre Peninsula'. Unpub. M.A. thesis, Dept of Geography, University of Adelaide, 1974.

are, in all probability, depositional landforms constructed largely from the sediments underlying the Utera Plain. Minor addition of sand-size grains may have resulted from material transported over the Cleve Hills from the northwest, but such a source need not be invoked in order to account for the Utera dunes.

2.5 Survival of Submerged Dunes

2.5.1 Description

What appear to be continuations of the Utera dunes cross the present coastline and plunge below the waters of Spencer Gulf. However, neither during aerial reconnaissance undertaken by light plane nor during analysis of aerial photographs could the morphology of these features be defined accurately. Further, if these landforms were indeed dunes, what factors could account for the preservation of the normally readily-eroded, unconsolidated sediments comprising dunes?

Field examination of these landforms indicated that they consist of low, indurated rises, with any unconsolidated sediment having been removed by marine erosion (Fig. 2.18). Levelling by semi-automatic Dumpy placed the elevation of these crests only a few centimetres above the intervening, low areas. Spatially, the crests of the rises corresponded with the immediately adjacent Utera dunes while the low areas correlated with the dune swales. Further, the alignment of the intertidal crests and low areas correlates with the trend of the Utera Dunefield. The low-lying areas (swales) are veneered by a thin layer of fine marine silts, sands, shells and, at a number of locations, algal matting. Offshore, both the indurated rises and the swales lose definition as a consequence of burial by marine sands or seagrasses.

Laboratory examination of the cement producing induration of

Fig. 2.18 Indurated dune core, intertidal zone, Lucky Bay.

Fig. 2.19 Intertidal platform. Note 'pillars' of micrite-cemented dune sand.

the rises indicates that it is a micritic form of calcium carbonate. The swales, in the main, consist of the same calcrete layer that supports the Utera Plain in various stages of reworking, as described above.

2.5.2 Analysis

The indurated rises are apparently dune continuations extending below sea level, and are believed to be the residual cores of the Utera dunes remaining after marine erosion of unconsolidated sediments. In order to verify that the rises are in fact indurated dune cores, it is necessary to establish the sedimentary characteristics (grain shape, size and mineralogy) of these submerged landforms and compare them with the grain parameters of the relict Utera dunes. To this end, samples of carbonate indurated sediment from several environments, including the submerged landforms, intertidal calcrete and inland calcrete, were analysed.

A series of thin sections were prepared from these samples. Material from the indurated rises consisted of quartz sand-size grains, in many instance with an iron oxide patina, cemented by micrite. Individual grains were subround to subangular, as were grains examined in the Utera dunes. More importantly however, within these sediments there was an absence of larger-sized grains. Samples from the inter-rise depressions and from the Utera seif swales contained sand-size fragments, but also consisted of larger clasts of quartz and feldspar. Comparison with core and auger samples taken inland indicates that these grains are related to material found below the calcrete layer. The material found in the intertidal, low-lying areas is therefore, considered to be the lower section of the calcrete layer supporting the swales on the Utera Plain. Similarly, the rises are the calcrete cemented cores of seif dunes. Field examination of the intertidal platform at a number of locations shows reddish coloured quartz grains cemented by micrite, often left as residual pillars above the platform surface (Fig. 2.19).

While these grains are sedimentologically similar to those forming the seifs of the Utera Plain and, in part, the dunes have survived submergence because of their induration, the question remains as to why the residual dune cores should stand higher in elevation than the swales. In answer, it has been noted that calcrete beneath the dunes stands at a higher elevation than that beneath the swales (Fig. 2.7) and this fact alone would explain why the dunes are still visible. However, such undulations of the calcrete surface are not merely fortuitous and need to be accounted for.

Rises and depressions have been reported to occur within calcrete duricrusts as a result of compressive stresses set up during calcrete formation. These features have been termed 'pseudo-anticlines' (Price, 1926; Jennings and Sweeting, 1963, 1967) and, in general, tend to produce an irregular surface, although Jennings and Sweeting (1963) have stated that there is some degree of regularity in the West Kimberley pseudo-anticlines. However, it is difficult to envisage that pseudo-anticlines could produce the regularity of undulations in calcrete on such a scale as the Utera Plains. Further, the alignment of the undulations correlates strongly with the resultant wind direction and thus with the Utera dunes, a feature not anticipated in pseudo-anticline formation.

It is more likely that the calcrete has formed pedogenically within the dune profile and beneath the swales as a result of the downward percolation of carbonate-rich water (Bretz et al., 1949; Arkley, 1963; Gile et al., 1966; Williams and Jennings, 1968). On Yorke Peninsula immediately across Spencer Gulf from the Utera

Plain, Dixon[1] has analysed the calcrete developed in the area and concluded it had formed pedogenically. Most important however, is the fact that aeolian sands are located beneath the calcrete layer in the dune profile. Further, within the dunes carbonate has cemented sand-size grains only, while the calcrete located beneath the swales contains coarse-grained sediments. The zone of carbonate precipitation occurs at a certain distance beneath the ground surface, the actual depth depending upon a number of factors including climate (Birkeland, 1974). As the dunes stand at a higher elevation than the swales, the zone of precipitation should occur higher in the dune profile, above the level of calcrete developed in the swale. However, as the dune sands more readily allow water percolation than the clay-bearing swale deposits, the calcrete layer in the dunes does not mirror exactly the land surface. Instead, it is located at some depth in the dune profile, but is higher than the calcrete beneath the swales. Towards the Cleve Hills, in areas where dunes are absent, the calcrete surface is consequently more planate.

Dune continuations that proceed below sea level are the residual cores of the Utera dunes cemented by calcite. The extent of dune penetration into Spencer Gulf is not known with accuracy but can be estimated on the basis of the available evidence. Beyond the immediate off-shore area, deposition of marine sediments and the growth of sea grasses makes it impossible to distinguish dune cores either on aerial photographs or in the field. To state with certainty that dune remnants are to be found on the

1. J. C. Dixon 'Morphology and Genesis of Calcrete in South Australia with Special Reference to the Southern Murray Basin and Yorke Peninsula.'

Unpub. M.A. Thesis, Dept of Geography, University of Adelaide, 1978 floor of Spencer Gulf, a close-spaced drilling programme, beyond the financial resources of the present research, is essential. However, even if resources were available, it would be extremely difficult to obtain conclusive evidence for the presence of dunes by such means for a number of reasons.

Unlike the submerged dunes examined by Jennings (1975) in Western Australia where much of the dune has survived, in the study area it is only the calcite-cemented residuals of the dune cores, standing only a few centimetres high, that remain. Further, as the relict Utera dunes often coalesce at Y-junctions or terminate, a similar spatial distribution is to be expected if the dunes continued below sea level. Because of these two factors, it would be difficult if not impossible to predict accurately where dunes may be located and thus recover samples for analysis. If samples were collected by drilling, it would not be possible to conclude with any certainty that the samples were in fact dune sands, as it is almost impossible to differentiate dune from marine sands on the basis of sedimentary characteristics (see below).

In all probability however, the Utera dunes did continue across the floor of Spencer Gulf. Immediately over the gulf from the Utera Plain, the seif dunes built across Yorke Peninsula share the same alignment as the relict Utera dunes. Further, Jessup (1968, a & b), on the basis of evidence from palaeosols, states that the Yorke Peninsula dunes were also constructed during a period of lower sea level. At present, these dunes are cliffed at the coast, but are believed by Jessup to have continued over the sea floor. Jessup suggests that the seif dunes were deposited upon the calcrete duricrust, in contrast with the Utera calcrete that developed within the dune profile. However, in roadside cuttings on Yorke Peninsula, calcrete examined within the dune, rises in conformity with the dune crests, similar to calcrete within the Utera dunes. Dixon's[1] research indicates that calcrete on Yorke Peninsula has developed over a number of periods of time separated by phases of erosion. Thus it is possible that the dunes examined by Jessup were deposited upon a calcrete layer and that subsequent carbonate deposition within the dune has produced the domed calcrete layer noted in the field. Howsoever it may be, calcrete, either that beneath the dune or that developed within the dune, is known to extend across the sea floor of Spencer Gulf (Gostin _et al_., 1981). Further, although the times of dune formation suggested by Jessup (between 85-90,000 and during the mid-Holocene) are challenged below, they have certainly formed after the Last Interglacial. The sea, however, has stood below the present level since the onset of the Wurm glaciation and, during interstadials, was of the order of 20 m below present (Bloom _et al_., 1974). As Spencer Gulf approaches depths of only 30 m at a maximum between the Utera Plain and Yorke Peninsula, the Utera dunes would have crossed the greater part, if not all, of the gulf.

2.5.3 The Spatial Distribution of Submerged Dunes

In the first instance, the distribution of residual dune cores is determined by the areal extent of the Utera dunefield, effectively from Franklin Harbour to Murninnie in the north. Within this sector however, not every relict dune that has been truncated at the coast by marine erosion continues as an indurated core below sea level, a feature requiring explanation. To this end, a number of possible causes need to be examined.

The degree of wave attack on different sections of the coast must be considered initially for, presumably, where the dunes have been subject to the most pronounced attack, the least, if any, amount

1. J. C. Dixon _op cit_.

of residual dune cores should be located. The coast adjoining the Utera Plain displays two major alignments; from Franklin Harbour to Shoalwater Point the trend is from N 256° to N 75° and between Shoalwater Point and Murninnie, immediately north of Plank Point, the alignment is N 205° to N 25°. The longest fetch would approach Franklin Harbour from approximately N 200°, the mouth of Spencer Gulf. Thus, the coast from Franklin Harbour to Shoalwater Point lies at an angle of around 56° to the maximum wave attack, but north of the latter location the alignment of the coast almost parallels the direction of wave approach. In relation to wave attack from an easterly direction, fetch is of the order of 50 km for all sectors of the coast, and thus is not considered to be of significance in this instance.

As a consequence of stronger wave attack on the section of coast south of Shoalwater Point, it is anticipated that relict dunes and dune cores would be less well-preserved. This is confirmed both in the field and by examination of aerial photographs. In contrast, north of Shoalwater Point, there are more dune cores extending into Spencer Gulf. This is the case, however, for approximately half of the distance to Plank Point; the northern section of the Utera dunefield apparently has few indurated dune cores below sea level, yet the coast shares the same alignment. It is possible that in this northern sector, residual dune cores are simply veneered to a greater extent by fine sediments, described more fully below, and thus, some are not visible rather than non-existent. The propensity of the broad intertidal area to retain such fine sediments is itself a result of the coast being aligned almost parallel to dominant wave attack.

Although the association of wave attack with coastal alignment explains the broad distribution of submerged dunes, it does not account for the location of such landforms within the major zone of preservation. Here, it is more the elevation of the dune and, in particular, the elevation of the calcrete duricrust relative to the position of the sea at the time of the Holocene maximum, that explains the location of submerged dunes.

During the post-glacial rise of sea level, unconsolidated dune sediments were stripped from the dunes and the indurated sediments eroded to varying degrees. Similarly, calcrete beneath the swales would have been eroded in part. However, the presence of calcrete on the floor of Spencer Gulf indicates that erosion could not have been complete. As sea level has stood at or about its present position for approximately 6000 years, it is within the zone of contemporary sea level that the greatest amount of erosion would have occurred. Where the land surface (and the calcrete duricrust) stands above present sea level, wave attack has eroded unconsolidated sediments from beneath the duricrust, leading to the collapse of the calcrete layer. Consequently, within the profile of dunes 'cliffed' at the coast, calcrete appears as a massive hardpan one to two metres above the interchenier swales (Fig. 2.20). The eroded calcrete has been reworked at some locations to form shingle ridges, as for example, at 'The Knob', south of Franklin Harbour. Thus, where the indurating calcrete layer stood higher topographically, relict dunes have not survived submergence. Conversely, where the relict dunes and calcrete occupy topographic lows, the indurated dune cores are buried beneath marine deposits in both the intertidal and offshore zones.

The spatial distribution of submerged dunes is therefore, due to the alignment of the coast in relation to wave attack, and the elevation of the calcrete duricrust relative to present sea level.

Fig. 2.20 Calcrete exposed in coastal cliff. Note seif dune on upper surface (a).

CHAPTER THREE

COASTAL DEVELOPMENT

3.1 Introduction

Following the submergence of the indurated Utera dunes the coastal zone between Franklin Harbour and Whyalla has prograded by means of beach ridges, cheniers, mudflats and mangrove colonies. The analysis of these landforms in relation to the Utera dunefield provides a means of dating the dunes, and of establishing whether the Utera Plain was partially submerged by faulting. A detailed discussion of these coastal features is, therefore, necessary to this investigation.

Within the coastal zone, three main groups of landforms can be distinguished. First, the Utera dune swales that have been inundated by Spencer Gulf to produce a series of embayments that currently lie above high water level (Figs. 3.1, 1.3, 1.4, 1.5). Such embayments may extend up to 2 km inland from the present high water mark, but are confined to the area between Franklin Harbour and Murninnie (the area of the Utera dunefield.) Second, the eastern ends of the dunes have been truncated by marine erosion, and the dune sands incorporated with marine sediment that have subsequently been deposited as beach ridges. Third, largely marine sediments have, by a variety of processes, prograded the shoreline towards the east. The landforms associated with this progradation include cheniers, beach ridges, mudflats, and mangroves. Each of these groups of landforms will be discussed in detail.

3.2 Inundated Utera Dune Swales

3.2.1. Distribution

The spatial distribution of the swale embayments (Appendix 1) extends from Franklin Harbour in the south, to Murninnie in the north. The end of the Utera dunefield results in a change in coastal configuration, for the undulating topography associated with the area of the dunes is replaced by a flat plain sloping seawards at a low angle. Consequently, the interfingering of marine sediments on the swale floors with terrestrial deposits (in particular, the Utera dunes), gives way to a former shoreline where terrestrial and marine deposits are intermixed and deposited as a beach ridge aligned parallel to the current coast. Further, the cessation of a supply of dune sands means that beach ridges constructed from these sediments are absent.

The distance over which the dune swales were embayed varies in direct response to topographical variations. Corridors between the dunes that were situated at a low elevation relative to present mean sea level, with low-angle swale gradients, experienced the greatest amount of marine penetration. On the other hand, areas of higher elevation formed 'headlands', although the relief amplitude of these features is in the order of only a few metres. Thus, at locations such as Shoalwater Point, the Utera dunefield is separated from the intertidal platform by a single line of foredune, there being no marine deposits within the swales. On the other hand, at Lucky Bay and Mitchellville, for example, the dune swales are veneered by marine sediments for up to 2 km from the present high water mark.

The degree of marine incursion is also dependent upon the relative height of sea level, and in particular the height attained during the mid-Holocene, for the swale deposits are Holocene in age (Table 4). However, the question of Holocene sea levels is surrounded by considerable controversy which, to date, has not been satisfactorily resolved (Fairbridge, 1961; Jelgersma, 1961; Thom <u>et al</u>., 1969; Thom, <u>et al</u>., 1972; Gill and Hopley, 1972;

Hopley, 1972, 1974, 1978; Thom and Chappell, 1975, 1978; Smart, 1976, 1977; McLean, et al., 1978; Belperio, 1979).

The evidence from northern Spencer Gulf (Gostin et al., 1981; Burne, 1982) and from the area covered in the course of this investigation, indicates that sea level stood between one and two metres higher than at present during the mid-Holocene. Marine sediments deposited on dune swales in the vicinity of Lucky Bay and Mitchellville, rest at elevations of up to 1.8 m above mean sea level, relative to local bench marks. Further, shingle ridges located south of Franklin Harbour at 'The Knob', and others, north of Whyalla, that were examined during this study, have crests as much as 4 m above high water level. The latter were considered by Hails and Gostin (1978) to be Pleistocene in age, but have now been shown to be Holocene features, on the basis of shells dated radiometrically (Van Deur and Polach, in prep.; Table 4). Gostin (Gostin et al., 1981) concluded that the shingle ridges indicated a maximum Holocene sea level some one metre higher than the present level and, further, that Quaternary sea level stood no higher than 3 m above contemporary mean sea level. Burne (1982) however, suggests that the beach ridges deposited in the northeastern Spencer Gulf region indicate a Holocene sea level as much as 3 m above present, although tectonism may, in part, be a contributing factor.

Although it can be argued that higher energy conditions are responsible for the deposition of the shingle ridges, a number of factors count against the assertion that the marine sediments in the swales were deposited under similar conditions. Shells deposited within the embayments consist of creepers (Batillariella estuarina), whelks and minor quantities of the estuarine cockles Macmona deltoidalis and Notospisula trigonella. These shells, in particular creepers, are, in general, located in low energy environments such as lagoons, swamps and estuaries. More importantly, the stratigraphic relationship between swale deposits and seif dunes indicates a low energy environment. The ends of the Utera dunes have been truncated by marine erosion, such 'cliffed' ends being sited at varying distances from the present shoreline. However, marine deposits are located up to 500 m farther inland from these dune ends, and interfinger into the dune swales. If marine sediments were deposited by medium to high energy conditions, the friable dune sands would have been eroded, and as such their presence implies a low energy environment.

If the environmental condition in the swales was one of low energy, then the argument that marine sediments were deposited up to 2 m above present mean sea level by higher energy conditions, cannot be maintained. Holocene sea level must, therefore, have stood at least 2 m above present. However, while this conclusion is valid for northeastern Eyre Peninsula, it is not suggested that similar conditions applied throughout South Australia, since the factors that determine the nature of the response of any area to the rise of sea level during the Holocene are such that it is relevant to describe and explain this response for given areas only.

3.2.2 Sedimentary Characteristics of Swale Deposits

The stratigraphic and sedimentary characteristics of swale deposits were examined at a number of locations between Franklin Harbour and Nurninnie, while the sedimentary parameters of these sediments were calculated from cores taken in the vicinity of Mitchellville. Located 5 km north of Shoalwater Point, the Mitchellville area consists of a large embayment where Holocene marine sediments have been deposited for up to 2 km from the present H.W.L. Core samples were taken from areas F, G and H (Appendix I, map 6).

Area F consisted of a swale between two seif dunes that were

Fig. 3.1 Dune swale embayment (area F), Mitchellville.

Fig. 3.3 Chenier development (area E), Mitchellville. Chenier (a), intertidal platform (b), Spencer Gulf (c).

connected by a transverse ridge, thereby enclosing the embayment. Core F/1 (Table 3), taken from the centre of the swale, penetrated white and brown-yellow mottled sands, silts and shell matter before striking the massive hardpan calcrete layer at 30 cm. A sample from a depth of 20 cm was analysed. The sample had a mean grain size of 6.67 Ø, was extremely poorly sorted, near symmetrical and very platykurtic. Over 50% of the sample consisted of sediment finer that 4 Ø with some 46% being clay-size particles. Material coarser than 4 Ø comprised mainly shell fragments, although the percentage of quartz grains increased in the finer sand fraction.

A number of cores were taken from the swale, both parallel to the seif dunes and across the swale, in order to confirm the stratigraphy and sedimentary characteristics of the samples analysed. The generalised profile (Fig. 3.2) of sediments covering the swale floor consists of a surface layer of fine sands, silts and clays to an average depth of 20 cm. Contained within the lower section of this surface layer are whole shells and shell fragments. The types of shells found, as described above, indicate an estuarine or, more probably, lagoonal-type environment, a supposition supported by the fine sands and silts found within the swales. Immediately beneath the layer of finer material, a zone of marine sands and shells rests upon the ubiquitous calcrete layer found in the area. Again, shells intermixed with these marine sands consist of creepers, whelks and minor quantities of bivalves. In appearance, the sands are white in the upper sections, but grade to a zone of white and brown-yellow mottled sands. At a number of locations, such as Lucky Bay, the calcrete beneath the swale embayments has become disaggregated and, in part, has been removed by marine erosion. Here marine sediments rest upon the poorly sorted, red-brown alluvial deposits underlying the Utera Plain. Core F/2, taken through a low ridge developed transversely to the swale, penetrated the same type of sediments as described

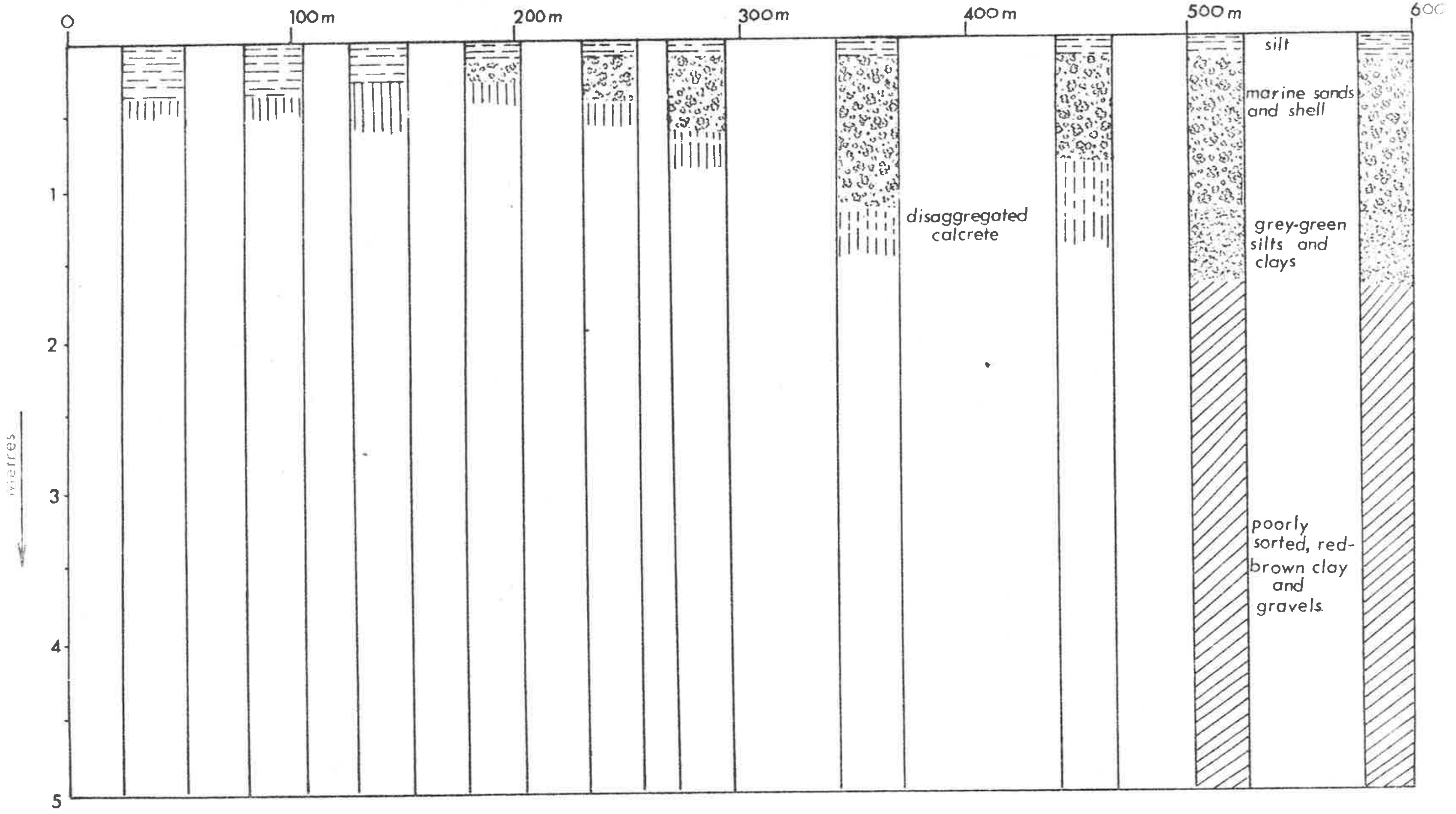


Fig. 3.2 Stratigraphy of dune swale embayment parallel to seif dunes, Lucky Bay (Spencer Gulf to right)

TABLE 3

SEDIMENTARY PARAMETERS OF BEACH RIDGES, CHENIERS AND SWALES

SAMPLE	DEPTH (CM)	MEAN	SORTING	SKEW	KURTOSIS
Ridge					
Cowled's Landing	15	2.07Ø	1.73Ø poor	0.36 strongly fine	1.51 very leptokurtic
	50	0.77Ø	0.98Ø moderate	-0.08 near symmetric	0.97 mesokurtic
Ridge					
B/1/1	15	1.1Ø	2.00Ø poor	0.21 fine	0.68 platykurtic
1/2	30	-2.13Ø	2.46Ø very poor	1.0 strongly fine	-0.72 very platykurtic
1/3	70	1.48Ø	1.31Ø poor	0.2 fine	0.90 mesokurtic
B/2/1	10	0.95Ø	1.38 poor	0.006 near symmetric	0.88 very platykurtic
Swales					
B/3/1	1	7.86Ø	4.62 extremely poor	-0.35 strongly coarse	0.66 very platykurtic
3/2	15	4.53Ø	4.03 extremely poor	0.36 strongly fine	1.06 mesokurtic
3/3	70	7.33Ø	4.57 extremely poor	-0.20 coarse	0.76 platykurtic
Ridge					
C/1/1	5	0.88Ø	1.20 poor	0.05 near symmetric	0.92 mesokurtic
1/2	20	4.5Ø	4.5 extremely poor	0.33 strongly fine	0.80 platykurtic
1/3	100	6.5Ø	4.93 extremely poor	-0.08 near symmetric	0.69 platykurtic
Swale					
C/2/1	50	3.4Ø	3.1Ø very poor	0.36 strongly fine	0.98 mesokurtic
2/2	90	4.0Ø	3.6Ø very poor	0.20 fine	1.03 mesokurtic
Ridge					
D/1/1	40	1.68Ø	1.29Ø poor	-.046 strong coarse	0.91 mesokurtic
1/2	50	0.78Ø	1.50Ø poor	0.19 fine	0.68 platykurtic
1/3	80	0.020Ø	1.47Ø poor	0.39 strongly fine	1.61 very leptokurtic
1/4	110	3.66Ø	1.66Ø poor	0.75 strongly fine	0.87 platykurtic
1/5	150	1.17Ø	1.25Ø poor	-0.28 coarse	1.11 leptokurtic
1/6	240	5.22Ø	3.89Ø very poor	0.78 strongly fine	0.75 platykurtic
1/7	300	6.13Ø	4.93Ø extremely poor	0.37 strongly fine	0.64 very platykurtic
Swale					
D/2/1	10	2.22Ø	1.83Ø poor	0.08 near symmetric	1.29 leptokurtic
2/1	50	5.17Ø	3.24 very poor	0.44 strongly fine	1.36 leptokurtic
2/3	80	2.23Ø	3.03 very poor	0.28 fine	2.28 very leptokurtic

SAMPLE	DEPTH (CM)	MEAN	SORTING	SKEW	KURTOSIS
Ridge					
E/1/1	20	1.77Ø	0.73Ø moderate	-0.13 coarse	1.58 very leptokurtic
1/2	120	1.30Ø	1.60Ø poor	-0.46 strongly coarse	0.85 platykurtic
1/3	150	2.70Ø	1.91Ø poor	0.13 fine	1.08 mesokurtic
1/4	250	4.70Ø	4.16Ø extremely poor	0.62 strongly fine	0.83 platykurtic
Swale					
E/2/1	20	2.4Ø	2.31Ø very poor	-0.08 near symmetric	3.23 extremely platykurtic
E/3/1	10	7.8Ø	4.6Ø extremely poor	-0.36 strong coarse	0.55 very platykurtic
3/2	30	4.35Ø	3.44Ø very poor	0.46 strong fine	4.7 extremely leptokurtic
Ridge					
F/2/1	5	3.65Ø	3.86Ø very poor	0.54 strong fine	2.02 very leptokurtic
2/2	60	6.12Ø	4.79Ø extremely poor	0.11 fine	0.70 platykurtic
F/3/1	30	1.6Ø	1.25Ø poor	-0.41 strong coarse	1.53 very leptokurtic
Swale					
F/1/1	20	6.67Ø	4.60Ø extremely poor	0.03 near symmetric	0.65 very platykurtic
Interdune Embayment					
G/1/1	20	4.26Ø	3.51Ø very poor	0.51 strong fine	0.74 platykurtic
1/2	50	4.8Ø	4.68Ø extremely poor	0.41 strong fine	0.84 platykurtic
H/1	25	3.98Ø	4.00 very poor	0.55 strong fine	1.15 leptokurtic
Ridge					
I/1/1	10	1.69Ø	0.76Ø moderate	-0.058 near symmetric	1.75 very leptokurtic
1/2	110	4.0Ø	2.98Ø very poor	0.66 strong fine	1.60 very leptokurtic
1/3	140	3.5Ø	2.24Ø very poor	0.54 strong fine	0.62 platykurtic
I/2/1	15	6.42Ø	3.21Ø very poor	-.063 strong coarse	0.52 very platykurtic
2/2	30	4.10Ø	3.38 very poor	0.54 strong fine	0.62 platykurtic
2/3	140	4.40Ø	3.29 very poor	6.52 strong fine	0.61 platykurtic
Ridge Lucky Bay					
1		2.03Ø	0.53Ø well sorted	0.05 near symmetric	1.02 mesokurtic

above. Sample F/2/2, located at a depth of 60 cm, had a mean grain size of 6.12 Ø, was extremely, poorly sorted, fine skewed and platykurtic, similar to core F/1. The ridges overlying these mudflat deposits are therefore, cheniers, and will be discussed in detail below.

Area F is situated approximately 0.5 km from H.W.L. at its seaward end, with marine deposits continuing inland for another 4-500 m. In order to establish the extent of marine penetration, sediments were analysed from areas G and H that appear, on aerial photographs, to be at the margins of the swale embayments (Appendix I, map 6).

Core G was taken at a distance of 1.5 km from H.W.L. and reached a depth of 90 cm before the calcrete layer was intersected. Samples from 25 and 50 cm were analysed (Table 3). Both samples are strongly fine skewed, platykurtic and very poorly sorted. Minor quantities of whole and broken shell were present only in the upper 10 cm of the core. Individual grains of sediment consisted of either round to subround quartz or feldspar, with only minor quantities of darker minerals. Some quartz grains were distinctly white in appearance, but the majority displayed a reddish colour. Such colouration results from either an iron-rich patina over the grain, or the adhesion of blebs or iron-rich clay to the grain. These sediments are essentially terrestrial in origin and have undergone only minor reworking and intermixing with marine deposits in a low-energy environment.

Core H, taken 1 km from the present coastline, consisted of 70 cm of marine sediments over calcrete. A single sample from 25 cm was analysed. Sand accounted for 72% of the sample, silt 10% and clay 18%, the entire sample being strongly fine skewed, very poorly sorted and leptokurtic. The profile consisted of reddish, subround to subangular grains of quartz and feldspar intermixed with marine shells. The most noticeable difference compared with Core G is the higher proportion of sand and the lesser amount of fines. This variation is explicable in terms of the slightly higher energy available closer to the coast that has selectively sorted and transported the finer material.

3.3 Marine Landforms Constructed From Reworked Dune Sediments

At a number of locations, ridges are developed normal to the seif dune across a swale embayment, thereby linking two dunes and enclosing the swale. The resulting landform can be classified as a barrier (Shepard, 1960; Hoyt, 1967, 1968; Hails and Hoyt, 1968; Bird, 1973). The sedimentary parameters of these features were established by analysing samples collected in Area I, north of the Mitchellville embayment (Appendix I, map 6), and from a ridge at Lucky Bay. Core I had samples analysed from depths of 10, 110 and 140 cm (Table 3, I/1/1, 1/2, 1/3). With increasing depth, sediments progress from moderately well sorted to very poorly and, finally, extremely poorly sorted. Skew changes from near symmetrical to strongly fine with depth. In explanation, as the core was logged on the ridge flank, approximately 1 m above the adjacent swale, the lower samples were taken below the swale surface which, as described above, contain relatively higher percentages of silt and clay.

All samples contained shell and shell fragments, the latter constituting an increasing percentage of the sand-size fraction as distance from the seif increased. However, the percentage of quartz grains increased in the finer sand-size fraction (2-4 Ø), with grain shape ranging from subround to subangular.

The sediment sample from a ridge at Lucky Bay had a mean of 2.03 Ø, was well sorted, near symmetrical and mesokurtic. In the main, the ridge was constructed of quartz sand, with some whole shell and shell fragments.

Barrier ridges constructed at the seaward margin of cliffed seif dunes, consist of varying mixtures of dune sand and marine sediment introduced from the south by longshore movement. However, it is not possible to differentiate dune from marine sands on the basis of sedimentary parameters, but the sands can be distinguished by colour variation. Dune sediments are reddish while marine sands tend to be white in appearance. The red coloration resulting from the presence of dune sands is most intense immediately adjacent to the seif dune, but grades through a red-white combination to predominantly white sand. In part, this variation may also be due to removal of the iron patina on individual grains, but the presence of marine shells in the lower sections of the ridge confirms the marine origin of much of the sand. Although the barrier ridges are of interest, they form only a small section of the landforms produced during coastal progradation. As such, their formation will be discussed in conjunction with chenier and beach ridge development.

3.4 Characteristics and Distribution of Holocene Coastal Landforms

Although the study area corresponds with the Utera dunefield, when considering the characteristics of coastal progradation of northeastern Eyre Peninsula, it is pertinent to examine the areas to the immediate south and north. In so doing, variations in both the type of sediment and of landforms can be noted. The main supply of marine sediments in northern Spencer Gulf has been carried from southern Spencer Gulf, with little addition of terrestrial sediment derived from northeastern Eyre Peninsula. Low cliffs situated between Point Gibbon and Port Gibbon, south of Franklin Harbour, a distance of 4 km, consist of fluvial and colluvial sediments that, upon erosion, are added to the coastal sediment compartment. However, few streams attain the coast, and those that do are, at best, intermittent. Consequently, cliff erosion is the only major source of terrestrial sediments.

Beaches south of Franklin Harbour are constructed largely of quartz sands, and display a number of rhythmic features (Komar, 1976), including cusps and berms. At Point Gibbon, an extensive transgressive dune complex has formed from sediments carried from the south. In contrast, the beach to the north of Franklin Harbour consists of either broad intertidal platforms developed on calcrete, saline mudflats and cheniers, beach ridges, or mangrove colonies.

Longshore drift is developed in response to south to southeasterly winds. The alignment of a number of landforms indicates the direction of movement, these landforms including foredunes between Port Gibbon and 'The Knob', shingle ridges at 'The Knob' and the orientation of the barrier-spit that almost entirely encloses Franklin Harbour (Appendix I, maps 1-13). These features all share an alignment of N 45°, having formed approximately normal to the south to southeasterly wave regime (Hails and Gostin, 1978). The barrier-spit extends from 'The Knob' over a distance of 12.5 km to its distal end at Germain Point, and is capped by foredunes stabilized by vegetation. A number of recurves have developed along the length of the barrier that bear an east-west orientation, reflecting secondary wave attack (Lewis, 1932; King and McCullagh, 1971).

The channel into Franklin Harbour lies between Germain Point and Point Victoria, passing to the south of Entrance Harbour, although a second, shallower channel known as 'False Entrance' also allows tidal movement into the harbour proper. The main transport of littoral sediments occurs to the south of Entrance Island, resulting in the deposition of a number of ebb and flood tidal landforms (Boothroyd, 1978). Sediment within Franklin Harbour is largely deposited in the lee of the barrier-spit, where the sand bank has been colonized by mangroves (Avicennia). In the main, sediments found in the barrier-spit, the beaches and foredunes to the south of Franklin Harbour, and the colonized sand bank, are quartz sands. The sediments are carried north to form beach ridges and cheniers, but are increasingly intermixed with shell and shell-sands. Howsoever it may be, an adequate supply of sediment is still available in the nearshore and offshore zones for further coastal progradation to occur in the northern sectors of the gulf. This sand is plainly visible on aerial photographs, and, at a number of locations both north and south of Franklin Harbour, forms sand waves that are attached to the beach at one end.

North of Franklin Harbour, the pattern of coastal progradation becomes increasingly complex in response to variations in the amount and type of sediment available, and local nearshore sediment dynamics. In the main, progradation is by mudflat sedimentation and ridge construction but, in detail, the nature of these ridges, and the formative processes involved in their construction, varies spatially.

Where the landsurface was at a slightly higher elevation, and consequently was not inundated by rising Holocene seas, a beach-ridge/foredune complex has been constructed. It is believed that these beach ridges are developed by cut and fill (Davies, 1957, 1958), rather than by swash as stated by Stapor (1975). However, these ridges have had their crests raised in elevation by the accretion of wind-blown sand (Thom, 1964). They result, therefore, from a combination of marine and aeolian activity.

Although the deposits located at points of higher elevation tend to be beachridge/foredune complexes, in low lying areas that were inundated, the ridges are cheniers (Russell and Howe, 1935; Fisk, 1948; Price, 1955; Byrne et al., 1959; Gould and McFarlane, 1959; Hoyt, 1969; Otvos and Price, 1979; Rhodes et al., 1980).

The sedimentary characteristics of ridge and swale deposits were determined from samples collected by auger at a number of locations between Franklin Harbour and Whyalla. Although coastal progradation has occurred over the entire area, two main sections can be distinguished; the first where the Utera dunefield is truncated at the coast and has added dune sediments to the coastal sediment compartment, and the second, north of Murninnie, where dunes are absent. Samples from the first section were collected from areas E and I (Appendix I, map 6) and analysed.

Area E is in the present intertidal zone (Fig. 3.3), is up to 0.5 km wide, and of low gradient. Core E/2 was taken on the intertidal flat and, in the main, consisted of yellow-brown coloured fine sands and shells overlying calcrete at a depth of 40 cm. Test pits dug along a transect normal to the strandline revealed the same stratigraphy as in the core. A single sample from a depth of 20 cm was analysed (Table 3).

Core E/1 (Table 3, samples E/1/1, 1/2, 1/3, 1/4) was logged on a ridge nearest low water mark and attained a depth of 250 cm without striking a calcrete layer. However, carbonate nodules were encountered, suggesting that calcrete has become disaggregated. The coarser material higher in the ridge profile consists largely of shell fragments that, with depth, is replaced by fine quartz sands. These sands are subround to subangular in appearance. Sample E/1/3 taken at a depth of 150 cm consisted of yellow-brown coloured sands similar to sediments examined in core E/2 and in test pits. Further, except for kurtosis, the sedimentary parameters of both samples are similar. As the ridge stood some 1.00 m above the surrounding intertidal flat, sample E/1/3 was taken at a depth of 50 cm relative to the surface of the intertidal flat. Thus, it would appear that the ridges constructed from coarser shell sediments were deposited over the finer marine sediments underlying the intertidal zone. The ridges, therefore, are cheniers.

In area I, nine ridges (Fig. 3.4, 3.5) have been constructed, including a ridge connecting the truncated ends of two seif dunes.

Fig. 3.4 Chenier constructed of shell and quartz sand, area I, Mitchellville.

Fig. 3.5 Prograding chenier plain, area I, Mitchellville.

Eleven cores were taken through these ridges and the intervening swales. The stratigraphic profiles for ridges and swales are shown in Fig. 3.6, with the sedimentary parameters taken from the landward ridge and swale presented in Table 3.

These ridges can be classified as cheniers as they are underlain by mudflat sediments that are continuous with the swales; the ridges having overridden the mudflat deposits either under normal energy conditions, or during periods of increased energy (Hoyt, 1969). However, while general theories of chenier development assume wave attack normal to the alignment of the ridges, the role of longshore transport tends to be ignored. Nossin (1965) mentioned the influence of such movement in describing the ridges of Malaya, and the importance of this process is clearly demonstrated in the cheniers (and to an extent, the beach ridges) of northeastern Eyre Peninsula. Viewed in plan, the majority - but not all - cheniers display prominent recurve development. In terms of classification therefore, these ridges should be described as chenier-spits. Many of these chenier-spits are seen to extend across an embayment from a single beachridge/foredune, indicating that the process of beach ridge and chenier deposition may have occurred concurrently.

In addition to beach ridges and cheniers being deposited contemporaneously at different locations along the coast, over time, beach ridge development at one point has been replaced by mudflat sedimentation and chenier emplacement.

With the end of the Utera dunefield, the gentle undulations of topography that, when inundated during the mid-Holocene produced the embayments described above, give way to a broadly horizontal conjunction of terrestrial and marine deposits. At this junction of terrestrial and littoral deposits, a single beach ridge has been constructed. This ridge can be traced from Murninnie to immediately south of Whyalla, although it has been

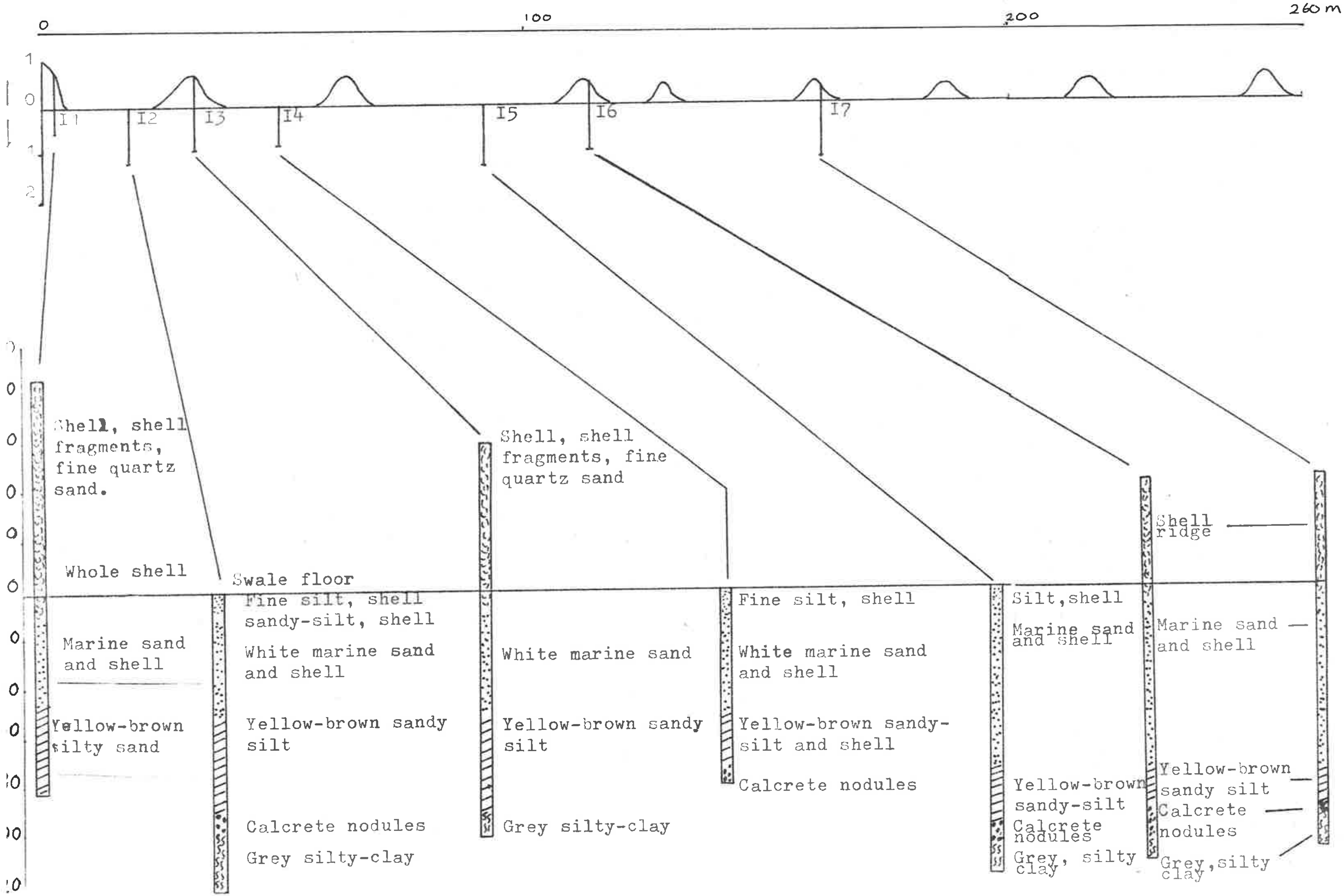


Fig. 3.6 Stratigraphy of beach ridge and cheniers, area I, Mitchellville.

breached at a number of locations. Samples from cores taken from this ridge in areas D, C and B (Appendix I, maps 10-13) were analysed in order to establish the characteristics of the sediments building the ridge. Results of this analysis are presented in Table 3, samples D/1, C/1, and B/1 and B/2.

In all instances, the ridge is constructed of shell fragments with varying amounts of quartz sand that, in part, explains the variation in sedimentary parameters noted between sites. All samples however, were poorly sorted, generally fine skewed and showed a fining of sediments with depth. As observed in samples from areas E to H, quartz grains are dominant in the finer sand-size fraction and are subround to subangular in shape. Further, many of these grains carry an iron oxide patina that is shared by quartz grains examined in cores taken inland from the ridge. In concert with similar sedimentary characteristics (Table 3, samples C/2/1 and C/2/2), this indicates that the ridge is constructed of terrestrial sediments reworked by marine processes, intermixed with marine sediments, in particular, shell matter.

At a depth of 300 cm in core D/1, there is an organically-rich layer of fine sediments, the organic matter consisting largely of sea-grass fibre. This grey-black layer also contains shells, either whole or fragmented, and is in turn overlain by yellow-brown and white, mottled sand and shell. This stratigraphy is repeated in cores drilled seaward of the ridge in area D

Burne (1982) has described a similar sequence from eastern Spencer Gulf and suggests that the sea-grass sediments are subtidal deposits that indicate a former minimum tide level. Upon the basis of this and other evidence, including cheniers constructed of shell matter, he has proposed a history of Holocene sea level transgression and regression for northeastern Spencer Gulf. At this juncture however, the data from northwestern Spencer

Gulf is not sufficiently detailed to allow correlation with Burne's stratigraphy. In particular, the exact spatial distribution and elevation of subtidal organic deposits needs to be established.

Seaward of the ridge described above, mudflats have prograded the coast over distances of between 0.5 and 1 km. The results of sedimentological analysis of these mudflats are presented in Table 3 (B/2, D/2). The stratigraphy of mudflat sediments is the same as recorded from beneath the landward ridge and also continue below shell ridges located seaward of the above ridge. The ridges therefore, are classified as cheniers.

Developed upon the mudflats between Murninnie and Whyalla, there are a number of such cheniers, the actual number varying between locations. Further, recurve development indicates a northerly movement of sediment by longshore drift; the landforms therefore, are considered to be chenier-spits. However, there are also a number of cheniers that display no recurve development. These cheniers are believed to have formed by swash activity normal to the strandline, possibly during phases of higher energy such as storms (Hoyt, 1969; Stapor, 1975). Many of these cheniers are located in the mangrove colonies that become more pronounced north of Mitchellville. The question arises as to whether the cheniers migrated landward through mangrove colonies, or if the mangroves colonised the mudflats and cheniers. The landward migration of cheniers during higher energy conditions has been described by Jennings and Coventry (1973), but in such instances the destruction of mangrove has occurred. No such destruction is discernible in the area under consideration. It is more probable that the cheniers formed on the seaward edge of the mangrove colony (upon the prograged mudflats), with mangrove colonisation occurring subsequently to seaward. At present, there are new stands of mangrove at numerous locations along the coast with only mudflats developed to seaward, supporting this scheme of progradation.

Howsoever it may be, detailed research beyond the province of this investigation is necessary to resolve the question satisfactorily.

3.5 Conclusion

The characteristics of coastal landforms associated with Holocene progradation vary spatially in terms of the types of landforms found, and the sediments of which these features are constructed. In the southern section of the study area, quartz sands predominate. In conjunction with a steeper offshore gradient and longer fetch, rhythmic beach forms and foredunes are the norm. Where the Utera dunefield abuts the coast, beach ridges and foredunes are located in areas of slightly higher elevation, with chenier-spits, constructed over mudflat sediments, deposited in low-lying embayments. In the south, these features are largely constructed of quartz sand and minor shell (whole and fragmented), but with increasing distance to the north, the proportion of shell increases. Further, the percentage of fines within both the ridges and the swales increases to the north.

3.6 Evidence Against Dune Submergence by Faulting

It is probable that the Utera dunes did at one time cross the floor of Spencer Gulf, and were continuous with the relict dunes of Yorke Peninsula. However, it may be suggested that the Utera dunes were deposited at a time when the sea stood at or near its present level and that faulting caused only the submergence of the eastern margins of the dunes. Certainly the area is bounded on both sides of the gulf by faults where minor seismic activity continues to the present (Sutton and White, 1968).

A number of factors however, argue against dune submergence by faulting in the recent past. First, streams dissecting the 'dirt scarps' (Miles, 1952) are short, steep-graded and intermittent (Fig. 2.2), and while it is difficult to ascertain the exact age of these streams, there is no evidence of recurrent uplift or lowering of baselevel, such as valley-in-valley forms. Second, and more importantly, it can be demonstrated that no movement has occurred along the faults during the Holocene.

Holocene beach ridges and cheniers along western Spencer Gulf examined in this investigation, are essentially level over considerable distances, indicating that warping has not occurred. It may be that the entire eastern seaboard of Eyre Peninsula between Franklin Harbour and Whyalla has subsided uniformly, but this would entail simultaneous, tectonic dislocation of the same magnitude along a number of faults. Further, the elevation of beach ridges and cheniers above present sea level along eastern Eyre Peninsula, is the same as reported from the coast of eastern Spencer Gulf (Burne, 1982). These ridges have developed on both sides of the gulf in response to Holocene sea levels up to two metres above present level. Similarly, Holocene shingle ridges north of Whyalla were deposited by an higher stand of the sea, and are not disturbed by tectonism (Hails and Gostin, 1978; Gostin et al., 1981). Further, Gostin (Gostin et al., 1981) states that a sedimentary feather edge of calcareous clays defines, in part, the maximum extent of Pleistocene submergence, and, because of its uniform elevation, indicates that tilting of the coast has not occurred since the late Pleistocene.

The evidence suggests that tectonism has not occurred during the Holocene. More importantly, if tectonic subsidence did submerge the Utera dunes during this time, then the beach ridges and cheniers must have been deposited relative to an Holocene sea level even greater than +2 m, which, when compared with Holocene sea level data from other areas, seems highly improbable.

Sea level has not stood at or about its present position (prior to the Holocene) since the last Interglacial, approximately

120,000 years ago. The data suggest that at that time, sea level was up to 3 m above mean sea level (Gostin _et al_., 1981). If the elevation of the Utera Plain has not altered since the last Interglacial, then, any dunes that were developed upon the plain would have been eroded farther to the west than the current limits of Holocene marine intrusion, but this is not so. However, if the plain stood at a higher elevation, and has subsequently subsided, then marine erosion of the dunes would have occurred farther east, in what is now Spencer Gulf, and any evidence would have been removed by rising Holocene sea level. Howsoever it may be, it is obviously essential to determine the absolute age of the relict dunes.

CHAPTER FOUR

THE AGE OF THE RELICT UTERA DUNES

4.1 Introduction

Although it is generally accepted that during glacial periods some parts of the world experienced marked aridity, rather than pluvial conditions as was previously assumed, it remains to determine accurately when aridity occurred over eastern Eyre Peninsula. The now stabilized Utera dunes attest to a period of increased aridity, but when were they deposited?

Jessup (1968, a & b) believed that the longitudinal dunes of Yorke Peninsula and northeastern Eyre Peninsula were deposited during two arid periods, the Last Interglacial and the mid-Holocene. There may have been two cycles of dune formation on Yorke Peninsula, the main area of Jessup's research, but the available evidence indicate only one phase of dune development on northeastern Eyre Peninsula, although Williams (1973) has shown that some seif dunes were formed during the Holocene on the Lake Torrens Plains, 200 km north of the Utera dunefield. Also, it appears that many areas were more humid than at present during the mid-Holocene (Jennings, 1975; Bowler et al., 1976), while Dodson (1974) has stated that there was not sufficient hydrological stress in southeastern South Australia and western Victoria to induce large-scale aeolian activity at that time. Howsoever it may be, an Holocene age cannot be discounted at this juncture.

In an effort to establish an interglacial age for the dunes of Yorke Peninsula, Jessup correlated the development of dunes and associated palaeosols with supposed higher stands of the sea during the Quaternary. The alleged evidence for such high stands consists of flights of (marine?) terraces recognized on the coasts of Europe (Deperet, 1906, 1918; Gignoux, 1913) and of Africa (de Lamothe, 1911), but these terraces are known to be tectonically disturbed (Castany and Ottman, 1957). Further, in the absence of Antarctic deglaciation, sea level would not have stood higher than approximately 10 m above present during the interglacials (Mesollela et al., 1968; Broeker et al., 1968; Broeker and Van Donk, 1970; James et al., 1971; Thurber et al., 1965; Veeh, 1966; Veeh and Chappell, 1970; Bloom, 1967, 1970, 1971). Thus Jessup's dating of the Utera dunes by correlation with the Mediterranean terraces is open to question while the evidence for very high stands of the sea in South Australia (Tindale, 1933; Bauer, 1959; Ward and Jessup, 1965) have been repudiated (Twidale et al., 1967).

Howsoever it may be, it is necessary to establish accurately the age of the Utera dunes by radiometric analysis. To this end, calcrete developed within the dune profile was dated, and the age derived, verified by radiocarbon dating stratigraphically superimposed samples of shell and other organic material.

4.2 Dating of Calcrete

Radiometric dating, by measuring the variation in the ratio of isotopic carbon C-14 to C-12, is one of the most important methods of dating late Quaternary events as carbon is contained in all living matter, as well as forming a chemical precipitate as in calcrete. There are a number of basic problems associated with all carbon dating such as, isotopic fractionation, reservoir differences and contamination of the sample after deposition by either C-14 rich or depleted materials such as groundwater. These problems have been expressed and discussed in detail by Polach (1975). Further, statistical error renders invalid results beyond 40,000 years for the majority of laboratories, although some, such as Groningen, can reach to approximately 70,000 years. Thus, if the dunes are, in fact, Last Interglacial (approximately 120,000 years), then they are beyond the range of radiocarbon dating in any event.

In theory, the dating of calcrete, which is a calcareous precipitate, presents greater problems than for organic carbonates. For calcrete to form, carbonate must be mobile within the soil profile, a factor which can lead to contamination of any material collected for dating. The problems of dating calcareous materials from soils, and in particular from palaeosols, have been examined by Williams and Polach (1969), Bowler and Polach (1971) and Williams and Polach (1971). One such problem is to determine whether a calcrete layer is in situ or has been reworked, for if reworked, the age of the calcrete is established but not the age of the landform to which the calcrete relates stratigraphically.

It can be shown however, that the calcrete of the Utera Plain has not been substantially reworked. As described above, the calcrete has formed pedogenically within the dune profile. The dunes, therefore, predate the time of calcrete formation, and for calcrete to be reworked it is first necessary to erode the dune. A calcrete sample taken from beneath the dune can therefore be considered to be in situ, and a date derived from such a sample would approximate the time of formation of the calcrete layer.

A large sample of calcrete was collected from beneath a dune adjacent to the Lucky Bay road, where recent excavation had exposed the calcrete layer. At a point approximately half way up the calcrete profile, the edge of the calcrete was removed by hammer and shovel. From within this excavation a large nodule of calcrete was collected.

Greater accuracy can be obtained by choosing a nodule of calcrete where visible alteration, and hence possible contamination, is absent. Further, if this sample is collected from the approximate middle of the calcrete layer it would yield an average

age for the time of formation of the entire layer. In theory, a concretionary nodule should have the least amount of contamination at the centre of the nodule. If the central zone is dated, possible contamination error would be further minimized.

While the dating of any carbonate material poses a number of problems, that of dating calcareous palaeosols presents greater problems than most. However, in many cases it is the only means of dating available, and it has been used extensively at a number of locations, both in Australia and elsewhere (see, for example, Geyh and Jakel, 1974). Further, it has been shown (Bowler and Polach, 1971) that results obtained from calcareous soil deposits developed at the lower (arid) limit of the rainfall gradient are more reliable. Cowell, approximately 5 km from where the radiocarbon dated calcrete sample was collected, has a mean annual rainfall of 285 mm, considerably below the suggested optimum rainfall for calcrete development (4-500 mm), thus increasing considerably the reliability of the age obtained.

The calcrete, and all other samples from the Lucky Bay area, were dated by Geochron in the USA. The calcrete sample was trimmed to remove any alterations and crushed to homogenize the sample. Using a Libby half-life of 5570 years, a C-13 corrected age of 11,825± 295 years was obtained (GX-4778, Table 4).

Financial restraints determined the number of samples of materials that were dated radiometrically. Shell and marine sea grasses - more reliable materials for carbonate dating - that are superimposed upon the calcrete were dated in order to cross-check the validity of the calcrete date. Further, these marine deposits were dated in order to establish the chronology of coastal progradation as described above. In retrospect, however, additional calcrete samples would have provided greater support for the age of the dunes suggested below, and should have been undertaken.

TABLE 4

RADIOCARBON DATES

LOCATION	NUMBER	AGE B.P.		MATERIAL
Utera Plain	GX-4778*	11,825 ± 295)		Calcrete
Central Eyre Peninsula	Gak-4071	10,310 ± 190)		"
	Gak-4072	16,690 ± 440)	Bourne et al. 1974	"
	Gak-4351	26,940 ± 1,200)		"
	Gak-4639	15,780 ± 350)		"
	Gak-4352	22,040 ± 760)		"
Lake Torrens Plains	ANU-281	12,050 ± 160)		Calcrete
	ANU-280	16,160 ± 250)		"
	ANU-100	14,840 ± 250)		"
	ANU-132	12,540 ± 150)		"
	ANU-295	30,880 ± 1,200) + 4,090)	Williams, 1973	"
	ANU-296	35,000 ± 2,860) + 2,300)		"
	ANU-226/2	35,010 - 1,700)		"
	ANU-227/2	28,780 ± 1,100) + 2,400)		"
	ANU-297	32,180 - 1,840)		"
	ANU-298	22,160 ± 500)		"
	ANU-299	27,600 ± 1,000)		"
	ANU-127	20,310 ± 360)		"
	ANU-226	31,360 ± 1,000)		"
	ANU-227	22,290 ± 450)		"
	ANU-225	25,600 ± 680)		"
	ANU-264	22,900 ± 500)		"
	ANU-228	23,450 ± 550) + 2,130)		" "
	ANU-300	33,270 - 2,130)		"
Lucky Bay	GX-477*	5,010 ± 190)		Shell
Coastal Zone	GX-4774*	4,150 ± 130)		Shell
	GX-4775*	1,650 ± 125)		Shell
	GX-4777*	1,245 ± 135)		Organic matter

TABLE 4

RADIOCARBON DATES

LOCATION	NUMBER	AGE B.P.	MATERIAL
Blanch Harbour	ANU-2386*	-2,870 ± 90 B.P.*	Shell
	ANU-2388*	-9,080 ± 130 B.P.*	Shell
Black Point	ANU-2387/2*	5,440 ± 120 B.P.*	Shell
	ANU-2387/1*	117.1% ± 2.0% B.P.	(Greater than modern) shell

* Samples dated in this study

4.3 Dating of Marine and Organic Deposits

The presence of shell within the swale embayments allows the time of embayment to be dated radiometrically, and since the stratigraphic relationship of the embayments with the dunes is known, a further delineation of the time of dune formation is possible. Shell samples were collected from two embayments, both from the Lucky Bay area. The first was taken approximately 1 km inland from the coast, while the second sample came from a similar embayment 2 km farther north.

Sample one (GX-4473), corrected for isotopic fractionation, gave an age of 5010 ± 190 B.P., while sample two (GX-4774) was slightly younger at 4150 ± 130 B.P. (Table 4). Corrected for oceanic reservoir effects (Stuiver and Polach, 1977; Rhodes et al., 1980) by 450± 35 years, these ages are 4560 ± 187 B.P.* and 3700 ± 125 B.P.* respectively.

Seaward of the embayed swales at Lucky Bay, a series of beach ridges parallel the coast. Overall, the swales separating these ridges stand above present H.W.L., and are infilled with fine lagoonal deposits. Marine sediments, consisting of sea grasses and shell, overlie the calcrete duricrust developed in the area and are emplaced seaward of the embayed dune swales, thereby affording a further means of testing the validity of the age of the dated calcrete and the shell matter from the embayments.

Shell taken from a swale at a depth of 80 cm, and a sample of organic matter overlying the shell bed were radiocarbon dated. The shell material gave an age of 1650 ± 125 years B.P. (GX-4775, Table 4) or 1200 ± 130 B.P.* corrected for oceanic reservoir effect. The overlying organic material dated at 1245 ± 135 years B.P., corrected to 795 ± 139 years B.P. (GX-4777).

These dates are in accord with those obtained from north-eastern Spencer Gulf (Burne, 1982) and from the St Kilda Formation near Adelaide, (Firman, 1968) South Australia, which represents a late-Holocene progradation of the coast in this area. Thus, the dates derived from the four samples, all of which are superimposed upon the calcrete, lend support to the age obtained for the calcrete sample.

4.4 Correlation to Dated Calcrete in South Australia

The validity of the calcrete date is further supported by the dates available from other calcrete samples (from Eyre Peninsula and from near Lake Torrens) that have been dated. Bourne (Bourne, et al., 1974) lists calcrete dates from Eyre Peninsula of 10,310±190 (Gak 4071); 15,780±350 (Gak 4351); 16,690±440 (Gak 4072); 26,940±1200 (Gak 4639); 22,040±760 (Gak 4352). Farther north, Williams (1973) has dated carbonate nodules from two palaeosols developed on the Lake Torrens plain. The Wilkatana palaeosol dated at 20-35,000 B.P. while the younger Motpena carbonates ranged from 12-16,000 years B.P. (Table 4). The Cowell sample would therefore appear to be contemporaneous with the Motpena calcrete. In addition, 20 km south of the study area at Red Banks, a second, older calcrete layer occurs lower in the stratigraphic profile and may, in all probability, be the equivalent of the Wilkatana palaeosol. Such a calcrete layer appears to exist beneath the Utera Plain, as at times the auger struck a solid, partially calcareous layer that it could not penetrate. As the Utera Plain is underlain by unconsolidated sediments to depths of up to 90 m, it is probable that this layer is a calcrete duricrust, although its exact characteristics are not known. Also, it is difficult to envisage calcrete forming over a considerable area of Eyre Peninsula, including the Red Banks area where seif dunes are also present, and not developing beneath the Utera Plain.

While it is problematic whether calcrete layers should be used as time-stratigraphic markers, such as has been done with the Ripon calcrete of the Murray Mallee, these calcretes do indicate that the climatic conditions conducive to calcrete formation prevailed during the periods of time obtained by radiometric dating.

4.5 The Age of the Utera Dunes

After examination of the available stratigraphic and radiometrically dated evidence, the question still remains as to when the Utera dunes were deposited. The time of formation was one of increased aridity, but did such aridity occur during a glacial or interglacial phase? Jessup (1968, a & b) had postulated that the longitudinal dunes of Yorke and northeastern Eyre Peninsulas were developed during the mid-Holocene and Last Interglacial but, as discussed above, his dating technique is open to question, especially in relation to an interglacial time of formation. However, could the dunes be Holocene features?

Williams (1973) has provided evidence from near Lake Torrens that limited dune formation occurred during the Holocene, but that environment is more arid than northeastern Eyre Peninsula, including the Utera Plains. Increased aridity during the mid-Holocene has been postulated, consequent upon the higher temperature that prevailed, but higher temperature would, in all probability, have led to increased rainfall, not aridity. (Kershaw, 1971; Bowler, 1975; Jennings, 1975).

Further evidence against a mid-Holocene age is provided by the radiocarbon dates described above. Shell and organic matter of mid-Holocene age embay the seif swales, indicating that the dunes were present at that time. It may be suggested that the formative period of the dunes occurred immediately prior to marine incursion, but this hypothesis is refuted by the age of the calcrete. The calcrete layer cementing the dune cores is of the order of 12,000 years and, according to the mode of origin suggested, formed within the dune; the dune therefore predates the calcrete, but by what time period?

In order to resolve this question, the time required to develop a calcrete duricrust must be known. However, although a number of estimates of formation time have been proposed, considerable disagreement exists. On the one hand, it has been demonstrated that calcareous deposits have developed in less than 100 years in certain localized environments (Smith et al., 1976). In contrast, Goudie (1973), after assessing the information available from a number of different locations, suggests the formation time is more of the order of 3-6,000 years. Goudie's values indicate that the calcrete cementing the dunes began to be deposited within the range of 15-18,000 years. Similarly, other calcretes from Eyre Peninsula (Bourne, et al., 1974) and from the Lake Torrens Plain (Williams, 1973), indicate that a calcareous duricrust was, in part, present by about 16,000 B.P.. The dunes therefore, can not be Holocene features as they predate calcrete formation.

That the dunes were deposited during the Last Interglacial can also be refuted. In the first instance, Jessup's (1968, a & b) dating technique, the correlation of the dunes with higher stands of the sea, is open to question in the absence of any radiometric dating.

Jessup's thorough investigation of palaesols and high-level marine deposits of Yorke and northeastern Eyre Peninsulas, concluded that the Yorke Peninsula dunes had formed before the '12 foot' (3.75 m) high sea level. The fact that the dunes proceed below sea level was explicable in that it was assumed that aridity occurred immediately before and after high stands of the sea. The Cunliffe palaeosol (Jessup, 1968 b) was deflated down to a calcrete horizon and acted as a sediment source for the seif dunes, although Jessup suggests that the seif profile is not related to the underlying calcrete horizon, but merely overrides it. Most important however, is the fact that the dunes do not overlie marine deposits due to the '12 foot' sea level; that is, the dunes predate this higher sea level.

Jessup's chronology of events, using long-range correlation with Mediterranean sea levels, suggested that the '12 foot' sea level occurred during the Last Interglacial, 70-85,000 years ago. Additional evidence for such a stand of the sea was described from northeastern Eyre Peninsula, where marine deposits containing Anadara trapezia are found. These deposits are essentially the shingle ridges described by Hails (1978), and were believed, at first, to be late Pleistocene features.

During the course of this investigation, these shingle ridges were examined in detail, with shell samples other than Anadara collected for radiocarbon dating (Van Deur and Polach, in prep.). The shell samples from between Port Augusta and Blanche Harbour comprised mainly Katelysia corrugata with some Anapella pinguis. From another series of shingle ridges near Black Point, immediately north of Whyalla, shell samples, consisting of Trochidae (in particular, Fractarmilla concamerate) and Anapella pinguis, were collected for dating. The results (Table 4 ANU-2386, 2387/1, 2387/2, 2388) all indicate that the shingle ridges are Holocene features. The dunes therefore, could not be Last Interglacial in age on the basis of the evidence cited by Jessup.

The above evidence however, does not exclude entirely the suggestion that aridity and dune formation occurred while sea level was either falling to, or rising from a glacial-low position. The sea has stood below present level since the Last Interglacial and, during interstadials, was of the order of 20m below present (Bloom et al., 1974), and thus it can be argued that the Utera (and Yorke Peninsula) dunes may have been deposited at any time over the last 120,000 years.

However, at a number of locations on Eyre Peninsula a second, stratigraphically lower calcrete duricrust is present, while the available evidence from the Utera Plain supports the existence of such a layer. Radiocarbon dating of this calcrete (Williams, 1973; Bourne, et al., 1974) has yielded ages of between 20,000 and 35,000 years (Table 4). The Utera dunes overlie this lower calcrete and are not cemented by it, while a layer of fluvial sediments beneath the upper calcrete horizon, that separates the two duricrusts, indicates two distinct phases of carbonate accumulation. Thus it would appear, on the basis of the available data, that the dunes were deposited at some time between the development of the two calcrete layers; that is between about 17,000 years and 20,000 years before present. Aridity and dune formation occurred at some point between these two periods of calcrete development, but this encompasses the time of maximum glaciation, and thus, is contrary to Jessup's suggestion that glacials in this region were periods of greater moisture availability.

CHAPTER FIVE

PALAEOCLIMATES OF NORTHEASTERN EYRE PENINSULA

5.1 Correlation of Palaeoclimates with Glacial/Pluvial Theory

The Utera dunes, presently stabilized by vegetation on both the crests and the flanks, attest to northeastern Eyre Peninsula having experienced greater aridity at some time in the past. As the dunes plunge below sea level, but were not drowned by tectonism, they must have formed at a time of lower sea level. Previous theories concerning late Quaternary climates held that during glacial periods, non-glaciated regions experienced pluvial conditions (Taylor, 1868), while interglacials were arid. However, if low sea levels occurred during glacials, and glacials were pluvial, how could these dunes have formed at this time? Jessup (1968, a & b) attemped to accommodate this contradiction by suggesting aridity occurred during interglacials, but before sea level had attained its maximum height. However, the time of formation, as indicated by radiometric dating, is between 17,000 and 20,000 years, at which time sea level was at its lowest. Thus, the association of glacial with pluvial must be questioned.

The association of glacial with pluvial can be traced to the last century (Jamieson, 1863; Russell, 1885; Gilbert, 1890), but all these workers were concerned with areas marginal to former ice sheets and their evidence and arguments are not necessarily relevant to the nature of climatic change in areas distant from the ice sheet. Nevertheless, Hull (1885), basing his conclusions upon observations made in the Palestinian desert, suggested that glacials were synchronous with pluvials. Further alleged evidence was introduced from East Africa (Nilsson, 1931), and from the area of the Nile and the Jordan valleys by Wayland (1934). Consequently, the Pan-African Congress, organized by Leakey in 1947, recognized four pluvial sequences by correlation with the major glacial periods established on the basis of stratigraphy in Europe and North America (Venetz, 1833; Charpentier, 1835; Agassiz, 1840; Penck, 1905).

Since the Pan-African Congress, new evidence concerning Quaternary palaeoclimates cast doubts upon not only the number of pluvial and arid phases, but the correlation of pluvial with glacial, and arid with interglacial periods. Foraminiferal evidence from deep sea cores (Emiliani, 1955, 1958, 1966, 1972; Shackleton and Opdyke, 1973, 1976), and the re-interpretation of terrestrial sequences in Europe (Kukla, 1977) indicates that rather than there having been only four glacial/interglacial cycles over a period of 0.8 m.y., seventeen of these cycles have occurred during the last 1.7 m.y..

More germane to this investigation are the recent findings from Africa and Australia which question the basis of the glacial-pluvial association. For example, changes in the depth and area of Lake Chad have been extensively studied (Grove and Pullen, 1964; Grove and Warren, 1968), as well as parts of the Niger Basin (Grove and Warren, 1968), of Senegal (Tricart, 1957, 1961; Chamard and Morin, 1973), and of the Sudan (Warren, 1970). Similar research has been undertaken in East Africa (Bakker, 1962; Butzer, 1972; Coetzee, 1972), Ethiopia (Grove, Street & Goudie, 1975; Street and Grove, 1976) and the Nile Basin (Butzer and Hansen, 1968), although the data from the latter area are somewhat limited.

It is concluded from these investigations (Selby, 1977), in conjunction with further evidence from North Africa, that although climatic conditions were moist between 30-40,000 years ago, during the last glacial maximum aridity dominated over much of the African subtropics.

Evidence of former aridity in the form of relict dunes has also been reported from Australia (King, 1956; Wopfner and Twidale, 1967; Twidale, 1972; Bowler, 1971, 1973, 1976, 1977; Bowler et al., 1976; Sprigg, 1965, 1979). Bowler's studies indicate a moist period occurred from 25-40,000 years ago, followed by increased aridity which peaked between 18-24,000 years B.P.

The unqualified association of glacial periods with pluvial conditions therefore cannot be maintained. Certainly there were times when climatic conditions were more akin to the present, but during the glacial maximum greater aridity prevailed over northeastern Eyre Peninsula. However, were climatic conditions substantially or only marginally different from the present? To resolve this question it is necessary to compare present conditions and former climates, insofar as the latter may be inferred from the available data.

5.2 Comparison of Current Climate with Palaeoclimates

Eyre Peninsula, which covers an area of 33,200 sq. kms, lies between latitude 32 and 35 degrees south, while the study area is about latitude 33°39'S, longitude 137°11'E. Climatically, the region is classified as semi-arid (Koppen Bsh) with rainfall increasing from 250 mm in the northeast to 500 mm in the vicinity of Port Lincoln.

Though the region is semi-arid in terms of the quantity of rainfall, this deficiency is to some extent compensated for by the distribution pattern of precipitation. Thus, the majority of rain falls during the winter months, the summers being dry except for occasional rains. In the south, Port Lincoln has a median rainfall of 8 mm in January while Whyalla experiences a similar amount of 7 mm. During winter, however, Port Lincoln has a median of 74 mm compared to Whyalla's 22 mm. This northern reduction in rainfall is matched by an increase in the rates of potential evaporation from south (1800 mm) to north (2400) during January, which continues, albeit at lesser amounts, throughout the year. What rain does fall is therefore less effective from south to north. While the effectiveness of this rainfall is enhanced by the winter concentration, it is nevertheless sufficient to allow the growth of a natural vegetation comprising low mallee woodland.

Winter rains are the result of frontal cyclonic activity associated with wave depressions which originate in high latitudes and migrate eastwards across the Southern Ocean and Great Australian Bight. During summer these wave depressions are forced south by the southward migration of the high pressure cells. As Eyre Peninsula lies well south of the influence of the summer monsoons which affect northern Australia, the summers tend to be arid.

Temperatures are moderate to high, with an increase in diurnal and seasonal ranges from south to north as a consequence of increased continentality. Thus for January, Cleve has a mean maximum of 28.3^{o} and mean minimum of 15.6^{o} (range 12.7^{o}) while Port Lincoln has values of 25.5^{o} and 15.7^{o} (range 9.8^{o}) respectively. During the winter months these figures drop to a mean maximum of 14.8^{o} and minimum of 6.8^{o} for Cleve while the comparative values for Port Lincoln are 15.9^{o}. and 8.4^{o} respectively. The winter range for Cleve during July is therefore 8.0^{o} on comparison to Port Lincoln's 7.5^{o}. The seasonal range for Cleve is 13.5^{o} while Port Lincoln's is 9.6^{o}, seasonal variation being greater on average than diurnal variation. Heat waves with continuous days of temperatures over 38.6^{o} occur, on average, five to six times per summer. On the coast these conditions are rarely sustained for more than two consecutive days, but inland the average period for a heat wave is three days.

Humidity, like rainfall and temperature, decreases towards the north, diurnally and seasonally. During July the mean humidity for Cleve at 0900 is 77%, falling to 61% at 1500 hours. Port Lincoln for the same period and times, experiences humidity of 81% and 67% respectively. During December the humidity values for Cleve are 44% and 33%, while Port Lincoln has averages of 65% and 54%.

Within the study area the nearest recording station is located at Cowell where data have been collected since 1885. Over this period the mean annual rainfall is 285 mm with a median of 273 mm, and a mean number of raindays of 84 which occur between April and October. Inland at Darkes Peak rainfall increases to 395 mm on average, with a median of 402 mm. It is suggested (Meteorological Survey, 1961) that there is a decrease in rainfall from west to east, the Cleve Hills exerting a topographical influence, placing the Utera Plain and Cowell in a partial rainshadow. Overall, however, climatic conditions are such that growth of vegetation is sufficient to stabilize the longitudinal dunes within the area. Deflation and 'desertification' are largely the consequence of land clearing accompanying settlement.

While the Utera dunes indicate aridity, evidence to allow precise estimates of palaeotemperature and precipitation are not forthcoming, but may perhaps be inferred from data obtained elsewhere in Australia.

Foraminiferal evidence from oceanic cores confirms and quantifies lower palaeotemperatures during the glacials, although not without some controversy (Shackleton, 1967), but similar quantified information is conspicuously absent from continental sites. From the New Guinea Highlands (Flenley, 1967; Powell, 1970; Hope and Peterson, 1975), and Australian Alps (Costin and Polach, 1973, a reduction of 10^{o}-11^{o} has been proposed. Further Australian enumerations are summarised and discussed by Bowler et al., (1976) but they, and others (eg Butzer, 1972; Rognon and Williams, 1977), rightly refrain from generalizing beyond the immediate area of investigation, especially to the semi-arid/humid boundary of southeastern Australia. Thus, in all probability, the Utera Plains were cooler than at present, but by what precise amount is not known at this juncture.

Similarly, estimation of precipitation levels poses a number of problems insofar as much alleged evidence for higher precipitation (eg vegetational changes to more moisture demanding species, and especially higher lake levels) is equivocal and equally explicable in terms of decreased evaporation rates - which increases moisture efficiency - consequent upon cooler temperatures. (Galloway, 1965, a & b).

For dunes to form, the erosional and transportational ability of sand-moving winds (10 knots) must overcome those agencies that stabilize sand-size sediments, in particular vegetation. It has been argued (Sprigg, 1979) that aeolian processes will operate even where considerable stands of vegetation exist if the prevailing winds are of consistently high velocity, as for example in northeastern Tasmania. However, it is more often than not the case that aeolian processes are brought into play by a reduction in the cover of stabilizing vegetation resulting from increased aridity.

The Utera dunes formed during such a period of enhanced aridity corresponding with the last glacial maximum, the degree of which may be estimated but not conclusively known. For inland sand transport to occur, precipitation under a lower, critical level must occur. Above this quantity of rainfall, moisture availability is sufficient to allow a stabilizing vegetative cover. The estimates for such a lower limit range from 100 mm in Australia (Mabbutt, 1971), to 200-275 mm in India (Goudie et al., 1973). Average annual rainfall for sites on northeastern Eyre Peninsula, ranges from 275 mm (Whyalla) to 285 mm (Cowell) and 403 mm (Cleve), but in all instances provides adequate moisture to support a stand of mallee scrub that stabilizes the Utera dunes. The critical limits suggested by Goudie (Goudie, et al., 1973) are not significantly different from the contemporary rainfall values for Cowell and Whyalla, and, as the dunes indicate greater aridity in the past, Mabbut's lower estimate is probably more accurate in this instance.

A number of factors complicate this estimation however. Certainly a value as low as 100 mm takes into consideration the increased efficiency of any moisture available due to lower evapo-transpiration rates, itself related to lower temperatures prevailing at that time. However, this supposition is open to question as the higher wind speeds operating at this time (Galloway, 1965 a & b) would have increased the evaporation rate. Thus, any decrease in evaporation rates due to lower temperature may have been offset by higher wind speeds increasing evaporation.

While changes in the intensity of anticyclones and the migration of the westerly wind pattern by about 5° have been cited (Wyroll and Milton, 1976) as possible factors producing aridity, Bowler (1976) suggests that, by itself, these factors would not account for relict dunes, lunettes or lowered lake levels in Australia. Rather, it was lower moisture acting in concert with higher wind velocity, thereby increasing evapotranspiration, that resulted in increased aridity. Bowler equates such conditions with high frequency outbreaks of hot, dry, continental air masses in summer, travelling in a south-easterly direction from the interior of Australia. Such increased wind velocity and frequency are believed to result from an increased pressure gradient between pole and equator (Lamb, 1972; Barry and Chorley, 1971; Webster and Streten, 1978). Supporting evidence for this theory, although at some remove, is found in the increased size and quantity of aeolian sediments deposited offshore (Parkin, 1974; Parkin and Shackleton, 1973; Diester-Haas, 1977).

At this juncture however, there is insufficient concrete data to confirm or refute whether wind speeds were higher than at present at the time of dune deposition, and whether or not such increased wind velocity was a contributing factor in producing aridity in the study area. At the present time, where clearing of vegetation has exposed the land surface, there is sufficient wind strength to promote active deflation.

In conclusion, it is probable that rainfall was lower than at present, perhaps as low as 100 mm, and that moisture efficiency was enhanced, if only marginally. Such aridity might have been intensified further by higher wind speeds, although there is no firm evidence to this effect. Also, at this stage, it is not possible to enumerate variations in temperature that occurred.

The presence of calcrete, which is suggested to develop under prescribed climatic conditions, indicates an amelioration of climate, away from aridity, some time after about 17,000 years B.P.. Pedogenic calcrete is believed to form in areas receiving at least 400-500 mm of rainfall distributed seasonally; a warm to hot, dry season being necessary to promote the upward migration and precipitation of carbonate (Mosely, 1965; Goudie, 1973). Such values are significantly higher than the rainfall received between Cowell and Whyalla, where calcrete is well-developed, implying that rainfall may have been higher than at present at some time after the cessation of aridity. However, such logic is open to question as the exact environmental conditions conducive to calcrete development are not understood fully. It has been suggested, for example, that carbonate deposition is occurring at present in the Simpson Desert and arid, northern Eyre Peninsula (C. R. Twidale, pers. comm.). Thus it is possible that the Utera calcrete has developed in response to a climate either similar to or only marginally different from that prevailing at present.

In summary, the presence of calcrete suggests the end of an arid phase during which time dunes, that are now relict features, were deposited. This calcrete layer began to form some 17,000 years ago, indicating that aridity was becoming less severe from that time. Further, a stratigraphically lower calcrete has minimum ages of about 20,000 years, suggesting climatic conditions conducive to carbonate deposition prior to that time. Aridity, therefore, prevailed between 17,000 and 20,000 years ago. This is the time of the Wurm glacial, further supporting the theory that glacial phases were arid. In particular, the evidence from north-eastern Eyre Peninsula correlates aridity with the glacial maximum and suggests that the actual time period of aridity is relatively brief, of the order of 2,000 to 3,000 years, in this area.

CHAPTER SIX

CONCLUSION

"The concept that "pluvial" conditions and soil formation prevailed in continental Australia during glacial periods, and that sandy deserts formed largely during interglacials, should be discarded.'

(Williams, 1973 p. 123)

As the formative processes of landform development and the climatic conditions under which they operate became better known, so it has become clear that many, if indeed not most, landforms are wholly or partially discordant with climatic conditions prevailing at present. Relict landforms include lacustrine features alluding to higher rainfall or run-off, while sand dunes attest to increased aridity, such climatic fluxes having occurred during the Quaternary.

In non-glaciated environments, higher lake levels were temporally correlated with the four glacial phases established in Europe and North America, and were presumed to result directly from increased precipitation or 'pluvials'. In contrast, aeolian landforms eroded or deposited during arid phases, were believed to have been created during interglacials. In summary, glacials were associated with pluvials and interglacials with aridity for all non-glaciated areas during the Quaternary. In recent years, however, this conventional sequence of glacial chronology has been challenged and found incorrect, for the radiometrically determined age of many relict aeolian landforms suggests that they formed during the last, glacial maximum. It would appear, contrary to previous theory, that parts of glacials were arid and not humid, and perhaps, interglacials were moister than present conditions.

The relict Utera dunes of northeastern Eyre Peninsula, stabilized under the present climatic regime, act as indicators of palaeoclimatic conditions of greater aridity. These dunes were alleged to have formed during the Last Interglacial and during the mid-Holocene (Jessup, 1968, a & b), but at a number of locations transgress the coast and plunge below Spencer Gulf, suggesting that they formed during a period of low sea level (in the proven absence of tectonism.) Eustatic control during the Quaternary was mainly glacial, with lowered sea level resulting during glacial periods. Thus the Utera dunes and their drowned counterparts below Spencer Gulf question an interglacial time of formation. Further, the dunes raise a number of problems, in particular their age, origin and means of survival.

The purpose of this study was to answer the questions raised by the submerged sections of the Utera dunes. That the submerged features were, in fact, dunes and relate to the Utera dunes, was resolved by an examination and comparison of the sediments comprising both the submerged landforms and the relict Utera dunes. On aerial photographs the submerged features appear as linear continuations of the seif dunes, separated by a belt of beach ridges and cheniers. Surface examination however, reveals that the 'submerged dunes' are little more than low rises of calcrete, which constitutes the broad intertidal platform. In detail, (as revealed by thin section analysis) the sediments are subangular to subround quartz grains cemented by micrite. Small 'towers' of sand grains cemented in this fashion are located upon the intertidal rises at a number of locations, which in conjunction with thin sections, were compared with samples of sand obtained from the relict dunes of the Utera Plain. The latter were noted to be subround and subangular and showed similar surface features to the sediments from the rises. Further, by coring into the dunes and the intervening swales, it was revealed that calcrete underlies both features, but, significantly, rises to a higher elevation beneath the dune.

The lower horizon of the dune has, therefore, been indurated by calcium carbonate, and it is these rises which are present upon the intertidal platform and proceed below sea level; the overlying, unconsolidated dune sands have been eroded, intermixed with marine sands and deposited as beach ridges and cheniers. Sediments from beneath the Utera swales, consisting of fluvial and colluvial deposits derived from the metasediments of the Cleve Hills to the west, were also analyzed and compared to sediments recovered from between residual dune cores, the previous swales. It was found that the sediments were the same from both locations. They consist of ill-sorted grains of quartz and feldspar, with minor amounts of other minerals. It was concluded that the submerged features were remnants of the Utera dunes, expressed as low residual cores of micrite cemented dune sands.

Although a number of fault scarps situated to the west of the Utera Plain allow a tectonic explanation for dune submergence, the plain either having been downfaulted or subsided, Holocene beach ridges and cheniers, and late Pleistocene marine deposits that fringe northeastern and northwestern Spencer Gulf, are undisturbed over long distances, discounting such an explanation. The Utera dunes could only have formed during a period of lower sea level, which effectively discounts interglacial and Holocene ages for the dunes.

It may be argued that interstadial sea levels did not reach the current position, and as such, the dunes may have formed during this period. While climatic conditions prevailing during the glacial maxima and during interglacials are the centre of controversy and much research, both continental and marine, little if any information is available concerning interstadials. In order to refute the hypothesis that dunes formed during these periods, the absolute age of the Utera dunes must be known.

In explanation of the survival of dunes below sea level it was noted that it is only the carbonate indurated dune cores that remain, and that calcrete had developed pedogenically within the dune profile; the dune therefore pre-dates the calcrete. A sample of calcrete revealed an age of about 12,000 B.P. which, in conjunction with other dated calcretes, implies that climatic conditions conducive to calcrete formation came into force about 17,000 years ago.

Aridity, essential for dune development, which must have prevailed before that time, ceased. The validity of the calcrete age was determined by dating shell and organic matter superimposed upon the calcrete and, near the coast, embayed the dune swales. These deposits were all Holocene in age, ranging from 5,000 to 1,400 years B.P. Comparison to dated calcrete from central Eyre Peninsula and Lake Torrens supports the age derived from the Utera calcrete sample. Also, at the latter locations, a second, stratigraphically lower calcrete duricrust has been dated at between 20,000 and 35,000 years B.P., again indicating a non-arid climatic regime. The arid period when the dunes formed is, therefore, believed to have occurred between approximately 17,000 years and 20,000 years ago.

The time period during which arid conditions prevailed on northeastern Eyre Peninsula corresponds with the last glacial maximum of North America and Europe. Glacial phases were synchronous with aridity, not with pluvials as had been supposed. It is not implied that such a conclusion may be extrapolated to other non-glaciated environments in Australia or elsewhere without a detailed analysis and dating of the landforms, relict and contemporary within that area, for while there is an increasing body of evidence to sustain such a conclusion, there is apparently conflicting evidence in other areas.

Inherent in the question of whether glacials were arid or pluvial is the larger dilemma of the factors that induce these conditions. The characteristics of climatic oscillation include: variations in atmospheric circulation patterns (as indicated by the non-alignment of relict dunes and current resultant winds); changes in the ratio of precipitation to temperature and evaporation, and changes in the velocity and frequency of wind. Current research may, in time, clarify or answer the exact nature of such changes. However, the further problem of what produced climatic oscillations during the Quaternary (eg, solar insolation flux), which resulted in the growth and retreat of ice sheets, is even more difficult to ascertain. While such matters are of concern, they are not directly germane to the province of this investigation.

Finally, it is concluded that the submerged features off northeastern Eyre Peninsula are terrestrial dunes and form part of the relict Utera dunes. These dunes were deposited during the last Pleistocene glacial maximum (c. 18,000 B.P.) under conditions more arid than those pertaining at present. For northeastern Eyre Peninsula, the assumption that glacials were pluvials cannot be maintained.

BIBLIOGRAPHY

AGGASSIZ, L. (1840) 'On Glaciers and the evidence of their having once existed in Scotland, Ireland and England. Proc. Geol. Soc. Lond. 3(2), 327-32

BAGNOLD, R. A. (1941) The physics of wind blown sand. Methuen, London

BAGNOLD, R. A. (1953) 'The Surface Movement of blown sand in relation to meteorology' in Desert Research, Res. Council Israel Spec. Publ. 2, 89-93

BAKKER, E. M. VAN ZINDEREN, (1962) 'A late glacial and post-glacial climatic correlation between East Africa and Europe'. Nature 194, (4824), 202-203

BAUER, F. H. (1959) A Regional Geography of Kangaroo Island Ph.D. thesis, A.N.U.

BELPERIO, A. P. (1979) 'Negative Evidence for a mid-Holocene high sea level along the coastal plain of the Great Barrier Reef Province' Marine Geology, 32, M1-M9

BIRD, E. C. F. (1973) 'Australian Coastal Barriers' in M. L. Schwartz (ed) Barrier Islands 410-426

BLANFORD, W. T. (1879) 'On the physical geography of the Great Indian Desert with especial reference to the former existence of the sea in the Indus Valley and on the origin and mode of formation of the sand hills'. J. Asiatic Soc. Bengal, 45, 86-103

BLOOM, A. L. (1967) 'Pleistocene Shorelines : A New Test of Isostasy'. Bull. Geol. Soc. Am., 78, 1477-1494

BLOOM, A. L. (1970) 'Paludal Stratigraphy of Truk, Ponape and Kusaie, Eastern Caroline Islands. Bull. Geol. Soc. Am., 81, 1895-1904

BLOOM, A. L. (1971) 'Glacio-Eustatic and Isostatic controls of sea level since the cast glaciation'. in '<u>Late Cenozoic Glacial Ages</u> (K. Turekian ed.) 355-379 Yale Uni. Press

BLOOM, A. L., W. S. BROECKER, J. CHAPPELL, R. S. MATTHEWS & K. J. MESOLELIA (1974) 'Quaternary sea level fluctations on a tectonic coast: New Th 230/234 dates from The Huon Peninsula, New Guinea.' <u>Quaternary, Res</u>. 4, 185-205

BLOOM, A. L. (1979) Atlas of <u>Sea Level Curves</u> Cornell University.

BOOTHROYD, J. C. (1978) 'Mesotidal Inlets and Estuaries'. in R. A. Davis (ed) <u>Coastal Sedimentary Environments</u>. Springer-Verlag, New York.

BOURNE, J. A., TWIDALE, C. R., SMITH, D. M. (1974) 'The Corrobinnie Depression, Eyre Peninsula, South Australia.' <u>Trans. R. Soc. S. Aust</u>. 98, 139-152

BOWEN, D. Q. (1978) <u>Quaternary Geology</u> Oxford, Pergamon Press

BOWEN, D. Q. (1980) 'Geographical Perspective on the Quaternary' <u>Progress in Physical Geography</u> 3, 167-186

BOWLER, J. M. (1971) 'Pleistocene salinities and climatic change : evidence from lakes and lunettes in S.E. Aust.' in D. J. McIvaney & J. Golson (ed) <u>Aboriginal Man and Environment in Aust</u>. ANU Press 47-65

BOWLER, J. M. & POLACH, H. A., (1971) 'Radiocarbon analysis of soil carbonates: an evaluation from Palaeosols in S.E. Aust.' in D. H. Yaalon (ed) <u>Palaeopedology - Origin, Nature and Dating Palaeosols</u>. International Society of Soil Science and Israel Universities Press. Jerusalem, 98-108

BOWLER, J. M. (1973) 'Claydunes: Their occurrence, formation and environmental significance'. <u>Earth-Sc Rev.</u>, 9 315-328

BOWLER, J. M. (1975) 'Deglacial Events in Southern Aust. Their age, nature, and palaeo-climatic significance. in R. P. Suggate, & M. M. Cresswell (ed) Quaternary Studies. The Royal Soc. of N.Z. 75-82

BOWLER, J. M. (1976) 'Aridity in Australia : Age, origins and expression in aeolian landforms and sediments. Earth Sc. Rev., 12, 279-317

BOWLER, J. M. (1979) 'Glacial Age Aeolian Events at high and low latitudes : A Southern Hemisphere Perspective' in Antarctic Glacial History and World Palaeoenvironments ed. E. M. van Zinderen Bakker, Balkema, Rotterdam.

BOWLER, J. M., HOPE, G. S., JENNINGS, J. N. SINGH, G. & WALKER, D. (1976) 'Late Quaternary Climates of Australia and New Guinea' Quaternary Res. 6, 359-394

BROEKER, W. S., THURBER, D. L., GODDARD, J., KU, T. L., MATTHEWS, R. K. & MESOLLELA, K. J. (1968) 'Milankovitch hypothesis supported by precise dating or coral reefs and deep-sea sediments' Science, 159, 297-300

BROEKER, W. S. & VAN DONK, J. (1970) 'Insulation change, ice volumes and the 018 records in deep sea cores'. Reviews of Geophysics, 8, 169-198

BROOKFIELD, M. (1970) 'Dune trends and Wind regimes in Central Australia' Z. Geomorph. 10, 121-153

BURNE, R. V. (1982) 'Relative Fall of Holocene Sea Level and Coastal Progradation, Northeastern Spencer Gulf, South Australia' B.M.R. Journal of Geology and Geophysics, 7, 35-45

BUTZER, K. W. (1972) Environment and Archeology Methuen & Co. London.

BUTZER, K. W., & HANSEN C. L. (1968) Desert and River in Nubia; Geomorphology and Prehistoric Environments at the Aswan Dam. Madison: Univ. of Wisconsin Press

BYRNE, J. V., LE ROY, D. O. & RILEY, C. M. (1959) 'The Chenier Plain and its stratigraphy, Southwestern Louisiana : Gulf Coast Assoc. Geol. Socs. Trans. 9. 237-259

CASTANY, G. & OTTMAN, F. (1957) 'Le quaternaire marin de la Mediterranee occidentale'. Rev. géographie phys. et géologie dynamique, Ser. 2 (1), 46-55

CHAPPELL, J. (1974) 'Late Quaternary Glacio-and-Hydro-Isostasy on a Layered Earth'. Quaternary Res. 4, 429-440

CHARPENTIER, J. DE. (1835) 'Notice sue la cause probable du transport des, blocs erratiques de la suisse.' Annls. Mines, Paris 3 (8), 219-36

CORNISH, V. (1897) 'On the formation of sand dunes' Geog. J. 2, 278-382

CORNISH, V. (1900) 'On desert sand dunes bordering the Nice Delta' Geog. J. 5, 1-50

CROCKER, R. L. (1946) 'Post miocene climatic and geologic history and its significance in relation to genesis of major soil types in Sth Aust'. C.S.I.R.O. Aust. Bull. 193

COSTIN, A. B. & POLACH, H. A. (1973) 'Age and significance of slope deposits, Black Mountain, Canberra. Australian Journal of Soil Research 11, 13-25

CURRAY, J. R. (1961) 'Late Quaternary Sea Level: A Discussion' Bull. Geol. Soc. Am. 72, 1707-12

DAVIES, J. L. (1957) 'The importance of cut and fill in the development of sand beach ridges'. Aust. J. Sc. 20, 105-111

DAVIES, J. L. (1958) 'Analysis of height variations in sand beach ridges' Aust. J. Sc. 21, 51-52

DE LAMOTHÉ, R. (1911) 'Les Anciennies lignes de rivage du Sahel d'Alger et d'une partie de la cote algerienne'. Mem. Soc. Geol. France, 1 (6) 288pp.

DE LAMOTHÉ, R. (1916) 'Les Anciennes lignes de rivage du bassin de la Somme et leur Concordance avec celles de la Mediterranee occidentale,' C.R. Acad. Sci. Paris, 62, 948-51

DE LAMOTHE, R. (1918) 'Les Anciennes Nappes alluviales et lignes de rivage du bassin de la Somme et leurs rapports avec celles de la Mediterranee occidentale' Bull. Soc. Geol. France, 18, 3-58

DEPÉRET, C. (1906) 'Les Anciennes lignes de rivage de la cote Francaise de la Mediterranee (1906) Bull. Soc. Geol. France, 6, 207-230

DEPÉRET, C. (1918) 'Essai de co-ordination chronologique general des temps quaternaires' : Acad. Sci (Paris) Comples rendus, 167, 418-422

DIESTER-HASS, L. (1976) 'Late Quaternary climatic variations in northwest Africa deduced from East Atlantic Sediment cores'. Quaternary Res. 6, 299-314

DODSON, J. R. (1974) 'Vegetation and climatic history near Lake Keilambete, Western Victoria. Aust.J. Botany, 22, 709-717

EMBLETON, C. & KING, C. A. M. (1975) Glacial Geomorphology Edward Arnold, London.

EMILIANI, C. (1955) 'Pleistocene Temperatures' Journal of Geography, 63, 538-78

EMILIANI, C. (1958) 'Ancient Temperatures' Sci. Am. 198, 54-63

EMILIANI, C. (1906) 'Isotopic Palaeotemperatures' Science,154, 851-7

FAIRBRIDGE, R. W. (1906) 'The changing level of the sea' Sci. Am. 202, 70-79

FAIRBRIDGE, R. W. (1961) 'Eustatic Changes in Sea Level' Physics and Chemistry of the Earth 4, 99-185

FAIRBRIDGE, R. W. (1964) 'African ice-age aridity' 356-363 in Problems in Palaeoclimatology. Ed. A.E.M. Nairn

FENNER, C. (1930) 'The major structural and physiographic features of South Australia' Trans.R. Soc. S. Aust. 54, 1-36

FISK, H. N. (1948) 'Geological investigations of the lower Mermentau River Basin and adjacent areas in coastal Louisiana: Vicksburg, Miss. U.S. Army Corps. Engineers, Mississippi River Comm.

FLINT, R. F. & BOND, G. (1968) 'Pleistocene sand ridges and pans in Western Rhodesia' Bull. Geol. Soc. Am., 79, 299-314

FLOHN, H. (1973) 'Atlantic and the global Cenozoic evolution: a geophysical model'. in E. M. Van Zinderen Bakker (ed) Palaeoecology of Africa, 8, 37-53

FOLK, R. L. (1971) 'Longitudinal dunes of the Simpson Desert'. Sedimentology, 16, 5-54

FOLK, R. L. (1974) 'Petrology of Sedimentary Rocks' Hemphill Pub. Co. Austin, Texas.

FOLK, R. L. (1978) 'Angularity and silica coatings of Simpson Desert Sand Grains, Northern Territory, Australia'. J. Sediment. Petrol. 48, 611-624

FREE, E. E. (1911) 'The movement of soil material by wind'. U.S. Dept. Agr. Bur. Soils, Bull., 68

FRERE, H. B. E. (1870) 'Notes on the Runn of Cutch'. J. R. Geog. Soc., 40, 181-207

GALLOWAY, J. J. (1919) 'The Rounding of sand grains by solution' Am.J. Sci. Ser. 4. (47), 270-280

GALLOWAY, R. W. (1965) 'Late Quaternary climates in Australia'. J. Geol. 73, 603-618

GALLOWAY, R. W. (1965 b) 'A note on world precipitation during the Last Glaciation'. Eiszeitalter gregenwart 16, 76-77

GENTILLI, J. (1961) 'Quaternary climates of the Australian Region' Ann. N.Y. Acad. Sci, 95, 465-501

GEYH, M. A. & JAKEL, D. (1974) 'Late glacial and holocene climatic history of the Sahara Desert derived from a statistical assay of 'C-14 Dates' Palaeogeography, climatology, ecology., 15, 205-208

GIGNOUX, M. (1913) 'Les Formations Marines pliocenes et Quaternaires de l'Italie du sud et de la sicice'. Ann. Univ. Lyon (N.S.) 1 (36), 693 pp.

GILBERT, G. K. (1890) 'Lake Bonneville' U.S. Geol. Surv. Monog. 1

GILL, E. D. (1961) 'Cainozoic climates of Australia'. Ann. N.Y. Acad. Sc. 95, 461-464

GILL, E. D. & HOPLEY, D. (1972) 'Holocene sea levels in Eastern Australia - a discussion' Marine Geology, 12, 223-233

GLENNIE, K. W. (1970) 'Desert Sedimentary Environments' Elsevier Pub. Co. Amsterdam

GOSTIN, V., HAILS, J. & POLACH, H. A. (1981) 'Quaternary Sea Levels in upper Spencer Gulf, South Australia'. Search, 12, 43-45

GOUDIE, A. S. (1973) Duricrusts in tropical and subtropical landscapes Oxford.

GOUDIE, A. S., ALLCHIN, B. & HEDGE, K. T. M. (1973) 'The Former extensions of the Great Indian Sand Desert'. Geog.J., 139, 243-57

GOULD, H. R. & MCFARLANE,, E. (1959) 'Geological History of the Chenier Plain Southwestern Louisana'. Gulf Coast Assoc. Geol. Socs. Trans. 9, 229-238

GROVE, A. (1969) 'Landforms and climatic change in the Kalahari and NGA Midland' Geog.J., 135, 194-208

GROVE, A. T. & PULLEN, R. A. (1964) 'Some aspects of the Pleistocene Palaeogeography of the Chad Basin'. in Howell, F. C. & Bourliere (ed) African Ecology and Human Evolution Methuen, London, 230-245

GROVE, A. T. & WARREN, A. (1968) 'Quaternary Landforms and climate on the south side of the Sahara'. Geog.J., 134, 194-208

GROVE, A. T., STREET, E. A. & GOUDIE, A. S. (1975) 'Former Lake levels and climatic change in the Rift Valley of Southern Ethiopia'. Geog.J., 141 (2), 177-202

HAILS, J. R. (1969) 'The origin and development of the Umina - Woy Woy Beach Ridge system, Broken Bay, N.S.W. Aust. Geogr. xi, 1, 1-12

HAILS, J. R. & HOYT, J. H. (1968) 'Barrier Development on Submerged Coasts'. Z. Geomorph. Suppl. 7, 24-55

HAILS, J. R. & GOSTIN, V. A. (1978) 'Stranded shingle beach ridges, upper Spencer Gulf, South Australia', Trans. R.Soc. S. Aust., 102, 169-173

HAYS, J. D., LOZANO, J., SHACKLETON, N. & IRVING, G. (1976) 'Reconstruction of the Atlantic Ocean and Western Indian Ocean sectors of the 18,000 B.P. Atlantic Oceans'. in R. M. Cline & J. D. Hays (ed) Investigation of Late Quaternary Palaeooceanography & Palaeoclimatology Geol. Soc. Am. Mem., 145, 337-372

HOPE, G. S. & PETERSON, J. A. (1975) 'Glaciation and vegetation in the High New Guinea Mountains'. Bulletin of the Royal Society of New Zealand 13, 155-162

HOPLEY, D. (1974) 'Investigations of sea level changes along the coast of the Great Barrier Reef'. Proc. 2nd Int. Symp. on Coral Reefs, 2, 551-562

HOPLEY, D. (1975) 'Contrasting evidence for Holocene sea levels with special reference to the Bowen-Whitsunday Area, Qld.' in I. Douglas, Hobbs, J. E., & Pigman, J. J. (ed) Geographical Essays in Honour of Gilbert J. Butland. Univ. New England. pp. 51-84

HOPLEY, D. (1978) 'Sea level changes on the Great Barrier Reef: An Introduction'. Philos. Trans.R. Soc. London, Serv. A., 291, 159-166

HOPLEY, D. (1980) 'Mid-Holocene high sea levels along the coastal plain of the Great Barrier Reef province : A Discussion'. Marine Geology, 35

HOLLIN, J. T. (1962) 'On the glacial history of Antarctica' Journal of Glaciology 4 (32), 173-195

HOLLIN, J. T. (1965) 'Wilson's Theory of Icé Ages' Nature 208, 12-16

HOLLIN, J. T. (1969) 'The Antarctic Ice Sheet and the Quaternary History of Antarctic'. Palaeoecol. Afr. 5, 109-38

HOYT, J. H. (1967) 'Barrier Island Formation'. Bull. Geol. Soc. Am., 78, 1125-1136

HOYT, J. H. (1969) 'Chenier versus Barrier, genetic and stratigraphic Distinction'. American Association of Petroleum Geologists Bulletin 53, 299-306

HOYT, J. H. (1967) 'Intercontinental correlation of late Pleistocene sea levels' Nature, 215

HOYT, J. H., HENRY, V. J. & WEIMAR, R. J. (1968) 'Age of Late-Pleistocene Shoreline deposits, Coastal Georgia.' in Morrison, R. B. & Wright, H. E. ed. Means of Correlating Quaternary Successions 381-94. Uni. Utah Press

HULL, E. (1885) Mount Seir, Sinai and Western Palestine. Richard Bentleuftson. London.

JAMES, N. B., MOUNTJOY, E. W. & OMURA, A. (1971) 'An Early Wisconsin Reef Terrace at Barbados, West Indies, and its climatic implications'. Bull. Geol. Soc. Am., 82, 2011-18

JAMIESON, T. F. (1863) 'On the Parallel roads of Glen Roy and their place in the history of the glacial period'. Q.J. Geol. Soc. London, 19, 235-59

JELGERSMA, S. (1961) 'Holocene sea level changes in the Netherlands. Meded. Geol. Stinchting, Serv. C. V1-7

JENNINGS, J. (1975) 'Desert Dunes and Estuarine fill in the Fitzroy Estuary, northwestern Australia'. Catena, 2, 215-262

JENNINGS, J. N. & SWEETING, M. M. (1967) 'Caliche Pseudo-Anticlines in the Fitzroy Basin, W.A.' Am.J. Sc. 259, 635-9

JENNINGS, J. N. & COVENTRY, R. J. (1973) 'Structure and Texture of a gravelly Barrier Island in the Fitzroy Estuary, Western Australia, and the role of mangroves in shore dynamics'. Marine Geology, 15, 145-167

JESSUP, R. W. (1967) 'The late-Quaternary eustatic and geological history of the northern Yorke Peninsula, South Australia' in Correlation of Quaternary Successions (R. V. Morrison & H. B. Wright, eds). Vol. 8, 395-406. Proceedings International Association Quaternary Research, 7th Conference, Boulder, Colorado 1965

JESSUP, R. W. (1968) 'Soil Development in coastal Sth. Aust. in relation to glacio-eustatic changes of sea-level'. Trans. 9th Int. Gong. Soil Sc., Adelaide 4, 641-649

JOHNS, R. K. (1961) 'Geology and Mineral Resources of Southern Eyre Penin.' Geol. Surv. S. Austr. Bull. 37, 102 p.

KERSHAW, A. P. (1971) 'Along continuous pollen sequence from northeastern Australia'. Nature 247, 454-455

KING, D. (1956) 'The Quaternary stratigraphic record of Lake Eyre north and the evaluation of existing topographic forms. Trans.R. Soc. S.Aust., 79, 93-103

KING, D. (1960) 'The Sandridge deserts of South Austr. and related aeolian landforms of the Quaternary arid cycles'. Trans.R. Soc. S. Aust., 83, 93-108

KING, C. A. M. & MCCULLACH, M. J. (1971) 'A simulation Model of a complex recurved spit'. J. Geol., 79, 22-36

KOMAR, P. D. (1976) Beach Processes and Sedimentation Prentice-Hall New Jersey

KUENEN, P. H. (1959) 'Experimental Abrasion, 3. Fluviatile action on sand'. Am.J. Sc., 257, 172-190

KUENEN, PH H. (1959 b) 'Sand - its origin, transportation, abrasion and accumulation'. Geol. Soc. of S. Africa. Annexure to V. LXIII

KUENEN, PH. H. & PERDOK, W. K. (1961) 'Frosting of Quartz Grains' Koningki. Akademie van Wetenschappen. Amsterdam, Proc. Ser. B., 64, 343-45

KUENEN, PH. H. & PERDOK, W. K. (1962) 'Experimental Abrasion, 5. Frosting and defrosting of quartz grains'. J. Geol. 70, 648-58

KUKLA, G. J. (1977) 'Pleistocene land-sea correlations I. Europe'. Earth-Science Reviews: 13, 367-374

LAMB, H. H. (1972) Climate: Past, present and future. Methuen, London, Vol. 1

LANDSBERG, S. Y. (1956) 'The orientation of dunes in Britain and Denmark in Relation to the wind'. Geogr. J. 122, 176-189

LEWIS, W. V. (1932) 'The formation of Dungeness foreland'. Geogr. J., 80, 145-51

LINDSAY, J. M. (1970) "Melton limestone: multiple mid-tertiary transgressions, south-eastern Gawler platform'. Quart. geol. notes, geol. survey, S. Aust., 33, 2-10

MABBUTT, J. A. (1971) 'The Australian arid zone as a prehistoric environment'. in Mulvaney, D. J. & Golson, J. (eds) Aboriginal man and environment in Australia. A.N.U. Press, Canberra.

MABBUTT, J. A. (1977) Desert Landforms A.N.U. Press Canberra.

MABBUTT, J. A. & SULLIVAN, M. E. (1968) 'The formation of longitudinal sand dunes: evidence from the Simpson Desert'. Aust. Geogr. 10, 483-7

MADIGAN, C. T. (1936) 'The Australian Sand-ridge Deserts' Geogr. Rev. 26, 205-227

MADIGAN, C. T. (1946) 'The Simpson Desert Expedition 1939'. Scientific Reports : No. 6, Geology.

MARSHALL, A. (1948) 'The size of the Australian Desert' Aust. Geogr. 5, 168-175

MCFARLAN, E. (1961) 'Radiocarbon dating of late Quaternary deposits, South Louisiana', Bull. Geol. Soc. Am., 72, 129-58

MCKEE, E. D. & TIBBETTS, G. C. (1964) 'Primary structures of a seif dune and associated deposits in Libya. J. Sediment Petrol. 34, 5-17

MCKEE, E. D. (1966) 'Structure of dunes at White Sands National Monument, New Mexico'. Sedimentology, 7 (1), 1-70

MCKEE, E. D. & DOUGLAS, J. R. (1971) 'Growth and movements of dunes at White Sands National Monument, New Mexico'. U.S. Geol. Survey Prof. Paper 750-D, 108-114

MCKEE, E. D. & MOIOLA, R. J. (1975) 'Geometry and growth of the White Sands Dune Field, New Mexico'. Jour. Research U.S. Geol. Survey, 3, 59-66

MCLEAN, R. F. STODDART, D. R., HOPLEY, D. & POLACH, H. (1978) 'Sea level changes in the northern Great Barrier Reef'. Philos. Trans.R. Soc. London Serv. A. 291, 167-186

MERCER, J. H. (1973) 'Cenozoic temperature trends in the Soutern Hemisphere: Antarctic and Andean Glacial Evidence'. in E. M. Van Zinderen Bakker (ed) Palaeoecology of Africa, 8, 85-114

MELTON, F. A. (1940) 'A tentative classification of sand-dunes: its application to dune history in the southern high plains'. J. Geol., 48, 113-174

MESOLELLA, K. J. MATTHEWS, R. K. BROEKER, W. S. & THURBER, D. L. (1968) 'The Astronomical theory of climatic change : Barbados Data'. J. Geol. 77, 250-74

MILES, K. R. (1952) 'Tertiary faulting in north-eastern Eyre Peninsula, South Aust'. Trans.R. Soc. S. Aust., 75, 89-96

MILES, K. R. (1954) 'The geology and iron resources of the Middleback Range Area' Geol. Surv. S. Aust. Bull. 33, 247p.

MILLIMAN, J. D. & EMERGY, K. O. (1968) 'Sea levels during the past 35,000 years'. Science, 162, 1121-23

MOSELEY, F. (1965) 'Plateau calcrete, calcreted gravels, cemented dunes, and related deposits of the Maallegh-Bomba Region of Libya'. Z. Geomorph., 9, 167-185

NILSSON, E. (1931) 'Quaternary glaciation and pluvial lakes in British East Africa'. Geografiska Ann. 13, 249

NOSSIN, J. J. (1965) 'Analysis of younger beach ridge deposits in Eastern Malaya'. Z. Geomorph. 9, 186-208

OTVOS, E. G. & PRICE, W. A. (1979) 'Progress of Chenier genesis and terminology: an overview'. Marine Geology, 31, 251-263

PARKER, J. (1980) Symposium on the Gawler Craton, 11 December 1979 J. Geol. Soc. Aust., 27, 45-53

PARKIN, D. W. (1974) 'Trade winds during the glacial cycles' Proc.R. Soc. London. A. 337, 73-100

PARKIN, D. W. & SHACKLETON, N. J. (1973) 'Trade-wind temperature correlation down a deep-sea core off the Saharan coast. Nature, 245, 455-457

PENCH, A. (1905) 'Glacial Features in the surface of the Alps'. J. Geol., 13, 1-19

POLACH, H. A. (1975) 'Radiocarbon dating as a research tool in archaeology - Hopes and Limitations in Ancient Chinese Bronzes and South East Asian Metal and other Archaeological Artifacts ed N. Barnard, National Gallery of Vic., 255-298

POWELL, J. M. (1970) The impact of man on the vegetation of Mt. Hagen Region, New Guinea. unpub. Ph.D. A.N.U. Canberra

POWERS, M. C. (1953) 'A new roundness scale for sedimentary particles'. J. Sediment. Petrol., 23, 117-119

PRICE, W. A. (1925) 'Caliche and Pseudo-anticlines' Bull. Ass. Am. Petro-Geol., 9, 1009-17

PRICE, W. A. (1955) 'Environment and formation of the Chenier Plain' Quaternaria, 2, 75-86

RHODES, E. G., POLACH, H. A., THOM, B. G. & WILSON, S. (1980) 'Age structure of Holocene coastal sediments, Gulf of Carpentaria, Australia'. Radiocarbon, 22, 2-3

ROGNON, P. & WILLIAMS, M. A. J. (1977) 'Late Quaternary climatic changes in Australia and North Africa. A preliminary interpretation' Palaeo: Geography, Climatology and Ecology. 21, 228-327

RUSSELL, I. C. (1885) 'Geological History of Lake Lahontan, a Quaternary lake of northwestern Nevada'. U.S. Geol. Surv. Manogr. 11, 1-288

RUSSELL, R. J. & HOWE, H. V. (1935) 'Cheniers of southwestern Louisiana'. Geogr. Rev. 25, 449-461

SANDFORD, K. S. (1935) 'Pluvial and Glacial climates' Antiquity 9, 343-347

SELBY, M. J. (1977) 'Pluvials in northern and east Africa and their relations to glacial climates in Europe'. Environmental Studies Occ. Paper 19. Dept of Geog. & Env. Stud. Univ. of Witwatersrand, Johannesburg.

SHACKLETON, N. J. & OPDYKE, N. D. (1973) 'Oxygen isotope and palaeomagnetic stratigraphy of Equatorial Pacific core V.28-238. Oxygen isotope temperatures and ice volumes on a 10^5 and 10^6 year scale'. Quaternary Res. 3, 39-55

SHACKLETON, N. J. & OPDYKE, N. D. (1976) 'Oxygen - isotope and palaeomagnetic stratigraphy of Pacific core V.28-239. Late Pliocene to latest pleistocene'. Geol. Soc. Am. Mem., 145, 449-452

SHEPARD, F. P. (1960) 'Gulf Coast Barriers, in recent sediments, northwest Gulf of Mexico'. Amer. Assoc. Petrol. Geol. 197-220

SMART, J. (1976) 'The nature and origin of Beach Ridges, Western Cape Yorke Peninsula, Queensland'. B.M.R.J. Geology and Geophysics

SMART, J. (1977) 'Late Quaternary sea level changes, Gulf of Carpentaria, Australia. Geology 5, 755-759

SMITH, H. T. U. (1965) 'Dune morphology and chronology in central and western Nebraska'. J. Geol. 73, 557-78

SMITH, D. I. & ATKINSON, T. C. (1976) 'Process, landforms and climate in limestone regions'. Geomorphology and Climate ed E. Derbyshire (Wiley, 367-409)

SORBY, H. C. (1880) 'On the structure and origin of non-calcareous stratified rocks' Quart. Jour. Geol. Soc. (Proc.) 36, 46-92

SPRIGG, R. C. (1965) 'The nature and origin of modern deserts' Aust. Nat. Hist., 15, 111-113

SPRIGG, R. C. (1979) 'Stranded and submerged sea-beach systems of southeast South Australia and the aeolian desert cycle'. Sedimentary Geology, 22, 53-96

STAPOR, F. W. (1975) 'Holocene beach ridge rain development, northwest Florida'. Z. Geomorph. Supp. 22

STREET, F. A. & GROVE, A. T. (1976) 'Environmental and climatic implications of late quaternary lake-level fluctuations in Africa. Nature. 261, 385-390

STUIVER, M. & POLACH, H. A. (1977) 'Discussion : Reporting of C-14 data'. Radiocarbon, 19 (3), 355-363.

SUTTON, D. J. & WHITE, R. E. (1968) 'The Seismicity of South Australia' J. Geol. Soc. Aust. 15, 25-32

THOM, B. G. (1964) 'Origin of sand beach ridges' Aust.J. Sci. 26,

THOM, B. G. (1973) 'The dimenna of high interstadial sea levels during the last glaciation'. Prog. in Geography , 170-246

THOM, B. G., HAILS, J. & MARTIN, A. R. H. (1969) 'Radio-carbon evidence against higher postglacial sea-levels in Australia'. Marine Geology 7, 151-160

THOM, B. G., HAILS, J. R., MARTIN, A. R. H. & PHIPPS, C. G. (1972) 'Postglacial sea-levels in eastern Australia - a reply' Marine Geology 12, 233-242

THOM, B. G. & CHAPPELL, J. (1975) 'Holocene sea-levels relative to Australia'. Search, 6, 90-93

THOM, B. G. & CHAPPELL, J. (1978) 'Holocene sea level, change : an Interpretation'. Philos. Trans.R. Soc. London.

THURBER, D. L., BROECKER, W. S., BLANCHARD, R. L. & POTRATZ, H. A. (1965) 'Uranium series ages of coral from Pacific Atolls' Science, 149, 55-8

TILLEY, C. E. (1920) 'The matamorphism of the precambrian dolomites of southern Eyre Peninsula, South Australia'. Geol. Mag., 57, 449-462

TINDALE, N. B. (1933) 'Tantanoola Caves, south-east of South Australia: Geological and physiographical notes'. Trans.R. Soc. S. Aust., 57, 130-142

THOMSON, B. P. (1969) 'Precambrian crystalline basement in Handbook of South Australian Geology ed L. W. Parkin, Govt. Printer, Adelaide

TRICART, J., MICHEL, P. & VOGT, J. (1957) 'Oscillations climatigues quaternaires en Afrique occidentale'. Resumes, V. Cong. Intern. INQHA (Madrid), 187

TRICART, J. (1961) 'Notice explicative de la carte geomorphologique du Della du Senegal'. Mem. BR6M. 8

TWIDALE, C. R., DAILY, B. & FIRMAN, J. (1967) 'Eustatic and climatic history of the Adelaide area, South Australia'. J. Geol., 75, 237-242

TWIDALE, C. R. (1972) 'Evolution of sand dunes in the Simpson Desert, Central Australia'. Trans. Inst. Brit. Geog., 56, 77-109

TWIDALE, C. R., BOURNE, J. A. & SMITH, D. M. (1976) 'Age and origin of palaeosurfaces on Eyre Peninsula and the southern Gawler Ranges, South Australia'. Z. Geomorph. N.F. 20, 28-55

TYLOR, A. (1868) 'On the Amiens Gravel' Q.J. Geol. Soc. Lond, 24, 103-25

VEEH, H. H. (1966) Th $^{230}/U^{238}$ and U^{234}/U^{238} ages of Pleistocene high sea level stand'. Journal of Geophysical Research 71, 3379-86

VEEH, H. H. & CHAPPELL, (1970) 'Astronomical theory of climatic change., Support from New Guinea'. Science, 167, 862-865

VENETZ, J. (1833) 'Memoire, surles variations de la temperature dans les alpes de la Suisse'. Mem. Soc. Helv. Sci. Nat., 1, pt. 2

WARD, W. T. & JESSUP, R. W. (1965) 'Changes in sea level in Southern Australia'. Nature. 205, 791-792

WARREN, A. (1970) 'Dune trends and their implications in the Central Sudan'. Z. Geomorph. - Supp. 10, 154-180

WAYLAND, E. J. (1929) 'The Geological history of the Great Lakes'. Geol. Surv. Uganda Ann. Rep. 1928, 1929, 35-38

WAYLAND, E. J. (1934) 'Peneplains and some erosional landforms'. Geol. Surv. Uganda Ann. Rep. Bull., 1, 77-79

WEBSTER, P. J. & STRETEN, N. A. (1978) 'Late Quaternary Ice Age climates of Tropical Australia: interpretations and reconstructions'. Quaternary Res., 10, 279-309

WILLIAMS, G. E. (1973) 'Late Quaternary piedmont sedimentation, soil formation and palaeoclimates in arid South Australia'. Z. Geomorph. 17 (1), 102-125

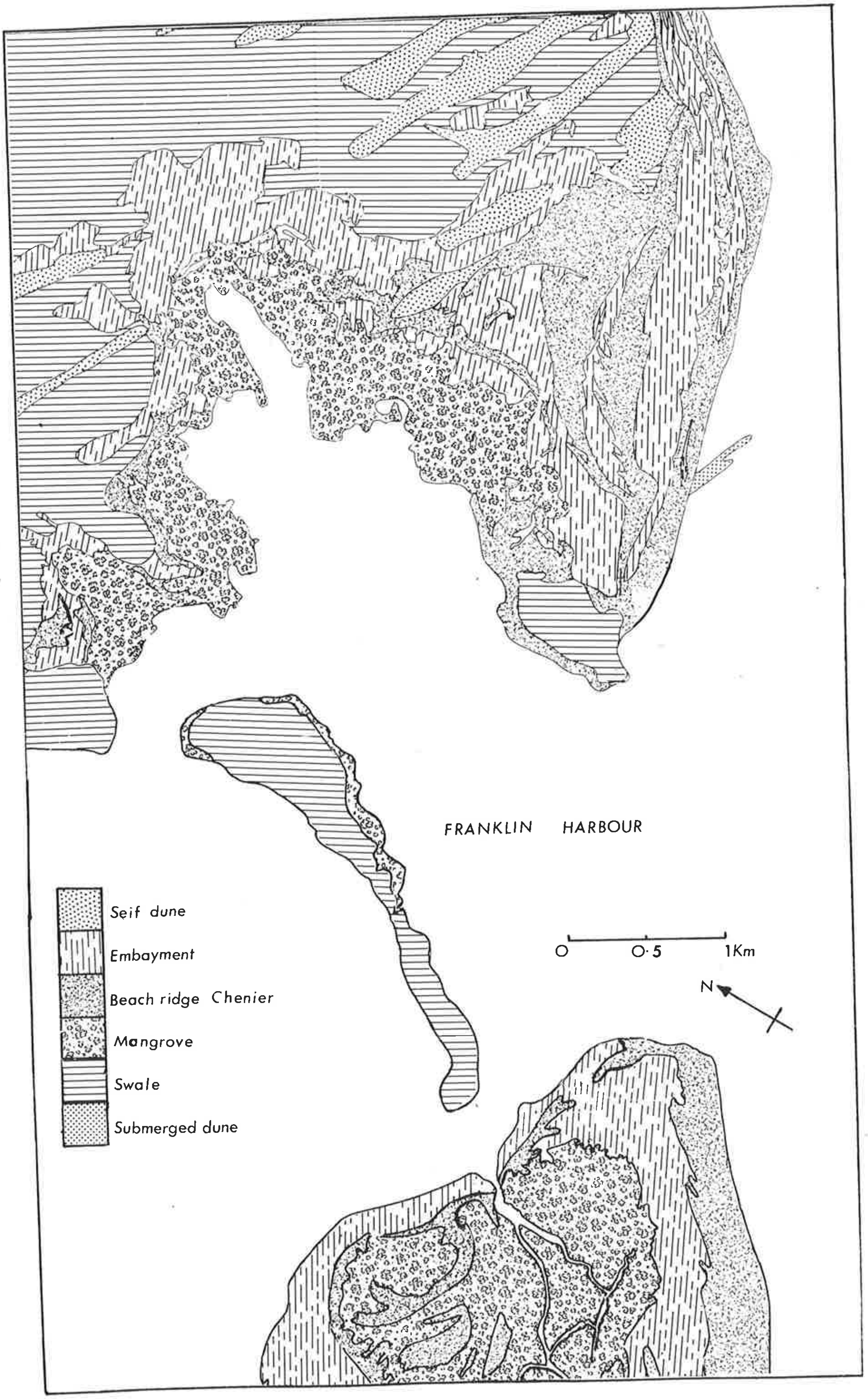
WILLIAMS, G. & POLACH, H. A. (1969) 'The evaluation of C-14 ages for soil carbonate from the arid zone'. Earth and Planetary Science Letters 7, 240-242

WILLIAMS, G. E. & POLACH, H. A. (1971) 'Radiocarbon dating of arid zone calcareous paleosols'. Bull. Geol. Soc. Am. 82, 3069-3086

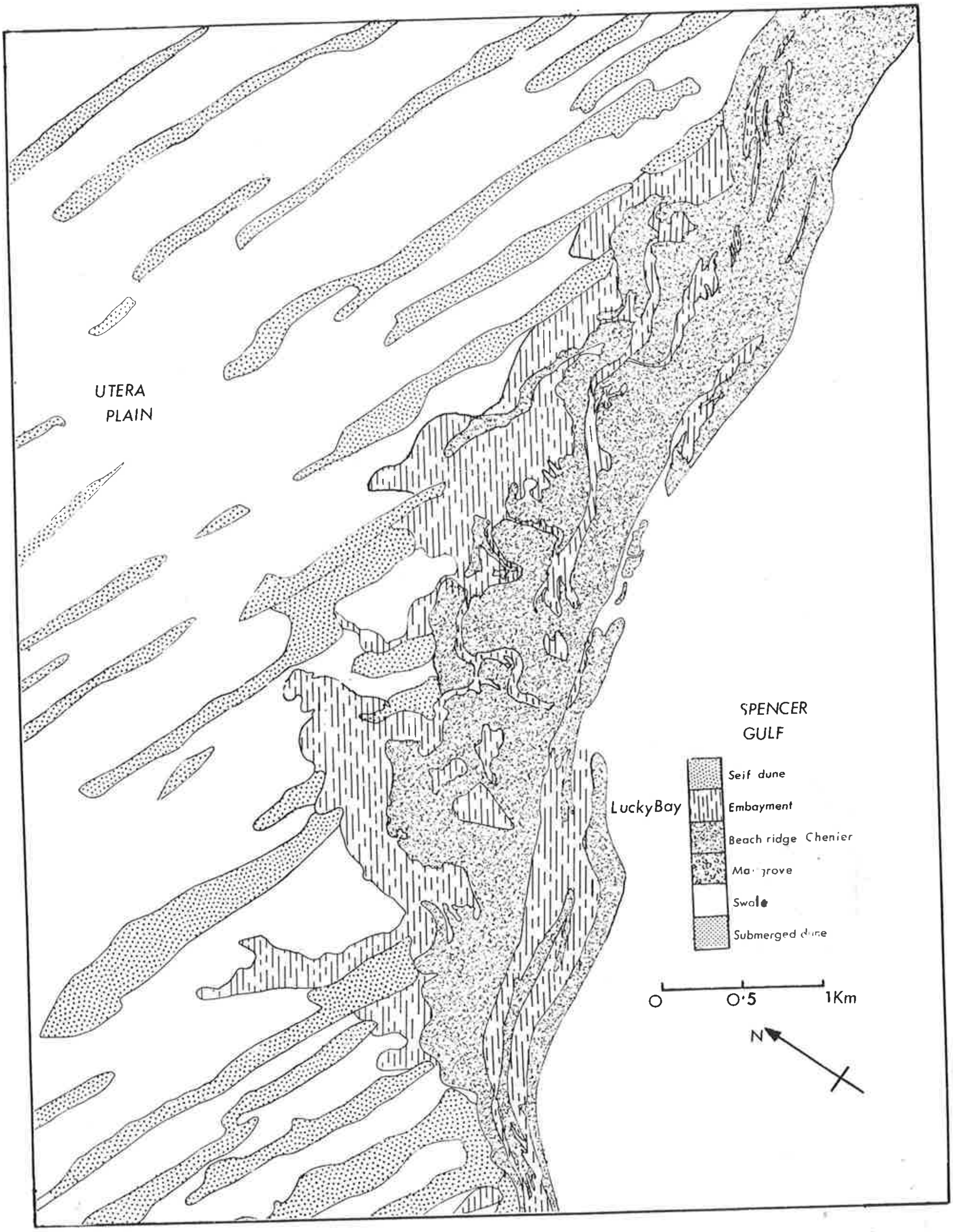
WOPFNER, H. & TWIDALE, C. R. (1967) 'Geomorphological history of the Lake Eyre Basin'. in Landform studies from Australia and New Guinea ed. J. N. Jennings & J. A. Mabbutt. A.N.U. Press, Canberra

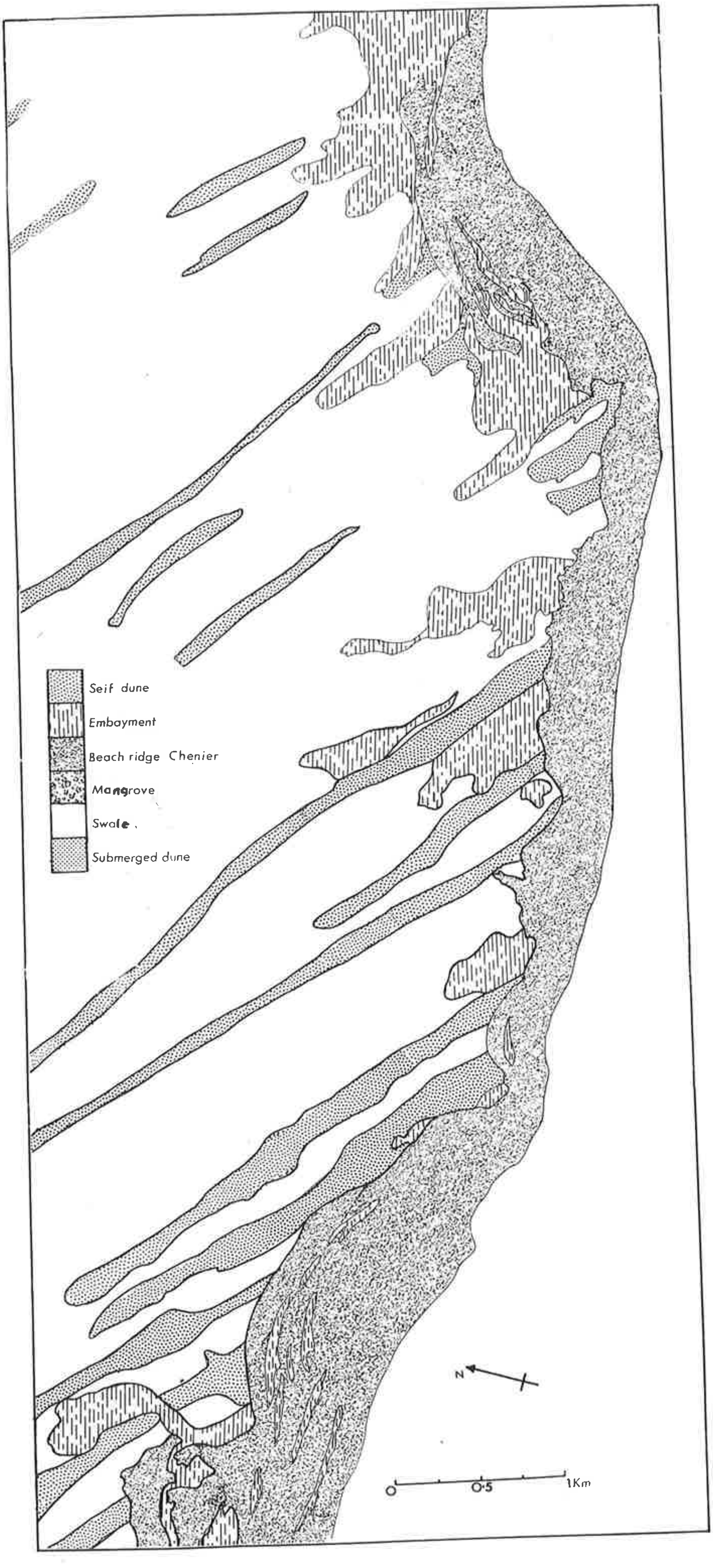
WYROLL, K. H. & MILTON, D. (1976) 'Widespread late Quaternary aridity in Western Australia' Nature, 264, 429-30

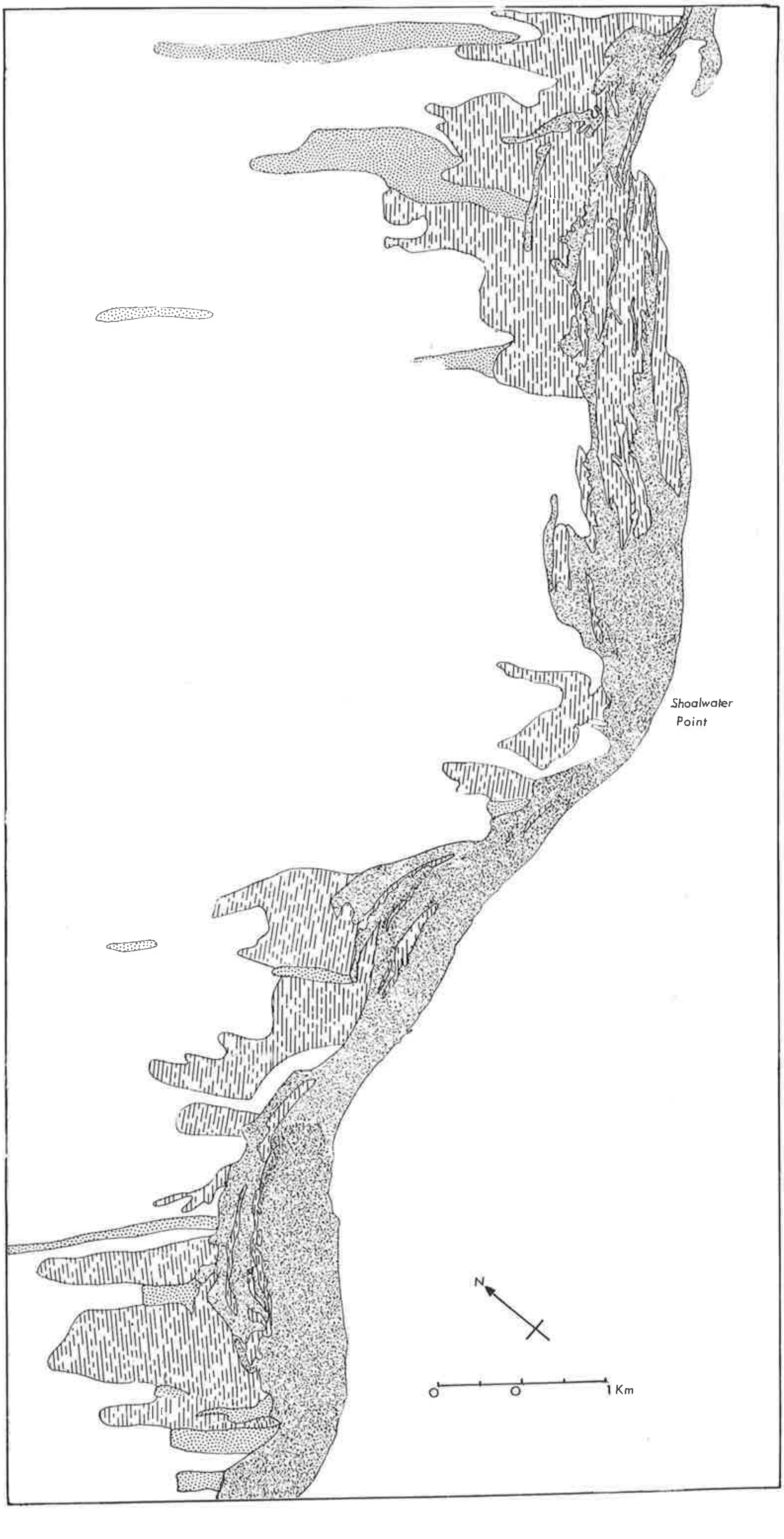
ZEUNER, F. E. (1959) The Pleistocene Period : Its Climate, Chronology and Faunal Successions. Hutchinson, London.

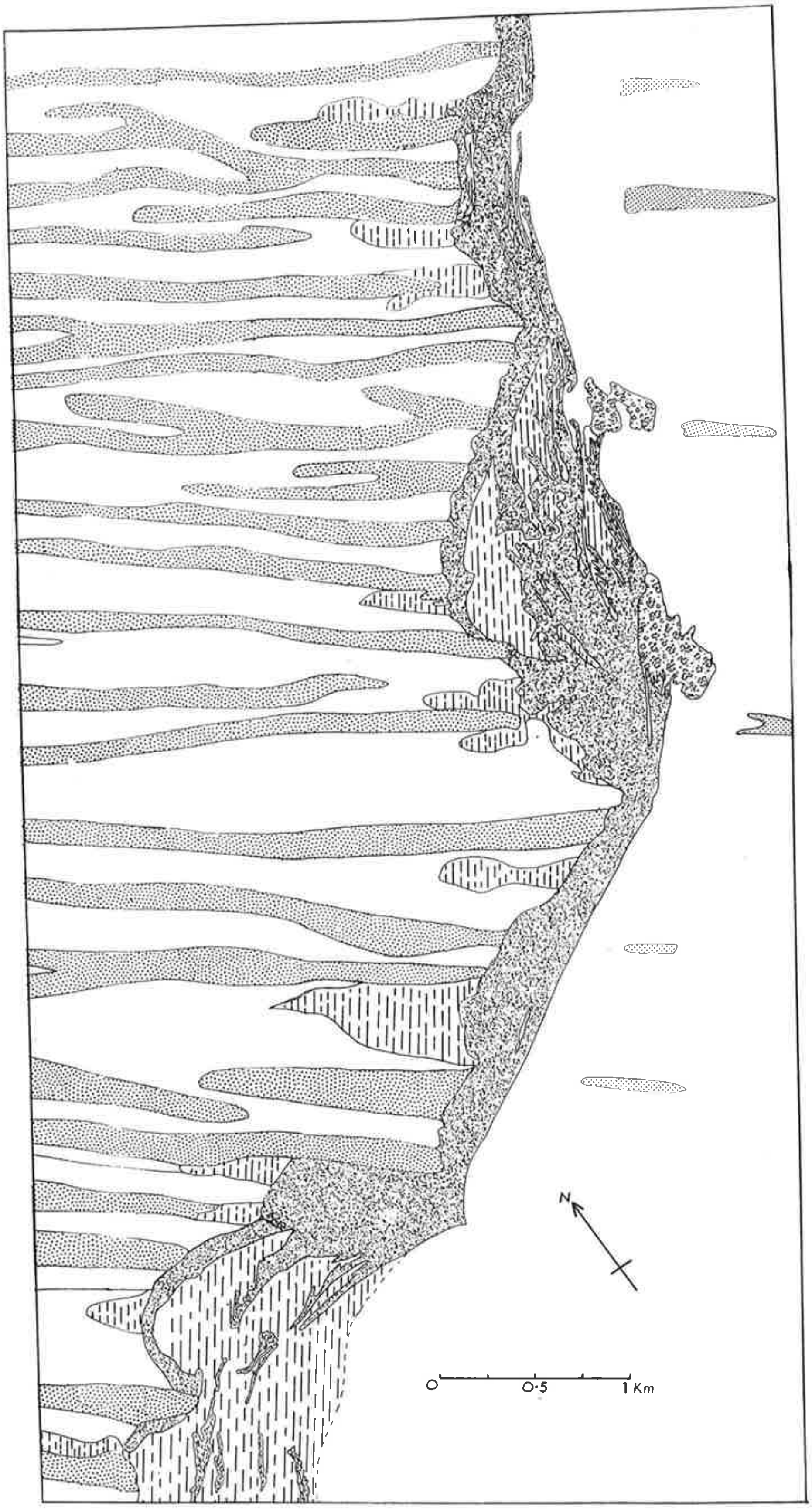


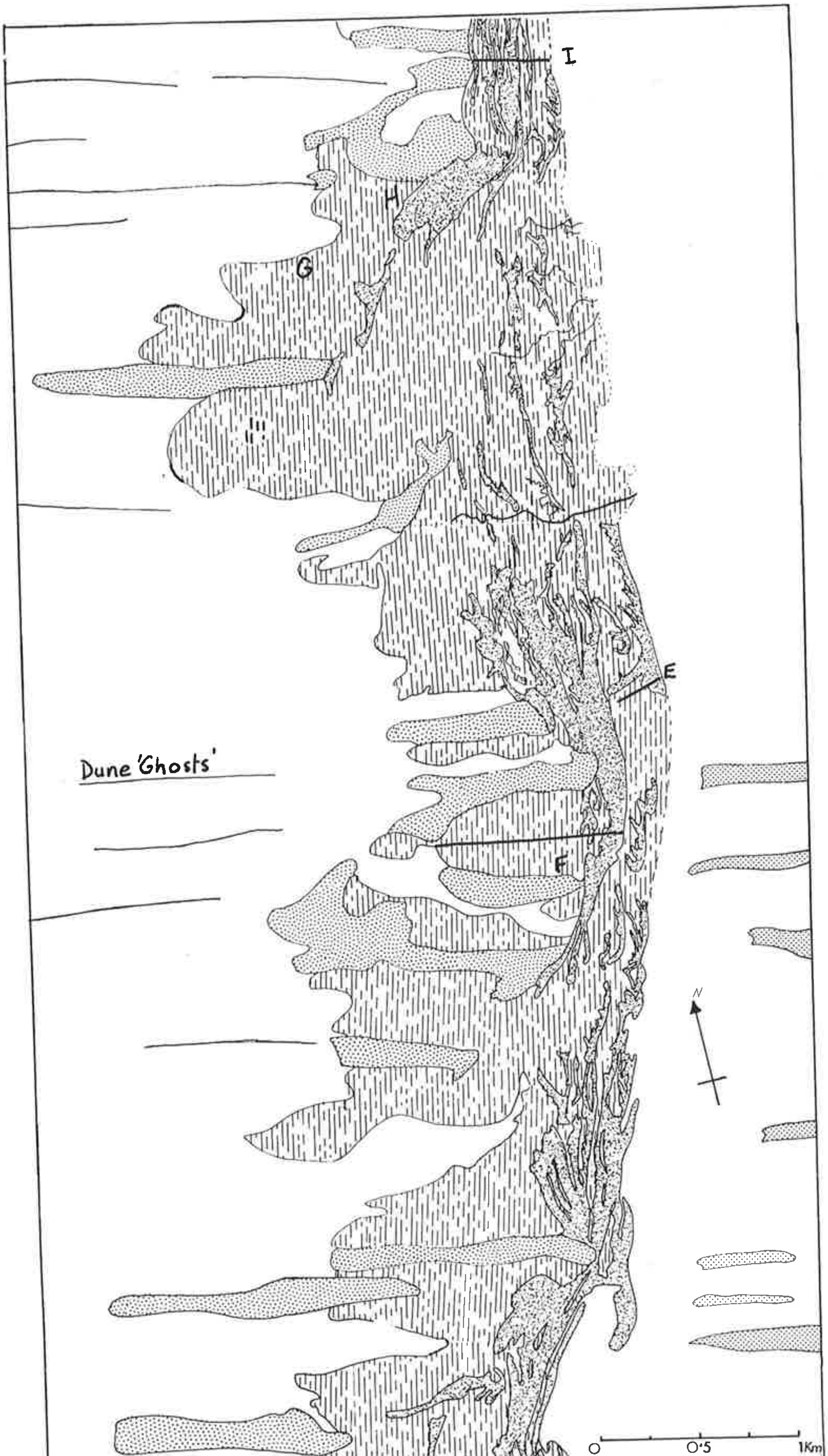
FRANKLIN HARBOUR
Seif dune
Embayment
Beach ridge Chenier
Mangrove
Swale
Submerged dune
0
0·5
1Km
N

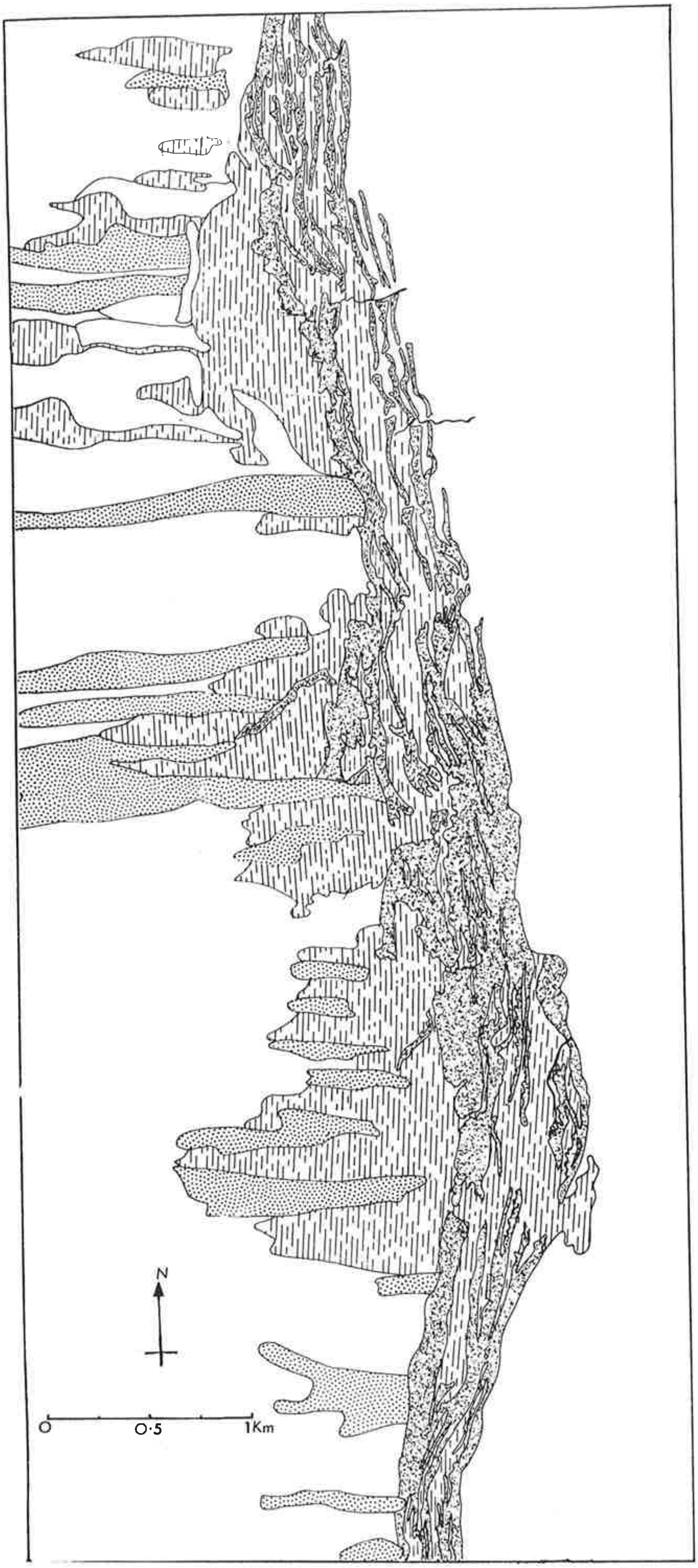

UTERA
PLAIN
SPENCER
GULF
Lucky Bay
Seif dune
Embayment
Beach ridge Chenier
Swale
0
0·5
1Km
N

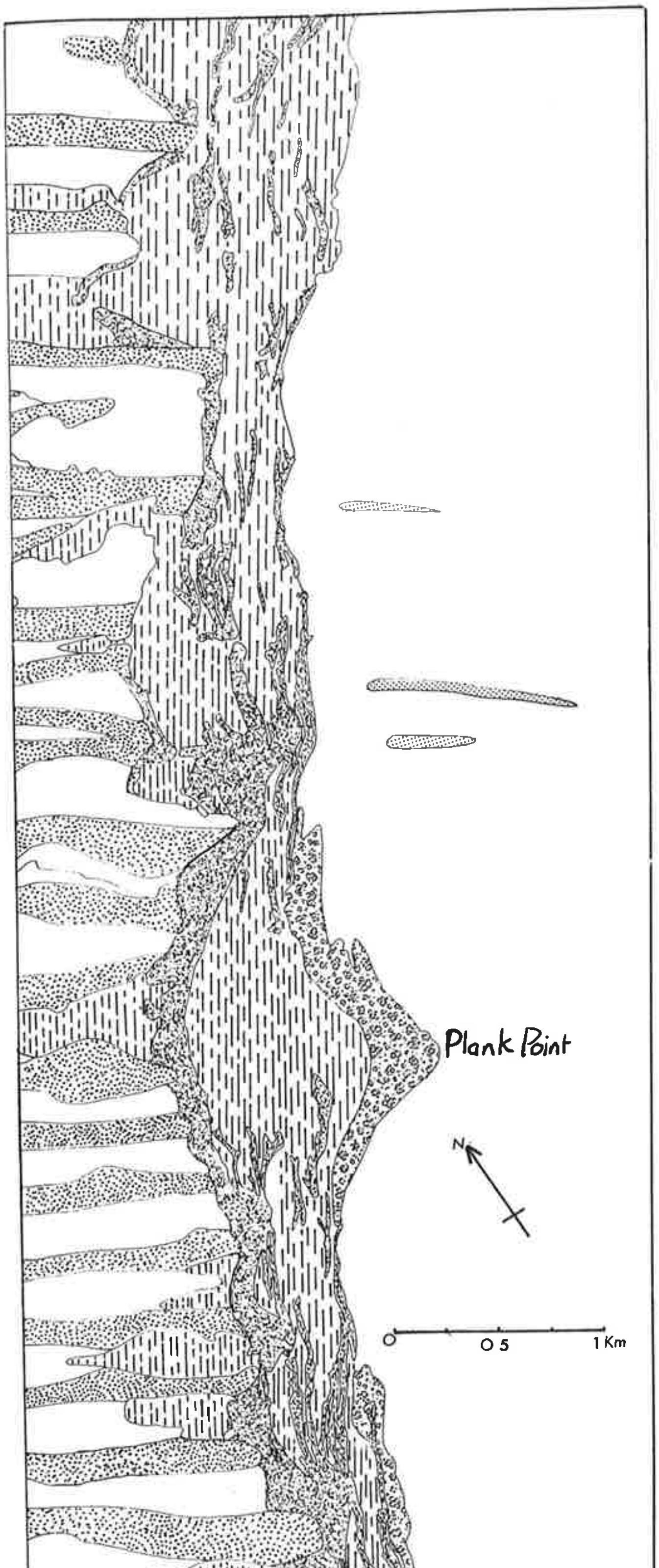

Seif dune
Embayment
Beach ridge Chenier
Mangrove
Swale
Submerged dune
N
0
0·5
1Km

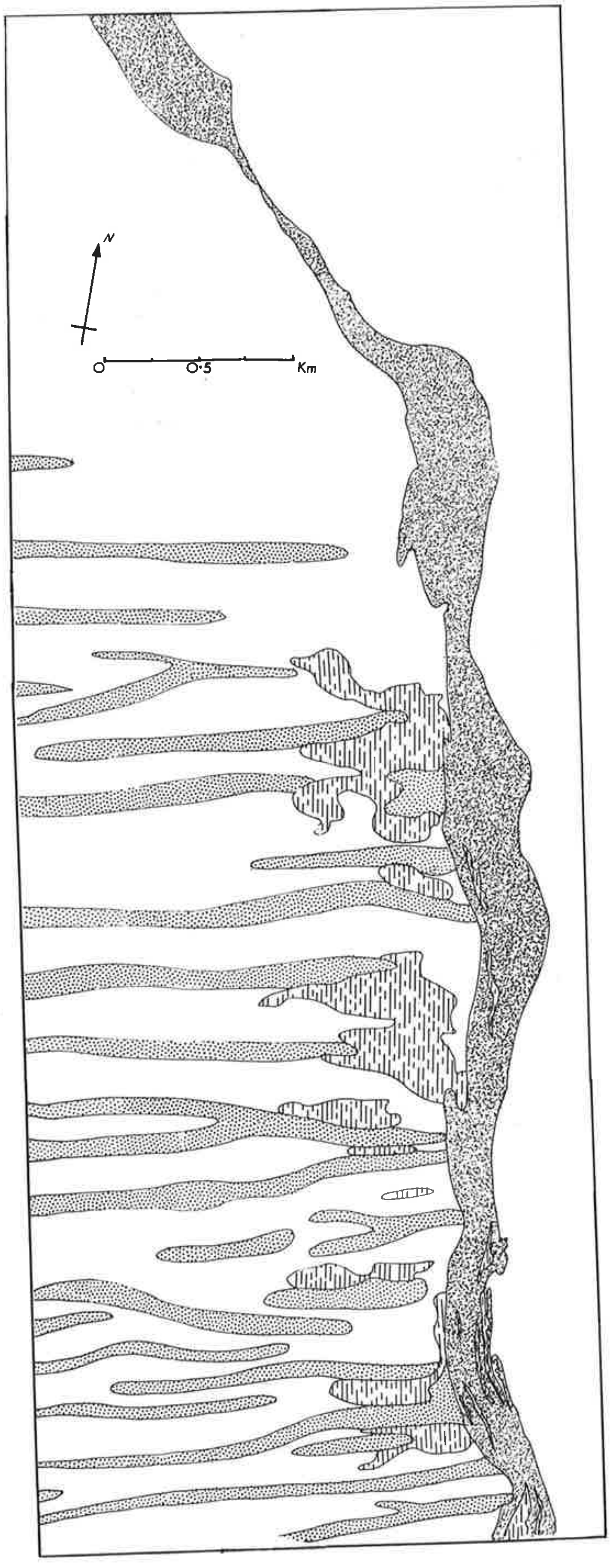

Shoalwater
Point
N
0
0
1 Km

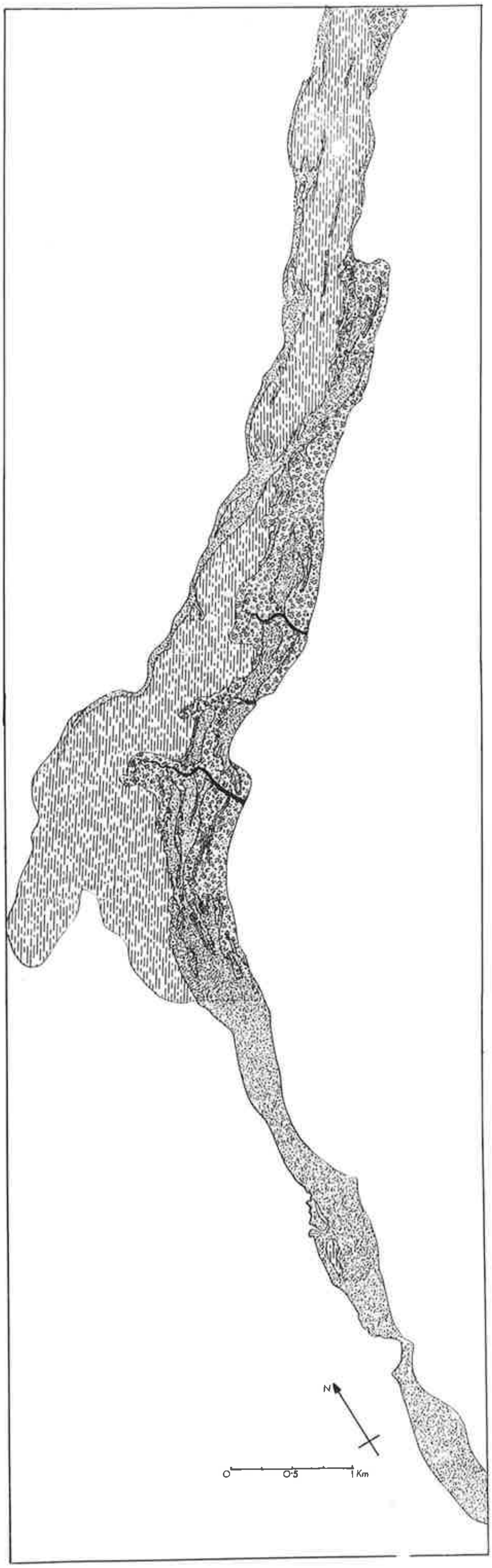

N
O
O·5
1 Km

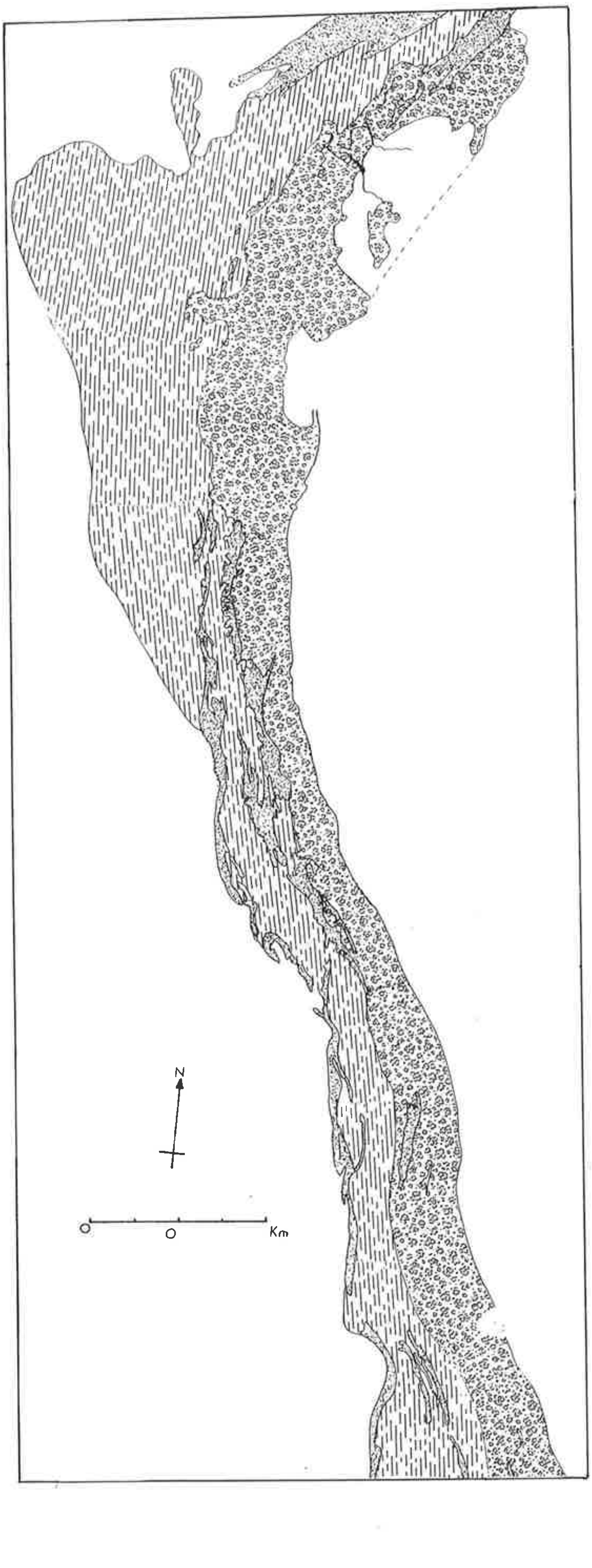

I
H
G
E
F
Dune 'Ghosts'
N
0
0·5
1Km

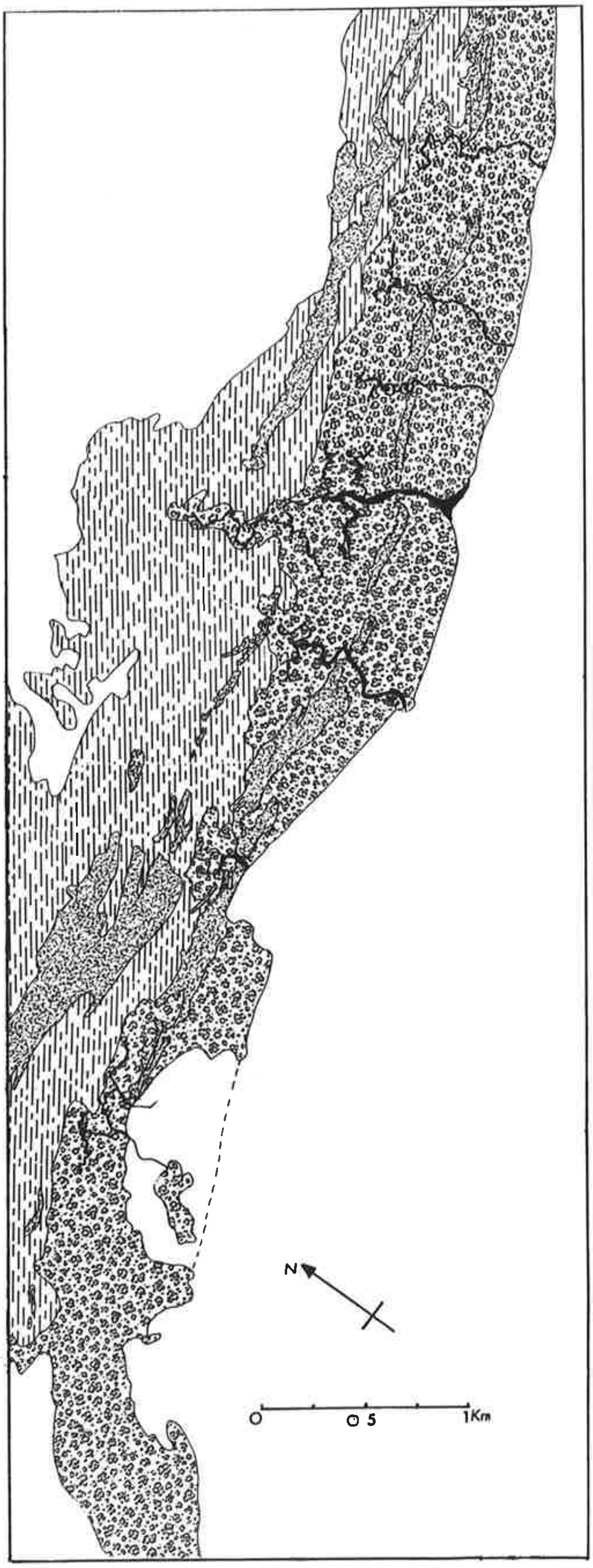

N
0
0·5
1Km

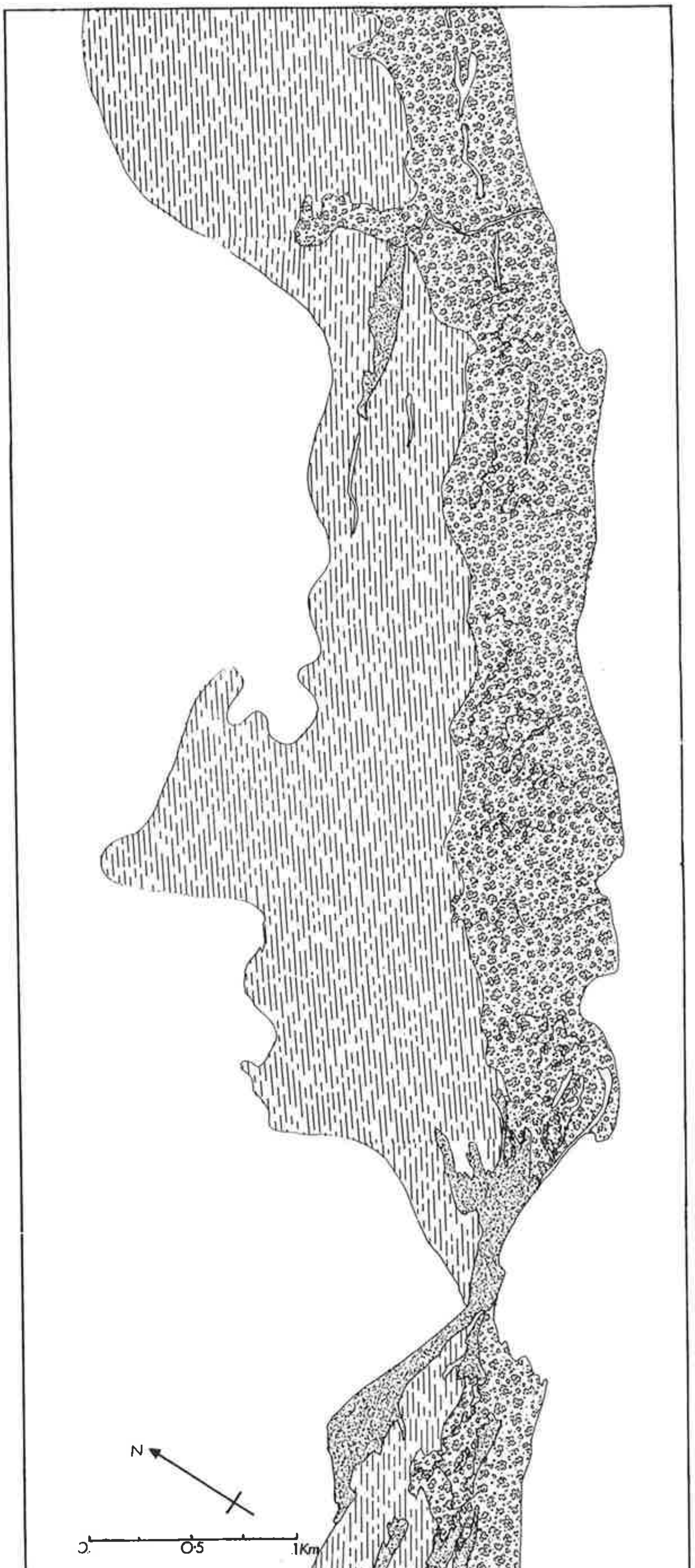

Plank Point
N
0
0 5
1 Km


N
0
0·5
Km


N
0
0·5
1 Km


N
0
0
Km


N
0
0 5
1Km


N
0
0·5
1Km