SOUTH AUSTRALIA

Department of Mines

GEOLOGICAL SURVEY OF SOUTH AUSTRALIA

BULLETIN No. 29

The Geology of the South-East Province, South Australia, with Special Reference to Quaternary Coast-line Migrations and Modern Beach Developments

By

R. C. SPRIGG, M.Sc., Senior Geologist

Issued under the authority of
The Honourable A. Lyell McEwin, M.L.C., Minister of Mines

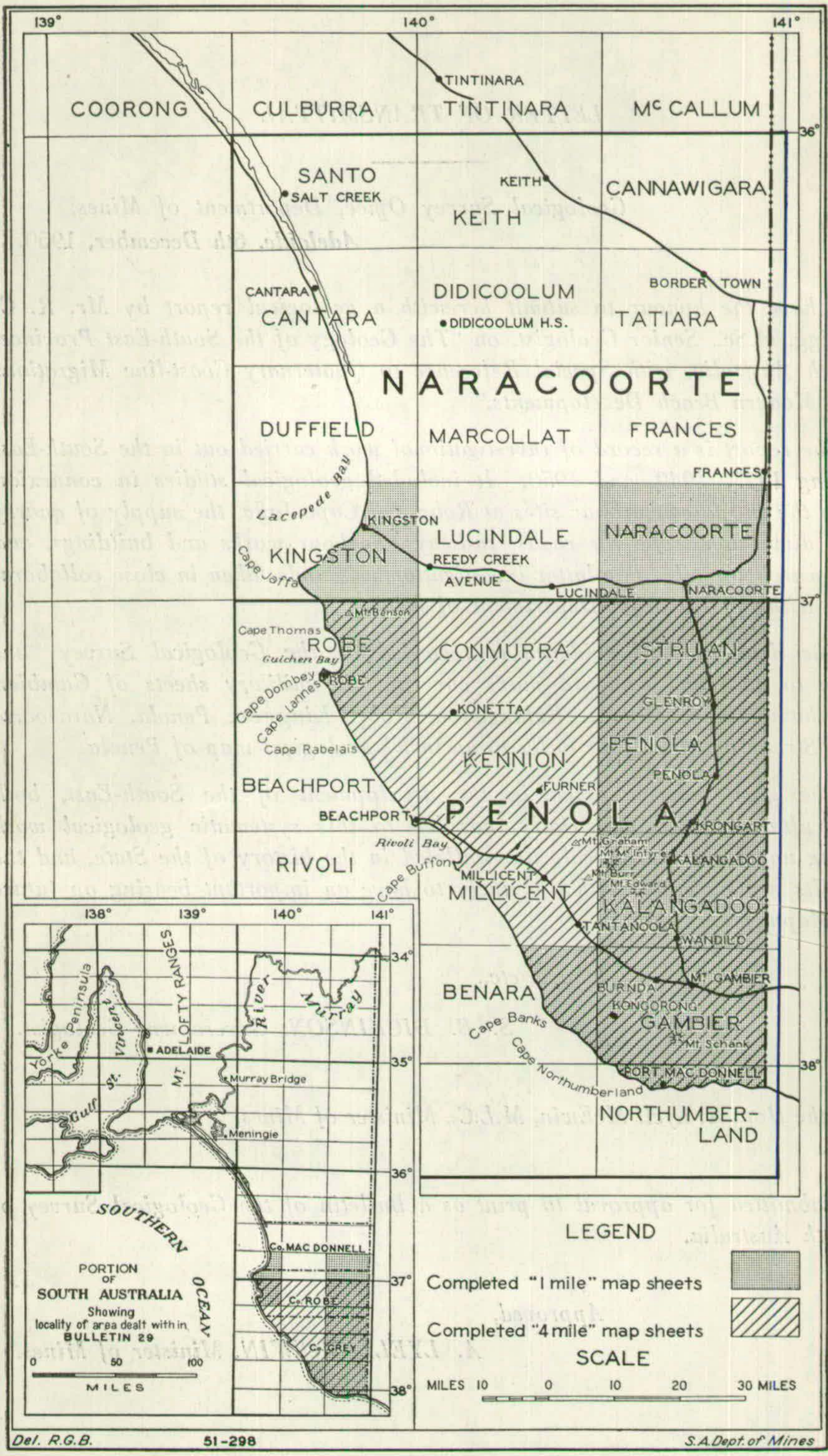

Fig. 1—Locality map

Frontispiece]

LETTER OF TRANSMITTAL

Geological Survey Office, Department of Mines,
Adelaide, 6th December, 1950.

Sir,

I have the honour to submit herewith a geological report by Mr. R. C. Sprigg, M.Sc., Senior Geologist, on "The Geology of the South-East Province, South Australia, with Special Reference to Quaternary Coast-line Migrations and Modern Beach Developments."

The report is a record of investigational work carried out in the South-East during 1947, 1949, and 1950. It included geological studies in connexion with the proposed harbour sites at Robe and Cape Jaffa, the supply of quarry and dimension stone for roads, railways, harbour works and buildings, and the search for oil. The latter investigation was undertaken in close collaboration with the Victorian Department of Mines.

The detailed field evidence is recorded on the Geological Survey "one mile to an inch" standard maps covering the military sheets of Gambier, Northumberland, Benara, Kalangadoo, Robe, Kingston, Penola, Naracoorte and Struan and the "four miles to an inch" geological map of Penola.

The great interest taken in the development of the South-East, both agriculturally and industrially, has led to this systematic geological work being undertaken on a scale unparalleled in the history of the State, and the results presented herewith are likely to have an important bearing on future developments.

I have, etc.,

S. B. DICKINSON, Government Geologist.

To the Hon. A. Lyell McEwin, M.L.C., Minister of Mines.

Submitted for approval to print as a Bulletin of the Geological Survey of South Australia.

Approved,

A. LYELL McEWIN, Minister of Mines.

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ABSTRACT

The South-East Province of South Australia is divisible into two zones, namely, the Gambier sunklands and the Padthaway "buried" horst. Tertiary overmass sediments in the sunklands attain a maximum thickness of more than 7,000ft and overlie an unknown thickness of Jurassic non-marine sandstones. Pre-Cambrian or Palaeozoic bedrock outcrops sporadically on the Padthaway horst or is covered by relatively thin veneers of Tertiary and restricted Jurassic sediments. (?) Permian glacigenes occupy infillings in the deeply sculptured Palaeozoic fossil land surface of the horst and may also occur at depth in the sunklands.

A major (Jaffa) fault zone (WNW.-ESE.) is thought to divide the sunklands and horst, and it joins with the NNW.-SSE. trending Kanawinka Fault near Comaum. Another WNW.-ESE. trending fault (Tartwaup fault zone) passes through Beachport and near Mt. Gambier and out to sea beyond Nelson. This zone is compound and its activity in the Beachport zone area has caused earthquakes in historic times. On the landward (upthrown) side of this fault the Tertiary sediments probably rarely exceed 2,000ft. in thickness, but to the south 7,000ft. or more have been proven in the Nelson bore.

A great geological hiatus occurs in the geological record of the area, but the terrestrial conditions of the Permian, Jurassic, and early Tertiary gave way in mid-Tertiary times to open-water marine conditions. During the Pleistocene epoch regional crustal warping and major eustatic oscillations of sea-level caused rapid migrations of the strand line. Volcanicity also had its influence on coastal configuration.

The area is poorly mineralized and most interest has centred on oil possibilities. Past drilling has given no grounds for optimism, and it is considered significant that although many strong faults are now known to outcrop in the sunklands, none have produced authentic oil seepages. In view of the vast amounts of escaping artesian waters along these lines of dislocation, this feature is most unhopeful. However, the geological picture in the deeper portions of the sunklands is still very incomplete and until more geophysical work is completed and drilling undertaken under geological supervision, the region's petroleum possibilities must be regarded as very incompletely tested.

Jurassic bituminous coal has been obtained in seams up to 3ft. thick in depth in the sunklands area (Robe bore) and may occur more shallowly adjacent to or overlapping the Padthaway horst.

Two new formational names have been introduced in this *Bulletin*. They are the lower Tertiary terrestrial and paralic sediments to be known as the Knight sands and clays and the bryozoal and marly limestones described as the Gambier limestones.

CHAPTER I

INTRODUCTION

Geological investigations in the South-East Province of South Australia, by the writer, were commenced in 1947 in connexion with a proposed harbour site at Robe and underground water supplies in the Bordertown-Mt. Gambier districts. Attention was directed initially to the study of Quaternary sea-level variations and beach-sand communities in the hope that some indication might be given of future relative sea-level changes and their effect on harbour installations. This aspect of the work involved a broad reconnaissance survey, using aerial photographs of the whole of the South-East Province south of the latitude of Kingston and the preparation of a regional map based largely on air-photo interpretation. The results were discussed with overseas authorities in 1948 and certain modifications have since been made.

Early in 1949 the geological investigations were resumed. They comprised the geological mapping of the Mt. Gambier, Northumberland, and Benara military sheets for reproduction on "one inch to the mile" scale, and the broad assessment of the mineral resources of the area including the petroleum possibilities, the supplies of crushed stone for railway, highway, harbour, and other public works, and certain underground water resources. The writer was assisted in this work by G. W. Cochrane (Assistant Geologist) who also undertook detailed investigations and supervised the diamond drilling of the Up and Down dolomite deposits of Tantanoola, and the Mt. McIntyre and The Bluff basalt occurrences in connexion with ballast supplies for the South Australian Railways. The geological mapping of the Kalangadoo and portion of the Millicent military sheets were also undertaken during this phase of the survey.

More recently the investigational work was extended to include the proposed Cape Jaffa deep-sea harbour site, and the possibilities of exploring underlying Jurassic sediments at moderate depths near Comaum for bituminous coal. The mapping of the Robe, Kingston, Penola, Naracoorte, and Struan military sheets comprised the major activity in this final programme. G. W. Cochrane and M. Solomon (Assistant Geologist) undertook a large proportion of this work.

The report is presented in four sections.

1. The General Geology of the South-East Province of South Australia.
2. Quaternary marine coast-line investigations.
3. Modern beach studies and sand communities of the S.-E. coast.
4. Geochronology of the Quaternary.

CHAPTER II

ACKNOWLEDGMENTS

The completion of this *Bulletin* would not have been possible without the generous co-operation of many organizations and persons. It is not possible to mention each of the individuals by name but it is hoped that the acknowledgment of the help received from the departments and organizations with which they are associated will be indicative of the writer's personal gratitude.

In undertaking regional geological mapping, aerial photographs have been of outstanding assistance. These were taken by the R.A.A.F. and freely made available at all times by the Photo. Library Section of the Australian Army in South Australia.

Levels indicated on the regional map and used in the interpretation of landwarping movements and relative sea-level oscillations were supplied by courtesy of the South-Eastern Drainage Board.

Accurate topographic surveys of the coastal platforms near Robe jetty and information concerning prevailing wind and swell directions were made available by the South Australian Harbors Board.

The Hydrographic Section of the Royal Australian Navy was responsible for the detailed echo-sounding surveys of Guichen Bay (Robe) and Lacepede Bay (Cape Jaffa-Kingston).

In the course of the Robe Harbour investigations the author systematically sampled sands of many beaches and beach dunes between Cape Lannes and a situation 40 miles north of Kingston. Shell beds in the interdune areas, and sands of the stranded coastal dunes, were also sampled. Sieving analyses of the sands were then undertaken by the C.S.I.R.O. in the Bonython Laboratories of the South Australian School of Mines. An investigation of the sub-fossil shell faunas in these various samples and of many borehole sections were made by Mr. B. C. Cotton, Conchologist of the South Australian Museum and Departmental Palaeontologist.

Miss I. Crespin, Commonwealth Micropalaeontologist, has aided with the investigation of microfaunas from various boreholes and from surface samples, and more recently Dr. Martin Glaessner has offered invaluable advice on problems of Tertiary stratigraphy.

The Zinc Corportion Ltd., in association with the Oscar Weiss Company, completed an air-borne magnetometer survey of the subcoastal belt in South Australia and Victoria. The results were subsequently corrected for latitude by the Geophysical section of the Bureau of Mineral Resources, Geology and Geophysics. This information has been of great assistance in the better understanding of certain regional problems.

Close co-operation was maintained with the Victorian Geological Survey in connexion with petroleum prospects.

The writer would like to make particular reference to the co-operation of Dr. F. Reeves and Mr. H. J. Evans, of the Vacuum Oil Company Pty. Ltd., who inspected the area and arranged the use of an aircraft for a broad reconnaissance survey.

Finally, appreciation must be warmly accorded of the assistance of the South Australian Government Geologist, Mr. S. B. Dickinson; of the Consultant Geologist, Dr. L. K. Ward; and of the Assistant Geologists, Messrs. G. W. Cochrane and M. Solomon.

CHAPTER III

PREVIOUS INVESTIGATIONS

Much has been written on various aspects of the geology and physiography of the South-East Province. A fairly complete bibliography is presented at the conclusion of this *Bulletin,* and only brief reference to the more important papers is given here.

The Rev. J. E. Tenison Woods (1862) was the first geologist to focus attention on the beach-dune range system of the province and he also referred to the Mt. Gambier volcanic activity. The stranded beaches have since been dealt with in greater detail by N. B. Tindale (1933 and 1947) and by R. L. Crocker and B. C. Cotton (1946), and also by C. Fenner (1930), L. Keith Ward (1944), and others.

Detailed investigations of the Mt. Gambier lavas and ash beds were carried out by Stanley (1909); general references to these have been made by W. Howchin (1901), Moulden (1895), and Hall (1907). C. G. Stephens (1941) and co-workers have prepared maps and reported on the soils of the volcanic areas. J. Prescott and C. Piper (1929) studied a typical Mt. Gambier volcanic soil in considerable detail. Physiographic features of volcanic cone and collapse structures of Mt. Gambier have been studied in detail by Fenner (1921) and also by Howchin (1901) and Ward (1944).

The problem of the oscillating water-level in the Blue Lake has been dealt with by Fenner (1921). It is also referred to by Ward (1941) in connexion with a comprehensive study of the underground water resources of the South-East. Solomon and Cochrane are preparing detailed underground-water reports, including underground drainage possibilities, for counties Grey and Robe.

Problems of modern coast development have not previously received detailed study, although Fenner (1930) and Ward (1944) have referred briefly to their broader features.

The petroleum possibilities of the region have been the subject of many inquiries, but few have involved detailed field mapping. The unpublished company reports held by the Geological Survey are listed in the bibliography. The main investigations on behalf of the Government were carried out by Wade (1915) and Ward (1944). Other economic mineral resources in the South-East have received little attention, apart from building stone (Jack 1923; Dickinson 1951) and crushed stone, Cochrane (1952).

CHAPTER IV

THE AREA AND CLIMATE

THE AREA

The survey covers an area of about 6,060 sq. miles of the most southerly portion of the State of South Australia of which a regional map (fig. 46) has been prepared. The limits are not defined by natural boundaries, rather by the requirements of the problems under investigation expressed in the Introduction.

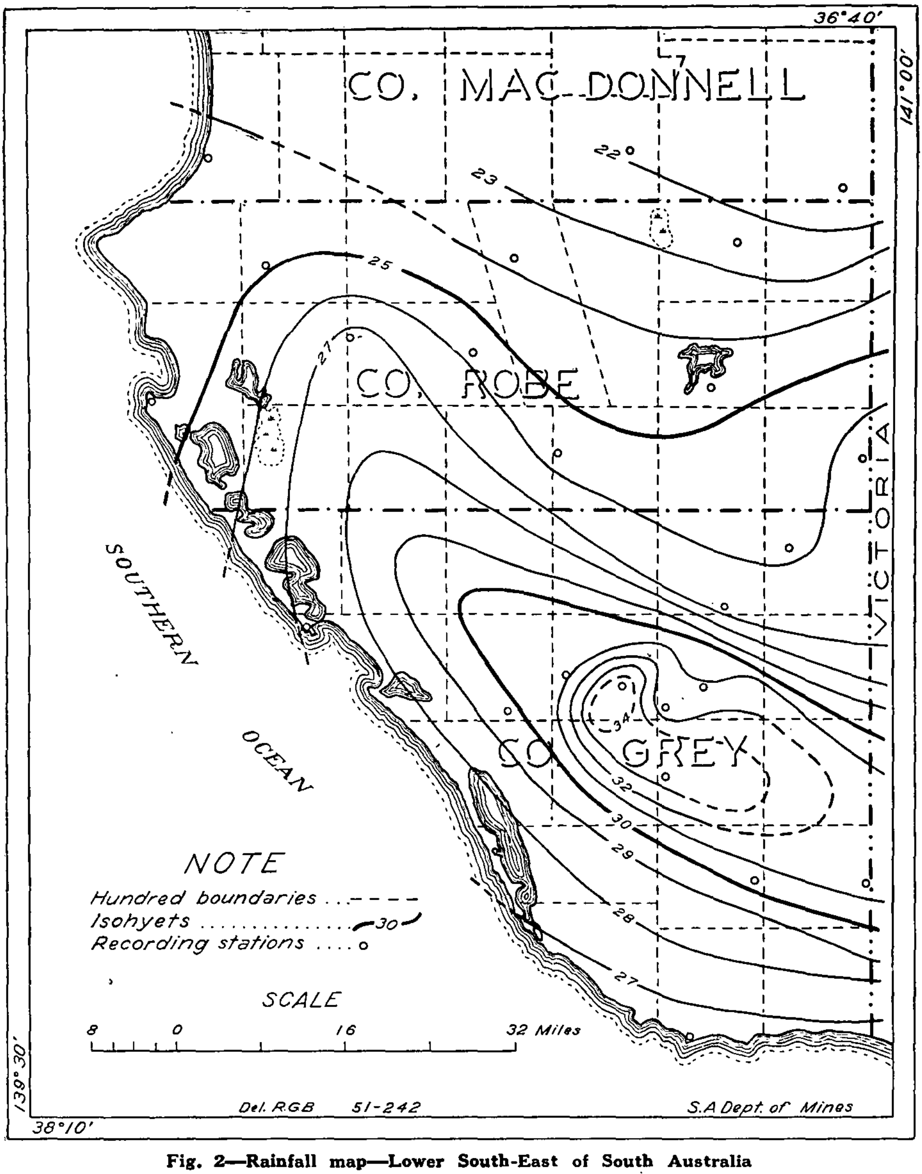

Fig. 2—Rainfall map—Lower South-East of South Australia

CLIMATE

The whole of the area receives more than 20in. of rain annually. In general, rainfall is heavier to the south (fig. 2), and the occurrence of volcanic hills and rises in the Mt. Burr-Mt. Gambier region increases the rainfall locally. The highest average rainfall is about 35in., recorded at Mt. McIntyre.

The region is included within Davidson's (1934) Semi-humid Warm Temperate Zone, in which the number of months with a P/E (ratio precipitation over evaporation) greater than 0.5, ranges from seven in county Robe to nine in the southern portion of county Grey. The mean annual temperature for the area is 56-58°F. Maximum seasonal rainfall occurs in the winter period, and there is a relative summer drought. The amplitude of mean annual temperature is 7-9°F., and phase lag 33-36 days behind solar radiation, Prescott and Skewes (1938).

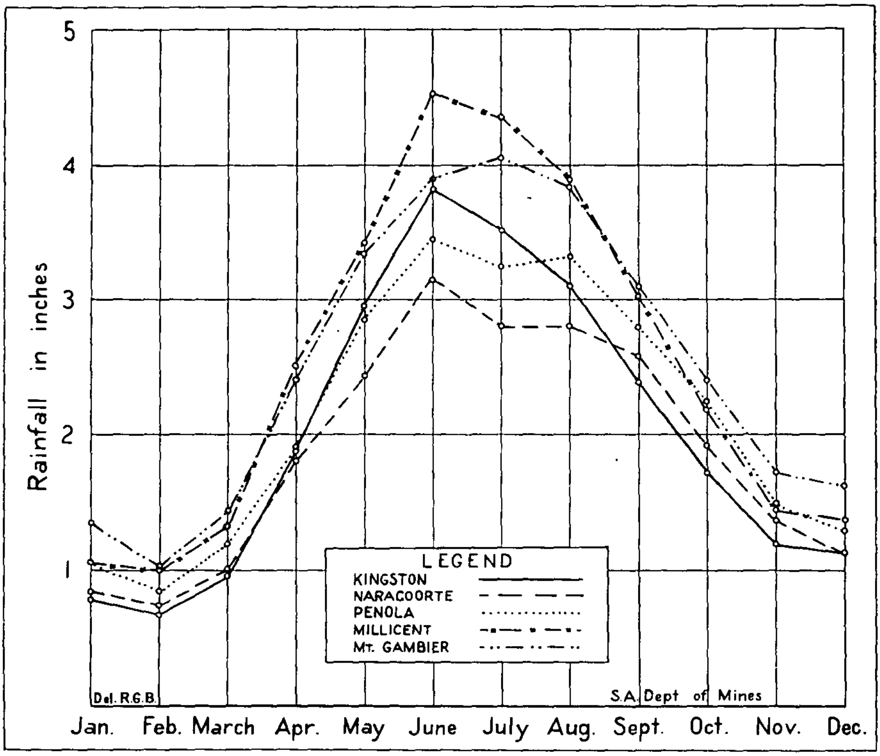

Fig. 2a—Mean monthly rainfall (70 years)—Lower South-East

CHAPTER V

PHYSIOGRAPHY

The area is essentially a subcoastal plain with a minor seaward slope. The greater part is less than 300ft. above sea-level and is practically devoid of obvious surface drainage features. A north-westerly downwarp tendency away from the volcanic area is also noticeable (*see* geological plan).

Superimposed upon this depressed terrain there is a well-developed system of sub-parallel "ranges" aligned in sympathy with the modern coast. These ranges are stranded ocean coastal dunes of Quaternary age. In relation to their interdune flats, they rarely exceed 100ft. in height. In general the ranges divert surface water north-westwards towards the lakes of the Murray Mouth. In this direction the drainage gradients are too flat to form definite stream channels. Marshes, swamps, and lagoons are prominent features of these interdune areas and an extensive flooding normally takes place in the wet winter season. A definite stream pattern, however, is recognizable near Millicent where steeper surface gradients occur adjacent to old volcanoes.

The inland limit of the "dune-range" country is marked by the Kanawinka Fault escarpment trending NNW. through Naracoorte. To the east of this boundary the land is higher and possesses definite drainage lines, although in many places they are lost in nets of swamps and lagoons.

The older "dune" ranges, *i.e.*, the most easterly, have a general trend in sympathy with that of the Kanawinka Fault. The trend is arcuate with easterly directed convexity in the central region, but reversing in the approach to the volcanic region to the south. To the north the ranges converge and finally lose their individuality as they telescope near Kingston and continue as a dune complex towards the Murray Mouth. The evenness of dune curvature is a function of the flatness of the pre-existing continental shelf on which the sea beaches have been stranded. It also suggests a relatively retreating sea margin on which aggradational as against erosional processes have dominated.

A feature of the younger dune ranges near the coast is their tendency to submergence. Much of the interdune corridor between the Robe and Woakwine Ranges now lies below sea-level. At several points the sea has broken through the coastal (Robe) "range" to form Guichen and Rivoli Bays, behind which beach-ridged dunes are now forming. Between Robe and Beachport in the same interdune corridor the levels of the fresh-water lakes are as much as 12ft. below mean sea-level.

The Coorong is another manifestation of submerged range and interdune topography. Its name was given originally to the lagoon lying behind the modern coastal sand dune, but it is now applied more generally to include both features. These are described in greater detail elsewhere.

Much of the modern coastline is developed in aeolianite dunes which have been eroded to produce a complex of low rugged cliffs, irregular platforms, reefs, shoals, sea stacks and islands. In the more southerly coastal stretches—beyond Cape Banks where the aeolianite dune has been entirely removed—mid-Tertiary bryozoal limestones have been sculptured to provide other varieties of shore-line features.

To the north, at Cape Jaffa, outcropping dolomite has been eroded to form submerged reefs extending a considerable distance from the coast.

The volcanic areas are those of greatest topographic relief, and although only rising to a maximum of 802ft., they form prominent land-marks, such as Mt. Burr (802ft.), Mt. Gambier (630ft.), Mt. Graham (676ft.), and Mt. Schank (520ft.). Late Cainozoic volcanicity has produced massive accumulations of basalt as at Mt. Burr and The Bluff, the building of several volcanic cones as at Mt. Schank, and the spreading of ash and the formation of the subsidence features (calderas) as at Mt. Gambier itself.

Of more recent origin are the lunettes which form striking topographic features, particularly from the air, in the Naracoorte-Kingston area. (Plates I and II.) These are arcuate mounds of wind-transported sediments. They rarely exceed 20ft. in height and practically always occur on the eastern (lee) margin of circular lagoons in the interdune flats. They are formed from calcareous clayey and gypseous material carried from the dry lake beds in the summer season. The vegetation marginal to the lake traps this wind-blown material and assists the slow building up of the lunettes. (Crocker 1946.)

CHAPTER VI

DRAINAGE

One of the main problems in connexion with the development of the South-East is the drainage of surface and underground waters. The relatively high winter rainfall, in association with the flat terrain, produces extensive seasonal floodings in the plains areas. In addition, excess surface-waters from the adjoining counties of Lowan and Follett in Victoria drain across the border.

Although practically the whole area is underlain by porous Tertiary limestones, downward percolation is impeded in the northern areas by the proximity of groundwater to the surface and by a veneer of impervious soil travertine and swamp clays. Reference has already been made also to the effect of the transverse aeolianite dunes on surface drainage.

For more detailed accounts of the drainage problems of the area than are given below, reference should be made to Dr. Ward's *Bulletin* (1941) "The Underground Water of the South-Eastern Part of South Australia". Plate I of Ward's *Bulletin* shows the salient hydrological features. The problem of drainage of surface and underground waters are dealt with separately.

SURFACE DRAINAGE

Surface waters from the higher lands east of the Naracoorte Range drain by way of the Mosquito, Naracoorte, and Morambro Creeks on to and across the Naracoorte Plain. Before the construction of artificial drains most of the surface waters from north of about Millicent and the Dismal Swamp migrated towards the Coorong. Reedy Creek was originally one of the principal watercourses of the region before artificial drains were constructed. It extended in a NNW. direction to Salt Creek where it joined the Coorong.

Drainage in Reedy Creek is intermittent, but minor streams, such as Stony Creek, discharge water continuously into Lake Bonney from springs on the ocean front of the Woakwine Range. Benara Creek also carries waters westward through the Woakwine Range. Maria Creek, near Kingston, was at one time a natural outlet for local flood waters and its flow has since been increased by artificial schemes.

The Dismal Swamp, to the north of Mt. Gambier, lies approximately 200ft. above sea-level, and according to J. E. T. Woods (1862) "In very wet seasons there is a current in the Dismal Swamps for about two months. It flows into the River Glenelg in Victoria."

In the karst (limestone) country near Mt. Gambier, surface drainage is practically absent. Practically all flood waters escape to the sea *via* subterranean channels.

UNDERGROUND DRAINAGE

Subsurface drainage plays a major role in the escape of waters to the ocean. Much of the area is underlain by very porous (bryozoal) limestones which are also cavernous. Groundwater flows rapidly in these limestones and issues in subcoastal areas in immense volumes. (*e.g.*, near Port MacDonnell.) According to Ward (1941) "Recent gaugings by the South-Eastern Drainage Board have shown that the total discharge from the area . . . (embracing the springs at Ewen Ponds and Eight-Mile Creek) . . . was 86,400,000gall. per 24 hr. in October, 1939, and 70,000,000gall. per 24 hr. at the end of summer in May, 1939." These are but a few of the many springs known in the area. Farther inland, another series of springs marks the trace of the Tartwaup Fault. The Snuggery Springs, 7 miles SE. of Millicent, for example, discharge water at rates of up to 4,000,000gall. per day.

For many years the South-Eastern Drainage Board has systematically recorded the rise and fall of groundwaters in a number of bores situated to the north of Millicent and Kalangadoo. Rainfall gaugings have also been kept, and from statistical studies many interesting facts have been deduced, namely—

(1) There is clearly a movement of groundwater from the western portion of Victoria into South Australian territory.

(2) Water-table contours have an approximately meridional trend in this region (Ward, 1941, plate I), and tend to converge around the highlands in the south producing steeper gradients locally.

(3) There is a general tendency for the highest expression of the water-table to be registered in September, at the end of the winter, and for the lowest level to be recorded in April at the close of the summer.

(4) The lag in the change of groundwater level compared with variation in rainfall is related to the westward migration of the waters.

(5) Abnormal heavy rains have a marked effect on the water-table.

ARTIFICIAL DRAINAGE

The draining of the large potentially agricultural areas of the South-East poses a major engineering problem. Except in a few favourable areas artificial drains must be constructed. In many places it is necessary to breach the various dunes to provide the more direct access to the ocean. Even so the average channel gradient is very low, and to compensate for this the cross-sectional area of the drains must be large to allow them to discharge the huge volumes of water. For example, at Robe, Drain L is 1·4 miles long and up to 60ft. deep. In some areas the flow of water is continuous even in the dry season where they have been excavated below the water-table. The flow is often impeded by heavy algal growths.

CHAPTER VII

GENERAL GEOLOGY

The area under review comprises mainly Tertiary and Quaternary rocks. The dominant outcropping rock type is the mid-Tertiary marine (bryozoal) limestone. Lower Tertiary fluviatile and estuarine (paralic) clays and sands are restricted in outcrop, whilst outcropping pre-Tertiary rocks are rare. The latter comprise early Palaeozoic plutonic and hypabyssal rocks. The volcanic rocks are of late Pliocene or younger age.

Borehole information has provided evidence of Permian and Jurassic formations which may be widely distributed at depth.

REGIONAL DEFINITION

Geologists and geomorphologists have mostly assumed the Mt. Gambier area to be simply a southern continuation of the Murray Basin. This conception has several weaknesses and recent discoveries favour an entirely different genesis. The Gambier-Portland coastal plain area forms a distinct geological province essentially unrelated to the Murray Basin in pre-Tertiary times. It is separated from the Murray Basin proper by a shallow horst-like structure which will be termed the Padthaway horst (fig. 3). The subcoastal area to the south will be termed the Gambier sunklands. The evidence for these subdivisions is briefly described as follows:

Geological Evidence

A simplified geological map (fig. 4) of the South-East and environs shows the broad lineal (NW.-SE.) "ridge" of sporadically outcropping igneous basement rocks, to the south of the Adelaide-Melbourne railway, extending away from the lakes of the Murray River Mouth. The ridge is bordered by strongly negative areas in which bedrock—from borehole information—lies at much greater depths. The shallow disposition of bedrock on this ridge is, therefore, horst-like.

Between Kingston and Robe a major structural discontinuity occurs. Adjacent to Kingston, granite outcrops or lies at shallow depth whereas at Robe a deep borehole, sunk for oil, failed to penetrate Jurassic (overmass) sediments by 4,504ft.

The horst structure trends towards the Dundas Peninsula in the Dergholm-Casterton area of Western Victoria where granitic bedrock and (?) Ordovician metasediments again outcrop. Its continuity, however, is broken by the Kanawinka Fault. Shelving overmass Jurassic and Tertiary sediments overlap the Dundas Peninsula from the south. Fig. 5 shows this interpretation in section. Bedrock shelves to the north of the horst, but to the south the Gambier sunklands exceed 7,302ft. to basement.

Air-borne Magnetometer Results

The south-western terrain is one particularly well suited to coverage by the air-borne magnetometer and the results of a survey have largely confirmed the foregoing geological interpretation. It has also revealed a number of other important regional features, particularly the Tartwaup Fault which will be described later.

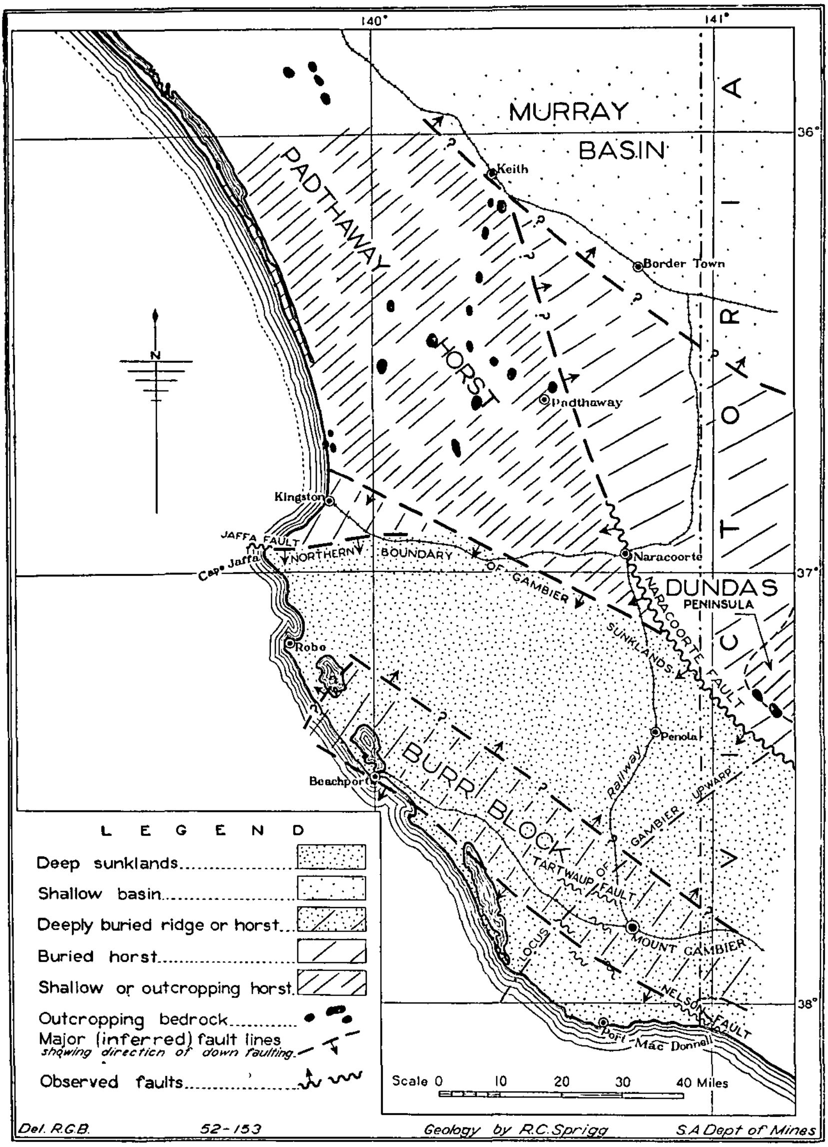

Fig. 3—Structural geological plan of the South-East Province, based extensively on results of the Oscar Weiss air-borne magnetometer survey

[*By courtesy of The Zinc Corporation Ltd.*]

(Note.—Naracoorte Fault = Kanawinka Fault)

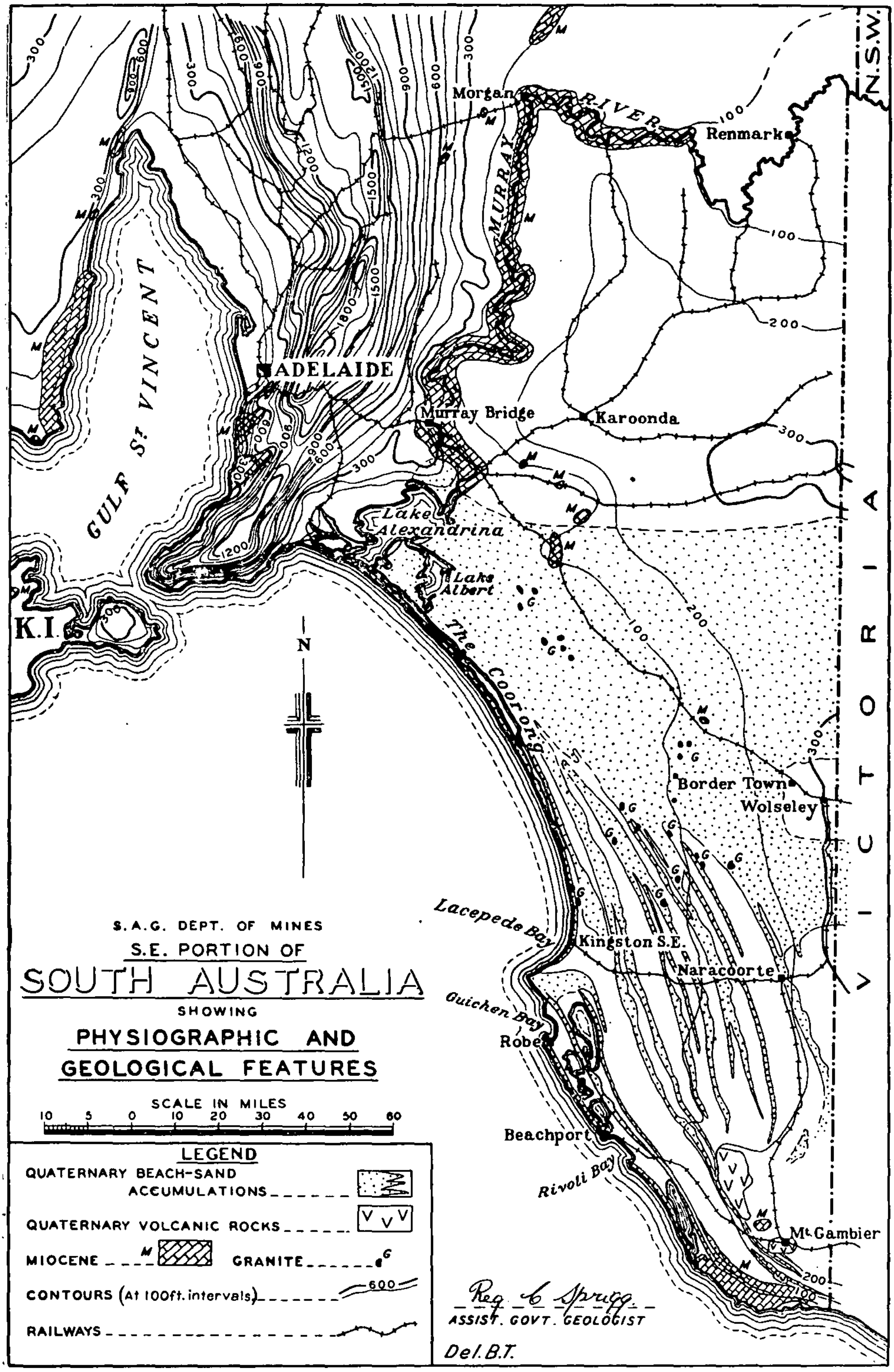
S.A.G. DEPT. OF MINES
S.E. PORTION OF
SOUTH AUSTRALIA
SHOWING
PHYSIOGRAPHIC AND
GEOLOGICAL FEATURES
SCALE IN MILES
10 5 0 10 20 30 40 50 60
LEGEND
QUATERNARY BEACH-SAND ACCUMULATIONS
QUATERNARY VOLCANIC ROCKS
MIOCENE
GRANITE
CONTOURS (At 100ft. intervals)
RAILWAYS
ASSIST. GOVT. GEOLOGIST
Del. B.T.
ADELAIDE
Morgan
Renmark
MURRAY RIVER
N.S.W.
VICTORIA
Murray Bridge
Karoonda
Lake Alexandrina
Lake Albert
The Coorong
GULF St VINCENT
K.I.
N
Border Town
Wolseley
Lacepede Bay
Kingston S.E.
Naracoorte
Guichen Bay
Robe
Beachport
Rivoli Bay
Mt Gambier

Fig. 4

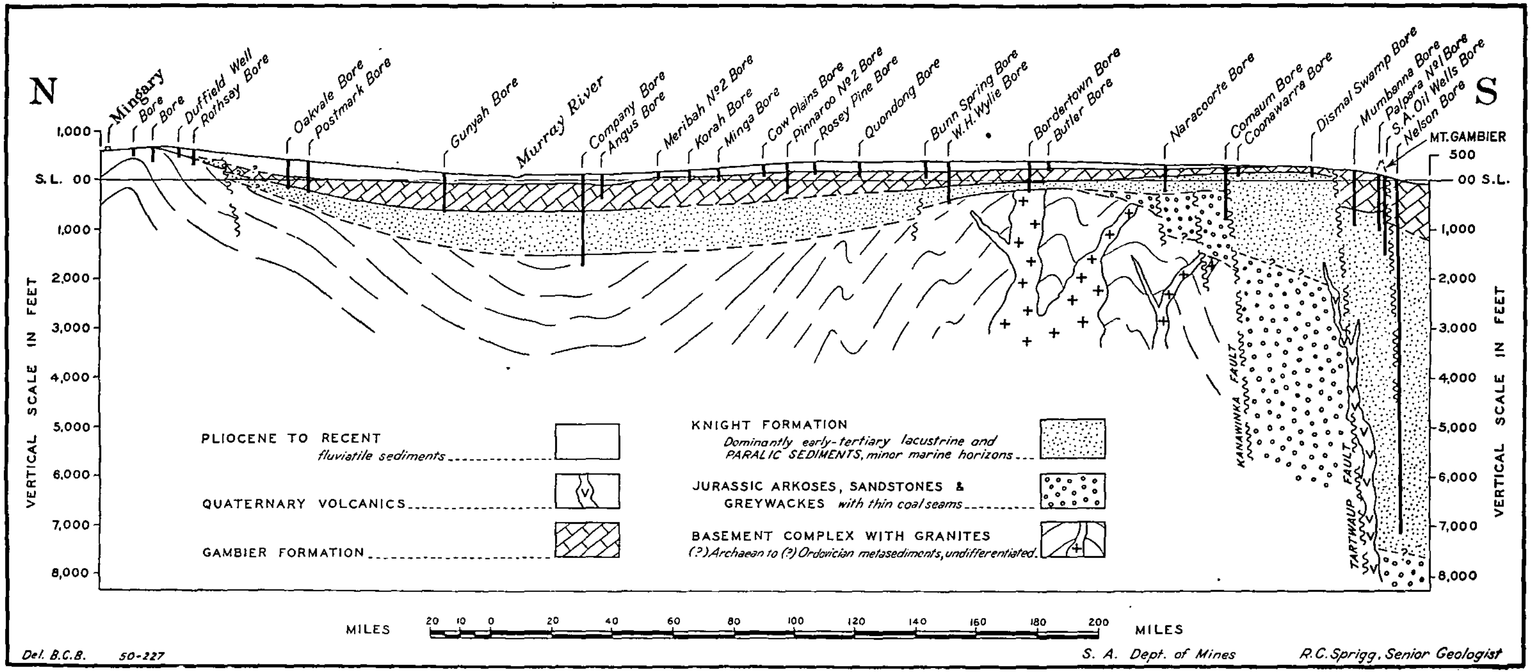

Fig. 5—Geological section—Mingary to Nelson

Widely spaced parallel traverses were selected primarily to define the southern escarpment of the horst structure previously described, and if possible to indicate the depth to basement in the Gambier sunklands. The traverses were at right angles to known regional structures. "Tie-in" traverses were also flown. The area covered extended from north of Kingston, thence southeast to Casterton in Victoria, down to Cape Otway and back along the coast to Kingston. Special traverses were flown out to sea to cross the continental platform.

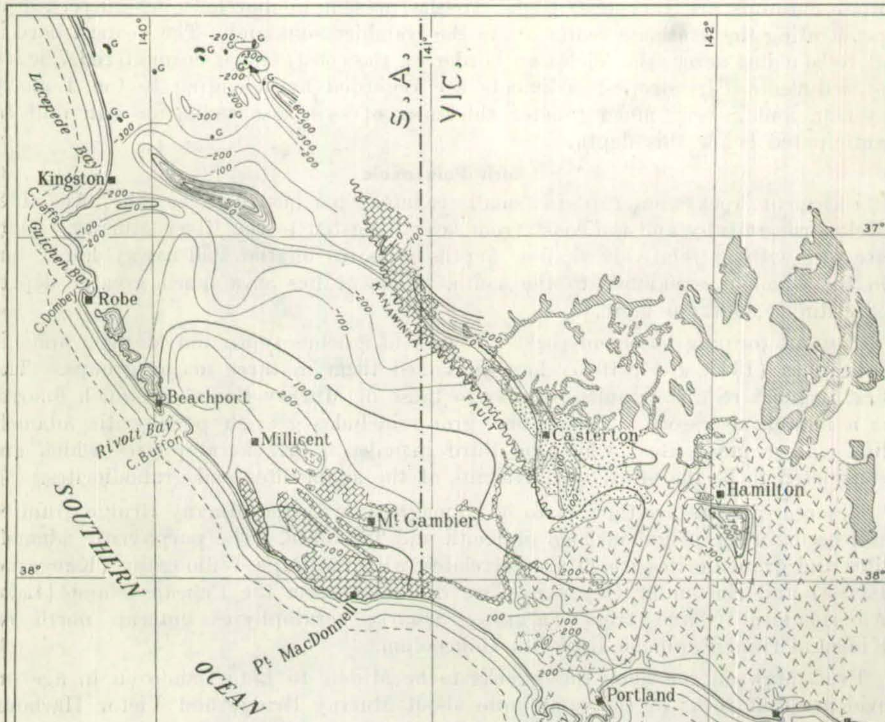

Fig. 6—Air-borne magnetometer survey of the Gambier sunklands

[*By courtesy of The Zinc Corporation Ltd.*]

The buried escarpment was located very convincingly by a major regional break in the geomagnetic pattern (fig. 6) from Cape Jaffa through a point about 10 miles N. of Penola and on to near Casterton. The complementary high altitude traverse (5,000ft.) from Casterton across Mt. Gambier confirmed this result as a major structural feature. To the north of the buried escarpment basement rock is much shallower and gave rapid magnetic variations, while to the south deep basin sediments produced very even low-intensity curves both at high and low altitudes. The individual profiles indicate an oceanward deepening of the basin sediments except in the vicinity of the Tartwaup Fault and the volcanic areas. In these latter areas there is evidence of the presence of a buried horst structure elongated in a northwest and southeast direction. Apparent down-throw from the inferred horst is to the northeast, northwest and southwest, with southeastern extension into Victoria. Between this magnetically positive area and the northern and eastern margins of the sunklands a fairly continuous trough appears to have developed.

STRATIGRAPHY

Knowledge of the stratigraphy is almost wholly dependent on borehole data. Rock outcrops are very restricted. To the present no borehole has succeeded in penetrating the overmass sediments in the Gambier sunkland. The deepest bore is at Nelson just across the Victorian border on the coast, and it encountered 7,302ft. of sediments. Its deepest sediments are regarded as belonging to the Tertiary system, and a very much greater thickness of overmass sediments can still be anticipated below this depth.

Early Palaeozoic

Basement rocks outcrop in small isolated patches between the Adelaide-Melbourne railway and the coast from near Kingston to the River Murray. They are met with at relatively shallow depths in bores on the Padthaway horst, but in the Gambier sunklands to the south, basement lies at a much greater depth, exceeding 4,000ft. or more.

The outcropping basement rocks are all acid igneous types and Mawson and his colleagues (1943, 1944, 1945) have classified them in three major groups. The first includes reddish granites similar to those of Murray Bridge in which fluorite is a notable accessory. The second group includes greyish porphyritic adamellites and granodiorites; while the third includes quartz keratophyres which are considered to be the effusive equivalents of the adamellites and granodiorites.

The red granites are thought to be co-magnetic with the Murray Bridge granites and occur in the neighbourhood of Keith and Tintinara. The porphyritic adamellites and granodiorites which are correlated with the Cape Willoughby (Kangaroo Island) and Encounter Bay suites are described from the Pelican Island (Lake Albert) locality and from Taratap. Quartz keratophyres outcrop north of Kingston from Papineau Rocks to Didicoolum.

Prof. Mawson considers these rocks to be Middle to Late Cambrian in age on evidence that rocks of the same suite about Murray Bridge and Victor Harbour intrude the Adelaide geosyncline (Adelaide System and Lower Cambrian sediments) and on the basis of similarities with the porphyroid series of the west coast of Tasmania with which correlation is also made.

The present writer notes further that red granites of the Murray Bridge and Keith-Tintinara suite occur near Dergholm in Victoria. Comagmatism is suggested, but the age of the Dergholm granites is doubtful.

Upper Carboniferous

Glacial sediments now considered to be upper Carboniferous (David and Browne 1950) have been intersected in bores on the Padthaway horst. They are recorded in the Alfred Flat bores (Coorong) from 510ft. down to bedrock at 924ft., and in other bores farther north. Similar conditions extend at least to Kingston. The bedrock surface on which these glacial beds occur is highly irregular and has much in common with the roches moutonees association of a glacially sculptured topography. The glacial beds are pictured as morainic deposits.

Although no petrological studies have been made, it is generally recognized that the morainic deposits of southern Fleurieu Peninsula and Yorke Peninsula contain many erratics from the South-East Province. The direction of glacier movement was dominantly north-westward from highlands in the vicinity of Bass Strait and Tasmania. Widespread evidence of glaciation in the South-East Province then is only to be expected. Thick morainic deposits may also be anticipated at depth in the Gambier sunklands.

Jurassic

Jurassic formations are not known to outcrop in South-Eastern South Australia, but they were encountered at depth in the Robe bore. They were entered at 1,475ft. and continued to the bottom of the bore at 4,504ft. Dr. Ward has described them as greyish-green argillaceous sandstones containing seams of bituminous coal. They probably extend continuously from west of Robe to the Casterton district in western Victoria where Jurassic beds containing similar bituminous coal outcrop extensively in overlap on the Dundas Peninsula. The age classification is based on this correlation.

Edwards and Baker (1943) have shown the Victorian Jurassic sediments to be of lacustrine or estuarine origin. They consist of arkosic sandstones, felspathic grits, sandy shales and minor conglomerates, grits and seams of bituminous coal. The sandstones and shales are mostly greenish-grey in colour due to chloritic cement. They describe the land mass which shed these sediments as having existed in the vicinity of Bass Strait and that its framework must have been of granite Palaeozoic sediments, dacites, and andesitic tuffs.

The maximum thickness of Jurassic sediments in the Gambier sunklands exceeds 3,000ft. at Robe, and 5,000ft. on the Otway Peninsula in Victoria. Characteristics of these sediments are the remarkable preservation of the more unstable mineral constituents, the poor sorting and widespread current bedding which are indicative of very rapid sedimentation in a deep landlocked fresh-water basin. Rapid accumulation and burial (Pettijohn 1943) appear to be responsible for the preservation of the unstable minerals rather than climatic factors.

No definite marine sediments have been recognized in the Jurassics, and this is perhaps remarkable considering the deep basin setting in what must have been at least in part a subcoastal area. There is no evidence of a land barrier to the west beyond the limit of the modern continental shelf in South Australia, but to the east in Victoria the distribution of the known Jurassic rocks suggests an elongate landlocked trough trending across the States in an east-west direction north of Bass Strait.

Tertiary Formations

There is little unanimity of opinion amongst palaeontologists concerning the subdivision of the Tertiary succession in southern Australia. Lateral variation, facies changes, environmental differences, and poor outcrops make the task of correlation extremely difficult. In the South-East Province especially, very little systematic work has been attempted.

The principal lower Tertiary formations in the Murravian Gulf and Gambier sunklands areas have been attributed to the Balcombian, Janjukian, and lower Aldingan or Anglesean. A thin veneer of (?) Pliocene (Kalimnan and Werrikooian) sediments also occurs in the Dartmoor area and extends irregularly across Coonalpyn Downs to the north-west. Definite Eocene formations (with *Hantkenina* fauna) have been recognized (Baker, 1947, etc.) near the base of the Tertiary succession at the eastern extremity of the Gambier sunklands (Moonlight Head, Victoria) but they have not yet been recognized in South Australia.

The age relationships of the Tertiary formations are indefinite, but the most recent opinion favours the Janjukian and Balcombian as including Oligocene and lower and middle Miocene sediments; and the lower Aldingan includes both Eocene and Oligocene sediments with dominantly paralic facies. The Werrikooian is placed at the conclusion of the Pliocene and extends into the basal Pleistocene. The formations are described in greater detail as follows: they are given local names, as mappable units, in conformity with the code of stratigraphic nomenclature (Raggatt *et alia* 1950).

Knight Sands and Clays

These beds and their probable equivalents at Anglesea in Victoria are paralic in character and consist chiefly of clays, sands, and gravels with a few brown-coal seams. The upper beds comprise chocolate mudstones and clays frequently pyritic and natrojarositic. The lower portion consists of sands and pebbly grits with brown-coal beds. The formation contains only a few marine fossils except the foraminifera *Cyclammina* which is abundant.

The beds are present throughout the Gambier sunklands, but are known to outcrop only in the vicinity of Knights quarry about 8 miles NW. of Mt. Gambier. On the other hand they are restricted in occurrence on the Padthaway and Dundas horsts. For example, they are missing in the Comaum bore near Penola.

In the Robe bore the sediments are described as green and grey clays with bands of pyrite and carbonaceous material, interbedded with sands and gravels; fossil shark teeth were recorded from the upper sections. These features indicate that paralic conditions prevailed over most of the area. The abundance of shark teeth suggests an oscillating sea-coast with numerous embayments of warmer water, in which many sharks would be stranded in intertidal reaches after heavy storms. The same shallow seas extended across the Padthaway horst region well into the southern limits of the Murray Basin.

The deep bore at Nelson has proved the greatest known thickness of Knight formation. Miss Crespin (1949) records it from 976ft. to the completion of the bore at 7,299ft. She describes the formation as comprising a sequence of dark- to light-grey micaceous and carbonaceous sandstones and dark-grey hard shales and sandstones with plant remains. She notes marine conditions at intervals down to 5,304ft. where the Anglesean foraminifera *Cyclammina* occurs with small fragments of bryozoa. Few fossils other than foraminifera and bryozoa occur in any of the bore-core sections, but Miss Crespin records a rich assemblage of forams, bryozoa, ostracoda, mollusca, and fish teeth at 1,924ft. to 1,943ft., which she correlates with similar assemblages found at 1,980ft. to 1,995ft. in Knight Dome No. 2 bore (40 miles to the NE.) and at 2,110ft. in the Associated Oil Company bore (5 miles to the NE.).

Fragmentary plant remains are common in the bore material and cf. *Banksia* sp. and cf. *Cinnamonum* sp. were encountered at 2,828ft. Doubtful algal markings were noted frequently in carbonaceous sandstones below.

Dr. Frank Reeves (1949) has noted that the sandstones below 5,336ft. are more indurated than at lesser depths, but concludes that they do not resemble Jurassic arkosic sandstones. He also concludes that the bore bottomed in grits like those of the basal Eocene beds of Moonlight Head in Victoria.

The lateral extent of the area occupied by excessive thicknesses of the Knight formation is unknown because no bore has penetrated it within a radius of 100 miles of the Nelson bore. Thicknesses on the elevated fault block between the Kanawinka and Tartwaup fault zones are probably lesser, and on the buried Padthaway horst the formation transgresses and thins out irregularly. Farther north, in the Murray Basin proper, equivalent beds thicken and attain a maximum known thickness of 1,596ft. (Company's bore, Coonalpyn).

Reeves and Evans (1949) suggest a possible thickening north-westward from the Nelson bore. This suggestion arises from a correlation of the base of the Gambier limestone and the rich Anglesean fossil horizon of the Knight formation in the Nelson, Knight Dome No. 2, and Associated Oil Company bores. The separation of these horizons—used for the correlation—were respectively 948ft., 1,805ft., and 1,968ft.

Known thicknesses from bore records of the Knight formation are as follows:

		ft.
Robe bore		965
Comaum bore		377
Associated Oil Co. bore		1,968+
Knight Dome No. 2 bore		1,838+
South Australian Oil Co. Bores	(1)	1,034+
	(2)	693+
	(3)	1,318+
Nelson bore		6,329+

The figures support the impression that the greatest thickening of the formation is subcoastal to the south of the Tartwaup Fault.

The most typical marine fossils of the upper Anglesean of Victoria and Knight formation of the Gambier sunklands are the foraminifera *Cyclammina* and *Victoriella.* They appear at a higher stratigraphical horizon than the *Hantkenina* beds (Eocene) of Moonlight Head in Victoria. The recent discovery of the latter marine molluscan bed rich in the Eocene marker foram, *Hantkenina,* near the base of Anglesean formations—just above the unconformity—at Moonlight Head, and the assumption of continuity of the Gambier sunklands between Nelson and Moonlight Head gives hope that fossiliferous Eocene beds are present below the bottom of the Nelson bore.

Gambier Limestone

The weight of opinion seems to favour the view that the lower bryozoal beds of the Gambier limestone are Janjukian (? lower Miocene) in age and that the upper beds are Balcombian (? middle Miocene). The exact demarkation between the Balcombian and Janjukian is not clear. Singleton (1939) has associated these two formations in his Barwonian "system". No definite upper Miocene marine formations have been recorded.

The Gambier limestone and its equivalents are the most extensive marine Tertiary deposits in southern Australia. They were deposited over practically the entire Murravian Gulf area (fig. 7) which was co-extensive with the sunklands of south-eastern South Australia and south-western Victoria, and apparently had their greatest vertical development in the vicinity of Portland, Victoria (2,265ft.+). The sediments are dominantly bryozoal limestones, marls, and argillaceous limestones with numerous flint bands. Foraminifera and mollusca are also very plentiful.

The accumulation of considerable thicknesses of highly bryozoal sediments over wide areas points to open clear water conditions simulating the nearby continental shelf environment of today. In the approaches to the modern Victorian highlands the clay content of the bryozoal limestones rises significantly suggesting local shore-line developments backed by a mature physiographic province.

Outcrops of Gambier limestone overlap Jurassic and older rocks in the Casterton district of Victoria (Glenelg River cliff sections) and the shallow bedrock granite on the Padthaway horst in South Australia. In those areas the Knight formation thins out or is absent. Thus it appears that as the early mid-Tertiary seas transgressed the old land surface to the north of Kingston, the area became the site of an extensive island archipelago far removed from the mainland mass. To the north the Murravian Gulf was uninterrupted to the base of the Olary divide, a distance of more than 200 miles. The archipelago was probably drowned at the height of this transgression and its presence would have been indicated only by shoals and reefs. The wedging out of these Tertiary sediments against the granite outliers clearly demonstrates the pre mid-Tertiary age of the Padthaway horst.

The Gambier limestone in places carries flint layers. Certain zones are also extensively dolomitized. The age of the dolomitization is incompletely known but it is clearly post sedimentational in most cases and for this reason it has very doubtful significance stratigraphically.

The most characteristic fossils of the Gambier limestone are *Cellepora gambierensis, Retepora* sp., *Pecten lucens, Lovenia forbesi,* and *Magellania* sp.

At present there are no known stratigraphic marker horizons within the area, but the base of the Gambier limestone has been used for structural interpretation.

Towards the close of the mid-Miocene period the sea retreated from most if not the whole of the Murravian Gulf area. In the South-East Province gentle land warping movements led to extensive emergence and subsequent terrestrial planation of the exposed beds. This retreat was possibly aided by negative eustatic movements of sea-level.

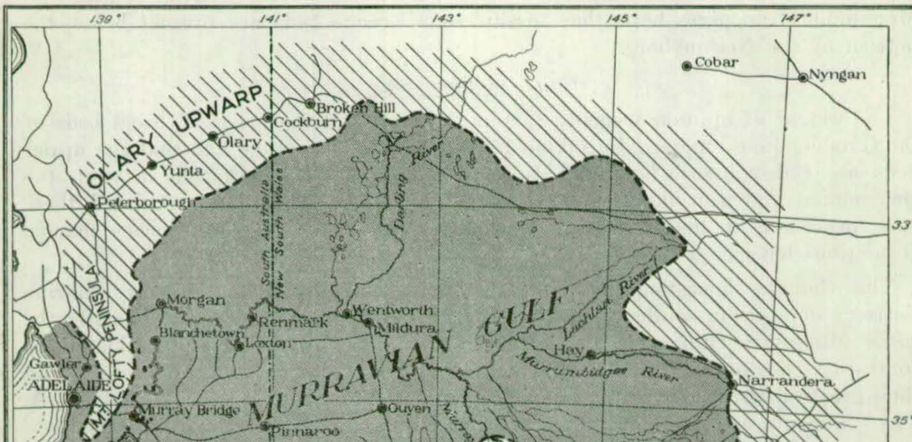

Fig. 7—Map of the Murravian Gulf—Showing maximum extent during the mid-Tertiary

Pliocene Formations

During the Pliocene period the sea had retreated from practically the whole of the Murravian Gulf area leaving only a few estuaries and inlets which are now only imperfectly known. One longitudinal arm of the sea has been located just east of the Victorian border in the vicinity of Dartmoor, another in the lower reaches of the now engrafted Murray River, and a third in the Tintinara locality. The main ocean coast is thought to have extended from a point a few miles inland from Meningie *via* a gentle arc passing several miles inland from Naracoorte and into Victoria. The old beach, more than 300ft. above sea-level, near Black Bream Springs (6 miles N. of Naracoorte) may have marked a Pliocene strand line which may represent the first indication of the approaching Pleistocene ice age. This is discussed fully in later sections.

Although no definite Pliocene deposits have been recorded in the area their presence at shallow depths seaward of the old coastline may be inferred. At Caldwell Cliff, on the Glenelg River in Victoria, Singleton (1939) has measured the following section:

(*m*) 4ft. sandy soil.
(*l*) 2ft. 4in. oyster bed; with *Pecten* (*Notovola*) *meridionalis*.
(*k*) 10ft. 6in. laminated and cross-bedded limestone; with sporadic oysters.
(*j*) 6ft. limestone; with abundant irregular concretions.
(*i*) 3ft. 4in. flaggy limestone.
(*h*) 6in. oyster band; with *Equichlamys bifrons* and mould of *Dosinia*.
(*g*) 1ft. 6in. limestone.
(*f*) 8in. oyster band; with quartz pebbles.
(*e*) 3ft. limestone.
(*d*) 6in. oyster band; with *Placunanomia*; locally with a 2-in. clay capping.
(*c*) 8ft. limestone; with sporadic oysters and other bivalves (*Placunanomia, Glycimeris*) chiefly in a 4-in. grit band 2ft. above its base.
(*b*) 1ft. shell bed resting unconformably on (*a*).
(*a*) 53ft. bryozoal limestone; largely masked by slip material.

Bed (*b*) contains the typical Werrikooian (? upper Pliocene) fauna (*Bankivia fasciata,* etc.) including 200 molluscan species of which about 5 per cent (and one genus) are now extinct. This horizon is referred by Singleton "to the summit of the Pliocene, and the succeeding strata may well bridge the boundary of the Pleistocene. For field mapping it is probably best to assume that the beginning of the Pleistocene is marked by the incoming of *Pecten* (*Notovola*) *meridionalis* Tate."

From the Tintinara bore (land surface 62ft. above sea-level) Tate (1898) has described newer Pleistocene shell beds occurring from 24ft. to 244ft. From 24ft. to 150ft. the sediment was essentially loose shell debris analogous to modern shell bank accumulations. All forms recorded were shallow-water types and only 3 per cent were considered non-living. Concerning the latter estimate, B. C. Cotton (personal communication) suggests that in the light of modern palaeontological research this figure would now be more like 5 per cent, which would suggest an upper Pliocene (Werrikooian) age determination. In this respect Tate recorded that the gasteropods *Bankivia fasciata,* still retaining their colour markings, were prominent from 220ft. to 244ft. This recalls the *Bankivia* beds of the Glenelg River (Victoria), which Singleton (1939) placed as upper Pliocene. The complete section from 24ft. to 244ft. thus probably represents the complete Plio-Pleistocene transition.

The only other Pliocene phenomena of note concern volcanicity. Mt. Burr activity probably commenced towards the conclusion of the Pliocene, and its rôle will be discussed in later sections.

Quaternary

Formations of this age in the South-East are restricted to thin veneers of sea-floor deposits, to swamp and lake deposits, and to a remarkable development of arcuate stranded coastal dunes. Volcanic activity also continued intermittently throughout much of the period in the Mt. Burr and Mt. Gambier vicinities.

The stranded coastal dunes reflect at least 16 separate Pleistocene high sea-levels, which were part of a world-wide phenomenon directly related to waxing and waning glaciation.

The closure of the Pleistocene was marked by the onset of the Great Australian Arid Period (Crocker 1946) and of the contemporary "Anadara" high sea-level. This climatic "improvement" following repeated glaciation in the northern hemisphere is known as the climatic optimum. Like all major climatic changes it wrought distinct modifications on existing fauna and flora.

The Quaternary history of the South-East Province forms section 2 of this report.

LATE TERTIARY AND QUATERNARY VULCANISM

Volcanic activity occurred in the Mt. Gambier area in late Tertiary and Pleistocene times. The outbursts, although spectacular were only an outlying manifestation of a much wider regional phenomenon. At least 16 cone eruptions occurred in South Australia, whereas there were more than 120 in Western Victoria. In Victoria they are known as Newer Volcanics as distinct from earlier Tertiary volcanic activity.

Fissure eruption played a major rôle in the Victorian eruptions with the development of extensive basalt sheets covering more than 10,000 sq. miles of the Western District plains and highlands (fig. 8).

The activity in South Australia was entirely basaltic, frequently with plentiful olivine. The various vents occurred along lines of fissuring and true fissure eruption was very restricted. Minor flows apparently preceded cone formation in each case, but the rapid accumulation of steam later led to the development of explosion craters. Where remnants of the old basalt fissures can be seen, as on the west rim of the Blue Lake, and at the north-western foot of Mt. Schank, the basalt is highly vesicular.

The vulcanism viewed broadly occurred along a general SE.-NW. zone and the more northerly manifestations in part appears to have been along the Tartwaup zone. It occurred in two definite periods. The earlier groups of these newer basalts, exemplified by Mt. Burr and Mt. McIntyre, are late Pliocene and early Pleistocene and the later group by Mt. Gambier and Mt. Schank are late Pleistocene. The earlier volcanics modified the Pleistocene coastline extensively whereas the later ones post-dated certain late Pleistocene beach dune accumulations over which they spread their ash deposits.

A feature of each of the periods of volcanism was the temporary sagging of the surrounding country towards the centres of activity.

The Earlier "Newer" Basalts (Mt. Burr-Mt. McIntyre)

The various volcanoes and fissure eruptives comprising the suite have been extensively modified by erosion and masked by ocean beach sand drift. Ocean coastal erosion during middle and late Pleistocene has also made considerable inroads on the seaward margins of some of these accumulations. The true form of some of the vents is, therefore, in doubt.

Boyce Hill preserves the only truly craterlike structure known in the area, but many outlets have imperfect conical forms. Of these Mt. Muirhead and Mt. Lookout are probably the best preserved. Mt. Graham and Mt. McIntyre are elongated ridged structures which possibly represent combined fissure and

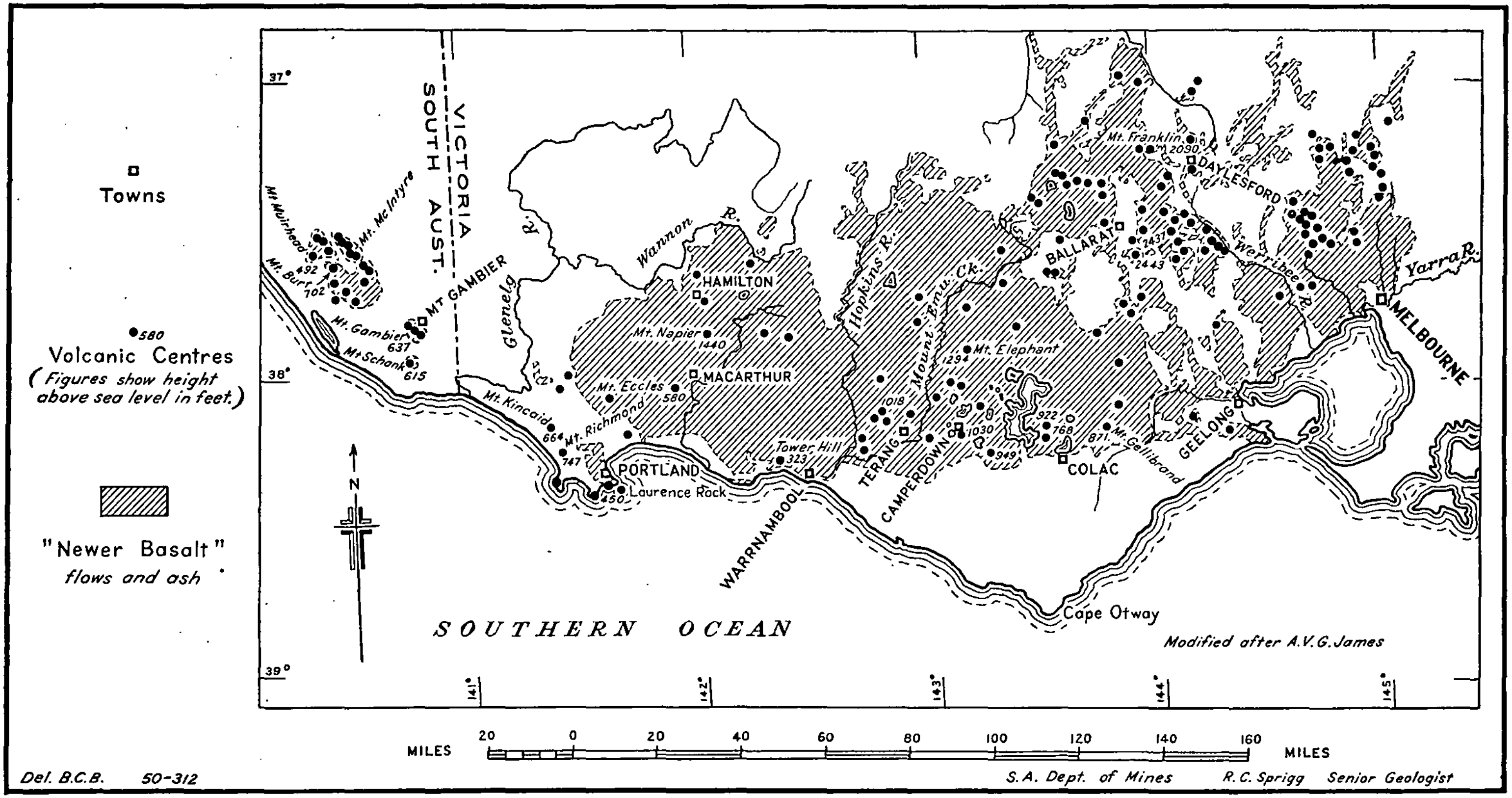

Fig. 8—"Newer basalt" flows and eruptions—Showing volcanic centres and basalt sheets in south-east South Australia and south-west Victoria

crater or multiple vent eruptions. Lake Leake and Lake Edward are volcanic subsidence features (Woods 1862) and small hills adjoining them were probably parasitic cones. The volcanoes occur along three principal lines which are part of the Tartwaup Fault zone (fig. 9). The northerly line includes vents of Campbell Hill, Mt. McIntyre, Boyce Hill, Lake Leake and Lake Edward, and Mt. Edward. The central line includes Mt. Graham, Mt. Muir, Mt. Burr, Mt. Frill and possibly another point near West Glencoe, and the southerly line includes Mt. Muirhead, Mt. Lookout, Mt. Watch, and The Bluff. Another ash accumulation occurs near Tantanoola.

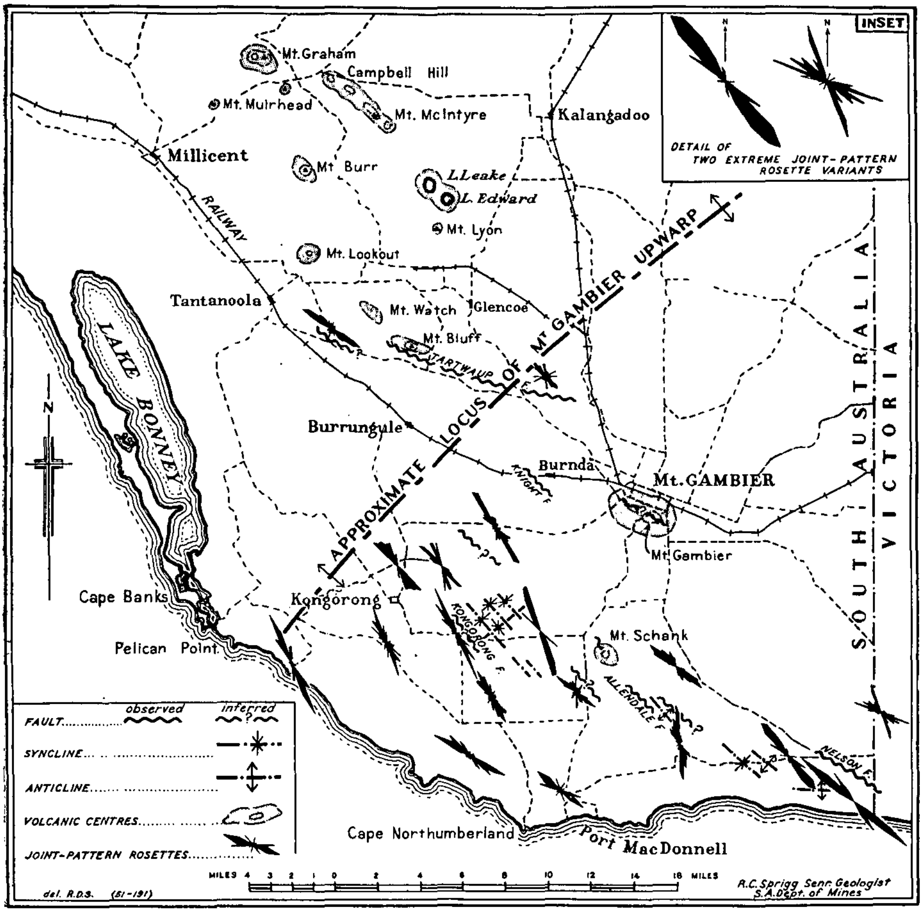

Fig. 9—Tectonic map of the Mt. Gambier area—Showing faults, fold and warp axes, joint patterns, and volcanic centres

Diamond drilling at Mt. McIntyre and at The Bluff has shown these accumulations to be of the composite type; ash basalt and vesicular basaltic flows alternate irregularly. In some cases deep weathering and the development of soil profiles within the volcanic accumulation indicate prolonged periods of quiescence.

The Later "Newer" Basalts (Mt. Gambier-Mt. Schank)

This group includes the Mt. Gambier and Mt. Schank volcanoes which are very little modified by erosion. The Mt. Schank depression bottoms near the level of the surrounding country. It has two very minor parasitic cones, and except for the original fissure flow of basalt the cones appear to be composed entirely of ejectamenta (tuffs, ash, lapilli, scoria, and bombs). The ash deposits thin rapidly away from the cone but a light mantle continues a considerable distance to the east. As at Mt. Gambier the ash has decomposed to give rich soils. The original fissure trends northwest and southeast.

Mt. Gambier is a compounded structure. There were at least three major centres of activity and several minor parasitic cones. Except for the original fissure-flow the accumulations are entirely ejectamenta. Eruption has occurred along a minor WNW.-ESE. fault of unknown lineal extent. Signs of the faulting can be seen in the northern walls of Brown Lake and Valley Lake.

In the late stages of activity, collapse of the subterranean magma chambers resulted in the formation of the present subsidence calderas. In each case the foundering has exposed the regional water-table, and in the Blue Lake has provided a depth of 260ft. of water and exposed the sub-horizontal Gambier limestone. Portion of the original basaltic flow is now well exposed.

The ejectamenta of this series of cones includes much bryozoal limestone, dolomite, and flint. A few pieces of light yellowish-grey sandstone—including plant remains—have been noted by the writer, and these may be early Tertiary sediments.

A few fossil leaves have been found in the tuff deposits at Mt. Gambier. They are closely related to modern flora of the locality.

The relative age of this period of volcanicity is easily established. The Mt. Gambier activity post-dates the local aeolianite beach dunes over which its ash has been spread. Nowhere have the Mt. Gambier deposits been eroded by sea action and the ash-covered dunes are middle to late Pleistocene in age.

The Mt. Schank cone came into existence contemporaneously with the Caveton dune range. The original fissure eruption poured out basalt which was eroded by the Reedy Creek (Caveton) high sea-level (*see* later) to form low cliffs; Caveton beach structures actually "tied" the cone to the nearby coast (fig. 10). Beach ridges swing seaward and "include" the developing cone, and shell deposits were subsequently stranded on the lower fringes of the cone (Howchin). The Reedy Creek sea then withdrew and the volcano distributed its ash over the stranded dunes and exposed sea-floor.

The Mt. Gambier and Mt. Schank activities are considered to be contemporaneous, and the beach dune and ash relations support this as far as the evidence permits. It is also supported by structural evidences which will be discussed more fully in section 4.

Air-borne Magnetometer Investigations with a Bearing on Tertiary-Quaternary Igneous Activity

As described previously the aerial magnetometer survey confirmed the major structural break or buried escarpment marking the southern limit of the Padthaway horst. Irregular (vertical intensity) magnetic profiles were obtained over the shallow basement rocks of the horst, but over the Gambier sunkland, with basement rock at great depths covered by several thousand feet of practically non-magnetic sediments, the profiles were generally smooth and flat. In places in the sunkland exceptional magnetic highs were obtained and in each case they could be related to centres of basaltic igneous activity (of the Newer Basalt Suite).

In the Western District of Victoria over the basalt plain a slight general increase in magnetic susceptibility, measurable only in a few gammas, was obtained, but at intervals in the flights significant magnetic peaks, comparable to those obtained in South Australia were recorded. By inference it is reasonable to interpret these peaks also as loci of fissure eruption.

The results over the basalt plains are thus of particular interest in that by revealing a remarkably strong mass magnetic effect from the centres of basaltic eruption compared with the uniform relatively low effect from the lava flows, it is still possible to use the aerial magnetometer results to indicate the regional structure under the lava sheet.

TECTONICS

The general paucity of pre-Pleistocene rock outcrops in the South-East Province and the absence of extensive borehole data only permits the broadest appreciation of geological structure. The aerial magnetometer survey results have been used freely in this study.

Three episodes of crustal deformation are broadly recognized. The oldest is probably post-Ordovician and pre-Jurassic, and the younger ones late Mesozoic-Tertiary and Pleistocene respectively.

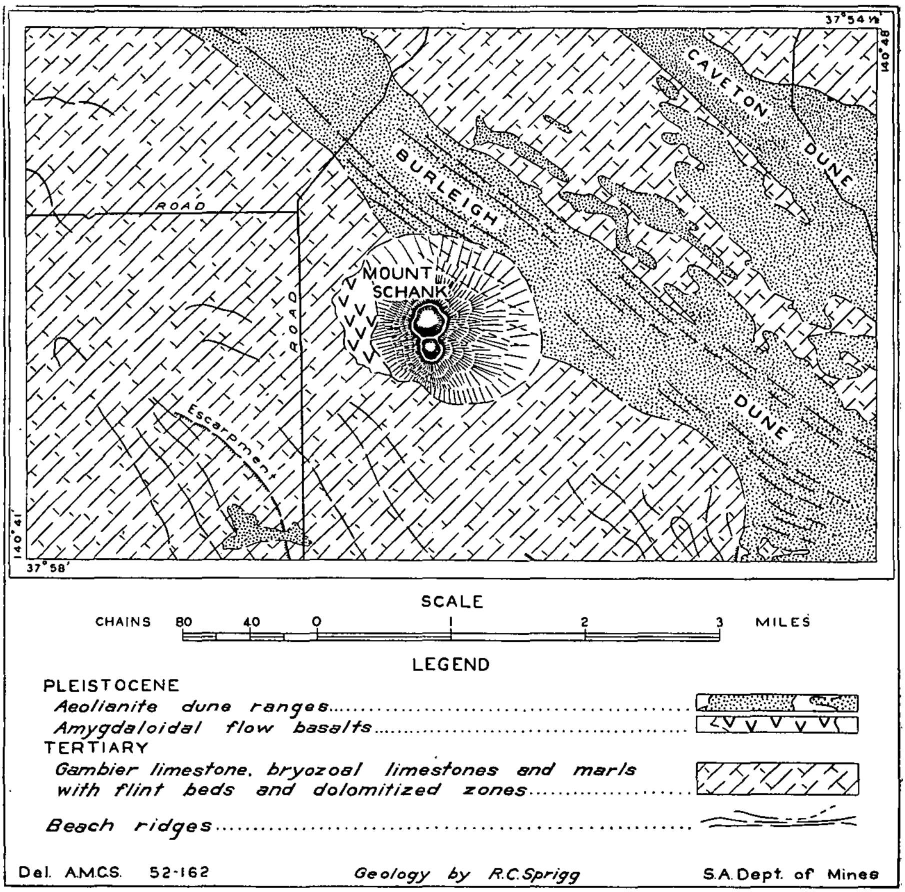

Fig. 10—Mount Schank and the related Pleistocene coast dunes

Pre-Tertiary

The buried escarpment of the Padthaway-Dundas horst (fig. 3) probably came into existence in pre-Mesozoic times, and movements took place intermittently throughout the Tertiary (fig. 5). It will be seen that Mesozoic sediments are notably absent from the Murray Basin proper. They occur on the northern side of the Olary upwarp with a gentle overlap from the Lake Frome embayment, and they reappear south of the Padthaway-Dundas horst where the structure is more complicated. Both Jurassic and Tertiary, near Comaum and Casterton, overlap the horst. The geological section (fig. 5) lends emphasis to an extensive pre-Tertiary block movement.

In the absence of outcrops in South Australia nothing is known of fold deformation of the Jurassic formations. Similar beds on Cape Otway Peninsula in Victoria are considerably deformed. No detailed structural maps are available, but they have been described as complexly folded with dominant NW.-SE. and

NE.-SW. axes (Reeves and Evans 1949) and that such folding is not all pre-Tertiary. Deformation of these overmass sediments in later Tertiary times is also described as having been caused by "fault folding" and overmass slumping (Hills 1940, Edwards *et alia* 1944).

Tertiary and Quaternary Deformation

Tertiary and Quaternary sediments over much of South Australia have been involved widely in Kosciusko epoch (late Tertiary and Pleistocene) block faulting and regional warping. These effects, although clearly recognizable in the South-East Province, are very gentle. Undulatory folds and minor faults are noted and subsequent (Pleistocene) regional warping is also distinguishable.

Tertiary Folding and Warping

Except under the direct influence of fault movement, folding in Tertiary sediments is believed to be absent or only slight in the Gambier sunkland and definitely absent on the Padthaway horst.

The extensive, flat marine erosion surfaces to the west and south of Mt. Gambier give the only directly observable evidence of folding in the whole South-East area. Aerial views (Plate III) show gentle folding of beds along NW.-SE. and NE.-SW. areas which tend towards dome and basin development. The photos give a rather exaggerated impression of intensity of folding. Beds rarely dip more than a few degrees.

Where dips exceed 40deg., faulting is either known or suspected. In such zones, as yet without exception, the Miocene limestones are highly dolomitized, and in some cases, sheared and brecciated. Examples include the dolomite cliffs of Tantanoola, the eastern aspect of Knight Dome, the Allendale Fault, the Nelson Fault and the inferred Cape Jaffa Fault. These will be discussed in detail later. The dolomites have been mapped as formations. On this assumption Knight Dome was outlined a few miles west of Mt. Gambier (Keble and Rudd, 1932) but drilling failed to confirm this structure. It is now known that dolomitization boundaries are not necessarily stratigraphic.

In considering possible fold structures in this Gambier province it appears that much, if not all, "folding" of the Tertiary rocks is related to "jostling" of blocks during the differential faulting of basement in the late Tertiary. Both in South Australia (Gulf St. Vincent senkungsfeld) and in Victoria (*e.g.*, Yallourn) "fault folding" and associated slumping is known to have played an important role in Tertiary tectonics.

Regional Warping of the Quaternary Period

Towards the close of the Tertiary period complementary vertical movements of certain sub-coastal fault blocks become accentuated. The Great Dividing Range in eastern Australia and the Mt. Lofty Range and related ranges in South Australia began to assume their modern appearance. The movements are generally conceded to have been climaxial at about the beginning of the Pleistocene although the crustal block jostling has not yet ceased completely. Local earth tremors still originate along some of these block faults.

In the gulf region of South Australia the complementary block movements produced well-defined horst structures and deep grabens. Early Tertiary erosion surfaces were dislocated and remnants came to be separated vertically by at least 4,000ft. In the South-East Province the movements have been far less spectacular. There has been some minor faulting but the most important feature concerns regional warping.

Investigations into the tilting of the old stranded beaches in the South-East (*see* later) have demonstrated a general (relative) downwarping away from the Mt. Gambier volcanic region and towards the base of the rising Mt. Lofty Range. The tilt of the oldest beach, for example, has exceeded 1ft. per mile for a distance of 100 miles. This negative movement can be correlated directly with the positive movement of the Mt. Lofty-Kangaroo Island horst. In the opposite direction altitudinal data and coastal truncation structures to the east of Cape Northumberland indicate a general downwarping away from Mt. Gambier to the east. The foregoing evidence shows that the Mt. Gambier region, during the Quaternary, was on a crestal locus of upwarping. This crest trends NNE. from Cape Douglas through Mt. Gambier towards Dergholm in Victoria. It has been noted elsewhere that there was restricted south tilt down towards Mt. Gambier and Mt. Burr during the respective periods of late Cainozoic vulcanism, but these movements were merely superimpositions on the general upwarping movement and they modify the picture but slightly.

Late Cainozoic Faulting

Minor late Tertiary faults are distributed throughout outcropping Tertiary limestones in the Mt. Gambier area. They conform very well with the major structural pattern of the area and they all strike WNW. or NW. This direction is also coincident with major regional jointing (*see* later). Fault downthrow is usually to the southwest and the extent of movement is generally small. In some cases (*e.g.*, the Nelson Fault) the movement may be much greater as the dolomitized zone is extensively sheared or sedimentary beds are dragged into steep attitudes in the immediate fault vicinity.

Five and possibly seven faults in "overmass" sediments are now clearly recognized, *e.g.*, the Nelson, Allendale, Kongorong, Tartwaup, Knight, Tantanoola, and Jaffa Faults, all of which are dolomitized and show shearing, fault drag, or brecciation.

The Nelson Fault crosses the State border within about 1 mile of the coast and its strongly dolomitized shear zone is highly ferruginized. It may be co-extensive with the fault skirting Mt. Richmond to the south and continuing beyond Cape Bridgewater and under the sea to the south of Cape Nelson lighthouse. This fault is notable for the terrific volumes of artesian water escaping through it in its oceanward development. Fishermen are reported to replenish their water supplies from the sea surface over this fault 2 miles from the coast south of Cape Nelson.

The faults, by reason of their coincidence with the major regional pattern, are considered to reflect bedrock faulting rather than local compaction subsidence.

Earthquakes

In spite of Quaternary volcanic activity and considerable land warping movements the South-East area is remarkably free of earth tremors. Within historic times there have only been two important disturbances. The first occurred on 10th May, 1897, and the second on 8th April, 1948 (fig. 11).

Mr. G. F. Dodwell (1909), the Government Astronomer, in describing the 1897 earthquake wrote that "tremors in the vicinity of Kingston . . . continued at intervals for some months, and all appeared to point to a focus in the ocean somewhere west of that neighbourhood." The earthquake showed a large epicentral area and was recorded over southern Australia from Streaky Bay and well into Victoria. Isoseismal maps prepared at the time suggest an epicentre near Beachport.

The shock dislocated the lighthouse machinery at Cape Jaffa, throwing the light off its beam and spilling the mercury at the base of the lamp. A large mass of aeolianite nearby was split and portions collapsed into the sea. To the northwest of Mt. Benson (opposite Nulook bark mill) the travertinized aeolianite was cracked deeply. According to one local resident (Mr. F. Winter) the tremors continued for some weeks.

The more recent tremor (8th April, 1948) had its epicentre beneath the sea 10 miles NW. of Beachport in much the same place as the 1897 earthquake. The shock was less severe even though it was felt up to 250 miles away. At Beachport it cracked buildings, stopped clocks, and dislodged crockery from shelves.

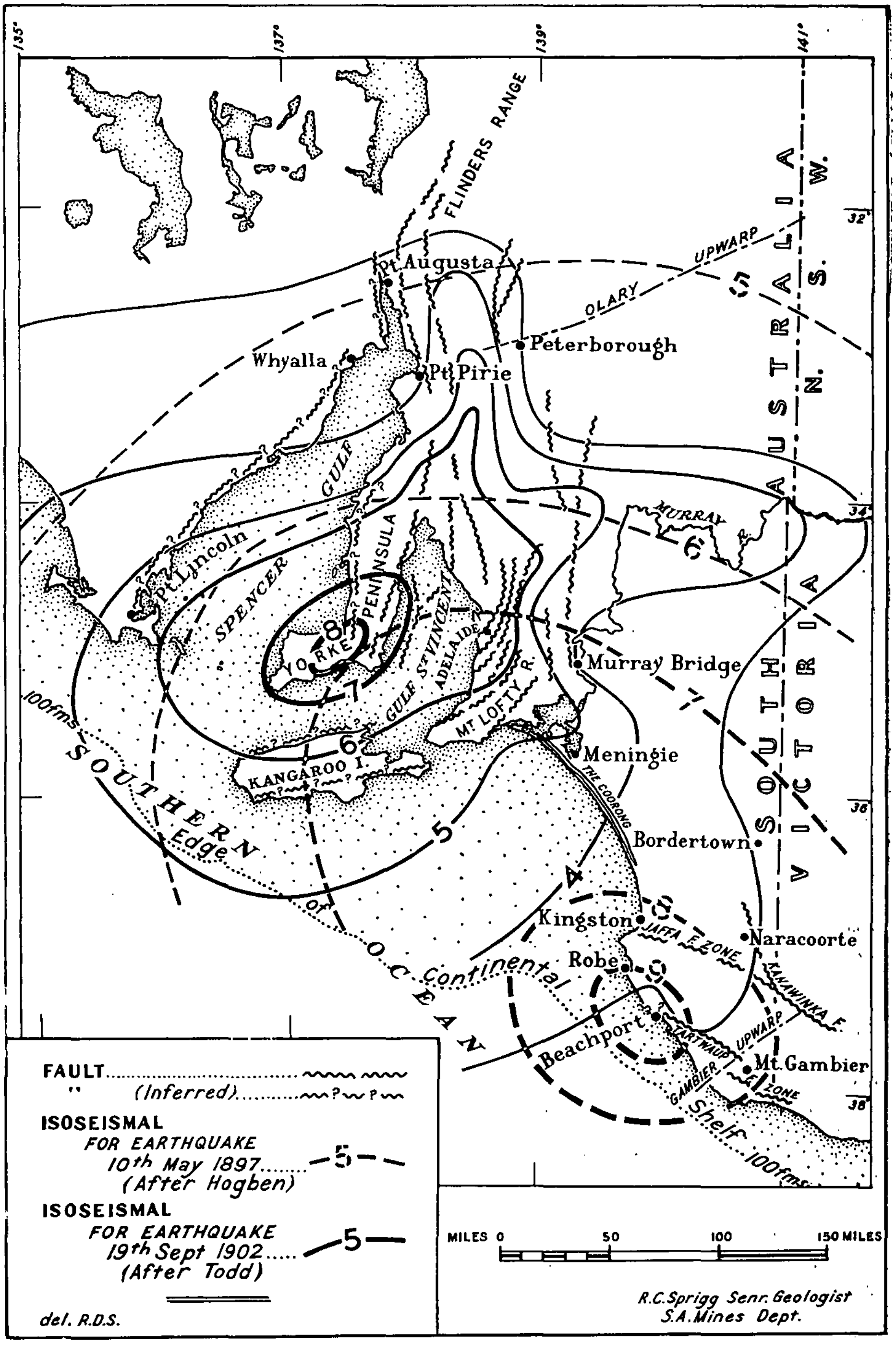

Fig. 11—Map showing isoseismals for earthquakes—Years 1897 and 1902

Near Adelaide the tremor lasted from a few seconds to five minutes, and in some areas it was preceded by low rumblings.

The evidence all points to some subcrustal readjustments taking place in the Beachport vicinity. If the origin is to be attributed to basement fault movements, there is certainly no surface expression of such differential movement. This is not surprising seeing that basement (igneous and metamorphic rock) probably lies much more than 5,000ft. below sea-level, and in which case much of the inferred minor movement would be absorbed in the overmass sediments.

It is significant that the broad positive magnetic anomaly shown by the airborne magnetometer survey (fig. 6), passing through Mt. Gambier and Mt. Burr, passes out under the sea a few miles north of Beachport near the epicentres of these earthquake disturbances. It probably represents deep basement faulting.

Tertiary Joint Systems

Outcropping Miocene limestones in the southeastern subcoastal belt all exhibit strong jointing systems which, by virtue of secondarily deposited lime, stand out prominently on exposed surface. These joint cracks may be continuous for many chains. The more prominent joints are generally parallel with axes of fold flexures and with known faults. Statistical counts were made and plotted as rosette diagrams. Fifteen areas were "sampled" and in each case 50 joint directions were recorded along two equal traverses at about right angles. The results, together with regional fault and fold information, are summarized in fig. 9. Enlargements of two extreme variants of the diagrams are also given. The relationship of the major joint fracturing with fold and fault patterns is plainly evident. The diagrams also reflect the cross-warping influence.

OIL PROSPECTING

Drilling for oil in the South-East Province was initiated with the discovery of coorongite in 1852. The widespread occurrence of marine Tertiary limestones and frequent reports of coastal bitumen have since maintained interest and encouraged sporadic search. Many of the investigations have been remarkable for their lack of scientific guidance and bores have been put down at random without regard for geological advice. Up to the present no major oil organization with oil-field experience has considered the South-East Province sufficiently attractive for examination either by detailed field surveys or drilling, although many have made reconnaissance surveys which are the forerunners of more detailed work.

In 1914 the South Australian Government proclaimed a reward of £5,000 for the first person or organization to obtain 100,000gall. of crude oil from a well in this State, and subsequently in 1920 the Commonwealth Government offered £50,000 for the first discovery of commercial oil in Australia. This stimulus had some effect on the search and encouraged "diviners" and speculators to play a considerable part in the early prospecting activity. A complete record of the many unsuccessful attempts to find oil is contained in Geological Survey *Bulletin* No. 22 (Ward, 1944).

Coorongite

In 1852 a black elastic sheet-like material was found floating in the lakes of Alfred Flat inland from the Coorong. The fresh material was green and cheese-like. It was found in the form of thin sheets which burn readily with a smoky flame.

The material represented the massed inflorescences of the blue-green alga *Botriococcus braunii* which has since proved to be particularly abundant in some seasons in fresh-water lakes in South Australia. In some years it is very prevalent in artificial reservoirs in the Adelaide region, where it may form thick scums.

At Alfred Flat the material was especially abundant in 1865 and 1920, and the ephemeral lakes of the area seem particularly favourable for its sporadic accumulation. The material is also known in buried deposits about 50 miles to the northeast of Alfred Flat where it occurs in a layer buried a foot beneath a greenish clay silt and sand along the east shore of Lake Albert near Meningie. Sir Douglas Mawson was the first geologist to visit this discovery. Post-hole bores have revealed a layer of the material varying in thickness from a few inches to 5ft. It is a moist, elastic, dirty, greenish-brown substance with a cheese-like break and possessing horizontal banding. It includes rootlets, plant spores, and diatoms.

This accumulation must have been rapid in view of its location near the mouth of the muddy Murray River. Mawson has aptly termed the material "proto-boghead," the source material of cannel coal.

A number of chemical analyses have been made of coorongite and various oils have been distilled from it. One, by the Government Analyst in 1903 (Ward, 1913), gave 69·2 per cent of an oily distillate, which, upon redistillation, gave the following fractions:

	Per cent by volume
From 110°C. to 170°C.	6·3
170°C. to 240°C.	27·3
240°C. to 295°C.	25·1
295°C. to 300°C.	27·3
Residue and loss	14·0

Cumming (1903) found that two substances were present in coorongite besides ash. One of these was an unsaponifiable wax-like solid which could be extracted by carbon disulphide. The other was insoluble in carbon disulphide but could be saponified by hot alcoholic solutions of caustic potash to give a soluble soap. Thiessen (1925) of the U.S. Bureau of Mines confirmed Cumming's work and found that the residue after extraction with carbon disulphide consisted of a residue of algae and fragments of the tissue and cuticle of higher plants, some diatoms and sand. The extract by carbon disulphide was a clear yellow waxy solid which was also soluble in benzene, ether, toluene, and chloroform. Its composition and molecular weight corresponded with the formula $(C_{10}H_{18}O)_8$. The insoluble residue was inelastic and tough and burned with a clear luminous flame. Its molecular weight and composition corresponded with the formula $C_{10}H_{18}O_3$.

Substances closely resembling coorongite are of world distribution. They occur as "N'hangellite" in Portugese East Africa (Boodle), "Balkaschite" in Russian Central Asia (Zalessky 1924) and "Marahumite" from the island of Tinhare, Brazil (Froes. Abreu 1937). The latter deposit varies in thickness from 1ft. to 30ft. in Pleistocene to Recent fluviatile and lacustrine clays and sands. It also forms at the present day as an algal scum on nearby lakes.

There is now no reason to associate coorongite with the subterranean occurrence of oil. The original assumed relation is of historic interest only.

Coastal Bitumen

Many varieties of bituminous substances have been reported along the southern coast throughout the whole period of white settlement. Some are fairly pure black bitumen, others include much sand and beach flotsam, while another group includes crude and refined paraffin wax and resin. Specific gravities of these bituminous substances give values slightly above and below that of the sea-water of the Southern Ocean (1·0285). The heavier varieties obviously had lost much of their volatile constituents while exposed to the hot sun on the beaches. They are almost invariably reported as "oozes" and "seepages", none of which have yet been substantiated. Among geologists there are three principal views concerning their origin.

Transport by Ocean Currents from Distant Sources

Dr. L. K. Ward (1913) has stated the case for extra coastal origin very fully and this is the theory most widely accepted by geologists. It is based on the distribution of the material which occurs frequently along the whole of the southern Australian coastline, and also along the shores of Tasmania, New Zealand, Chile, and South Africa. Bituminous deposits occur in the Straits of Magellan and on the Antarctic continent, and bituminous substances from these sources could be transported to all the foregoing localities by the normal ocean currents.

Relics of Shipwrecks and Ship Jetsam

Coastal bitumen was recorded long before the days of oil-fired ships, but whaling ships based at Portland and Bridgewater Bay in Victoria must have carried large quantities of bitumen as pitch for caulking purposes. These or other wooden ships wrecked would provide flotsam for wide distribution along the southern coast.

Derivation from Local Sources

This view is popular amongst laymen and has been expounded at length by McIntosh Reid (1931). The bitumen is considered to be a derivative of petroleum exuded from deep-seated beds *via* outcrops or fault fissures on the Southern Australian continental platform.

McIntosh Reid concluded that the close approach of the 100-fathom line to the coast near the Victorian border indicated a fault there. This conception cannot be substantiated from accurate cross-sections of the ocean platform. The air-borne magnetometer in its traverse well beyond the platform edge also gave no indication whatever of such faulting.

In support of the local origin hypothesis, it has been argued that much of the bitumen when washed ashore, is light and plastic, and soon loses its plasticity and becomes denser than sea-water. It could not, therefore, have been exposed long to air as would be the case had it been carried from far-distant sources by ocean currents. The fallacy of this argument is obvious because whilst in suspension in sea-water the bitumen would be subject to little evaporation and loss of volatile constituents.

Alleged Oil Seepages

Surface indications of oil have been reported in many localities within the Mt. Gambier sunklands belt. None of these have withstood reliable geological investigation. Where human agency is not suspect the "oil" mostly proves to be of some humic product or simply iridescent films of iron hydroxide upon chalybeate water.

This absence of surface seepages of oil throughout the province is disheartening. Practically every producing field in the world has abundant oil seepages, and yet in this area in which numerous faults are now known, there are no such indications. Also unfavourable is the apparent absence of oil indications in deep-seated artesian spring waters.

Drilling Operations

Drilling for oil in the subcoastal area of the South-East began in 1892 when seven bores were drilled at Alfred Flat adjacent to the Coorong, where the first discovered accumulations of coorongite were erroneously thought to indicate the presence of oil. Four of these bores reached bedrock (Palaeozoic or pre-Cambrian) at depths between 190ft. and 581ft. after passing through the Gambier limestone, and the Knight clays and sands. One continued to 924ft. before striking bedrock, but had encountered upper Carboniferous tillite at 510ft. The Alfred Flat area lies within the Padthaway horst.

Questionable reports of oil seepages and "favourable" geological structures led to further drilling to the southeast of Alfred Flat. Near Robe a deeper bore was located on a Pleistocene aeolianite dune ridge in which sand avalanche structures were apparently mistaken for anticlinal folding. The bore which was drilled in 1915 by the South Australian Oil Wells, N.L., passed through the Tertiary sediments at 1,475ft. and was still in Jurassic sands at the completion of operations at 4,504ft. On completion of the Robe bore a hole was drilled on the upthrow side of the Tartwaup Fault near Up and Down Rocks. It penetrated the Gambier limestone at 392ft. and continued to 1,532ft. in the Knight formation. Inflammable gas was reported at 1,321ft., but no analysis is available. The company also drilled four more wells in the extreme southeast of the State near the mouth of the Glenelg River (hundred of Caroline). Three of these bores were sunk respectively to 1,226ft., 1,824ft., and 1,561ft. near Donovans Landing to test a supposed closed anticline mapped by H. S. Lyne (Gray and Croll 1938). The Gambier limestone was penetrated in each bore at 533ft., 506ft., and 527ft., and failed to substantiate significant anticlinal structure. A fourth bore was drilled 2½ miles to the south, near the coast, and was reported to have been abandoned at 839ft. in the Knight clays. It may be noted that this alleged anticline lies in the vicinity of the prominent Nelson Fault.

The Adelaide Oil Exploration Company drilled a 1,045-ft. hole near Mt. McIntyre apparently to test either for oil trapped in beds against the basaltic intrusions or for oil distilled from early Tertiary lignites by volcanic activity. Lower Tertiary lignites of the Knight clays were encountered in the bore but no oil.

The same company drilled two wells a few miles northwest of Mt. Gambier in the period 1923-32, on an asymmetrical domed anticline delineated by R. A. Keble. This structure became known as Knight's Dome. Before drilling was undertaken a magnetic survey, carried out by J. M. Rayner, demonstrated that no igneous intrusion was present at depth to account for this structure. A pilot-hole was drilled to the southwest of the mapped anticlinal axes followed by a deeper one a few hundred yards to the northeast in the "crestal" region. The deeper bore reached 2,013ft. and passed through the Gambier limestone into the Knight clays at 35ft. depth below sea-level, whilst the pilot-bore entered the same beds at 60ft. above sea-level. These results show big discrepancies with the field mapping and discount the presence of the so-called dome. The sands between 1,825ft. and 1,869ft. and between 1,996ft. and 2,013ft. in this area are reported to have contained traces of oil, but on examination proved to be lubricating oil probably derived from the drilling machinery.

In 1923 the Associated Oil Company drilled a bore in search for oil 8 miles northwest of Mt. Gambier. It reached 2,110ft. after having penetrated the Gambier limestone at 108ft. The reasons for the selection of this site are obscure, and since abandonment of the bore, unsubstantiated statements have been made that oil was struck at 1,960ft. The current rumours that a foreign oil interest had suppressed this and other "promising" discoveries must be completely discounted.

A bore was drilled near Comaum, actually in Victoria (½ mile east of the border) to test for accumulation "up dip" towards outcropping basement rock on the Dundas Peninsula. It reached a total depth of 1,170ft. penetrating "superficial" deposits to 132ft., and then the Gambier limestone to 509ft., followed by Jurassic sediments with coal measures to the bottom. Mr. F. Chapman, who examined the cores of the Gambier limestones considered them to be of Oligocene age. He described them as glauconitic in part.

Future Oil Prospecting

The concentration of marine beds at the top of the Tertiary stratigraphic column without extensive impervious caprock is unfortunate. The porous nature of many of the marine sediments composed of massed bryozoal remains and the presence of abundant caves and faults, and the general absence of cap-beds reduces the chances of significant shallow oil-accumulations in most areas.

The complete absence of proven oil-seeps from such a considerable area—particularly adjacent to faults—is itself a disappointing feature, and may suggest that petroleum may never have been present in the beds in significant quantity, or if so, has been flushed out by ground or artesian waters. However, these features are not entirely condemnatory of oil occurrence. Petroleum does occur in glauconitic beds of Tertiary age in Victoria (Lakes Entrance) although the origin of this oil is debatable. It may be derived locally or may have migrated from some deeper and older oceanward source beds. Similar conditions are possible in this South-East Province as glauconite beds are known to occur, but so far without oil being associated with them. The glauconitic beds occur near the top of Knight clays and sands in an estuarine setting which is conducive to the formation of a variety of sedimentary traps. Overlap type traps can be anticipated in this environment and the subsequent deformation by fault block jostling would tend to facilitate the accumulation of oil from local oil-source beds if such were present. At higher stratigraphic levels even where primary cap-beds are lacking, secondary dolomitization may possibly form barriers to migrating petroleum.

At lower stratigraphic levels prospective horizons are not nearly so well-known, but in view of the environmental setting (paralic) they are likely to be narrow and irregular in field distribution. The Nelson bore has sectioned a fairly complete succession of marine intercalations within the main mass of the Knight clays and sands. A fossiliferous horizon at 1,924ft. to 1,943ft. is apparently widely developed as it is recognizable at 1,980-1,995ft. in the Knight Dome No. 2 bore and at 2,110ft. in the Associated Oil Company's bore. The occurrence and landward lensing of this open-water marine horizon between less pervious beds is favourable to the development of sedimentary traps.

Another stratigraphically lower marine intercalation in the Knight clays and sands may possess similar characteristics. It constitutes the *Hantkenina* beds (Eocene) of Moonlight Head, Victoria. These beds, which are about 20ft. thick, occur only about 40ft. above the post-Jurassic erosion surface. There is good reason to anticipate that they must extend and be even more strongly developed in the deeper sections of the Gambier sunklands. However, they were not encountered in the Nelson bore, possibly because they lie at still greater depth.

Another favourable environment for possible oil accumulation is associated with overlap traps created by complex sedimentation along oscillating sea-margins. Whether such oscillations have been controlled by eustacy or local isostacy is hard to predict. Two zones within the Tertiary sunklands, in which these conditions were possibly present, occur respectively along the foot of the Padthaway-Dundas horst and confronting the Tartwaup Fault. Seaward from each of these zones there appears to be significant basin deepening and if the faults are in part pre-Tertiary they would conceivably have influenced coastline developments.

If it is assumed that oil formed at some stage in the Tertiary history of the Gambier sunklands, the range of structural traps possible as distinct from sedimentary traps, previously described, is likely to be very variable. For example, structural domes have been formed in the overmass sediments by basement block jostling as previously described. Also the dolomitization of fault lines may have produced dams to migrating oil. Likewise the faults themselves may have provided barriers for oil accumulation. Volcanic intrusions, particularly associations of dykes and sills, also could provide useful traps.

Obviously the search for oil in the Gambier sunklands is fraught with many difficulties and although certain basic features are not particularly encouraging, the possibilities cannot be ruled out. Great thicknesses of unexplored Tertiary sediments are present in the coastal areas extending from Beachport to Portland, in Victoria, and these warrant further exploration.

CHAPTER VIII

QUATERNARY MARINE COAST-LINE MIGRATIONS

The study of the marine coast-line migrations in the South-East Province is intimately concerned with alternate glaciation and deglaciation of the Pleistocene period. The first precursors of widespread glaciation were recorded during the upper Pliocene period, and the first major continental glaciation of the northern hemisphere generally marked the onset of the Pleistocene glacial epoch.

Climate during the late Tertiary deteriorated continuously, apparently concommitantly with relatively declining sea-level. The interdependence of these two tendencies is incompletely known, but in general it is reasonable to assume that the resulting increased elevation of the land would also favour mountain and polar glaciation.

The cause of late Cainozoic sea-level decline is unknown. An acceptable theory concerns oceanic crustal subsidence which would cause extensively continental emergence both eustatically and isostatically. The associated changes in land and sea distribution and in temperature and precipitation may well have accounted for much of the climatic deterioration and generally favoured widespread glaciation when some other conditions were satisfied. The nature of these secondary factors can only be conjectured, but possible influences include abnormal concentrations of volcanic dust in the atmosphere*, solar climatic† variations, and mountain building. They in turn might affect temperatures, precipitation, and/or wind patterns. They could conceivably bring about intensification or amelioration of various glacial phases and thus control the succession of phase glaciation and interglaciation.

The degree of relative sea-level decline other than by glacial eustacy was probably quite extensive, and certainly during the Pleistocene (Daly, 1934, Zeuner, 1945-46) amounted to 250ft. to 300ft. Previously, late Tertiary seas had contracted markedly from most continents, and again may have involved some hundreds of feet in fall, although estimation is difficult in view of the faulting and warping which occurred concurrently and latterly. Such tectonic behaviour in itself was probably a reflection of the great oceanic crustal readjustments which were occurring during those times.

In addition to the general sea-level decline of the late Quaternary, due to isostatic factors during glacial maxima, the sea-level temporarily receded another 300ft. (Daly and others). At the present time the earth is in an interglacial phase and the sea-level has risen about 240ft. since the last glacial (Wurm) phase. Complete deglaciation would probably bring about an additional sea-level rise of 60ft. (Daly 1934).

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* Fine volcanic dust in the atmosphere would reflect solar heat energy before it could be captured by the earth, and it is considered (Fuchs) capable of causing a lowering of earth temperatures sufficiently to favour glaciation. By an ingenius theory two such phases of world volcanicity, it is claimed, could cause four glacial periods.

† Variation in the amount of solar energy reaching the earth has always provided a popular explanation for major variations in world climate. The case is unproven, but Ahlman's researches (1949) do suggest the importance of influences of this type. He has noted widespread *improvemcnt* in climate in higher latitudes since about 1870, causing a winter temperature rise of nearly one degree. With this change, major modifications are being wrought on local wind patterns, precipitation, sea-ice formation, etc. In general, deglaciation is occurring rapidly. On the other hand, Morris (1949), on theoretical grounds, claims that a rise in temperature should favour glaciation by increasing evaporation and, therefore, precipitation, so that in areas of glacier formation, accumulation should exceed wastage by melting and ablation.

A new theoretical development has been introduced with the discovery of submarine canyons about all continental coasts. A group of geologists, foremost among whom is F. P. Sheppard (1948) claim that glaciation was much more extreme than is generally believed and caused the lowering of sea-level by tens of thousands of feet. Another group explain the deep canyoning by assuming temporary upwarping of the continental margins to give the appearance of sea-level falling by tens of thousands of feet. These remarkable theories arise from the authors' failure to appreciate the efficiency of turbidity currents (Daly 1936) and others, as agents of submarine erosion. Kuenen's (1938) classic researches on submarine canyon formation, turbidity currents, and still more recently, upon brecciola structures (co-authored with Migliorini 1950) avoid the need for postulating sub-aerial erosive agencies in submarine canyon formation. If the lowering of sea-level to such vast extents is to be accounted for by the piling of ice to many tens of thousands of feet on continental and polar areas, surely the great load pressures would produce such rapid flowage at the margins and at depth that the thickness could never be maintained or even attained. Moreover, the isostatic depression of the underlying crust would tend to offset the sea-level fall by causing major positive movements within the peripheral sub-oceanic crust.

However, whatever the true explanation may be, agreement seems fairly general that relative sea-level has been declining continuously and extensively during the late Cainozoic and that superimposed upon this decline have been the oscillations associated with glacial eustacy. As to the cause of the ice age there is no unanimity of opinion.

THE AEOLIANITE DUNE SYSTEM

The South-East Province is unique in the world for its preservation of a series of successively younger beach deposits which occur as a sub-parallel system of dune ranges (fig. 4). They are massive elongated ridges of ocean beach sand essentially transverse to prevailing wind directions. The sands are mostly lightly consolidated and travertinized at the surface and in many places at several horizons within them.

These fossil beach dunes have been variously described as "raised" sea-beaches or as stranded sand-bars of the bay-bar type. The reference to bay bars is incorrect and the term "raised sea-beach" is misleading. The latter implies positive movement of the land in relation to sea-level whereas in this case land and sea-level have both oscillated. The term "stranded coastal dunes" is non-committal and preferable.

Tindale (1933) associated the dunes with eustatic movements of Pleistocene sea-level and attempted a correlation with the North American marine terraces as described by C. Wythe Cooke (1930). Later (1947) he attempted further correlation with F. E. Zeuner's (1946) summary of European "terraces." Tindale related the unusually heavy accumulation of shell sand to several environmental factors. Firstly the local intermingling of Murray water was said to provide a concentration of calcium salts locally; also the continuous movement of great food-laden currents from the west supported thriving shellfish populations whose shells are finally destroyed in the heavy ocean surf to produce the massive accumulations of beach sands. Tindale's first point is debatable as the Murray waters would actually tend to dilute the local sea-waters. Any such effect is bound to be small considering the great volume of ocean water moving about the local continental platform under tidal and current influence. Perhaps the most important factor in the rapid accumulation of shell material is the presence of such a wide continental platform in the Coorong area. This leads to wide shallow marine flats endlessly churned by ocean breakers on which the pelecypod *Plebidonax deltoides* thrives. To the south where the continental platform is much narrower and where reef conditions and shingle beaches are common, the shell populations are much smaller.

Under the influence of strong westerly winds the beach sands are continually migrating inland and in some places (particularly to the leeward of the Coorong) they have drifted as far as the Little Desert of Western Victoria, 200 miles from their points of origin. In most cases the dunes become lightly consolidated following stranding partly through climatic influences, partly by colonizing vegetation and travertinous soil formation. Sub-aerial stream erosion has been almost insignificant due to the flat nature of the terrain and well-developed underdrainage. There are few defined surface drainage channels in the whole area and the underlying Gambier limestones are extremely porous besides being riddled with open cave systems. The highly calcareous nature of the dunes in association with aridity (Crocker 1946) has aided the semi-consolidation of the dunes and their consequent fixation. The formation of travertinous soil profiles on the surface of dunes has produced hard thick crusts which protect the underlying weaker dune material from most processes of weathering and erosion. The remarkable preservation of these dunes was first described by Tindale (1933).

The aeolianite dunes have been inspected widely by the writer and have proved to be typical ocean coastal backshore dunes. Aeolian structures (coarse cross-bedding and landward avalanche laminations) indicate that the dunes have accumulated transversely to the prevailing winds, a factor which must have been important in the massive development of the dunes.

Sand constituting the dunes is of the medium-coarse type except where modified by soil-forming processes. It is mostly quite typical of the local modern sandy ocean beaches. The deposits are usually well stratified, the cross-laminations being of the "avalanched" type, steeply dipping and aeolian. Except where their continuity is broken by headlands of aeolianite or dolomite, or where shingle beaches dominate, the dunes are analogous to the modern coastal dunes of the Coorong.

There can be little doubt that this series of stranded beach dunes provide evidence of former relative high sea-levels. If the fossil mean sea-level relationships of the various dunes can be determined, the relative movements of land and sea-level since stranding can also be assessed. Knowing that the strand line of each dune structure was originally approximately horizontal, subsequent land tilt movements can also be determined. In this connexion a major problem would be to decide just where mean sea-level (or for that matter any relatively consistent marine level) originally stood in relation to the seaward foot of the dunes as now exposed. This is not a simple matter as the toe region of most dunes is obscured by drift or vegetation or by marsh and soil accumulations. Studies carried out in Drain L (Woakwine Range) indicate that there at least swamp level does not closely approximate fossil mean sea-level as the aeolian structures pass steeply out of sight beneath marsh deposits. However, the Woakwine dune has had an unusually complex history, bringing about many subsequent modifications. It is therefore not typical and should not be used in inference. A bore through this same range, 6 miles east of Robe, proved the base of the dune (which rests on eroded Gambier limestone) to be 20ft. below modern low sea-level and consequently 30 or more feet below interdune flat level.

The author has not observed any definite change of slope in the toe region of any aeolianite dune which may be interpreted as a beach "nick-point." A few coarse shell berm accumulations have been found, as on Mt. Graham and in the Naracoorte dune near Mosquito Creek, which by comparison with present-day Coorong conditions, as an open coast would indicate a level about 15ft. above fossil mean sea-level. However, in general, without a continuous section across the dune toe region it appears probable that fossil mean sea-level determinations will always be only approximate with an accuracy of about $\pm$ 10ft.

Shingle beaches near The Bluff and elsewhere also give only broad indications of fossil sea-level, but researches conducted elsewhere in the world show that coarse cobble accumulations on open ocean beaches may range from well below sea-level to 40ft. or more above.

In succeeding discussions where the aeolianite dune systems are discussed at length, it is assumed that immediate fore-dune flat levels are approximations of fossil mean sea-level. These are probably low in the extreme southeast, but become high in the north where the original sea floors of the present-day dune corridors are buried more deeply by subsequent deposits. Flats farthest inland may be expected to have thicker sedimentary blankets than younger ones nearer the coast; and in flats west of Reedy Creek dune, and in the Mt. Gambier area, subsequent marine inundations have introduced still more complexities. The immediate fore-dune structures in some of these cases have been eroded by these later incursions and secondary low sea-level features have been superimposed on the original dunes.

In the following sections some of the more obvious features of the main fossil beach dune associations will be outlined, and attention will be directed in turn to successively younger ranges, which with few exceptions, lie at lower levels.

The Naracoorte Beaches

This beach association is one of the oldest and most consistent in the area, although remnants of a still older one (the Hynam dune) lie approximately 6 miles northeast of Naracoorte at a considerably higher level.

The Naracoorte fossil coast is compounded of at least two major strand lines. The older is developed along the base of a cliff which has been eroded back from the original Kanawinka Fault escarpment. The younger strand preserves a true backshore dune lying about 1½ miles to the west. It extends for at least 75 miles along its strike from near the Victorian border. Unlike the older coastal cliff line which strikes south-south-east from beyond the Big Gap through Naracoorte into Victoria, the younger (west) Naracoorte dune curves oceanward near Penola, sweeping out to include the Mt. Burr-Mt.Graham volcanic area. Shell deposits of this beach occur high on the volcanic accumulations proving beyond doubt that much of the volcanicity had occurred earlier.

South of the Big Gap there are no very significant sand accumulations or aeolianites along the base of the cliff, although wind-blown siliceous sands do occur to the east on higher ground. The younger dune to the west, however, is a typical aeolianite dune and except in the volcanic region was obviously originally very much like the modern Coorong dunes and beach. Its even curve indicates conditions of temporary stability and equilibrium on a very gently rising floor. In the Penola vicinity the younger dune is composed of two or three secondary beach ridges indicating more rapid outbuilding (spreading) of the beaches.

In the absence of significant indenting along the Kanawinka Fault escarpment it is assumed that this coast was not one of long duration. Mostly the fossil cliff is remarkably straight, but rarely exceeds 50ft. in height. It can be traced beyond the Glenelg River towards Heywood in Victoria.

In the Mt. Burr region Crocker and Cotton (1946) have suggested a beach of the open ocean "reef" type high on the slopes of Mt. Graham, but this may be the equivalent of the Naracoorte aeolianite range or of the slightly younger Stewart Range and Cave Range. The deposits are estimated to lie at 205ft. to 210ft. above sea-level. At Mt. Burr there is a similar beach association but on an average about 15ft. lower. Another at about the same altitude (200-215ft.) passes to the north of Wandilo forming the southern boundary of the Dismal Swamp.

Northward through Krongart, Penola, Struan, Naracoorte, Koppoch, and Padthaway, the fore-dune flat levels are respectively 215ft., 210ft., 185ft., 175ft., 150ft., and 135ft. above modern sea-level. They indicate a very considerable regional warping.

In the almost complete absence of fossils, the ecology of the Naracoorte beaches is practically unknown. Fragmentary fossils have been found along the developments of sand beaches near Mosquito Creek (Howchin 1929) and Crocker and Cotton have recorded a typical ocean reef suite from the slopes of Mt. Graham. The faunas are scarcely distinguishable from modern reef associations of the nearby coast of today. In the lee of the volcanic area oyster beds and sea-floor sand deposits are prominent features.

There has been considerable wind redistribution of beach sands from the northern extensions of the Naracoorte ranges. Much of the shell material has been ground finely and distributed for hundreds of miles inland as calcareous loess (Crocker 1946) to produce highly travertinous soils. The remnant siliceous element of the original beach sands has been driven up to 200 miles due east under strong prevailing winds to form the "Little Deserts" of South Australia and Western Victoria. Crocker has related much of this redistribution to his "Great Australian Arid Period" (of the mid-Recent period) although the process probably continued intermittently through most of the Quaternary.

Despite the early Pleistocene age (*see* later) of the ranges, processes of weathering and erosion have wrought little modification. Few drainage lines dissect the dunes and of these the Morambro, Naracoorte, and Mosquito Creeks are prominent examples.

Stewart and Cave Ranges

This coastal dune sytem is the next of importance west of the Naracoorte stranded coast-line. It parallels the Naracoorte dune and exhibits a corresponding but less marked sweep to the southwest in the approach to the Mt. Burr volcanic centre. A maximum divergence of about 14 miles between the two range systems occurs near Penola and the south continuations of these two shore lines have telescoped to a large degree in the Mt. Burr-Mt. Graham area. The several shell deposits noted previously on these two mountains at about 200ft. above modern sea-level are related to either or both beaches.

The Stewart Range can be traced clearly for at least 40 miles to the north, and although not recognizable, due to subsequent dune telescoping and masking by drift sand, originally was continuous to the base of the Mt. Lofty Range. The Cave Range, which is the southern continuation of the Stewart Range is traceable for 20 or more miles. The dune system does not exceed 2 miles in width nor 50ft. in height. Over much of the length two, and sometimes three, secondary beach ridges are plainly evident. Judging from the mass of accumulated material compared with that of Naracoorte, the Stewart high sea-level was of shorter duration than the Naracoorte one. Fore-dune flat levels range from a maximum of 210ft. in the south to less than 120ft. in the north.

Between the Stewart and Naracoorte coast lines there is evidence of minor subsidiary sea-level still-stands, for example, Harpers Range, a small dune lying approximately 3 miles to the east of the Stewart strand line and 15 to 20 miles northwest of Naracoorte. It is a simple structure. A second, much smaller dune, aligned sympathetically, occurs midway between Harpers and Stewart dunes.

Woolumbool and Peacock Ranges

This dune association is extensive and has sub-parallel east and west components with strand lines 1 to 2 miles apart. The westernmost dune lies 3 to 4 miles west of the Stewart and Cave Ranges. To the west of Naracoorte the interdune flats have been bridged by sand blows, and farther north the blows have extended across to the Stewart Range.

The system is at least 50 miles long, and the components exhibit secondary beach ridging. The eastern one displays two or three such ridges and the western one as many as eight. The immediate fore-dune flat grades from 150ft. in the south to less than 90ft. inland from Kingston. The lower strand line lies 15 to 20 miles west of the Naracoorte Range. Beach equivalents for these dunes in the volcanic region have not yet been distinguished.

Bakers Range

This is yet another multiple or compounded stranded coastal dune, and its beach ridging is more pronounced than in older ranges to the east. Five or six beach ridges can be recognized. The range generally attains almost 4 miles in width, although sand blows have increased the overall width to more than 6 miles in the south.

The easterly "shore line" within this dune complex, by reason of greater sand accumulation, probably represents a more prolonged still-stand. Dune accumulations of the later ridges lying to the west are much smaller and may represent "hesitations" in the decline of sea-level following the earlier more sustained still-stand.

Bakers Range extends for more than 50 miles before it is obscured in the "sand sea" to the east of the Coorong. Fore-dune flat levels range from 120ft. in the south (near Wattle Range Head Station) down to 80ft. and less in the north. The dune lies 18 to 26 miles west of the Naracoorte Range.

Ardune Range

With the exception of one or two quite minor remnant aeolianite structures on the flats a short distance west of Bakers Range, the Ardune Range is the next younger beach development of importance. It is a simple dune structure with maximum width a little more than 1 mile.

At its southern (preserved) limit opposite Conmurra, the fore-dune flat level lies at approximately 100ft., but to the north this level declines to 75ft. before the dune is lost in the dune complex north of Keilira Homestead. The dune lies 20 or more miles west of the Naracoorte Range.

East Avenue Range

This is another compounded dune which displays seven or eight beach ridges in its oceanward development. The normal smooth sweep of the dune front is interrupted to the south of the township of Avenue by gentle oceanward deflections of the younger ridges. These deflections are unusual and may have been caused by outcropping basement rocks which are now obscured, or by contemporaneous faulting.

The range in places, where there has been some sand migration, exceeds 3 miles in width, but generally it is less than two. It lies 22 to 27 miles westwards from the Naracoorte Range and fore-dune flat levels descend from 115ft. or more opposite Mt. Bruce Head Station to about 60ft. at the northern boundary of the hundred of MacDonnell.

West Avenue Range

This dune complex, by reason of its relative youth, has more minor structures preserved in it than in any of the older beaches to the east. Beach ridges are also plainly visible beyond both borders of this range, and those immediately to the east are indicative of minor still-stands or hesitations in the retreat of the East Avenue high sea-level. There are three or four such ridges.

In the central mass of West Avenue Range, wind-blown sand has effectively obscured former dune ridges, but several distinct ridges are still preserved in the fore-part.

The West Avenue Range rarely exceeds 3 miles in width, and within counties MacDonnell and Robe lies 29 to 33 miles west of the Naracoorte Range. From south to north the fore-dune flat level declines from 97ft. above sea-level at Furner townsite to 50ft. near Blackford Head Station.

Reedy Creek Range

The Reedy Creek Range is a compounded association of numerous beach ridges which have a variable spread exceeding 2 miles, but less than 4 miles.

The ridges are generally very well preserved and remarkably continuous linearly. They are the product of a single fairly well sustained high sea-level still-stand, except in the Reedy Creek vicinity where the lower or western-most ridges were formed during certain subsequent high sea-levels, namely, the Woakwine "truncation" high sea-levels and the Anadara still-stand which are described later.

Within the range proper there are several sand blows associated with particular beach ridges. The blows may relate to more decisive "hesitations" during the general high sea-level which were sufficiently prolonged to allow sand to accumulate excessively and produce unstable drifting dunes. In general, sand blows do not exceed ½ mile in length nor are they very continuous laterally. Immediately south of Reedy Creek the sand redistribution has obscured ridge structures over practically the whole range width.

North of Reedy Creek the range exhibits at least 10 beach ridges in a width of ½ mile, and includes two periods of appreciable sand drift. To the south, inland from Robe and Beachport, the range is an aggregation of up to 20 such ridges in a width of 1 to 2 miles.

The Reedy Creek dune continues to the southeast, clear of the main volcanic area where it becomes the Burleigh Range. The Reedy Creek coast is therefore the most direct coastline of the whole series of stranded sea beaches and can be followed for more than 200 miles from Nelson in Victoria to the mouth of the River Murray.

Northwest from the volcanic area the fore-dune flat levels fall from 60ft. near Millicent to 42ft. opposite Kingston, and to below sea-level towards the River Murray lakes.

In the interdune zone between the West Avenue Range and Reedy Creek Range there are at least 10 fairly regularly spaced beach ridges. These may be part of the Reedy Creek Complex or more probably stages in the retreat of the West Avenue high sea-level.

The lower ridges immediately confronting the main Reedy Creek structures were probably shoals belonging to the much later Anadara (mid-Recent) high sea-level. They are much smaller developments, and the youngest of them grades away into Anadara sea beach deposits in which the subtropical pelecypod *Anadara trapezia* locally assumes spectacular dominance.

Dairy Ranges

These two dune systems are best developed adjacent to Robe and will be described as the East Dairy Range and West Dairy Range respectively.

The East Dairy Range is poorly preserved, but remnants can be recognized at intervals from near Mt. Benson, *via* Millicent, to the southeast corner of the State. It is typically a low aeolianite structure which has been modified by subsequent high sea-level floodings, including the Anadara and two "Woakwine truncation" high sea-levels. The modification of this and younger dunes is a characteristic which has not been found to apply to the dunes older than the Reedy Creek dune, except in the Mt. Gambier volcanic area.

The West Dairy Range, unlike its eastern associate, is relatively well preserved over most of its length of 70 miles towards Kongorong. It converges within 1 mile of the younger Woakwine Range in this direction and in itself narrows to less than ½ mile in width except near Kongorong where it attains its maximum width of more than 2 miles. Beach ridging is most prominent opposite Lake Hawdon where 14 ridges occur in a width of 1 mile.

Subsequent high sea-levels have modified the younger Dairy Ranges in several ways. The Woakwine truncation high sea-levels for example eroded fore-dune structures and established shell deposits on the eroded surfaces. A prominent cliff beach nick-point (noted in Bray Drain) was also developed, which, together with some of the foregoing shell deposits was covered by later consolidated beach sand of the tidal zone. The Anadara sea-level in its turn eroded the face of the range, invaded inlets and flooded around behind the ranges and finally left shoal structures confronting it (fig. 12) (Plate IV).

The use of fore-dune flat heights as an indication of fossil strand level is most unreliable in complicated circumstances such as these, although they may give very rough approximations. Values for the Beachport and Robe vicinities are about 40ft. and 30ft. respectively.

Woakwine Range

(PLATE V, FIG. 1)

This dune is probably the most complicated aeolianite structure of the whole series, but because two deep drainage-cuts (near Robe and Beachport) have been made through it, much is known of its internal structure.

Upon superficial inspection the dune appears to be a simple but exceptionally high structure over much of its length. Except in the Cape Jaffa vicinity, the dune is like a single large consolidated coastal dune which has resulted from one prolonged high sea-level still-stand. It averages about 1 mile in width, but at times exceeds 2 miles. Near Beachport and Cape Banks there is limited indication of beach ridging.

The dune complex is remarkably regular, and in many places exceeds 100ft. in height. At Mt. Benson it rises to more than 260ft. It can be traced from near Kongorong in the south to within 1 mile of Cape Jaffa, where it has been truncated by later sea coasts, namely, the Anadara and Osborne high sea-levels and the modern sea. Adjacent dune-flat levels fall from 15ft. to 20ft. opposite Beachport to about 4ft. near Robe. A bore sunk 6 miles east of Robe revealed that the dune sits directly on eroded Miocene bryozoal limestone 20ft. below modern sea-level (L.W.O.S.T. at Robe) and that the fore-dune flat deposits in this area are at least 25ft. in thickness.

The internal structural complexities exposed in Drain L cutting (fig. 13) concern at least three complete or partial marine submergences. Following the initial dune sand accumulation (Stage 1) either by a rise in sea-level, or by a negative movement of the land, or by a combination of both, the sea advanced beyond this dune nucleus and completely submerged it (Stage 2). Judging by the clean truncation of the dune bedding structures and by the establishment on this planed surface of a *typical reef fauna,* the dune nucleus must have been consolidated before the advance of the sea. The sea thus receded from the original Woakwine strand line for a sufficiently long period to allow travertinization of the original dune before readvance and submergence. The relative rise of this sea-level of Stage 2 beyond Stage 1 must have exceeded 30ft. During Stage 2 the flooding of inland flats extended to the base of the Reedy Creek Range.

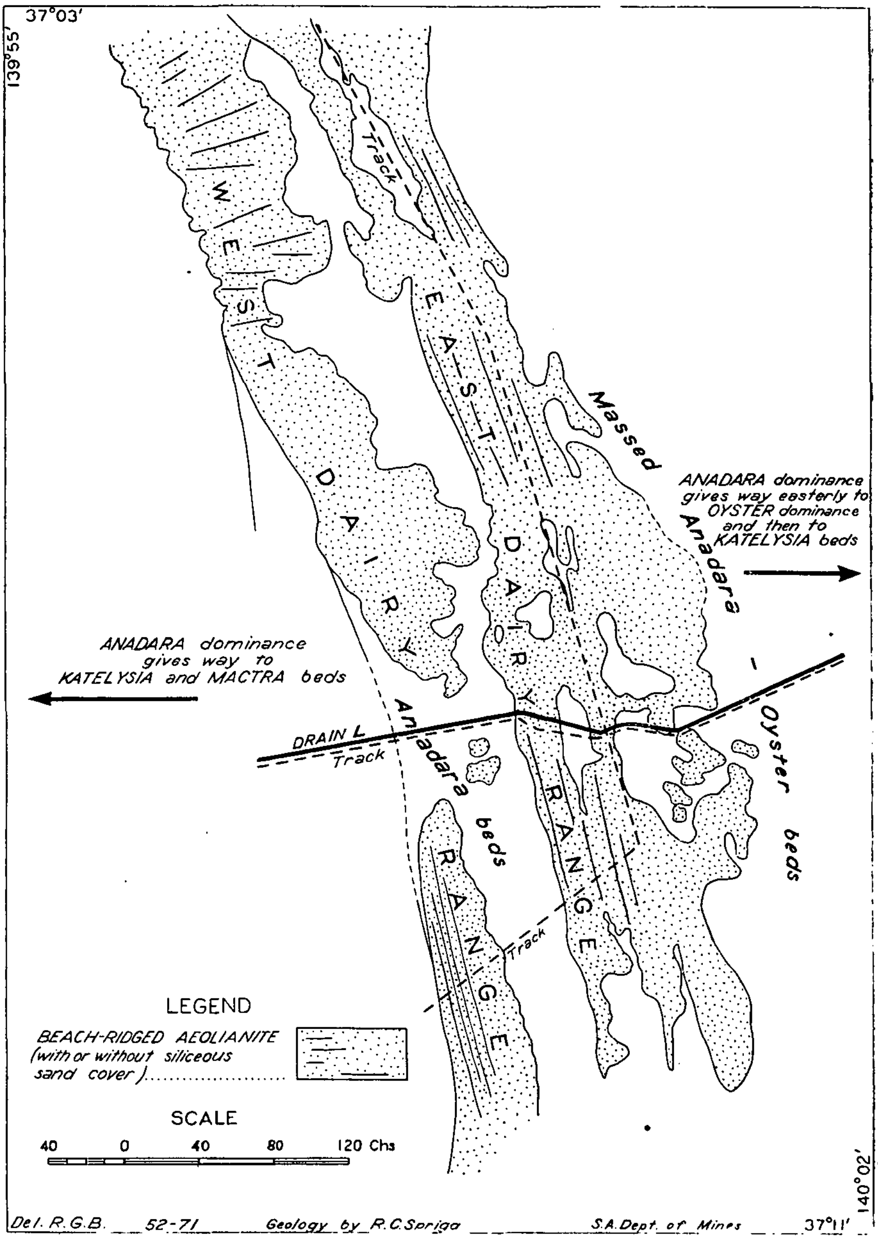


Fig. 12—The mid-Recent or "Anadara" coast-line of the Dairy Archipelago (13 miles east of Robe)

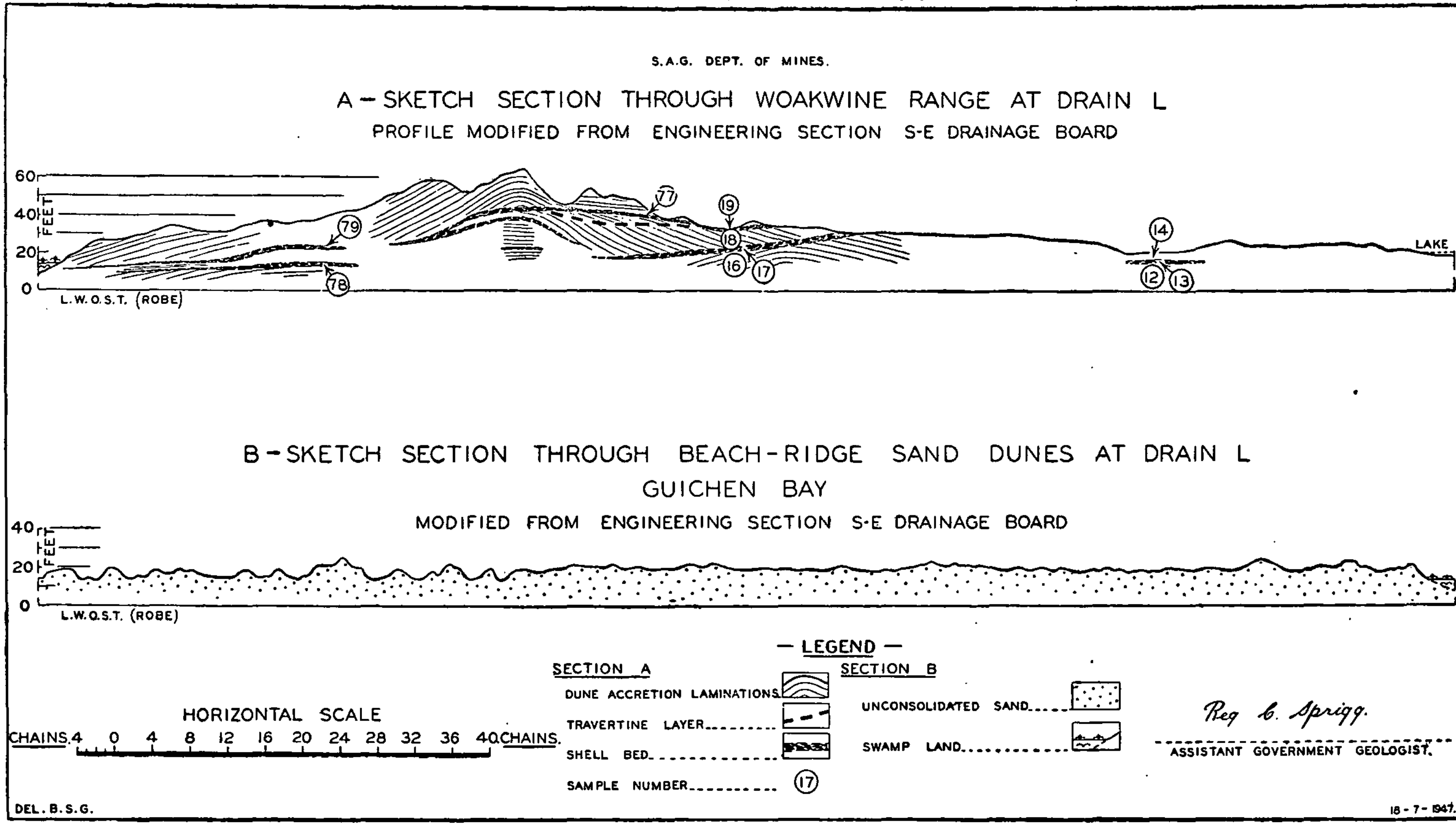


Fig. 13—Sketch sections—Drain L cutting

Following the first submergence (Stage 2) the sea again receded allowing further dune consolidation and travertinization of the reef shell-bed. The sea margin must have migrated clear of the dune base relatively quickly as no aeolian sand was spread over the shell bed until the travertinization process was well advanced. Still later another sea-level rise, probably to the base of the dune, allowed aeolian sand to accumulate over the latter reef shell-bed which also became consolidated.

The sea continued rising (Woakwine Stage 3) eroding deeply into the upper sections of the dune and for the second time established reef faunas at higher level. This sea-level exceeded the Stage 1 sea-level by at least 40ft. repeating the inundation of interdune corridors to the east. The sea retreated a third time permitting travertinization of the Stage 3 shell beds and allowing further aeolian beach sand accumulation. The sequences are illustrated diagrammatically in fig. 15.

Apparently identical stages can be recognized in topographic expression in the dune in the Mt. Benson-Cape Jaffa extremity. Here a low wide-spread dune structure forms the landward base of the main range, but it has been practically buried by the more massive and higher dune accumulations of Eagle Hill and Mt. Benson (260ft.) itself. This complex is in turn bounded on the seaward margin by a third stage of "foot-hill" aeolianite accumulations. The zones are easily recognized and these relations are indicated in fig. 14.

At a much later date the Anadara high sea incursion also partly inundated the Woakwine Range. The sea flowed in around the range isolating it as a long narrow peninsula. A permanent east-west trending bay-bar and hook structure known as the Benson "hook" (Sprigg 1948) developed around its northern extremity, while in the sheltered bay behind the peninsula the mud-flat dweller *Anadara,* thrived in great abundance. Its remains form massed accumulations on the lee slopes of the dune.

The continuations of the Woakwine beaches to the north can only be conjectured at present. Sea-bottom topography to the north of Cape Jaffa shows no indication of continuity of the submerged aeolianite ridge in that direction. Recent sea-bed drilling at the proposed Jaffa harbour site did not disclose beach structures but revealed that the northwest trending shoal in this vicinity was a dolomitized zone in Gambier limestone, probably associated with faulting. It is likely, therefore, that the Woakwine Range terminated somewhere in this vicinity, probably under the influence of faulting. To the north of this point the rapid appearance of a host of beach-ridged structures behind the Coorong may be significant in relation to the apparent non-continuation of the Woakwine dune. In this area nearly 100 travertinous beach ridges occur between the main Reedy Creek beach and coast. The relationship of these to any of those previously described is difficult to decide. In all there are eight "post-Reedy Creek" recognizable high sea-levels, and probably only three, namely, the Robe, Anadara, and Osborne stages (*see* later) can be correlated with any certainty.

The Robe Dune Range and the (?) Twelve-Fathom Stand

(Plate V, Fig. 2)

The Robe Range is the youngest and lowest recognizable aeolianite dune ridge. Bores in Robe Harbour which penetrated the aeolianite to Gambier limestone on the central and eastern margins of the range indicate a base level of deposition more than 40ft. below modern sea-level.

The Robe Range aeolianite is now being actively eroded by the modern sea. Much of the original dune has been reduced to reefs, stacks, and islands, and the dune remnants can be traced from the Margaret Brock Reef near Cape Jaffa, *via* a series of submerged pinnacles to Baudin Island and Cape Dombey

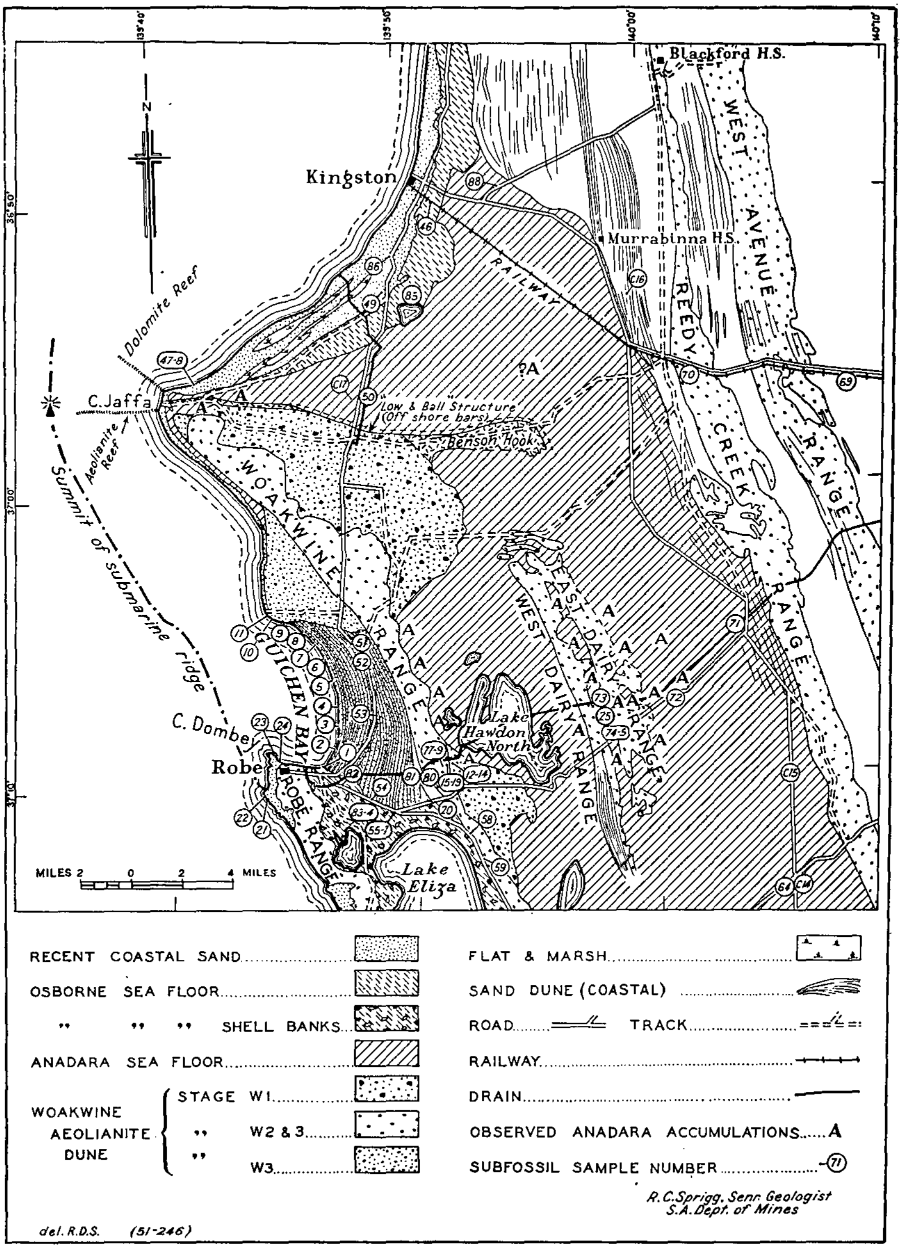


Fig. 14—Coastal deposits of the late Quaternary—Robe-Kingston region

(Robe) and thence as shoals and reefs which form a protective skirting to the modern coast as far south as Cape Banks. Near Beachport they form the prominent headlands of Cape Martin and Cape Buffon, and also Penguin Island.

The Robe dune is in part a double dune and its eastern limb has been called the Canunda Range by Campbell, Cleland, and Hossfeld (1946). They describe (p. 453) the Canunda Range as the "partly consolidated but now disintegrating dune ridge lying between the Woakwine Range and the present coastal dunes", also that it is distinct (p. 473) from "isolated remnants of still another former coastal dune, which was partly consolidated and probably formed a continuous series, of which only a few headlands remain, such as Cape Buffon, Carpenter Rocks, Cape Banks, etc." The author does not agree with the separation of Canunda Range from what is now termed the Robe dune as the aeolianite is mostly continuous between the two developments, and because multiple ridging is a common feature of aeolianite dune ranges generally. Deep erosion by a subsequent high sea-level has tended to obscure the westernmost element of the ridge but its continuity can be followed clearly on aerial photographs by the presence of endless shoals and reefs. The Canunda ridge forms the headlands of Cape Thomas, Boatswains Point, and Baudin Rocks in Guichen Bay, but it is continuous with the main Robe Range.

Soundings taken oceanward from Guichen Bay indicate a plane of marine erosion about 70 or more feet below sea-level from adjacent to the foot of Robe Range. It could be genetically related to the Robe Range, but the great difference between this base level (70ft. below Robe L.W.O.S.T.) and the base of the central or lee portion of the Robe dune (—40ft.) even with due allowance for the seaward slope of the erosion platform from the dune base, cannot be reconciled adequately for this relationship. It seems more probable that the initial stranding of the Robe dune allowed semi-consolidation of the dune sands and surface travertinization and that a subsequent rising sea-level advanced almost to the base of the range and eroded the aeolianite toe as well as the underlying Gambier limestone. This later erosion level will be referred to tentatively as the Twelve-Fathom Stand.

No marine fossils have been found within the mass of the Robe dune as in the Woakwine Range. The Robe dune was formed after the two inundations which affected the Woakwine Range (Stages Woakwine 2 and 3). On the other hand the marine flooding of the interdune flats west of the Reedy Creek Range during the Anadara high sea-level is later than the Robe dune as its shelly deposits overlie the landward apron of the dune. These relations are shown in fig. 15.

The Robe Range is now again partly drowned, and north of Cape Dombey (Robe) little remains above sea-level, but it can be traced as a submarine ridge and series of islands and reefs to the Margaret Brock Reef near Cape Jaffa. Beyond this point all evidence of dune continuity is lost and sea-bottom topography falls away sharply. The Anadara and later high sea-levels formed capes at about this point and it is very doubtful whether the dune ever persisted much farther. Field evidence suggests that the coast may have swung sharply inland north of this area, trending behind the present Coorong lagoons. Even the Woakwine and Dairy beaches probably have their equivalents farther east in this region.

The Coorong Aeolianite Range

Remnants of an aeolianite dune, which may be the "Robe" equivalent, have been found within the mass of the modern Coorong ocean beach dune complex. They have been observed at intervals of 30 miles and 40 miles north of Kingston and probably continue more strongly to the north.

The Coorong lagoon itself occupies two interdune corridors. Due to progressive downwarping the lagoon deepens to the north and in consequence the central aeolianite ridge becomes gradually submerged and its presence is indicated only by a string of islands and shoals.

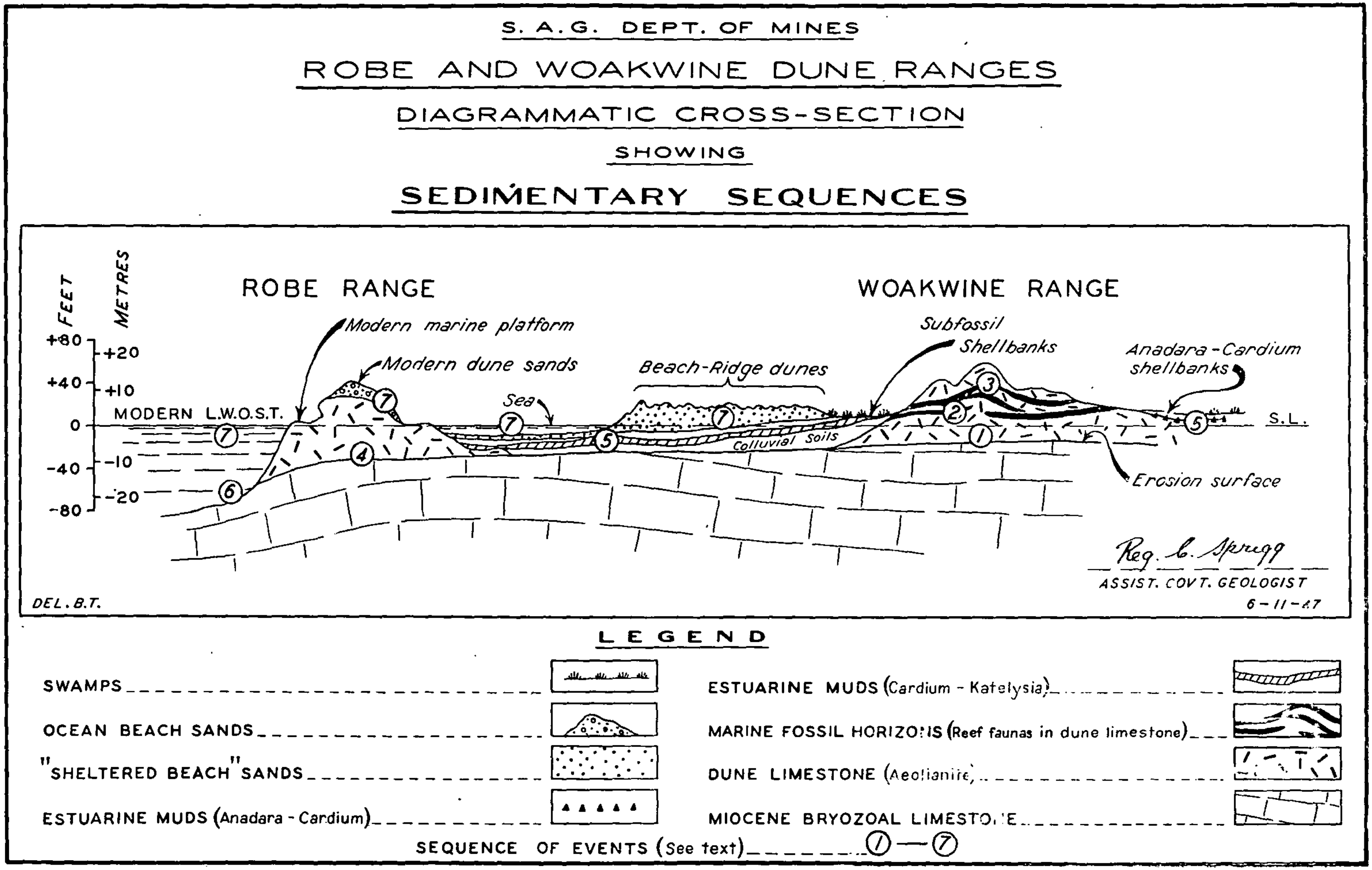

S. A. G. DEPT. OF MINES
ROBE AND WOAKWINE DUNE RANGES
DIAGRAMMATIC CROSS-SECTION
SHOWING
SEDIMENTARY SEQUENCES
FEET
METRES
+80
+40
0
-40
-80
+20
+10
-10
-20
ROBE RANGE
WOAKWINE RANGE
Modern marine platform
Modern dune sands
MODERN L.W.O.S.T.
Sea
Beach-Ridge dunes
Colluvial Soils
Subfossil Shellbanks
Anadara - Cardium shellbanks
S.L.
Erosion surface
Reg. C. Sprigg
ASSIST. GOVT. GEOLOGIST
6-11-47
DEL. B.T.
LEGEND
SWAMPS
OCEAN BEACH SANDS
"SHELTERED BEACH" SANDS
ESTUARINE MUDS (Anadara - Cardium)
ESTUARINE MUDS (Cardium - Katelysia)
MARINE FOSSIL HORIZONS (Reef faunas in dune limestone)
DUNE LIMESTONE (Aeolianite)
MIOCENE BRYOZOAL LIMESTONE
SEQUENCE OF EVENTS (See text) 1 — 7

Fig. 15

The Beaches of the Volcanic Zone

Fossil beaches in the Mt. Burr-Mt. Gambier region occupy a much narrower zone than in the north. To some extent certain of them are telescoped upon each other, and the small landward spread is a function of the steeper seaward gradients in this locality.

The older volcanics of the Mt. Burr-Bluff zone were in existence at the outset of the Pleistocene period when beach development began, and for much of the period formed a strong promontory, herein named the Mt. Burr Peninsula. The Mt. Gambier-Mt. Schank activity on the other hand occurred much later in the Pleistocene and did not modify the strike of the local beaches significantly.

In the more restricted Mt. Gambier area, practically all the dunes are compounded as a result of inundation by one or more high sea-levels. Reef shell and shingle beds at high levels are superimposed on the consolidated dune sands. In many cases minor cliffs were developed within the pre-existent aeolianites and in others the tops of dunes were completely truncated to provide widespread *reef* conditions.

Correlation of beaches on either side of the Mt. Burr Peninsula is difficult for several reasons. First, Mt. Gambier volcanic activity is known to have caused significant temporary downwarping which in turn caused flooding of older beaches by one or more high sea-levels. This has reduced the number of dune ranges by at least one. Secondly, fore-dune levels are not of much application in correlation as the land in this vicinity is downwarped to the east. Finally in the Millicent-Tantanoola area the tracing of fossil beaches is practically impossible on account of the drifting of sand and dune telescoping.

The nature of the beach deposits in the Mt. Burr-Mt. Gambier area is extremely varied. While coarse dune sands (now aeolianites) predominate, cobble beaches and bay bars (cobble and sand) are not at all uncommon. In the "peninsula" zone, "reef" beaches and sea cliffs are prominent features. As in the areas farther to the north, the shell beds at the base of major dune associations are rarely visible, being obscured by the later sands and soil developments. The only visible shell beds are those associated with numerous overlying beach deposits formed by subsequent flooding which were accompanied by different depositional conditions from those of the original beaches. For example, Crocker and Cotton (1946) relate the marine faunas of the fine sandy beaches on the tops and leeward of the Caveton and Burleigh Ranges to those of the original beaches whereas actually they are related to subsequent inundations when outer (aeolianite) reefs destroyed the energy of oncoming waves. Similarly the writer has found multitudinous younger overlying shell beds, including a variety of ecological conditions from the true reef associations (*Haliotis, Turbo, Brachyodontes erosus,* etc.) through cobble and fine sandy beaches to estuarine embayments. The latter include typical massive oyster beds, as for example to the east and south-south-east of Mt. Gambier township.

The delineation of the many fossil sea beaches in the older volcanic area may never be worked out satisfactorily. The Pleistocene sea in its earliest phases probably surrounded the seaward volcanoes to form a series of islands, tied islands, and shoals. The west-facing coast would have been rugged and highly indented. Subsequent sea coasts by westward migration, and deposition, would probably have been more direct, culminating in the almost uninterrupted Reedy Creek (Burleigh) beach.

At the present day, aeolianites and sand drifts ascend many prominences. They have been found at altitudes of several hundred feet above sea-level and give no indication of actual fossil strand line levels. However, Crocker and Cotton (1946) noted a shell bed at 205-210ft. in association with travertinous dunes rising to 240ft. on Mt. Graham. The fauna reflects reef conditions on an exposed steep ocean beach facing deep water. A similar ocean beach was recorded by Howchin (1929), on the Mt. Burr Reserve. This occurs 190ft. to 195ft. above sea-level. These beaches may be correlated with either the Naracoorte or Stewart high sea-levels.

In the Tantanoola caves area the close association of several high sea-levels can be seen very plainly. Reef shell beds with abundant *Haliotis, Brachyodontes erosus* and *Turbo undulata* occur completely over-running the cliff tops at Up and Down Rocks. The old cliffs themselves are vertical and "nicked" at their bases with reef shells indicating a subsequent beach at about 205ft. above sea-level (fig. 16). Finally, coarse beach shell sands exist to a much greater depth beyond the cliff base.

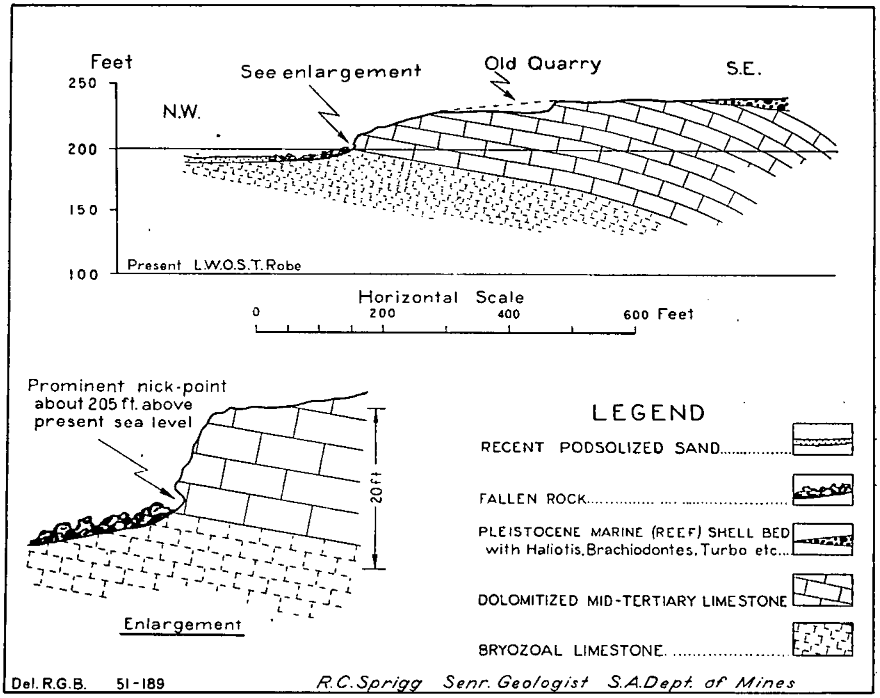


Fig. 16—Stranded marine cliff—Up and Down Rocks, Tantanoola

In the Gambier "embayment" (fig. 17) which is to the southeast of the Mt. Burr Peninsula, five or more distinct dune associations can be recognized up to the time of the Reedy Creek (Burleigh) high sea-level, and at least one more high sea-level can be inferred.

The oldest of this series is the Dismal Range (fig. 17). Its fore-dune flat level approximates 230ft., and it may therefore be related with the main Naracoorte high sea-level. The only known older coast on its landward extreme is the East Naracoorte cliff-beach along the Kanawinka Fault in Victoria.

The next younger is a consolidated beach deposit (non-aeolianite), the Mingbool beach, which lies at approximately 210ft. Eroded remnants of the Compton dune occur at about 180ft., followed at about 150ft. by the Glenburnie dune which passes through Mitchell and Murrawa on the immediate north boundary of Mt. Gambier township. This dune is deeply eroded over much of its length with the formation of secondary embayments. Marine limestones, including many oysters, overlie this aeolianite about 1 mile WNW. of Murrawa, and these, in turn, are overlain by volcanic ash from Mt. Gambier. To the northeast the dune

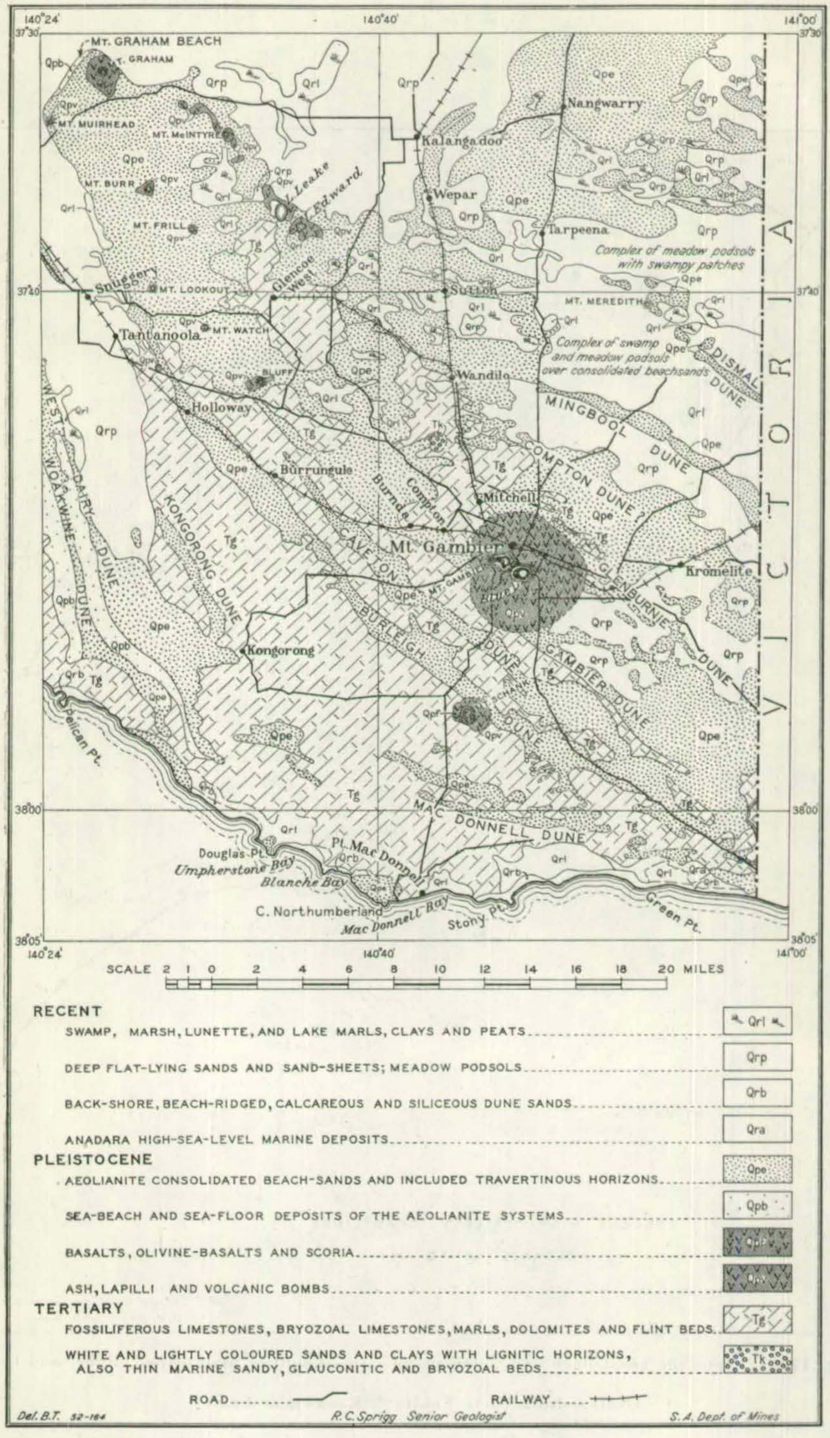


Fig. 17—Detailed geological map of the Mount Gambier area, South Australia

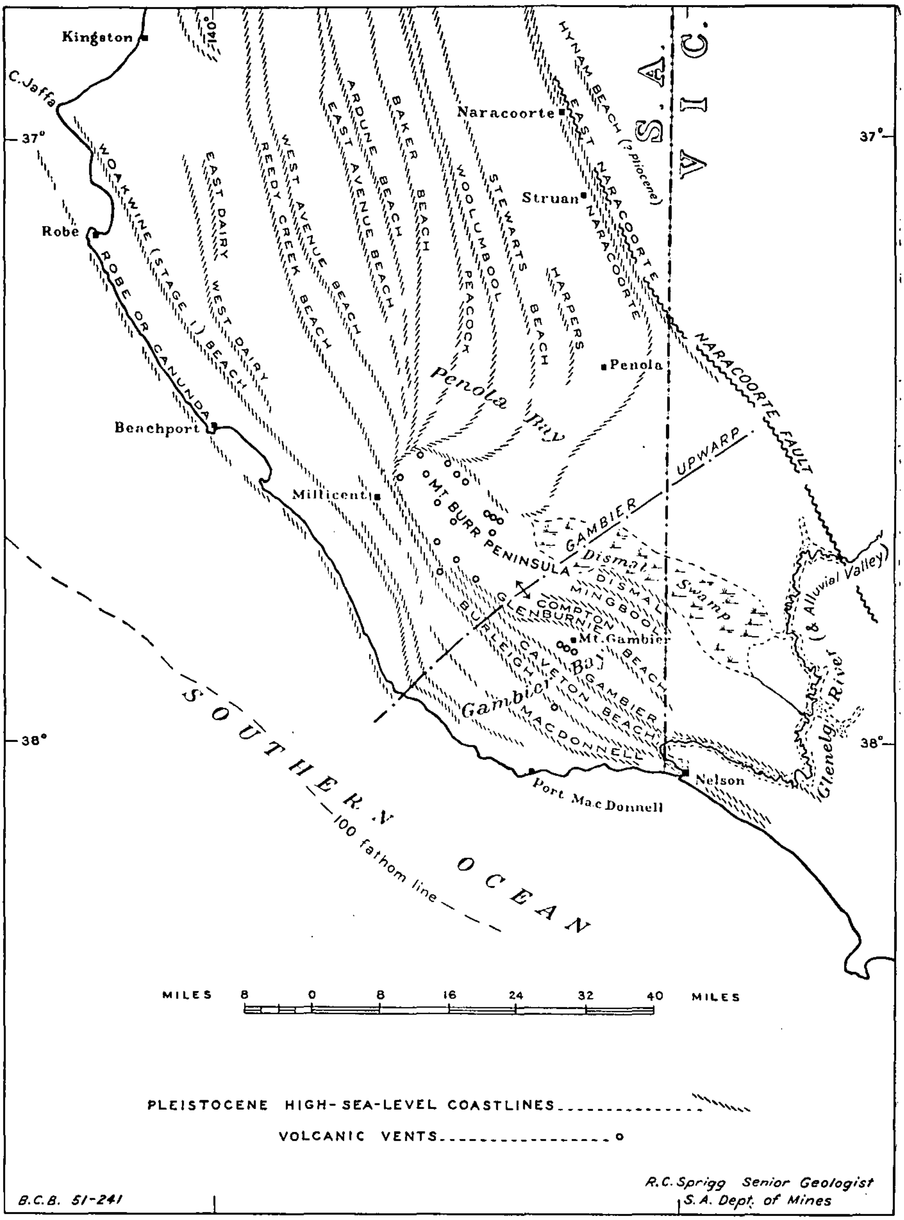


Fig. 17a—Pleistocene coast-lines and Gambier upwarp—Counties MacDonnell, Robe, and Grey

(Note.—Naracoorte Fault = Kanawinka Fault)

grades into a line of cliffs in Gambier limestone. Near Murrawa the base and fore-slopes of the dune are overlain by flat-bedded consolidated sands with occasional oysters which may exceed 20ft. in thickness.

Confronting the Glenburnie sea beach there are lower aeolianite structures which arch seawards as if to include the nucleus of the early Mt. Gambier volcano. This arching indicates that the original activity may have been contemporaneous, although most of the outpourings came later as witness the distribution of massive ash deposits over the Glenburnie and Gambier dunes.

The Gambier Range is the next dune. Its seaward margin is very direct from the Victorian border to near Burnda where it fuses with an area of low dolomite rises, the westernmost of which formed a series of low cliffs probably rarely more than 50ft. in height. The sea margin, thereafter, continued more or less irregularly in a series of capes and bays around the volcanic area. The Gambier Range is heavily blanketed by volcanic ash and its fore-dune flat level opposite Mt. Gambier stands at about 125ft. The writer knows of no marine complexities within this range, although it has over-run a more ancient dune remnant to the south of Yahl.

Caveton Range is probably to be correlated with the younger Avenue Range to the north. It is a typical ocean beach coarse-sand dune, direct in its strike, but has been modified somewhat by a later marine inundation which may not have drowned it completely. The sea flooded the base of the range and probably extended to the base of the Gambier Range. Opposite Mt. Gambier its fore-dune flat levels average about 100ft. above sea-level.

The Burleigh Range is one of unusual interest. It is the direct extension of the Reedy Creek beach and is, therefore, the most extensive and least interrupted of all the southeastern stranded beaches. It is intimately related with the development of Mt. Schank. It is compounded and displays some peculiar beach structures.

The original Mt. Schank activity appears to have occurred during the late stages of the Burleigh dune development. In the vicinity of the mount, the younger beach ridges swing seaward (fig. 10) as if to include a seafloor irregularity such as the beginning of an igneous outpouring. Such a feature occurs to the west of the mount in the form of a basalt flow which has been eroded by marine agencies. Ash deposits also envelope the western apron of the local Burleigh dune, indicating subsequent activity. In general, the contemporaneity of this volcanic activity and the Burleigh high sea-level is well established. A high sea-level subsequent to this Reedy Creek phase appears to have almost, if not completely, swamped the Burleigh Range, and left shell beds on the slopes of Mt. Schank (James 1949). The same high sea would also have been responsible for the less complete inundation of the Caveton Range and of the low lands to the base of the Gambier Range. The "truncation" sea beaches include cobble beaches and subfossils of the reef and fine-sand beaches.

A remarkable "periodic" structure occurs approximately 8 miles to the southeast of Mt. Schank and on the seaward margin of the Burleigh Range. A series of beach ridges lie strongly obliquely to the beach ridges of the Main Range and approximately parallel with the dominant wind direction. However, the ridges are not drift ridges of the "down wind" type as they are definitely curved and far too subparallel for a region with a complex wind regime. In the writer's mind the origin of the ridges remains obscure, although it was noted that a small scarp in underlying (Gambier) limestones confronting the western extremities of the ridges may exercise some control. The sands of the dunes are aeolian and the structures are not of the submarine bay-bar type. The dunes rise to as much as 50ft., but probably overlie true beach structures.

In the extreme southeast of the State the Burleigh dune follows a strong regional fault, and has formed low cliffs along it, although there is no evidence of significant interference by the fault with the main coastal configuration.

Beaches to the west of the Burleigh Range are poorly developed and occur as remnants. The MacDonnell dune has been sculptured deeply by later seas and its relations with beaches to the west and northwest are difficult to decipher, although correlation with one of the Dairy Ranges seems most likely. The East Dairy Range in its southerly continuations probably becomes the poorly developed Millicent dune and as such it is trending as if to telescope with the Reedy Creek (Burleigh) Range near Tantanoola. This is in keeping with other facts, as at this time the regional subsidence accompanying the Mt. Schank activity would be causing a local drowning of some of the older ranges in the extreme southeast. The East Dairy sea-level in all probability is the post-Burleigh truncation high sea-level, and the MacDonnell beach could be the West Dairy equivalent. On this interpretation the minor dune and cobble association trending northwest from Kongorong is unaccounted for. However, the accumulation is small and may represent a minor hesitation only, in the retreat of the East Avenue sea-level. Its development may in some way be associated with shoaling tendencies amid the tremendous flint accumulations characteristic of this area.

The Woakwine and Robe dune developments are unknown in the area. They probably existed seaward of the modern coast and were probably extensively eroded, if not destroyed, during the Anadara high sea-level. One or more post-Dairy high sea-levels has invaded the MacDonnell dune and formed cliffs in it and left shell deposits over much of its area, but their age equivalents are not known.

A correlation of the foregoing sea-beach developments with those to the north is summarized as follows:

Naracoorte-Robe Zone	*Mount Gambier Zone*
East Naracoorte	East Naracoorte
Main Naracoorte	Dismal and (?) Graham
Stewart	Mingbool
Woolumbool	Compton and (?) Burr
Peacock	Glenburnie
Bakers	? pre-Gambierian inundation
Ardune	
East Avenue	Gambier
West Avenue	Caveton
Reedy Creek	Burleigh
East Dairy	Post-Burleigh inundation
West Dairy	MacDonnell
Woakwine	Evidence destroyed by the modern sea
Woakwine truncation 1	
Woakwine truncation 2	
Robe	
Anadara	Port MacDonnell truncation
Osborne	(?)

Dune Blow-Out Structures

The Coastal dunes of the South-East practically all lie transverse to the prevailing winds. Exceptions are recorded at Lacapede Bay and in the Mt. Gambier region. This configuration in relation to prevailing winds has assisted the mountainous piling of sand in many places to more than 100ft., particularly where specialized vegetation has held and fixed these accumulations. However, quite frequently the sand masses become unstable. Wind agencies open up weaknesses and initiate secondary sand blows which may spread to very considerable dimensions. The "weaknesses" may include the sites of aboriginal kitchen middens, burned areas, uprooted trees, or animal burrowings. The blows spread laterally as an elongate fan-like tongue as a result of the influence of several wind directions. Vegetation is undermined or buried at the border of the blow-out and the central exposed sand surface is continually lowered and expanded. The advance of the sand is temporarily halted at its lee margin by vegetation which in turn is slowly smothered and destroyed. The margin consequently advances slowly. Eventually a condition of equilibrium is reached, either due to the exposure of the groundwater table or some underlying sedimentary deposit resistant to wind erosion. The blow-out under this condition will have developed to the stage of a wide sub-triangular shallow basin with apex down wind. Its sides will be marked by converging sand ridges which coalesce at the apex to produce a much higher accumulation. The Mt. Benson blow-out is a good example of this phenomenon and in its apical development the sands are more than 260ft. high.

PERIODICITY IN MARINE SEDIMENTATION

(Plate XI)

Periodicity in marine sedimentation is strikingly evident in the beach dune systems of the South-East. Beach ridging is prevalent, and in the modern coastal dunes the phenomena is displayed to perfection. Multiple bay-bar hooks also exhibit a degree of halting cyclicity in growth.

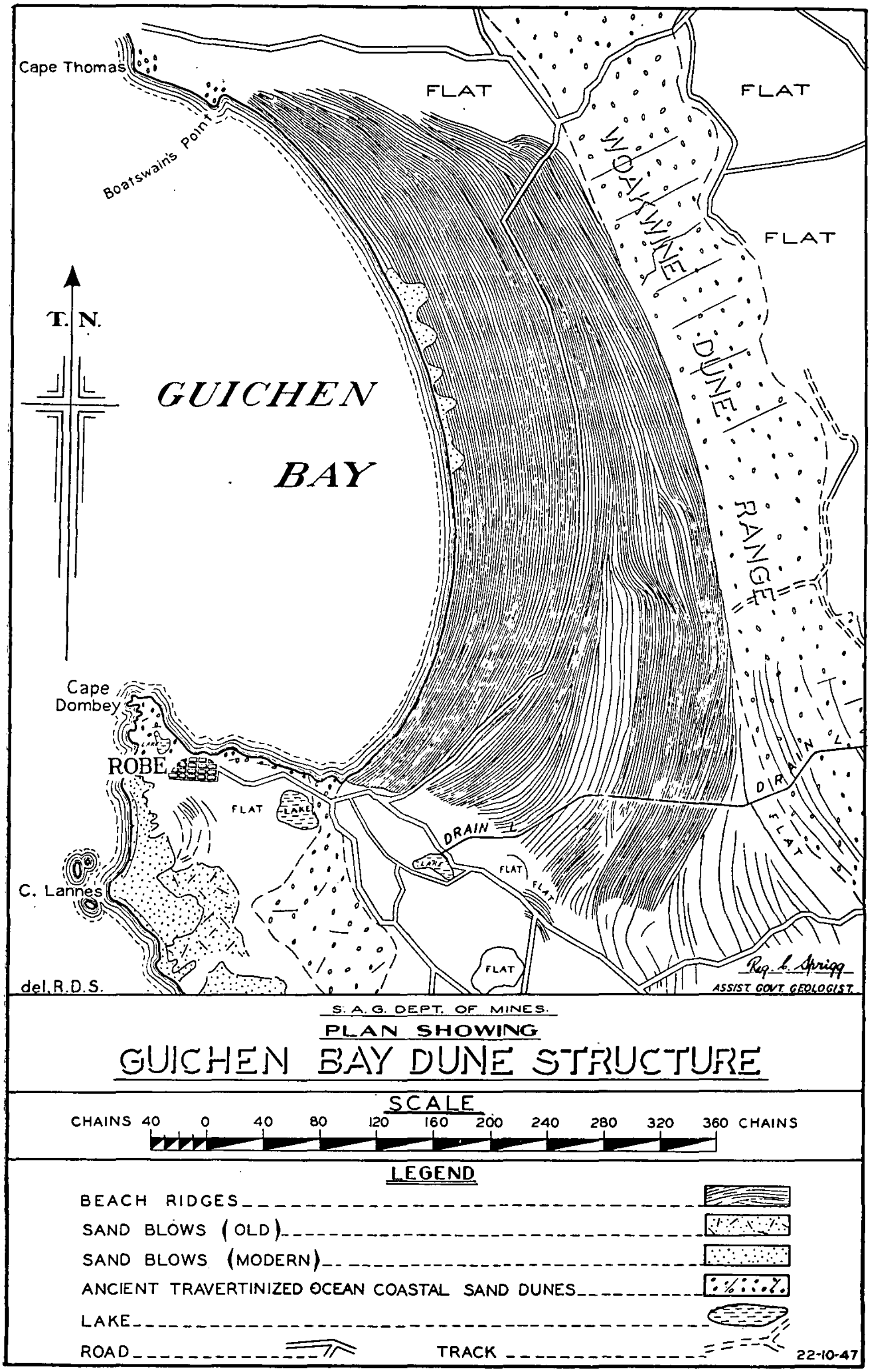
At least two sets of rhythmic controls have operated in the formation of the dune systems of the South-East Province. One is a long period cycle obviously measured in tens of thousands of years while the other is of much shorter duration. The major periodicity is related to glacial eustacy which in turn may be related to latitudinal variations in the solar radiation increment and other factors (*see* later under Geochronology of the Quaternary). Within this broader cycle the effects of shorter-term cycles are also frequently well developed in the dune of a particular high sea-level, and as many as 20 subsidiary beach ridges may be preserved.

The most striking examples of this short period cycle occur behind Guichen Bay (fig. 18) and Rivoli Bay (fig. 19) and to the northeast of Kingston. At Guichen Bay more than 80 almost perfectly parallel beach ridges have been stranded in a width of about 6 miles. The individual ridge summits rise to about 25ft. to 30ft. above sea-level (L.W.O.S.T. Robe) and the interdune depressions are usually 5ft. to 10ft. lower. Such even development suggests a powerful control of rhythmic regularity.

Upon first appearance it may seem that periodic shoals confronting these beaches should present ideal nuclei for dune aggradation or accumulation. However the widths of these sea-floor topographic oscillations are not coincidental with those of the beach ridge associations. It is also recognized that these "low and ball" features of the sub-tidal zone are ephemeral only and unlikely to build above sea-level except under the most exceptional circumstances. Also such structures along tidal coasts of this type are discontinuous phenomena and would not build up continuous beach ridges if extended vertically. Fossil "low and ball" structures have been observed on the flats confronting the Mt. Benson Hook (fig. 14, Plate IV).

Another possible cause of regular beach ridging may be in controls exercised by minor variations in sea-level causing oscillatory migrations of the strand line. Providing the beach is one of moderately rapid sand accumulation, it could be reasoned that, with a temporary minor retreat of the sea margin, the beach shore dune would be spread out resulting in a lower sand accumulation or dune trough. With the return of sea-level new sand accumulations would build up in part of this dune trough to form a high sand-accumulation or dune ridge. By repetition of this process it is conceivable that a series of beach ridges could form.

A more probable explanation is concerned with a periodic tidal range variation. (*See* also under "Geochronology of the Quartenary: The chronologic implications of periodic beach ridging.") With increased tidal range, sands can be transported to higher levels on a beach and in larger quantities at high tide than at any other tide (storm tides excepted). An increased tidal range also produces a greater effective range of erosive agency. Sand would tend to be "worked in" from outlying depths more extensively during higher tides, resulting



Cape Thomas
Boatswain's Point
FLAT
FLAT
FLAT
WOAKWINE DUNE RANGE
T. N.
GUICHEN
BAY
Cape Dombey
ROBE
C. Lannes
FLAT
LAKE
DRAIN
LAKE
FLAT
FLAT
FLAT
DRAIN
FLAT
del. R. D. S.
Reg. C. Sprigg
ASSIST GOVT. GEOLOGIST
S. A. G. DEPT. OF MINES.
PLAN SHOWING
GUICHEN BAY DUNE STRUCTURE
SCALE
CHAINS 40 0 40 80 120 160 200 240 280 320 360 CHAINS
LEGEND
BEACH RIDGES
SAND BLOWS (OLD)
SAND BLOWS (MODERN)
ANCIENT TRAVERTINIZED OCEAN COASTAL SAND DUNES
LAKE
ROAD
TRACK
22-10-47

Fig. 18

in more massive sand accumulation than at other times to form the ridges of dune associations. The influence of storms on transport and deposition will also be greatest during high tides, and providing the storms have a frequency much greater than the frequency of the tidal range variable, its effect should be only to enhance the degree of development of dune ridging.

Along Long Beach, in Guichen Bay, and along the southern Coorong beach a dune trough is in process of formation. The beach ridges of the South-East have little in common with the shingle ridges at Dungeness in England (Lewis and Balchin 1940) and in the Abrolhos Islands (Teichert 1947) where periodicity in marine sedimentation is also evident. At Dungeness more than 200 shingle ridges have been built up in a few centuries and their formation is undoubtedly controlled by violent storm incidence and not by absolute changes in sea-level or tidal factors, although these two influences may have a bearing on the height of the individual ridges which vary from 15ft. to 20ft. above sea-level. Shingle supply at Dungeness is copious, but the rate of formation of successive ridges is irregular, being largely dependent on the incidence of severe storms which pack the cobbles to heights determined by storm severity, the direction of approach of the wave trains, and the state of the tides during the particular storms. Hence it is to be noted that although the ridges form a remarkably regular series, the major controlling factor is irregular and unpredictable. The beach ridges of the South-East differ markedly from these cobble accumulations as they represent deposition dominantly beyond tidal reach under aeolian influence where colonization by vegetation keeps abreast of dune development. Cobble ridges on the other hand are essentially marine deposits. A single cobble ridge is thought to be the product of a single storm, whereas the internal structure and vegetation relationships of a massive aeolian beach ridge 30ft. high and 50ft. or more in width indicates a time relation measured in years.

There is still much to be learned of the mechanics of cyclical beach ridging, but certain conditions are obviously necessary for the uninhibited development of beach ridges, namely:

(1) A large and continuous sand supply.

(2) A degree of coastal stability and protection—

  (*a*) To facilitate sand deposition.

  (*b*) To prevent undue sand accumulation leading to drift and dune telescoping.

(3) Shallow offshore water.

(4) Absence of nearshore reefs and islands which would destroy wave energy excessively or complicate wave patterns unduly by refraction.

(5) Dominant winds should be from "offsea" and preferably transverse to the coast.

(6) A relatively stationary sea-level.

(7) The action of a cyclic control, *e.g.*, a tidal agency (*see* later section).

(8) The rapid stabilizing of fresh sand additions by colonizing vegetation.

A study of cross-sectional heights of the cyclic dunes behind Guichen Bay would suggest that sea-level has not varied very significantly for some centuries. Dune crest levels (fig. 19) all lie between 20ft. and 30ft. above L.W.O.S.T. (Robe datum) over a width of 6 miles.

INTERDUNE CORRIDORS

The interdune corridors are mostly flats of accumulation sloping gently seaward and harbouring extensive lakes and lagoons which tail off into marshes and flats only periodically flooded. Under favourable ecological conditions, the lakes may become sites of peat deposition (*e.g.*, Ten-Mile Creek fen), but where the lakes dry out annually, lunettes figure prominently. (Plates I and II.) The fresh-water lakes, marshes, and lagoon systems abound in fresh-water snails (*Limnea, Corbiculina angasi, Lenameria pectorosa,* and *Sphaerinova tatiarae*) but where salinity is high, *Coxiella confusa* assumes dominance.

Interdune sea-floor deposits and planes of marine erosion are exposed only in a few places in the northern areas, but extensively in the Mt. Schank-Kongorong district. In the north the corridor between the Woakwine and Robe dunes is the site of extensive lakes and has had a complex history of marine inundation in Recent times.

Perhaps the most striking physiographic feature of the South-East is the Coorong. Its ribbon-like lagoon varies in length with the wet and dry season from 80 miles to 100 miles, and until the erection of the Murray Mouth barrages, its salinity varied over a wide range dependent on the proportions of river and sea water entering it, and on the local rainfall and seasonal evaporation. Since the construction of the barrages the salinity of the water has remained sufficiently high to maintain brackish water molluscan faunas which include *Coxiella confusa, Anapella adelaidae, Macoma deltoidalis, Soletellina donacoides* and *Salinator fragilis.* Subfossil molluscan suites in the same lagoon areas include the dominant forms *Eumarcia fumigata* and *Katelysia scalarina.*

Peculiar features of the Coorong flats include the "pipe clay" deposits and the algal coorongite "scum". Mawson (1929) has shown the "pipe clay" deposits to be dolomite, and coorongite was identified by Blackburn and Temperley (1936) to be a rubbery gel accumulation of the inflorescences of *Botriococcus braunii.*

Robe Harbour Bores

(PLATE VII, FIG. 1)

In the course of investigations of the sea bottom for a proposed deep-sea harbour at Robe a series of 23 bores were sunk into the sea. The bores were sunk on the lee of the partially submerged Robe dune. Some penetrated the modern marine sediments into the Robe aeolianite, others into the underlying Gambier limestone. They provided excellent information on post-Robe dune sedimentation which was controlled by a fine interplay of marine, lacustrine, and terrestrial agencies (fig. 20). The sediments and their faunas and floras practically all reflect environmental conditions of impeded drainage or of marine backwaters. The bores revealed that the Robe aeolianite dune was deposited directly on an erosion surface in Gambier limestone, and the accumulation of the original shell sands was erratic in this lee aspect. As many as five travertine ("B") soil horizons were found in a thickness of less than 10ft. In a few places Robe dune shell-sand is mixed with varying amounts of colluvial clays which is indicative of local swampy conditions in the rear of the dune.

ROBE HARBOUR BORES*

NOTE.—F.S. = Fine sand suite : Est. = Estuarine suite : R. = Reef suite : W. = Weed : S.L. = Salt lake : F.W. = Fresh-water lake : Filosa = Confusa.

BORE NO. 1

Depth	Description
14ft.—15ft. 4in.	Light cream-grey calcareous sand. *Bankivia fasciata* (F.S.), *Mactra australis* (F.S.), *Katelysia scalarina* (F.S.-Est.).
15ft. 4in.—18ft.	Dark-grey heavy clay ; with grey sandy pockets. Shelly band at 17ft. 8in. to 18ft. *Katelysia scalarina* (F.S.-Est.), *Cominella eburnea* (R.).
18ft.—21ft............	Very dark-grey heavy clay becoming sandy clay at bottom. Band of shells at 19ft. *Katelysia scalarina* (Est.-F.S.), *Ostrea sinuata* (Est.), *Brachyodontes erosus* (R.).

* Subfossils identified by B. C. Cotton, Departmental Palaeontologist and Museum Department Conchologist.

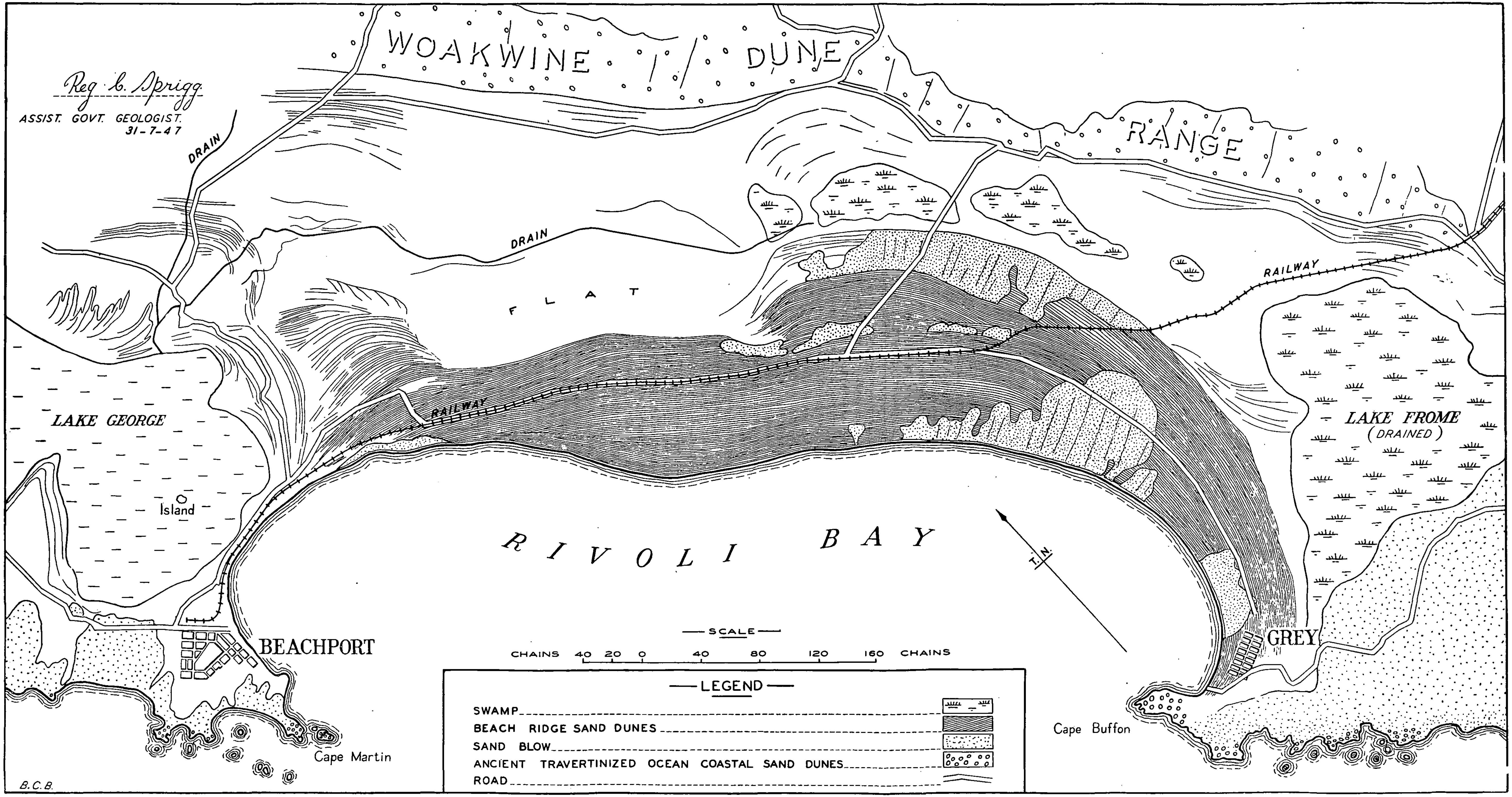


Fig. 19—Beach ridging—Rivoli Bay

ROBE HARBOUR BORES—*continued*

BORE NO. 1—*continued*

Depth	Description
21ft.—23ft. 6in.	Grey and dark-grey sand; with odd shells. *Katelysia scalarina* (Est.-F.S.).
23ft. 6in.—24ft. 8in. ...	Dark greenish-grey sandy clay; with pockets of light-grey white marly limestone.
24ft. 8in.—26ft.	Dark-grey sandy (?) swampy clay.
26ft.—26ft. 3in.	Dark grey-brown peaty clay.
26ft. 3in.—27ft. 3in. ...	Light cream-brown sand.
27ft. 3in.—30ft.	Dark-brown clayey peat becoming dark grey-bluish peaty clay.

BORE NO. 2

17ft.—20ft. 6in.	Grey calcareous sand; with pockets of cream-grey sand from 19ft. to 20ft. 3in.
20ft. 6in.—21ft. 2in. ...	Speckled grey (? organic) calcareous sand; with coarse shell. *Tawera gallinula* (F.S.), *Anapella adelaidae* (Est.), *Glycimeris striatularis* (F.S.), *Ostrea sinuata* (Est.-R.), *Mactra australis* (F.S.), *Venerupis galactites* (F.S.), *Thalotia conica* (W.), *Bankivia fasciata* (F.S.), *Phasianella australis* (W.), *Floraconus anemone* (R.), *Diala lauta* (Est.), *Pyrene lincolnensis* (Est.-W.), *Pyrene yorkensis* (Est.-W.), *Cymatiella lesueri* (R.).
21ft. 2in.—28ft.	Speckled brownish-grey calcareous medium-fine sand.
28ft.—31ft. 4in.	Speckled grey calcareous medium-fine sand.
31ft. 4in.—31ft. 7in. ...	Very dark-grey heavy clay; with small gastropods. *Corbiculina angasi* (F.W.), *Sphaerinova tatiarae* (F.W.). Fresh-water mussels indicated by nacre. *Planorbis isingi* (F.W.), *Lenameria pectorosa* (F.W.), *Notopala hanleyi* (F.W.).
31ft. 7in.—31ft. 11in. ..	Grey heavy clay; with less gastropods.
31ft. 11in.—32ft. 1in. ..	Black and dark-grey heavy clay; with small gastropods. *Diaphoromactra versicolor* (S.L.), *Coxiella filosa* (S.L.).
32ft. 1in.—33ft. 4in. ...	Dark-grey to very dark-grey heavy clay; with root fibres in the top 2in.
33ft. 4in.—34ft. 7in. ...	Grey to light-grey marl; with few shells in the bottom 3in. *Zeacumantus diemenensis* (Est.), *Diaphoromactra versicolor* (S.L.), (?) *Coxiella filosa* (S.L.), *Lenameria pectorosa* (F.W.).
34ft. 7in.—35ft.	Dark greenish-grey marl.
35ft.—35ft. 9in.	Grey to light-grey marl; with limestone fragments.

BORE NO. 6

25ft.—26ft. 6in.	Grey calcareous medium sand; with cream sand pockets. Few complete shells including spatangoid echinoderm.
26ft. 6in.—28ft.	Speckled grey fine calcareous sand becoming clayey sand towards the base. *Austromactra* sp. (F.S.), *Notocorbula* sp. (F.S. or mud).
28ft.—28ft. 10in.	Grey slightly clayey calcareous sand. *Bankivia* sp. (F.S.), *Tellina* sp. (F.S.).
28ft. 10in.—29ft. 2in. ..	Speckled grey medium sand; with complete shells. *Cardium racketti* (F.S.-Est.), *Anapella adelaidae* (Est.).
29ft. 2in.—31ft. 6in. ...	Speckled grey medium sand almost free of coarse shelly matter. *Mytilus planulatus* (R.), *Anapella adelaidae* (Est.).
31ft. 6in.—32ft. 3in. ...	Grey shelly heavy clay. *Cardium racketti* (F.S.-Est.), *Anapella adelaidae* (Est.), *Diaphoromactra versicolor* (S.L.).
32ft. 3in.—32ft. 7in. ...	Dark-grey to black sandy micaceous and organic heavy clay. One-inch band of salt-lake fauna near top. *Tatea rafilabris* (S.L.), *Diaphoromactra versicolor* (S.L.).
32ft. 7in.—33ft. 5in. ...	Grey to dark-grey heavy clay (? marly); with little fine shelly matter. Fragments of (?) fresh-water shells.
33ft. 5in.—35ft. 5in. ...	Dark-grey to very dark-grey sandy heavy clay; with no visible shelly matter.
35ft. 5in.—36ft. 3in. ...	Light greenish-grey medium-grained shelly clay. *Trichomya hirsutus* (R.), *Rissoa* sp. (Est.), *Katelysia scalarina* (F.S.-Est.).
36ft. 3in.—37ft. 10in. ..	Light greenish-grey medium to coarse clayey shell material. *Bellastraea squamifera* (R.), *Zemitrella* sp. (W.), *Phasianotrochus* sp. (W.), *Katelysia scalarina* (F.S.-Est.).
37ft. 10in.—39ft. 4in. ..	Light greenish-grey medium shelly bryozoal material (? in part redistributed Miocene bedrock).
39ft. 4in.—40ft. 3in. ...	Very light-grey medium-coarse Miocene bryozoal limestone (Gambier limestone).

ROBE HARBOUR BORES—*continued*

BORE No. 8

Depth	Description
29ft. 3in.—31ft. 6in. ...	Grey medium-grained shelly sand with light-cream pockets.
31ft. 6in.—34ft. 2in. ...	Grey speckled fine-medium shelly sand.
34ft. 2in.—34ft. 9in. ...	Dark-grey heavy clay; with small gastropods. *Lenameria pectorosa* (F.W.), *Cardium racketti* (F.S.-Est.), *Tatea rufilabris* (S.L.), *Sphaeronova tatearae* (F.W.).
34ft. 9in.—35ft. 4in. ...	As above; with *Cardium racketti* (F.S.-Est.) abundant. Also *Anapella adelaidae* (Est.), *Ostrea sinuata* (Est.-R.), *Diaphoromactra versicolor* (S.L.).
35ft. 4in.—36ft. 6in. ...	Light-grey medium calcareous clay (marl); with a few shells. *Lenameria pectorosa* (F.W.).
36ft. 6in.—37ft. 3in. ...	Grey marl; with few shells. *Planorbis isingi* (F.W.), *Lenameria pectorosa* (F.W.).
37ft. 3in.—37ft. 5in. ...	Dark-grey marly clay; with few shells.
37ft. 5in.—38ft.	Light-grey and grey clay; with 2-in. rock bar or pebble (calcareous) at base.
38ft.—38ft. 7in.	Light-grey calcareous sandy clay; with fine broken shell fragments. *Zeacumantus diemenensis* (Est.), *Katelysia* (?) *scalarina* (F.S.-Est.).
38ft. 7in.—40ft.	Light greenish-grey clay; with small amount of shell matter increasing towards the base. *Austrocochlea adelaidae* (R.).
40ft.—42ft.............	Light greenish-grey clay; with included coarse shell-sand fraction. *Phasianella angasi* (R.), *Isoclanculus yatesi* (R.).
42ft.—44ft. 3in.	Miocene bryozoal limestone, decomposed and clayey towards the top.

BORE No. 10

27ft.—28ft. 8in.	Grey fine sand; with very little shell sand.
28ft. 8in.—29ft.	Sandy shell bed.
29ft.—31ft. 1in.	Speckled grey (? organic) calcareous fine sand.
31ft. 1in.—31ft. 10in. ..	Dark-grey mud; with little shell. *Cardium racketti* (F.S.-Est.).
31ft. 10in.—32ft. 3in. ..	Shelly dark-grey muds. *Cardium racketti* (F.S.-Est.), *Anapella adelaidae* (Est.).
32ft. 3in.—35ft.	Grey to light-grey marl; with a few small gastropods. *Coxiella filosa* (S.L.).
35ft.—35ft. 2in.	Grey travertine band. *Coxiella filosa* (S.L.).
35ft. 2in.—36ft. 4in. ...	Grey becoming light-grey very calcareous sand; with few shells. *Zeacumantus diemenensis* (Est.).
36ft. 4in.—38ft. 3in. ...	Grey to light greenish-grey clay; with coarse shell-sand fraction. Few complete shells. *Katelysia scalarina* (F.S.-Est.), *Bellastraea squamifera* (R.), *Isoclanculus dunkeri* (R.).
38ft. 3in.—39ft. 6in. ...	Miocene bryozoal limestone.

BORE No. 21

6ft.—9ft..............	Light-grey, with pockets of grey, calcareous fine sand.
9ft.—9ft. 10in.	Grey speckled calcareous sand; with plentiful shells. *Katelysia scalarina* (F.S.-Est.).
9ft. 10in.—16ft. 7in. ...	Grey speckled medium-fine calcareous sand.
16ft. 7in.—17ft. 6in. ...	Grey to dark-grey slightly sandy clay.
17ft. 6in.—18ft. 3in. ...	Dark-grey heavy clay; with prolific shells. *Cardium racketti* (F.S.-Est.), *Ostrea sinuata* (Est.-R.).
18ft. 3in.—20ft. 1in. ...	Very dark-grey heavy clay; with infrequent shells. *Corbiculina angasi* (F.W.), *Tatea rufilabris* (S.L.), *Tellina* sp. (F.S.).
20ft. 1in.—20ft. 4in. ...	Very dark-grey clay; with abundant shells. *Macoma deltoidalis* (Est.), *Katelysia scalarina* (F.S.-Est.), *Zeacumantus diemenensis* (Est.).
20ft. 4in.—22ft.	Grey to light-grey calcareous shell sand, in part lightly consolidated.

The older post-Robe dune sediments were deposited under terrestrial and/or lacustrine conditions probably corresponding in time with the last glacial low sea-level (pre-Flandrian regression of the northern hemisphere). Light-grey and light greenish-grey clayey shell sands and limey clays and some oolitic materials accumulated in the "depressed" areas. The marshy deposits are seamed with travertine indicating recurring dry land conditions sufficiently prolonged to allow soil profile development. The shell-sand fractions present in some clayey horizons were probably derived from the Robe dune. In lower situations this dominantly

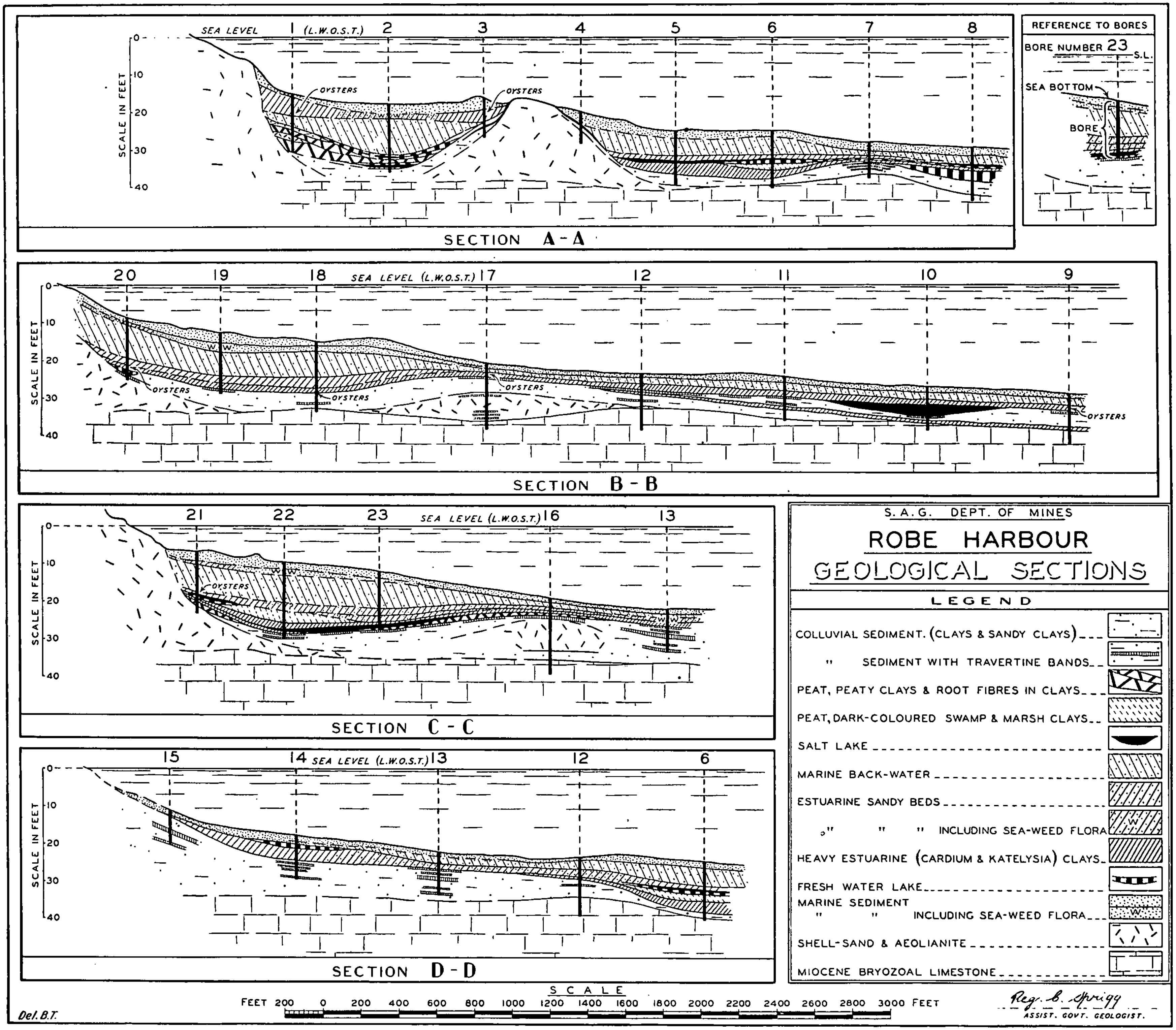


Fig. 20

To face page 68]

terrestrial period was closed by one in which brownish peat formed in a series of minor lakes. Following this period of peat formation, the sea-level rose considerably and brought into play an alternation of marine, lacustrine, and terrestrial conditions resulting in the deposition of marine, salt lake, fresh-water, and terrestrial sediments in many places interfingering with one another in a very narrow vertical range (*see* bores Nos. 1, 2, 6, 8, 10, and 21). In most cases the marine subfossils occurring in these sediments are identical with modern species living locally, and only in one or two instances do unusual variants occur. The oldest marine deposits in this complex are strongly estuarine in character and reflect the presence of reefs to the seaward. Heavy black organic muds carrying massed populations of *Cardium racketti, Katelysia scalarina* predominate, and in favourable situations, oysters (*Ostrea sinuata*) are present. The relative sea-level rise which produced these deposits was more than 20ft. in excess of the Robe dune sea-level. ("Robe dune" sea-level was approximately 40ft. below modern L.W.O.S.T. at Robe).

Following this higher sea-level phase there was a definite marine recession with the sea retreating completely from the area for a short period, marked locally by the development of salt lakes which gave way later to fresh-water lakes and then to swamps even in the lowest situations. The fall is estimated to be of the order of *at least* 16ft. (*i.e.,* to 36 or more feet below L.W.O.S.T. Robe).

The sea-level subsequently again rose ushering in yet another period of salt lake conditions, which gradually became more estuarine in character and ultimately changed through the environment of the marine backwater to open marine conditions. This transformation could have resulted, to some extent, from local breaching of the Robe aeolianite dune.

The youngest sediments, those of the modern sea floor, are grey sands containing molluscs of the *Mactra australis, M. polita,* and *Cardium racketti* suite. They were almost certainly deposited during the period of beach ridging in which Guichen Bay coastal dunes were formed.

In fig. 21 an attempt has been made to show sea-level trends from the bore information plotted against (relative) time. The graphs so produced are based on the assumption that the sedimentary environmental series—terrestrial, fresh-water lake, salt lake, estuarine, marine backwater, open marine water—reflect a progressively rising sea-level. In each case there is evidence to show that following the last glacial low sea-level (pre-Flandrian regression) the sea-level advanced (the Anadara high sea-level), retreated slightly, and then re-advanced to about its present level (the "Osborne" and modern high sea-levels).

PALAEOECOLOGY OF THE STRANDED SEA BEACHES

Several hundred samples from marine subfossil beds have now been collected from the stranded sea beach system. Crocker and Cotton (1946) systematized their sampling in order to obtain a better idea of the marine ecology of the area, and their methods were adopted by the writer as routine procedure. The authors listed the subfossil suites and interpreted their environmental associations (the environment of estuarine, fine sandy beach, etc.) by reference to modern coastal conditions. The time interpretation, however, is not so simple, as the dunes, at least as far back as the Reedy Creek beach, have each been partially or wholly submerged several times by subsequent high sea-levels, and the suites, in many cases are younger than the dunes on which they are found. For example, the Woakwine Range near Robe has been flooded three times since its original development and great caution is necessary in determining the relative ages of random marine fossil suites associated with it. In this case one would expect the original Woakwine beach shells to be strictly of the "open ocean sand beach", but the later high sea-level deposits on the consolidated dune contain reef types. In the lee of the dune (to the east), the subsequent fossil suites would show varying effects

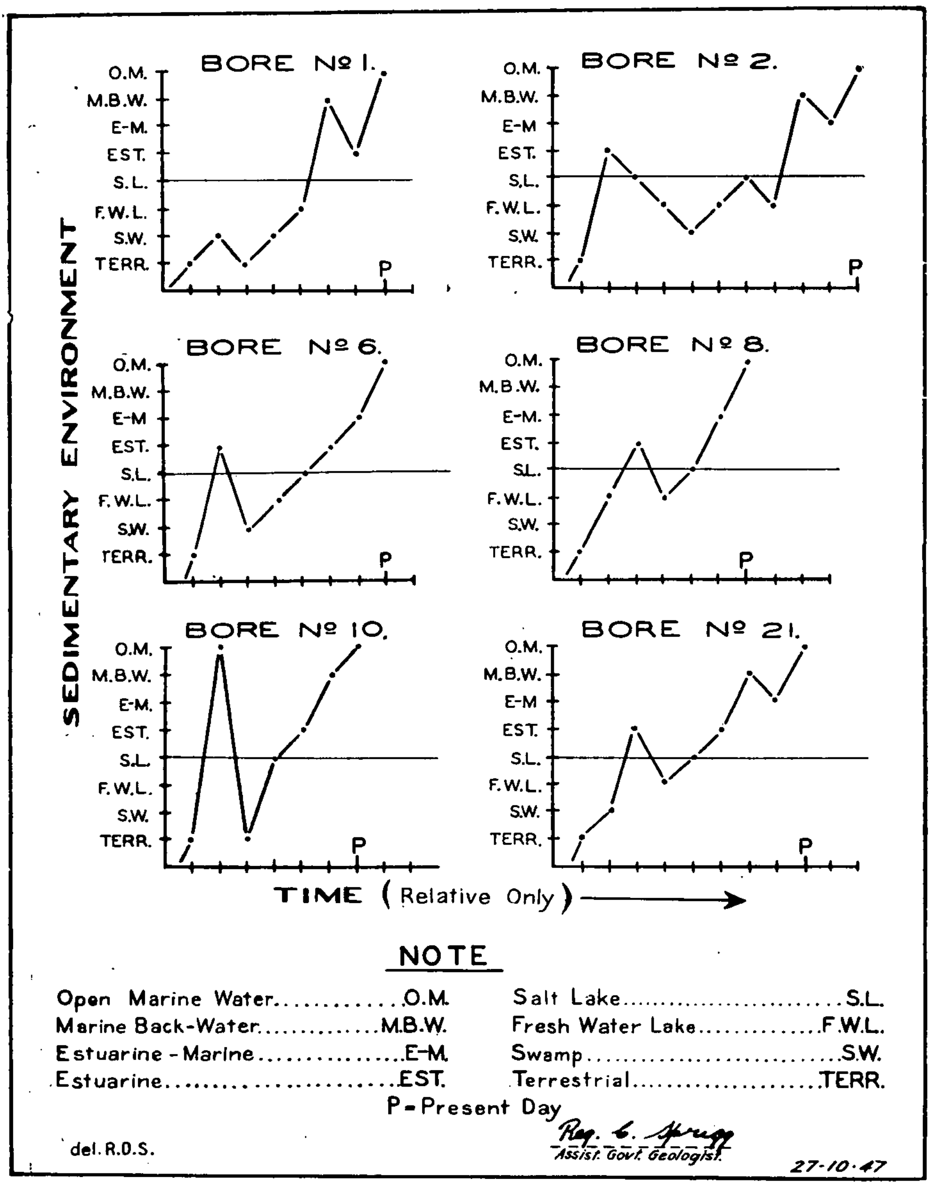


Fig. 21—Sea-level trends as interpreted from submarine boreholes—Robe Harbour

of the degree of shelter or coastal protection offered. Actually the Woakwine "truncation" high sea-level deposits (Stages W.2 and W.3) are superb reef types in which *Haliotis, Turbo, Brachyodontes,* etc., dominate, and the later *Anadara* subfossil faunas, occurring at the surface in the lee of the dune, are typical of warm tidal flats or shallow estuarine waters.

The earlier misconception is largely based on the difficulty of understanding estuarine conditions in the South-East in the absence of evidence of ancient streams associated with the old shore-lines. It is now obvious that estuarine conditions were brought about simply by the flooding of interdune corridors. The estuarine deposits are, therefore, younger than *both* their enclosing aeolianite ranges.

THE ANADARA PROBLEM

The climatic significance of the subfossil *Anadara* (*Arca*) *trapezia* was first appreciated by Howchin (1923). By its restricted habitat and its strict association with typical warm-water faunas it forms an unusually useful marker fossil. Notable for its extreme dominance under favourable ecological conditions its massed remains form prominent deposits around the southern Australian coast in association with a mid-Recent high sea-level.

Recently, Tindale (1933) has correlated the Lake Eliza shell beds and the adjacent Woakwine Range with the Anadara high sea-level but to account for the absence of *Anadara* from the the beds in both these localities he postulated a theory of zonal migration. This theory was subsequently challenged by Crocker and Cotton (1946) who maintained that the absence of *Anadara* from these beds could be due to other factors than climate. The discovery by the author in 1946 (Sprigg 1952) of massed remains of *Anadara* in an estuarine setting in the lee of the Woakwine and Dairy Ranges now clearly demonstrates that the deposition of the *Anadara* beds post-dates the late Pleistocene Woakwine and Robe Ranges but pre-dates the sub-Recent or Holocene Lake Eliza shell banks which are much younger than Tindale supposed.

The Anadara sea thus swamped the Robe, Woakwine, and Dairy Ranges very considerably, and in the Kingston-Rendelsham area the mainland coast stood at the base of the Reedy Creek Range. The Woakwine dune formed an enormously long and narrow promontory, while the other dunes existed as intermittent shoals and island chains. *Katelysia-Chione* shell populations dominated on the seaward aspects of the dunes, while *Anadara-Ostrea* associations choked the mud flats high on the lee of the Woakwine dune and in and behind the Dairy dunes. Drain L, in its cuts through the Woakwine Range to the base of the Reedy Creek Range, provides an excellent illustration of the influence of environment on faunal association. In the lee of the East Dairy Range, for example, solid beds almost exclusively of *Anadara* and oysters, gradually give way over several miles to *Katelysia* dominance. After about 4 miles *Anadara* becomes quite rare and finally cannot be found at all, although the beds are stratigraphically quite continuous. Oysters suffer a rather similar fate although their lateral range is rather more extensive. The Anadara beach in this area extended to at least 30ft. above Robe L.W.O.S.T.

The Anadara sea entered the extensive flats confronting the Reedy Creek Range *via* the Kingston area. Where it rounded the northern extremity of the Woakwine "Peninsula" it developed a long east-west coastline, connecting the Robe "Archipelago" with the Woakwine "Peninsula" which faded out into quieter waters to the east as the Benson Bay bar and hook (fig. 14). This shallow submarine feature gave added protection to waters to the south and favoured the *Anadara* dominance. *Anadara* was also found along this east-west coast in small numbers sufficient to fix the age of the structure beyond doubt.

To the south in the Mt. Gambier area the limits of the Anadara sea are less easily fixed, but its coast almost certainly included the base of the MacDonnell dune range, in which cliffs were developed.

Crocker (1946) relates the Anadara high sea-level to the period of extreme aridity from which much of Australia has only recently emerged. At the height of this aridity all Australian deserts were on the move, and the aeolianite dunes were stripped of their leached siliceous upper soil horizons. On this evidence Crocker placed the aridity as *post*-Woakwine. This conception can also be used to place the age of the Robe Range also as pre-"Anadara" and pre-climatic optimum. In the writer's mind there is little doubt that the Anadara high sea-level and Crocker's "Great Australian Arid Period" equate directly with the climatic optimum of the northern hemisphere when glaciers retreated far beyond their modern limits (*circa* 7-9,000 years ago).

Following the Anadara high sea-level there was a period of marine recession of the order of 60ft. or more, to lower than 36ft. below modern L.W.O.S.T. The exposed shell beds were extensively travertinized in most places, but in other areas (*e.g.*, Guichen Bay) they were covered by peat beds and a variety of terrestrial and lacustrine sediments.

THE HOLOCENE SEA BEACHES AND THE OSBORNE HIGH SEA-LEVEL

Along much of the Australian coast there is evidence of a very recent minor marine recession. Such wide distribution and evenness in effect suggests a negative eustatic movement of sea-level rather than a positive movement of the land.

The actual decline in sea-level was only of the order of a few feet, but in flat subcoastal zones appreciable areas of shell beds have been exposed. The subfossil shell faunas are practically identical with the local living suites although it is probable, on the evidence of glacial eustacy, that the earlier climate might have been very slightly warmer. In the Adelaide area the writer has referred to these subfossil shell deposits as the Osborne sea beach and the stage as the Osborne high sea-level. This latter term is thus used for this very recent minor marine inundation generally.

In the South-East Province, evidence of a slightly higher stand of the sea can be found in most protected subcoastal areas. The Coorong lagoon was essentially a marine arm of the sea and had open connexions with the ocean in the Kingston area (fig. 14). The Coorong outer dune was in existence and comprised a core of aeolianite and a mass of accumulating sand. The shell faunas of the ocean beach were of the *Plebidonax* suite while the lagoonal area had great *Katelysia-Bittium* populations. In the Kingston area a multitude of shallow marine micro-environments were evident and shell faunas varied rapidly from site to site. No widespread equilibrium was reached, and it is concluded that this period of high sea-level was a very short one. The evidence elsewhere in South Australia supports this conclusion.

The Holocene sea beach is present on most of the seaward flats beyond the Woakwine Range, to the corner of the State. At that time Lake Eliza and Lake Bonney were arms of the sea with heavy marginal shell banks (*Ostrea-Katelysia-Brachyodontes* associations) on their eastern margins. The Robe aeolianite dune was temporarily cut off from the land and persisted for a time as an archipelago with deeply eroded islands. Some of these islands, now completely "stranded" can be seen a few miles south of Robe, with their bases surrounded by massive accumulations of *Katelysia, Brachyodontes, Notovola, Bittium,* etc., overlying oyster (*Ostrea sturtiana*) beds (Plate VI). The occurrence of these massive accumulations of essentially unbroken shells on the eastern and northern margins of "Eliza Gulf" indicate a degree of "openness" sufficient to permit the development of large waves which threw the shells into great banks but lacked sufficient power to pound them to shell sand as on the outer more exposed ocean coast.

The close of the Osborne stage seems to have been moderately rapid, the sea returning to about its modern level and commencing the formation of the remarkable "rhythmic" beach ridges which continue to the present.

THE SUBMARINE TOPOGRAPHY OF GUICHEN BAY

Guichen Bay is the sea area lying between Cape Dombey (Robe Peninsula), Long Beach, Cape Thomas, and Baudin Rocks. It has been formed by a marine breaching of the partly drowned Robe aeolianite dune.

A detailed echo-sounding survey of the bay and its approaches was carried out by the Hydrographic Branch of the Royal Australian Navy in the summer seasons of 1946-7. The "fair chart" prepared during this survey was analyzed in accordance with procedure described and modified by Maze (1944) and Sprigg (1945), to determine more precisely the submarine topographic features. The "generalized" contour map (fig. 22) provides a simplified picture of the sea-bottom topography

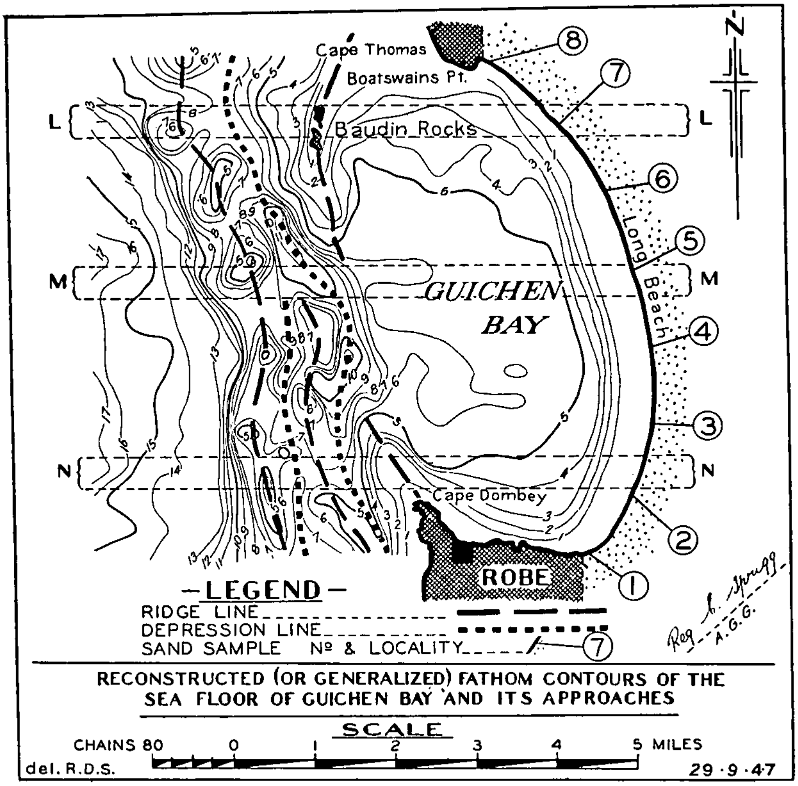
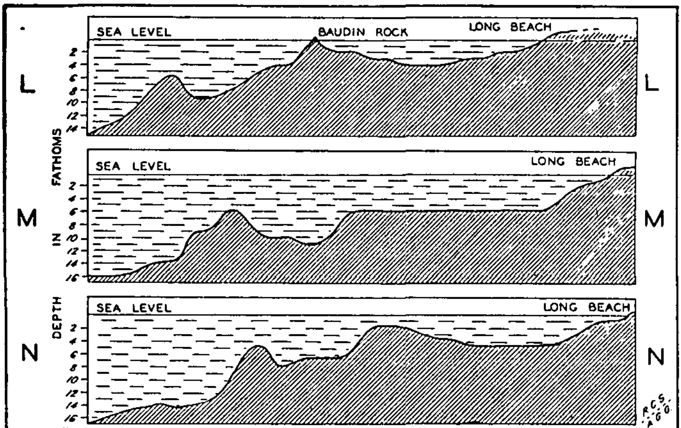


Fig. 22

of the bay. The bay proper is seen to be a broad (sand) flat shallowing gently towards the north and south and less gently eastwards. The area of "flat" lying between 5 fathoms and 6 fathoms (as calculated from the generalized contour plan) is approximately 6 sq. miles as against a total area of about 20 sq. miles. The bay sea-floor is practically nowhere deeper than 7 fathoms, and two prominent landward-trending troughs lying between 6 fathoms and 7 fathoms are fairly obviously related genetically to two relative deeps confronting the bay. Guichen Bay floor is, therefore, a surface of erosion and deposition in equilibrium with modern sea-level. Where deeper water confronts the bay relative scouring occurs and to the lee of shallows or of headlands there is a degree of "relative" deposition. (The term "relative" is used as it is obvious that deposition and erosion are not continually occurring, but that a state of "near equilibrium" is maintained.)

Oceanwards from Guichen Bay the immediate sea-bottom topography is controlled by submerged portions of the Robe aeolianite dune remnant. The strong axial alignment of the structure (note the ridge and depression lines) is apparent and the width exceeds 2 miles. The sea-bottom topography conforms closely with that of the original dune, and subsequent marine erosion and deposition have only modified to a minor degree its original outline. There were at least two major ridges and perhaps three, with corresponding inter-ridge troughs. The innermost ridge as it is today has extreme expression in Cape Dombey and Baudin Rocks, while the outer one forms shoals of rarely less than 5 fathoms. The troughs only occasionally exceed 13 fathoms in depth.



STRIP "HIGH POINT" PROFILES ACROSS GUICHEN BAY AND ITS APPROACHES

Fig. 23

Beyond the line of the submerged dune range the sea floor is relatively flat to the edge of the surveyed area, shelving gently from 17 or 18 fathoms to about 15 fathoms at the submerged toe (?) of the consolidated dune range. Bottom grade in this zone averages about 15ft. per mile.

Strip high-point profiles are shown in fig. 23. Profile LL, passing through Baudin Rocks, shows the form of the dune range and the degree of shallowing in the lee of the rocks. This shoaling is a reflection of the protection offered by the rocks from rough seas in this vicinity. Profile MM, passing more or less centrally through the bay, gives a somewhat exaggerated view of the flatness of the broad sand sheet noted previously. It also shows the trough and ridge structure

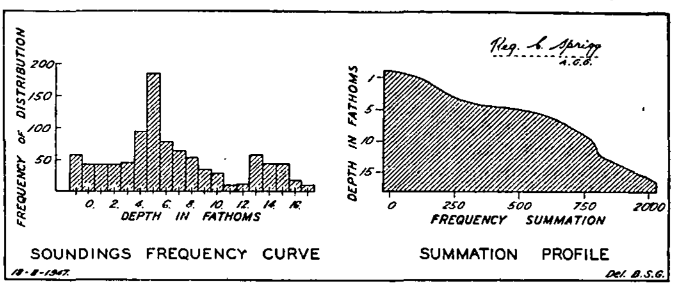


Fig. 24—Soundings frequency curve and summation profile—Guichen Bay

of the submerged dune range and the gently sloping sea-bed confronting the dune. The most southerly strip profile (NN) immediately north of Cape Dombey, is essentially similar to that of the northern strip (LL) except that more of the fore-dune sea-floor is included.

Frequency curves of soundings and a summation profile are also shown on fig. 24. These illustrations show the presence of level surfaces between 5 fathoms and 6 fathoms, and to a much smaller degree at 12 fathoms to 13 fathoms.

Of particular interest in these investigations is the obvious relation (within the bay proper) of "depth" to "protection" offered from ocean swell and waves. Where headlands or relative shallows confront the bay, shallower water occurs to leeward, but landwards of deeps and troughs there is deeper water. As the bay bottom is almost wholly sandy these relative shallows and deeps must reflect the power of oncoming waves and swell to erode or deposit material in the most favourable locations. The erosion surface at about 12 fathoms to 13 fathoms corresponds approximately with the lower inter-ridge depression level (10-11 fathoms) and may correspond with the original Robe strand level.

THE GLENELG AND MURRAY RIVERS

Although these rivers lie almost wholly outside the South-East Province, discussion would be incomplete without mention of them, as they have been influenced considerably by oscillating Quaternary sea-level. The rivers have much in common in that they are sluggish in their lower reaches and possess deep gorges eroded largely in soft Tertiary or later sediments. Both have suffered repeated alternate grafting and betrunking coincident with sea-level changes.

Glenelg River

This river which drains the extreme western portions of Victoria has its head-waters amongst broad expanses of Jurassic sediments and inliers of Palaeozoic igneous and metamorphic rocks in the Dundas highlands. Its upper reaches beyond the Kanawinka Fault (near Casterton) have undergone little change since Pliocene times, whereas the lower reaches have been modified repeatedly by successive advances and retreats of Quaternary sea-level.

Late Pliocene and earliest Pleistocene coasts followed the Kanawinka Fault faithfully and developed cliffs in it for much of its length. Subsequent coasts, however, were stranded successively farther west and the second Pleistocene sea beach came to skirt and include the volcanic area to the southwest. To accommodate this coastal migration, the Glenelg River was engrafted markedly and its course wandered along the back of the embryo Gambier upwarp, generally with a dominantly south-south-west trend. On two occasions it deflected to the north-west to reach the sea in the great Penola Bay (fig. 17). Portions of these older courses are still obvious as depressed lines and alluvial deposits and the younger of the two can be followed west-north-west to Dismal Swamp. It is not known for how long these westerly outlets persisted, but "channel" flow was later reversed in the Dismal Swamp area (Wood recorded significant currents on these swamps towards the modern Glenelg River). The reversal of flow is thought to have occurred after Mt. Burr volcanic activity had diminished or ceased, when regional upwarping along the Gambier axis had begun to assert itself.

In later stages the river entered the sea at various intervals along its present course depending upon the stage of marine retreat. Successive coastal dunes interfered with respective outlets and caused some major subcoastal deviations of the river's course. Faulting in Victoria (Boutakoff 1949) also influenced its development. The major engraftings consequent to the low sea-levels of the glacial period are now lost beneath subsequent deposits and the modern "inter-glacial" high sea-level. The present bed of the river in the lower gorge has been eroded far below modern base level, and river depths of 90ft. are known in the lower few miles.

River Murray

The Murray is Australia's longest river and the most sluggish large river in the world. From the Victorian border to the sea its natural fall is only 60ft. and from Wentworth to its mouth, a distance of 617 miles, its fall is never more than 3in. per mile. In the South Australian section its bed frequently lies more than 50ft. below sea-level—a fact which cannot be accounted for merely by current erosion in view of its general sluggishness.

In this investigation interest is mainly concerned with the lower reaches of the river where it has eroded its bed successively through a veneer of lacustrine and other terrestrial sediments, through Tertiary oyster beds, marine calcareous sandstones and fluviatile sediments, and finally into granite bedrock. As in the case of the mouth of the Glenelg River the River Murray bed is now well below sea-level over most of its length in South Australia, reaching 100ft. in some places. At Murray Bridge the river has eroded to granite at depths more than 120ft. below sea-level and erosion of hard bars of this type (with formation of granite gravels) implies a much lower erosion base level than that ruling at present. The answer to the necessary sea-level lowering is supplied largely by the theory of Pleistocene glacial eustacy, but a downwarp factor, which is discussed later, was also important.

Elsewhere in the world it has been found that changes in sea-level are frequently best reflected in the lower courses of large rivers. Fluctuations of base level cause successive erosion and deposition by both fluviatile and marine agencies to form thalassostatic terraces in the lower reaches of rivers. Unfortunately practically no information is available in the most favourable locations of the Murray River, but bores on the river flats, and cliff outcrops are informative.

During various investigations connected with the building of railway bridges at Murray Bridge, three lines of bores were sunk and a correlation of the bore data is shown on figs. 25 and 26. Doubtful estuarine or marine fossils are recorded in some very incomplete bore logs (Section A), but there is evidence of an excellent series of aggradational sediments all apparently related to the one pronounced sea-level rise following the last glacial period. The bore information also indicates that when base level was lowered by about 40ft. or more, the increased erosive power of the river (related to pluviality of the glacial period and to locally increased channel gradients) produced large suites of gravels from local and upstream sources. Later as the sea-level rose, and as the extreme cataract conditions over the granite bars were relieved, sand was deposited, grading above into silts and clays. During the deposition of the clays a restricted period of peat formation intervened producing beds several feet in thickness at levels now between 20ft. and 40ft. below modern sea-level. The increasing fineness of the sediments deposited in the valley is interpreted in part as being due to progressive decrease in rainfall (and snowfall in the Kosciusko region) since the height of the last glacial and also to rising base level. The peat bogs *may* indicate a restricted cold phase during the retreat of glaciation temporarily staying the rise in sea-level.

As evidence of higher sea-level stands, in the cliff sections of the river at Murray Bridge, Cotton (1935) has noted the occurrence of the carinate freshwater gastropod *Notopala wanjakalda* at levels considerably in excess of modern flood level. He argues that this form which is now extinct is a water's edge dweller, and as such, its remains *in situ* provide excellent evidence of former high river levels, for example at 50ft. and 60ft. at Sunnyside (Cotton 1935) and at 90ft. at Swan Reach (Sprigg unpublished, Tate Excursion report 1937). Tindale (1947) correlated these occurrences with the Reedy Creek beach on the basis of altitude measurements, but unfortunately made no allowance for regional landwarping.

The occurrence of *Ostrea arenicola* near cliff tops (90ft. to 120ft. above sea-level) which has been noted previously, also indicates former (Late Tertiary) high sea-level stands. They occur from Swan Reach to Murray Bridge. It is to be noted also that *Anadara* beds occur near the River Muray mouth indicating that the lakes there must have been strongly estuarine during the Pleistocene period.

The structure and stratigraphy of the lower Murray gorge like that of the Glenelg River, clearly reveals the extent of Quaternary sea-level oscillation. In particular, low sea-levels 120ft. or more below modern datum must have occurred to explain the deep erosion of the beds of the two rivers.

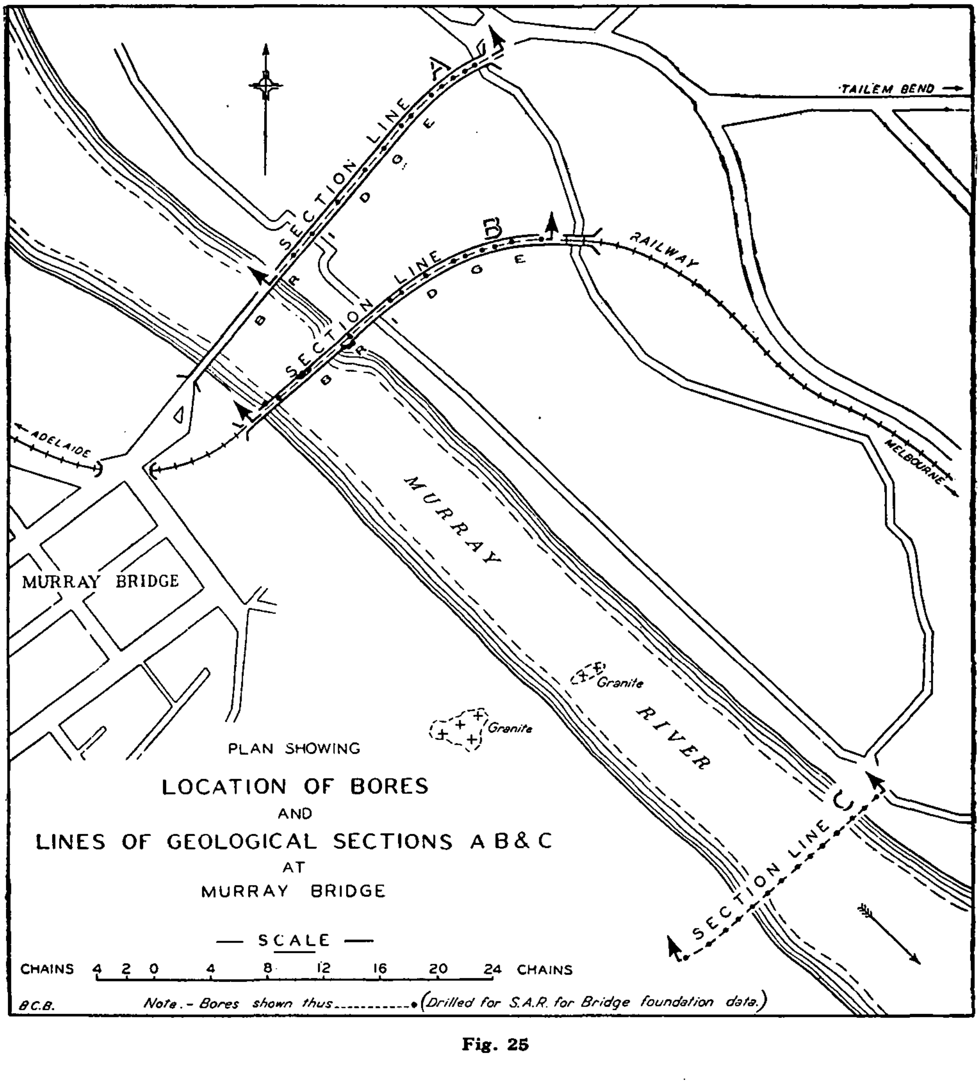

SECTION LINE A
SECTION LINE B
SECTION LINE C
BRIDGE
BRIDGE
RAILWAY
TAILEM BEND
ADELAIDE
MELBOURNE
MURRAY BRIDGE
MURRAY
RIVER
Granite
Granite
PLAN SHOWING
LOCATION OF BORES
AND
LINES OF GEOLOGICAL SECTIONS A B & C
AT
MURRAY BRIDGE
— SCALE —
CHAINS 4 2 0 4 8 12 16 20 24 CHAINS
B.C.B.
Note.- Bores shown thus (Drilled for S.A.R. for Bridge foundation data.)

Fig. 25

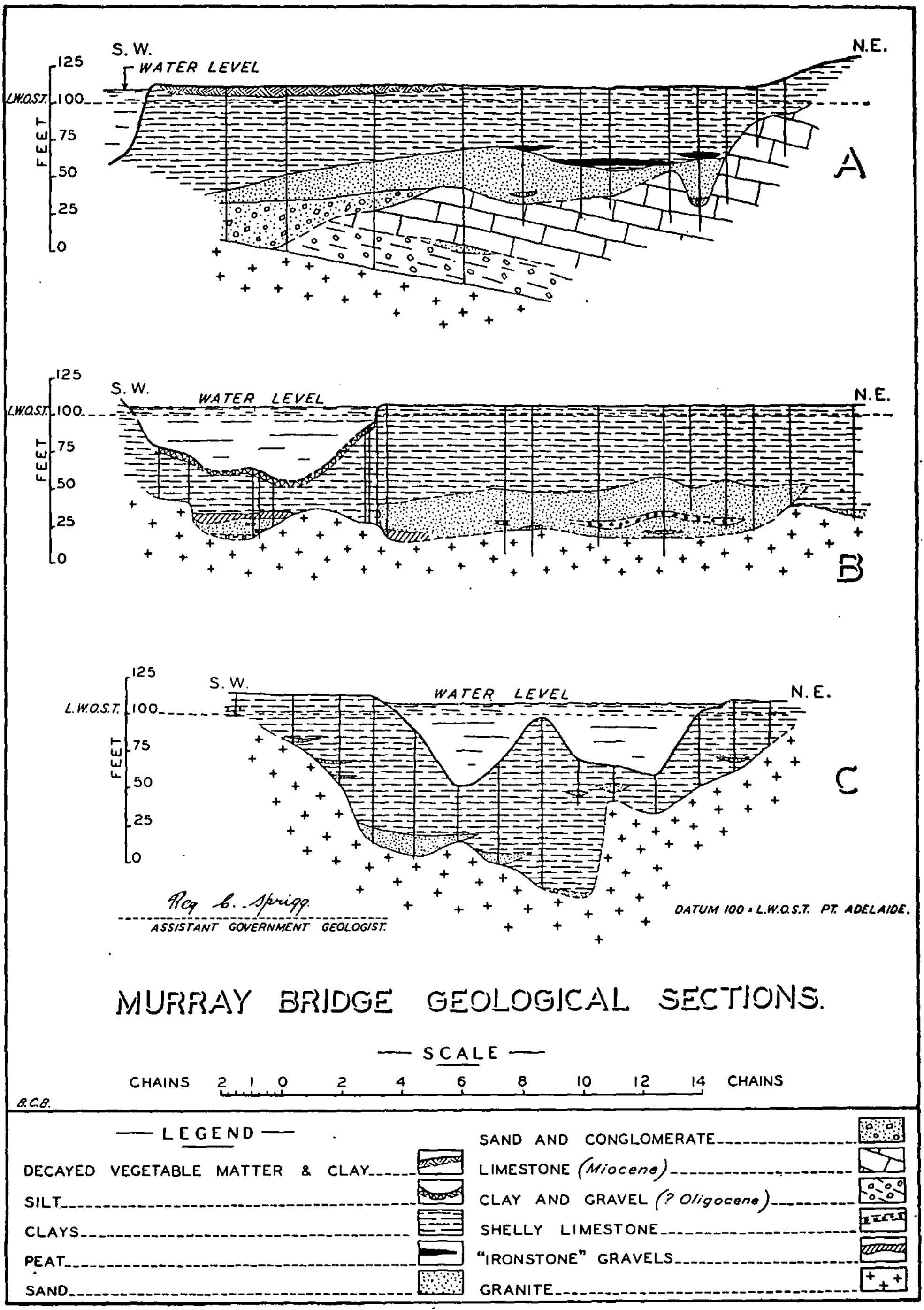

S. W.
N.E.
WATER LEVEL
L.W.O.S.T.
125
100
75
50
25
0
FEET
A
B
C
Reg. C. Sprigg
ASSISTANT GOVERNMENT GEOLOGIST.
DATUM 100 = L.W.O.S.T. PT. ADELAIDE.
MURRAY BRIDGE GEOLOGICAL SECTIONS.
SCALE
CHAINS 2 1 0 2 4 6 8 10 12 14 CHAINS
B.C.B.
LEGEND
DECAYED VEGETABLE MATTER & CLAY
SILT
CLAYS
PEAT
SAND
SAND AND CONGLOMERATE
LIMESTONE (Miocene)
CLAY AND GRAVEL (? Oligocene)
SHELLY LIMESTONE
"IRONSTONE" GRAVELS
GRANITE

Fig. 26

CHAPTER IX

MODERN BEACH STUDIES AND SAND COMMUNITIES OF THE SOUTH-EAST COAST

A beach may be defined as the zone extending from low tide level to the upper or landward limit of effective wave action. The upper levels of the beach are covered only during periods of storm, particularly where the latter coincide with high spring tides.

The terminology applied to various zones of the beach profile is presented in fig. 27 (U.S. Beach Erosion Board 1933). "Berms" are defined as small impermanent terrace structures formed by erosion or deposition during storms; "Plunge point" is the zone where waves break and its location depends upon height of the waves and the state of the tide; "Upper strand line" is the variable zone of deposition of coarse debris during high tides and storms. Its position is largely coincident with the backshore. It is to be noted that the slope of a beach is determined to a large degree by the texture of its sediments, but the extent of the beach depends upon the tide range.

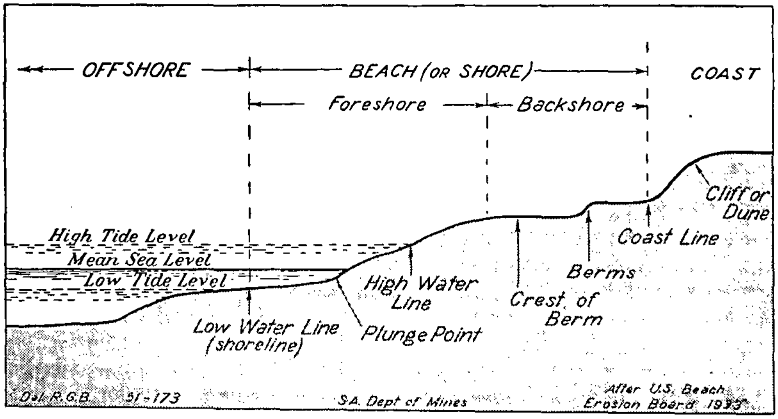


Fig. 27—Beach terminology diagram

Where beach structures have been measured along the southeast coast, altitudinal figures are related as closely as possible to low-tide level; where marine erosion benches were surveyed by officers of the South Australian Harbors Board, levels were related to L.W.O.S.T. on the Robe tide gauge. The tide range along the South-East open ocean beaches averages approximately 4ft.

Systematic sand samples were collected from low tide level, the seaward margin of the upper strand zone and from the fore-slope of the main coastal dunes. Where there were complex beach structures more samples were taken, and their positions indicated on sketches. Also some beach sands showed definite (but impermanent) double layering and in these cases representative samples of each layer were collected. Offshore bars and troughs were not investigated and the only sea-floor samples collected were those from the Robe Harbour bores.

Sand sampling was by the random grab method. A 2-lb. sample was collected by taking small handfuls to a depth of 3in. or 4in. at intervals over an area of about 50 sq. ft. along the particular zone. One portion was submitted to sieving analysis (I.G.M. standard) to determine grain-size distribution, and another to treatment with hydrochloric acid to determine insolubles. The grain-size distribution data were analyzed statistically and values which were used to characterize the sediments, were obtained directly from cumulative or simple frequency curves. The "mode," for example, is the peak of the simple frequency distribution curve, and the "modal diameter" is that which occurs most frequently in the distribution. The latter indicates the most abundant and, therefore, the most typical particle of that sample. "Sorting coefficient" (S_0) is a measure of the degree of sorting, and is calculated from the following formula:

$$S_0 = \frac{Q_3}{Q_1}$$

where Q_1 and Q_3 are the first and third quartile diameters*.

The value S_0 approaches unity as the material becomes more uniform in grain size. It has been found (Trask, 1932) that values of S_0 less than 2·5 indicate a well-sorted material, whereas when value S_0 exceeds 4·5 the sediment is considered poorly sorted. Beach sands of the southeast coast on this basis are relatively well sorted.

"Skewness" (S_k) is a measure of the asymmetry of grain-size distribution about the median diameter and is given by the following equation:

$$S_k = \frac{Q_1 \cdot Q_3}{M_2}$$

where M_2 is the median diameter.

Where the size-frequency distribution is symmetrical the value of S_k is unity. Values may range from less than, to greater than one, indicating that skewness is either towards the finer or coarser sizes.

In the following discussion two major beach environment categories are assumed. The first is that of the open ocean beach and the second the sheltered (or "repressed") ocean beach. Between these two extremes there is a complete gradation. In geologically Recent times other coastal environments, including the estuarine, mud flat, and swamp associations, have been important, but these are no longer present.

THE OCEAN BEACH ENVIRONMENT

The ocean coastal sands are cream-white in colour and highly calcareous. Acid-soluble material which is dominantly calcium carbonate averages about 77 per cent. The sands in the main are from the destruction of local shell populations, but there are other more minor sources, which will be referred to later. The sands are typically coarse grained and show a strong tendency to double generations within respective samples. It appears from this latter feature that two erosional and/or depositional controls are at work. The coefficient of sorting varies from 1·02 to 1·67, although most sands fall between 1·3 and 1·5 with an average of about 1·36. The co-efficient of sorting of simple sands or of the individual generations of composite sands is naturally much lower, *i.e.,* they are better sorted.

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* The median and first and third quartile diameters are those at which in an individual sample there is 50, 25 and 75 per cent by weight respectively of particles of smaller diameter.

TABLE I

Ocean Beach Sand Samples

	Sample No.	Location	Percentage soluble in acid	Mode (in inches)	Mode percentage§	Modal ratio	S_0	Sk
Coorong	27	H.T.L.	66·5	0·0200	3·5	—	1·30	1·00
	33‡	"		{0·0090	9·5	2·33	1·50	0·90
				0·021}	15			
	34‡	"		{0·0090	9	2·33	1·51	0·92
				0·021}	16	2·00		
	39‡	"		{0·0075	19	2·40	1·26	1·01
				0·018}	3·5			
	43‡	"	78·0	{0·0095	13·5	2·16	1·41	1·04
				0·0205}	13			
	45*‡	"	64·8	{0·0105	22	1·77	1·30	1·10
				0·0185}	10			
	48*‡	"	85·2	{0·0083	11	2·53	1·58	1·03
				0·021}	12			
	26	L.T.L.	64·9	0·0280	15	—	1·02	1·04
	35‡	"		{0·0073	15	2·95	1·63	0·94
				0·0215}	13			
	37	"		0·0038	26·5	—	1·21	1·00
	38‡	"		{0·0083	6·5	2·82	1·57	0·92
				0·023}	12			
	41	"	71·2	0·0072	13	—	1·43	0·95
	42‡	"	75·6	{0·0100	12·5	1·90	1·43	1·01
				0·019}	14·5			
	47	"	88·3	0·0074	20·5	—	1·26	1·02
	29	S.H.	69·2	0·020	23·5	—	1·33	0·91
	30†	"	53·0	0·0045	24·5	—	1·18	1·00
	36‡	"		{0·0078	13	2·37	1·50	0·91
				0·0185}	8			
	40	"	71·1	0·0108	16	—	1·35	0·96
	44	"		0·0106	26	—	1·20	0·99
Cape Lannes ...	21A‡	L.T.L.	90·2	{0·0090	7	2·67	1·44	0·91
				0·024}	17·5			
	21B‡	H.T.L.	87·8	{0·0096	4	2·29	1·30	0·94
				0·022}	20			
	21C‡	S.H.	87·1	{0·0092	8	2·39	1·30	0·96
				0·022}	22	2·39	1·30	0·96
	22‡	H.T.L.	75·0	{0·0082	16	3·05	1·51	1·14
				0·025}	5			
Cape Thomas ..	10	"	70·0	0·0086	40·5	—	1·07	0·99
	11‡	"	79·7	{0·0082	28	2·38	1·17	1·05
				0·0195}	3	2·38	1·17	1·05
Boatswains Point	9‡	"	88·9	{0·0088	28	2·15	1·26	1·15
				0·0190}				

* Samples collected at extra-high strand line at base of beach dunes.

† Sample collected on inland border of complex coastal dune system.

‡ " Composite " sands; modes are given for each " generation ".

§ Percentage at mode corresponding to a class interval of 2.

H.T.L. = High tide level; L.T.L. = Low tide level; S.H. = Fore-slope of beach dune.

S_0 = Sorting coefficient.

Sk = Skewness (*see* text).

TABLE II

LONG BEACH SAND SAMPLES

Sample No.	Location	Percentage soluble in acid	Mode	Mode percentage †	Modal ratio	S_0	Sk
1A*	L.T.L.	77·9	{0·0039 0·0084	10 18	2·15	1·33	0·92
3A*	"	90·3	{0·0050 0·0073	12 13	1·46	1·27	1·02
5A	"	94·3	0·0067	25	—	1·19	1·03
7A*	"	89·1	{0·0050 0·0073	12 14	1·46	1·27	0·99
8A	"	92·5	0·0051	26·5	—	1·20	0·99
1B	H.T.L.	72·1	0·0090	27·5	—	1·16	0·99
2B	"	78·9	0·0072	25·5	—	1·17	0·99
3B	"	83·0	0·0068	26	—	1·16	1·01
4B	"	90·5	0·0063	26	—	1·16	1·04
5B	"	86·4	0·0065	24	—	1·17	1·03
6B*	"	95·4	{0·0058 0·0084	21 10	1·45	1·22	1·03
7B	"	87·7	0·0050	30	—	1·16	0·98
8B	"	82·8	0·0080	21·5	—	1·25	0·94
24	"	81·0	0·0064	26	—	1·29	0·95
1C	S.H.	72·4	0·0076	33·5	—	1·15	0·92
3C*	"	83·0	{0·0082 0·020	33·5 1·5	2·49	1·13	0·97
5C*	"	90·8	{0·0077 0·019	32 1·5	2·47	1·15	0·95
7C	"	72·4	0·0090	40	—	1·14	0·97
51	B.D.	80·7	0·0096	25	—	1·27	0·97
52	"	77·9	0·0052	19	—	1·28	1·02
53	"	68·6	0·0070	22	—	1·24	1·03
54	"	79·9	0·0060	25·5	—	1·20	0·99
81	"	84·4	0·0088	22	—	1·27	0·96
56	S.F.	69·9	0·0045	20·5	—	1·29	1·04

* Composite sands ; modes are given for each " generation ".

† Percentage at mode corresponding to a class interval of 2.

L.T.L. = Low tide level ; H.T.L. = High tide level ; S.H. = Fore-slope of beach dune; B.D. = Beach-ridged dunes ; S.F. = Sand flats behind beach dunes.

S_0 = Sorting coefficient.

Sk = Skewness (*see* text).

The alternate modes of composite sands vary between 0·0073 and 0·0105 and 0·0185 and 0·025 in. respectively. The "modal ratios" of the respective generations of each composite sand vary from 1·77 to 3·05, the average being about 2·4. Judging from the sands analysed there is no consistent rule to indicate which mode is in excess on a percentage basis. Either generation may dominate suggesting that the state of the tide and/or of the ruling wave amplitude at the time of sampling may be most important.

The Skewness factor (asymmetry of the distribution about the median) does not vary greatly between samples and the most extreme cases recorded are only 0·90 and 1·15 respectively.

Additional categories of ocean beach sands occur where there are complex beach structures. For example, in some localities, particularly about the lower tidal reaches, there may be layering of sands with finer sands overlying a more typical coarse sand. Such relationships are probably quite impermanent indicating a temporary decrease in wave intensity. Along the more northern stretches of the Coorong beach there is a notable development of deltoid periodic depositional structures near the upper strand line. Very coarse marine debris (complete shells, cuttle "bones", etc.) is contained within the deltoid structures, whereas between these structures in the equivalent strand line zone, the sand is typically coarse-grained.

Coorong Beach Sands

(Figs. 28 and 29)

Low-Tide Level

These sands are generally less well sorted than associated sands of the high strand line and the sand-hills. The tendency to double generations is strong. Samples taken beyond 10 miles north of Kingston show a slight progressive increase in coarseness to the north with the coarser generation dominant. Complexities are introduced where the beach sands, when sampled, were layered, *e.g.*, at 10 miles and 20 miles north of Kingston. At the south end of the Coorong (King Village) the sand is of the simple generation type, relatively well sorted, but having a much finer mode.

High Strand Line

The strong tendency to double generation development as noted in the low tide samples, is reflected in this zone. The coarser mode is more important in the north, and the finer in the south.

Sand-Hills Fore-Slope

Sorting on the whole is better than in the two previous zones and the tendency to double generation is less marked. As in the high strand zone the tendency to better development of the coarser mode of composite sands to the north is again apparent. Sample No. 30 which was taken from the "C" horizon of a dune, a mile or so inland, is much finer indicating either destruction of the coarse material by prolonged wind traction-abrasion and/or by solution effects accompanying processes of soil formation. It is also much lower in soluble (lime) material and both factors seem to support Crocker's theory of calcareous loess formation from "winnowed" dune lime.

Coorong Beach Sections

(Fig. 30)

King Village

The low tide sample is a simple sand, well sorted and fine grained. That of the high strand line, which is relatively poorly sorted, bears little resemblance to it. A sand-hill sample was not collected as the beach dunes in this area were only very poorly developed.

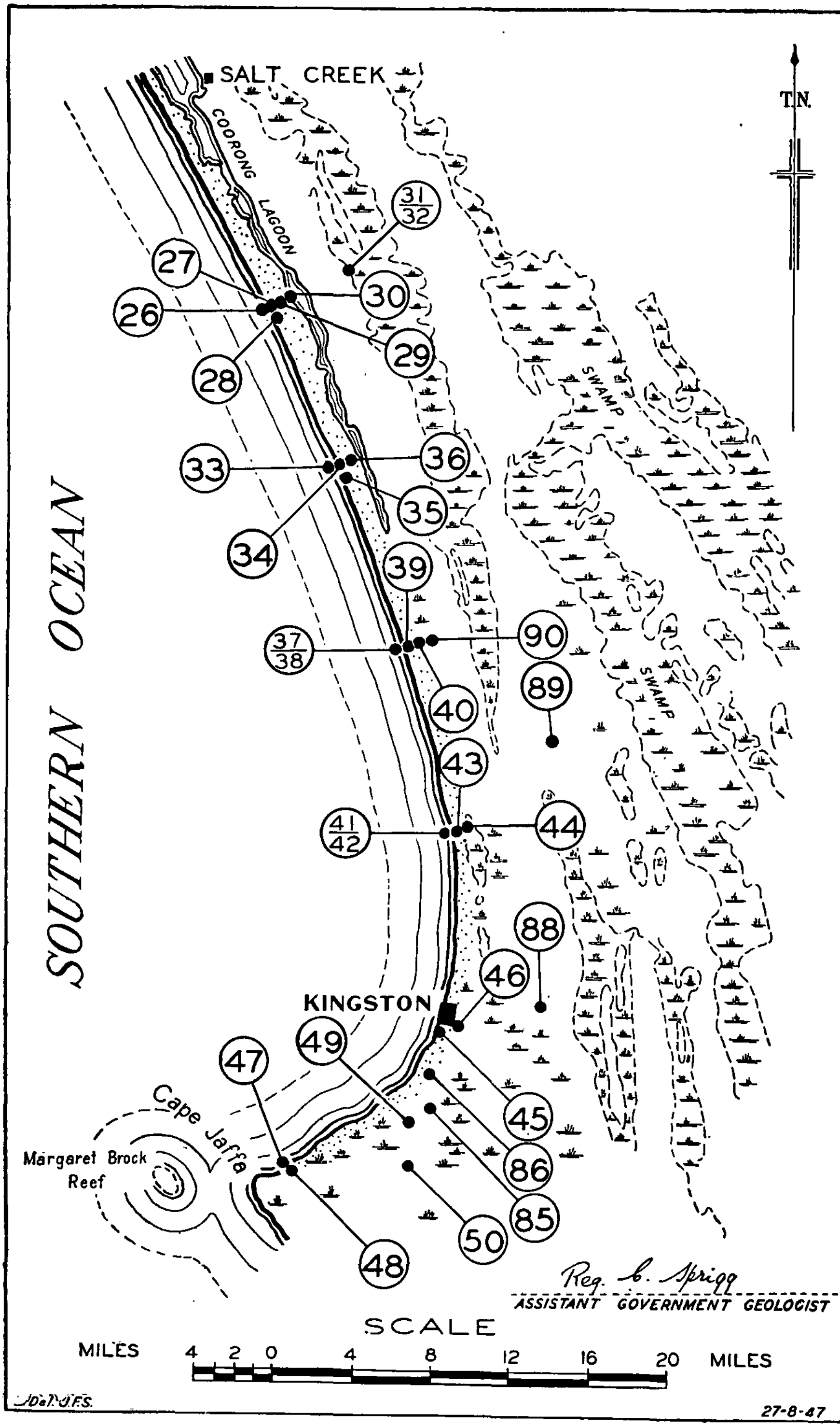

Fig. 28—Location of sand samples—South Coorong area

Kingston

Only the high sea-level sample was taken in this situation as the original dunes have been obliterated by town-site developments and the low tide zone is covered by massive seaweed accumulations.

Ten miles North of Kingston

The sand-hill sands are relatively well sorted, but those of the beach zone are complicated by double generation. The sub-stratum of the low tide zone is very similar to the high strand sample, both being strongly composite with alternate modes almost equally well developed. The overlying sand of the lower beach zone is also composite, but in it the finer constituent is in excess. The coarse mode is very similar to that of the underlying stratum and of the high strand sample, but the alternate mode is finer in the former case.

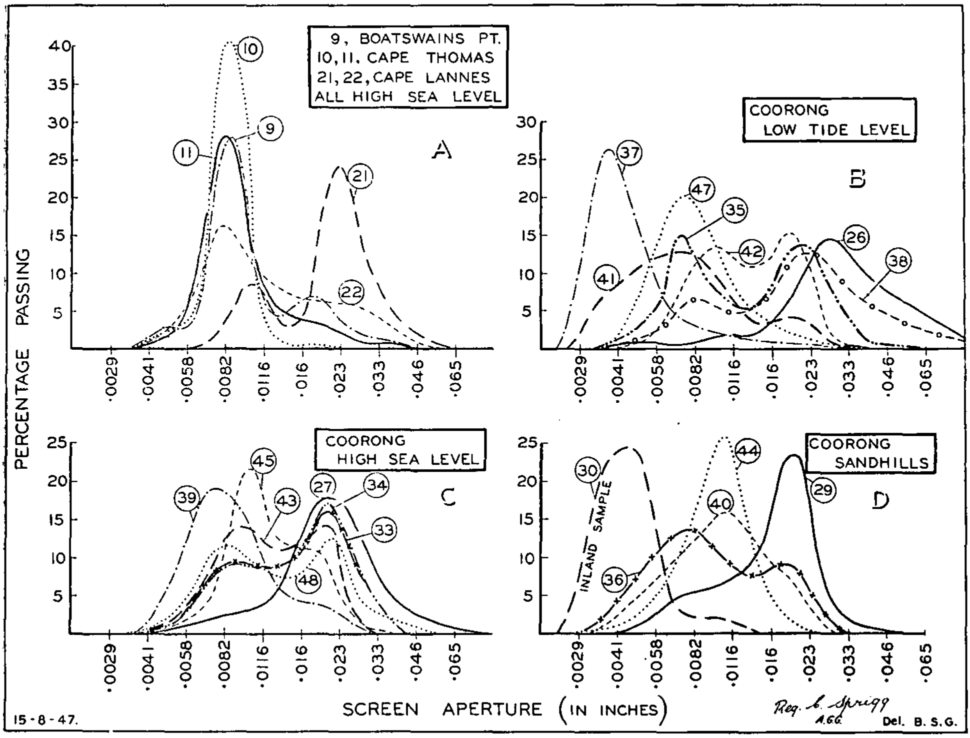

Fig. 29—Sand-sieving analyses for Coorong ocean beach—Shown graphically and illustrating lateral variations in grain size

Twenty miles North of Kingston

All samples are moderately well sorted with tendencies to double and even triple generations in all but the upper stratum of the low tide zone.

Thirty miles North of Kingston

Samples from each zone show similar tendencies, including the development of double generations and modal relations.

Forty miles North of Kingston

The sands are all moderately well sorted and "simple" with relatively coarse modes.

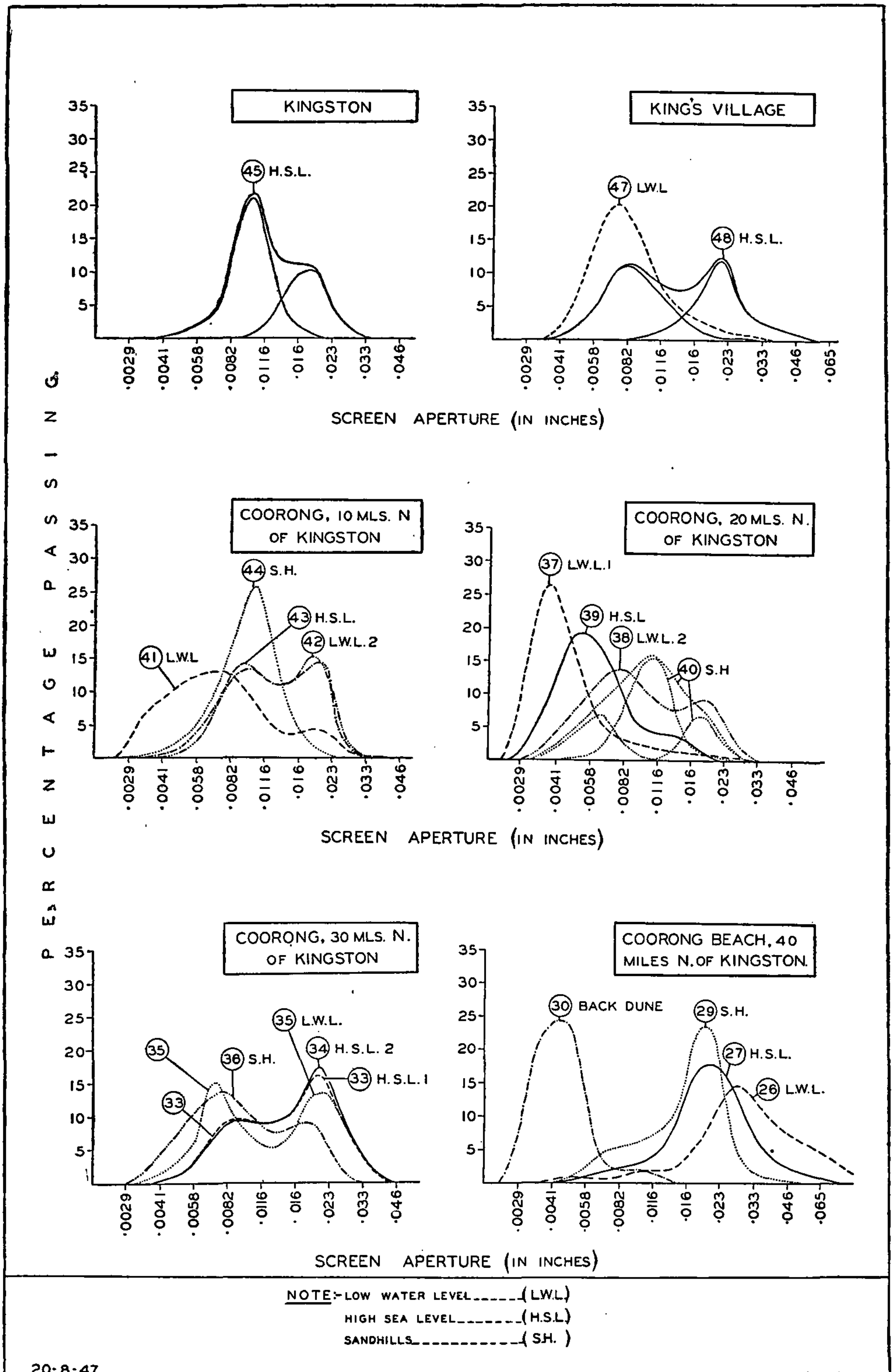

Fig. 30—Sand-sieving analyses for Coorong ocean beach—Shown graphically to illustrate transverse variations in grain size across the beaches

Headlands of Guichen Bay

(Fig. 31)

Cape Lannes

Samples taken in the three principal beach zones show marked similarities. All are composite sands which are only moderately well sorted. The size relationships of the alternative modes are reasonably consistent and the coarser generation in each sample is the better developed.

High Sea-Level Samples of Cape Lannes and Cape Thomas

All are moderate to very well sorted and with the exception of sample No. 10 they are composite. In general the finer generation is most plentiful but sample No. 21 is exceptional.

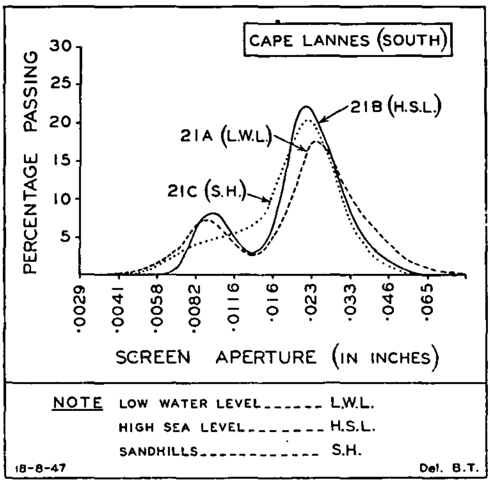

Fig. 31—Graphic analyses of Cape Lannes beach sands

THE SHELTERED OR REPRESSED OCEAN BEACH

(Long Beach, Guichen Bay—Figs. 32 and 33)

Long Beach is an excellent example of the sheltered ocean beach; its sands were sampled at mile intervals. The beach itself is an equilibrium structure in which the overall curvature of the beach is directly controlled by the sheltering influence of its headlands in relation to the ruling wind and wave regimes. Its growth by accretion is now proceeding evenly along the whole of its length.

Compared with the open-ocean beach sands, those of the sheltered beach are more calcareous (averaging 82 per cent $CaCO_3$-$MgCO_3$), finer, much better sorted and, except in the case of the low tide samples, show little tendency to double generation development. The modal ratios of composite sands are generally smaller than in the ocean sand suite.

Low-tide level

On the whole the grain-size distribution curves do not show very large variation. Modal diameters are fairly similar, although the tendency to the development of double generations introduces complexities. The samples are the least well sorted of the sheltered beach suite. There appears to be no significant tendencies as to the relative importance of either alternate generation in the respective composite sands; the sands generally tend to become finer towards the north.

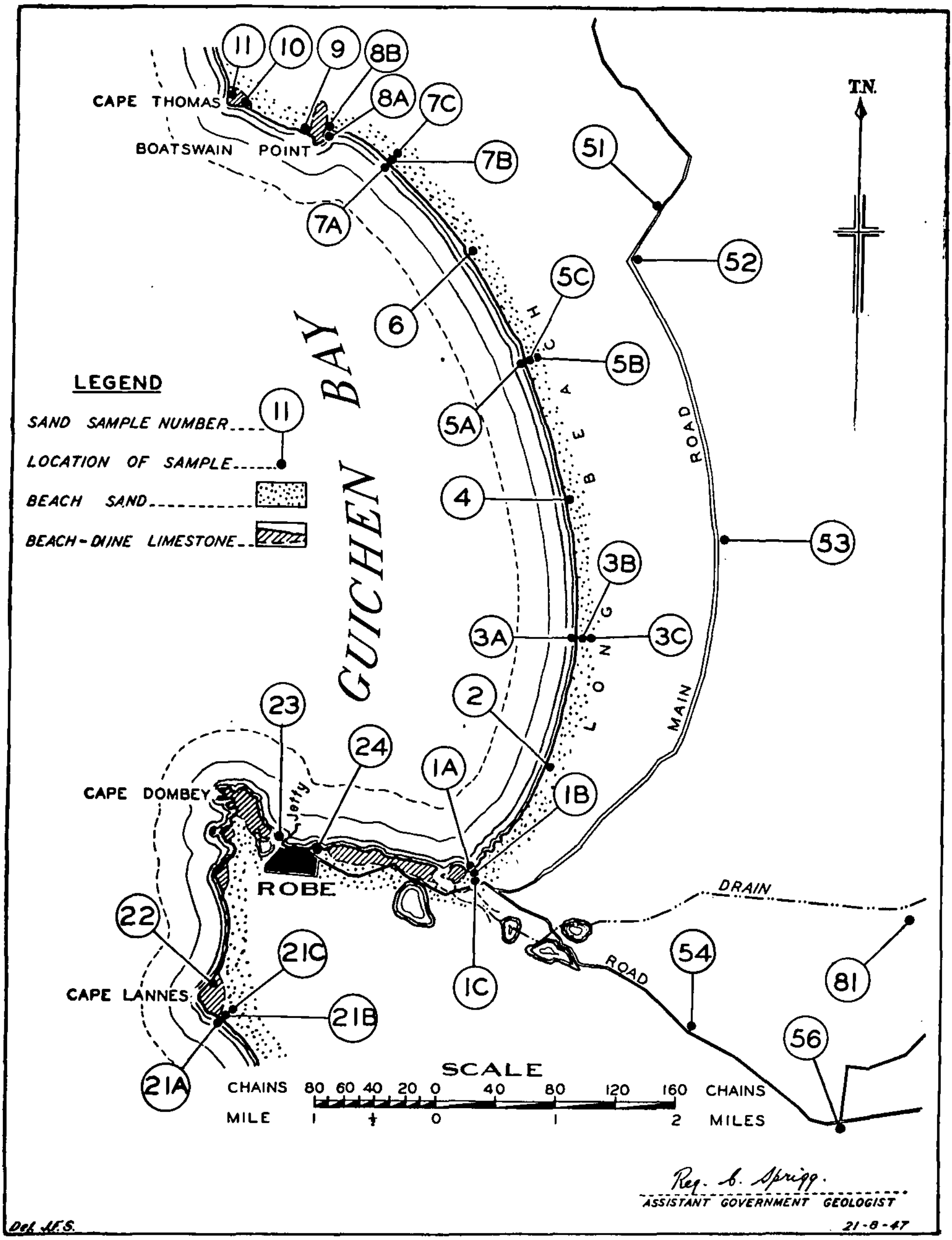

Fig. 32—Location of sand samples—Guichen Bay

High-tide level

The series indicate slight but progressive decrease in mean grain-size north along the beach, and a slight increase in calcareous material in the same direction. In each sample the percentage soluble in acid (mainly $CaCO_3$) increases with the coarseness of the fraction, except in sample No. 1. Thus it appears that this soluble ($CaCO_3$) fraction reflects the general decrease in grain size north along the beach most strongly. It is to be noticed also that the maximum development of soluble material is on the coarser side of the overall sample mode. The

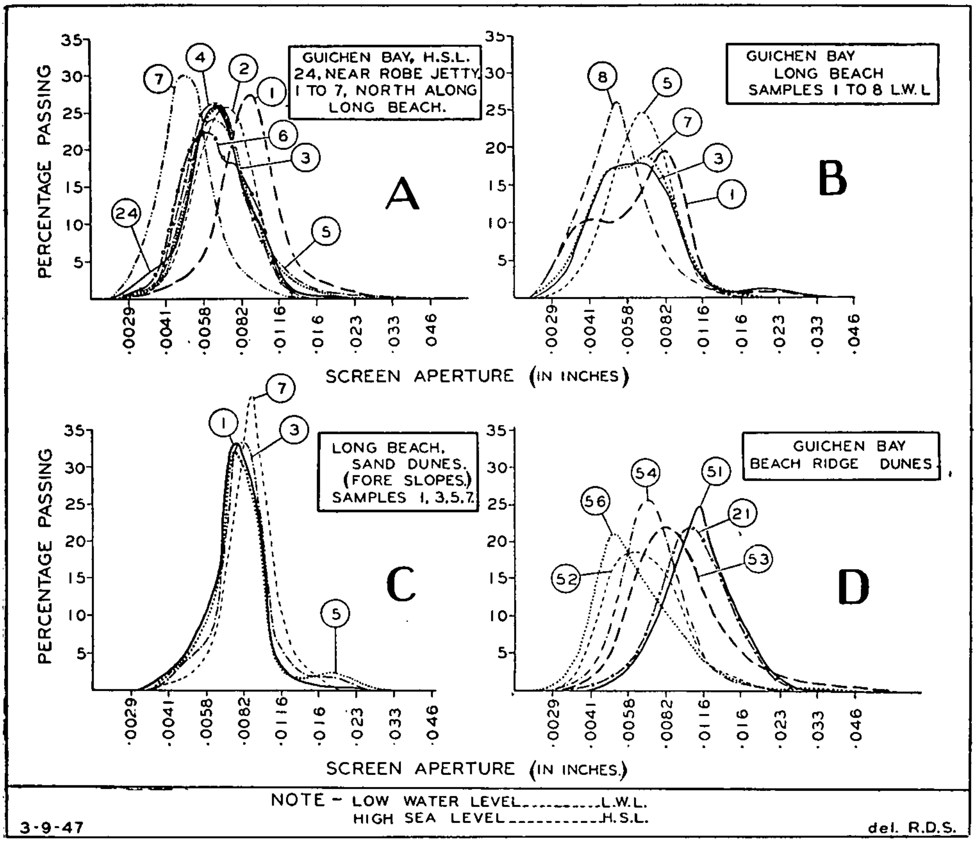

Fig 33—Graphic representation of sand-sieving analyses for sands of the sheltered beach—Showing lateral variations in grain size

soluble portion (chiefly $CaCO_3$) is lighter than the insoluble material (chiefly quartz) and therefore within any particular transporting environment, allowing for the specific gravity and surface area of the individual grains, this relation is to be expected.

A very marked feature of the high-tide level samples is their excellent sorting compared with that of sands of the open-ocean beach environment or of the local low tide zone. There has been double generation formation in only one case.

Sample No. 24 was taken from near the centre of a small beach about ¼ mile east of Robe jetty. Sieving analysis data indicates that it is closely related to sands far removed from the headland influence along Long Beach.

Fore-Slopes of Sand-Hills

Sands of this zone are extraordinarily well sorted, mostly better than those of any other beach group. Some of the sands tend towards double generation, but the secondary group is only very poorly developed. Modal diameters are relatively constant. In the case of sample No. 1 there is a distinct similarity with its equivalent high-tide level sample, whereas to the north there is progressive deviation, the sands of the dune slopes becoming *relatively* coarser. It would appear, therefore, that local wind action acts selectively on the sands of the local beach.

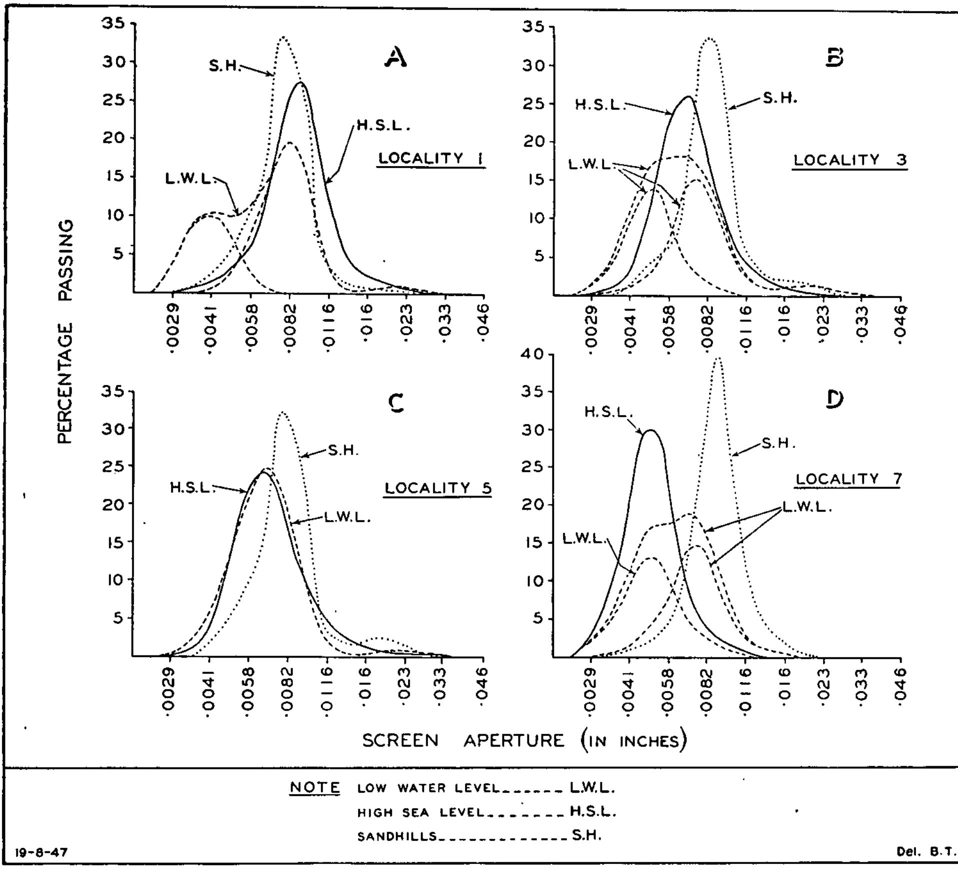

Fig 34—Graphic representation of sand-sieving analyses for sands of the sheltered beach—Showing transverse variations in grain size

Beach Ridged Dunes

The sands sampled of this suite are moderately well sorted, but definitely less so than those of the modern fore-dune slope and of the high strand line. There is no sign of secondary sand generation in any of the samples and the modes are much less regular than in the latest beach dune ridge.

Beach Cross-Sections at Mile Intervals

(Fig. 34)

Although all samples are relatively well sorted, the degree of sorting usually improves up the beach and the general tendency to composite sand formation is lost in this same direction. This is probably because low tide reaches are acted upon by the quieter waters of low tide and the deeper and usually more turbulent waters of high tide whereas high tide level sands are only affected by the latter (and of course, storms). The mode of the coarser generation of the low-tide samples usually approximate more closely the mode of upper beach samples, although sample No. 7 is exceptional in this respect.

SPECIAL BEACH STRUCTURES

The Modern Coorong Beach

This beach is a single unit more than 100 miles in length. For most of this distance it is very slightly concave landwards but towards each extremity it curves strongly oceanwards to link up with its headlands. It is backed by massive irregular sand drift dunes which to the south diminish in size and become beach ridged (fig. 35) at first parallel but then irregularly so between Kingston and Cape Jaffa. As already stated the sands become progressively coarser to the north and contain more calcium carbonate. Beyond 20 miles north of Kingston they also provide a perfect environment for *Plebidonax deltoides,* a pelecypod which thrives in coarse sand of the open ocean margin.

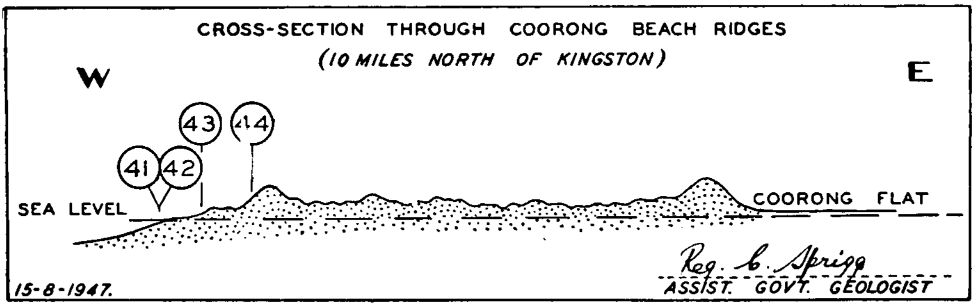

Fig. 35

The Coorong beach is backed by a ribbon-like lagoon and/or flat, and to the north the lagoon has invaded a second more-landward interdune lane to produce an archipelago of islands from the second dune range.

Dr. Fenner (1931) has described the Coorong beach and its associated lagoon as a haff and nehrung association with the dune structure being an abnormally elongate bay bar essentially closing off the Murray lakes from the sea. This mode of origin has been supported by other writers, while more recently Tindale (1947, p. 628) has attributed its origin to an "off-shore" bar formed during a drop in sea-level along a shallow coast: "As the sea falls the shoreline moves seawards and a foreland or strand plane is developed at the land's edge. Because of the shallow water on such a strand plain the larger erosive waves will break a great distance off-shore and as formation of detritus begins, a submarine bar will appear. . . . Eventually the submarine bar will rise above sea-level and become a permanent shore bar, comparable with the coastal dunes of the present Coorong. . . . Behind the bar forms a swamp lagoon compared with the Coorong lagoon and with lakes such as Bonney, George and Eliza." Both these conceptions are open to criticism. Concerning the "bay bar theory" the main objections may be summarized as follows:

1. There is no suggestion of bay bar growth structures (*i.e.,* accretion lines or hooks) within the dunes.
2. There is definitely no sufficiently strong regular littoral drift necessary to build an elongate bay bar over 100 miles long, to carry it across a large river mouth and to tie it to its extreme land connexion.
3. The most massive sand accumulations are in the central region and not at one end as would be expected if growth occurred away from this point.

4. Spits or bay bars increase in length only when the waves and shore drifts move from the direction of their land connexion. Waves from any other direction tend to destroy them. In the present case the major erosive control is by transverse waves which arrive directly upon the beach.
5. If a spit *could* conceivably have developed over the distance, wave refraction around the tip of the growing peninsula would have led to the formation of terminal hooks. Evidence of these is conspicuously absent.

Under the present wind and wave regimes there is little likelihood of a bay bar of any significance forming along the line of the Coorong. Also if any bar formed at all it would become recurved landwards almost immediately to form a looped bay bar and certainly could not develop with *seaward* curvature for a distance of 100 miles in perfect parallelism with the pre-existing coastline. Regarding the "offshore bar theory" certain remarks by Price (1939) are informative. He writes, "It is possible, where rapid variations in water level occur, as with tides, that a ridge formed at high tide by the plunging breakers might be exposed at low tide. A beach ridge might then be formed by the waves and be further elevated by dune building; and so under a fortuitous combination of conditions, an offshore bar might be built above the water. However, as far as I know, this process has never been observed." Offshore bars by their very nature are extremely unstable sedimentary structures and owe their ephemeral existence to special and usually temporary sets of conditions. When such conditions are modified by new influences, any offshore bars previously formed will be subject to immediate modification. Hence for an offshore bar to build a permanent structure above sea-level, some protecting influence must be brought into operation, such as a sudden negative movement of the sea-level or positive movement of the land. In the case of the Coorong, such an explanation could have little application as the bar would have had to form more than a mile out to sea in a considerable depth of water. It would seem most unlikely that an offshore bar could form fortuitously over a distance of 100 miles in perfect arc form on an exposed ocean coast.

There is no doubt that a receding sea margin can definitely give a spread of beach dune structures, and, depending on the sea-bottom gradient and the rapidity of (relative) sea-level fall, beach dunes may be stranded at intervals leaving shallow interdune flats in which marshes and lagoons can form. By a subsequent rise of sea-level, the sea may enter the interdune flats and reproduce conditions similar to those of the Coorong. This certainly could happen, but in the present case there is no reason to believe that the origin of the Coorong is different from that of other dune associations at higher levels to the east, and marks a major high sea-level stand. That is, the dune complex was initiated during one of the recurring interglacial high sea-levels (in this case post-Glacial) which were superimposed upon the general declining sea-level of late Cainozoic.

Deltoid Shell Berms

(PLATE VII, FIG. 2)

At 40 miles and 30 miles north of Kingston, respectively, the author has noted the occurrence of deltoid shell berms—strong upper beach structures—which appear to be a consistent feature of the more northern reaches of the Coorong. The local coastline is broadly crenulate in plan with "points" jutting seaward for perhaps a maximum of a score or more yards. These prominences occur at rather regular intervals of ½ mile to about 1 mile, and within the "embayments" so formed there are triangular berm-like accumulations along the upper strand line of very coarse shell and other coarse material (fig. 36). Their development from the normal berm can be studied progressively away from any one of the points. The berm or impermanent upper strand-line terrace away from the vicinity of a "point" becomes interrupted at intervals and the discontinuous terraces so formed become more acutely triangular as the separation distance from

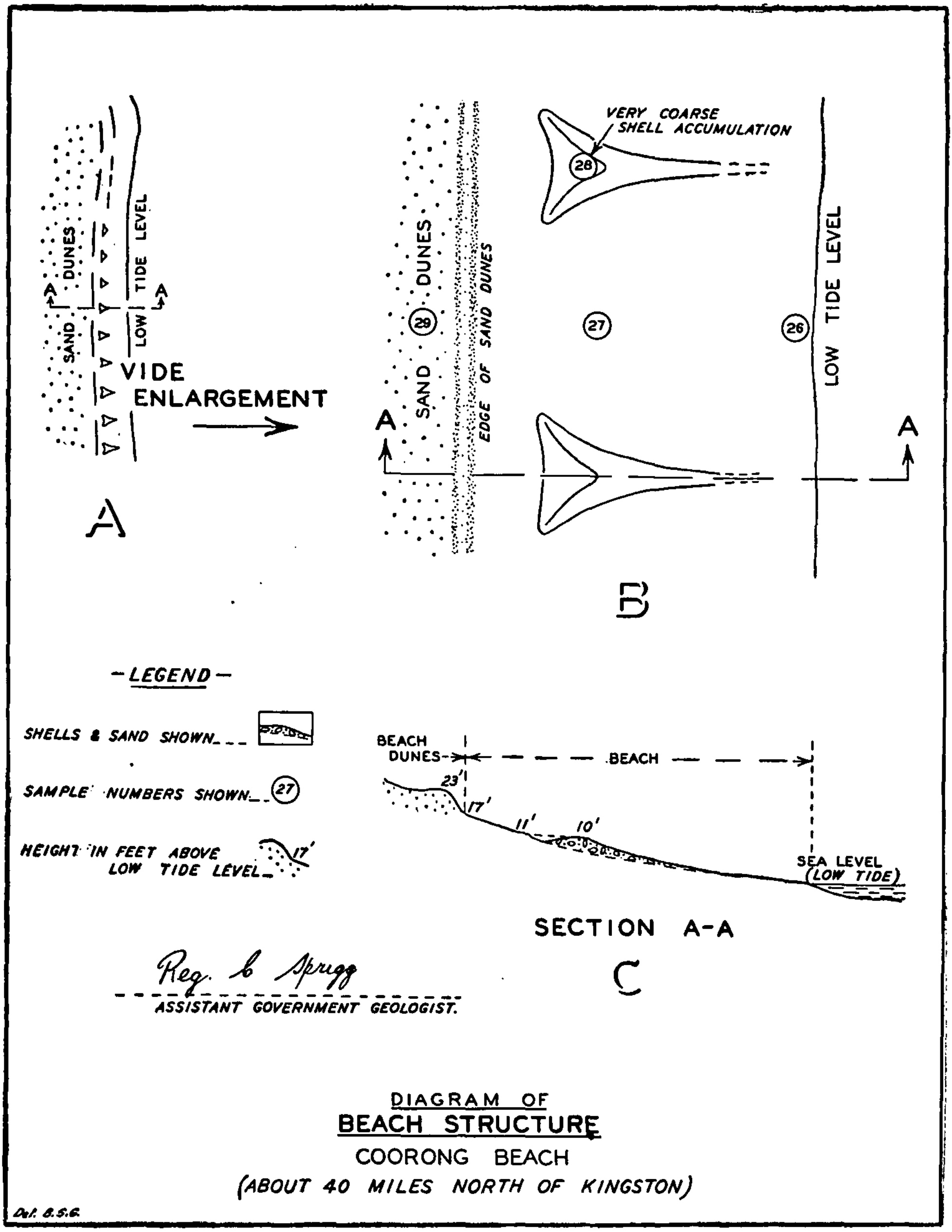
SAND DUNES
LOW TIDE LEVEL
A
A
VIDE ENLARGEMENT
A
VERY COARSE SHELL ACCUMULATION
28
SAND DUNES
29
EDGE OF SAND DUNES
27
26
LOW TIDE LEVEL
A
A
B
-LEGEND-
SHELLS & SAND SHOWN
SAMPLE NUMBERS SHOWN
27
HEIGHT IN FEET ABOVE LOW TIDE LEVEL
17'
BEACH DUNES
BEACH
23'
17'
11'
10'
SEA LEVEL (LOW TIDE)
SECTION A-A
C
Reg. C. Sprigg
ASSISTANT GOVERNMENT GEOLOGIST.
DIAGRAM OF
BEACH STRUCTURE
COORONG BEACH
(ABOUT 40 MILES NORTH OF KINGSTON)
Del. R.C.S.

Fig. 36

a particular "point" increases. The triangles are strongly isoscelene with apex directed down the beach. Axial length of the triangles may be as much as 25yds. to 30yds. and the width of base averages 15yds. The formations where they are best developed are 35yds. to 45yds. apart. They are regular within themselves, and the coarsest shell material is deposited along the two equal sides of a secondary (inner) triangular substructure. The main triangular base is usually 9yds. to 10yds. from the line of beach dunes and about 30yds. from low tide line. The beach surface between each triangular berm and between the berms and the low tide line is gently concave (in sectional elevation).

The deltoid berms are obviously strong periodic structures, which in groups dove-tail into a much larger coastal periodicity. The reason for either periodicity has not been determined, although it is noticeable in the case of the smaller structures that waves on breaking on the beach spend their energy running up the steep beach, swirling along the length of the beach in one or other direction and then receding. In this manner a parabolic motion is described, apparently exerting a strong inflence or control in deltoid berm formation. The separation of the deltoid berms is probably a function of the degree of embayment protection offered, of beach slope, and of sand coarseness.

Marine Solution Benches

(PLATE VIII, FIG. 1)

The "Robe" aeolianite dune at the extremities of Guichen Bay is the site of a very extensive marine planation. Platforms aggregating many thosuands of square feet extend at intervals along the coast for many miles. They are particularly well developed about Capes Dombey, Lannes, and Thomas.

Accurate levels taken by the South Australian Harbors Board indicate that the platforms are remarkably horizontal at about 2ft. to 4ft. above low water (L.W.O.S.T. Robe) (fig. 37). This indicates a level in general a little above mean sea-level (tide range is approximately 4ft.). Although there can be little doubt that the bench-forming processes are active at the present day, the benches are also being actively eroded and destroyed at their outer margins. Very often they are adjacent to deep water into which their outer margins fall away vertically or are undermined (fig. 38). At Cape Dombey the reefs are extensively undercut and soundings proved the water to be 20ft. deep immediately off portions of the bench; these features may indicate cliff nick-point and cave development by a former lower sea-level.

Little or no sand occurs on the platforms and aeolianite lamination structures frequently stand in relief if the layering is not flat. In this way the platforms are extensively corrugated, the corrugations rarely exceeding about 2in. in height. Rock debris and sand when present on the benches is restricted to the beach or cliff lines. Chitons, barnacles, and mussels thrive on the main platform and at the cliff bases (fig. 38), while seaweeds (particularly the massive brown kelp) are strongly established around the platform edges. These tough seaweeds effectively build up the bench margins to impound water on the reef an inch or so deep. During low tide, the water remains on the shelves concentrating on the solution of the limestones at water level to produce remarkably flat benches over large areas. If the benches were purely mechanical erosion features the surfaces would shelve landwards. Further, it is apparent that, although each bench is remarkably flat in itself individual platforms (fig. 37) show considerable variation in level. Thus each is essentially an entity in which control is by the solution effects of water impounded on the benches rather than by wave action. On this basis the height of a particular (solution) bench is arbitrarily determined within a narrow vertical range.

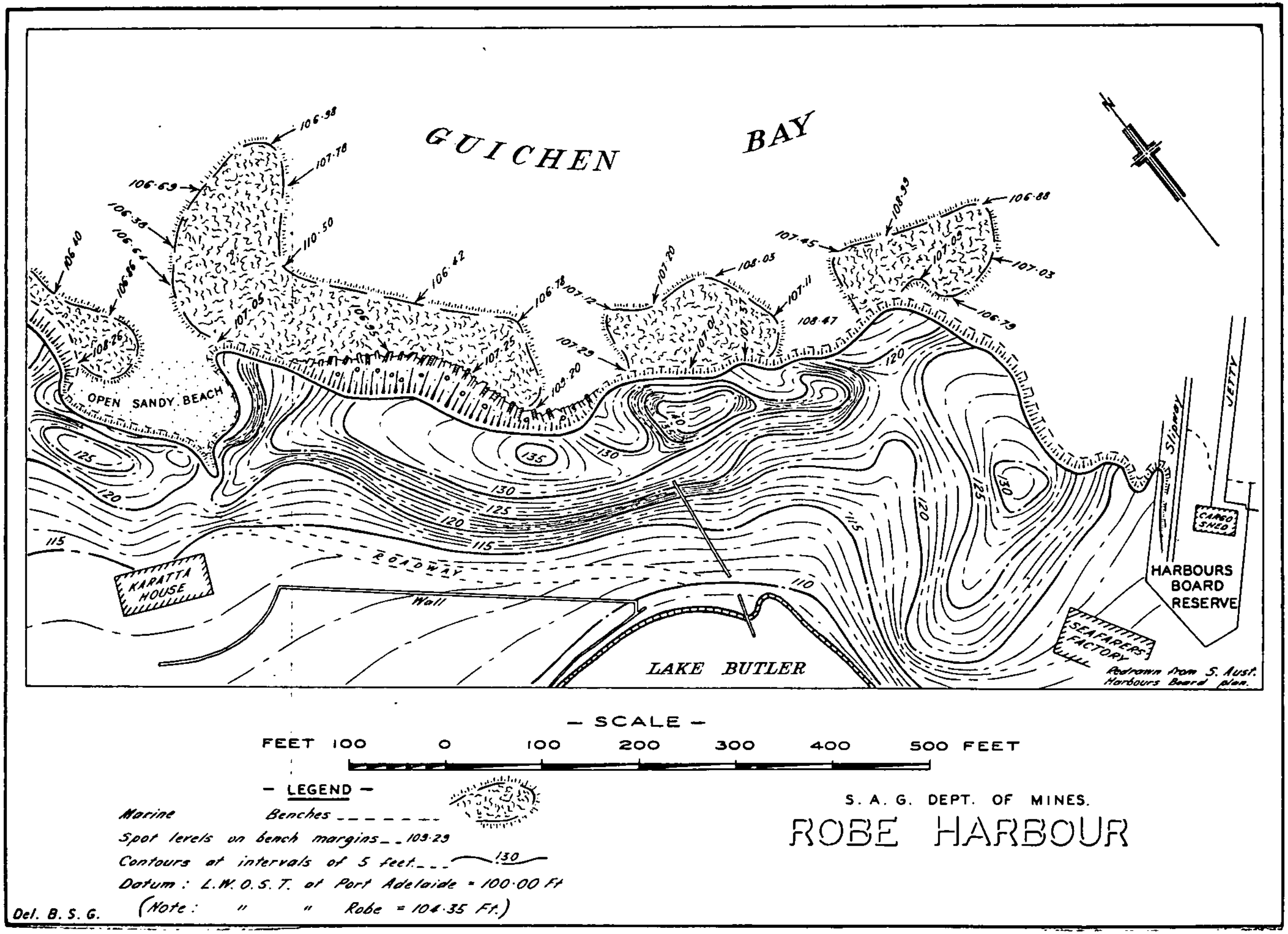

Fig 37—Robe Harbour—Showing marine solution benches

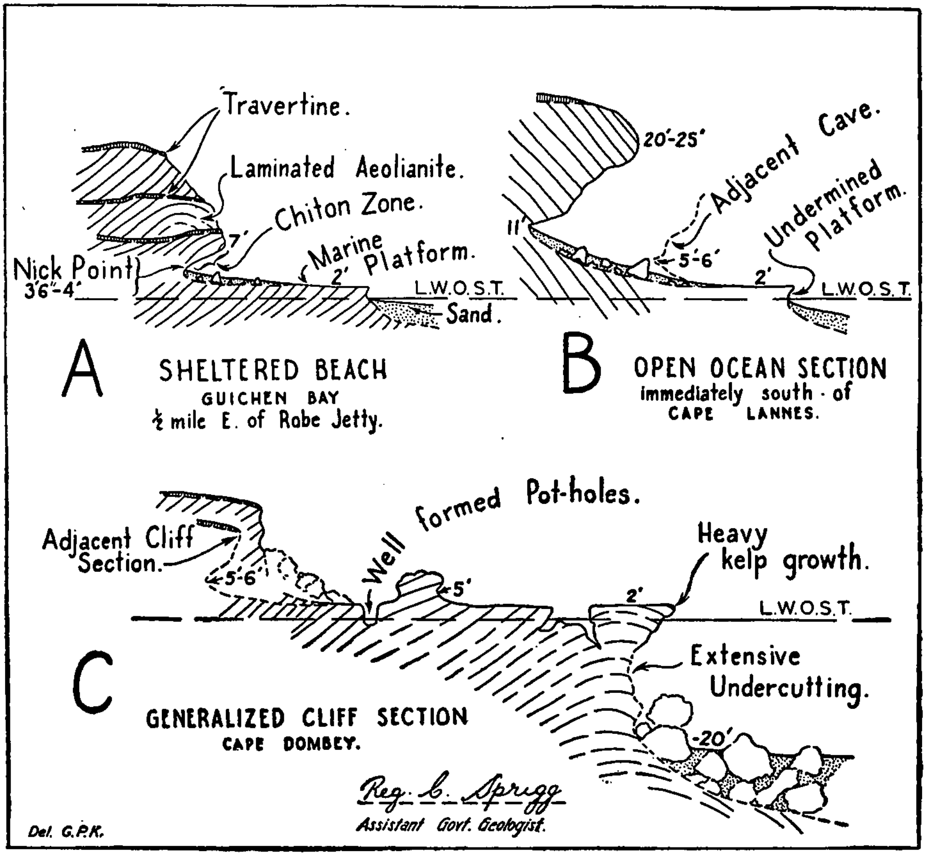

Fig. 38—Sections through solution benches and associated cliffs developed in aeolianite at Cape Dombey

It is difficult to see how in an exposed position—such as Cape Dombey—the platforms could be cut by wave action. Ocean waves pounding on to rocky shores out of deep water must have a relatively large vertical range of action, both below and above sea-level, and unless there is some other control, the net effect would be relatively indiscriminate erosive attack. The formation of deep, well-formed pot-holes on the Dombey platform provides an excellent example of this erosion. Nick-points in caves and on sea stacks also are found at different heights according to the degree of coastal "exposure". They range from 3ft. to 11ft. or more above L.W.O.S.T. Also, where sea caves are developed, the height of the nick-point appears to increase with the depth of the cave, and this in turn is frequently a function of local wave intensity.

Sands of the Robe Harbour Sea Floor

Sand samples from the uppermost 3in. or 4in. of the Robe Harbour sea floor were submitted to sizing analysis and the results are summarized diagrammatically in fig. 39. The figure shows the relationships of sand suites with sea-floor topography which are important in the study of present-day sand movements on the sea floor.

On the basis of grain size three groups of sand are clearly distinguishable, namely, a fine sand with a modal diameter of about 0·0035mm., a relatively coarser sand of modal diameter about 0·009mm., and a third sand which is essentially a mechanical admixture of the former sands.

The finer sands are recorded only from the immediate lee of the Cape Dombey Peninsula which provides protection from ocean swell and from storm waves from the west and southwest. Prevailing winds are from the southwest (fig. 40). In these protected shallower marginal waters the transporting power of the refracted waves is greatly reduced, allowing accumulation of the finer sands. No other simple fine sands were sampled in the harbour area.

Coarser sands have a wider distribution and reflect conditions of more open water where translatory movements are stronger. In general these sands become better sorted and somewhat coarser in the deeper water away from the coast.

The composite sands apparently occupy zones intermediate between the two latter suites, although in some cases the spacing of bores was insufficient to substantiate this conclusion fully, for example, see bores Nos. 7 and 8. The mechanics of the origin of the composite sands is not clear. Two possibilities present themselves. In the first case there could be mechanical mixing in the manner of two "simple" sands being fed into the one environment, either alternatively or concurrently from different sources, or secondly, a composite sand could arise in the course of local manufacture by the alternate action of two different transporting agencies. The composite nature of the sands suggest a degree of layering.

The local sea-bed is very sandy and forms part of an area of sand manufacture and dispersal; it must be considered to be in a state of unstable equilibrium. That is, although its submarine topography is essentially fixed under prevailing wind and wave regime there must be a movement of sand into and from the area; it is not a site of final deposition. This movement in the Robe Harbour (fig. 39) is to the east or northeast in the direction of swell and wave propagation. It would thus be across the entrance to any proposed harbour structure. Furthermore, the sand analytical data show that the sand movement would be strongest in the deeper waters in the vicinity of any entrance channel.

THE ORIGIN AND FATE OF LOCAL BEACH SANDS

South-East beach sands are composed very largely of shell material. The proportion of carbonate material in sands along the coast averages slightly less than 80 per cent, with some sands as high as 95 per cent and others as low as 65 per cent. The shell detritus constituent, in view of its softness, cannot be far travelled, a fact which is borne out by other considerations (*see* below under "Littoral Drift").

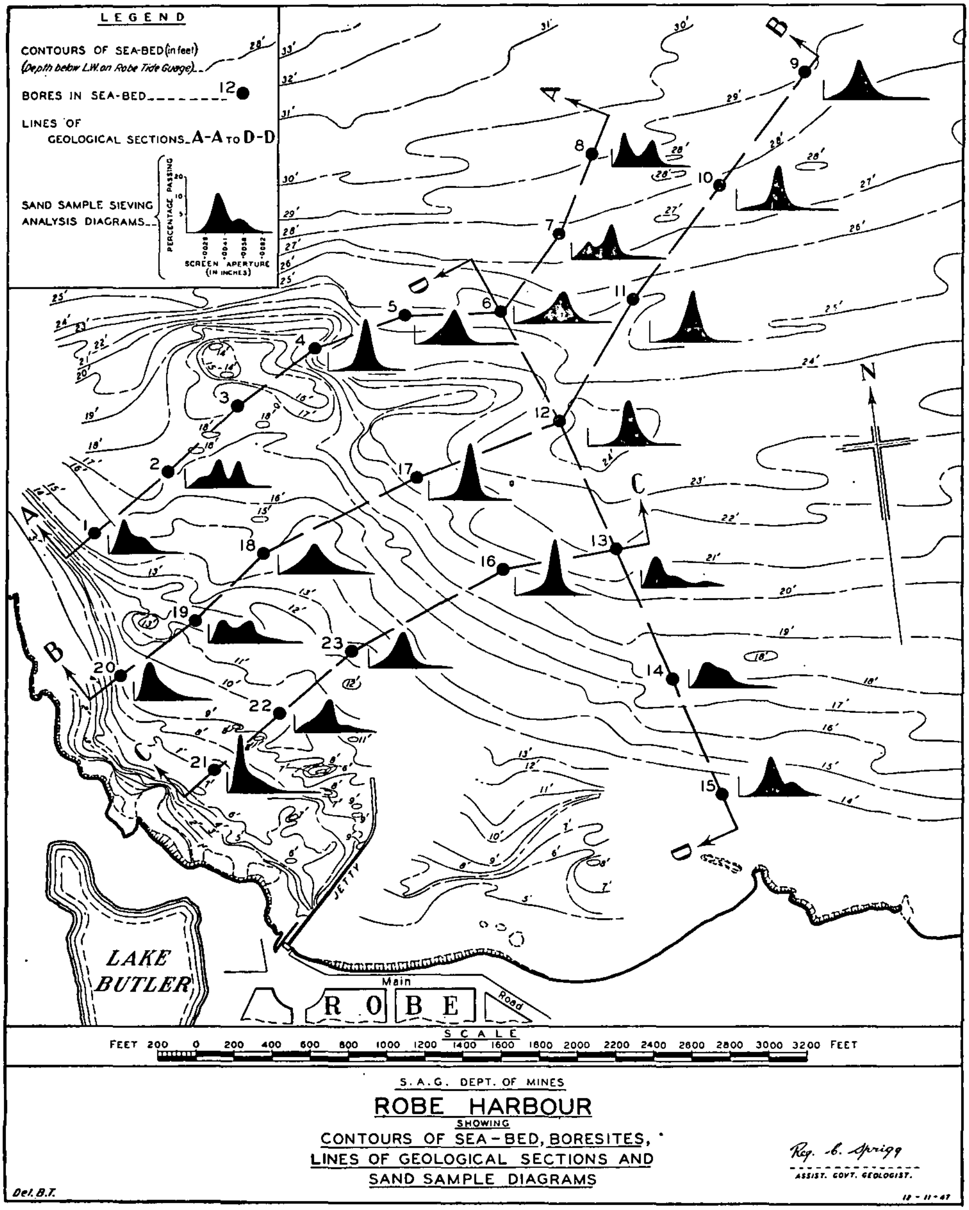
LEGEND
CONTOURS OF SEA-BED (in feet)
(Depth below L.W. on Robe Tide Guage)
BORES IN SEA-BED
LINES OF GEOLOGICAL SECTIONS A-A TO D-D
SAND SAMPLE SIEVING ANALYSIS DIAGRAMS
PERCENTAGE PASSING
SCREEN APERTURE (IN INCHES)
LAKE BUTLER
JETTY
Main Road
ROBE
SCALE
FEET 200 0 200 400 600 800 1000 1200 1400 1600 1800 2000 2200 2400 2600 2800 3000 3200 FEET
S.A.G. DEPT. OF MINES
ROBE HARBOUR
SHOWING
CONTOURS OF SEA-BED, BORESITES, LINES OF GEOLOGICAL SECTIONS AND SAND SAMPLE DIAGRAMS
Reg. C. Sprigg
ASSIST. GOVT. GEOLOGIST.
Del. B.T.

Fig. 39

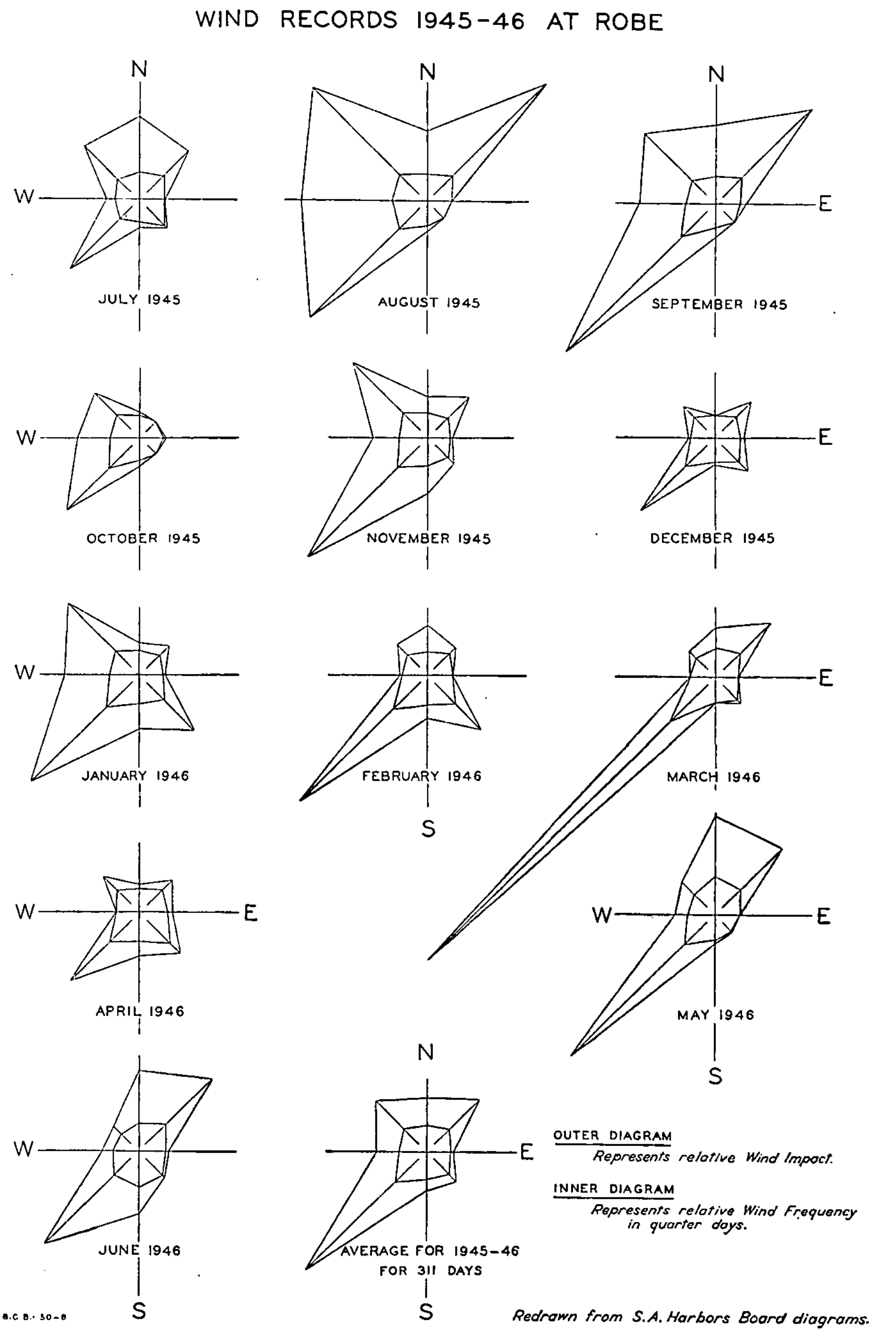
WIND RECORDS 1945-46 AT ROBE
N
W
JULY 1945
N
AUGUST 1945
N
E
SEPTEMBER 1945
W
OCTOBER 1945
NOVEMBER 1945
E
DECEMBER 1945
W
JANUARY 1946
FEBRUARY 1946
S
E
MARCH 1946
W
E
APRIL 1946
W
E
MAY 1946
S
W
JUNE 1946
S
N
E
AVERAGE FOR 1945-46
FOR 311 DAYS
S
OUTER DIAGRAM
Represents relative Wind Impact.
INNER DIAGRAM
Represents relative Wind Frequency
in quarter days.
Redrawn from S.A. Harbors Board diagrams.

Fig. 40

In most cases the shell sands originate quite locally. Most shell material is reduced to sand in the zone of breaking waves particularly along the shore line, but also on sand bars and in other coastal shallows; the greatest production will be where shell banks flourish in open shallow waters. However, all the calcareous constituent of the sand is not from modern shell populations, as an additional supply of calcareous sand material is afforded by erosion of Pleistocene dune aeolianite and of outcropping Tertiary limestones.

The insoluble portion of the beach sands rarely exceeds 30 per cent, and this fraction is dominantly silica. Most of it is quartz sand but minor amounts represent siliceous organic remains, and some arises from the destruction of flint cobbles eroded from the Tertiary limestones outcropping along the coast and on the sea floor. Quartz by reason of its superior hardness and elasticity is almost indestructible, particularly when it reaches a certain limiting diameter, and thus it may wander considerable distances from its primary source and survive many generations of erosion. The origins of the quartz sands of the South-East beaches are therefore varied and may have been local or distant. The sands probably include much material which has survived several erosion cycles. Primary sources would include granite outcrops such as those occurring on the Coorong beach 12 miles north of Kingston or related submerged outcrops. Secondary supplies would be derived from submerged outcrops of Tertiary and Jurassic sediments on the local continental platform which has experienced many successive advances and retreats of sea-level during Pleistocene and Recent times. The sands in the platform area have undergone rapid environmental changes; some have probably outlasted several cycles of sub-aerial, intertidal, and submarine erosion before arriving on the modern beaches.

Most beach sands are eventually piled locally into the backshore sand dunes by storm, wave, and wind action. Wind action also either carries the sands far inland or returns them temporarily to the sea. An important amount of lime is lost in the process as loessial dust. The lime eventually becomes incorporated in the soil profile in inland areas, and has played a great part in the genesis of the travertinous soils of southern Australia.

Under the influence of wave action some beach sands accumulate temporarily in local, deeper and quieter water so tending to reduce sea-floor inequalities, others settle in sheltered positions behind projecting headlands. After storms much of the finer products of shore erosion remain in suspension long enough to drift into the deeper waters of the continental platform, but the quantities concerned are believed not to be large.

LITTORAL DRIFT

Littoral drift, its mechanics and magnitude, are of great importance in the study of proposed harbour sites on the South-East coast. The existence of a northward drift of sediment along the South-East coast has been assumed for a long time from actual observation and the knowledge of local ocean currents. The siltation of the Warrnambool Harbour (Victoria) is an experience against which a repetition must be guarded.

The control of littoral drift is usually vested in prevailing winds, tides, and near shore currents. Prevailing winds, for example, in striking an elongate sand shoreline obliquely, must cause some transport of sediment in the direction of progressive wave impingement on the shoreline. Wind alone can also cause considerable sediment transfer and erosion along a beach, and although the final repository of the sand is in the backshore dune, there may be an overall movement in a particular direction. Tidal and current influence in littoral drift is likely to be secondary or insignificant along open ocean coasts. Such movements tends to be laminar with least effect adjacent to the sea floor. Tides are essentially oscillatory whereas ocean currents have more definite directional drift tendencies.

The investigations in the South-East have shown very clearly that littoral drift is not taking place on a large scale. The sands forming the backshore dunes are chiefly products of local shell destruction and at best there are only "tendencies" for littoral drift in particular directions. Sands are not being transported along the coast from Victoria to and beyond the Murray Mouth as has been claimed.

The catastrophic harbour siltation, *e.g.*, at Warrnambool, has given a false impression of large-scale sand movements. Sand, nevertheless, changes position locally during storms in immense quantities if an old equilibrium is upset, as for example, from the influence of an unfavourably situated or badly designed harbour construction.

The occurrence of vast seaweed meadows in sheltered bays, some of which are continuous with the seaweed banks deposited on shore (*e.g.*, Lacepede Bay), demonstrates very clearly that littoral migration of sediments in the South-East is insignificant. "Sand lanes" in the seaweed meadows obviously do not play much part in transfer either as their sands are quite different from those locally onshore. The poorly developed nature of the backshore dunes of the seaweed meadow vicinity also points to restricted sedimentation locally.

Finally, consideration must be given to the interesting phenomena recorded by F. Andres of the South Australian Harbors Board. Cloudlike suspensions (Plate 13, fig. 1) apparently travelling northwards have been photographed at intervals along most of the South-East coast. The formations hug the coast and edge out to depths of 20 fathoms or more. They frequently exhibit clean, bold and billowy margins which photograph plainly. The formations have been referred to as sand clouds, but as it is quite unlikely that sand would remain in suspension for many hours after rough weather it is proposed to refer to them herein as "suspension clouds", implying suspended matter of near colloidal dimensions. They have not been sampled, but they are certainly extremely tenuous. Their formation is probably closely related with storm incidence. These phenomena were observed from Moonlight Head in Victoria and from Cape Dombey, but there was no opportunity to sample them because of rough seas. The suspended materials, with little doubt, are the finer products of shallow-water erosion although they probably also include increments from deeper waters disturbed during the storms. It would appear that these finer products settle slowly in quiet near-shore waters after storms and then with the next increased wave activity they are stirred into suspension and because of their fineness may be transported by currents for considerable distances before resettling.

At Moonlight Head it was noted that individual waves may produce vertical vortices which stir sand and silt to the surface. By reason of rapid colour "dilution" it was obvious, even at a distance, that the coarser sand quickly settled, leaving tenuous clouds which slowly dissipated. These individual suspension clouds usually persisted for many minutes, while in more favourable areas (*e.g.*, where a sea-floor irregularity stimulated consistent vorticular motions) the sediment "clouds" were continuously rolling away in billowy masses. The process of production would continue either until the erosive influences had subsided sufficiently or until all locally available fine material had been winnowed away.

These suspensions, away from their immediate sources, are unlikely to be of much consequence in harbour constructions in view of their tenuous nature. Disturbances by rougher seas and the passage of ships would tend to keep them moving.

CHAPTER X

GEOCHRONOLOGY OF THE QUATERNARY

In this section an attempt will be made to date various geological events of the Quaternary period by methods of both *relative* and *absolute* chronology. Relative chronologies are based on stratigraphical successions, whereas absolute chronologies can be based on correlations with cyclical events which can be dated relatively accurately.

THE SIGNIFICANCE OF THE SOUTH-EAST STRANDED BEACHES AND THE PROBLEM OF THEIR RESPECTIVE AGES

By the theory of glacial eustacy, low sea-levels of the Pleistocene were caused by the excessive accumulation of water in continental ice sheets during the glacial phases, and high sea-levels by the return of melt waters to the ocean during the interglacials. On this basis the stranded coastal dune system of the South-East has been interpreted (Tindale 1933, 1947) as evidence of the interglacial high sea-level stands. With the exception of the Robe, Woakwine, and Dairy Ranges, the dunes have not been submerged since their formation which indicates that they are successively younger to seaward (west). Similar systems of dune "terraces" occur in many parts of the world.

If these dunes are related to successive interglacial high sea-levels of the Pleistocene then it must be assumed that "overall" sea-level since the Pliocene has been continuously falling. This theory has been expounded by Daly (1934), Zeuner (1945 and 1946), and others. The cause of this continued decline in sea-level is unknown, but may be due to crustal sagging in the oceanic areas and related uplift in the continental areas. Such sea-level movement would, therefore, be both isostatic and eustatic.

In the South-East the evidence of this simple process of marine shore-line recession has been complicated by the effects produced by land movements—both simple positive or negative in type—and warping movements which have been taking place during the same period. The problem then is to define as far as possible the relative degree of stranding of the various beach dunes; to correlate the dune sequence with those of extra-Australian territories or with scales of absolute chronology; and finally to assess the relative warping which the land may have undergone during the period of "terrace" formation.

RELATIVE CHRONOLOGY—WORLD CORRELATION

Zeuner (1945 and 1946) has summarized world evidence of interglacial high shore-lines and shows that average heights for the major strands above modern sea-level are respectively about 330ft., 200ft., 100ft., 56ft., and 23ft. There appear to be more minor terraces within the complete range, as for example at about 250ft. and 140ft. The shore lines are referred to by their Mediterranean names or by their approximate height above sea-level. Zeuner has attempted to relate them to various interglacial periods as follows: Sicilian 330ft. to 250ft. (pre-Early Glacial); Milazzian 200ft. and ?140ft. (Ante-penultimate Interglacial); Tyrrhenian 100ft. (Penultimate Interglacial); and finally the main and late Monastirian at 56ft. and 23ft. respectively (Last Interglacial). The ages of these interglacials, estimated by Penck and Bruckner (1909), Eberl (1930), and Soergel (1925), are given in Table IV.

TABLE III

TENTATIVE CORRELATION OF STRANDED SEA-BEACHES WITH NORTHERN HEMISPHERE GLACIATION

General correlation	Phase		Stranded beach	Radiation date (in years before present)	
	E.Gl.I			590,000	
Early glaciation		H.S.L.	(?) Early Naracoorte		580,000
	E.Gl.II			550,000	
First interglacial.......		H.S.L.	Naracoorte		538,000
		H.S.L.	Harpers		504,000
		H.S.L.	Stewart		483,000
	Ap.Gl.I			476,000	
Antepenultimate glaciation		H.S.L.	Woolumbool		460,000
		H.S.L.	Peacock		445,000
	Ap.Gl.II			436,000	
Great interglacial		H.S.L.	Baker		425,000
		H.S.L.	Ardune		370,000
		H.S.L.	East Avenue		330,000
		H.S.L.	West Avenue		294,000
		H.S.L.	Reedy Creek		249,000
	P.Gl.I			230,000	
Penultimate glaciation .		H.S.L.	East Dairy		210,000
		H.S.L.	West Dairy		200,000
	P.Gl.II			187,000	
Last interglacial		H.S.L.	Woakwine		175,000
		H.S.L.	First truncation H.S.L.		130,000
	L. Gl.I			115,000	
Last glaciation		H.S.L.	Second truncation H.S.L.		83,000
	L.Gl.II			72,000	
		H.S.L.	Robe		44,000
	L.Gl.III			25,000	
Post-glacial phase (Recent period)		H.S.L.	Anadara		10,000

NOTE.—H.S.L. = High sea-level.

TABLE IV

ESTIMATE OF THE DURATION OF THE MAJOR PLEISTOCENE INTERGLACIAL PERIODS

Author	Pre-Early Glacial (Sicilian)	Ante-penultimate Interglacial (Milazzian)	Penultimate Interglacial (Tyrrhenian)	Last Interglacial (main and late Monastirian)
	m. years B.P.	m. years B.P.	m. years B.P.	m. years B.P.
Penck & Bruckner (1909)	?—600,000	500,000—450,000	390—160,000	85,000— 65,000
Eberl (1930)	?—650,000	590,000—475,000	440,000—230,000	210,000— 80,000
Soergel (1925)	?—700,000	?	430,000—260,000	205,000— 85,000

NOTE.—A comparison of three geological estimates of the climatic phases of the Pleistocene, modified from Zeuner, 1945.

In attempting correlation it is first necessary to assume correlation of one of the terraces of the South-East system with one of the "world" group. This seems simplest by starting either with the oldest or youngest beach.

The Robe Range was the last aeolianite dune to be stranded. It pre-dated the last low sea-level (pre-Flandrian regression of Europe) and may therefore be correlated with the late Monastirian "terrace." The Woakwine Range by its relatively close relation may therefore be considered as the main Monastirian equivalent. At the other end of the scale there is the problem of relating one of the stands (pre-Early Glacial) with the uppermost "terrace" of the South-East. In this instance the first major dune is the Naracoorte Range. It is preceded by a poorly preserved range remnant at a considerably higher level, which may or may not be representative of still earlier (*i.e.*, earlier Milazzian or Pliocene) high sea-levels. As the Naracoorte Range is the first undoubted stranded beach dune, and one which is strongly developed it will be assumed to be a late Sicilian equivalent.

Between these upper and lower strand correlations, in the absence of more definite geological evidence, other placings are at present largely matters of choice, with relative altitude and dune mass as the only—admittedly risky—correlative evidence.

Fig. 41 has been produced to facilitate correlation of the dune terraces on the basis of "relative" elevation in relation to modern sea-level. The estimated levels of the South Australian terraces were taken from the Robe-Naracoorte line of section. The altitudes are shown on the left of the diagram with the major ranges accentuated. The sea-level relations of the "world" group as summarized by Zeuner (1945) are plotted opposite. On the assumption that the Robe and Naracoorte "high sea-levels" are the respective equivalents of the late Monastirian and late Sicilian stands, and assuming that land movements have been small or consistent in rate and direction, a definite graphic relation between the two series should hold if the two series are equivalent.

It can be seen that a fairly direct relationship does appear to hold between the major beaches although an additional major terrace is present in South Australia. In general, it would appear that the Naracoorte Range belongs to the Sicilian sea-levels, Bakers and the Avenue Ranges to the Milazzian, Reedy Creek to the Tyrrhenian, and Woakwine and Robe to the Monastirian intervals. As the Tyrrhenian period was by far the longest interglacial period of the Pleistocene it may have included one or both the Avenue Ranges.

In passing it is to be noted from fig. 41 that all of the South-Eastern dunes have been depressed relatively since their deposition. The noticeable telescoping in elevation of the dune levels is due to local warping (discussed elsewhere) during the course of the Pleistocene while the overall lowering of the system as a whole in relation to the world group suggests a Recent (post-Robe) negative movement of the land.

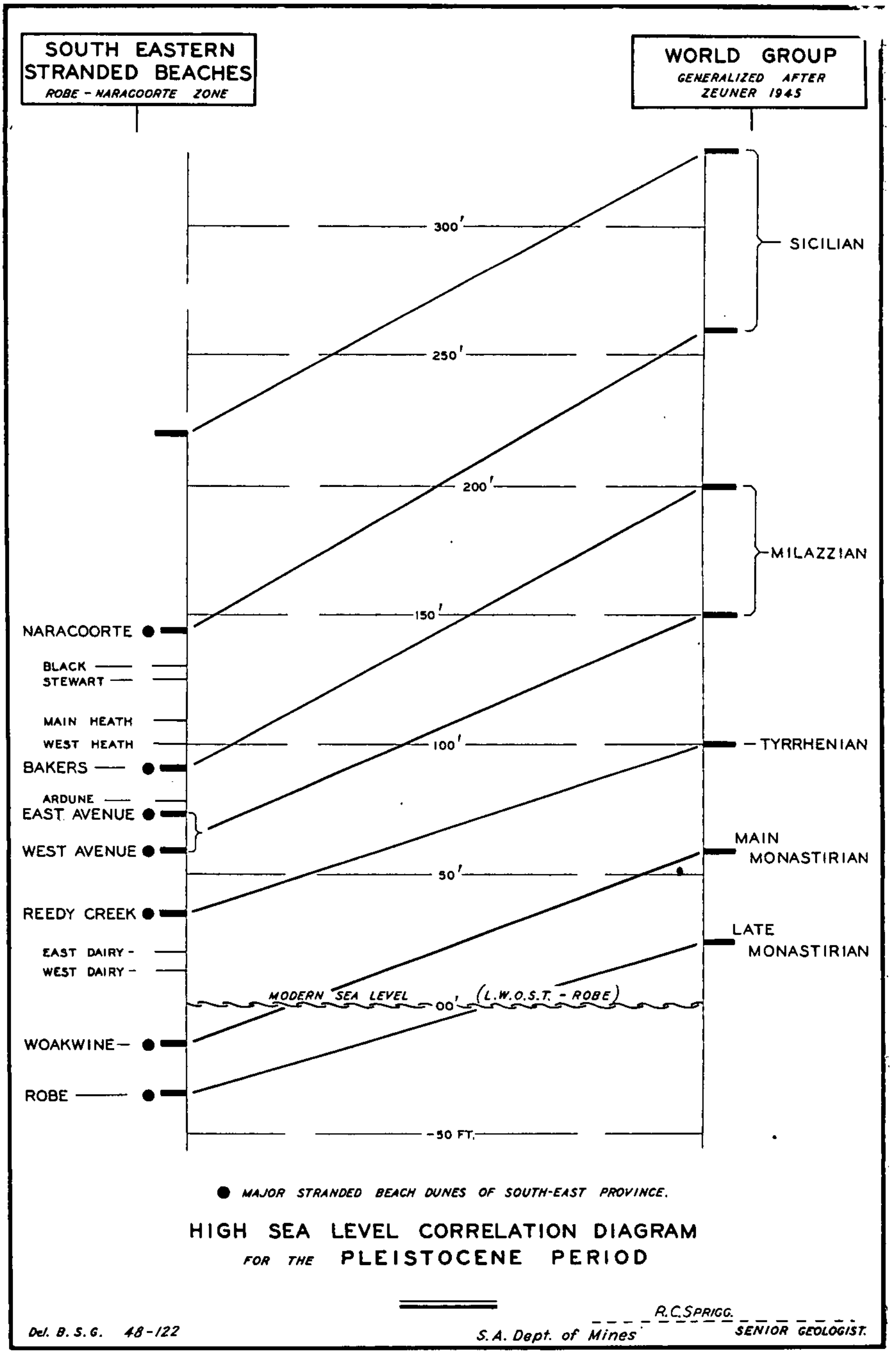

Fig. 41—Comparison of major Pleistocene sea beaches of the South-East Province with those of the Northern hemisphere

(Note.—For Black, Main Heath, and West Heath read Harpers, Woolumbool, and Peacock respectively)

ABSOLUTE CHRONOLOGY—THE MILANKOVITCH ASTRONOMICAL THEORY

According to the Milankovitch solar climatic theory (1938), fluctuations in the quantity of solar radiation received by any zone of latitude of the earth's upper atmosphere, can be caused by variable elements in the earth's orbit, called "inequalities" or "perturbations." These have periods of many thousands of years. They do not alter the total amount of radiation striking the earth, but they are thought by some to effect the relative intensities and durations of the seasons. The major perturbations referred to are:

1. Obliquity of the ecliptic.
2. The eccentricity of the earth's orbit.
3. The precession of the equinoxes.

These elements fluctuate with periods of about 40,000 years, 92,000 years, and 21,000 years respectively.

Applying these variables, astronomers have constructed tables and curves for the amount of radiation received by the various latitudinal zones of the earth's upper atmosphere. Of these, the Milankovitch (1938) tables are considered to be most satisfactory. The tables probably leave much to be desired in accuracy, and in view of other complicating factors the value of the calculations are reduced significantly, and can only be applied in climatic studies for a period of about 1,000,000 years before the present.

Data of this type could not explain an ice age alone, but some authorities suggest that they can account for the glacial and interglacial phases of a particular ice age. The glacial phases are regarded as controlled by periods of high winter radiation and low summer radiation, and the interglacials by periods of low winter radiation and high summer radiation. In the following discussions, reference will be made only to summer radiation as winter radiation displays an almost exactly reversed relation.

The Milankovitch curves (lowest part of fig. 42) reveal serial maxima and minima at intervals of a few tens of thousands of years. The intensities of these maxima and minima vary irregularly, but some workers (Zeuner, 1945, and others) have noted that groupings of stronger minima may correspond with glacial phases of the Pleistocene Ice Age, and consequently, also with periods of low sea-level. Conversely it would appear that successive maxima may be correlated with periods of high sea-level, and in which case a series of high sea-level beaches could be expected to form. Stranded Quaternary sea beaches are common on many coasts, and it has been suggested (Sprigg, 1948) that the South-East affords an excellent test for the theory. There are, however, difficulties. One complication concerns the phenomenon of "retardation" which may be defined as the lag in ice front retreat due to heat absorption in the melting process. It would result in a delay in the culmination of a glacial phase after summer radiation minima. According to Zeuner (1945) the error is probably less than 12,000 years for the last Glacial as inferred from de Geer's varve counts for the Southern Swedish moraines. Glacially eustatic sea-levels will lag similarly. Other complications include secondarily induced glaciations by relative lowering of snow lines due to sea-level fall (200ft. or more) and through increased extra-terrestrial escape of heat by reflection from expanded snow-covered areas. Deflection of ocean currents by ice blockage, and modifications of air mass movements will also influence the spread of glaciation and introduce additional lag effects.

Milankovitch's tables also show that summer radiation maxima and minima change their position slightly on the time scale with geographic latitude; and amplitudes vary considerably more. It is therefore necessary to consider the zone of latitude in which a particular glaciated area is situated, *e.g.*, maxima affecting the spread of glaciers in the northern hemisphere may pre- or post-date maxima in the southern hemisphere by several thousand years. Maximum capture or release of water by ice-caps in each hemisphere may therefore not coincide, with the result that overall rises or falls of sea-level will be somewhat reduced.

As indications of the non-coincidence of maxima or minima, the summer radiation curves for latitudes 65°N. and 75°S. (fig. 42) are informative. These curves are thought to exercise a major control in glaciation in the northern hemisphere and southern hemisphere respectively. Zeuner has noted (1945) that the curve for 65°N. has been most widely used for the Scandinavian area as this is the latitude of the Northern Scandinavian mountains where the glaciating

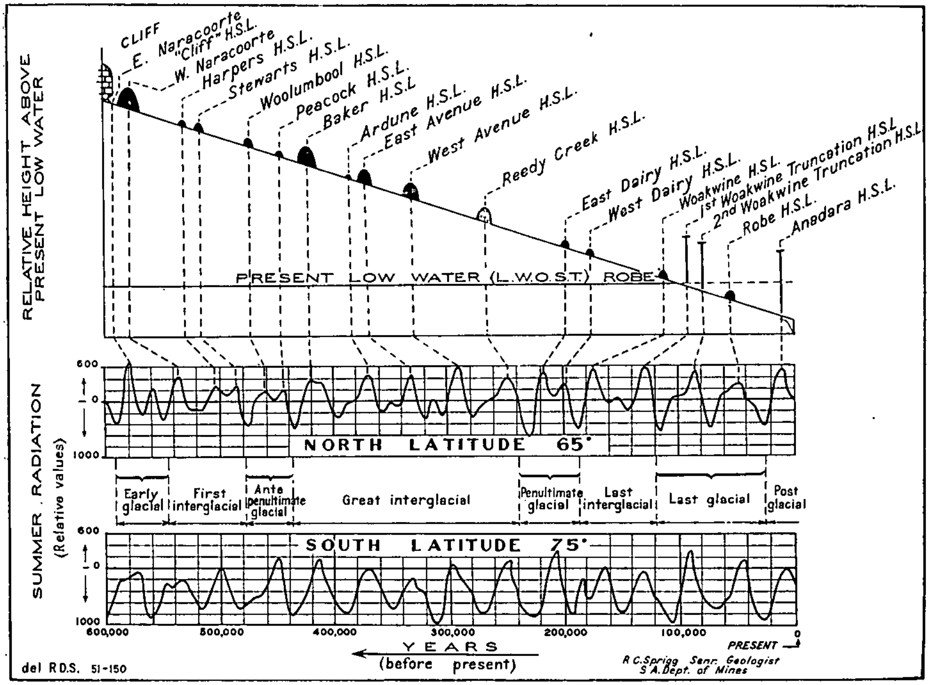

Fig. 42—High sea-level correlation diagram for the Quaternary period

processes were probably cradled. The differences between the curves for 65°N., 55°N., and 45°N. are small and for the most part insignificant, and the phases of European Alpine Glaciations can be dated by this 65°N. curve also. It is to be noted that the maxima and minima for the 65°N. and 75°N. curves show reasonably close correspondence in time, but their respective amplitudes vary very considerably, predicting an amount of averaging out in sea-level effects.

Daly (1934) and Zeuner (1945) and others have estimated the eustatic sea-level rise after the last glaciation to have been between 280ft. and 330ft. Of this Zeuner considers only 13 per cent to 17 per cent to be due to Antarctic ice, and as there were no other great ice sheets south of the equator, the sea-level variations of the Pleistocene must have been dominated by events in the northern hemisphere. It appears therefore that fluctuations in the summer radiation values for 65°N. (and associated latitudes) may bring about sea-level changes of up to about 250ft., while those due to Antarctic (*e.g.,* 75°S.) variations, less than 60ft.

Problems of the Application of the Astronomical Theory

Correlations between field evidence and theoretical data of the astronomical theory appear to have met with considerable success, although there has been considerable unsubstantiated antagonism to such work. Inaccuracies in the computation of long-term curves such as these are inevitable and admittedly the climatological significance of the curves is problematical. However, these are not reasons to discard the theory but rather to stimulate deeper investigations of the problems involved, as, if the significance of the curves could be substantiated their value in chronology would be inestimable.

Previously attempted correlations have been concerned largely with phases of glaciation where repeated advances and retreats of ice fronts must have destroyed much valuable evidence. The peri-glacial areas on the other hand are less complicated and seem to provide some remarkably good comparisons, but it is in the province of the stranded sea beaches, particularly in the more stable land areas, that possibilities of correlation are most promising. The apparent continuous decline in sea-level—other than due to glacial eustacy—by about 240ft., or on an average of approximately 1/10mm. annually (Daly, 1934), during the Quaternary, has favoured the preservation of these fossil beaches and facilitates correlation.

On this assumption of the declining sea-level, progressively younger interglacials or interstadials (*i.e.,* warm intervals during actual glacial phases) if of similar intensity, would result in stranded beaches successively lower than their predecessors. In this manner, high sea-level beaches would be stranded beyond tidal reach unless negative land movements were in progress. Under favourable conditions beaches representing all important interglacials and interstadials would be preserved. Further, in a gently sloping subcoastal and continental platform area if no unduly large or irregular land movements occurred during the period, the vertical spacing of the beaches should be a function of the time interval between the interglacial high sea-levels.

It is assumed that all continental glacial ice, other than of the massive Greenland and Antarctic nuclei, melted during the more severe interglacials, permitting the establishment of relatively stable eustatic coast-lines. In general, the greater the duration of high sea-level still-stand, the more massive would be its dune accumulation.

The Local Application of the Theory

The summer radiation curves from Milankovitch's tables for 65°N. and 75°S. (after Zeuner 1945 and 1946, respectively) are given in fig. 42 for the last 600,000 years. The sloping line above these curves represents the assumed even "overall" decline of Quaternary sea-level down to the present. Stranded sea beaches at their estimated altitudes along the Robe-Naracoorte line of section are superimposed on it. The two Woakwine "truncation" high sea-levels, and the Anadara high sea-level, have been purposely displaced to the right from their true altitudinal positions to preserve the correct relative age relations. The relative importance or "intensities" of the high sea-level stands is also illustrated graphically from information based primarily on the average width of the respective dunes.

Zeuner considers the astronomical curves back to 600,000 years to cover the Quaternary period from the onset of the early Glaciation. Continuation of the curve back to 1,000,000 years, in so far as it is reliable, reveals no very significant associations of low values which may be indicative of widespread glaciation. The summer radiation minimum 590,000 B.P. (before present) has therefore been selected as marking the first phase of the "Early Glaciation". Subsequent glaciations representing ante-penultimate (476,000 years and 435,000 years B.P.) penultimate (230,000 years and 187,000 years B.P.) and the last (115,000 years, 72,000 years, and 25,000 years B.P.) glacial advances can be deduced at intervals along the curve. Conversely, maxima along the curve should represent high sea-level phases, both as interglacials and interstadials. It should also be noted that the glacial phases and high sea-level contributions to be anticipated from the curve 75°S. show no exact correspondence with conditions in the northern hemisphere.

In applying the theory it was argued previously (Sprigg, 1948) that two simple approaches are available which should facilitate specific matchings, namely:

1. By correlating the last high sea-level with the latest radiation maximum and attempting a matching of earlier high sea-levels, with preceding radiation maxima.
2. By assuming the first Pleistocene high sea-level beach to be formed following the early glaciation inferred at 590,000 years B.P. and then matching progressively younger high sea-levels.

Both methods give remarkably close matchings of the field evidence with the theoretical inferences. The first method gives a fairly simple correlation and the oldest beach (Naracoorte) equals the first high sea-level of the first interglacial which is very reasonable.

In applying the second method, attention is drawn to the sudden appearance of "prominent" sea beaches in the South-East area. The Naracoorte dune marks the first phase of a new environmental development which may well mark the beginning of the Pleistocene period. Little is known of Pliocene shore lines in the area, but the weakly developed Hynam aeolianite dune a few miles east of the Naracoorte beaches and at a much higher level, may be representative. Elsewhere (*e.g.*, Tintinara district) these earlier coast lines were probably irregular with marked estuarine developments and massive shell-banks. Quite sharply these conditions gave way to well-marked sandy beaches backed by continuous and massive dune accumulations. Such a rapid change could be explained by postulating a temporary retreat of the sea followed by an advance which swept sand from the recently exposed inner margin of the continental shelf to build up the first "massive" dune. (The earlier Hynam dune may similarly reflect one of the known—minor glacial—phases of the Pliocene). Just such a sequence of events could be anticipated with the onset of marked glacial eustacy; as each eustatic sea-level rise followed each glacial phase, additional masses of platform sands would be worked back to the limit of the new strand line which in each successive case would be at a slightly lower elevation due to "declining" sea-level. By this theory then, the first Pleistocene high sea-level would be correlated with the radiation maximum at 590,000 years B.P.

The influence of southern latitude glaciation on sea-level is considered to be only about one-quarter or one-fifth of that of the northern hemisphere; hence, unless otherwise stated, the radiation maxima quoted are from the curve for 65° N. This would involve the eastern (cliff) beach of the Naracoorte association. The younger beach could be equated with the next important maximum at 538,000 years B.P., but there is no evidence of a minor sea-level equivalent for the weak radiation maximum at 559,000 years B.P. The occurrence of severe Antarctic glaciation (*see* curve for 75°S.) at that time may have negatived any significant high sea-level development. If this solution is acceptable the matchings of younger sea-levels would be identical with the results of the first method.

As to the complete matching the results are almost "suspiciously" good. The Naracoorte dunes are well developed, if perhaps a little too much telescoped, while Harpers and Stewart dunes are small and altitudinally closely related. Woolumbool and Peacock Ranges are also poorly developed as would be anticipated, and the succeeding Bakers Range is much stronger. The Ardune Range is rather weaker than anticipated and the East Avenue Range rather stronger. West Avenue and Reedy Creek Ranges correlate very well. The East Dairy Range, on the other hand, by comparison with the curve for 65°N. only, is too poorly developed, but the corresponding low radiation value on the 75°S. curve at this point offers a plausible solution. The Antarctic area would be experiencing a more severe glacial phase, weakening the northern hemisphere's deglaciation influence on sea-level. The next, or West Dairy Range, is suitably weakly developed.

The Woakwine Range which follows has had a complex history. Its original development probably satisfied the radiation maximum at about 175,000 years B.P. Subsequently, however, the Woakwine dune was truncated at least twice by abnormally high sea-levels (Woakwine Stages 2 and 3). In each case a fall in sea-level followed allowing travertinization of newly established "reef" shell beds and then further shell-sand accumulation. Only a temporary negative movement of the land, a temporary halting of "overall" sea-level decline or a more complete melting of continental ice than previously could have accounted for such complications. A study of the relative intensities of coincident radiation maxima of the two curves between 180,000 years and 80,000 years B.P. does suggest the remote possibility that excess ice melting may have occurred. However, whether it was sufficient to cause two high sea-levels at least 40ft. in excess of the original Woakwine beach is very debatable. Possibly the region also underwent general negative movement at about this time.

The only remaining beach dune association to be accounted for is the Robe dune. This moderately well-developed aeolianite dune system is satisfied by the radiation maxima at 42,000 years B.P. The high sea-level was followed by a prominent radiation minimum which is generally correlated with the pre-Flandrian (last Glacial) regression of the northern hemisphere. This agrees with the field evidence in the South-East. The Robe aeolianite range was stranded sufficiently long to allow travertinization of the range before the sea rose again.

With this final sea-level rise following the last glaciation, the Pleistocene period is assumed to have ended. The rise exceeded the modern stand locally by 30ft. as the Anadara high sea-level which is evidently to be correlated (not allowing for effects of retardation mentioned earlier) with the radiation maxima at 10,000 years B.P. (the climatic optimum). According to the radiation curves, modern sea-level should again be falling, and certainly this "general" tendency has dominated since the Anadara phase, although at present it appears to be rising very slowly.

The partial submergence of the Robe and Woakwine Ranges by the Anadara high sea-level raises some difficulties. There are no significant associations of radiation minima which could cause excessive sea-level rise sufficient to swamp several earlier high sea-level beaches. Only a recent negative movement of the land or the arresting and reversal of the Pleistocene sea-level decline tendency could be responsible.

DATING SEA-LEVEL CHANGES OF THE RECENT PERIOD

For convenience the end of the Pleistocene period is taken as coinciding with the retreat of the major continental glaciers of the last glacial phase in the northern hemisphere. Actually not all glaciers had disappeared and there is no guarantee that there may not be further large recrudescences of glaciers or ice sheets before the sequence is finally closed. Moreover, as yet there seems no single event which can be dated narrowly to define the end of the Pleistocene on the foregoing basis and which would conveniently apply to the whole world. However, a rather arbitrary division has been made by Swedish workers, based on the halt of the central Swedish moraines which according to varve counts occurred at about 7,912 B.C. Zeuner (1945) believes that this event coincided with great changes in the vegetation of northern Europe. On this basis the Recent period began about 10,000 years ago.

Glacier retreat accompanying rising temperatures seems to have continued into the Recent, well beyond present limits, and sea-level rose correspondingly. The warm phase at the height of this development is known as the "Climatic optimum" and its temperatures generally exceeded those of today. It is variously dated between 3,000 years and 8,000 years ago, with a duration of several thousand years.

Subsequently (*i.e.*, during the last 3,000 years to 4,000 years) there has been a deterioration in climate resulting in a slight overall fall in temperature, a notable lowering of the snow line, enlargement or renewal of glaciers, and a fall in sea-level. This latest cold phase has been termed the "Little Ice-Age." Little detailed information is available concerning oscillations within this phase, but there were probably several; minor interstadials may have been responsible for the minor eustatic high sea-levels recorded by Godwin (1945) at 700 B.C. and 700 A.D. respectively. However, the last maxima of the "Little Ice-Age" was reached in the seventeenth to nineteenth centuries A.D., when great havoc was caused in the Alps by the advance of ice into mountain settlements and timber forests.

The modern phase is one of glacier recession. The 1850's (A.D.) witnessed the turning point, and since 1920 A.D. recession has proceeded at accelerated rates, with only minor hesitations. In many parts of the world the retreat is continuing so rapidly that there is alarm that valuable melt-water supplies will be lost. With the increased melting of ice there seems to have been the anticipated minute rise in sea-level (Marmer 1948) although land movements in periglacial areas (Europe and North America) have caused complications where tide gauging records are most complete.

World evidence then seems to indicate the following more pronounced sea-level trends for the European post-Pleistocene period:

1. Continued rise of sea-level to above ordinance datum (O.D.) until the height of the "climatic optimum".
2. Considerable fall of sea-level below O.D. during the "Little Ice-Age" but including one or more secondary interstadials.
3. A further general rise in sea-level to O.D. since the last cold phase of the seventeenth to nineteenth centuries.

Upon all of these major trends, various influences, both eustatic and isostatic, have superimposed other more minor variations, detailed information of which is available only for the most modern times.

In fig. 43 an attempt is made to correlate sea-level tendencies in the "post-Robe" dune period with known changes in the northern hemisphere. A period of high sea-level was followed by marine recession and then by a further advance to just above the present level and finally back to the modern sea-level. The general similarities with conditions in the northern hemisphere are apparent. The high sea-level of the climatic optimum equates readily with the Anadara sea-level (and the great Australian Arid Period of Crocker) during which the sea stood 20ft. or more higher than today. Then followed a low sea-level which may correspond in part with the Little Ice-Age. The extent of sea-level lowering locally was in excess of 36ft. below O.D. allowing extensive sea-floor travertinization in some areas. It is here named the Vincentian phase as it is markedly well developed in Gulf St. Vincent.

Finally, in Holocene times the sea-level temporarily rose to just above its modern level as the "Osborne phase" and has since receded slightly (a few feet) to modern level. This last interval, including the Osborne phase, may be termed the modern high sea-level and during its interval the beach ridged systems of Guichen and Lacepede Bays were formed. This latest very minor fall in sea-level may be correlated with either of those described in England by Godwin (1945)—occurring at about 700 B.C. and 700 A.D. respectively.

In earlier descriptions of the amazingly rhythmic beach-dune ridging which occurs in the South-East and elsewhere, it was suggested that the sea-level, or more likely some tide range factor may be oscillating relatively rapidly.

From field evidence it is quite certain that the time interval during which this process has been operating to produce, say, the Guichen Bay beach ridges, is less than the interval since the Vincentian low sea-level, *i.e.,* less than 2,000 or 3,000 years. As the cyclic dune formation must be still continuing—huge quantities of sand are still reaching the beach as a final repository—it is obvious that the 80 to 90 ridges have been formed in 3,000 years or less. On the assumption that the cyclic control is a regular one, a periodicity of about 30 years or less can be assumed. The problem then is to seek cycles with about this period which could influence dune formation suitably.

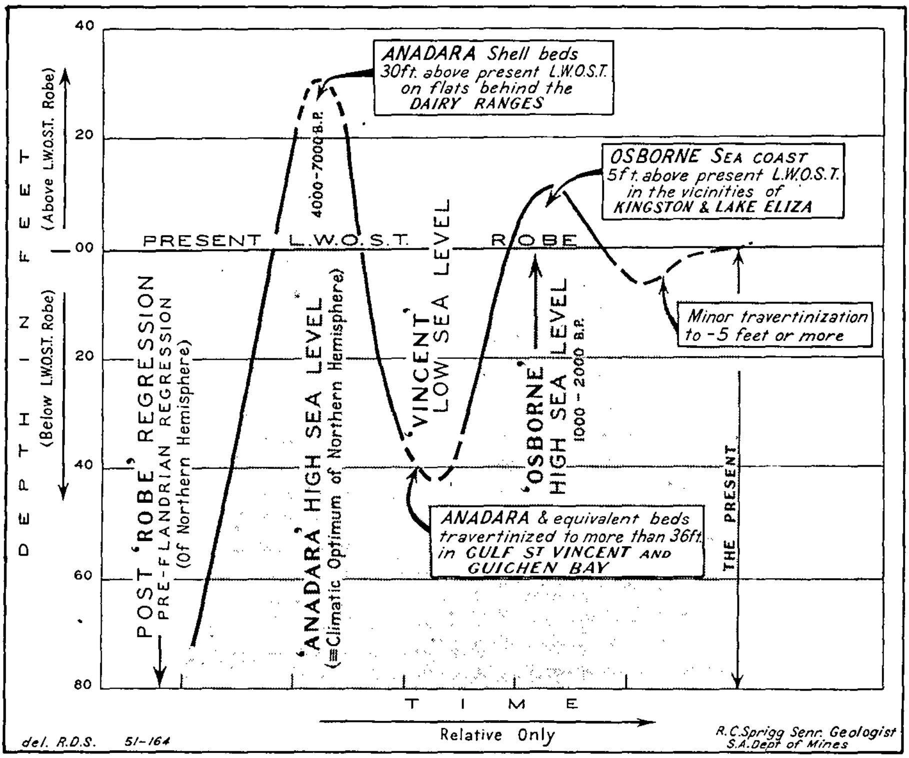

Fig. 43—Changes in relative sea-level since the Pleistocene epoch—Robe-Kingston area

Statistics for minor glacier retreats and advances indicate oscillations at 6 years to 8 years (Meinzer 1942) but the cycle is far too rapid to apply in this case, even if a related sea-level variation could affect beach ridging. From historic experience the cycles are probably much longer.

Sunspot cycles are also of too short duration (11·5yr.), but the Bruckner (33-yr.) cycle is of interest. As to just how such a sunspot-controlled cycle could influence beach ridging is difficult to comprehend. A related variation in storm incidence and intensity is a possibility as sand would be thrown higher on to the beaches during storms; as yet there seems little evidence to favour it.

Perhaps a more fruitful line of research may concern cyclic changes in the orbit of the moon (18·61yr.). This cycle influences mean sea-level to the extent of only ½in., and the range of tide by 3 per cent (*i.e.,* in the case of Robe about ¾in. variation in high water). When the writer first began investigating this latter possibility it was felt that mean sea-level variations might exercise the anticipated control, but the minute variation in amplitude involved did not offer much support. Dr. A. T. Doodson of the Liverpool Observatory and Tidal Institute (personal communication), has suggested, however, that the control, if present in the 18·61 cycle, is more likely to be related to the range of tide. At very high tides sand can be transported higher up the beach and

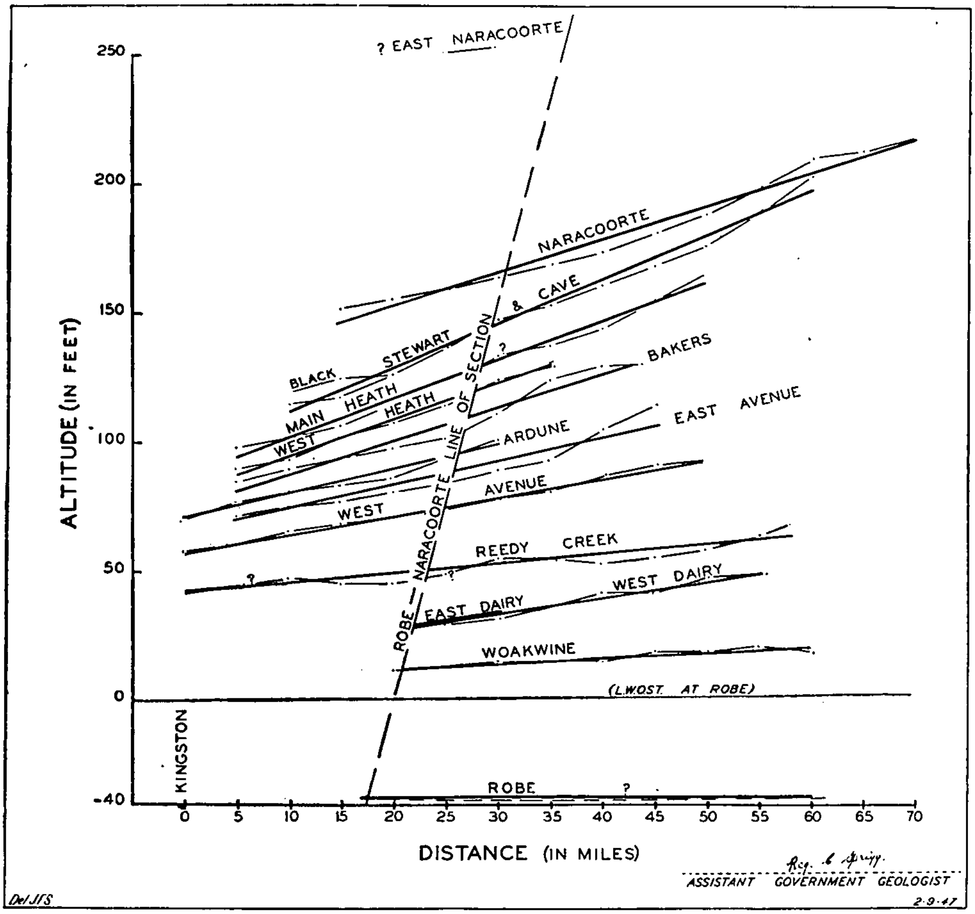

Fig. 44—Extent of Quaternary warping in the northern South-East Province

(Note.—For Black, Main Heath, and West Heath read Harpers, Woolumbool, and Peacock)

between high water and low water effective wind transport is increased. Field investigation seems to indicate that if this control is dominant in the dune ridging, the process is now at, or just past, a "low" (*i.e.,* a dune valley is in formation), whilst for the lunar orbital cycle a minimum occurred in August, 1950. However, the influence of this particular phenomenon is as yet completely unproven, and reference to it herein is merely a suggestion which may be worth investigating further. If the lunar cycle did exercise control in dune ridging the oldest ridge of the local series would be about 1,600 or 1,700 years old.

DATING LAND-WARPING MOVEMENTS AND VOLCANIC ACTIVITY

On the assumption that flat levels immediately confronting the various stranded beaches conform relatively closely with the ancient dune strand lines—which were originally horizontal—it was claimed earlier that a study of those levels should reveal the general course of land warping along the successive old coasts during the period of beach dune deposition. In this way it can be demonstrated clearly that throughout that interval (Quaternary period) the South-East area has undergone almost continuous (relative) upwarping in the Mt. Burr-Gambier volcanic area. This tendency, however, was reversed temporarily during the periods of volcanic activity. Unfortunately sufficiently reliable levelling data is available only to the north of the volcanic area, hence only this area can be dealt with in detail.

In fig. 44 "sample" altitudes of flat levels at 5-mile intervals confronting each stranded beach have been projected on to a single plane lying approximately parallel to the axes of the various beaches. The plane is actually parallel with one including the southeastern corner of the State and the River Murray Mouth. In the figure the values for the various intervals have been joined by lighter lines, while the heavier lines represent an approximate evening-out of the serial values.

It is immediately apparent that the warping movements in this restricted section are dominantly north-down and that they have, in general, been fairly continuous. As a consequence the older dunes are mostly downwarped progressively more in the north than younger ones. For the oldest dunes, the north tilt down attains 1·7ft. or more per mile, while younger beaches approach horizontality. Values for the degree of tilting of the respective beaches are given in table V.

TABLE V

VARIOUS STATISTICAL FACTORS CONCERNING STRANDED SEA-BEACHES OF THE SOUTH-EAST PROVINCE

Beach	Observed length	Width			Height of fore-dune flats above sea-level		" North tilt-down "	" North tilt-down " in relation to previous beach
		Max.	Min.	Ave.	Max.	Min.		
	miles	miles	miles	miles	ft.	ft.	ft./mile	ft./mile
Hynam	2+	—	—	0·5±	250+	240—	?	?
Naracoorte	90+	8·0	1·5	2·0	230	<150	1·3	?
Harpers........	9+	0·5	nil.	0·4	128	90	?	?
Stewart and Cave	60+	1·5	0·5	1·0	210	120	1·7	—0·4
Woolumbool....	50+	2·0	0·2	1·0	180	<100	1·5	+0·2
Peacock	35+	1·0	0·2	0·6	145	< 90	1·4	+0·1
Baker	40+	3·0	1·0	2·0	130	< 78	1·3	+0·1
Ardune	35+	1·1	0·2	0·5	105	< 75	1·0	+0·3
East Avenue ...	45+	4·0	0·3	1·5	120	< 70	0·9	+0·1
West Avenue ..	55+	2·5	0·7	1·7	100	< 50	0·7	+0·2
Reedy Creek ...	60+	3·0	0·5+	1·5	65	< 42	0·4	+0·3
East Dairy	10+	0·6	0·4	0·5	30	—	?	?
West Dairy	80+	2·1	0·1	0·5	45	< 35	0·7	—0·3
Woakwine	90+	2·7	0·4	1·0	20*	< 15	0·4	+0·2
Robe	80+	2·0	?	?1·0	?†	—45	?	?

* From bore information (Robe " oil " bore). † From Robe Harbour submarine bores.

The calculation of "relative" downwarp of successive beaches is most informative. By so doing, reversals in the direction of tilting are more readily appreciated; the values can be expressed positively or negatively in terms of north tilt down. It is seen, for example, that although warping is extensively north-down, temporary reversals post-date the deposition respectively of the Naracoorte and Reedy Creek beaches. These latter periods were occasions of tilt down *towards* the volcanic area.

In fig. 45 the values for relative north tilt down are displayed graphically. The graph has been produced on the assumption that the movements have been continuous, and on a time background of the astronomical scale. If the same detail were plotted against a "relative" time background, taking equal intervals between the various major beaches, the resultant curve would differ only slightly from that produced. Actual point plots have been placed intermediate between the previously interpreted beach datings.

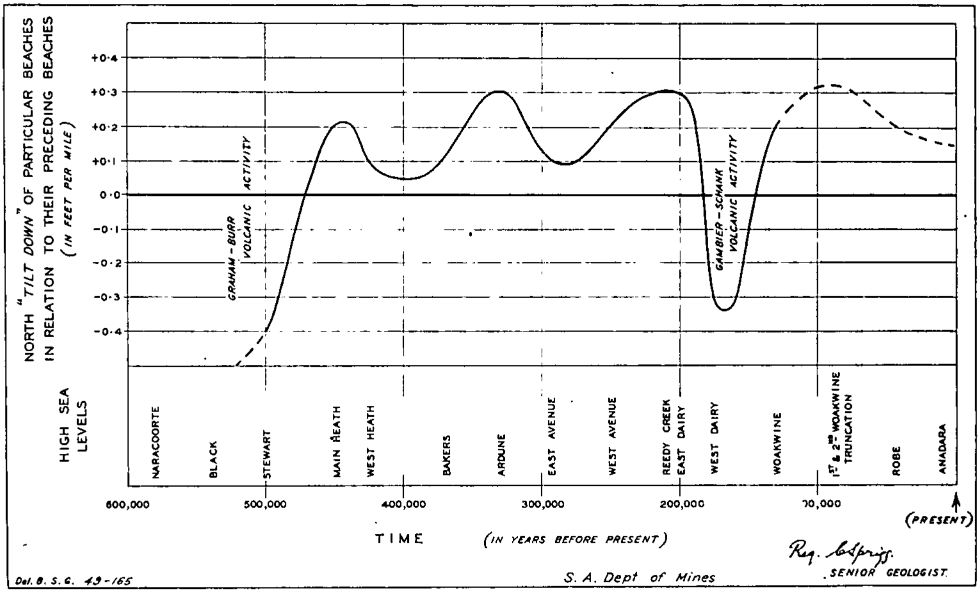

Fig. 45—Diagram illustrating progressive relative north-down warp in the South-East Province during the Quaternary period

The graph demonstrates the original south-down warping influence for the restricted area and then the reversal following the Main Heath beach which continued with minor variations in intensity to slightly later than the Reedy Creek beach. This general movement was arrested at, or just before, deposition of the West Dairy beach, and, after a short interval, once again reverted to north-down tilt until perhaps the present day.

On the evidence submitted maximum south tilt down occurred at, or prior to, the Naracoorte beach and again later during the interval between the two Dairy beaches. On the basis of the astronomical time-scale correlations, the reversal maxima occurred at about 600,000 $\pm$ and 185,000 years B.P. respectively.

These various warping movements are thought to reflect local volcanic activity and upwarping across the Gambier axis. The major downwarp tendency was north-down to the northwest and this appears to be related also to the late evolution of the Mt. Lofty Range to the northwest. The continued uplift of the Mt. Lofty horst block through the late Tertiary and Quaternary periods was almost certainly accompanied by downfaulting and downwarping along both of its margins.

On its west the Gulf St. Vincent senkungsfeld was deepened, and to the east there appears to have been a depression of the strip of country through which the Murray River now escapes to the sea. The depressed area near the Murray River mouth is now the site of large lakes.

South tilt down in the upper South-East is thought to be controlled by the recurrent volcanic activity of the locality as it is assumed that the extrusion of lava would render the volcanic area isostatically unstable leading to negative land movements locally.

As there are two periods of south downwarp there should have been two periods of volcanic activity, and there is abundant evidence that this is the case. The later Naracoorte coast was obviously influenced by volcanic accumulations as in its south continuation it swung out around the Mt. Burr-Mt. Graham centres. This period of activity obviously began before the latter coast was established and may have continued after its stranding. The second interval of south downwarp almost certainly reflects Mt. Gambier and Mt. Schank activity.

In confirmation of the latter correlation Crocker and Cotton (1946) have shown that Mt. Gambier overlies the Gambier and Caveton dunes, and in the present paper it has been shown that the Caveton dune (or Reedy Creek) equivalent was largely contemporaneous with Mt. Schank activity. Fenner (1921), on the other hand, considered the igneous activity to be much younger, in fact so recent as to be "pre-historic", and it has been suggested also that certain aboriginal legends of south-eastern tribes may refer to volcanic activity. Both these claims, however, remain unsubstantiated.

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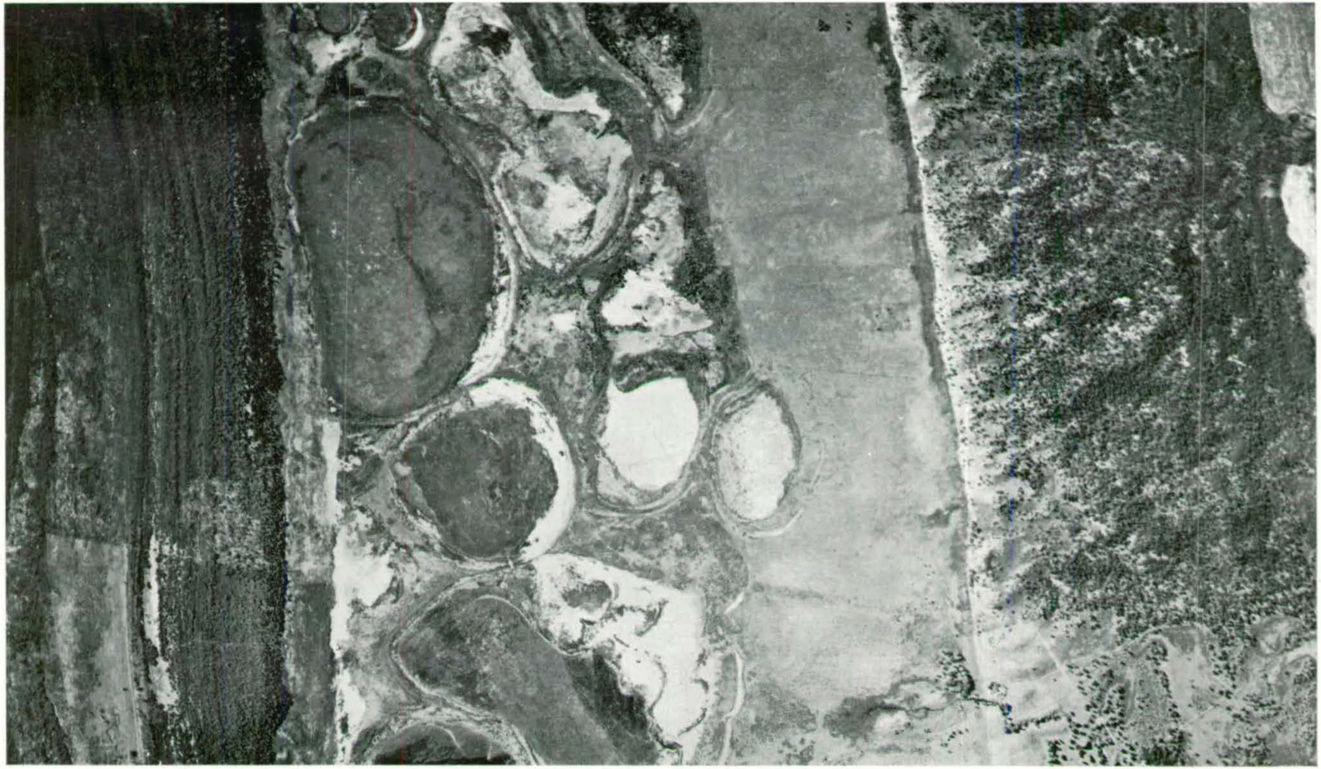
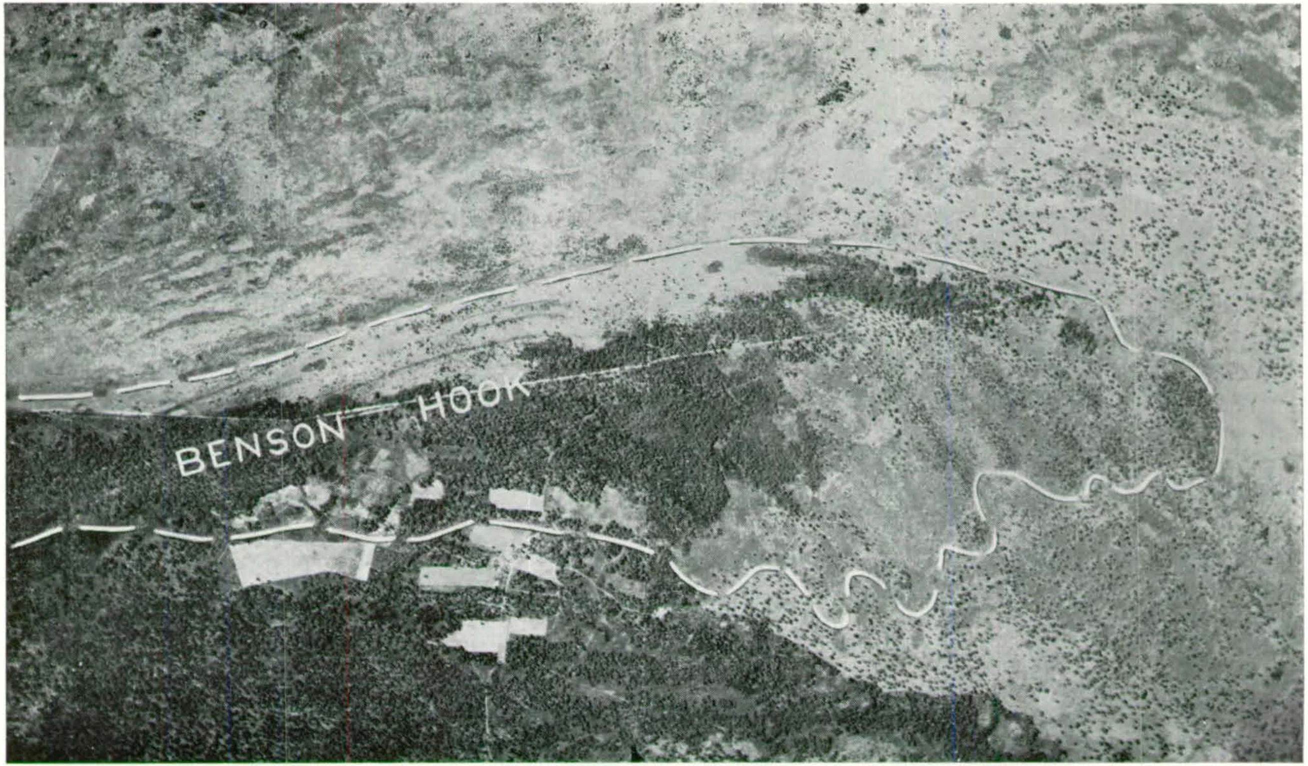
Bool Lagoon near Naracoorte—Showing cluster of lunettes within older lagoon limits



Lunettes in aeolianite interdune corridor

Gentle warping in Gambier limestone, apparently related to basement block faulting



Benson hook structure of the "Anadara" high sea-level phase, extending landwards from the northern extremity of the Woakwine dune

Note.—Fossil "low and ball" structures at the seaward foot—Locality 10 miles SE. of Kingston

Fig. 1—Drain L cutting—Woakwine dune

Fig. 2—Aeolianite structure—Robe dune, Cape Dombey

Fig. 1—Stranded "island" in aeolianite surrounded by flat-lying oyster beds—Near Robe

Fig. 2—Oyster beds 3 miles south-east of Robe

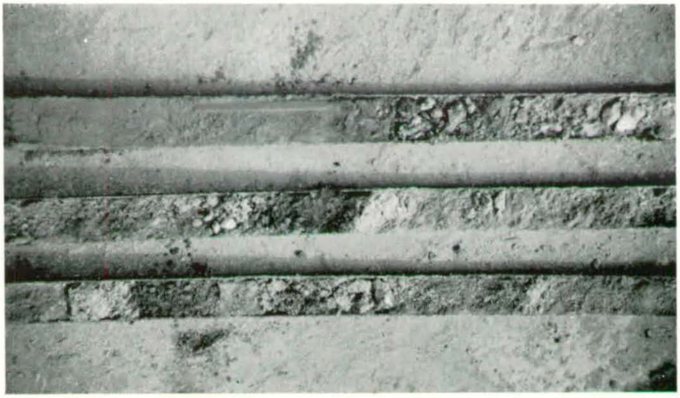


Fig. 1—Robe Harbour submarine bore-cores

Fig. 2—Deltoid shell berms on Coorong Beach, 40 miles north of Kingston

Fig. 1—Marine solution benches in aeolianite—Cape Dombey

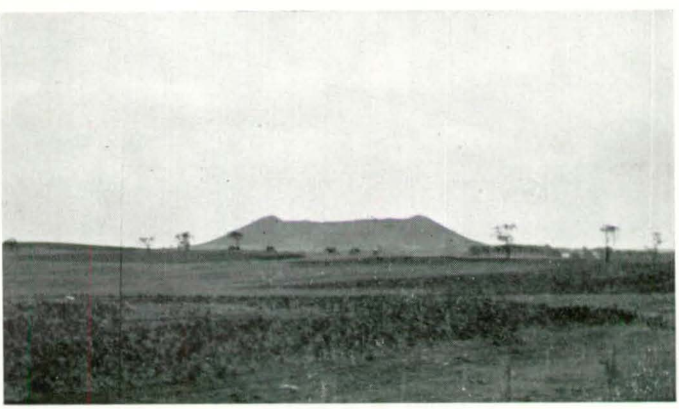
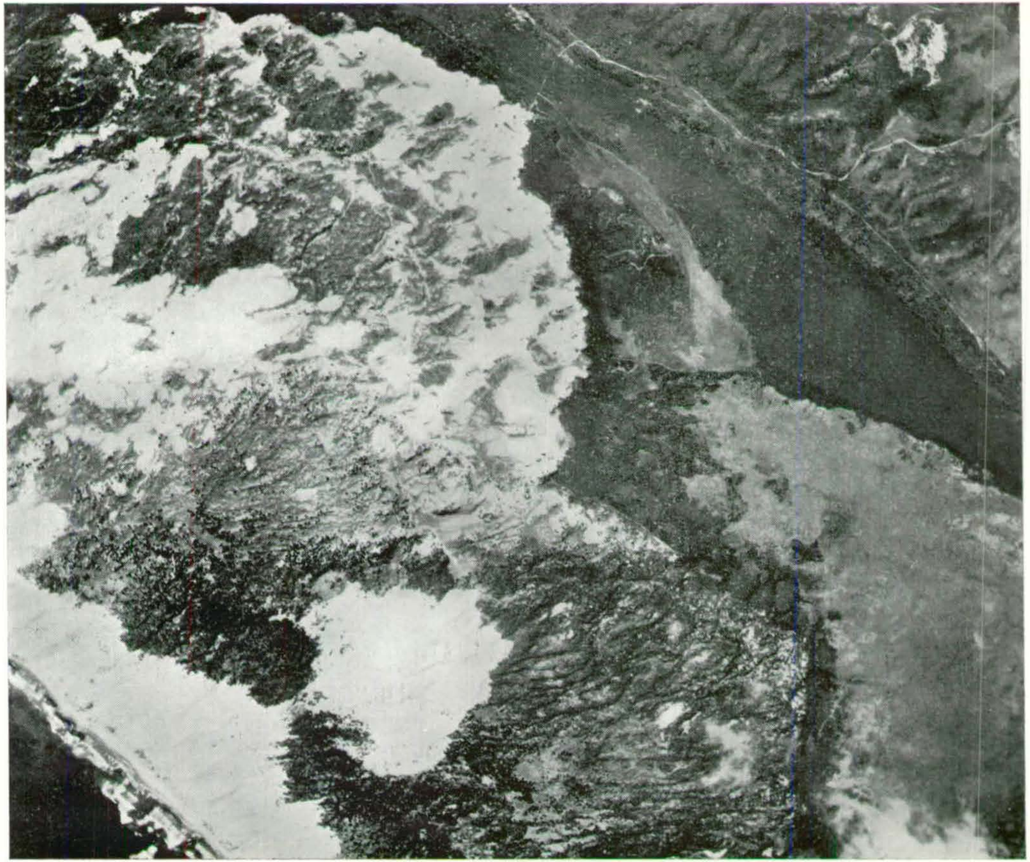
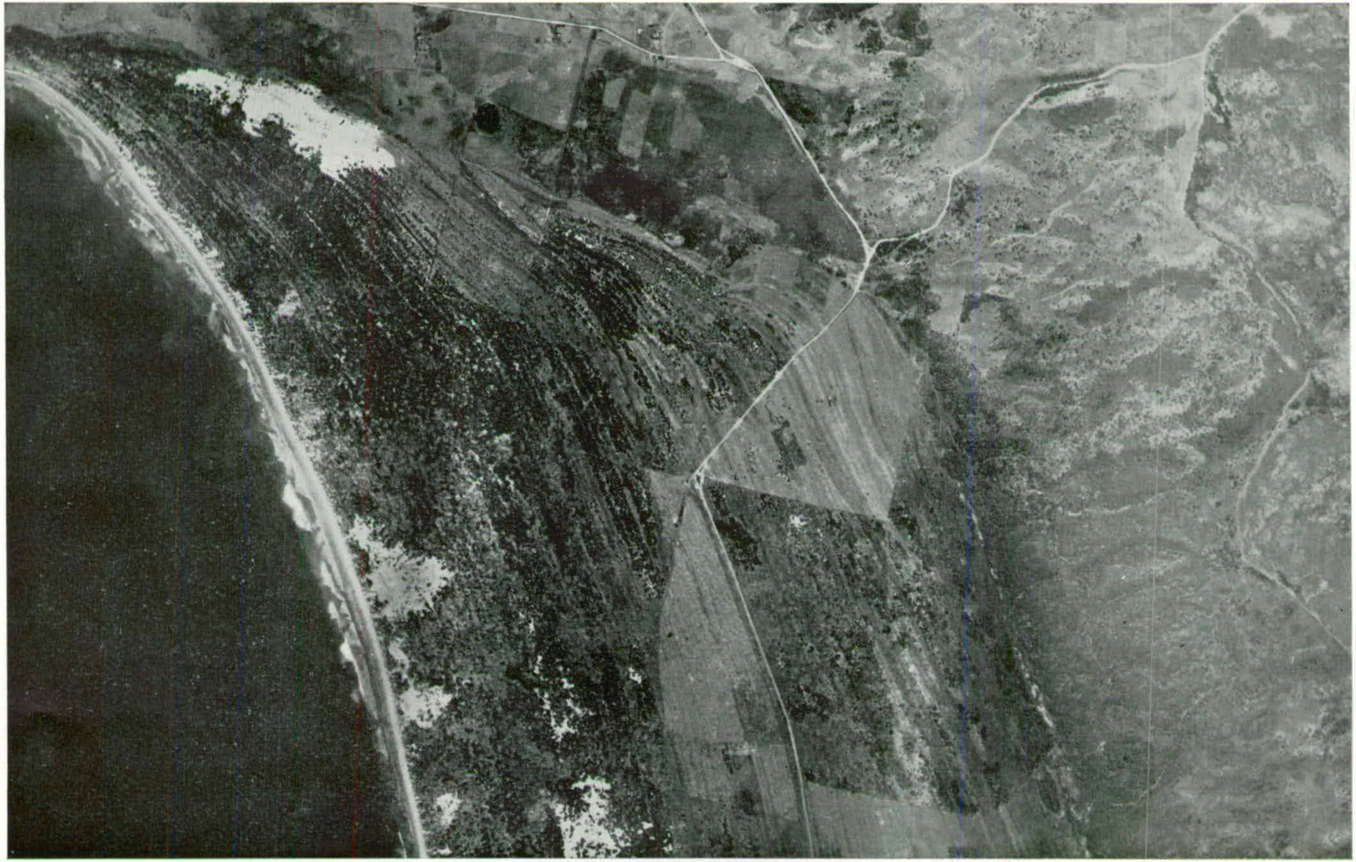


Fig. 2—Mount Schank

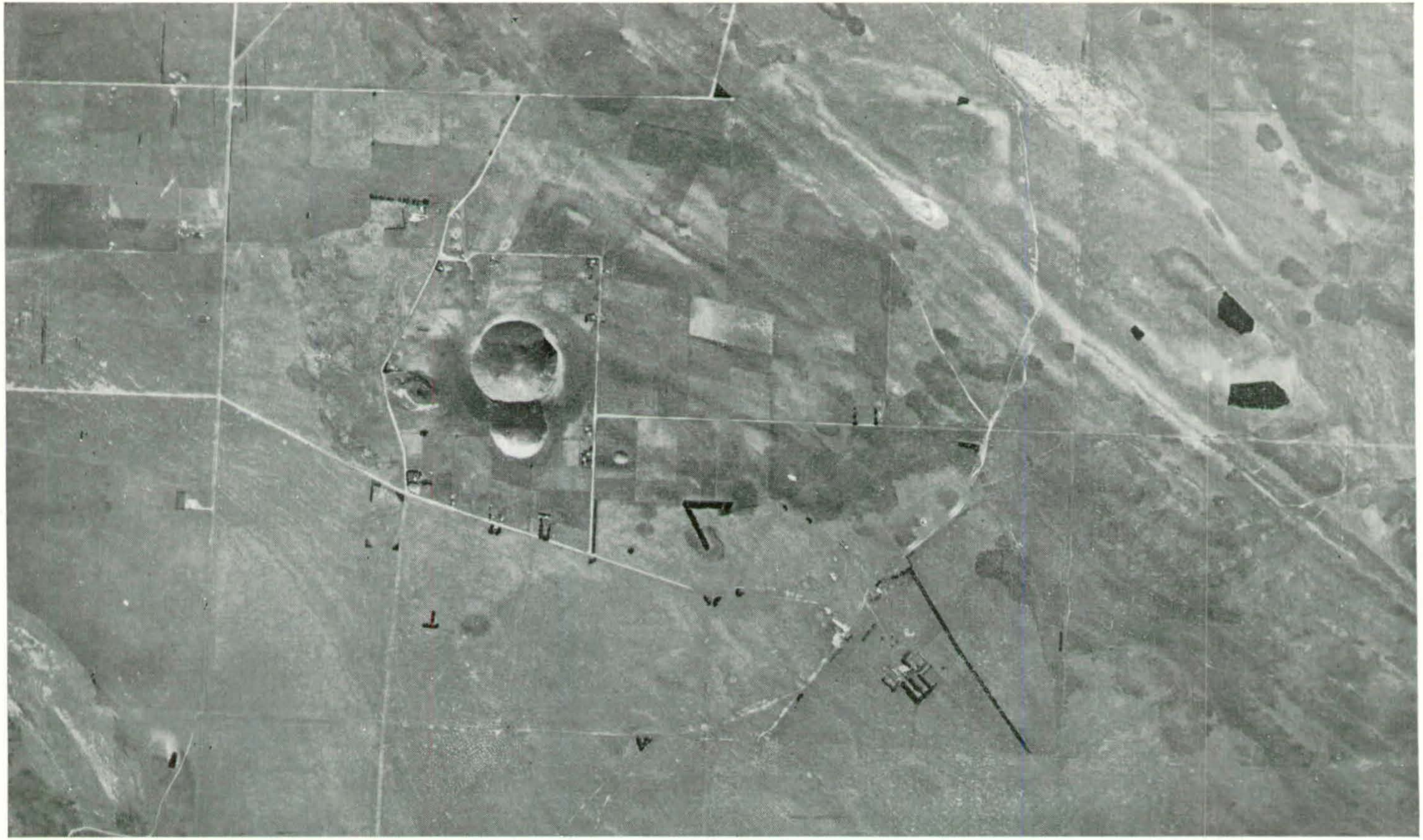
Complex dune structure of Caveton Range, with MacDonnell Range to the south-west



Massive sand blows of the "Robe" coastal dune—South-east of Cape Northumberland



Guichen Bay beach-ridged dunes of the modern coast—Woakwine aeolianite dune to landward

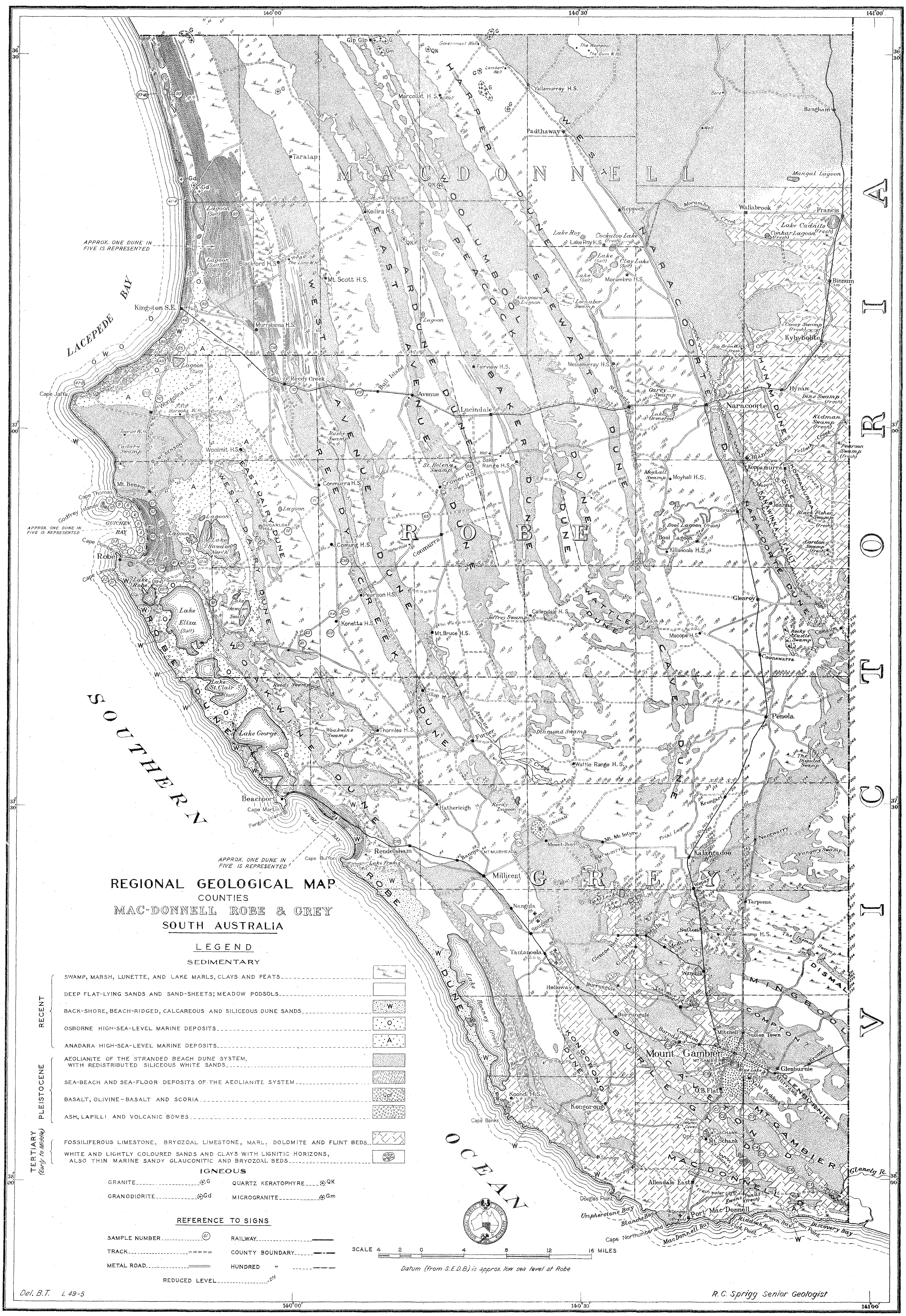


Mount Schank overlapping the Caveton dune

Note the later formed beach ridges arching seaward as if to include the embryo volcano, and also the flat-lying bryozoal limestones confronting the dune

Fig. 1—Turbid "suspension clouds" moving northward along the ocean coast between Beachport and Robe

Fig. 2—Robe aeolianite dune forming Cape Dombey, with Guichen Bay beach-ridged coastal dunes—Showing Robe township



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