MEMOIRS

OF THE

NATIONAL MUSEUM OF VICTORIA

MELBOURNE

(World List abbrev. Mem. nat. Mus. Vict.)

No. 27

Issued 2nd November, 1966

J. McNALLY
DIRECTOR

Published by Order of the Trustees

MELBOURNE

5050/64.

PORT PHILLIP SURVEY 1957–1963.

THE GEOLOGY AND GEOMORPHOLOGY.

by *J. M. BOWLER.*

Department of Geology, University of Melbourne.

CONTENTS.

SUMMARY.

Port Phillip Bay lies in a tectonically controlled depression in which recurrent faulting has occurred from Palaeozoic to Recent time. Stratigraphic and geophysical evidence indicates maximum vertical displacement in the sunkland of more than 2,000 feet.

Variations in lithology and topographic relief affect the coastal landforms developed on the east and west. On the east coast, cliffs and shore platforms are more common than on the west; beaches are broader and off-shore bars are larger and more complex. Coastal sand ridges which are rarely developed on the east are common on the west.

The submarine geology has been studied from fathograms and underwater observations using aqualung equipment. Fifty cores were obtained in Recent marine sediments in the northern part of the bay. Many cores penetrated through Recent sediments to older deposits with a fossil soil horizon. The age of the marine transgression which flooded this horizon is estimated as approximately 8,000 years ago. Rates of Recent sedimentation on the buried surface of 0·4 to 1 foot per 1,000 years are indicated from sediment thickness.

The formation of the widespread aeolianite on the southern coast is reviewed, and evidence in favour of formation during periods of Pleistocene high sea level is proposed. Quaternary downwarping in the sunkland of approximately 400 feet is necessary to explain the continuation of the aeolianite in depth.

Evidence for a small late Quaternary emergence of the shores of Port Phillip Bay is discussed in the light of a mid-Recent fall in sea level claimed by many workers from widely separated areas on the Australian coast. The evidence favours emergence of less than 10 feet but is complicated by combined tectonic and eustatic effects.

The pattern of present coastal changes is described from observations on the eastern beaches during severe storms in July, 1964. Some of the sand eroded off beaches by northerly gales was deposited off-shore; the remainder was carried south by littoral drift. By February, 1965, the winter pattern was reversed with greatest sand accumulation on the northern end of beaches.

Small beaches on the east coast with limited quantities of sand are being depleted by natural and artificial processes. Their conservation requires urgent attention.

Wind statistics show a strong seasonal alternation in frequencies and velocities from winter northerlies to summer southerlies. Westerlies may occur throughout the year but easterlies are always weak and infrequent. This asymmetry in wind distribution partly controls the different landforms and sedimentation patterns between east coast and west. On the east coast, complex sediment movement is controlled by changes in wave patterns from the north, west and south. On the west coast, north-easterlies are weak, and stronger northerlies and north-westerlies are limited by short fetch; the dominance of southerly winds produces littoral drift from south to north.

A geomorphic sequence for the Port Phillip area is proposed, in which structural, lithological, tectonic, eustatic and climatic factors combine to produce a complex pattern of landforms and sedimentary features.

INTRODUCTION.

In the last 100 years since A. R. C. Selwyn, the first director of the Victorian Geological Survey, described the geology of the Mornington Peninsula in 1854, many workers have contributed to the geology of the Port Phillip region. Few, however, have devoted their studies specifically to Port Phillip Bay.

This paper brings together the work of others, reassesses some former concepts of the geology of Port Phillip Bay and points out some misconceptions.

New information is provided from work carried out by the author in recent years. This falls into three parts:—

1. Results are included from submarine coring operations in the northern part of Port Phillip Bay during 1963–64. Cores were obtained by diving to the sea floor and driving a weighted clear plastic butyrate coring tube into the bottom sediment. By using this method, core recovery averaging 60–70 per cent. depths of penetration was possible. Penetration depths were usually limited by sediment strength and the length of coring tube available. Coarse shelly sands were difficult to core but lengths up to 6 feet of medium to fine sands, silts and clays were recovered. Cores returned to the laboratory were cut into halves lengthways on a circular saw for further study.

Detailed core information has been obtained in collaboration with A. G. Link, whose assistance is gratefully acknowledged.

2. Through the co-operation of the Ports and Harbors Division, Public Works Department, and by using a boat chartered by the Department of Geology, University of Melbourne, continuous fathograms have been obtained on selected traverses both inside and outside the entrance to Port Phillip Bay. By providing a continuous graph of bottom topography, these supplement the detailed and accurate bathymetric charts from soundings carried out by Commander Cox in 1861–64. A reliable geomorphic interpretation of the topographic features is therefore possible.

3. A brief analysis of the present physical environment of Port Phillip Bay is made using wind data from recording stations in the area. In this way, observed geomorphic and sedimentary features on the coastline, including present sediment movement on beaches, can be related to directional variations in wave energy distribution.

This work provides a regional assessment of the geomorphic features and problems in Port Phillip Bay. As such, specifically local detail, when used, has not been treated exhaustively. Conclusive answers to many problems are often not possible, and where the evidence is still open, conclusive answers have not been attempted.

GEOLOGICAL STRUCTURE.

Port Phillip Bay on the South Central Victorian coast, is located in a tectonically controlled depression or sunkland, bounded by two major faults, Selwyn's Fault on the east and the Rowsley Fault on the west (Fig. 1).

Selwyn's Fault trends north-north-easterly with downthrow on the north-west, and controls the northern margin of the Mornington Peninsula horst. The south-eastern part of Port Phillip Bay occupies the fault-angle depression formed on the downthrown side of the fault which cuts across the Nepean Peninsula from near Cape Schanck to Dromana. It extends north towards Frankston, on the seaward side of the Mt. Martha and Mt. Eliza granodiorites (Keble, 1950; Thomas and Baragwanath, 1950). Palaeozoic rocks are sheared near the fault contact and Tertiary sediments are warped in the area. Continuation of seismic activity to recent time was established by an earthquake in 1932 with the epicentre near Mornington on the line of the fault (Holmes, 1933).

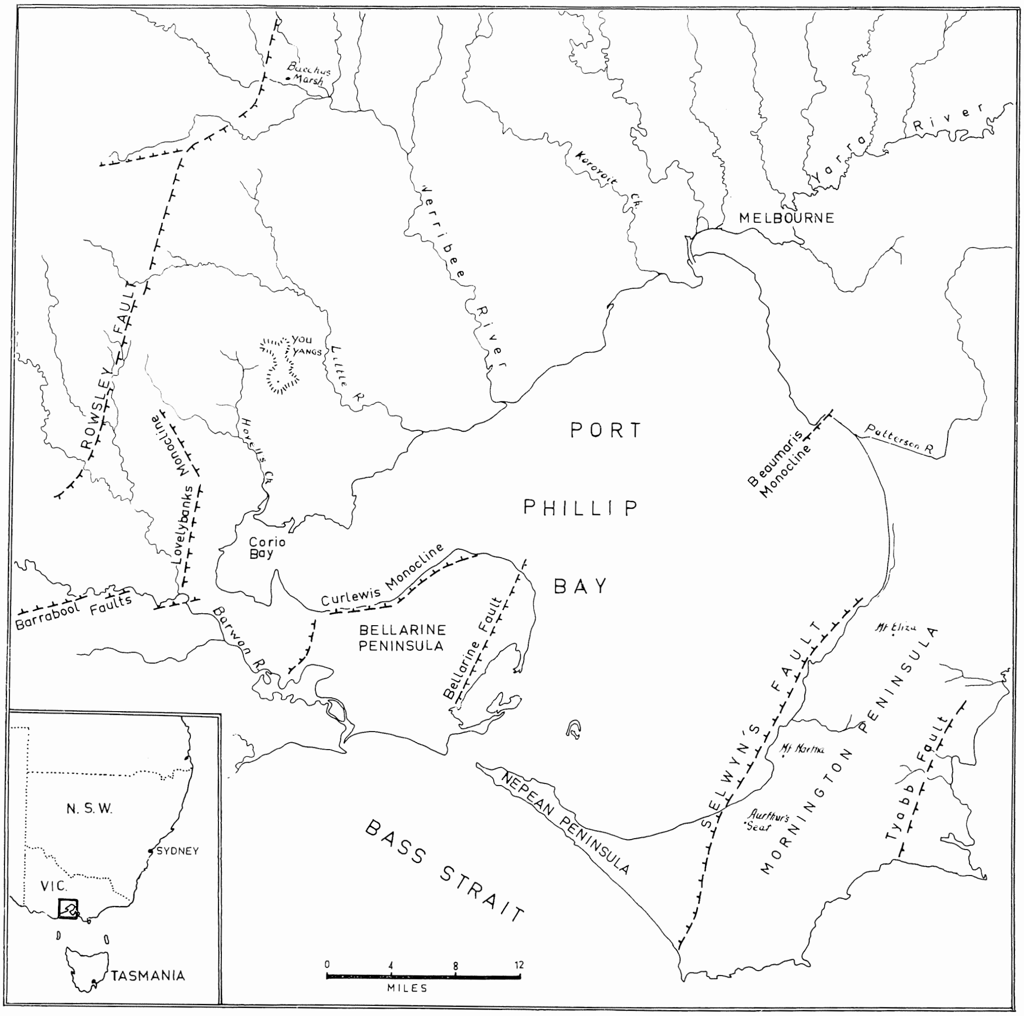


Fig. 1.—Locality diagram and structural map of Port Phillip Sunkland showing the major tectonic features of the area. (c.f. Plate II)

The Rowsley Fault which controls the western margin of the sunkland, commences 10 miles west of Geelong and continues north-north-easterly for approximately 30 miles to north of Bacchus Marsh. The uplifted western block, now being dissected by rejuvenated streams, forms the Brisbane Ranges which rise in places to 700 feet above the sunkland. These have accordant summit levels falling from 1,350 feet in the north to near 500 feet at the southern termination of the fault near Bannockburn (Fig. 1). Near Steiglitz and Anakie, a deep lateritic profile forms plateau remnants on interfluves which increase in width towards the south, corresponding to smaller displacement on the fault and less active dissection. This structure, like Selwyn's Fault, dates back to Palaeozoic times with periods of recurrent activity to Late Pleistocene and Recent.

Newer Basalt is displaced across the fault near Bannockburn, The Anakies and Bacchus Marsh, while late movements have modified drainage in the valleys of the Moorabool and Werribee rivers. From the foot of the Rowsley Fault, a gently sloping plain extends east to the shores of Port Phillip Bay, interrupted only by the volcanic cones of The Anakies and the residual granitic peaks of the You Yangs. The Palaeozoic granites rise through a surface cover of alluvium and Newer Basalt which on parts of the western shore passes beneath the waters of Port Phillip Bay (Fig. 2).

In addition to the two major structures, several subsidiary structures contribute to the present outline of the Bay.

Near Geelong in the south-west, the Lovelybanks Monocline runs north for 8 miles between Corio Bay and the Rowsley Fault, then trends north-west towards The Anakies. Its close association with the Rowsley Fault is indicated by a similar sense of movement (downthrow to the east) and evidence of Late Pleistocene to Recent activity. Newer Basalt is warped across the monocline, and near Geelong the course of the Moorabool River has been modified by Recent movements.

In the south-west, a system of east-west structures extends along the north side of the Barrabool Hills to the Geelong suburb of Newtown, with uplift on the south and downthrow to the north. This structural trend extends east to near Curlewis on the shores of the Bellarine Peninsula. West of Geelong, uplift along a line south of the present Barwon River has resulted in the elevation of Mesozoic sandstones, now undergoing dissection to form the Barrabool Hills (Coulson, 1960). As in the structures further north, movement post-dates present drainage. At Queen's Park, Geelong, the valley of the Barwon has been interrupted by faulting and the river has cut a gorge through the uplifted block with a corresponding development of upstream terraces.

East of Geelong, along the southern shores of Corio Bay, the Curlewis Monocline controls the northern edge of the Bellarine Peninsula horst, where Miocene limestones and clays are warped down to the north and pass beneath the floor of Corio Bay (Coulson, 1933). The age of movements, by association with other faults in the area, is late Quaternary. The combined effects of these, and movements of similar age on the Lovelybanks Monocline, have produced a triangular fault-angle depression or local basin within the sunkland. When flooded by rising sea level, this formed Corio Bay.

The south-eastern margin of the Bellarine Peninsula is controlled by the Bellarine Fault, which Keble showed extending into Bass Strait to near Cape Otway in the south and across the floor of Port Phillip to Beaumaris in the north (Keble, 1946; Fig. 1, 2; 1950, Fig. 43). Later evidence from bores on the Bellarine Peninsula indicates the fault has a more northerly trend than indicated by Keble, and does not extend across Port Phillip Bay (see Spencer Jones, 1962).

In the north, the Beaumaris Monocline forms a north-easterly trending structure with downthrow on the south-east and uplift on the north-west. It is expressed in cliffs near Beaumaris where Pliocene ferruginous sandstones are warped into a dome near Rickett's Point. This structure controls the coastal indentation from Rickett's Point to Mentone and

Mordialloc. On the upthrown side, resistant sandstones form the cliffed headlands at Rickett's Point, while on the downthrown side Quaternary and Recent deposition has occurred at Mordialloc, Carrum and Frankston.

To account for a great increase in the thickness of Older Basalt near Flinders, Keble (1950) postulated a fault trending north-west across the southern side of the Mornington Peninsula towards Mud Island with downthrow to the south. He called this the Flinders Fault, but confirmatory evidence for its existence is not available.

Other structures of lesser importance have been suggested or established around the coast of Port Phillip Bay including the Gellibrand Fault (Condon, 1951), the Footscray Warp (Keble and Macpherson, 1946), the Chechingurk and Balcombe Faults (Keble, 1950) and Manyung Rocks Fault (Gostin, 1964). Their direct influence on the topography of the area is insufficient to warrant consideration here.

The main geological structures are reflected in the gravity anomalies recorded in the Bay by Gunson, Williams and Dooley (1959). The principal feature of the gravity map is the large negative anomaly in the south with positive anomalies on the east and west over both Mornington and Bellarine Peninsula horsts (Fig. 3). In the south-east, the trends of the anomaly contours correspond closely to the observed and postulated positions of Selwyn's Fault. Between Dromana and Cape Schanck where the fault crosses the Peninsula, steep anomaly gradients closely follow the fault scarp and cross the coast near Dromana. They then swing north-east, corresponding to the postulated off-shore position of the fault, dying out in intensity towards Frankston, where displacement decreases towards the hinge of the fault (Hills, 1951). A gravity contrast of 45 milligals exists between the negative anomaly centred near Mud Island and the "high" located over the Mornington Peninsula. The gravity minimum thus corresponds to the area of predicted maximum downwarping in the sunkland.

The gravity pattern suggests the existence of a second structure sympathetic with the Rowsley Fault located near Sorrento (Fig. 3).

The subsurface stratigraphy in the region of the anomaly, is known only from evidence in the Sorrento Bore. However, the thickness of Recent sediment in the Bay is insignificant compared to Tertiary and Mesozoic sequences in the area. Without detailed stratigraphic or density information, the magnitude of the total displacement can only be estimated from the Sorrento Bore where displacement in excess of 1,700 feet is indicated (Chapman, 1928) although total displacement of 3,000 feet to 4,000 feet is probably more realistic.

Further north, Tertiary and Mesozoic sediments probably decrease in thickness on Palaeozoic basement rising towards the areas of positive gravity anomalies in the northern parts of Port Phillip Bay and the coastal area near Beaumaris.

Small negative anomalies correspond to the structural depressions in the Carrum Swamp and Moolap Sunkland, but the established east-west structures from Geelong to Portarlington are not evident in the gravity picture. Moreover, the postulated Flinders Fault (Keble, 1950) is not reflected in the gravity evidence.

COASTAL GEOLOGY.

Rock types outcropping around the coast of Port Phillip Bay vary from east to west.

On the east coast, Palaeozoic granitic rocks outcrop on the Mornington Peninsula at Mt. Eliza, Mt. Martha and Arthur's Seat. Between Balcombe Bay and Frankston, the coastal sections are composed mainly of Tertiary Older Basalt, Tertiary calcareous clays and Upper Tertiary sandstones and one small occurrence of Mesozoic sandstone. Upper Tertiary sandstones also outcrop on the cliffed sections and foreshores further north from Beaumaris to Brighton.

Between Beaumaris and Frankston, in the low-lying area formerly occupied by the Carrum Swamp, Quaternary alluvium has accumulated. This is an area of local subsidence within the sunkland, formed by the combined effects of downthrow on the Beaumaris Monocline and Selwyn's Fault.

The western coastline of Port Phillip Bay lies close to the edge of the extensive Newer Basalt flows, which extend west to the South Australian border. The lithologies on the west coast from Williamstown to Geelong consist exclusively of Quaternary alluvium and Newer Basalt. Basalt is continuous from Williamstown to 3 miles north of the Werribee River, where low cliffs are cut in Quaternary alluvium. These extend 2 miles south of the river mouth to the basaltic plain which continues along the coast to Hovell's Creek, Corio Bay.

The eastern shores of Corio Bay are cut in horizontal Tertiary sands, limestone and calcareous clay. Deposits of Quaternary sandy clays form Point Henry Peninsula on the southern shores of Corio Bay, while Quaternary non-marine limestone occurs in the valley of Hovell's Creek at Limeburner's Point.

The northern shores of the Bellarine Peninsula near Curlewis and Portalington consist of Tertiary Older Basalt, limestone and calcareous clay. Upper Tertiary ferruginous sandstone forms cliffs east of Portarlington and near St. Leonards.

Aeolian deposits are widely distributed around the margins of Port Phillip Bay. These consist of two different types: siliceous dunes developed near Brighton, Frankston and on the Bellarine Peninsula near Drysdale, and calcareous dunes developed along the southern coastline between Cape Schanck and Barwon Heads. The siliceous dunes lie inland from the present coast and are now largely stabilized by vegetation. Large irregular dunes with deep podsolic soils occur near Frankston and extend west to near Cranbourne. Near Brighton and Mordialloc, the dunes have more regular longitudional form with low elongate crests and swales. Whincup (1944) suggested they were formed by north-westerly winds during a period of Quaternary aridity.

An additional siliceous dune occurs $1\frac{1}{2}$ miles in from the present coastline in the Carrum Swamp. It extends for approximately 8 miles from Frankston as a low ridge on which Wells' Road is built. From the existence of marine shell beds along the seaward edge of the dune, Hills (1940) concluded it was a coastal foredune stranded inland by coastal emergence.

The calcareous aeolianite is confined to the present coastline but continues to 428 feet below sea level in the Sorrento bore (Chapman, 1928). It extends from Cape Schanck along the Nepean Peninsula to Port Phillip Heads and Queenscliff. Its northerly extent is not defined, but shallow bores reported by Keble (1946, 1947) on the shoal near Mud Island penetrated a thin veneer of unconsolidated Recent sands to 30 feet, overlying dune limestone.

In the calcareous dunes, successive periods of dune formation alternated with periods of soil formation. Up to five buried soils have been recorded in dunes on parts of the Victorian coast (Hills, 1939; Boutakoff, 1963).

On the northern margin of Port Phillip Bay, in the region of the Yarra estuary, fluviatile sediments near Yarraville interfinger with marine and estuarine deposits (Dorman & Gill, 1958; Gill, 1961).

A large triangular-shaped deposit of alluvium occurs on the western coast and extends from the mouth of the Werribee River inland to the township of Werribee. River cliffs up to 25 feet high are cut in clays and sandy clays in this area which has been referred to as the Werribee Delta (Condon, 1951). Along the coast, deep fluviatile sediments extend 3–4 miles north and south of the river mouth. They were not deposited by the present Werribee River which cuts through them, and are not deltaic in any sense except that they occur near the present river estuary. They originated by deposition in an earlier (?Pleistocene) phase of stream activity in the area.

COASTAL GEOMORPHOLOGY.

Topographic relief varies considerably around the coast of Port Phillip Bay.

In the south-east, Palaeozoic granitic rocks at Mt. Eliza, Mt. Martha and Arthur's Seat rise to 500, 520, and 1,000 feet respectively. Further north, the coastal elevation rises from the lowlands of the Carrum Swamp, which is often only a few feet above sea level, to an undulating surface beween Beaumaris and Brighton, which averages 50 to 100 feet above sea level.

The western coast along the basaltic plain is one of uniformly low relief. Coastal elevations from Williamstown to Geelong never exceed 50 feet, and are rarely more than 20 feet above sea level. Relief increases in Corio Bay and along the Bellarine Peninsula, reaching a maximum near Curlewis, where Mt. Bellarine, 2 miles inland, reaches an elevation of 463 feet. From Portarlington, relief decreases towards St. Leonards until, from St. Leonards to Queenscliff and Point Lonsdale, the landward elevation of the coast is often only a few feet above sea level, as on the shores of Swan Bay.

Cliffs.

Relatively high cliffs alternate with sandy beaches along much of the eastern coast of Port Phillip Bay.

Cliffs in Pleistocene aeolianite occur in the occasional headlands on the north side of the Nepean Peninsula, between Point Nepean and Dromana. More extensive cliffs occur on the upthrown side of Selwyn's

Fault between Dromana and Frankston. Cliffs are cut in granitic rocks at Dromana, Mt. Martha and Oliver's Hill, near Frankston. Between Balcombe Creek and Frankston, cliffs are cut in Miocene clays and Pliocene ferruginous sandstone (Baxter Sandstone of Keble, 1950). This often forms resistant headlands as at Fisherman's Beach and Schnapper Point, Mornington (Chart I back of volume).

Further north, cliffs occur in Upper Tertiary ferruginous sandstone and unconsolidated sands (Sandringham Sands of Gill, 1957) in the rising topography near Beaumaris and continue north towards Sandringham, dying out as relief decreases near Brighton.

Along the eastern coast, the most active cliffs are developed on headlands, and often alternate with vegetated cliffs backing sandy beaches in protected bays, as in Canadian Bay, Frankston, and Half Moon Bay, Black Rock.

Comparatively few cliffs occur on the western coast, particularly between Williamstown and Geelong. The only cliffs developed in this area are cut in the alluvial deposits north and south of the Werribee River. North of the river mouth, low cliffs averaging approximately 15 feet high, extend 3 miles towards Point Cook. Further south in Corio Bay, steep active cliffs up to 50 feet high extend from North Shore to Eastern Beach, and recur on the tip of Point Henry Peninsula. The Eastern Beach cliffs are cut in marine Tertiary limestone, marls and sands (Bowler, 1962) but those on Point Henry Peninsula are developed in Pleistocene clays and sandy clays.

East along the Bellarine Peninsula, low cliffs are developed in tilted Tertiary clays and limestone (Coulson, 1933) and reach a maximum elevation of 30 feet near Portarlington. South-east of Portarlington, cliffed headlands occur at St. Leonards (30 feet in Pliocene ferruginous sandstone) and at Queenscliff, (approximately 50 feet in Pleistocene aeolianite).

On the higher energy ocean beaches facing Bass Strait, the coastline from Point Lonsdale to Cape Schanck is dominated by erosion. High cliffs are developed in aeolianite along this coast, reaching a maximum height of 180 feet near the ocean beach at Sorrento. Near Cape Schanck on the upthrown side of Selwyn's Fault, cliffs up to 300 feet high occur in Older Basalt.

Shore platforms.

Additional evidence of coastal erosion is provided by broad shore platforms developed on rocks of intermediate hardness around the coast in the Port Phillip region. They occur extensively on the cliffed ocean beach from Point Lonsdale to Cape Schanck. At Point Lonsdale, platforms extend seawards from the cliffs for almost a quarter of a mile, and are broken in places by deep channels. Hills (1949, p. 145), commenting on these, noted " they are remarkable for their almost perfectly plain surfaces, marred only by rare residuals, potholes and chasms, and equally for their horizontality, great breadth, and lateral extent."

Platforms developed within Port Phillip Bay are usually narrower and more limited laterally than those on similar rocks on exposed parts of the Victorian coast. At Point Lonsdale and Point Nepean, broad aeolianite platforms backed by high, actively eroding cliffs continue for only a short distance inside Port Phillip Heads, although the rock type remains unchanged. Inside the Bay, abraded dune limestone is covered by sandy beach deposits at Queenscliff and Portsea.

Jutson (1940) and Hills (1940) have described platforms developed in granodiorite at Mt. Martha. Here the widest platforms occur in zones of softer weathered rock on the northern and southern margins of the intrusion. The limited development in the centre reflects the resistant nature of the fresh rock to wave action.

Further north, platforms occur in ferruginous sandstone near Mornington, Frankston, Beaumaris and Sandringham, and a minor development is recorded on Newer Basalt near Williamstown (Hills, 1940). The best developed platform in the northern part of Port Phillip Bay occurs in horizontally bedded Pliocene ferruginous sandstone near Rickett's Point, Beaumaris. Here the near-horizontal platform extends seawards 300 feet from the cliffs which rise to 60 feet and form the headland at Table Rock. Eroded platform remnants form shallow bedrock outcrops near Brighton and St. Kilda.

A feature of the platforms in Port Phillip Bay is their almost exclusive occurrence on the east coast. The only occurrence on the west, besides that at Williamstown, is at Portarlington, where a small platform is cut in Older Basalt (Jutson, 1931).

The problem of platform development within Port Phillip Bay is complicated by the presence on the east coast of platforms above the level of present high tides.

Beaches.

Broad sandy beaches occur in two main regions on the eastern coastline of Port Phillip Bay. One extends 11 miles from Mordialloc to Frankston, the other 16 miles from Dromana Bay to Portsea on the northern side of the Nepean Peninsula (Chart I back of volume). These constitute the most extensive areas of clean, well-sorted beach sands in Port Phillip Bay. In the Mordialloc–Frankston region, the beach grades seawards into a broad zone of off-shore sands (see Beasley, this volume), and is supplemented on the landward side by a sandy foredune, running the length of the coast from Chelsea to Frankston (Hills, 1940; Whincup, 1944).

Smaller beaches in bay heads and pocket beaches alternate with eroding headlands on the Mornington Peninsula from Dromana Bay to Frankston, and further north from Beaumaris to near Brighton. These are usually narrow and relatively thin, and often rest on an abraded rock surface as at Balcombe Beach, Beaumaris, Sandringham and Brighton.

The eastern beaches are the popular holiday resorts in Port Phillip Bay, and have largely influenced the concentration of residential and tourist development on the east coast.

On the west coast, narrow sandy beaches extend continuously from Williamstown to Corio Bay. Often a thin veneer of sand overlies basalt and grades out to a shallow off-shore zone as near Altona, Point Cook, and south of Little River. The sands are usually poorly sorted and often carry large quantities of accumulated drift material, including decomposing seaweed.

Narrow beaches continue along the low cliffed area of the Bellarine Peninsula from Geelong to near Curlewis and Portarlington. Beyond Portarlington, the sand cover becomes broader and deeper due to increased exposure of the area to currents and waves. Near Queenscliff and Point Lonsdale, exposure to tidal currents and ocean swell through Port Phillip Heads has developed a broad well-sorted sandy beach overlying abraded dune limestone.

Grain sizes and mineral composition of beaches varies around the coast. In a detailed study of the beach sands of the Brighton area, Baker (1963) recorded significant variations in sorting, median parameters and mineral constituents over short distances along the coast. Beach sands here consist principally of detrital quartz with the content of calcareous shell fragments varying between 7 per cent. and 35 per cent. (Baker, *op. cit.*, Table 10).

Off-shore bars.

Shallow off-shore sand bars occur opposite beaches on both the east and west coasts of Port Phillip Bay.

On the east coast, they extend from Mordialloc to Frankston, and from Dromana to Sorrento. In the Mordialloc–Frankston region, several bars often remain parallel to the beach for up to seven miles. The number of bars may vary in places, although two are usually present from Mordialloc Creek to Seaford. At Frankston in August, 1960, two bars were present north of the jetty, but by August, 1964, three bars had formed in this area. These persisted at least until February, 1965. Over much of their length, the regularity of bars is affected by annual and seasonal variations in winds and waves. Near Seaford, however, the bars are nearly always irregular, and small lobate bars separated by rip channels often develop obliquely to the beach.

On the Nepean Peninsula, irregular bars commence in Dromana Bay, and become very complex further south near Rosebud where a system of multiple bars extends in a continuous zone to near Sorrento. In this zone near Rye and Blairgowrie, seven to eight bars are parallel to each other and sub-parallel to the beach. They occur in water 7 feet to fifteen feet deep on a sandy shoal extending 2,500 feet off-shore until the outer edge drops steeply to 40 feet in Capel Sound. On the seaward edge of the shoal the bars are regular, but become more irregular towards the shore, where in places lobate and oblique bars emerge to form small sand barriers. These join the beach and result in complex cuspate structures.

A single bar runs the length of Balcombe Beach, maintaining a position approximately 700 feet off-shore, and joins the southern headland, Balcombe Point.

In the shallow waters along the west coast, a system of small irregular bars extends from Altona, south towards Point Cook and to beyond Little River. At low tide, low ridges and runnels belonging to this system are exposed e.g. near Altona. At low water, waves often break on the outer limit of the bar shoal which varies in depth from 5 feet to 10 feet below low water. In the north, the shoal extends 1,600 feet off-shore, comes in to near 500 feet off Point Cook and remains parallel to the coast down to the Werribee River. Off the mouth of the river, two parallel bars are displaced seawards. These approach the coast again south of the river, and the bar system follows the coast to Little River and Kirk's Point, where the shoal again extends further out to sea towards Point Wilson.

Bar development on sandy shoals is more persistent along the entire length of the west coast than on the east, where single and multiple bars are developed only off sandy beaches. But in the east coast systems, individual bars are larger and more regular than on the west, suggesting differences in the controlling wave energy from east to west.

Bars form only in the shallow off-shore zone where bottom sands are constantly moving in response to changing winds and wave conditions.

Near-shore topographic profiles have been constructed from detailed charts prepared by Cox (1861, 1862) with soundings taken at approximately every 120 yards. Although these do not show individual bars, they reveal a consistent topographic break on the edge of the sandy shoal on which the bars occur. On the east coast, this break occurs at approximately 24 feet in both the Mordialloc–Frankston and Dromana–Rosebud areas (Fig. 4). On the west coast, the break occurs at approximately 14 feet, with some variations along the coast depending on local bedrock outcrops. The entire shoal is a depositional feature in the shallow zone of relatively high wave energy. The depths to the topographic break on the outer edge reflect variations in wave energy distribution from the beach to the off-shore zone on different parts of the coast.

Sand Ridges.

Around the coast of Port Phillip Bay, a variety of sand ridges occurs, many of which lack the characteristic features of true beach ridges as described by Johnson (1919) and Davies (1958).

Widely separated low sand ridges with lobate landward extensions are associated with shell beds containing Recent faunas from near Altona to Point Cook. These lack the closely spaced, fine-textured " crest-and-swale " topography of true beach ridges as noted by Hills (1940), although sometimes regarded as such (Gill, 1961).

Near Point Cook, a narrow sand belt with a low ridged topography follows the coast south towards the cliffed section north of the Werribee River. The ridges are closely spaced, but weakly defined unlike typical beach ridges.

At Point Richards near Portarlington, a ridged foreland has developed over shell beds, but again lacks the fine-textured beach ridge topography. Sand ridges are still developing on the present coast of the foreland, some of which have not yet been fixed by vegetation.

At Observatory Point near Point Nepean, vegetated parallel sand ridges extend 1,000 feet inland from the present coastline. Here a linear " crest-and-swale " topography has developed resembling the beach ridges described by Davies (*op. cit.*). Ridges have developed under the influence of refracted swell entering the Bay through Port Phillip Heads. They are thickly vegetated and are not developing under present conditions.

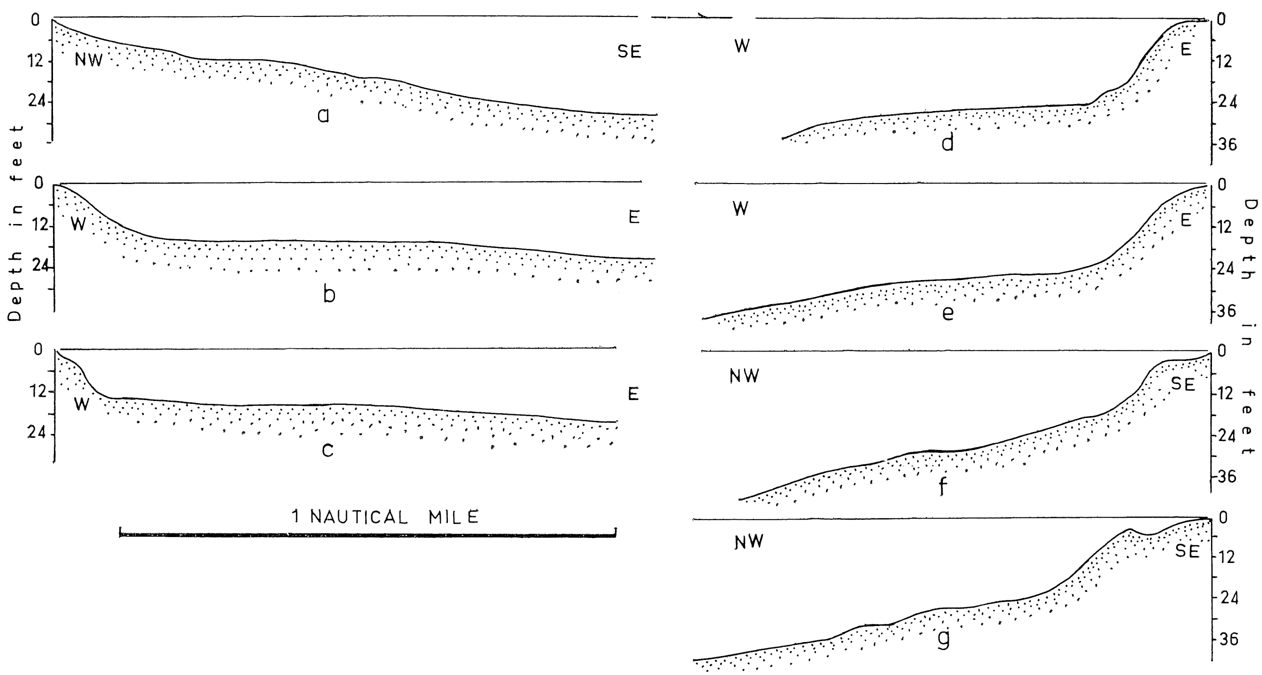


Fig. 4.—Near-shore topographic profiles constructed from detailed soundings of Cox (1861, 1862). Profiles a–c are from the west coast, d–g from the east coast. Shoals developed close to the shore constitute zones of mobile sand, often carrying off-shore bars. These zones are subject to rapid profile changes in response to local sand and wave conditions. The outer edge of the sand shoal drops into deeper water off the east coast than the west, reflecting the high-energy wave conditions generated on the east coast by exposure to northerly and westerly winds.

At Swan Point, on the eastern tip of Swan Island, a cuspate foreland of sand ridges has developed during historic time. Here little vegetation cover has been established; the ridges are stabilized only by a sparse grass cover. A comparison between recent photographs of the area and the oultines of the island surveyed by Cox (1864) shows a progradation of approximately 800 feet along half mile of coastline during the last 100 years.

On the eastern side of the Bay between Mordialloc and Frankston, a sand ridge or coastal foredune extends along the present coastline of the Carrum Swamp (Hills, 1940). Near Aspendale, two parallel ridges occur south to Frankston with Kananook Creek developed in the swale between. These are aeolian foredunes, resting on beach deposits as shown by Whincup (1944).

The coastal sand ridges, with the exception of those at Swan Point and the tip of Point Richards, have developed under conditions which no longer exist in Port Phillip Bay. Many are stranded inland above the level of present high water, and have developed while sea level was relatively higher than at present.

In summary, the coastal features on the east are geologically and physiographically distinct from those on the west (cf. Jutson, 1931, and Hills, 1940). Not only do geological structures and lithological types vary from east to west, but also the extent of erosional and depositional features developed. Cliffs and shore platforms, common on the east, are rarely and only weakly developed on the west. Broad well-sorted sandy beaches, sometimes with a coastal foredune, are more representative of the east coast than the west.

The most extensive sand ridge development occurs on the west coast. This has sometimes been regarded as exhibiting the greatest degree of progradation (Jutson, 1931), but the west coast has maintained an irregular outline even though it has low relief, and only a small quantity of sediment is necessary to produce coastal straightening. The smooth arcuate beaches on the eastern coast formed by extensive infilling of formerly large coastal indentations, have no equivalents on the west. The alternation between erosion on headlands, and deposition in bays, characteristic of the east coast does not occur on the west. Moreover, the observed progradation by sand ridge construction is not due to accretion at present sea level but is complicated by possible tectonic and eustatic factors in the coastline evolution.

SUBMARINE GEOLOGY.

Topography.

The bathymetric contours and cross-section (Fig. 5) show Port Phillip Bay is deeper on the east than on the west. The near-shore region on the east, especially near Frankston and Mt. Martha, maintains a steeper gradient than corresponding areas on the west. This asymmetry is due to the major influence of Selwyn's Fault with the fault-angle depression developed close to the Mornington Peninsula.

During 1964, continuous fathograms were obtained on selected traverses across the Bay. The location of traverses is shown on Chart I. (back of volume) with corresponding topographic sections at reduced scale in Fig. 6.

Allowing for vertical exaggeration, the sea floor from east to west across the Bay is very flat with small irregularities confined to the western side. The steepest slopes on the irregularities shown on traverses B–B and C–C, when reduced to natural scale, have gradients of 1 in 37 and 1 in 66 respectively. Both are in the area regarded by Keble (1946) as the location of a drowned river channel formerly continuous with the Yarra River. Initial irregularities on the land surface which was submerged by marine transgression in the formation of Port Phillip Bay, have either been eroded down by wave action or smoothed out by the uneven deposition of Recent sediment.

Recent sediments.

In cores obtained by the author from the floor of Port Phillip Bay, two separate formations are represented:

(*a*) Recent marine sediments which disconformably overlie;

(*b*) an older formation, represented usually by the bottom few inches in some cores.

The main features distinguishing the two formations are summarized in Table 1.

TABLE 1.

Recent Marine Sediments.	*Older Formation.*
Unconsolidated sands, silts and clays ..	Consolidated clays, and sandy clays.
Carbonate common in foraminiferal and and molluscan shells.	Carbonate rare, occasionally in nodules indicating secondary mobilization and cementation.
Unoxidized, mottling rare	Evidence of oxidation common, mottling common.
Non-micaceous	Sometimes micaceous.
Clays unorganized	Clays often organized into ped and cutan structures typical of soil organization (Brewer, 1960).
Plant remains absent	Plant remains sometimes present as root fibres.
Recent foraminifera	Replaced Tertiary foraminiferal moulds.

Summary of the characteristic features of the two formations represented in cores through Recent sediments in Port Phillip Bay.

All the characteristic features of the older formation are not necessarily present in any one core, e.g., in-shore near Sandringham Harbour the older formation is represented by oxidized Tertiary sands with limonitically replaced foraminiferal moulds, but 2½ miles south of Sandringham, 4 feet of Recent sediments rest on stiff consolidated silty clays showing soil organization (peds and cutans). Underwater coring in the older formation is difficult due to the stiff consolidated nature of the material. Maximum penetration into this material of only 1 foot has been effected, and extraction of the corer at this depth proved difficult even with a powerful winch.

Of the 50 cores from the northern part of the Bay, the older formation is represented in seventeen. Cores from near-shore stations often penetrate only 1 foot or 2 feet before encountering the older material. Of those from depths greater than 30 feet, ten have reached the older surface after penetrating an average of 3–4 feet of Recent marine sediments, and sixteen failed to reach the base of Recent sediments after penetrating 6 feet to 8 feet. Further south, a core in water 60 feet deep near the West Pile Light, $2\frac{1}{2}$ miles east of St. Leonards, penetrated 10 feet into Recent marine sands without reaching the base of that formation.

The thickness of Recent sediment is therefore variable throughout the Bay. In the north, which is an area of relatively high deposition close to the Yarra estuary, Recent marine sediment forms only a thin cover on the older consolidated material. But in the south near the Nepean shoal, a deeper sand cover has accumulated under the influence of strong tidal currents through Port Phillip Heads.

Samples from two cores in the Recent sediments were submitted to Mr. A. C. Collins who kindly examined the foraminiferal content. The cores studied were No. 19 from a depth of 50 feet and No. 25 from 57 feet, located $2\frac{1}{2}$ miles W.S.W. and 4 miles S.W. from Sandringham Harbour respectively. The cores consist of 153 cms. (No. 19) and 115 cms. (No. 25) of marine silty clays. The foraminiferal assemblages reported by Mr. Collins showed significant differences in ecology from top to bottom of the cores. The bottom samples yielded assemblages typical of enclosed Victorian waters (39 species were recovered from No. 19, 22 from No. 25). The top samples furnished fewer species (17 from No. 19, 13 from No. 25), both of which were dominated by *Ammonia cf. beccarii* (Linne). This genus has a wide tolerance of salinity variation but favours low salinity, and is often found in estaurine or lagoonal environments (Collins, pers. comm.). Its occurrence indicates a salinity decrease in Port Phillip during the period of deposition represented by the sediment in the cores.

A full description of cores is being provided by Link (1965).

Bedrock outcrops.

In shallow areas, bedrock sometimes outcrops through a thin cover of Recent sediment to form rocky shoals or "reefs".

On the west coast, basalt outcrops on the sea floor near Williamstown, Altona and Point Cook, and forms a submarine ridge south from Point Lillias and Point Wilson in Corio Bay. A basalt sample from the Point Wilson ridge obtained during dredging is a medium to fine grained vesicular iddingsite labradorite basalt. It is identical with flows on the plains near Geelong, and it therefore was extruded under sub-aerial conditions before the formation of Port Phillip Bay.

On the east coast, resistant submarine outcrops of Pliocene ferruginous sandstone occur at the Anonema Shoal south of Sandringham, near Beaumaris and off Fisherman's Beach, Mornington. Extensive areas of rock also occur off headlands on the Mornington Peninsula between Frankston and Balcombe Bay as well as in the north from Beaumaris to Black Rock and Brighton.

Tidal scour often exposes bedrock in channels near Port Phillip Heads and on the Nepean shoal. Channels are cut in Pliocene ferruginous sandstone off St. Leonards and in Pleistocene aeolianite near Port Phillip Heads. Eroded benches and cavernous undercut ledges in dune limestone have been examined by the author to approximately 80 feet below sea level near the entrance to Port Phillip Bay and are known to continue to much greater depths. In the narrowest constriction between Point Lonsdale and Point Nepean (Fig. 7), a deep tidal colk with near vertical sides has been scored to nearly 300 feet (Armiralty Chart 2747; Benson and Raeside, 1963).

EVOLUTION OF PORT PHILLIP BAY.

Terracing and Eustatic Sea Level Changes.

Evidence from coasts throughout the world has clearly established the significance of the post-glacial rise in sea level which commenced approximately 18,000 years ago when sea level was some 300 feet lower than at present (Shepard, 1961; Fairbridge, 1961). The rise to near its present position has flooded river valleys, estuaries and lowlands in many parts of the world. In Victoria, both Port Phillip Bay and Westerport Bay (Fig. 1) owe their present outlines to the combined effects of tectonic movements which formed the sunklands, and the post-glacial eustatic rise which later flooded them.

Keble (1946, Fig. 2) has used the bathymetric contours of Port Phillip Bay to reconstruct the course of the Yarra trunk stream and its tributaries which drained the former land surface now occupied by Port Phillip Bay. He showed the Yarra discharging through the centre of the area now occupied by the Bay, picking up tributaries from east and west, and passing south to the ocean across Nepean Peninsula. On the ocean side of the Peninsula, submerged outlets or tideways and river channels were postulated from indentations in the bathymetric contours. However, detailed fathograms obtained by the author inside the Bay across the projected underwater trend of the Werribee and Little rivers, has provided little evidence for the existence of channels in the present submarine topography. In the north, submarine irregularities on the profile B–B, may represent the valley of the Yarra River, but on the next profile south (C–C) and remaining profiles, stream courses cannot be recognized. Additional fathograms from the ocean side of the Nepean Peninsula have revealed no evidence of the tideways and river channels claimed by Keble. Jennings (1959) has further questioned the reliability of the seaward extension of the Yarra channel into Bass Strait (Keble, 1946, Fig. 12). Similarly, evidence for eustatic terraces inside the Bay as claimed by Keble (*op. cit.*) do not show on continuous soundings in Fig. 6. Traverse E–E south of Little River is close to the line of section illustrated by Keble (1950, Fig. 43) but does not show terraces at the depths claimed. They were probably due to inaccuracies in contouring and the choice of the section line position rather than to real breaks in slope at consistent depths.

On the ocean side of the Nepean Peninsula in King Bay Sound, bathymetric contours show an undulating topography sloping away from the coast to the relatively flat sea floor of Bass Strait at approximately

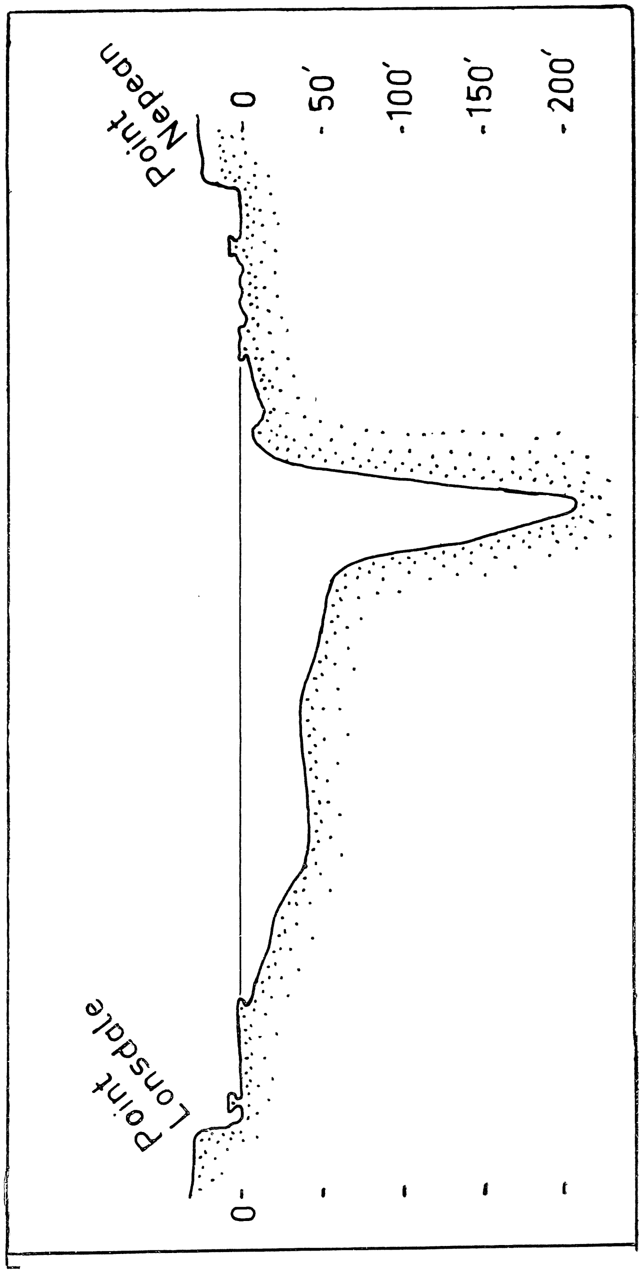


Fig. 7.—East-west topographic section across Port Phillip entrance, showing the deep scour channel cut in aeolianite at the point of tidal construction.

40 fathoms deep. From a reconstructed contoured chart of this area, Keble (1946, Fig. 8) illustrated eustatic erosion benches at 42 feet, 84 feet, and 210 feet, and later at 120 feet and 210 feet (Keble, 1950, Fig. 42). These like the eustatic levels inside the Bay, were not reproduced by continuous soundings in the area.

Eustatic sea level changes have been further invoked to explain river terraces in the valleys of the Werribee and Maribyrnong Rivers and Moonee Ponds Creek. In the Maribyrnong River, Keble and Macpherson (1946) recognized three terraces which they named Keilor, Braybrook and Maribyrnong. Gill (1955, 1961) modified this sequence to include an older and higher terrace and excluded the Braybrook. The sequence as presently known at Keilor, from highest (oldest) to lowest (youngest) is Arundel, Keilor and Maribyrnong. The Arundel terrace, which continues into the Yarra Delta, is correlated with a warmer period before the last glaciation corresponding to the Riss–Würm interglacial in the European sequence (Gill, 1961). A sequence of carbon samples obtained through the Keilor terrace sediments have yielded the following radiocarbon dates:

8,500 (± 250), 15,000 (± 1,500) and 18,000 (± 500) (for earlier references see Dury, 1964).

The terrace sediment was therefore deposited at the end of the last glaciation and during the post-glacial transgression. The Maribyrnong terrace represents the river flood-plain adjusted to present sea level.

Pleistocene Tectonism and the Formation of Aeolianite.

In an area of tectonic instability such as the Port Phillip Sunkland, it is difficult, and sometimes impossible, to evaluate the relative importance of tectonic deformation and eustacy especially when both processes may have operated simultaneously.

Definite evidence of late Quaternary faulting exists on the west where late flows of Newer Basalt are tilted near Geelong, and drainage is affected in the valleys of the Barwon, Moorabool and Werribee rivers. Further evidence of the extent of Pleistocene downwarping in the sunkland is provided by the occurrence of Pleistocene dune limestone to 428 feet below sea level in the Sorrento Bore (Chapman, 1928).

The significance of calcareous aeolianite in the evolution of Port Phillip Bay depends on the environment in which it formed. Formation during periods of low sea level has previously been suggested, based largely on evidence of aeolianite in Bermuda with similar buried soils, sedimentary structures and mineral composition. This was regarded by Sayles (1931) as having formed during periods of glacial low sea level. Formation near present sea level was later postulated by Bretz (1960) and confirmed by MacKenzie (1964).

In the Victorian aeolianite, the following features also suggest formation near present sea level:

1. In plan, the dunes are coincident with the present coastline intermittently from Portland in the west to Wilson's Promontory in the east. Seaward occurrences are limited to within a few miles of the present coast. Formation during glacial periods would require accretion of a transverse dune ridge inland from

the sand source along the glacial shoreline, which was then situated many miles southwest of its present position. This is inconsistent with the development of modern transverse dunes, which are always located close to the sand source.

2. The occurrence of up to five buried soils in dunes along much of the coastline indicates five alternate periods of stability and accretion. The superposition of alternatively younger dunes over older, separated by a soil horizon, requires an abundant source of calcareous sands close to the dune ridge during successive stages of dune accretion, a coincidence explained only by the occurrence of an active beach on the seaward side of the dunes.

3. The dunes show no evidence of submergence by interglacial high sea levels as might be expected if they had formed during periods of low sea level.

4. The depth to which aeolianite occurs in the Sorrento Bore (428 feet) is below the average depth of Bass Strait (approximately 300 feet), and below the deepest level accepted for glacial reductions in sea level. Some tectonic downwarping is therefore necessary even if the glacial theory were accepted.

The Victorian aeolianite, as in Bermuda, is therefore best explained by deflation of calcareous beach sands while sea level was close to its present position. Accumulation occurred during interglacials with intervening periods of stability and soil formation during phases of lower sea level. A similar account has been independently proposed by Boutakoff (1963) from a study of dunes in the Portland area. Jennings (1961) has also suggested formation of calcareous dunes on King Island, in Bass Strait, under climatic conditions similar to those of the present day.

The deep occurrence of aeolianite in the Sorrento Bore is due almost entirely to Pleistocene downwarping, which therefore exceeded 400 feet in the sunkland. In the same bore, an horizon at 498 feet containing Recent mollusca " exactly resembles estuarine beds " found at the mouths of present Victorian rivers (Chapman, *op. cit.*, p. 180). This provides further support for a large negative movement in the Port Phillip area during the Pleistocene.

Coastal Emergence.

The evidence of Recent coastal emergence in Port Phillip Bay has been disputed by many workers since the early studies of Selwyn (1854) and Lucas (1887).

Jutson (1931) reviewed the problem, but like Pritchard (1910), he was unable to cite conclusive evidence of emergence. Hills (1940), in a comprehensive examination of the evidence stated (p. 84), " definite evidence of Recent emergence has been observed at practically all localities where the conditions of erosion and deposition are such as to favour its preservation ".

At many places on both the east and the west coast, beach deposits and shell beds occur inland and often rise above the level of present high water. On the south-east, Hills (*op. cit.*) described high level beach deposits extending from near Sorrento to Dromana, which rise 5 feet to 6 feet above present high water. The bedding of shells, occurrence of paired valves, and the preservation of ornament and fragile shells indicate deposition below the swash zone, or even lower (Hills, p. 90, 1940). The extension of similar beds with Recent marine mollusca south into the Tootgarook Swamp was later established by Keble (1950).

In the Carrum Swamp, north of Frankston, marine shell beds extend inland to the stranded foredune near Wells' Road (Hills, *op. cit.*). The original level of the shell beds above present sea level is not known since compaction of the swamp occurred after draining. The absence of beach ridge development between Wells' Road and the present coastal foredune indicates a shift in coastline by means other than normal progradation, as indicated by Hills.

In the northern part of the Bay at Port Melbourne, formerly known as "Sandridge", a system of coastal ridges existed on the seaward side of the West Melbourne Swamp. These were recorded by Selwyn (1854) and by Lucas (1887) as rising $7\frac{1}{2}$ feet to 10 feet above highwater level. They rested on sands and Recent shells 2 feet above high water (Jutson, 1931), but have now been destroyed by industrial development and little detailed information is preserved (see also Pritchard, 1910, p. 41).

In the south-west, evidence of a former strandline occurs from south of St. Leonards to near Ocean Grove. In this area, widespread shell beds are located slightly above high water. Jutson (1931) noted,

> "the low-lying area in which Recent marine shells occur, between the high Tertiary belt and the Point Lonsdale–Ocean Grove ridge, comprises—
>
> (*a*) several low isolated ridges more or less elongated (which were islands in the ancient sea) and a less elongate 'peninsula', all of dune limestone, and
>
> (*b*) four lakes of varying size".

The lakes represent remnants of a shallow sea which once occupied this area and has now retreated to Swan Bay. They are isolated from the sea and from each other by a complex development of barriers and beach ridges (Gill, 1948). Thick shell beds occur on the floor of the Lake in well-stratified deposits with gently inclined bedding planes (Hills, 1940).

On the northern side of the Bellarine Peninsula near Portarlington, a system of weakly developed ridges and associated shell beds forms a cuspate foreland at Point Richards. The coastline has prograded approximately 3,000 feet from the landward margin of the ridges which mark the former position of the shoreline. Further west, on the south-western shore of Corio Bay, Jutson (*op. cit.*) recorded an oyster bed of Recent origin up to 8 feet above high water.

Shell beds occur extensively along the west coast from Corio Bay to Port Melbourne. They continue along the valley of Hovell's Creek 2 miles inland to Geelong Road (Hills, *op. cit.*), and were also recorded near Little River (Jutson, *op. cit.*).

From the R.A.A.F. base at Point Cook to near Skeleton Creek, further evidence of progradation is provided by the belt of sand ridges plastered along the coast.

Further north, a system of sand and shell ridges in the Altona–Williamstown district has been the subject for considerable discussion. Low dunes and swales run parallel to the coast for approximately 5 miles, and extend $\frac{1}{2}$ mile inland to near Lake Truganina and Lake Altona. The ridges number seven or eight and are relatively low and broad as recorded by Hills (1940) who noted that "a ridge 4 chains wide is only 4 feet to 5 feet above the neighbouring swales". This contrasts with normal beach ridge morphology which is typically high compared with its breadth (Hills, *op. cit.*, p. 96). Jutson (1931) and also Pritchard (1910) in earlier examinations of the area believed the sand ridges could form at or near present sea level. Hills however, showed that although the ridges are now situated above high water, they had in part formed below high water. He concluded they were emerged submarine bars similar to those found on the sea floor in other parts of Port Phillip Bay.

Gill (1961) later described two separate formations—stratified marine shell beds overlain by superficial sands which form the ridges. He suggested their formation by slight eustatic fall in sea level accompanied by normal beach ridge building.

Link (1965) has recently postulated their development by the growth of sand spits from south to north accompanied by a fall in sea level.

In the region of the Yarra Delta, Gill (1956) has recorded marine faunas approximately $7\frac{1}{2}$ miles upstream from Hobson's Bay in the valleys of both the Yarra and Maribyrnong rivers. In the latter region, marine shells occur *in situ* near Essendon to 4 feet above low water mark.

Additional evidence of emergence of the shores of Port Phillip Bay is provided by shore platforms now above sea level and by the common occurrence of inactive, vegetated cliffs. Shore platforms cut in both granite and Tertiary ferruginous sandstone were recorded by Hills (1940) to elevations of 3 feet above present high water. Near Dromana Bay and Frankston they are overlain by cobbles and shingles above the reach of present high tides and similar to cobbles found on present beaches in the area. On the south side of Picnic Point, Hampton, a raised shore platform in ferruginous sandstone occurs to 6 feet above present high water (Gill, 1950). This is backed by a former sea cliff now inactive and covered by younger detritus. Vegetated cliffs occur in most small bays on the eastern coast. These have been explained by a relative change in the level of sea and land which would allow erosion to continue on headlands and on areas opposite deep water, while reducing wave attack on shallow bay heads (Hills, *op. cit.*).

There is, therefore, ample evidence that the coastline in many places was once situated further inland on both the east and west side of the Bay. The change to its present position was not due to simple progradation but was accompanied by a change in the relative level of land to sea, of from 2 feet to 10 feet. The shells examined from the high level shell beds consist exclusively of living forms, and this, with the physiographic evidence cited above, established the Recent nature of the emergence as stressed by Hills, and later confirmed by radiocarbon dating.

From the differential elevation along and across an emerged shore platform in granite at Dromana Bay, of shell beds at Hovell's Creek, Sorrento, and Portarlington, Hills concluded that the emergence was at least in part due to tectonic deformation, assisted by a Recent eustatic fall in sea level, the evidence of which exists in many places along the southern coast of Victoria (Hills, *op. cit.*, p. 100). Keble (1950) has invoked both tectonics and eustatics to explain—

1. warping of submarine terraces in Port Phillip (the existence of which have here been questioned), and
2. the recently emerged shell beds in Tootgarook swamp.

Gill (1956, 1961) regarded the shell beds of Port Melbourne, Altona and Hovell's Creek as due to eustatic sea level change accompanying the post-glacial climatic optimum. In support of this claim he has obtained radiocarbon dates from sites of emerged shell beds as follows:

wood fragment bored by *Teredo* in shell bed from Maribyrnong Valley near Essendon	4,820	(± 200)	
shells from emerged shell bed on right bank of Hovell's Creek near Geelong	5,620	(± 90)	
shells from Altona shell beds overlying basalt	5,560	(± 80)	(for early refs. see Dury, 1964).

Although the detailed effects of eustatics and tectonics are not yet clear, there is substantial evidence to support a relative change in level between land and sea in post-Pleistocene time. The widespread evidence of Recent emergence, although complicated locally by tectonic deformation, is consistent with a small mid-Recent change in sea level recorded by many workers from widely separated parts of the Australian and New Zealand coasts (Davies, 1959; Fairbridge, 1961; Jennings, 1961; Schofield, 1964).

Age and Depositional Environments.

Before the marine transgression, most of the area now occupied by Port Phillip Bay was a land surface. This surface is now represented by the older formation containing relict soil features recovered in cores through Recent sediment in the northern part of the Bay. In this formation, the zone with soil structures and plant rootlets represents the upper few feet of the former land surface. For this to be preserved, little erosion could occur during marine transgression. This is consistent with the flooding of a low-lying estuarine environment similar to that now found on the coast of Westernport Bay. In such an environment, shoreline deposition rather than erosion would occur. Extensive erosion would commence only when the transgression encroached to areas of moderate relief, by which time the combined effects of longer fetch and deeper water would permit wave attack on the coast.

Assuming that any Recent deformation in the centre of the Bay was small compared to present water depths, an estimate of the time at which marine flooding of the sunkland occurred can be made from the depths at which the older formation is now found in the Bay. The deepest occurrence so far obtained is in water 56 feet deep, 4½ miles east of Point Cook (core 29). The older sediment was encountered here 6 feet below the surface of Recent marine sediment, i.e. at 62 feet below sea level. The age of flooding of a surface at this level can be estimated from the established curves of the post-glacial sea level rise from other parts of the world (Fairbridge, 1961; Shepard, 1961; Curray, 1960). Sea level was approximately 60 feet lower than present during the period from 9,000 to 8,000 years ago. This correlates with the evidence of a eucalypt recovered *in situ* 63 feet below sea level during excavations for the Spencer Street bridge. Samples have yielded radiocarbon dates of 8,780 (± 200) and 8,300 (± 310) (Gill, 1955, 1956).

A single valve of *Anadara trapezia* found in core 18, located 2½ miles west-south-west from Sandringham Harbour in water 47 feet deep, was submitted for radiocarbon dating. This core consists of 76 cms. of Recent calcareous sands and clays overlying 10 cms. of stiff consolidated sandy clays of the buried soil. The molluscan valve selected for dating was located at 73 cms. in the core, 3 cms. above the contact with the buried soil, and yeilded a radiocarbon age of 5,990 (±160) (N—155). This is consistent with the age of the marine transgression across the soil surface as estimated from the known rates of sea level change in post-glacial time.

Assuming that transgression in this area occurred approximately 8,000 years ago, the rate of later marine deposition in the northern part of the Bay can be determined from the thickness of Recent marine sediments overlying the buried soil. This varies in the north-central part of the Bay from 3 feet to more than 8 feet corresponding to sedimentation rates of approximately 0·4 feet to 1 foot per 1,000 years.

From the foraminiferal evidence quoted earlier, the environment in which deposition occurred after the transgression 8,000 to 9,000 years ago, was of higher salinity than in the same area today. The Recent decrease in salinity may be due to an increase in the relative percentage of fresh water to oceanic water in the Bay brought about by:

1. A Recent increase in the discharge of streams flowing into the Bay, resulting from increased precipitation.
2. A decrease in the evaporation rates within the Bay.
3. A restriction of the inward flow of oceanic water by a Recent narrowing of the entrance to Port Phillip Bay (cf. Hall, 1909, p. 77).

The aeolianite barrier now forming the Nepean Peninsula, was already in existence before the formation of Port Phillip Bay. The entrance to Port Phillip Bay, cut through the aeolianite, is still actively eroding. Contrary to the suggestion by Hall, the entrance has probably never been wider than in its present form.

On the other hand, independent evidence exists for a mid-Recent period of mild aridity 6,000 to 4,000 years ago with lower rainfall and higher evaporation rates than at present. The age of the climatic optimum is in close agreement with the estimated age of sediments deposited during the period of high salinity. The close correlation between these two events suggests that salinity changes were climatic effects brought about by changes in temperature, evaporation rates and precipitation in the Port Phillip area.

PRESENT ENVIRONMENT.

Sediment Transport and Coastal Changes.

The physiographic variations between the east and west coasts of Port Phillip Bay depend not only on lithological and structural differences but also on the direct influence of the present system of currents, winds and waves in the area. These determine the patterns of erosion, transportation and deposition.

Sediment is transported in the shallow marine environment mainly by two types of currents:—

(*a*) tidal currents and

(*b*) wave generated currents.

Although little detailed information is available on water circulation patterns due to either of these processes in the Bay, some general observations can be made.

In the south near the Nepean shoal, the influence of tidal currents is dominant. The pattern of scoured channels and shifting shoals is controlled almost entirely by the ebb and flood tidal streams, which at Port Phillip Heads reach velocities to 8 knots (see The Australia Pilot, 1956). Moreover, the effects of waves and wave-generated currents is minimized near the entrance to Port Phillip Bay by the protection offered from all but northerly and north-westerly winds.

In the northern and central part of the Bay, the combined effects of exposure to winds from all directions, long fetch, and relatively deep water, permit the development of high wave energy. Tidal currents are weak and thus waves and wave-generated currents control sedimentation. The magnitude and rapidity of coastal changes, resulting from changes in winds and wave conditions, was spectacularly demonstrated during July, 1964, when a series of intense cyclonic depressions passed south of the Victorian coastline. These caused steep pressure gradients over southern Victoria with gale force winds often reaching more than 30 knots, and generated steep storm waves which caused extensive damage to the eastern shores of Port Phillip Bay.

The approach of each depression from the west was preceded by strengthening northerly winds reaching gale force. The winds backed to moderate westerlies and finally to weaker southerlies as the depressions moved east away from the coast into the Tasman Sea.

Storm waves and strong rip currents generated by northerly gales stripped sand off the beaches, especially off those oriented obliquely to the direction of wave fronts and exposed to long fetch as on the eastern and south-eastern sides of the Bay. At Fisherman's Beach near Mornington, erosion on the northern end completely stripped sand back to the sea wall protecting the cliffs. Simultaneous deposition occurred at the southern end where the beach prograded seawards more than 50 feet.

At Balcombe Beach near Mt. Martha, similar changes occurred. A sandy beach to 5 feet deep and 100 feet wide was stripped for a length of nearly 600 feet from the northern end, while simultaneous deposition occurred further south. Boatsheds were undermined and many completely destroyed. The beach was cut back to the foot of the cliff and active erosion was initiated in freshly exposed Tertiary lignitic clays. Progradation on the southern end of the beach resulted in the deposition of a cuspate foreland 200 feet wide, south of the mouth of Balcombe Creek which was blocked by the deposition of a high berm.

On the coast between Mordialloc and Frankston extensive erosion occurred near Seaford. This was accentuated by the presence of groynes which impeded the littoral drift, thus concentrating erosion on the downdrift side. On the immediate downdrift side of a groyne, the beach was eroded back 50 feet to the backshore region, accompanied by a lowering of more than 5 feet. Cliffs up to 10 feet high were cut in the foredune behind boatsheds on the foreshore, many of which were undermined and destroyed. Eroded sands were deposited off-shore, producing shoals separated by rip channels which remained visible from the beach for more than two days.

After a northerly storm on July 1st and 2nd, weaker southerlies and south-westerlies initiated the return of sand to the erosion sites by on-shore drift. But further severe depressions followed throughout July and early August, and the events of the early storms were repeated. The climax was reached on July 12th when the atmospheric pressure dropped to 28·96 inches (980·6 millibars), the lowest July pressure ever recorded at Melbourne, and the lowest pressure since December, 1863. This was accompanied by gale force north-westerly winds with gusts over 60 m.p.h.

By late August, much of the sand had returned to areas previously stripped by erosion. By December, sand had been restored almost equally along the beaches. In a later aerial inspection during February, 1965, the winter pattern at Fisherman's Beach and Balcombe Bay was reversed with greatest sand accumulation on the northern ends of beaches. Further north at Seaford, a broad sandy beach had built out 150 feet in front of the foredune cliffs developed during the previous winter. This was accompanied by the accretion of sand to depths of 5 feet over the August profile.

Although the winter of 1964 was in some ways exceptional (July was the windiest month ever recorded at Melbourne), nevertheless the pattern of coastal changes observed from July, 1964, to February, 1965, corresponds in type if not in magnitude, to the winter-summer changes of a normal year.

A similar pattern has been observed in the migration of the off-shore bars between Mordialloc and Frankston over the same period. In July, the inner bar was irregular with oblique small bars oriented in a south-south-westerly direction and often joining the beach. These had a steep sand-slip face on the south-eastern side and were adjusted to waves from the north. Their form indicated movement from north to south. Near Seaford, both inner and outer bars were irregular with lobate bars separated by rip channels. By February, 1965, bar patterns were more regular with both inner and outer bars continuous and parallel for long distances along the coast. Moreover, minor oblique bars linking the inner bar with the beach were changed in form and orientation. Their trend was changed to north-west–south-east; the slip-face was developed on the north-east, indicating northerly migration in response to southerly or south-westerly waves.

The rapidity of bars changes near Seaford has been further confirmed by local fishermen and has resulted in several drownings due to the migration of shoals and rapid changes in the location of rip channels.

In a comprehensive study of the littoral drift patterns in the north-east of Port Phillip Bay, Baker (1963, 1964) was able to estimate the rates of sediment movement along the shore. Pyrite cinders dumped at low water mark off Head Street, Brighton, were rapidly dispersed by waves produced by strong northerly winds, and were carried south 7 miles to Rickett's Point in 62 days (Baker, 1964, Fig. 9). Moreover, off-shore sampling showed that material transported along the coast was kept close in-shore. Baker's conclusion indicates a net north to south movement for the period of the test—180 days from August, 1963, to February, 1964. During this period minor reversals occurred from south to north in response to changes in winds and wave directions.

On the east coast, observations on the same day sometimes show different drift patterns on different parts of the coastline. Accumulation on the northern sides of groynes and artificial structures was observed on the northern and eastern sides of the Bay during an aerial inspection in August, 1964. But further south in the Dromana–Rye area on the same day greatest accumulation was on the southern side of groynes (Baker, *op. cit.*).

On the west coast, net sediment movement occurs from south to north. This is confirmed by (*a*) the construction of sand barriers or spits on the southern side of streams entering the Bay at Skeleton Creek, Kororoit Creek and Little River and (*b*) the accretion of sand only on the southern sides of drains projecting across the beach and acting as groynes near the Metropolitan farm, south of the Werribee River. The largest quantities of sand on the west coast occur in the region between Point Cook and Williamstown, where extensive sand ridges have developed. Accumulation in this area is assisted by the dominant effect of south to north drift. Deposition here is cumulative since the protection afforded from northerlies by the coastal orientation permits little drift in the reverse direction.

Natural headlands often protect beaches by impeding the sediment movement from one part of the coast to another. Thus pocket beaches, as at Fisherman's Beach, owe their protection to the projecting headlands at the ends of the beach. The more indented areas such as near Mordialloc and Dromana, protected on the north by projecting headlands facing relatively deep water, act as sand traps. Some sand moves north to south past the headlands but movement in the reverse direction is prevented by the nature of the submarine topography and the trend of the coast. A progressive accumulation of sand occurs in these areas with continuous depletion from the thin pocket beaches located along the north-eastern section of the coastline from St. Kilda to Rickett's Point, and in the south-east from Frankston to Mt. Martha. In these areas, only limited quantities of sand are available, usually in a thin veneer covering abraded rock platforms. The sand shortage is further aggravated by some of the artificial structures in the area, e.g., breakwaters at Sandringham and Brighton, which have trapped large quantities of sand which would otherwise be available for distribution along the coast.

Little material is available to replenish beaches lost by natural or artificial causes (Baker, 1963, 1964). Some have already been completely destroyed as along Beach Road, Sandringham. The conservation of remaining sediment suitable for beach building in these areas is a matter of public concern.

Wind Statistics.

Detailed wave records are not available for Port Phillip Bay, but information on the distribution of wave energy may be obtained from analyses of wind records from recording stations near the coast. Wind statistics are available from the R.A.A.F. aerodrome at Laverton on the west coast, from two stations in Melbourne—the Flagstaff Observatory in West Melbourne, and the Commonwealth Bureau of Meteorology in Victoria Street—and from the C.S.I.R.O. Division of Meteorological Physics at Aspendale on the east coast. These stations are suitably situated to obtain representative figures for winds on the eastern, western and northern sides of the Bay. Some variations exist in the wind patterns at different stations, e.g., the southerlies recorded at Melbourne in summer often have a more westerly component at Aspendale. However, the wind systems at the three stations are sufficiently consistent to serve as a basis for discussion of general wind patterns around the coastline of Port Phillip Bay.

In a complex system involving winds, waves and sediment transport, some empirical relationships have been established. Steep and high storm waves generated by strong winds, erode sediment off the beaches and deposit it in the off-shore region. Smaller waves generated by winds of intermediate velocities transport sediment back onto the beach and deepen the off-shore region. This pattern established by Bascom (1954) and Rector (1954) was observed in the coastal changes on the eastern beaches in July–August, 1964. Waves generated by low velocity winds, even if they persist for long periods, transport comparatively small quantities of sediment and may be omitted from consideration.

To evaluate the overall effects of winds and waves on coastal sediment movement, variations in the frequencies, velocities and distributions of the wave-generating winds must be considered.

The monthly percentage frequency distributions for winds at Melbourne and Aspendale are shown in Figs. 8 and 10.

Monthly, seasonal and annual means for Melbourne and Laverton are shown in Table II. Monthly means for Aspendale are shown in Table III.

In the data from all stations, a strong seasonal variation in wind direction is evident at different times of the year. Northerlies and north-westerlies are prevalent in autumn, winter and spring, but southerlies and south-westerlies are prevalent in summer, especially in the afternoon readings (cf. Fig. 8A and B). Easterlies however, are subordinate to winds from other directions throughout the year. Similar seasonal variations in wind directions were recorded by Neumayer (1867, p. 15) who noted that for the period April 20th to September 14th, the mean direction was northerly (31°). But from October 15th to April 5th, the mean direction was south–south-westerly (196°).

TABLE II.

—	Mean Direction Melbourne † 1858–63	Vector Mean, Laverton * 1959–63	
		Direction	Knots
March	SSW 207	WNW 285	2
April	NW 305	NNW 329	3
May	NNW 345	NW 309	4
AUTUMN	NW 324	NW 313	3
June	N 8	NNW 332	3
July	NNW 347	NW 326	5
August	NNW 337	NW 317	5
WINTER	N 351	NW 324	4
September	NNW 328	NW 312	4
October	W 279	WNW 295	3
November	SW 235	WNW 285	4
SPRING	WNW 286	WNW 298	4
December	SW 224	WSW 255	2
January	SSW 208	WSW 254	1
February	SSW 195	WSW 252	2
SUMMER	SSW 207	WSW 254	1
ANNUAL	NW 307	NW 306	3

Monthly, seasonal and annual mean values for winds recorded at Flagstaff Hill, Melbourne, and Laverton during the periods 1858–63 and 1959–63, respectively.

* From Neumayer, 1867.

† From Maher and McRae, 1964.

TABLE III.
MEAN VELOCITY IN KNOTS.

Direction in degrees	January	April	July	October
30	4·9	4·1	7·8	5·1
60	2·9	2·5	3·4	3·1
90	4·9	4·1	6·7	4·6
120	6·4	6·6	6·6	7·0
150	5·0	4·8	5·6	4·4
180	6·5	5·6	7·1	6·4
210	8·3	7·7	8·2	8·4
240	6·9	7·6	8·9	7·9
270	7·0	9·9	10·4	10·9
300	7·7	8·2	8·3	10·0
330	7·4	7·1	7·9	8·5
360	9·6	9·1	10·1	10·6

Monthly mean velocities of winds to 12 points of the compass recorded at Aspendale for the years 1955–64 inclusive. Note the consistently high velocities of westerlies and northerlies compared with easterlies.

(Computed from data supplied by C.S.I.R.O. Division of Meteorological Physics, Aspendale.)

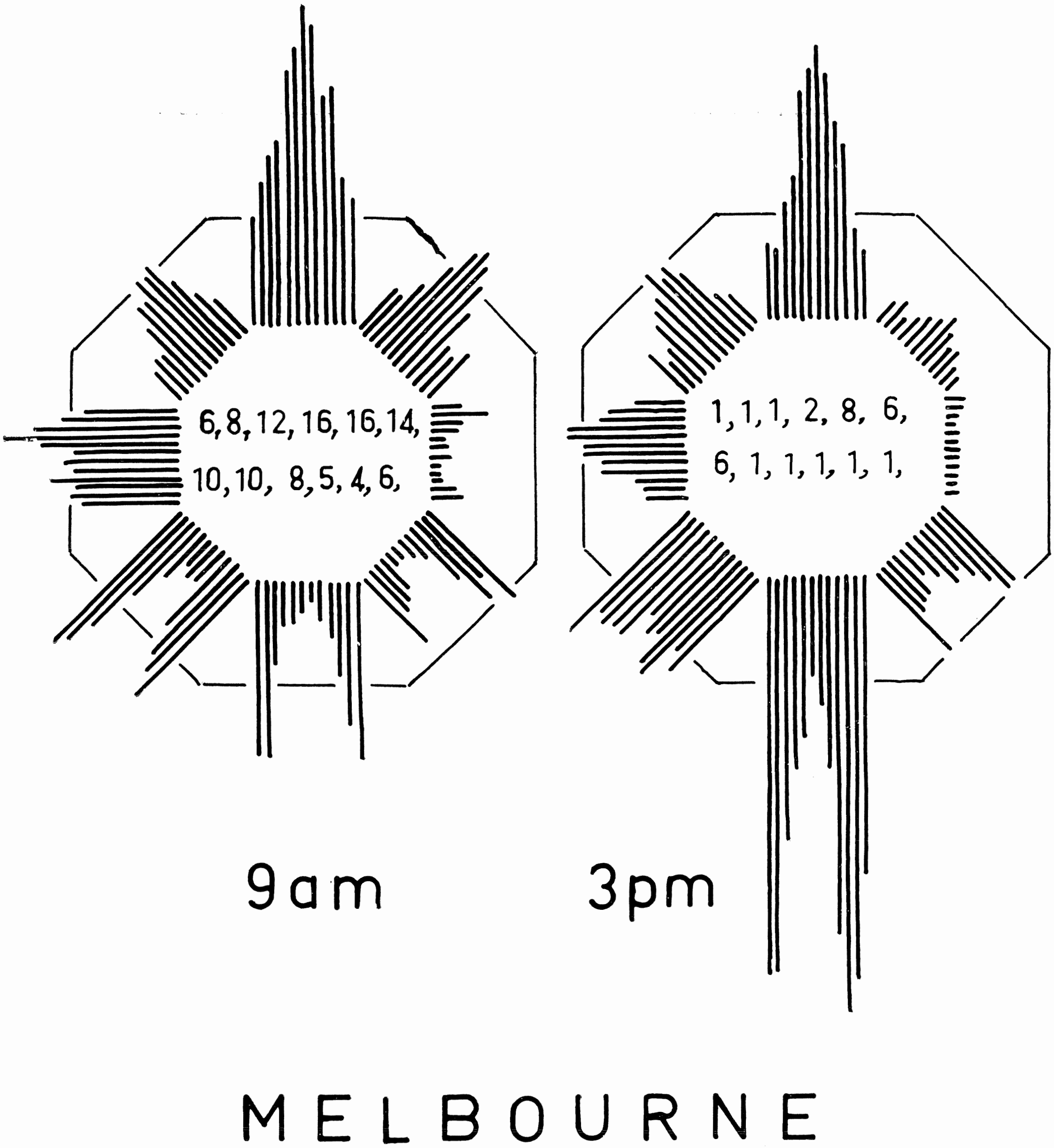


Fig. 8.—Wind roses showing monthly percentage frequency distribution of wind directions to eight points of the compass recorded at Melbourne, by the Commonwealth Bureau of Meteorology.

The sides of the octagons face toward the cardinal and semi-cardinal points. Projecting from each side are twelve columns representing the twelve months of the year, and the lengths of the columns are proportional to the percentage frequencies of winds from the given direction in the successive months, working round clockwise from January to December. The outer octagons are separated from the inner octagons by a distance representing 12½%. The percentage frequency of calms for the 12 months is shown by figures within the octagons. (From Bureau of Meteorology, Bull. No. 1, 1964.)

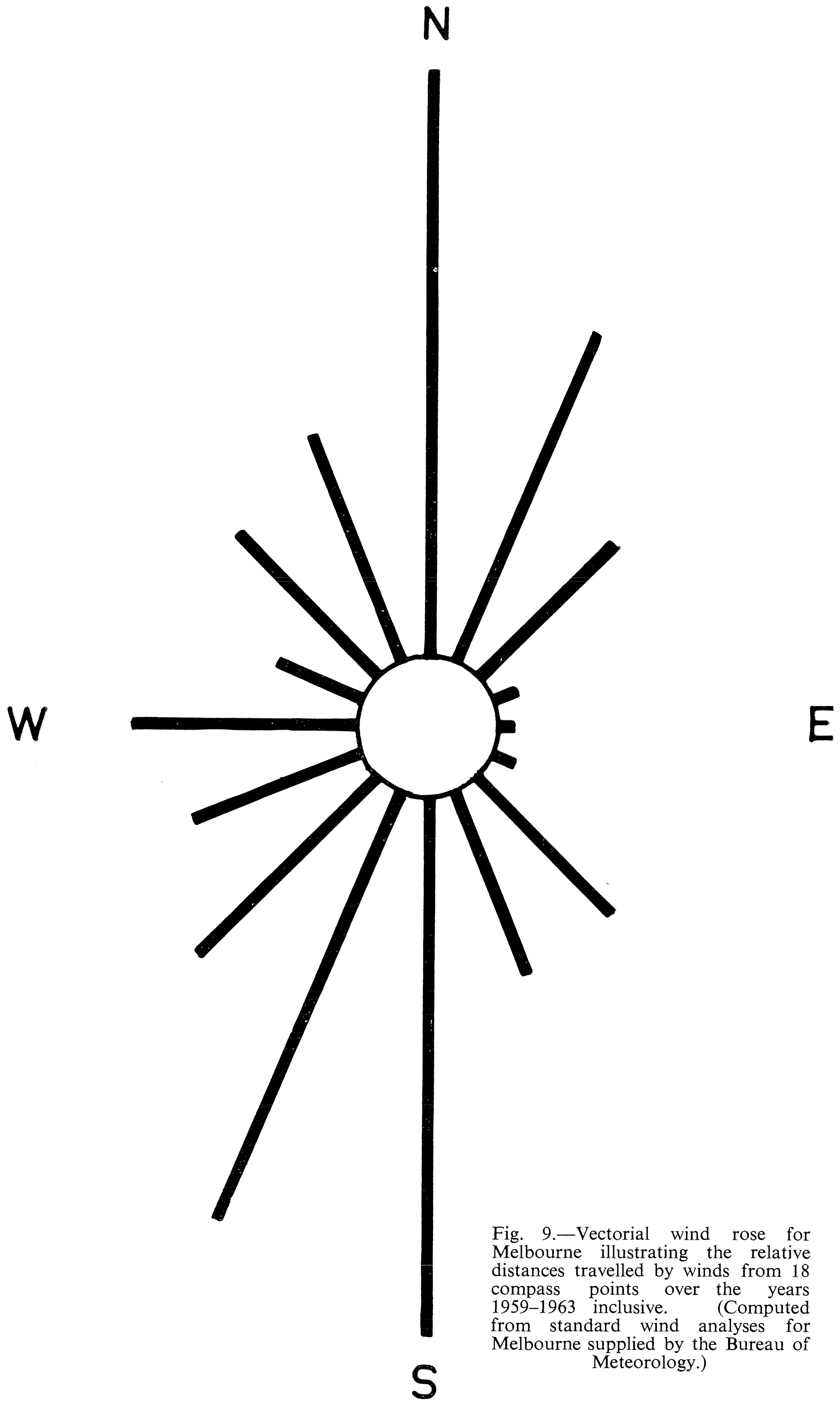


Fig. 9.—Vectorial wind rose for Melbourne illustrating the relative distances travelled by winds from 18 compass points over the years 1959–1963 inclusive. (Computed from standard wind analyses for Melbourne supplied by the Bureau of Meteorology.)

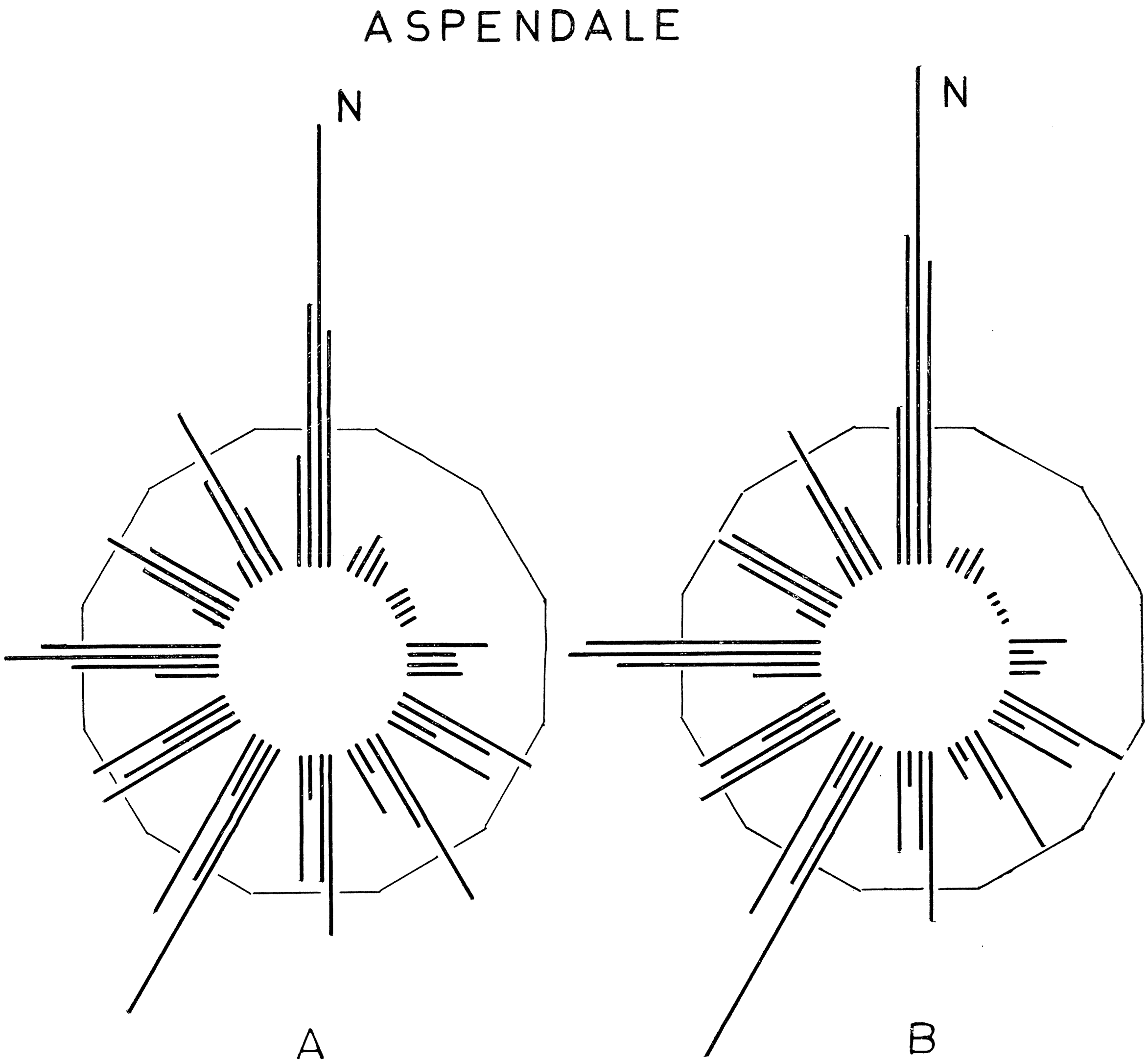


Fig. 10.—Wind roses showing (A) the percentage frequency distribution, and (B) the percentage vector distribution of winds to 12 points of the compass recorded at Aspendale for the months January, April, July and October, 1955–64 inclusive, at two-hourly intervals.

The magnitude of percentage frequencies and vectors is represented by the proportional lengths of columns in a given direction in successive months working clockwise from January to October.

The distance from the outer to the inner polygon represents 10%.

(Computed from data supplied by C.S.I.R.O. Division of Meteorological Physics, Aspendale.)

A relative measure of the variation in annual wave energy distribution with direction is obtained by combining wind frequencies and velocities to determine the vector distribution of winds. This has been determined from data obtained at Melbourne (Fig. 9) and at Aspendale (Fig. 10B). Northerlies and southerlies have a clear overall dominance over winds from other directions, while the relative insignificance of easterlies is emphasized.

In the high velocity group, gales from the north are most frequent. Of the total number of gales recorded at the Flagstaff Observatory for the years 1859 to 1863, 79 per cent. had a northerly component (cf. also monthly mean velocities from Aspendale, Table III).

Gales occur throughout the year, but from the Flagstaff records, they are most common in spring and summer (Table IV.). The monthly mean velocities however, are highest during winter (cf. Tables II. and III.).

There is, then, not only a 180° change in dominant wind direction from summer to winter, but also an important variation in wind speed with direction; northerlies are composed mainly of high velocity winds and the southerlies of relatively low velocity. In winter, when the southerly influence is weak, the northerly gales dominate the pattern of coastal sediment movement. In summer, the eroding effects of the northerly gales are more than off-set by the prevalent southerlies which not only reverse the direction of littoral drift but also produce on-shore drift.

Sediment movement and the coastal changes produced, are most evident on parts of the coastline oriented obliquely to the direction of the prevailing wave fronts. Northerlies produce waves oblique to all parts of the Port Phillip coastline, except to parts of the Bellarine and Nepean Peninsulas. Southerlies similarly, produce waves oblique to all sections of the coast, except for short segments in the north-east from Beaumaris to St. Kilda, for the Port Melbourne–Altona area, and for the northern shores of Corio Bay. Westerlies and easterlies on the other hand, both produce wave fronts approximately parallel to the configuration of the shores on opposite sides of the Bay. But while northerlies, southerlies and westerlies are important at various times of the year, easterlies remain relatively unimportant throughout the year.

Thus an important variation exists in the wave energy distribution around the coast of Port Phillip Bay. The western coast, protected by limited fetch from northerly, westerly and southerly winds, is exposed only to low energy easterlies and south-easterlies. In contrast, the eastern coast is exposed to high energy waves from the north, west and south. Erosion, sediment transport and deposition is therefore more active on the eastern coast, and more complex than on the west.

The general pattern of sediment movement from St. Kilda to Mt. Martha is determined by coastline orientation and the occurrence of northerly, westerly and southerly winds. The seasonal changes in wind frequency and strength produce erosion, with north to south littoral drift during winter and reversal of the net drift direction with progradation during summer. Off-shore easterlies cause little sediment movement and favour deposition.

The coast from Dromana to Point Nepean, however, does not reflect the same pattern due to its different orientation. It is adjusted at right angles to the direction of maximum fetch and exposed to northerlies and north-westerlies but protected from both southerlies and easterlies. It is a zone of sediment accumulation by north to south and west to east movement.

TABLE IV.

—	E	ESE	SE	SSE	S	SSW	SW	WSW	W	WNW	NW	NNW	N	NNE	NE	ENE	Total
Summer ..					3		3		4		4		29				43
Autumn									3		6		20		6		35
Winter ..									2		1		11	3	4		21
Spring ..			2				2		14		10	1	16		14		59
Totals ..			2		3		5		23		21	1	76	3	24		158

Seasonal distribution of gales greater than 25 knots recorded during the years 1858–63 inclusive at the Flagstaff Observatory, Melbourne.

(Adapted from Neumayer, 1867, Appendix p. VII.)

TABLE V.

—	E	ESE	SE	SSE	S	SSW	SW	WSW	W	WNW	NW	NNW	N	NNE	NE	ENE	Total
December ..						1		1									2
January ..				1							1		1				3
Feburary ..						1								2			3
SUMMER																	8
March ..																	0
April ..								1			1	1	1	1			5
May ..							1				1	1	2		1		6
AUTUMN																	11
June ..				1									2	1			4
July ..							1							1			2
August ..													1				1
WINTER																	7
September						1	1	1					3				6
October. ..							1						2	1			4
November ..							1						1				2
SPRING																	12
Totals ..	0	0	0	2	0	3	5	3	0	0	3	3	12	6	1	0	38

Showing the monthly distribution of gales (greater than 30 knots), for the five years 1959–63 inclusive. Computed from standard wind analyses for Melbourne, supplied by Commonwealth Bureau of Meteorology.

TABLE VI.

QUADRANTS IN WHICH WINDS WERE RECORDED.

—	0–90° (*NE*)	90°–180° (*SE*)	180°–270° (SW)	270°–360° (NW)
January	3	9	17	24
April	0	1	26	16
July	3	0	11	48
October	2	9	54	61
4 month total	8	19	108	149

Occurrence of winds greater than 20 knots, recorded at Aspendale during the period 1955–64 inclusive. Readings at two hourly intervals.

Note the importance of north-westerlies and south-westerlies over easterlies.

(From data supplied by C.S.I.R.O., Division of Meteorological Physics.)

CONCLUSIONS.

The geomorphic sequence in the development of Port Phillip Bay may be summarized as below:

Palaeozoic to Tertiary movement on Rowsley and Selwyn's Faults forming the Port Phillip sunkland.

Outpouring of (?) Late Pliocene–Early Pleistocene Newer Basalt of Western Plains near Geelong.

Incision of ancestral rivers of Moorabool, Barwon and Leigh Rivers on margins of basalt flows.

Late Newer Basalt flows near Geelong, infilling ancestral rivers of Moorabool, Barwon and Leigh.

Incision of present Moorabool, Barwon and Leigh Rivers.

Faulting on Rowsley and Barrabool Hills Faults, Lovelybanks and Curlewis Monoclines.

Non-marine limestone deposited in basin formed in fault-angle depression near Geelong.

Post-glacial rise in sea level inundating Yarra floodplain and Corio Basin. Aggradation in rivers entering bay. S.L. rise continued to 6–10 feet above present. Cliffs cut in dunes and marine invasion behind line of Pleistocene aeolianite ridge. Salinity higher than present.

Mid-Recent fall in S.L. exposing Recent shell beds, complicated in places by tectonic deformation. Formation of coastal sand ridges on west. Progradation in Carrum and Tootgarook Swamps on east. Drop in salinity. Erosion and deposition to present.

Post-Tertiary early-Quaternary climatic deterioration. Early glacio-eustatic sea level changes.

Period of (?) aridity with formation of siliceous dunes at Brighton, Frankston and Drysdale.

Mid-Pleistocene sea level changes. Calcareous dunes built during high sea level; soils formed during low sea levels.

Movement on Selwyn's Fault with uplift on Mornington Peninsula, and downwarping of sunkland and early aeolianite.

Further glacio-eustatic fluctuations with alternate periods of dune building and soil formation. Late Pleistocene downwarping. S.L. fall to –300 feet during last glaciation.

Many of the geomorphic differences between the east and west coasts of Port Phillip Bay are explained by the asymmetrical distribution of wave energy determined by the local wind patterns, and coastal configuration. Thus the different depths at which breaks occur in the near-shore topographic profiles in Fig. 4 are due to variations in wave energy from east to west. On the east coast, sands are shifted to greater depths than on the west, which rarely experiences high energy storm wave conditions.

Larger quantities of sediment are moved along the east coast than on the west. The view expressed by Jutson (1931) that the east coast is an area of erosion while the west is an area of deposition is not in complete agreement with the present evidence. Taken section by section, the east coast is almost equally divided between areas of erosion and deposition. But on the west, little erosion occurs, so that deposition appears to dominate. Moreover, little evidence exists for sediment transport across the Bay except for fine silts and clays which travel in suspension. In cores, the thickness of Quaternary silts and clays on the eastern region is as great as on the west.

The few erosional landforms on the west coast provide further evidence of the low energy available to this area. Although basalt forms well-developed shore platforms on exposed parts of the Victorian coast, only one small elevated platform is present on the west coast of Port Phillip near Williamstown.

Depositional features also vary according to the available coastal energy. East coast beaches are in places broad, deep, well-sorted and adjusted to directions of maximum fetch, while those in the west are narrow, thin and poorly sorted. The combined effects of geology and climate explain these and other elements of geomorphic asymmetry from east to west which are summarized in Table VII.

From the available wind data, field observations and from aerial photographs, the complex patterns of sediment movement along the coast may be summarized as follows:

1. On the west coast, movement is mainly south to north due to the dominant influence of southerlies over winds from all other directions.

2. Movement on the east coast is complex, but on beaches with a north-south alignment, an overall seasonal alternation exists. North to south movement occurs in winter controlled by dominant northerlies, with a south to north movement in summer controlled by southerlies.

3. The larger coastal indentations on the east coast act as sand traps. Sands once transported south past Rickett's Point and Martha Point cannot move back in the reverse direction. This results in progressive infilling and progradation in the indented areas at the expense of sediment removed from headlands or beaches further north.

4. Artificial structures have in places trapped sediment which would otherwise be available to replenish areas subject to erosion.

The present environment of Port Phillip Bay has developed by a complex history in which climate, lithological variations, tectonic deformation and eustatic sea level changes have all played an important part. This environment is now undergoing further change both on the sea floor and along the coastline due to human interference resulting from economic, residential and recreational pressures. Some irreversible changes have already occurred. Conservation of the remaining resources of Port Phillip Bay requires a greater understanding of the magnitude and complexity of the processes responsible for its development and for maintaining its natural equilibrium.

TABLE VII.

COMPARISON OF THE GEOMORPHIC FEATURES DEVELOPED ON THE EAST AND WEST COAST OF PORT PHILLIP BAY.

—	West Coast.		East Coast.
	Bellarine Peninsula		
Off-shore depth ..	Intermediate ..	Very shallow ..	Relatively deep
Average gradient to 10 fathoms contour	.. .. ..	1 in 500 ..	1 in 250
Relief on land ..	Moderate ..	Very low ..	Moderate to high
Main rock types..	Tertiary sands, clays and Older Basalt	Newer Basalt and Quaternary alluvium	Palaeozoic granitic rocks, Tertiary sands, clays and Older Basalt, Pleistocene aeolianite, Quaternary alluvium
Cliffs	Common — intermediate height	On small length of coast and low	Common on areas of moderate to high relief, intermediate to high
Shore platforms ..	Rare	Very rare ..	Common on headlands
Beaches ..	Narrow, shallow mud and sand	Narrow, shallow mud and sand	Broad and deep sandy beaches in large indentations; shallow sand on smaller bay-head beaches
Off-shore bars ..	Rare	Small, regular and extend long distances	Larger, very irregular in places. Occur only opposite larger sandy beaches
Coastal sand ridges	Portarlington, Point Lonsdale	Altona—Point Cook	Rare
Littoral sediment movement	.. .. ..	South→north small quantities, little infilling	North⇆south large quantities resulting in considerable infilling

ACKNOWLEDGMENTS.

This work was supported by research funds in the Department of Geology, University of Melbourne.

Many willing workers too numerous to mention assisted in the coring operations. Particular mention must be made of the Underwater Explorers Club, whose members assisted the author in diving operations, and of Mr. L. H. Norton of the Geology Department, who built and helped design the coring apparatus.

Dr. G. Baker and Mr. A. Link kindly read and criticized the manuscript.

REFERENCES.

Australia Pilot, The, Vol. 11, 1956.—Admiralty Hydrographic Dept.

Baker, George, 1938.—Dacites and associated rocks at Arthur's Seat, Dromana. *Proc. Roy. Soc. Vic.*, 50, 258–77.

Baker, George, 1963.—Brighton foreshore reclamation plan, Port Phillip Bay, Victoria. Sand drift studies, Part I. *C.S.I.R.O. Miner. Invest. Rept.* 857, 35 ps.

Baker, George, 1964.—Brighton foreshore reclamation plan, Port Phillip Bay, Victoria. Sand drift studies, Part II. *Ibid*, Rept. 899, 82 ps.

Bascom, W., 1954.—Characteristics of natural beaches. 4th Conf. Coastal Eng., 163–80.

Beasley, A. W., 1965.—Bottom sediments of Port Phillip Bay. *Mem. nat. Mus. Vic.*, 27.

Benson, W. N., and J. D. Raeside, 1963.—Tidal colks in Australia and New Zealand. *N.Z. Jour. Geol. Geophys.*, 6, 634–40.

Boutakoff, N., 1963.—The geology and geomorphology of the Portland area. *Mem. Geol. Surv. Vic.*, 22, 172 ps.

Bowler, J. M., 1962.—Tertiary stratigraphy and sedimentation in the Geelong–Maude area, Victoria. *Proc. Roy. Soc. Vic.*, 76, 69–137.

Bretz, J. H., 1960.—Bermuda: a partially drowned, late mature, Pleistocene karst. *Bull. Geol. Soc. Amer.*, 71, 1729–54.

Brewer, R., 1960.—Cutans—their definition, recognition and interpretation. *Jour. Soil Sci.*, 11, 280-92.

Chapman, F., 1928.—The Sorrento Bore, Mornington Peninsula, with description of new or little known fossils. *Rec. Geol. Surv. Vic.*, 5 (1), 1–195.

Condon, M. A., 1951.—Geology of the Lower Werribee River, Victoria. *Proc. roy. Soc. Vic.*, 63, 1–24.

Coulson, A., 1933.—The Older Volcanic and Tertiary marine beds at Curlewis near Geelong. *Ibid*, 45, 140–9.

Coulson, A., 1960.—Some structural features of the Barrabool Hills. *Ibid*, 72, 45–52.

Cox, H. L., 1861–2.—Coastal charts of Port Phillip Bay, Nos. 5–11. Unpublished copies lodged in Dept. Lands and Surv., Vic.

Cox, H. L., 1864.—Port Phillip Charts, 1171, 2747. Admiralty Hydrographic Charts, London.

Curray, R. Joseph, 1960.—Sediments and history of Holocene transgression, Continental Shelf, Northwest Gulf of Mexico. *In* Recent Sediments—Northwest Gulf of Mexico. *Amer. Assoc. Petrol. Geol.*, 221–266.

Davies, J. L., 1958.—Analysis of height variation in sand beach ridges. *Aust. Jour. Sci.*, 21, 51–2.

Davies, J. L., 1959.—Sea level change and shoreline development in south-eastern Tasmania. *Pap. & Proc. roy. Soc. Tas.*, 93, 89–95.

Dorman, F. H., and E. D. Gill, 1958.—Oxygen isotope palaeotemperature measurements on Australian fossils. *Proc. roy. Soc. Vic.*, 71, 73–98.

Dury, G. H., 1964.—Australian geochronology: checklist 1. *Aust. Jour. Sci.*, 27, 103–8.

Fairbridge, R. W., 1961.—Eustatic changes in sea level. *In* Physics and Chemistry of the Earth. Pergamon Press, London, 99–185.

Gill, E. D., 1948.—Geology of the Point Lonsdale–Queenscliff area, Victoria. *Vic. Nat.*, 65, 2–10.

Gill, E. D., 1950.—The geology of Picnic Point, Port Phillip Bay, Victoria. *Proc. roy. Soc. Vic.*, 62, 121–7

Gill, E. D., 1955.—Radiocarbon dates for Australian archaeological and geological samples. *Aust. Jour. Sci.*, 18, 49–52.

Gill, E. D., 1956.—Radiocarbon dating of late Quaternary shorelines in Australia. *Quaternaria*, 3, 133–8.

Gill, E. D., 1957.—The stratigraphical occurrence and palaeoecology of some Australian Tertiary marsupials. *Mem. nat. Mus. Vic.*, 21, 135–203.

Gill, E. D., 1961.—Eustacy and the Yarra Delta. *Proc. roy. Soc. Vic.*, 74, 125–33.

Gostin, V. A., 1964.—The Tertiary stratigraphy of the Mornington Peninsula. Unpublished MSc. Thesis, Univ. of Melbourne.

Gunson, S., L. W. Williams, and J. C. Dooley, 1959.—Preliminary report on gravity survey of Port Phillip Bay and adjacent areas. *Bur. Min. Res.*, Rec. 1959/34, 3 ps.

Hall, T. S., 1910.—Victoria Hill and Dale. Lothian, Melbourne. 160 ps.

Hills, E. S., 1939.—The age and physiographic relationships of the Cainozoic rocks of Victoria. *Proc. roy. Soc. Vic.*, 51, 112–39.

Hills, E. S., 1940.—The question of Recent emergence of the shores of Port Phillip Bay. *Ibid*, 52, 84–105.

Hills, E. S., 1949.—Shore platforms. *Geol. Mag.*, 86, 137–52.

Hills, E. S., 1951.—Physiography of Victoria. Whitcombe and Tombs, Melbourne, 292 ps.

Holmes, W. M., 1933.—The Mornington earth tremor of 3rd September, 1932. *Proc. roy. Soc. Vic.*, 45, 150–1.

Jennings, J. N., 1959.—The submarine topography of Bass Strait. *Ibid*, 71, 49–72.

Jennings, J. N., 1961.—Sea level changes in King Island, Bass Strait. *Zeit. für Geomorph.*, Supp. 3, 80–4.

Johnson, D. W., 1919.—Shore processes and shoreline development. John Wiley & Son, N.Y., 584 ps.

Jutson, J. T., 1931.—Erosion and sedimentation in Port Phillip Bay, Victoria, and their bearing on the theory of a recent relative uplift of the sea floor. *Proc. roy. Soc. Vic.*, 43, 130–53.

Jutson, J. T., 1940.—Shore platforms of Mount Martha, Port Phillip Bay, Victoria, Australia. *Ibid*, 52, 164–74.

Jutson, J. T., 1949.—Shore platforms of Point Lonsdale, Victoria. *Ibid*, 61, 105–11.

Keble, R. A., 1946.—The sunklands of Port Phillip Bay and Bass Strait. *Mem. nat. Mus. Vic.*, 14, 69–122.

Keble, R. A., 1947.—Mud Islands, Port Phillip Bay. *Ibid*, 15, 131–8.

Keble, R. A., 1950.—The Mornington Peninsula. *Mem. Geol. Surv. Vic.*, 17, 84 ps.

Keble, R. A., and J. Hope Macpherson, 1946.—The contemporaneity of the Maribyrnong River terraces with those of the Upper Pleistocene of Europe. *Mem. Nat. Mus. Vic.*, 14, 52–68.

Link, A. G., 1965.—Sediments of northern Port Phillip Bay, Victoria. Thesis in preparation, Univ. of Melb.

Lucas, A. H. S., 1887.—On the sections of the delta of the Yarra displayed in the Fishermen's Bend cutting. *Proc. roy. Soc. Vic.*, 23, 165–73.

MacKenzie, F. T., 1964.—Bermuda Pleistocene aeolianites and palaewinds. *Sedimentology*, 3, 52–64.

Maher, J. V., and J. N. McRae, 1964.—Upper wind statistics, Australia. Surface to 55,000 feet. Met. Summ., Comm. Bur. Met., 108 ps.

Neumayer, George, 1867.—Discussion of the meteorological and magnetic observations made at the Flagstaff Observatory, Melbourne, during the years 1858 to 1863. Mannheim, 160 ps.

Pritchard, G. B., 1910.—The geology of Melbourne. Tait, Melbourne, 187 ps.

Rector, R. L., 1954.—Laboratory study of equilibrium profiles of beaches. Beach Erosion Board, Corps of Eng., Tech. Mem. 41.

Sayles, W., 1931.—Bermuda during the Ice Age. *Proc. Amer. Acad. Sci.*, 66, 382–467.

Schofield, J. C., 1964.—Postglacial sea levels and isostatic uplift. *N.Z. Jour. Geol. Geoph.*, 7, 359–70.

Selwyn, A. R. C., 1854.—Report on the Mornington Peninsula. *Parl. Papers Leg. Council*, 1854–55.

Shepard, F. P., 1961.—Sea level rise during the past 20,000 years. *Zeit. für Geomorph.* Supp. 3, 30–35.

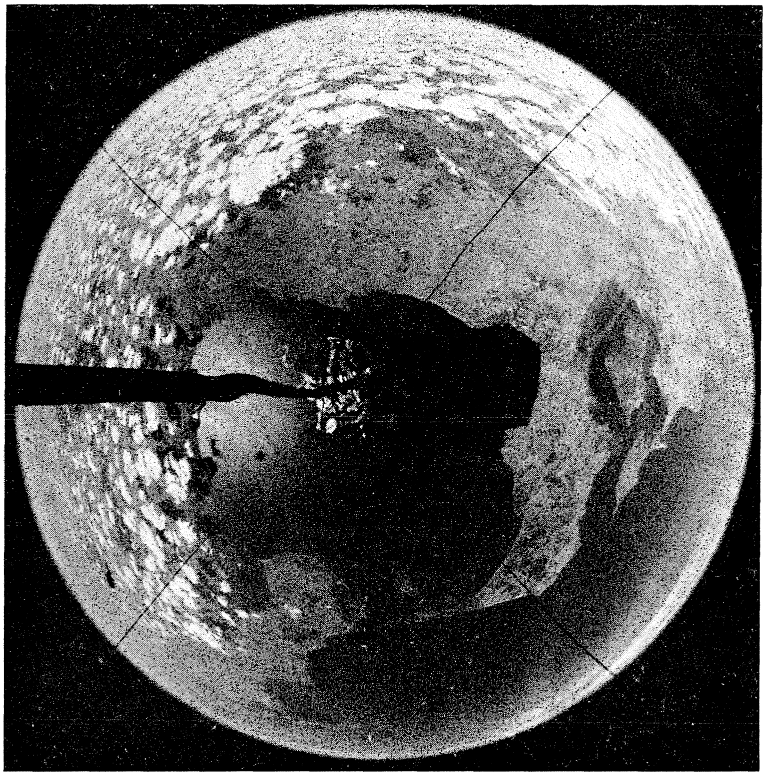
Spencer Jones, D., 1963.—Portarlington Geological Map. *Geol. Surv. Vic.*, 1 Mile Series.

Thomas, D. E., and W. Baragwanath, 1950.—Geology of the brown coals of Victoria. *Min. & Geol. Jour.* 4 (2), 41–63.

Whincup, Sylvia, 1944.—Superficial sand deposits between Brighton and Frankston, Victoria. *Proc. roy. Soc. Vic.*, 56, 53–76.

5050/64.—**5**

PLATE I.



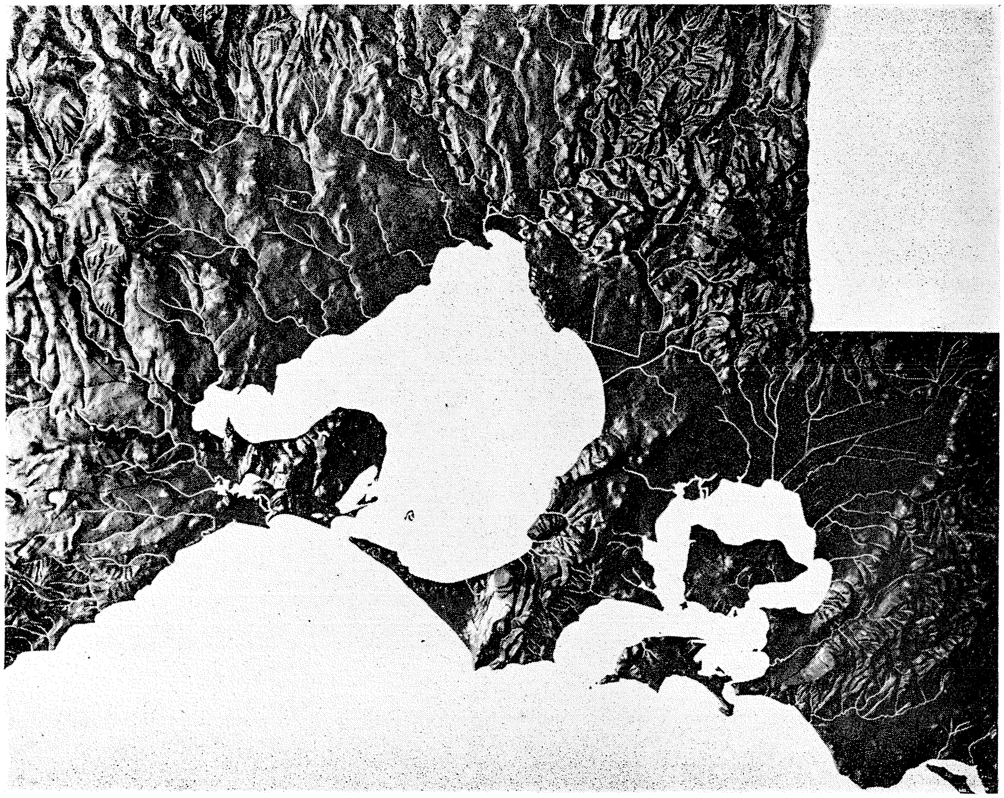
Photograph taken from a meteorological balloon at an altitude of 95,000 feet over Port Phillip Bay at 2.15 p.m. on 1st February, 1961.

The balloon was situated slightly east of the centre of Port Phillip and portion of the camera assembly obscures the area near Frankston. Coverage extends from the Otway Ranges in the far west to Westernport Bay and Anderson's Inlet in the east.

Note the partial cloud coverage which has been spread inland from the coast by the development of an afternoon sea breeze.

(Photo by courtesy of Prof. V. D. Hopper.)

PLATE II.



Photograph of a block model of South-Central Victoria in the Department of Geology, University of Melbourne, showing the topographic relief and drainage in the vicinity of Port Phillip and Westernport Bays.

Note the linear escarpments corresponding to major tectonic structures (see Hills, 1951, p. 161).

PLATE III.

FIG. 1.

FIG. 2.

FIG. 1: View along the north eastern shore of Port Phillip Bay with Rickett's Point in the foreground and Black Rock in middle distance. Note the irregular nature of the coastline with headlands protected by shore platforms cut in Pliocene ferruginous sandstone and exposed here in the intertidal zone.

(Photo—J.M.B. 12/2/65.)

FIG. 2: View looking north along Mornington Peninsula with Fisherman's Beach in foreground and Mornington pier in middle distance. Ferruginous Baxter Sandstone forms the resistant cliffed headlands with sand deposition in the protected bays. The outline of Fisherman's Beach shows maximum sand deposition in the north with south to north littoral movement impeded by groynes in the centre. This summer pattern is the reverse of that developed in the previous winter when erosion in the north was accompanied by deposition in the south where the beach prograded 130 feet beyond its present position.

(Photo—J.M.B. 12/2/65.)

PLATE IV.

FIG. 1.

FIG. 2.

FIG. 1: Aerial view looking south along the east coast of Port Phillip Bay towards Frankston. Two off-shore bars developed in the foreground near Seaford pass south to three bars near Frankston pier. Waves from the south-west break obliquely over the bars producing south to north littoral drift.

(Photo—J.M.B. 12/2/65.)

FIG. 2: Aerial view along the ocean beach near Sorrento towards Point Nepean in the west. Broad horizontal shore platforms in Pleistocene aeolianites are developed in the intertidal zone backed by steep cliffed headlands with sandy beaches developed in protected bay-heads. The entrance through Port Phillip Heads is visible in the background.

PLATE V.

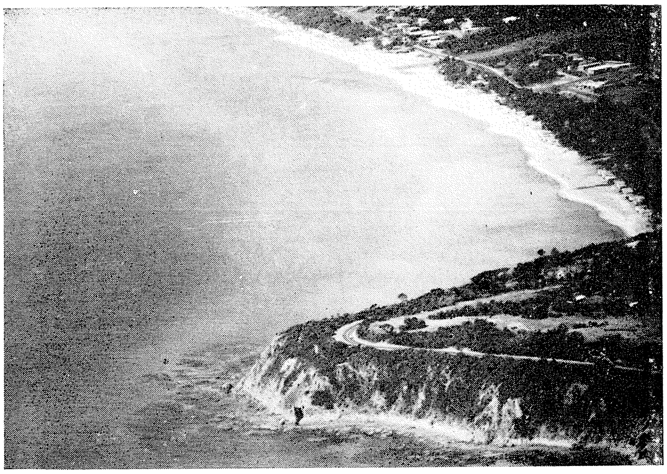


FIG. 1: Oblique aerial view looking north-east across Balcombe Point towards Balcombe Beach, Mornington. In the foreground, steep cliffs now largely vegetated, are developed in Mt. Martha granodiorite with small shore platforms emerging above low water. The mouth of Balcombe Creek in the background is blocked by a summer berm. The broad sandy beach in the protected embayment has prograded under the influence of summer waves.

(Photo—J.M.B. 12/2/65.)

FIG 2: View from a point north of the Werribee River looking across the west coast basaltic plain north-east towards Point Cook. Note the irregular outline of the coast with poorly developed beaches. Shallow off-shore bars remain parallel to the coast for more than 4 miles to Point Cook in the background. Waves breaking over the bars were generated by winds to 25 knots from the south.

(Photo—J.M.B. 4/2/65.)

PLATE VI.

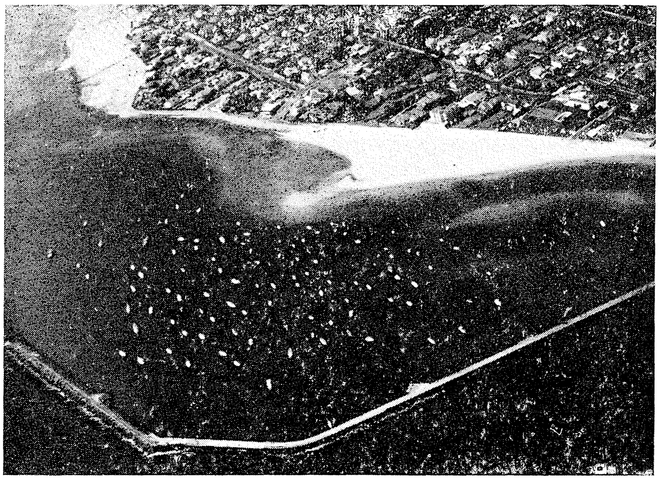


FIG. 1: A recent cuspate foreland developed by sand deposition in the low energy zone behind the solid portion of the breakwater at Brighton harbour. Erosion of beaches has occurred on both the north and south sides of the breakwater. Note the adjustment of the recurved spit to waves from the south passing through the open piled eastern end of the harbour.

(Photo—J.M.B. 12/2/65.)

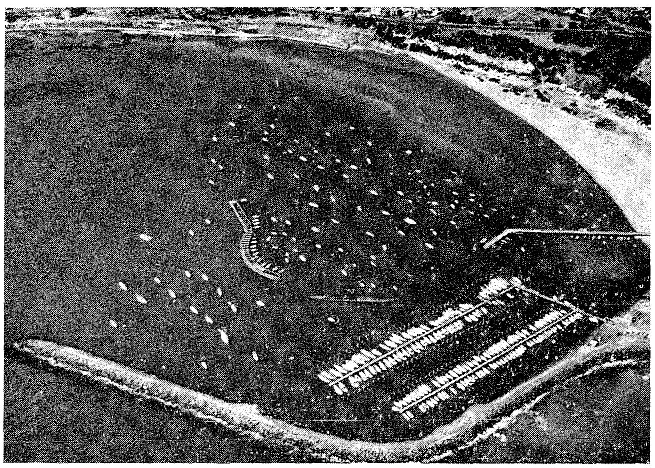


FIG. 2: Sandringham harbour protected by a solid breakwater built in 1950. Extensive deposition of sands and silts has occurred in the harbour since the breakwater construction. The former position of the shoreline is visible in top right, where steep cliffs and a row of boat sheds are now separated from the shore by more than 100 yards of recently deposited sand. Sand has been stripped from beaches along the north coast, which is now protected by a sea wall. Active erosion is occurring between the eastern end of the sea wall and the western edge of sand deposition.

(Photo—J.M.B. 12/2/65.)

PLATE VII.

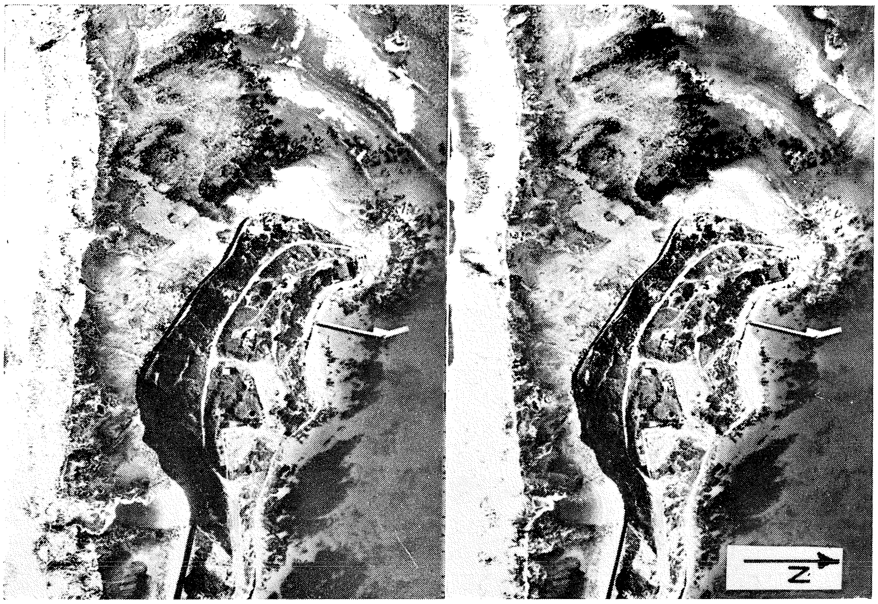


FIG. 1: Vertical stereo-pair showing the western end of the Nepean Peninsula with the high energy coastline on the left and Port Phillip Bay on the right.

A broad horizontal shore platform cut in Pleistocene aeolianite extends for 300 yards beyond the end of cliffed dunes on the ocean side but dies out inside Port Phillip Bay.

Ocean swell entering Port Phillip Heads is refracted through nearly 180° around the tip of Point Nepean.

(1″ = 10 Chns. Photo by courtesy Lands Dept. Vic. 29/7/60.)

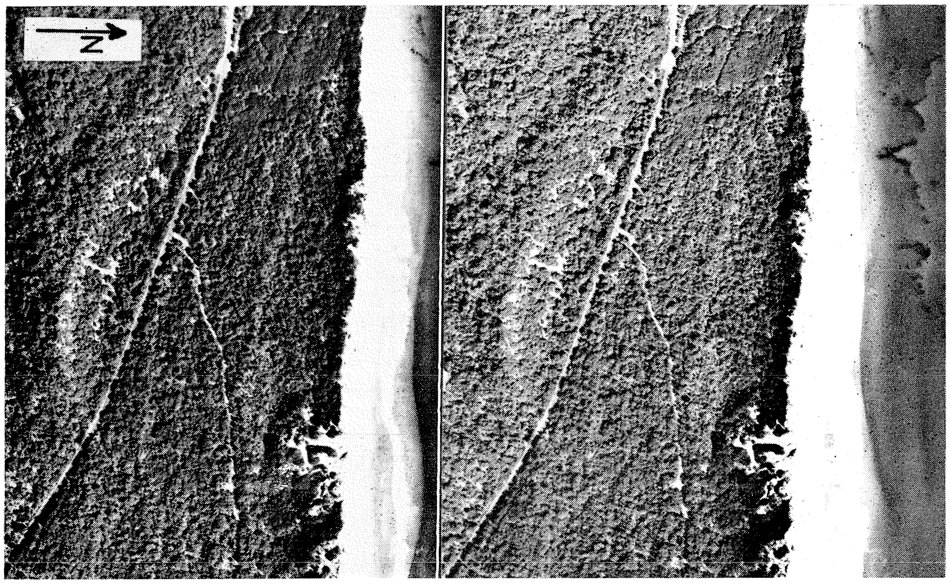


FIG. 2: Vertical stereo-pair of beach ridges developed near Observatory Point 1 mile east of Point Nepean. A vegetated cliff on the left represents a post-glacial strandline. Progradation by beach ridge building was accompanied by a slight relative drop in sea level to near its present position.

(1″ = 10 Chns. Photo by courtesy Lands Dept. Vic. 29/7/60.)

PLATE VIII.

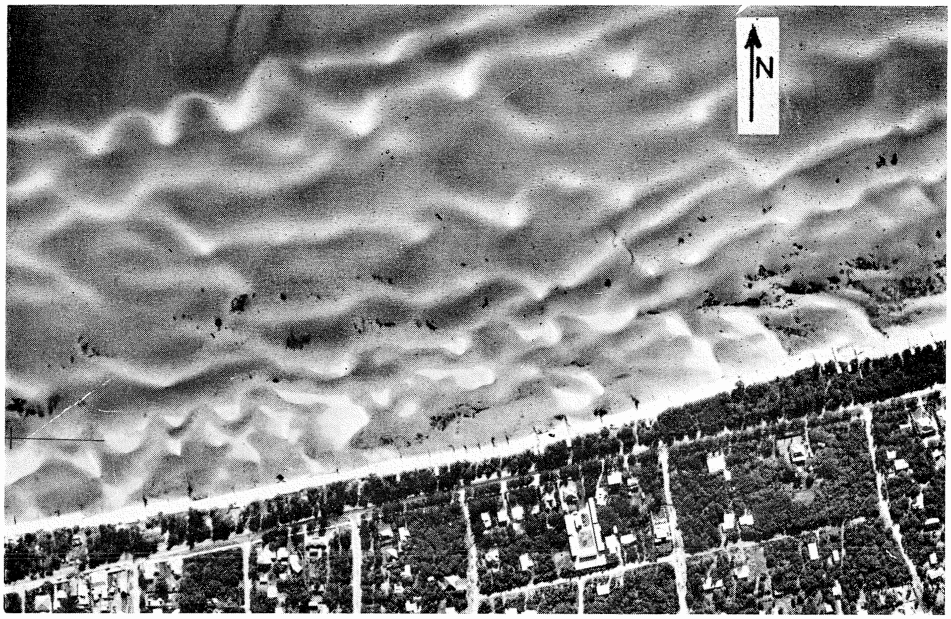


FIG. 1: Multiple and complex bars developed on a sand shoal near Rye on the southern coast of Port Phillip Bay. At its outer edge the shoal is 8 to 12 feet deep, but drops sharply to 24 feet in top left corner.

(1″ = 10 Chns. Photo by courtesy Lands Dept. Vic. 29/7/60.)

FIG 2: Off-shore sand barriers developed in shallow water off the low energy western coast of Port Phillip Bay between Kirk's Point and Point Wilson. Emerged shell beds above the level of present high water extend inland on Newer Basalt to near top left corner.

(1″ = 13·3 Chns. Photo by courtesy Lands Dept. Vic. 25/2/63.)

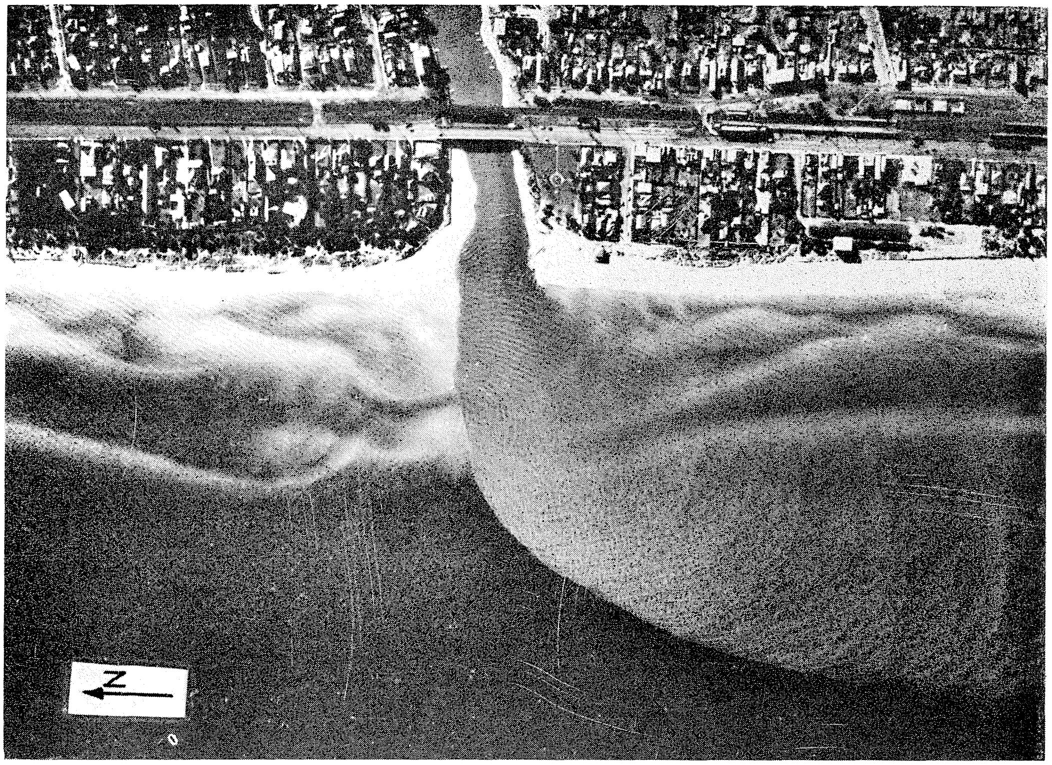
PLATE IX.

Vertical view with partial stereo-cover of coastal sand ridges on the west coast of Port Phillip Bay between Point Cook and the outlet of Skeleton Creek. Ridges with lobate landward extensions overlie the Newer Basaltic plain, a small part of which is exposed in the bottom left corner.

Small irregular bars are developed off-shore while south to north sand movement has displaced the mouth of Skeleton Creek to the north.

(1″ = 13·3 Chns. Photos by courtesy Lands Dept. Vic. 8/3/64.)

PLATE X.



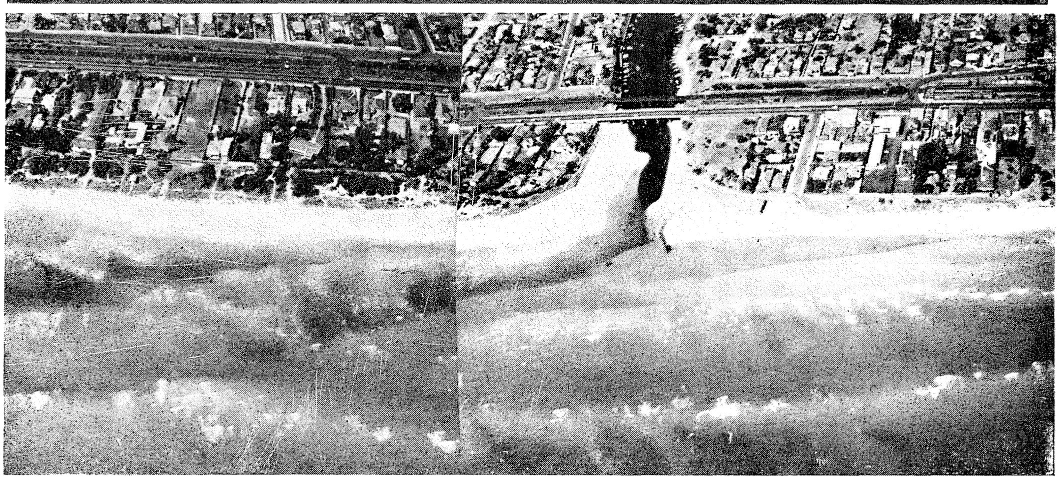


FIG. 1: Coastline near the mouth of the Patterson River, Carrum, on the eastern coast of Port Phillip Bay showing the winter pattern of off-shore bars and the broad sandy beach. Bars oblique to the shore on the right are adjusted to waves from the north and north-west and show evidence of migration from north to south. Waves in the photograph are generated by the influence of north westerly winds. Note the southern diversion of turbid river water on top of sea water.

(1″ = 10 Chns. Photo by courtesy Lands Dept. Vic. 13/7/60.)

FIG. 2: Oblique view of the same locality in summer, 1965. The outlet channel of the Patterson River is diverted north by the northerly migration of sand bars developed obliquely to the beach and adjusted to waves from the south-west. Waves in photograph were generated by 20 knots winds from the south-west and, in places, break on all three bars before reaching the beach.