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BEACH SANDS OF THE SOUTHERN SHORE OF PORT PHILLIP BAY, VICTORIA, AUSTRALIA

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Abstract

The textural and constituent composition of 23 samples of beach sand collected along the S. shore of Port Phillip Bay are described. The sand is coarse along the shore of Dromana Bay but grain size diminishes to the W., the median diameters from McCrae to Point Nepean ranging between 0·18 and 0·52 mm. Except for two samples, all sands are well sorted. The sands are composed mainly of quartz grains and shell particles. The content of acid-soluble (mainly shell) material is low in the E. part of the study region, but between Rye and Point Nepean it ranges between 22·2 and 50·1 per cent. The heavy mineral composition of the samples is given and the minerals described. It is concluded that most of the sand constituents have been derived from disintegration of granitic rocks and dune-limestone which outcrop along the coast in the study region. Much of the shell material in the sand from Rosebud to Point Nepean is considered to have come from the dune-limestone which is composed largely of shell fragments of sand size. The beaches are relatively stable, but human interference appears to be partly responsible for coastal erosion at certain places.

Introduction

The sandy beaches on the S. shore of Port Phillip Bay, Victoria, being not far distant from the city of Melbourne, are popular playgrounds. They constitute a scenic and recreational resource of major importance, and thereby are of commercial value. No previous work has been carried out on the beach sands of Port Phillip Bay's S. shore. The present research was conducted primarily to obtain information about the nature of the sands and to enquire into their origin. However, is was realized that the work could be of value in projects associated with the prevention of coastal erosion and the control of sand accumulation.

Field work was carried out during July, 1966, when mid-tide beach sand samples were collected at approximately one-mile intervals from the NE. corner of Dromana Bay to Point Nepean, a distance of 22½ miles. During the period of collection, calm weather prevailed and wind conditions were fairly constant. The position of each sampling station was fixed by surveying methods with reference to the maps of the Mornington Peninsula Area Base Map Series (scale 400 ft to 1 in.). Figure 1 shows the localities whence the samples were collected; information about precise locations and remarks about the places of collection are given in the Appendix.

Sand samples of approximately 350 grams were collected at about the reported time of low tide, by pushing down a thin metal cylinder to a depth of 3 in., removing the sand around the outside of the cylinder, and sliding a thin board underneath. Width and gradient of the shore at each collecting locality were determined. Rock samples were collected from coastal cliffs, to assist in the enquiry into the origin of the sands.

Coastal Geomorphology, Geology and Environment

The S. shore of Port Phillip Bay extends along the NW. and N. margins of the Mornington Peninsula—that region of the Victorian mainland between Westernport Bay and Port Phillip Bay. The shore consists of sandy beaches alternating with rock-cliffed sections and headlands. Topographic relief varies along the coast. The surface is usually low and hummocky behind long sandy beaches, and gently undulating to hilly behind rock-cliffed sections of the shore. At Mount Martha and Arthur's Seat, near the coast, the land rises to heights of 520 ft and 1,000 ft respectively.

The extreme E. part of the region of study is known as Dromana Bay. The N. shore of this Bay consists of a cliffed coastline cut in the Mount Martha Granodiorite (Palaeozoic). From the S. limit of the granodiorite cliffs a broad sandy beach stretches for 11 miles to White Cliffs. The beach is bordered in many places by a belt of weakly defined sand ridges which are fixed by vegetation. The sand ridge bordering the shore is subject to wave attack during gales, and rock sea-walls have been constructed at a number of places to prevent coastal erosion. There are small outcrops of granite on the sandy shore at The Rocks, Dromana. White Cliffs is a headland of Pleistocene dune-limestone (aeolian calcarenite).

From White Cliffs a sandy beach extends for about 3 miles in a WNW. direction to The Sisters. This stretch of shore is bordered for most of its length by vegetated sand ridges which are higher than those between White Cliffs and Dromana. In the vicinity of Blairgowrie and at certain other places between White Cliffs and The Sisters, groynes and retaining walls have been constructed to control erosion. The Sisters are two headlands of dune-limestone separated by a small sandy beach.

The shore extends in a WNW. direction from The Sisters for 8 miles to Point Nepean. It consists of a series of sandy beaches separated by cliffed sections and headlands of dune-limestone. Between Sorrento and Portsea, Point King, Point McArthur and Point Franklin form conspicuous headlands, and cliffs of dune-limestone rise steeply from the shore in many places. These cliffs reach a height of 70 ft in the vicinity of Point McArthur. From the Army Officer Cadet School at Portsea to Point Nepean the shore mainly consists of a broad sandy beach bordered by sand ridges. At Point Nepean (the E. Head of Port Phillip Bay) a broad, horizontal shore platform is developed in dune-limestone but this wide platform dies out inside the Bay. Erosion is active at Point Nepean, and the headland is partly protected by a sea-wall.

The width of sandy shore varies along the coast (see Appendix), reaching 250 ft near the Rosebud Jetty. Where the beach is wide, the angle of slope is small, being only 1° near the Rosebud Jetty. Where the shore is comparatively narrow, the gradient is higher, reaching 7° at some places. Since the tide range is small, the foreshore is narrow where the slope is relatively steep; the spring tide range diminishes from 3·5 ft at Point Nepean Jetty to 3 ft at Dromana Jetty. However, where the shore gradient is low, the foreshore is wide; this is so in the Rosebud-Rye area where the sandy foreshore attains a width of 200 ft.

The S. shore of Port Phillip Bay lies approximately at right angles to the direction of maximum fetch in the Bay and is exposed to N. and NW. winds but protected from both S. and E. winds. Strong winds from the N. and NW. generate powerful waves which erode sand off some of the beaches and deposit it in the off-shore region; but smaller waves generated by weaker winds transport sand back on to the beaches. Bowler (1966) regards the coast from Dromana to Point

Nepean as a zone of sediment accumulation by N. to S. and W. to E. movement, and he believes that the protection afforded by the coastal orientation permits little drift. The accumulation of sand alongside groynes on various beaches along the coast certainly is not great; and variable drift is indicated at different places and at different times by the building up of sand on opposite sides of groynes. At the time when field work was carried out most accumulation of sand was on the W. side of groynes in the Rye-Sorrento region.

Emerged beach deposits and other evidence of emergence of the land can be seen at various places along the S. coast of Port Phillip Bay. These features have been described by Hills (1940), Bowler (1966) and others, and are believed to have formed in mid-Holocene times when sea-level was about 10 ft higher than now. There are no streams of any significance entering Port Phillip Bay along its S. shore.

Figure 1 shows the geology of the region of study. Maps showing the geology of the coastal region immediately to the N. are included in papers by Keble (1950) and Gostin (1966). A cliffed coast of Mount Martha Granodiorite extends N. from Safety Beach to Balcombe Bay, and from there for about 11 miles the coastal sections are composed largely of Upper Tertiary ferruginous sandstones known as the Baxter Sandstones.

With reference to submarine topography, bathymetric contours indicate that much of the near-shore region is fairly shallow. The near-shore profile off the cliffed coastline of Mount Martha Granodiorite is relatively steep, but flattens S. in Dromana Bay. Proceeding SW. as far as Tootgarook the near-shore gradient is also low. A system of shallow sand bars begins off the beach at McCrae, and these off-shore bars continue W. subparallel to the beach to near Sorrento. Off-shore between The Sisters and Point King, the Bay floor is nearly flat over a large area (part of the region known as the South Sand) and the 5-fathom line is about 2 miles from the coastline. Between Point King and Point Nepean the 1-fathom and 5-fathom contours are closely spaced near the shore for long distances, particularly where the coast is steeply rock-cliffed.

Sand covers the floor of Port Phillip Bay for a considerable distance N. from its S. shore (Beasley 1966), extending out to about the 10-fathom line. In shallow areas off-shore between Sorrento and Point Nepean dune-limestone outcrops through a thin cover of sand to form rocky shoals or 'reefs'; and in deeper water near Port Phillip Heads tidal scour has exposed dune-limestone. Tidal currents are fairly strong in the channels off the southern shore of the Bay, the tidal streams in the entrance to Port Phillip attaining velocities up to 8 knots.

Laboratory Procedure

Each beach sand sample was dried and reduced in bulk with a Jones splitter to about 50-75 g. Soluble marine salts and organic (weed) matter were removed by decantation and, after drying, the material was sieved using Wentworth intervals. A cumulative frequency curve and a histogram were constructed for each sample, and the median diameter and Trask's sorting coefficient were determined. Size fractions were examined with a binocular microscope, recombined and treated with dilute 1:2 hydrochloric acid to determine the weight percentage of acid-soluble (mainly carbonate) material in each sample. Sieve analysis of the acid-insoluble residue was carried out and the median diameter and sorting coefficient of the

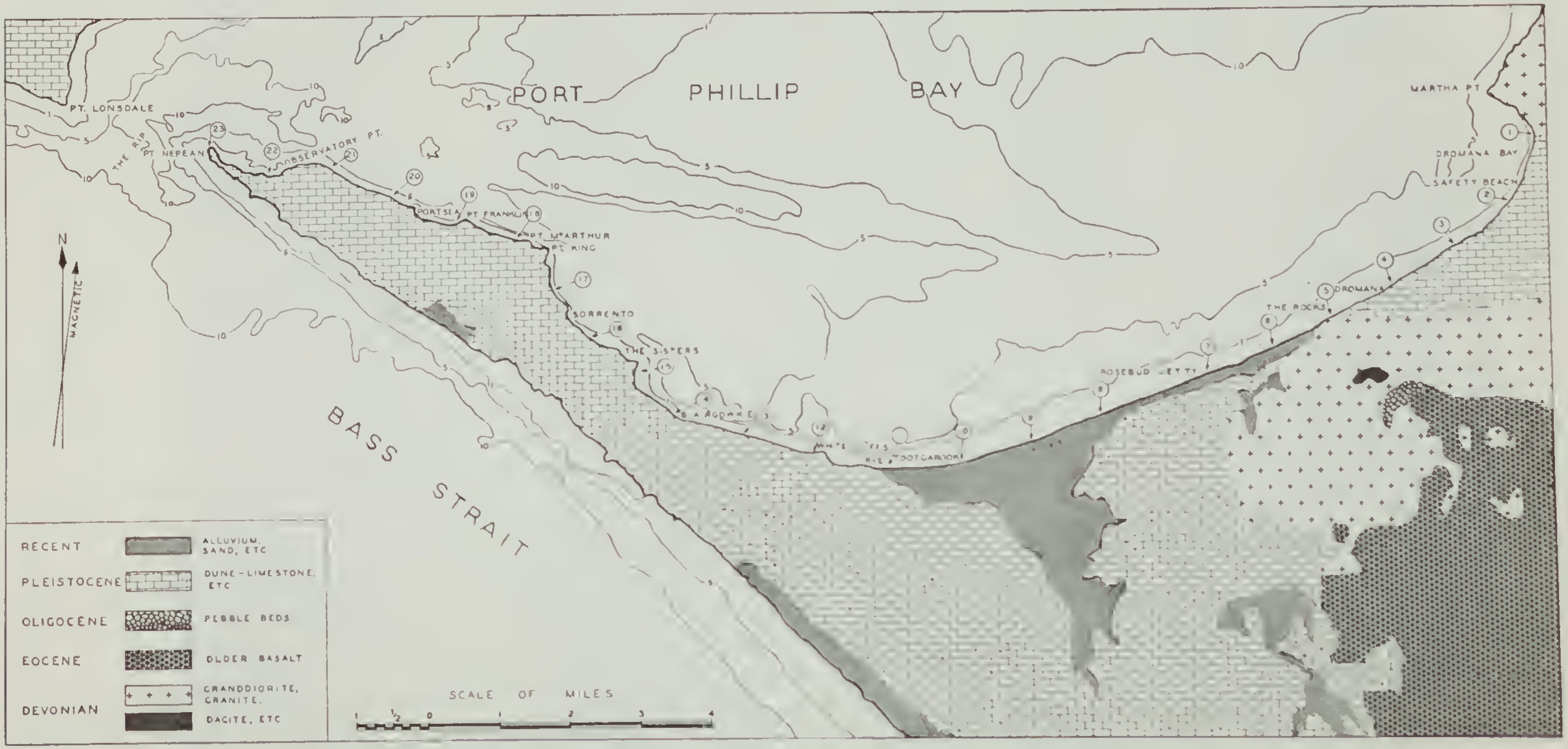

FIG. 1—Map showing location of sand sampling stations, geology and submarine contours.

leached sand (free from shell fragments, etc.) were determined. A histogram was constructed for each sample of acid-treated sand.

Heavy minerals were separated from the acid-treated $\frac{1}{16}$ to $\frac{1}{4}$ mm size-grades of each sand sample using bromoform, and the weight percentage of heavy minerals (index number) for this size range was determined. An Alnico hand magnet was used to detect the presence of magnetite; its relative abundance was estimated and the grains returned to the heavy mineral fraction prior to mounting in Canada balsam for examination under the microscope. Heavy mineral species were identified under the petrological microscope and their relative proportions were determined by counting random fields of grains in each microscope slide. Percentages were determined to the closest whole per cent; less than $\frac{1}{2}$ per cent was recorded as a trace. Types of rock fragment and the nature of composite grains in the beach sediments were determined by microscopic examination.

Rock samples from coastal cliffs were crushed in a steel mortar and each sample was reduced in bulk by coning and quartering to about 75 g. The weighed sample was then soaked in water and completely disaggregated by wet crushing. Clay and water-soluble salts were removed by decantation. The sample of disaggregated rock (minus clay and soluble salts) was then sieved and the median diameter and sorting coefficient were determined. Each size-fraction was examined with a binocular microscope. After recombining these fractions, the sample was treated with dilute hydrochloric acid and the weight percentage of acid-soluble material was calculated. The acid-insoluble residue was sieved, and the median diameter and sorting coefficient of this material was determined. Heavy minerals were separated from the $\frac{1}{16}$ to $\frac{1}{4}$ mm size-grades of the acid-treated sample with bromoform and the index number determined. The heavy mineral grains were identified and their relative abundance calculated.

Textural Composition of the Sands

Results of the mechanical analysis of the sands and their acid-insoluble residues are presented in Table 1 and Figure 4.

Median Grain Size

Figure 2 shows the median grain size of the sands and their acid-insoluble residues plotted against distance along the coast. The median grain size of the sands ranges from a maximum of 0·83 mm at station 1 to a minimum of 0·18 mm at station 11 (Rye). From station 1 to station 11 there is an almost continuous decrease in median grain size. The decrease from station 1 (adjacent to granodiorite cliffs) to station 2 is particularly steep, and this trend continues to station 3, indicating that appreciable S. drift of the larger sized particles does not occur. From station 3 the median grain size coarsens slightly to station 4 and this coarsening continues to station 5 (Md 0·62 mm) at The Rocks, Dromana. This local increase in the median may be related to the occurrence of granite outcrops near station 5. There is a sharp decrease in median grain size from station 5 to station 7 (Md 0·27 mm) near Rosebud Jetty, but the differences from there to station 11 are less great. The comparatively small medians in the Rosebud-Rye region may be related to low wave energies there, much of the wave energy having been expended over the wide near-shore zone of shallow water with numerous sand bars.

From station 11 the median diameter increases to station 12 and continues to coarsen W. to station 13 (Md 0·40 mm). The larger median at station 13 can be related to an unusually great content of large shell fragments, presumably broken

TABLE 1

Statistical constants of beach sands from Port Phillip Bay

Sample No.		Md (mm)	Q3 (mm)	Q1 (mm)	So	Acid-soluble per cent
1		0·83	1·70	0·26	2·56	4·0
1	A.I.R.*	0·81	1·63	0·29	2·37	
2		0·66	0·79	0·55	1·20	0·4
2	A.I.R.	0·64	0·76	0·54	1·19	
3		0·55	0·71	0·44	1·27	0·5
3	A.I.R.	0·55	0·71	0·44	1·27	
4		0·58	0·64	0·49	1·17	0·5
4	A.I.R.	0·56	0·68	0·50	1·14	
5		0·62	0·76	0·46	1·28	1·6
5	A.I.R.	0·62	0·73	0·48	1·22	
6		0·48	0·57	0·42	1·16	8·2
6	A.I.R.	0·47	0·56	0·40	1·18	
7		0·27	0·32	0·23	1·18	4·6
7	A.I.R.	0·27	0·33	0·23	1·20	
8		0·30	0·36	0·26	1·18	15·2
8	A.I.R.	0·31	0·37	0·26	1·19	
9		0·28	0·34	0·24	1·19	18·1
9	A.I.R.	0·28	0·32	0·25	1·14	
10		0·21	0·24	0·17	1·17	28·6
10	A.I.R.	0·20	0·24	0·17	1·20	
11		0·18	0·20	0·15	1·16	39·5
11	A.I.R.	0·17	0·20	0·15	1·15	
12		0·33	0·44	0·26	1·29	28·6
12	A.I.R.	0·32	0·41	0·27	1·24	
13		0·40	>4·00	0·23	>4·17	50·1
13	A.I.R.	0·29	0·40	0·16	1·60	
14		0·33	0·46	0·26	1·34	31·8
14	A.I.R.	0·35	0·45	0·26	1·31	
15		0·33	0·37	0·29	1·12	23·7
15	A.I.R.	0·33	0·38	0·28	1·16	
16		0·29	0·34	0·27	1·12	24·8
16	A.I.R.	0·32	0·37	0·28	1·14	
17		0·52	0·59	0·42	1·19	22·2
17	A.I.R.	0·52	0·59	0·43	1·17	
18		0·52	0·60	0·48	1·12	27·5
18	A.I.R.	0·52	0·56	0·47	1·10	
19		0·26	0·33	0·23	1·19	38·1
19	A.I.R.	0·28	0·33	0·25	1·15	
20		0·28	0·34	0·24	1·20	34·8
20	A.I.R.	0·28	0·31	0·24	1·13	
21		0·22	0·26	0·19	1·15	50·1
21	A.I.R.	0·24	0·27	0·20	1·15	
22		0·25	0·33	0·21	1·27	46·8
22	A.I.R.	0·26	0·31	0·23	1·14	
23		0·30	0·35	0·25	1·18	36·6
23	A.I.R.	0·30	0·36	0·26	1·19	

Key: Md = Median, Q3, Q1 = Quartiles, So = Sorting coefficient, A.I.R.* = Acid-insoluble residue.

and transported by fairly powerful waves. The median diameters at stations 14, 15 and 16 are all very close to that at station 12, suggesting similar wave energies and similar source materials at these localities. There is a marked coarsening of the sand at stations 17 and 18 (near Sorrento); this appears to be due more to higher wave energy and the removal of finer fractions by wave and current action than to

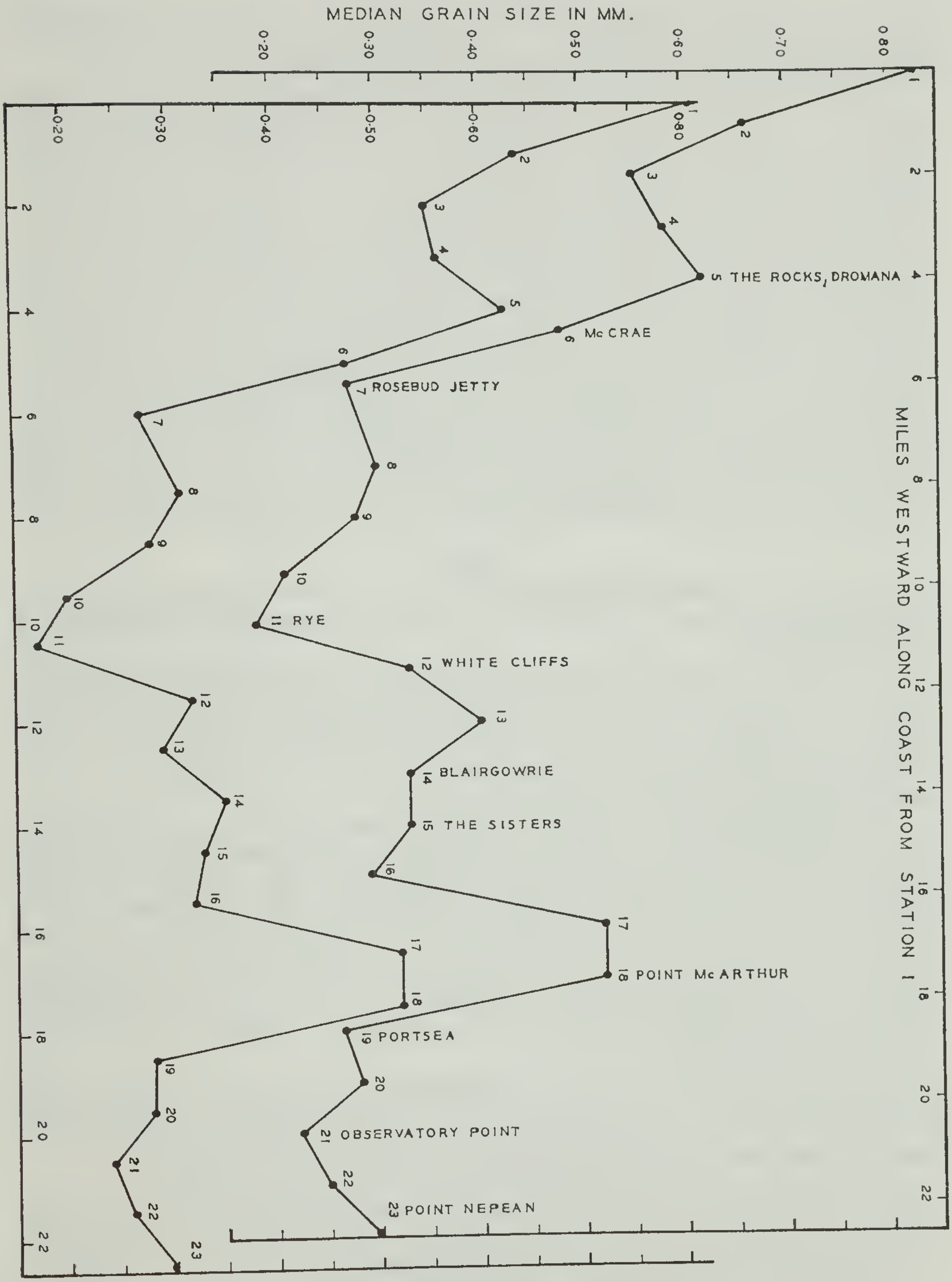

FIG. 2—Median grain size of sands (top) and their acid-insoluble residues (bottom) plotted against distance along coast.

the presence of small fragments of dune-limestone in the sand. The median diameters at stations 19 to 23 do not differ greatly from one another, that at station 23 (Point Nepean) being the coarsest of these five samples.

The upper graph in Fig. 2 reveals two regional characteristics. The first is the occurrence of relatively coarse sand in the far E. part of the study region. Median diameters at station 5 and all stations E. are greater than the other samples. This coarseness appears to be due more to the proximity of source material (Mount Martha Granodiorite) than to higher wave energies; wave energies are similar on other sections of the coast. The second observation is that the sands from stations 7 to 23 do not have a wide range in median diameter, if those from stations 13, 17 and 18 are excluded. The similarities in median grain sizes along this stretch of coast from Rosebud to Point Nepean suggest that the source materials of the sand are essentially similar. The coarser sand at stations 13, 17 and 18 is probably due to local variations in wave energies and current velocities at these localities.

In most cases the median grain size of the acid-insoluble residues is slightly finer than that of the beach sand samples. However, treatment with acid resulted in a marked decrease in the median of the sand from station 13. The median diameters of the acid-insoluble residues of the sand from stations 17 and 18 are identical with those of the untreated samples. The coarseness of the sand at these stations therefore is not due to marine skeletal material or to fragments of dune-limestone.

Sorting

Trask's (1932) coefficient of sorting (So) of the beach sand samples and their acid-insoluble residues are listed in Table 1 and are plotted against distance along the coast in Fig. 3.

The sand from station 13 has a coefficient of sorting considerably greater than that of any other sample and, adopting Trask's (1932) classification, is poorly sorted. Sorting values of the other sand samples range from a maximum of 2·56 at station 1 to a minimum of 1·12 at stations 15, 16 and 18; they are all well sorted sands except that from station 1 which has moderate sorting. Sixteen of the 23 sand samples have sorting coefficients of 1·20 or less.

The occurrence of sand with only moderate sorting at station 1 may be related to its location adjacent to cliffs of decomposed granodiorite. Sorting improves markedly along the shore away from the granodiorite cliffs, but there is a local decrease at station 5 (The Rocks, Dromana) near small outcrops of granite. From station 6 (McCrae) to station 12 (White Cliffs) the sorting coefficients are almost identical, and the sands are very well sorted. Poor sorting at station 13 may be related to an unusually large shell content with shell fragments of various sizes. This poor sorting indicates turbulent conditions, but it is only local in occurrence and at station 14 the sand is well sorted. From station 15 to station 23 the sorting values are all very similar.

The upper graph in Fig. 3 indicates that, apart from the marked improvement in sorting from station 1 to station 2, there are no regional trends of sorting with shoreline distance. The improvement in sorting in the far E. part of the study region suggests that the direction of drift there is SW. along the shore.

There appears to be a relationship between the sorting coefficient of the beach sand and its median diameter. Sands which are very well sorted usually have small values for their median diameter, and a decrease in the degree of sorting commonly corresponds with an increase in median grain size.

Most commonly sorting was improved slightly after removal of the acid-soluble

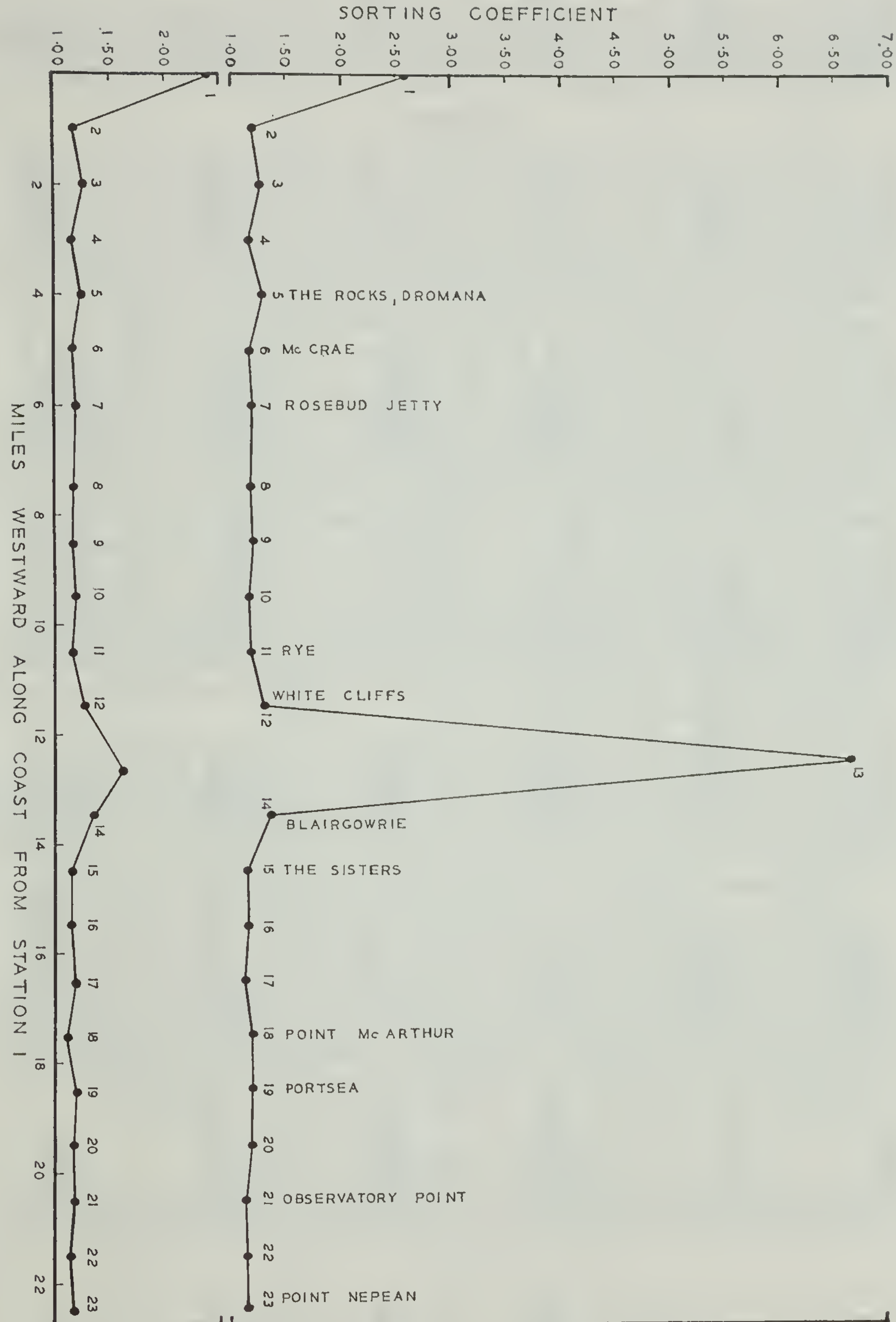

FIG. 3—Sorting coefficient of sands (top) and their acid-insoluble residues (bottom) plotted against distance along coast.

fraction. However, the sorting coefficient of the acid-insoluble residue of the sand from station 13 is considerably less than that of the untreated sand. After removal of the acid-soluble fraction from each sample, the residues are all well-sorted sands and most are very well sorted.

Histograms

In the histograms, weight percentage of material greater than 4 mm in size is indicated by vertical lines, since it represents material retained on the coarsest sieve used. In most cases none or very little material was retained on this sieve.

The sands from stations 1, 5 and 13 are bimodal but the other 20 are unimodal. Sand from station 1 has a primary mode in the very coarse sand size-grade and a lesser mode in the fine sand. Its large secondary maximum and spread indicate an immature condition of sorting. Two sources for this sand are suggested by the nature of the histogram; there appears to be loading with coarse material supplied from the nearby granodiorite. A very conspicuous maximum size-grade occurs in the coarse sand grade of the samples from stations 2, 3 and 4, and fine proximate admixture exceeds coarse proximate admixture in each of them. The bimodal nature of the sand at station 5 suggests two sources, one of which is granitic rock nearby. The maximum size-grade in the samples from stations 6 to 9 is medium sand, but this maximum shifts to fine sand at stations 10 and 11. The histograms reveal a coarsening in size and a lower degree of sorting at station 12, and show that 30% of the sand from station 13 is greater than 4 mm in size. The bimodal character of the latter sample is due to the mixing of finer quartzose sand with coarser bioclastic material mainly of molluscan origin. There is a conspicuous maximum in the medium sand grade at stations 14, 15 and 16. At stations 17 and 18 the maximum size-grade is coarse sand, but at stations 19 and 20 it has shifted back to medium sand and fine proximate admixture is considerably greater than coarse. The histograms reveal a decrease in size at station 21 and 22, but at station 23 (Point Nepean) the maximum is again in the medium sand grade and fine proximate is the dominant admixture.

Of the 20 unimodal sands, five have the maximum in the coarse sand grade, 11 in the medium sand grade and four in the fine sand grade. It is a common characteristic for the histograms to have few grades with a conspicuous maximum size-grade towering above the neighbouring grades; the narrow spread indicates a high degree of sorting. None of the samples west of station 13 have a secondary maximum.

Acid-insoluble residues of the beach sands from stations 1, 5 and 13 are bimodal like the sands, but the other acid-treated samples are unimodal. Since the histograms for the acid-insoluble residue and the untreated sand from station 1 are almost identical, shell content does not cause the bimodality of that beach sand. Comparison of histograms also indicates that bimodality at station 5 is not due to calcareous shell content. Histograms for most of the acid-insoluble residues very closely resemble those for the untreated sand, but show that the acid-insoluble residues commonly are slightly finer. Histogram shape for the acid-treated sand from station 13, however, is very different from that for the untreated sand and, although a wide spread still exists, a marked decrease in size is apparent.

Constituent Composition of the Sands

The constituent composition refers to the acid-soluble (mainly carbonate) content and the acid-insoluble content of the beach sediments. Some of the samples

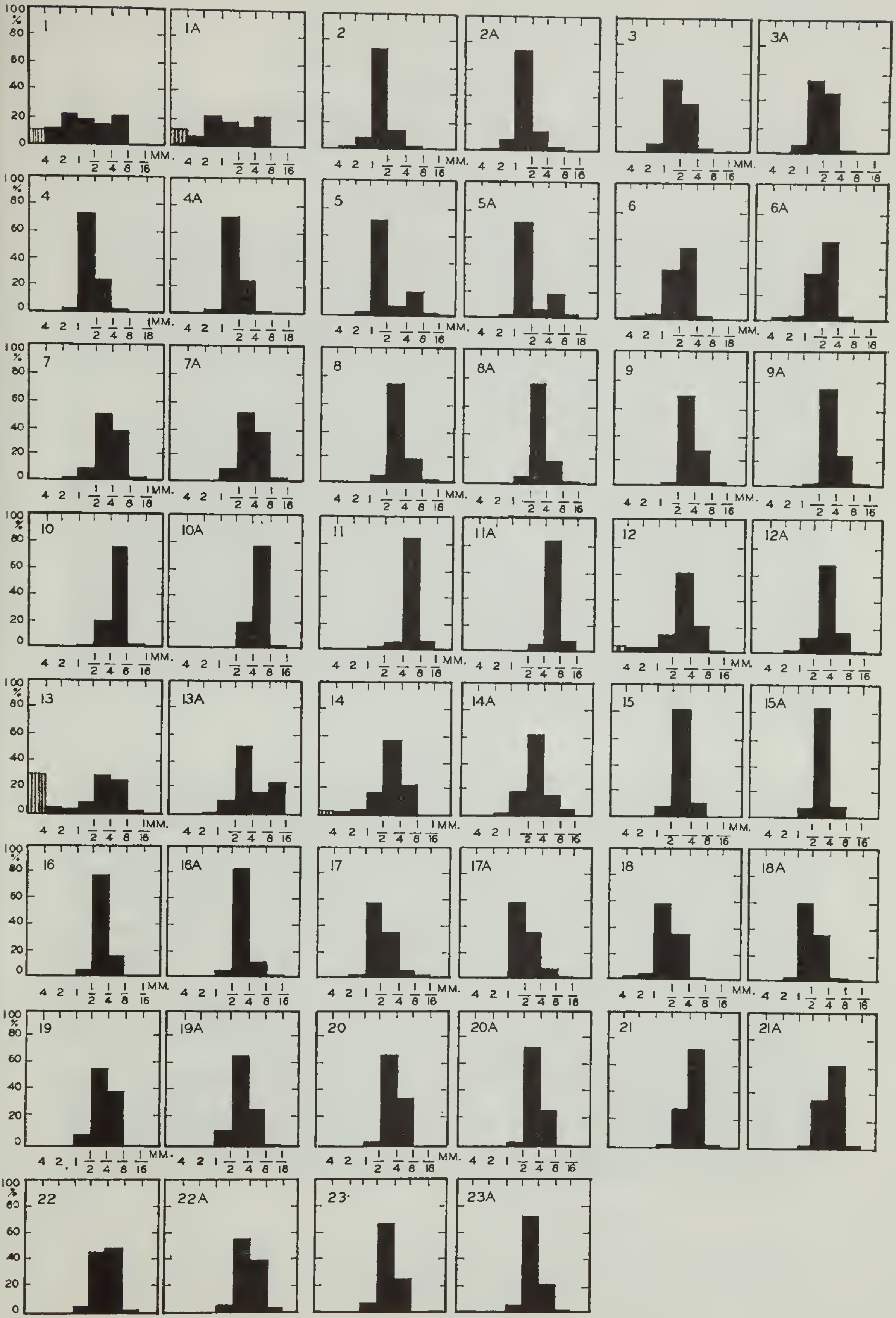

FIG. 4—Size-analysis histograms of sands and their acid-insoluble residues (A).

contain rock fragments, and a separate statement is made concerning them, since they serve as important indicators of source and assist in tracing sediment drift along the coastline.

Acid-soluble Content

The weight percentage of acid-soluble material in each sample is listed in Table 1 and these percentages are plotted against distance along the coast in Fig. 5. The acid-soluble content ranges from a minimum of 0·4 per cent at station 2 to a maximum of 50·1 per cent at station 13. From station 1 W. for 6 miles the acid-soluble content is less than 8·5 per cent, but from there is rises steeply reaching 39·5 per cent at station 11 (Rye). Between Rye and Point Nepean it varies between 22·2 per cent and 50·1 per cent. There is, accordingly, a low content of acid-soluble material in the sands from the E. part of the study region, and a relatively high content in those from the central and W. parts.

Microscopic examination indicates that organogenic material makes up almost all of the acid-soluble content. It comprises whole shells and shell fragments of Holocene age as well as material derived from the disintegration of Pleistocene dune-limestone, which is composed largely of shell fragments of sand size. It seems likely that much of the shell material in the sand from Rosebud to Point Nepean has come from disintegration of the dune-limestone which outcrops along the coast. All size-fractions of the sand from this region contain shell material, and it is common in most fractions. The low content of shell material in the sands east of McCrae seems to have come mainly from organisms indigenous to the nearby seafloor; it is present mainly in the coarser size-fractions of the sand. Microscopic examination indicates that shell material greater than 2 mm in size in the other sand samples is of similar Holocene origin. The presence of a large amount of shell derived from the indigenous marine fauna in the sand at station 13 points to considerable on-shore drift in the vicinity at certain times.

Rock Content

Fragments of granitic rock and hornfels occur in the sand at station 1. Apparently they have come from local sources; hornfels occurs around the Mount Martha Granodiorite as well as at The Rocks, Dromana (Baker 1938, Keble 1950). Much of the granitic rock is of pebble size but the fragments range down through granule to coarse sand size; most of the smaller fragments exhibit a fairly low degree of roundness and it is clear that they have not been subjected to much transportation. The amount of granitic rock at stations 2, 3 and 4 is considerably less than at station 1, but at station 5 there is a slight increase apparently due to local outcrops. Much less granitic rock is present at stations 6 to 9, and there is a decrease in size and increase in roundness of the fragments as one proceeds W. Granitic rock was not found at stations 10 and 11, but one small fragment was present in the sample from station 12 and a few from station 13; it is probable that these came from material used in the construction of retaining walls in the vicinity. No fragments of granitic rock occur in the samples W. of station 13.

Dune-limestone fragments are present in all samples from station 12 (White Cliffs) to Point Nepean but do not occur in the samples E. of White Cliffs. The fact that fragments do not occur far distant from dune-limestone outcrops may be related to the friable nature of much of this rock which is fairly easily disintegrated. The absence of dune-limestone fragments from the sands E. of Rye, however, may

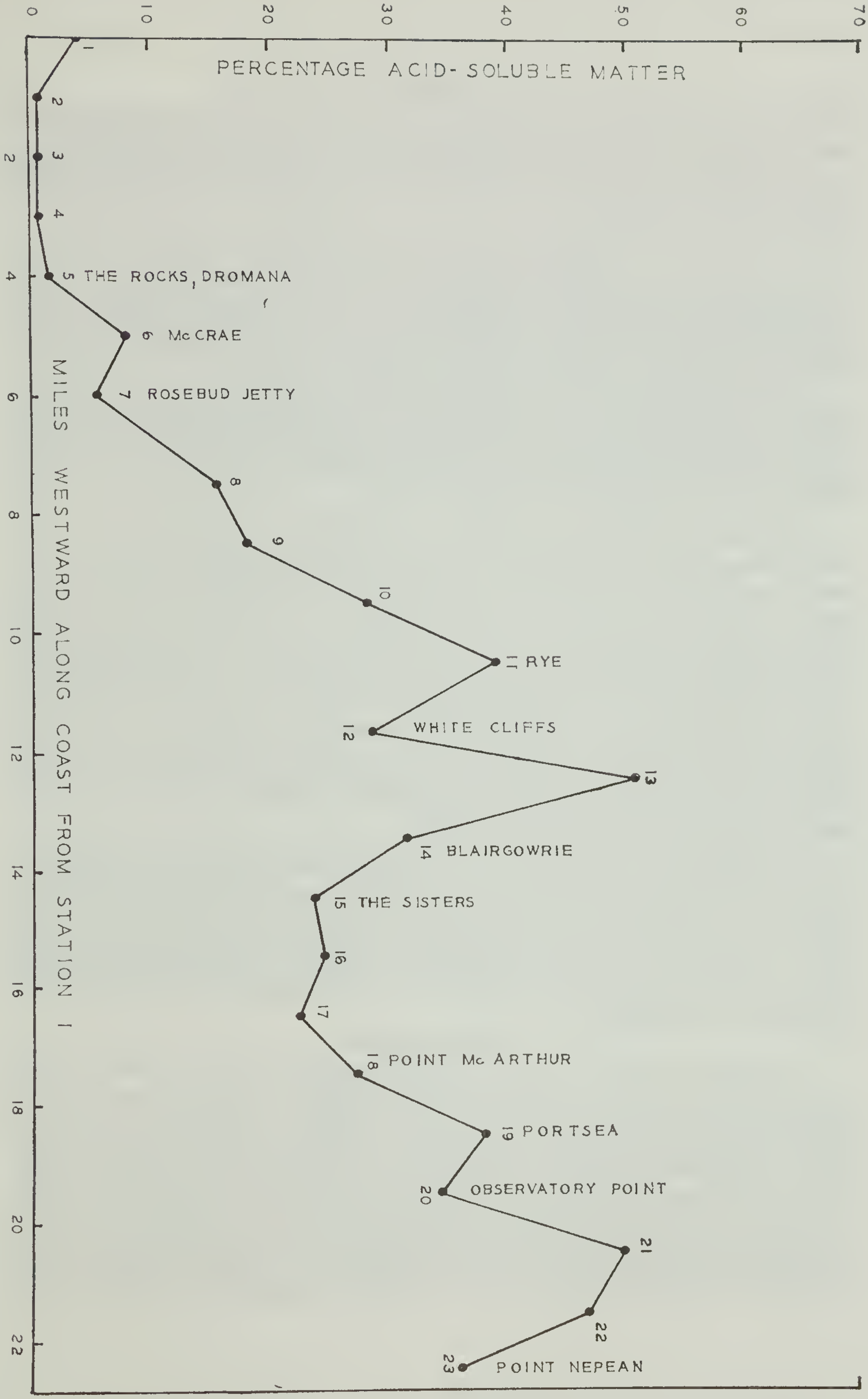

FIG. 5—Weight percentages of acid-soluble material in beach sands plotted against distance along coast.

indicate that sediment drift from the W. and central parts of the study region E. along the coastline is not very considerable.

A few granules and sand-size particles of ironstone occur in many of the samples. Their amount is never great, but they are more common in the Dromana-Safety Beach area than elsewhere.

Acid-insoluble Mineral Content

The acid-insoluble mineral content of the beach sands consists mainly of quartz. This is chiefly the transparent to translucent variety originally of granitic origin, but small amounts of opaque reef quartz occur. Feldspar grains are fairly common in certain samples, rare in others and not recognized in some. White mica occurs in minor amounts in the finer size-grades of certain samples.

The quartz grains are usually either colourless or yellowish and brownish from a thin coating of limonite; occasionally they are coated with hematite and are pinkish. Most ironstained grains reveal films of secondary iron hydroxide or iron oxide along cracks and flaws. Reef quartz grains are usually whitish-grey in colour, but some are deeply ironstained to a reddish colour.

Most of the quartz grains at station 1 are colourless and subangular to subrounded. Reef quartz is conspicuous there and feldspar is relatively common. Most of the mineral grains at station 1 appear to have come from the granitic rocks nearby and to have been transported little. The degree of roundness of the quartz grains in the sands from station 2 (Safety Beach) to station 6 (McCrae) ranges from angular to well rounded, but the majority are subangular to subrounded and most grains are colourless. Some of the quartz grains in the coarser size-fractions of the sands at these stations are angular; this points to a short detrital history, since rounding of larger size particles occurs at a relatively rapid rate. The ratio of ironstained quartz grains to colourless ones increases in a SW. direction along the shore from Safety Beach to McCrae. There are a larger number of subrounded quartz grains at station 7 (Rosebud) and station 8 (Rosebud West) than at the stations to the E. Feldspar and reef quartz particles diminish in amount in a SW. direction along the coast from Safety Beach.

From station 9 (Tootgarook) to Point Nepean colourless quartz grains are more abundant than ironstained ones; the former are commonly subangular and the latter are commonly subrounded. This fact suggests two different sources for the quartz. The less rounded colourless grains may have come from granitic rocks not far away, whereas the ironstained grains have a longer detrital history. The ratio of colourless to ironstained quartz grains remains almost constant along the central and W. parts of the study region. Some of the grains have frosted surfaces and others are well polished.

Heavy Fractions

The index number for the $\frac{1}{16}$ to $\frac{1}{2}$ mm size-grades of each acid-treated sand sample is listed in Table 2. The weight percentages of heavy minerals (index numbers) range from a maximum of 3·97 at station 3 (Dromana) down to a minimum of 0·22 at stations 11 (Rye) and 12 (White Cliffs). The relatively high values at Dromana and Safety Beach may be attributed to the location near the E. end of the arcuate stretch of shore between Point Nepean and Martha Point. Presumably the heavy minerals, transported by wave and current action, have become more concentrated along the shore of Dromana Bay partly because of the configuration of the coastline; they are prevented from moving northward by the headland of Mount Martha Granodiorite which has steep cliffs and relatively deep water near-shore. Some of the heavy minerals in these sands have apparently been derived from the granodiorite, and the higher index numbers may be partly due to closer proximity to this source rock.

In the central part of the region under consideration the index numbers are low in value but typical of most beach sands. The index number is 0·55 at station 7 near Rosebud Jetty and, with the exception of the sample from station 13, the values are all below unity until station 18 (Point McArthur) is reached. These low values may be connected with low-energy wave conditions resulting from the shallow near-shore topographic profile and the presence of sand bars subparallel to the beach. The higher value at station 13 may be related to higher wave energy in the vicinity connected with a steepening of the near-shore profile, greater heavy mineral concentration being affected by more powerful wave action.

The index numbers of samples from the W. part of the region are usually higher than those from the central (Rosebud-Sorrento) part, the value at station 23 (Point Nepean) being 1·35. The higher values may be attributed to the interruption to heavy mineral sand movement along and near the shore caused by the Rip, as well

TABLE 2

Mineralogical composition of heavy fractions (in % by number) and index numbers

STATION	ANATASE	ANDALUSITE	APATITE	AUGITE	BIOTITE	BLACK OPAQUES	BROWN OPAQUES	CHLORITE	EPIDOTE	GARNET	HORNBLENDE	IDDINGSITE	KYANITE	LEUCOXENE	MAGNETITE	MONAZITE	OLIVINE	PYRITE	RUTILE	SPHENE	STAUROLITE	TOPAZ	TOURMALINE	ZIRCON	ZOISITE	OTHERS	INDEX NUMBER
1	-	tr	tr	-	2	67	1	tr	tr	tr	2	-	-	9	C	tr	-	tr	1	-	-	-	7	8	-	tr	1.90
2	tr	-	tr	-	3	61	1	-	-	1	1	-	-	9	C	-	-	-	1	tr	-	tr	10	10	-	1	2.00
3	-	tr	tr	-	2	67	1	-	tr	1	1	-	-	7	C	tr	-	-	2	-	-	-	9	9	-	tr	3.97
4	-	-	-	tr	2	66	tr	tr	-	-	2	-	-	8	C	-	-	tr	2	-	-	-	8	8	-	1	1.99
5	tr	tr	tr	tr	1	52	tr	-	tr	tr	3	-	-	15	C	-	-	-	1	tr	-	-	11	11	tr	tr	0.55
6	-	-	-	tr	2	64	tr	-	tr	tr	4	-	-	7	C	tr	tr	-	2	-	-	tr	7	12	tr	-	1.06
7	-	tr	-	1	1	56	-	tr	1	1	2	-	-	7	C	-	1	-	2	tr	-	-	18	8	tr	tr	0.55
8	-	-	tr	2	1	59	-	-	1	-	3	-	-	10	O	tr	1	-	tr	-	-	-	11	8	tr	-	0.65
9	-	tr	-	3	1	54	-	-	1	-	5	-	tr	9	O	-	3	-	tr	-	-	tr	12	8	2	-	0.73
10	-	-	-	2	tr	56	-	-	1	-	4	-	tr	10	O	-	2	-	tr	tr	-	-	11	10	1	tr	0.34
11	tr	-	-	2	tr	45	-	-	2	tr	9	-	-	10	O	-	4	-	tr	-	-	-	12	10	2	-	0.22
12	-	-	-	2	tr	61	tr	-	1	-	3	-	-	10	O	-	2	-	tr	-	-	-	11	10	1	-	0.22
13	-	tr	-	3	-	66	-	-	1	-	2	tr	-	8	O	-	2	-	1	tr	-	-	7	9	1	tr	1.34
14	-	-	-	4	-	63	-	-	2	-	2	-	tr	8	O	-	3	-	1	-	tr	-	7	7	1	-	0.38
15	-	-	-	6	-	55	-	-	tr	-	2	tr	-	11	O	-	4	-	1	-	-	-	6	10	2	tr	0.37
16	tr	-	-	6	-	44	tr	-	2	-	2	tr	-	15	O	-	5	-	1	-	tr	-	10	12	2	-	0.27
17	-	-	-	4	-	62	-	-	2	-	2	tr	-	11	O	-	4	-	1	-	-	-	4	6	1	-	0.69
18	-	-	-	3	-	56	-	-	1	tr	1	1	-	12	O	-	5	-	2	-	tr	-	4	12	1	tr	1.14
19	-	-	-	4	-	53	-	-	1	tr	2	1	tr	15	O	-	4	-	1	-	-	-	5	9	1	-	0.52
20	-	tr	-	4	-	54	tr	-	1	-	2	tr	tr	14	O	-	4	-	2	-	tr	-	4	10	1	tr	1.29
21	tr	-	-	5	-	55	-	-	2	tr	3	tr	-	12	O	-	4	-	1	-	-	-	4	12	2	-	1.24
22	-	-	-	5	tr	50	-	-	2	-	4	1	-	10	O	-	6	-	1	-	tr	-	5	11	1	tr	1.11
23	-	-	-	4	-	58	-	-	1	-	2	tr	-	12	O	-	5	-	1	-	-	-	6	7	2	-	1.35

tr = less than ½% - (hyphen) = not detected C = common O = occasional as to the close proximity of a source rock (dune-limestone) and somewhat higher-energy wave conditions near the entrance to Port Phillip Bay.

Magnetite is present in the heavy fraction of each sample. Its relative abundance is listed in Table 2, estimated according to the following scale: A = very abundant; a = abundant; C = common; o = occasional; r = rare; V = very rare. Magnetite is classed as common in the heavy fraction of the sands from stations 1 to 7, that is, from the E. part of the region under consideration. In all samples W. of station 7 the relative abundance of magnetite is classed as occasional.

The mineralogical composition of the heavy fractions is given in Table 2. In this Table, 'others' refers to grains which could not be positively identified, usually because their weathered condition obscured diagnostic optical properties; it also includes some composite grains.

The heavy fractions of the sands from the E. part of the region (from station 6 E.) contain a granitic and metamorphic group of minerals, basaltic minerals such as augite and olivine being absent or present only in trace amounts (less than ½ per cent). Black opaque minerals (mainly magnetite and ilmenite) comprise more than 50 per cent of the heavy fractions, and magnetite is more common in them than in the other samples. This is also the case with brown opaque minerals (limonite and other coloured opaque ferruginous minerals) and biotite. The nature of the heavy mineral assemblages and the fact that many of the mineral grains do not have a high degree of roundness suggest that they were derived from local sources—mainly from granitic rocks nearby. Many of the zircon grains are euhedral and subhedral, and tourmaline occurs commonly as prismatic crystals showing only slight abrasion. Some grains of zircon, tourmaline, rutile and ilmenite are rounded and well-rounded, and apparently have had a longer detrital history; they may have come from the Tertiary sandstones exposed in coastal cliffs to the N.

The heavy fractions of the sands from W. of McCrae (station 6) contain basaltic minerals (olivine, augite and iddingsite) as well as granitic and metamorphic minerals. The amount in the sands from McCrae to Rye is small, but it is somewhat larger and remains nearly constant between Rye and Point Nepean. The olivine and augite are commonly coarser grained than the granitic-metamorphic group of heavy minerals. Some of the grains of basaltic minerals are angular and many are subangular to subrounded. The relatively slight abrasion of so many of these grains indicates that they have not had a very long detrital history. Black opaque oxide minerals comprise more than 40 per cent of the heavy fraction of the sands W. from McCrae, and ilmenite is more abundant than magnetite. Some ilmenite grains show partial alteration to leucoxene, and the percentage of leucoxene grains is higher along this stretch of shore than along that to the E. The zircon content of the heavy mineral assemblages does not vary greatly, but the amount of tourmaline is less in the samples W. of White Cliffs.

Grain Characteristics of the Heavy Minerals

Anatase. The very rare grains are usually blue but a few are yellow. They are commonly tabular and prismatic. Some grains show striations and zoning.

Andalusite. Occurs as pink and colourless grains which are elongate to irregular in shape. Some grains are cloudy from alteration.

Apatite. This mineral is rare in the assemblages. It may have been partly or wholly removed from the samples by acid digestion, since it is soluble in HCl. The grains are colourless and usually rounded, although slightly worn elongate prismatic ones are present.

Augite. Most grains are pale brownish-violet; some are greenish, greyish, various shades of brown and almost colourless. Grains are often elongate cleavage fragments of irregular shape, sometimes with dentate ends. Most particles do not show a high degree of roundness, many being subangular. Grain size is commonly larger than most of the other heavy minerals. Some particles show corrosion features.

Biotite. Occurs as brown and greenish-brown grains which are commonly irregular in outline with jagged edges. Many flakes are fresh but some show partial alteration to chloritic matter and others are bleached almost white. The flakes are usually larger than most of the other heavy minerals.

Black Opaques. These grains are mostly magnetite and ilmenite. The degree of roundness of the magnetite grains ranges from angular to well-rounded. Some magnetite grains show edges of crystal faces and a few octahedra occur. Ilmenite grains generally have a higher degree of roundness than magnetite; many are subangular but most are subrounded. Some ilmenite grains are partly altered to leucoxene.

Brown Opaques. These are mostly limonite but include other coloured opaque ferruginous minerals. Most of these grains are subrounded and irregular in shape.

Chlorite. Occurs as greenish grains often of blotchy colour. The grains are irregular in outline and often have a ragged appearance.

Epidote. The grains are pale greenish-yellow in colour and usually subangular or subrounded. Pleochroism is weak.

Garnet. Most grains are pink, but some are colourless and a few brown. The grains are often angular and subangular, and some show surface etching. Crystal faces are seen on some grains.

Hornblende. Grains range in colour from green to brown, brownish-green ones being most common. Grains are usually elongate cleavage fragments and many appear relatively fresh. They are often larger than most of the other heavy minerals.

Iddingsite. Occurs as reddish-brown grains of irregular shape. Most grains are subangular.

Kyanite. Grains are colourless and usually elongated with rounded ends. Traces of cleavage at right angles to the length of the grains are common.

Leucoxene. Occurs as creamy-white, greyish-white and yellowish-white grains with a dull lustre. Most grains are subrounded or rounded. The surface is sometimes minutely pitted. A few grains reveal remnants of residual ilmenite.

Monazite. Grains are pale yellow in colour. They are usually rounded and faintly pleochroic.

Olivine. Most grains are colourless but some are pale yellowish-green. Many appear relatively fresh but some show traces of decomposition and others are clouded from alteration. Grains are commonly subangular and irregularly shaped; some show edges of crystal faces. The grains are often larger than most of the other heavy minerals.

Pyrite. The rare pyrite occurs as small pale brass-yellow crystals.

Rutile. The foxy-red variety is most common, yellow and yellowish-brown grains being less common. Grains are usually elongate and subrounded; some show edges of prism faces.

Sphene. The rare grains are pale-yellow and pale-brown. They are usually subangular and irregular in outline. Some grains are clouded through decomposition.

Staurolite. Occurs as brown and brownish-yellow grains which are subangular and irregular in shape. Inclusions are fairly numerous in some grains.

Topaz. The grains are clear and colourless. They are mostly subangular and irregularly-shaped.

Tourmaline. Brown varieties predominate but there are yellow, green, blue, grey, pink and parti-coloured grains. Grains show all degrees of roundness. Elongate prismatic crystals showing only slight abrasion are present, and some grains are well-rounded. The well-rounded grains, some of which show a high degree of sphericity, point to survival through more than one sedimentary cycle.

Zircon. Most grains are clear and colourless but a few are pale-yellow. The grains range from euhedral and subhedral to well-rounded. Rounded grains in most assemblages are approximately equal in number to those showing well-preserved crystal edges and faces. A polycyclic origin is postulated for the well-rounded grains. Inclusions are common in well-preserved crystals but the rounded grains are generally free from inclusions. Zoning is sometimes observed, and some grains have a dusky appearance due to the crowding of inclusions.

Zoisite. Occurs as colourless, prismatic grains which are usually subrounded.

Sources of the Sand Constituents

To enquire into the origin of the sand constituents, samples of dune-limestone from White Cliffs (near station 12) and Point Franklin (near station 19) were studied. Use is made of Baker's (1938, 1942) studies of the heavy minerals of granitic rocks in the area.

The relative abundance of the mineral species in the heavy fraction of the Mount Martha Granodiorite, as determined by Baker (1942) is: apatite (common), biotite (very abundant), chlorite (very rare), garnet (very rare), hematite (rare), hornblende (occasional), ilmenite (rare), limonite (very rare), magnetite (rare), pyrite (rare), rutile (very rare), sphene (very rare), zircon (common). Baker (1942) lists the heavy mineral assemblage of the Dromana Granite as: anatase (very rare), apatite (occasional), biotite (common), chlorite (occasional), epidote (rare), hornblende (common), magnetite (common), pyrite (occasional), sphene (occasional), zircon (common), zoisite (very rare).

It is clear that granitic rocks have been the primary source for most of the detrital minerals in the beach sands, and it can be presumed that the Mount Martha Granodiorite and the Dromana Granite have been important contributors. The Mount Martha Granodiorite is decomposed and soft along the NE. shore of Dromana Bay where erosion makes the rock an important source for supply of the sand constituents. Fragments of granitic rock are not uncommon in the beach sands of Dromana Bay but are rare or absent in the samples to the W. At station 1 particularly a large proportion of the acid-insoluble constituents are coarse-grained and have a relatively low degree of roundness, and the sand there shows only moderate sorting. Apparently, many of the constituents have been derived directly from the granodiorite. The mineral species in the heavy assemblages of the Dromana Bay sands and the freshness and state of abrasion of many grains reflect the close proximity of granitic rock. In particular, the presence of well-preserved zircon, tourmaline and magnetite crystals and fresh brown biotite flakes in the samples E. of McCrae indicates relatively recent liberation from granitic rocks.

The median grain size of the disaggregated dune-limestone from White Cliffs is 0·18 mm and that from Point Franklin is 0·17 mm; the sorting coefficients are 1·29 and 1·30 respectively. The median diameters are both somewhat smaller than those of the sand nearby (at stations 12 and 19). The degree of sorting of the material composing the White Cliffs rock is identical with the beach sand nearby, but the detrital constituents of the Port Franklin rock are somewhat less well sorted than the beach sand from station 19.

The weight percentage of acid-soluble (mainly shell) material in the disaggregated dune-limestone from White Cliffs is 63·9 per cent and that from Point Franklin is 67·1 per cent. These percentages compare with 28·6 and 38·1 per cent in the beach sands from near these two places.

Median grain size of the acid-insoluble residue from the disaggregated White Cliffs dune-limestone is 0·20 mm, which is slightly coarser than the material before acid treatment; but the median diameter of the acid-insoluble residue from the Point Franklin material (namely 0·17 mm) is identical with that of the untreated disaggregated rock.

Median diameters of the acid-insoluble residues from the disaggregated dune-limestones are both less than those of the acid-insoluble residues of the beach sands from nearby stations (0·32 mm and 0·28 mm). This fact suggests that there are contributors other than dune-limestone to the mineral composition of the beach sands in this region.

Sorting coefficients of the acid-insoluble residues of the disaggregated dune-limestones from White Cliffs and Point Franklin are 1·27 and 1·21 respectively. As with most of the sand samples, sorting improved slightly after removal of the acid-soluble (mainly carbonate) content. The sorting of the acid-insoluble residues of the disaggregated rocks is not quite as good as that of the acid-treated beach sands from stations 12 and 19.

Microscopic examination of the various size-fractions of the disaggregated dune-limestones shows that the rock is composed mainly of quartz grains and fragments of marine skeletal material. Most of the quartz grains are subangular or subrounded, but some are angular, rounded and well rounded. The quartz grains closely resemble those in the beach sands, colourless grains being more abundant than yellowish, ironstained ones. The colourless quartz grains are commonly subangular while the yellowish grains tends to be subrounded. Some quartz grains have a frosted surface. Marine skeletal material is common in all size-fractions.

Fragments of dune-limestone, derived from coastal erosion, are found in the beach sands from White Cliffs to Point Nepean, and it is clear that this rock is an important source of the sand constituents in this region. The relatively high content of marine skeletal material in the sands from Rosebud West to Point Nepean may be related to the high content of bioclastic material in the dune-limestone. E. of Rosebud, farther away from the coastal outcrops of dune-limestone, the content of marine skeletal material in the beach sands is much lower.

The weight percentages of heavy minerals (index numbers) for the $\frac{1}{16}$ to $\frac{1}{4}$ mm size-grades of the acid-treated disaggregated dune-limestones from White Cliffs and Point Franklin are 0·42 and 0·45 respectively. These compare with index numbers of 0·22 for the acid-treated beach sand from near White Cliffs and 0·52 for that from near Point Franklin. The index numbers for the dune-limestones and nearby beach sands thus are approximately of the same order of magnitude. They are considerably smaller than the index numbers for the beach sands from the E. part of the coastal region under consideration. The mineralogical composition of the heavy fractions of the dune-limestone samples is very similar, and there is a close similarity to that of the neighbouring beach sand samples.

The present research indicates that the acid-insoluble mineral content of the beach sands has been derived mainly from the rocks forming the cliffs and wave-cut platforms in the study region. The shell fragments, which make up most of the acid-soluble content of the beach sands, have originated by comminution of material derived from organisms indigenous to the nearby seafloor, as well as by disintegration of coastal outcrops of dune-limestone.

Conclusions

The beach sands of the S. shore of Port Phillip Bay consist essentially of quartz grains and shell fragments. The relatively high content of shell fragments in the sand W. of Rosebud is due largely to the disintegration of dune-limestone which is composed largely of shell fragments.

The main source materials are the rocks which outcrop along the coast in the study region. Dune-limestone is the major source rock. In the E. (Dromana Bay) area the Mount Martha Granodiorite is an important source rock. This is why the sand there is coarser and less well-sorted, and composed mainly of granitic minerals. Shell material derived from marine organisms living nearby is constantly being added to the sands.

The beaches are relatively stable. Powerful waves generated by strong N. and NW. winds erode sand from some of the beaches and deposit it off-shore, but smaller waves generated by weaker winds transport sand back to the beaches. Sand drift along the shore occurs in different directions at different times according to seasonal weather. It does not have very considerable or markedly permanent effects on the sandy beaches. Where the sand ridge bordering the shore is subjected to wave erosion during stormy weather, 'new' material is made available to the beach. In some places where coastal erosion has made the construction of rock sea-walls necessary, man appears to have been partly responsible for the erosion by interfering with vegetation and removing portion of the sand ridge bordering the shore. This is so particularly between Dromana and Rye, and it will be necessary to guard against further human interference.

Heavy minerals are not common in the beach sands, but local concentrations occur at the N. end of Safety Beach.

Results of the present research will be of value in any subsequent study of sand drift.

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Explanation of Plate

PLATE 1

Fig. 1—View from station 1 showing the cliffed coastline cut in the Mount Martha Granodiorite which forms the N. shore of Dromana Bay.

Fig. 2—Wave-cut beach scarp showing parallel layers of heavy mineral sand near station 1, Safety Beach.

Fig. 3—The Sisters (western headland) looking towards Sorrento. This headland of dune-limestone is undergoing erosion and supplying sand-size detritus to the neighbouring beaches.

Fig. 4—Sandy beach between Point King and Point McArthur, near Portsea. Vegetated cliffs of dune-limestone rise steeply from the shore.

Appendix

Sample stations

1. 40′ S. of line of projection of S. boundary, Bruce Rd., m.s.* 70; s.w.† 52′, s.g. 6°.
2. 300′ SW. of line of projection of S. boundary, Wattle St., m.s. 90; s.w. 81′, s.g. 6°.
3. 310′ NE. of line of projection of S. boundary, Nepean Highway, m.s. 89; s.w. 87′, s.g. 5°.
4. 350′ WSW. of line of projection of W. boundary, Verdon St., m.s. 89; s.w. 48′, s.g. 7°.
5. 345′ WSW. of line of projection of W. boundary, Burrell Rd., m.s. 108; s.w. 62′, s.g. 3°.
6. 300′ WSW. of line of projection of W. boundary, Bartels St., m.s. 108; s.w. 87′, s.g. 5°.
7. 610′ ENE. of Rosebud Jetty, m.s. 108; s.w. 250′, s.g. 1°.
8. On line of projection of W. boundary, Brendel St., m.s. 127; s.w. 107′, s.g. 3°.
9. 150′ ESE. of line of projection of W. boundary, Truemans Rd., m.s. 127; s.w. 97′, s.g. 3°.
10. 200′ W. by S. of line of projection of W. boundary, Romney Avenue, m.s. 126; s.w. 100′, s.g. 3°.
11. 175′ W. of line of projection of W. boundary, Weir St., m.s. 126; s.w. 111′, s.g. 2°.
12. 125′ E. of line of projection of W. boundary, White Cliffs Rd., m.s. 125; s.w. 67′, s.g. 5°.
13. 470′ E. by S. of line of projection of W. boundary, Murray St., m.s. 125; s.w. 24′, s.g. 7°.
14. 800′ WNW. of line of projection of W. boundary, Inverness Av., m.s. 125; s.w. 84′, s.g. 4°.
15. 1180′ N. by W. of line of projection of W. boundary, Hughes Rd., m.s. 104; s.w. 162′, s.g. 2°.
16. 405′ SE. by E. of line of projection of W. boundary, St. Pauls Rd., m.s. 104; s.w. 43′, s.g. 6°.
17. 685′ NNW. of line of projection of N. boundary, St. Aubins Way, m.s. 84; s.w. 27′, s.g. 7°.
18. On line of projection of E. boundary, Hemston Av., m.s. 83; s.w. 56′, s.g. 6°.
19. 600′ E. of Portsea Jetty, m.s. 83; s.w. 83′, s.g. 5°.
20. 1024′ ESE. of Quarantine Jetty, Portsea, m.s. 62; s.w. 36′, s.g. 6°.
21. 1170′ ESE. of Observatory Pt., m.s. 62; s.w. 98′, s.g. 5°.
22. On compass bearing 115° from base of Pt. Nepean Jetty, m.s. 62; s.w. 110′, s.g. 5°.
23. 125′ WSW. of most northerly part of Pt. Nepean, m.s. 62; s.w. 170′, s.g. 1°.

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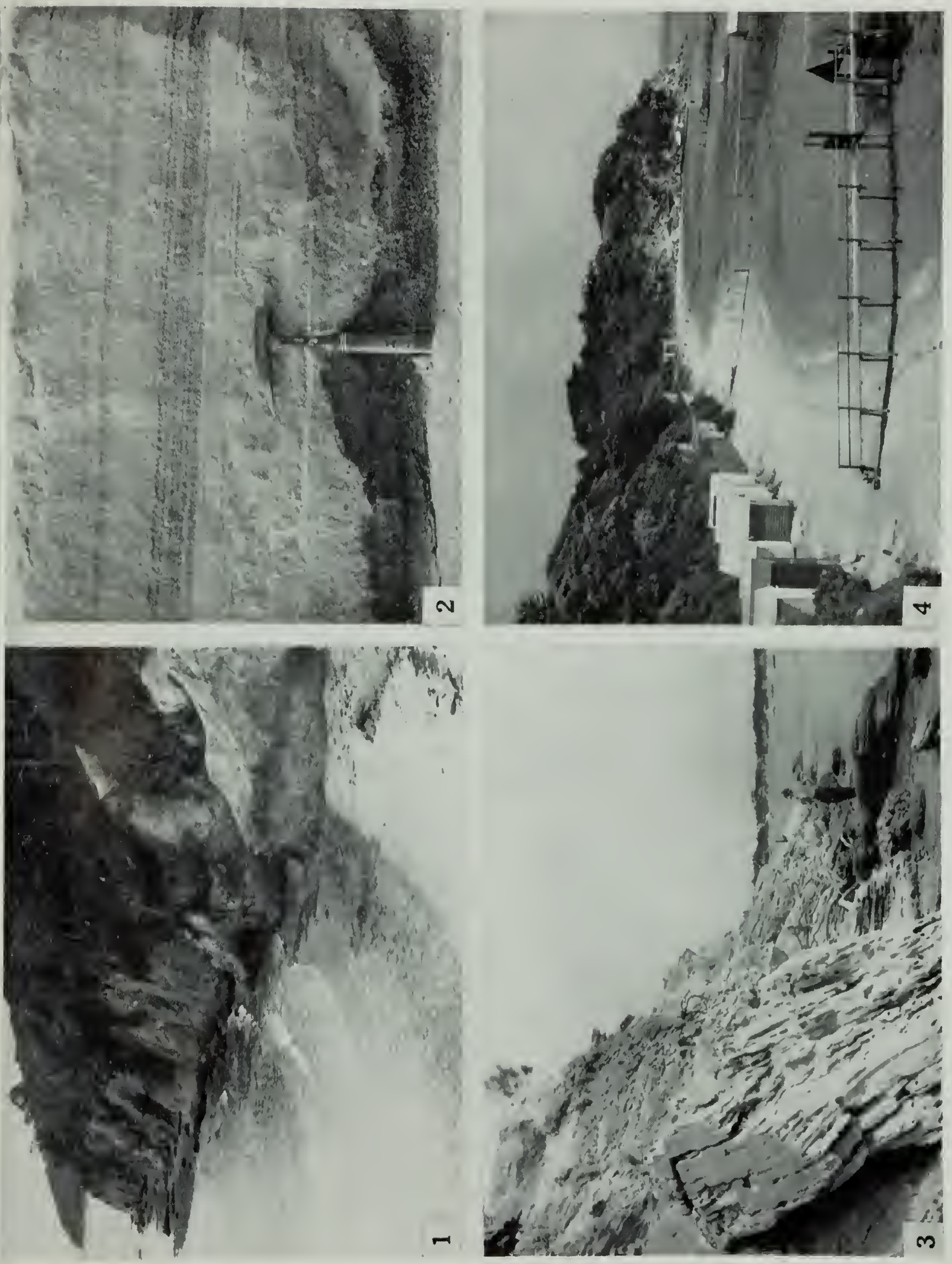
* = Map sheet, Mornington Peninsula Area Base Map Series.
† s.w. = shore width, s.g. = shore gradient.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