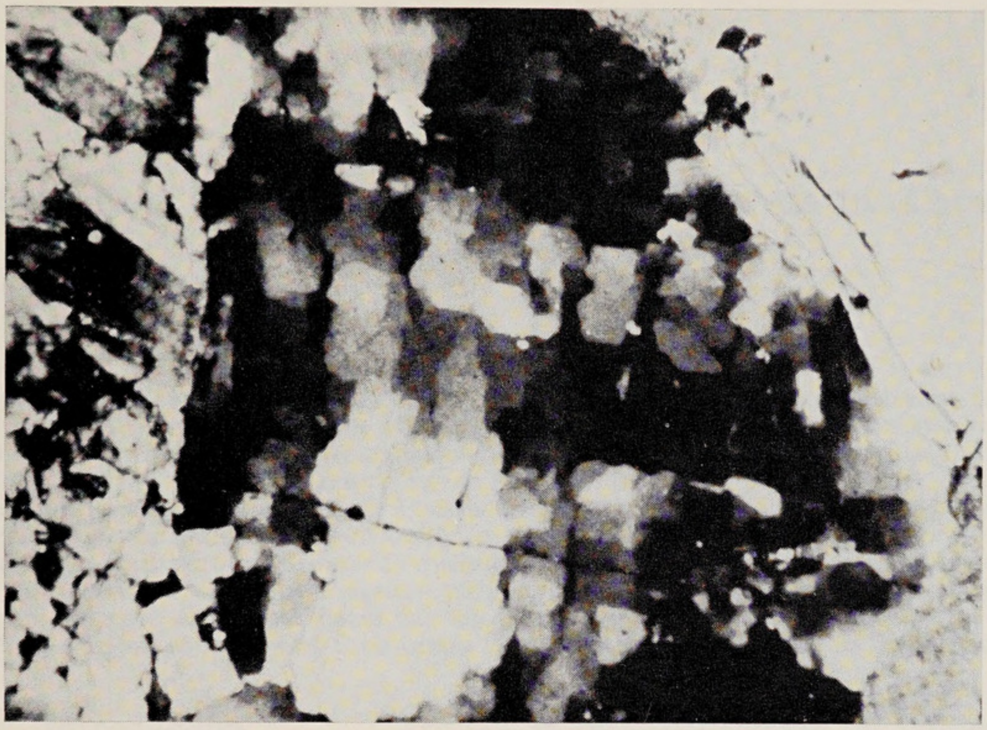

PLATE 1 (*a*)

Cell structure in a quartz grain from the Corryong Granite (spec. 21809). Note the polygonal arrangement of the small domains. Crossed nicols, ×120.

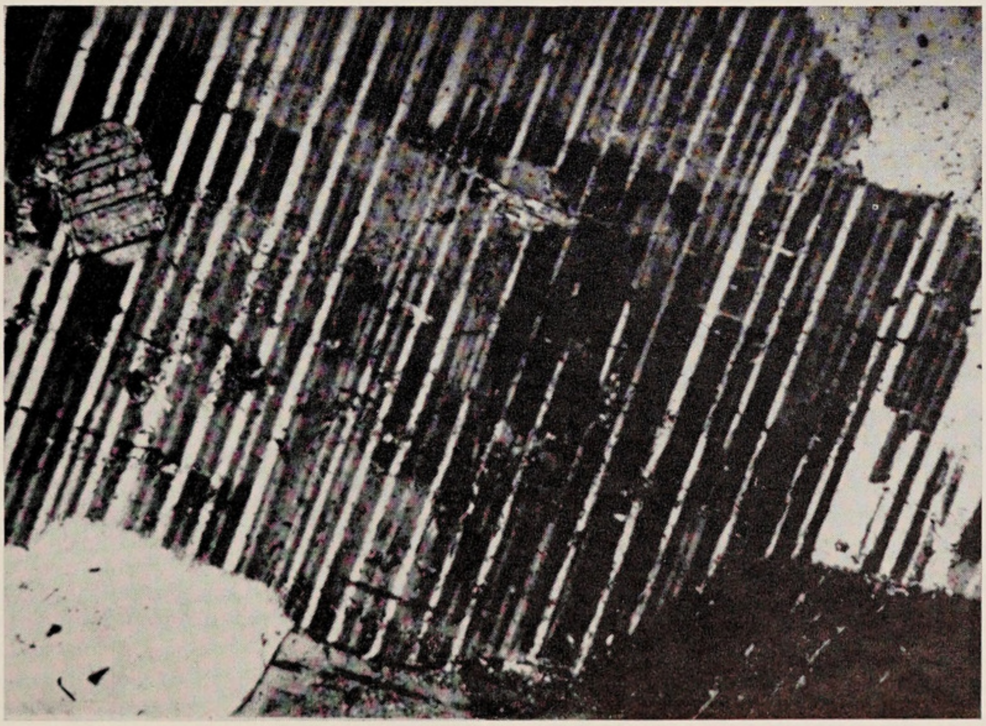

PLATE 1 (*b*)

Section of a plagioclase grain displaying patchy zoning, from the Corryong Granite (spec. 21842). This zoning is evident only near the extinction positions. Crossed nicols, ×45.

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# The Nature and Occurrence of Heavy Minerals in Three Coastal Areas of New South Wales

J. R. Hails[1]

Abstract—A detailed mineralogical study has been undertaken in an attempt to determine the sources of heavy minerals in three areas of New South Wales. The areas studied are Twofold Bay and neighbouring South Coast districts between Pambula and Disaster Bay, Broken Bay near Sydney, and the Mid-North Coast between Port Macquarie and Grassy Head. The percentage variations of different minerals in both Pleistocene and Holocene sediments have been evaluated. Diagnostic heavy minerals have been traced in some barrier and dune sands, and it is believed that these were transported shorewards during marine transgressions accompanying interglacial periods, and reworked locally by longshore drifting. Most of the minerals in the unconsolidated deposits on the east Australian coast can be described as *polygenetic* because they have been derived from various sources, and their origin is very complex in relation to both time and place.

## Introduction

*(a) The Nature of the Problem:*

The barriers[2] and dunes on the New South Wales coast are composed of sediments that were reworked during Pleistocene fluctuations of sea-level and during the post-glacial or Holocene marine transgression. Such deposits can therefore be described as *polygenetic* since they have been derived from various sources and their origin is very complex in relation to both time and place. The writer has analyzed Pleistocene and Holocene sediments in an attempt to determine the sources of the heavy minerals in three coastal areas of New South Wales. The areas, which differ geologically and physiographically, are Twofold Bay and neighbouring South Coast districts between Pambula and Disaster Bay (Figure 1), Broken Bay near Sydney (Figure 2), and the Mid-North Coast between Port Macquarie and Grassy Head (Figure 3).

The origin and distribution of heavy mineral beach sands in New South Wales and south-eastern Queensland have been mentioned briefly in technical reports by Gardner (1955), Whitworth (1956) and Connah (1962). Jones (1946) and Beasley (1948, 1950) have discussed the concentration of heavy minerals in beach deposits. Culey (1933, 1939) studied the heavy mineral assemblages of the Narrabeen and Hawkesbury Sandstones. However, no detailed investigations have been made to determine the relationship between heavy mineral concentration and longshore drifting, aeolian activity and the shoreward movement of material from the sea floor during marine transgressions.

*(b) The Physiography and Geology of the Areas:*

Dual barrier systems, composed entirely of quartzose sand and separated by swamps and lagoons, have been mapped on several sectors of the New South Wales coast. These have been termed Inner (Pleistocene) and Outer (Recent) Barriers by Langford-Smith and Thom (1969).[3]

The Holocene (Recent) barriers developed across the mouths of drowned river valleys to enclose estuarine lagoons partly or completely from the sea after 7000 B.P. (before the present), at a time when the rate of the post-glacial or Holocene rise of sea level slowed down appreciably (Hails, 1968). The barrier systems of the Central and South Coast of New South Wales are not as clearly represented by Pleistocene and Holocene components as those on the Mid-North Coast which border large fluvial-deltaic

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[2] The term *barrier* applies to littoral sand accumulations—either beaches, spits or islands—that stand permanently above high-tide level and enclose lagoons or shallow bays. Barriers are usually characterized by multiple beach ridges, but a few are comprised of a single ridge. A few beach ridge systems, for example, the Umina-Woy Woy system in Broken Bay, are not separated from a bedrock hinterland by large coastal lagoons.

[3] The terms Outer (Recent) Barrier and Inner (Pleistocene) Barrier will be used in the same context as originally defined by Langford-Smith and Thom (1969).

plains. This is because former broad protected bays of the North Coast, and an abundant supply of sand from large rivers, favoured the development of wide barriers, while the more rugged embayments and lack of large rivers on the Central and South Coast did not. The limited extent to which the estuarine lagoons on the South Coast have been filled by fluvial deposits also reflects the size, discharge and sediment yield characteristics of the river catchments (Bird, 1967).

Twofold Bay (Figure 1) and adjacent areas are composed of strongly folded and faulted Devonian strata, with Ordovician metamorphic rocks and Tertiary basalts (Brown, 1930, 1933 ; Steiner, 1966). The sedimentary rocks around Twofold Bay are of variable composition, and are associated with rhyolites, basalts and dolerites. Unconsolidated sands and gravels of varying thickness which directly overlie the Devonian rocks have been designated Tertiary (Hall, 1957).

Twofold Bay, one of the largest embayments on the South Coast, is actually a succession of smaller bays, with bayhead beaches, which are separated by headlands and small promontories. The Boyd Town barrier system is the largest of its kind inside the bay, and is situated between the Nullica River and Boyd Town Creek. It consists of a series of abandoned beach ridges with intervening swales and is backed by degraded sea cliffs. Eden barrier spit impounds Curalo Lake which occupies the drowned valleys of Bellbird Creek and adjacent coastal streams. Whale Beach barrier encloses the Towambah (Kiah) estuary and north of Twofold Bay, Pambula barrier spit partly encloses Merimbula Lake.

Broken Bay (Figure 2) is part of the dendritic drowned valley of the Hawkesbury River, and is dominated by vertical cliffs cut in resistant, almost horizontally-bedded, Hawkesbury and Narrabeen sandstones of Triassic age. Lenticular layers of shale are interbedded with the sandstones which are characterized by major systems of vertical joints (David, ed. W. R. Browne, 1950). Tertiary dykes and sills have been reported in a few coastal sections. Patonga Beach is a sand barrier which almost completely encloses the mouth of Patonga Creek in Brisk Bay, whilst Pearl Beach barrier originally developed across the mouth of a small embayment.

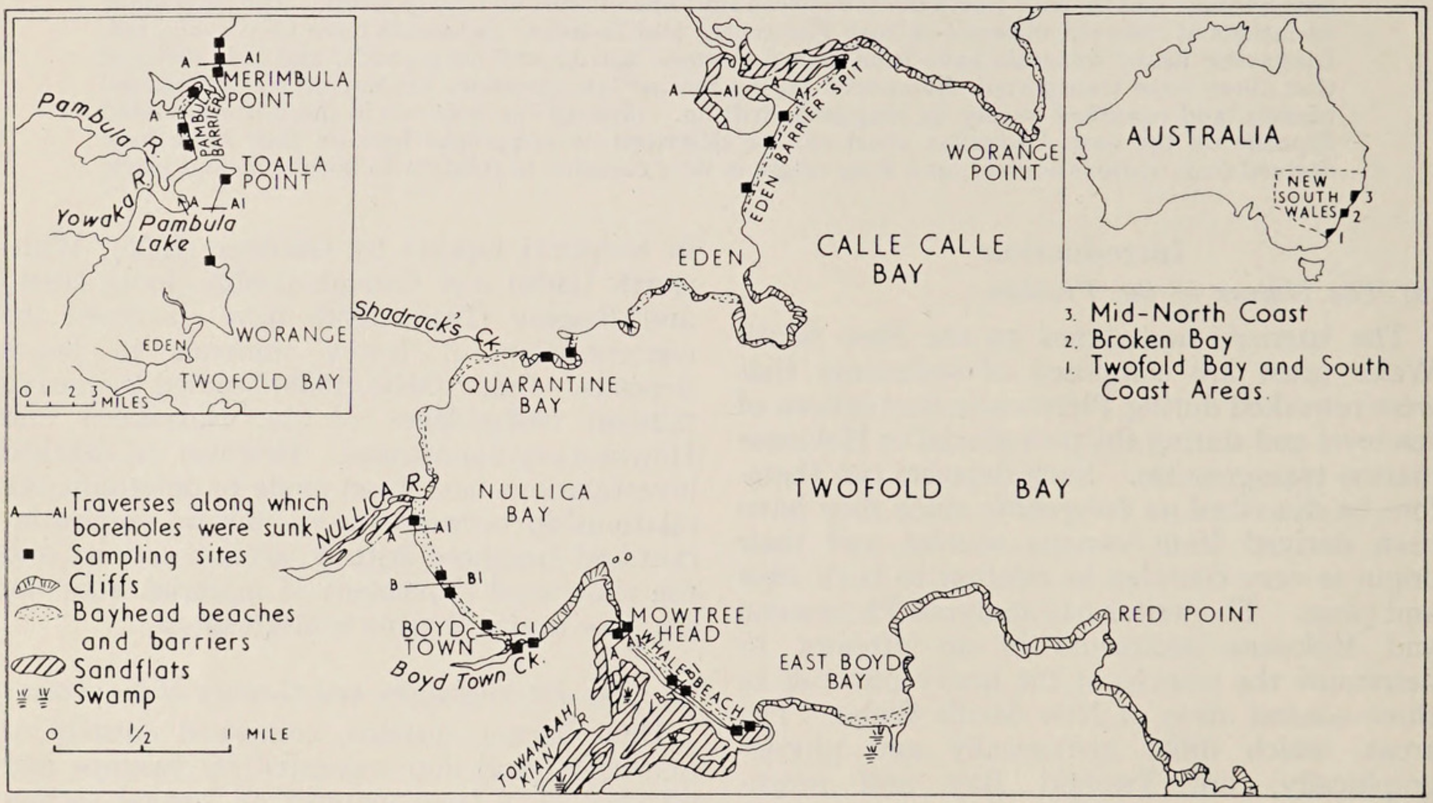



FIG. 1—Twofold Bay and adjacent South Coast areas. Inset map of Australia shows location of the three study areas in New South Wales.

The Umina-Woy Woy barrier is the largest depositional feature in Broken Bay. It consists of a series of abandoned beach ridges aligned parallel to the shoreline. There is some evidence to suggest that this barrier may be composed of Pleistocene as well as Holocene sediments (Hails, 1969), in contrast to Pearl Beach and Patonga Beach which are Holocene barriers.

The Mid-North Coast (Figure 3), is characterized by zeta-curved or arcuate bays which are flanked by resistant bedrock headlands. Some of the headlands are mantled with deeply podzolized Pleistocene cliff-top dunes that stand between 100 and 400 feet above present sea level.

According to Voisey (1934), the headlands are composed mainly of sandstones, tuffs, mudstones, claystones and shales with minor conglomerate bands. These deposits, termed the Kempsey Series, are believed to be of Permian age. The hinterland of the Mid-North Coast forms part of the New England Plateau which is composed predominantly of Palaeozoic rocks, and Tertiary basalts. The Macleay is the largest river on the Mid-North Coast, and its headwaters occupy valleys which have been incised into the New England Plateau. No deltas have been built seaward of the modern coast in northern New South Wales. Instead sedimentation and alluviation have taken place between an ancient bedrock coastline and the dual barrier systems, resulting in the construction of fluvial-deltaic plains.

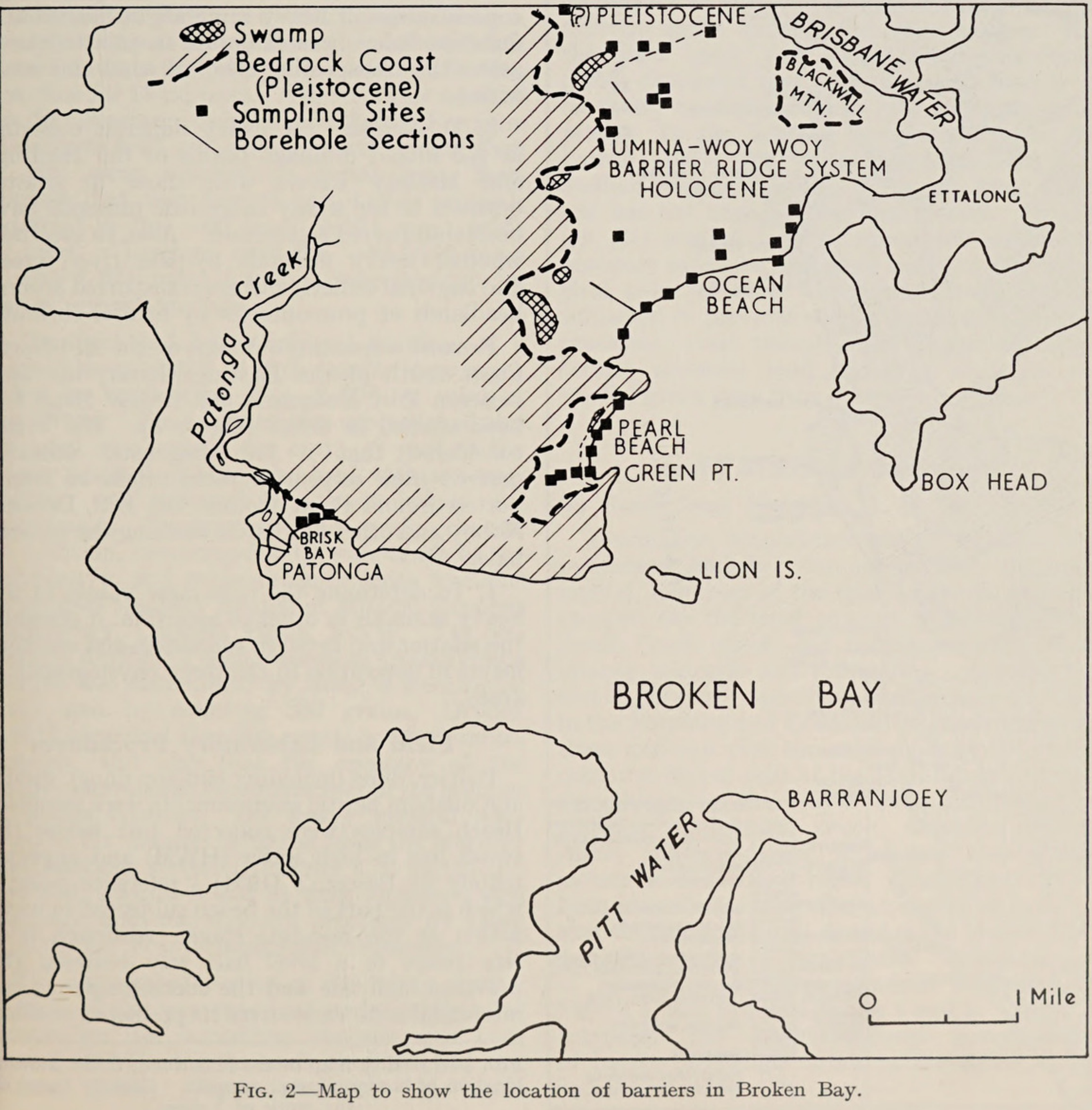
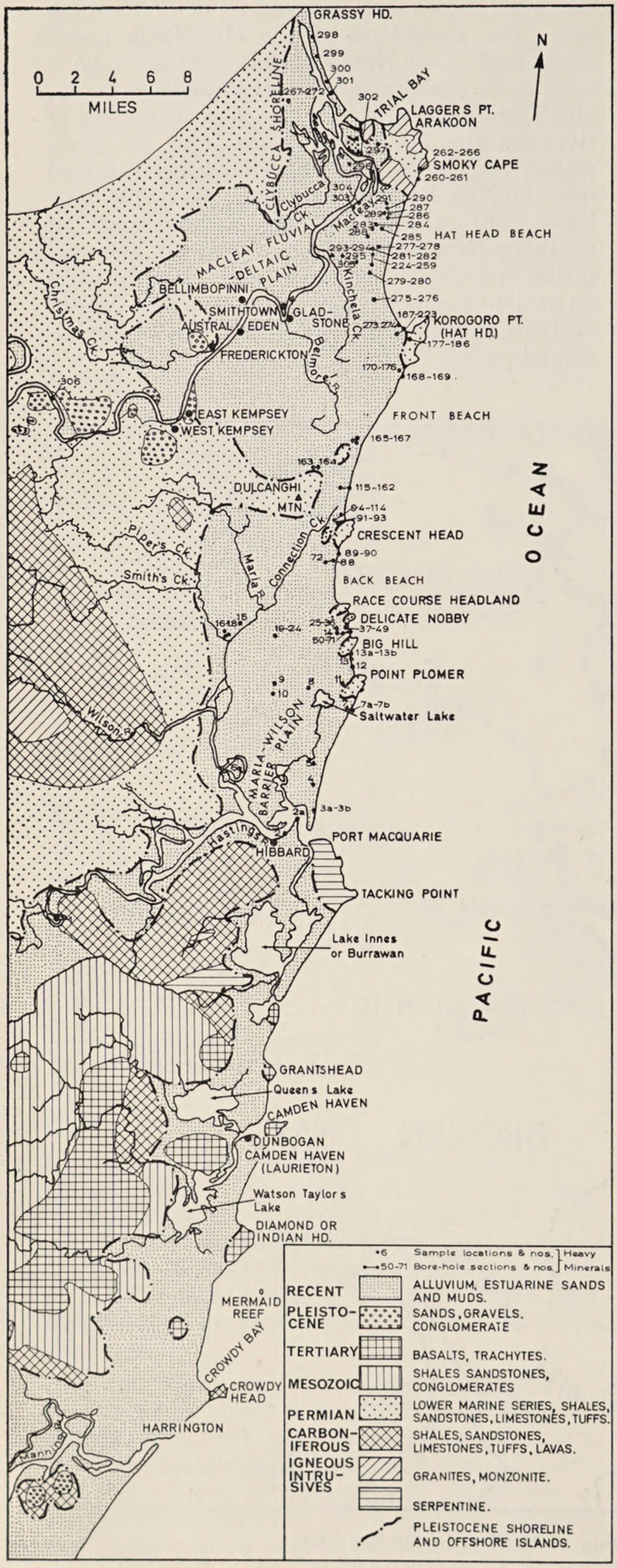



Fig. 2—Map to show the location of barriers in Broken Bay.




(*c*) *The Aims of the Study :*

The purpose of this study has been :

1. To trace the sources of the heavy minerals. Sources can be sub-divided into : indirect sources, such as material being reworked from immediately offshore, and direct sources, whereby minerals are derived from eroded adjacent cliffs and headlands.

2. To evaluate the percentage variation of the different minerals in Pleistocene and Holocene barrier and dune sands in order to determine whether there is any significant difference with age. An assessment has been made of the chemical stability of the heavy minerals and their resistance to abrasion. The percentage concentration of heavy minerals in barrier and dune sands has been examined in an attempt to assess the transporting effect of wind and wave action.

3. To compare the heavy minerals collected in the inland drainage basins of the Hastings and Macleay Rivers with those in coastal deposits to see if any diagnostic minerals have been transported alongshore. Also, to ascertain whether heavy minerals by-pass river, creek and lagoonal outlets, and are transported around headlands or promontories by littoral currents.

Because serpentine outcrops on the Mid-North Coast south of the Hastings River, the area between Port Macquarie and Grassy Head has been studied in detail (Figure 3). The writer considered that a few diagnostic minerals derived from serpentine rocks might be transported around Point Plomer, Big Hill, Delicate Nobby and other headlands flanking the arcuate bays.

4. To determine the roundness values of the heavy minerals in order to ascertain, if possible, the relationship between roundness and environments of deposition in the three physiographical areas.

### Field and Laboratory Procedures

Barrier, dune (including cliff-top dune), fluvial and offshore neritic environments were sampled. Beach samples were collected just below the swash line of high water (HWM) and approximately at Bascom's (1951) " reference point " which is the part of the beach subjected to wave action at the mid-tide stage. Although mid-tide refers to a level half way between the previous high-tide and the succeeding low, the inter-tidal zone varies from its predicted position

FIG. 3—Locality map of the Mid-North Coast showing location of heavy mineral samples. Geology based on the work of Voisey.

according to local conditions at the time of sampling. Barrier and dune samples were collected at one-foot intervals from boreholes sunk along surveyed transects across the barriers and deltaic plains. Lines of section were approximately perpendicular to the beach and extended from low water mark to a degraded coastline behind either the barriers or deltaic plains. No samples were collected below the water table because of the risk of contamination by material washed into the boreholes.

Samples collected from the swamps and deltaic plains which contained a high content of silt and clay were analyzed by the hydrometer method of Bouyoucos (1936).

All sand samples were oven dried and a 100 gm. sample split was sieved through a set of B.S.S. 8-inch sieves at the ¼(Φ) phi interval on a Ro-Tap machine for 15 minutes. The fractions retained on the sieves were weighed on a Mettler Precision Balance to 0·01 gm. and amounts smaller than 1 gm. were weighed to 0·001 gm. Tests showed that very few, if any, heavy minerals occurred in the —60 mesh (0·251 mm.) grade of sand. Therefore, only the —60+200 mesh (0·251–0·074 mm.) fractions were retained for heavy mineral analysis.

The light and heavy mineral fractions of a 5-gram sample split of each sample were separated in bromoform (S.G. 2·90) by using a centrifuge. The heavy residue was weighed and recorded as a weight per cent. A part of the heavy mineral residue, obtained with a micro-splitter, was mounted in Canada balsam for microscopic examination and grain counts. In addition, microscope slides were made of the light-heavy, and rutile-zircon-ilmenite fractions of samples specially treated at Mineral Deposits Laboratory, Crescent Head, N.S.W. The percentage number of each mineral in an individual sample was determined by using a mechanical stage and by counting 300 grains. Dryden (1931) suggested that 300 counts is an optimum number, and also that the accuracy of the counts increases as the square root of the number of grains counted. The heavy mineral fractions of six samples collected from the Macleay and Hastings Rivers (Numbers 1, 2–2a, 3a–3b, and 306, Figures 3 and 8) were separated into magnetic and non-magnetic fractions by using a Model L-1 Frantz Isodynamic Separator.

The unmounted portion of the heavy residue of each sample was examined under a binocular microscope, and roundness analyses were conducted by following the method of Shepard and Young (1961). They modified the scale developed by Powers (1953) by introducing " pivotability ", whereby grains were viewed under a binocular microscope and compared visually with a scale of roundness (pivotability) which is divided into six categories. In order to prevent operator bias the samples were renumbered, so the writer was unaware of their location. 100 grains were counted in each sample.

The accuracy of heavy mineral analyses, depending upon errors in both field sampling and laboratory studies, has been discussed by Dryden (1931), Krumbein and Rasmussen (1941), Manning (1953) and other workers. Rubey (1933) stated that large variations in the relative abundance of various minerals will be found in different grain sizes of the same sample. On the other hand, Van Andel (1955) and Poole (1958) concluded that only in special cases is it necessary to study various size fractions separately. In the light of more recent work by Carroll (1957) the writer considers that the method employed in this study has been valid and has not impaired the final results. Carroll (*op. cit.*) pointed out that procedural errors can probably safely be neglected from the mineralogical point of view when minerals have been subjected to previous sorting and sedimentation processes, even though it is recognized that certain minerals tend to occur in larger or smaller grain sizes than others.

### Heavy Mineral Occurrences

(*a*) *South Coast Samples:*

Tourmaline, amphiboles (chiefly hornblende), pyroxenes (chiefly titan-augite and diopsidic augite), members of the epidote group, and the opaques are the most common minerals in the South Coast beach and barrier samples. The opaque minerals and tourmaline constitute 70 and 80 per cent respectively of the heavy fraction in the Pambula and Eden barrier sands, whereas these minerals plus the amphiboles and epidote comprise 86 per cent of the total heavy mineral assemblage in the Boyd Town samples. In addition, andalusite, zircon, enstatite, topaz, rutile, sphene, garnet (colourless and pink), monazite and other minor constituents have been identified. With the exception of andalusite, the other minerals do not occur in sufficient quantities to be of importance. The variation in percentage of these minerals is shown in Figure 4, and listed in Tables 1 and 2. Table 1 compares the heavy mineral concentrates of barrier and dune sands in the three study areas.

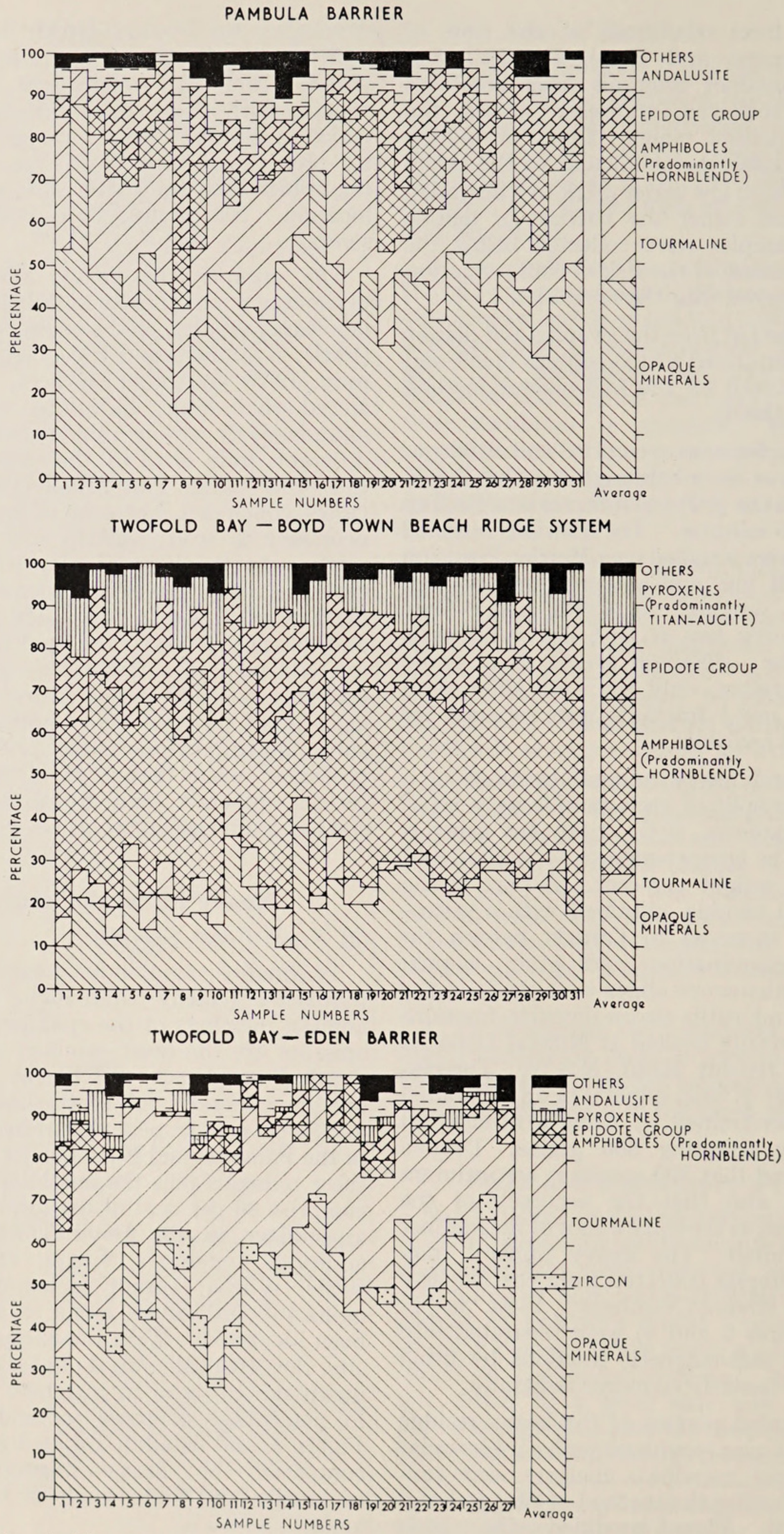



FIG. 4—The percentage occurrence (by number) of heavy minerals identified in South Coast barrier samples. The average composition is also shown. Sample numbers refer to sections and sampling sites shown in Fig. 1.

TABLE 1

*Average Percentage Occurrence (by Number) of Heavy Minerals in Some Mid-North Coast, Broken Bay and South Coast Barrier and Dune Samples*

| Locality/ Environment | Mineral | | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Rutile | Zircon | Tourmaline | Monazite | Garnet | Apatite | Staurolite | Kyanite | Epidote Gp. | Amphiboles (chiefly Hornblende) | Andalusite | Topaz | Sphene | Pyroxenes (chiefly Augite) | Hypersthene | Enstatite | Picotite | Spinel |
| Mid-North Coast: | | | | | | | | | | | | | | | | | | |
| Delicate Nobby | 21·23 | 16·29 | 50·60 | 0·21 | 2·08 | 0·02 | 1·25 | 0·08 | 1·93 | 0·27 | 4·08 | 0·19 | 0·02 | 0·21 | 0·27 | 0·95 | 0·32 | — |
| Back Beach (inner barrier) .. | 24·53 | 42·64 | 26·67 | 0·60 | 0·12 | — | 1·06 | — | 0·06 | — | 3·23 | 0·06 | 0·12 | 0·18 | — | 0·06 | 0·67 | — |
| Killick Creek, nr. Crescent Head (inner barrier) | 32·51 | 37·02 | 24·95 | 0·08 | 0·08 | — | 1·16 | 0·08 | 0·25 | — | 3·75 | 0·12 | — | — | — | — | — | — |
| Front Beach (outer barrier) .. | 15·77 | 17·41 | 53·73 | 0·40 | 0·90 | 0·04 | 1·50 | 0·21 | 1·64 | 1·18 | 5·00 | — | 0·37 | 0·37 | 0·41 | 1·03 | 0·04 | — |
| Hat Head (outer barrier) .. | 14·54 | 8·00 | 62·38 | 0·60 | 2·00 | 0·35 | 1·18 | 0·16 | 2·48 | 0·18 | 4·94 | 0·37 | 0·13 | — | 0·22 | 2·27 | — | 0·20 |
| Hat Head (inner barrier) .. | 9·72 | 32·40 | 52·69 | — | 0·06 | 0·11 | 1·08 | — | 0·28 | — | 3·60 | 0·06 | — | — | — | — | — | — |
| Hat Head (cliff-top dunes) .. | 17·90 | 35·70 | 42·10 | — | — | 0·40 | 0·90 | — | 0·40 | — | 2·40 | 0·20 | — | — | — | — | — | — |
| Smoky Cape (cliff-top dunes) .. | 14·20 | 40·40 | 44·20 | — | — | — | — | — | — | — | 1·20 | — | — | — | — | — | — | — |
| Front Beach (transgressive dunes) | 22·28 | 27·42 | 43·59 | — | — | — | 0·71 | — | — | — | 6·00 | — | — | — | — | — | — | — |
| Clybucca shoreline | 24·53 | 71·03 | 3·83 | — | 0·16 | — | 0·16 | — | 0·16 | — | 0·33 | — | — | — | — | — | — | — |
| Maria - Wilson barrier plain .. | 39·00 | 38·69 | 19·83 | — | — | — | 0·83 | — | 0·16 | — | 1·16 | 0·33 | — | — | — | — | — | — |
| Broken Bay: | | | | | | | | | | | | | | | | | | |
| Umina-Woy Woy beach ridge system; Pleistocene (?) samples | 36·95 | 26·85 | 24·71 | 1·80 | 0·09 | — | — | — | 1·83 | 3·68 | 3·68 | 0·02 | — | 0·32 | 0·07 | — | — | — |
| Holocene samples | 30·08 | 30·62 | 22·96 | 0·55 | 0·96 | — | — | — | 6·44 | 4·88 | 3·11 | — | — | 0·22 | 0·11 | — | 0·07 | — |
| South Coast: | | | | | | | | | | | | | | | | | | |
| Boyd Town beach ridge system .. | 0·09 | 0·51 | 6·35 | — | 0·49 | 0·03 | — | — | 21·87 | 54·00 | 1·29 | 0·35 | 0·22 | 14·19 | — | 0·61 | — | — |
| Eden barrier spit | 0·55 | 6·66 | 64·99 | 0·52 | 1·74 | — | — | — | 6·74 | 4·26 | 10·49 | 0·44 | 0·07 | 3·33 | 0·14 | 0·07 | — | — |
| Pambula barrier spit .. .. | 0·45 | 1·55 | 46·20 | 0·19 | 1·70 | — | — | 0·06 | 19·23 | 16·35 | 12·42 | 0·40 | 0·13 | 0·64 | — | 0·68 | — | — |

(*b*) *Broken Bay Samples:*

The most abundant heavy minerals for all samples are the opaques, rutile, zircon and tourmaline (Figure 5; Tables 1 and 3). Together, they generally constitute almost 90 per cent of the heavy minerals in the Broken Bay barrier and beach sands, and offshore sediments. Other minerals present in significant quantities include those of the amphibole (chiefly hornblende) and epidote groups, andalusite and monazite. Minor constituents in order of decreasing occurrence are garnet (colourless and pink varieties), pyroxenes (chiefly augite), hypersthene, topaz, picotite, staurolite, sphene, spinel, enstatite and apatite (Tables 1 and 4).

TABLE 2

*Average Percentage Occurrence (by Number) of Heavy Minerals in South Coast Barrier Samples*

(Percentage taken to nearest whole number)

| Mineral | Eden Barrier Spit (Twofold Bay) | Boyd Town Barrier Beach Ridge System (Twofold Bay) | Pambula Barrier Spit |
|---|---|---|---|
| Opaques (magnetite, ilmenite, leucoxene, haematite, limonite) | 50 | 23 | 46 |
| Zircon | 3 | 0* | 0* |
| Tourmaline | 30 | 5 | 24 |
| Rutile | 0* | 0* | 0* |
| Andalusite | 5 | 0* | 6 |
| Amphiboles (chiefly hornblende) | 3 | 41 | 10 |
| Pyroxenes (chiefly titan-augite and augite) | 3 | 11 | 0* |
| Epidote | 3 | 17 | 11 |
| Others | 3 | 3 | 3 |

* Included in 'Others' as percentage occurrence in samples is less than 3%.

(*c*) *Mid-North Coast Samples:*

The minerals identified in the Mid-North Coast samples can be divided into three distinct groups: opaque minerals, which include ilmenite, magnetite and leucoxene; common detrital minerals, such as zircon, tourmaline and rutile, and those designated "others", of which staurolite, andalusite, garnet, kyanite, epidote, picotite, hypersthene and spinel are considered to be the important diagnostic minerals. The first two groups together constitute more than 85 per cent of the heavy minerals present in the sedimentary environments that were sampled.

TABLE 3

*Average Percentage Occurrence (by Number) of Heavy Minerals in Broken Bay Barrier Samples*

| Mineral | Umina (Ocean Beach)-Woy Woy Beach/Dune Ridge System | | Pearl Beach Barrier Numbers | |
|---|---|---|---|---|
| | Holocene | Pleistocene (?) | 1–7* | 1–93* |
| Opaques (magnetite ilmenite, leucoxene, haematite, limonite) | 36 | 44 | 31 | 21 |
| Zircon | 18 | 16 | 29 | 31 |
| Tourmaline | 15 | 12 | 6 | 6 |
| Amphiboles | 2·50 | 1·78 | — | — |
| Epidote group | 3·75 | — | — | — |
| Rutile | 20·50 | 22·25 | 33 | 40 |
| Andalusite | 2·25 | 2 | — | 1 |
| Others | 2 | 1·97 | 1 | 1 |

* See Figure 5.

TABLE 4

*Percentage Occurrence of Minerals in Pearl Beach and Patonga Samples*

(Percentage occurrence is not expressed by numbers per sample, but number of times the minerals have been found in the total number of samples analyzed. For example, Andalusite has been found in 38 of the 100 Pearl Beach barrier samples)

| Mineral | Pearl Beach Barrier (100 samples) | Patonga Barrier Spit (217 samples) | Patonga Offshore (70 samples) |
|---|---|---|---|
| Monazite | 31 | 18 | 27 |
| Garnet | 10 | 8 | 6 |
| Apatite | — | 1 | — |
| Staurolite | 2 | <1 | — |
| Epidote group | 17 | 30 | 54 |
| Amphiboles (chiefly Hornblende) | 21 | 20 | 54 |
| Andalusite | 38 | 44 | 51 |
| Topaz | — | 4 | 7 |
| Sphene | 1 | — | 1 |
| Pyroxenes (chiefly Augite) | 2 | 9 | 11 |
| Hypersthene | 6 | 3 | 4 |
| Enstatite | — | 1 | — |
| Picotite | 6 | 2 | 1 |
| Spinel | — | <1 | — |

Minerals are arranged with the least persistent mineral last. As picotite and spinel are not shown in the Order of Persistence Table (Table 5B), they have been placed below the dashed line.

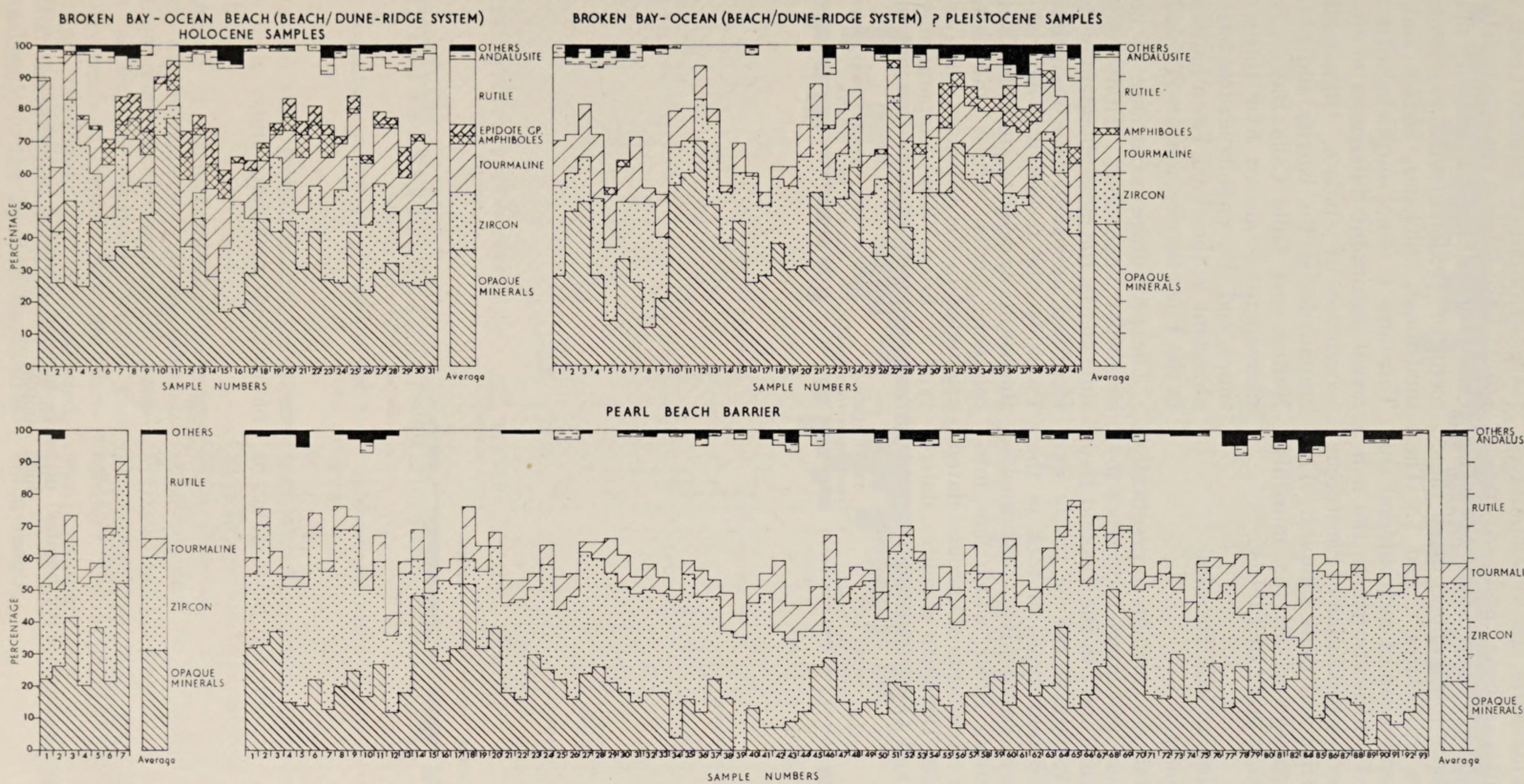



FIG. 5—The percentage occurrence (by number) of heavy minerals identified in Broken Bay barrier samples. Sample numbers refer to sections and sampling sites shown in Fig. 2.

Small quantities of monazite, apatite, amphiboles (hornblende), topaz, sphene and pyroxenes (chiefly augite) have been identified. The percentage occurrence (by number) of all these minerals is shown in Figures 6 and 7. The percentage range and mean of each mineral are plotted in Figure 7 which also shows the non-opaque heavy mineral composition of Pleistocene and Holocene barrier and dune samples. The variation in percentage of all the minerals, except the opaques, is listed in Table 1.

## Discussion of the Results

(*a*) *South Coast Samples:*

The same minerals are common to practically all samples, but their percentage occurrence (by number) varies significantly in the Twofold Bay deposits. These variations can be partly explained by the different types of rock in the immediate vicinity of Twofold Bay. Shadrack's Creek and the Nullica River, which flow into Nullica Bay, drain catchments of unconsolidated Tertiary (?) deposits, Devonian rhyolites, dolerites and felsites, and Ordovician metamorphic rocks. In contrast, Bellbird Creek, which enters Curalo Lake (almost entirely isolated from Calle Calle Bay by Eden barrier spit), drains a catchment of predominantly sedimentary rocks—sandstones, siltsones, shales and quartzites. Therefore, it is not surprising that the analyses reveal significant differences in the percentage occurrence of epidote, titan-augite and the amphiboles in the barrier and beach sands of Nullica and Calle Calle Bays. For example, titan-augite is almost four times, epidote six times, and the amphiboles fourteen times more abundant in the Boyd Town barrier sands than in the Eden barrier samples (Table 2).

The percentage occurrence of hornblende is somewhat anomalous. Titan-augitê and diopsidic augite, the most abundant of the pyroxenes identified, appear to have been derived locally. Probably, the former was derived from either the basalts or dolerites, in which it often replaces common augite, whilst the latter possibly originated in the rhyolites, such as the potash type at Eden. The comparatively small percentages of rutile, zircon and other minor

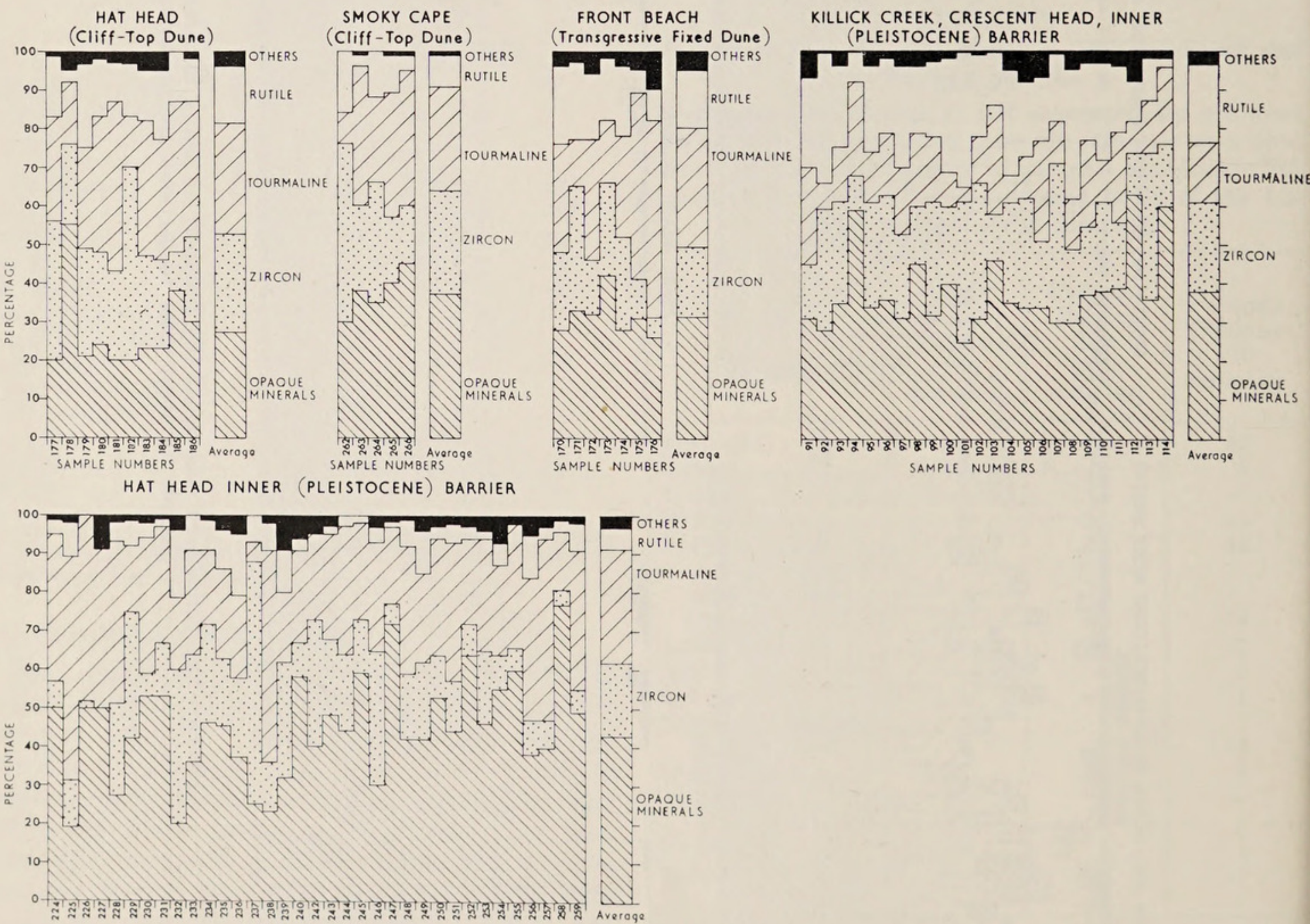



Fig. 6—The percentage occurrence (by number) of heavy minerals identified in Mid-North Coast barrier and dune samples.

(Fig. 6 — *continued.*)

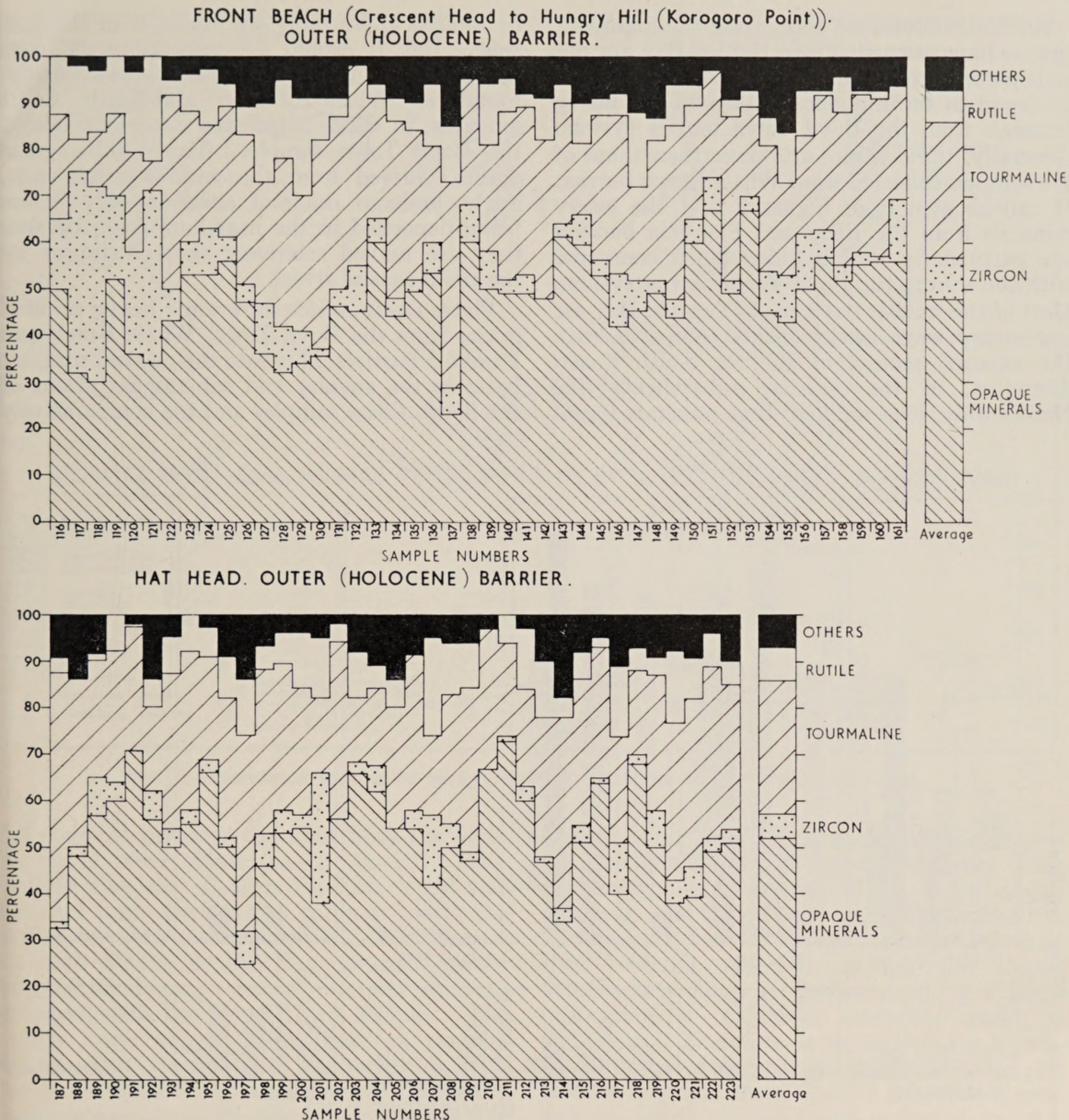



Fig. 6—The percentage occurrence (by number) of heavy minerals identified in Mid-North Coast barrier and dune samples.

constituents also seem to indicate the composition of the rocks being eroded in the Twofold Bay hinterland.

The variation in the percentage occurrence (by number) of the respective heavy minerals provides some evidence to discount the possibility that sediments, deposited within the smaller embayments of Twofold Bay, are transported around headlands. It is concluded, therefore, that the sediment yield, derived from the weathered rocks of the Twofold Bay hinterland and delivered to the nearshore zone by way of the rivers, is reworked and redeposited locally by wave action to nourish the barriers and bay-head beaches. This supply of sediment is supplemented, on a limited scale, by material derived from the erosion of adjacent headlands. Fine-grained material carried a short distance offshore, also appears to be transported shoreward subsequently without drifting around the headlands that separate the smaller embayments.

Additional evidence supporting the argument that sediments carried into Nullica Bay are not transported around neighbouring headlands can be found in the roundness values of the heavy minerals from the Boyd Town barrier system. Generally, these values are lower than those of the samples collected from Whale Beach barrier. It can be seen from Figure 9 that the heavy minerals from the Eden and Pambula barriers are particularly well rounded when compared with those from the Boyd Town barrier system. Most of the smaller bays inside Twofold Bay are low-energy wave environments compared with the exposed sectors of the far South Coast. Therefore, in the smaller embayments like Nullica Bay, it is unlikely that minerals would be altered appreciably by abrasion in the surf zone. But it would be presumptuous, considering some of the points made later about the roundness values of the Mid-North Coast minerals, to make conclusive statements about the Boyd Town samples. Fairly sub-angular grains, derived from the various catchments, might undergo minimal abrasion only before being deposited in the nearshore zone, because they are moved relatively short distances by the small coastal rivers.

Plates 1D–1F, which show some heavy mineral grains from the Boyd Town, Whale Beach and Pambula barriers, illustrate the marked contrast between the angular and sub-angular grains of the South Coast samples and the comparatively

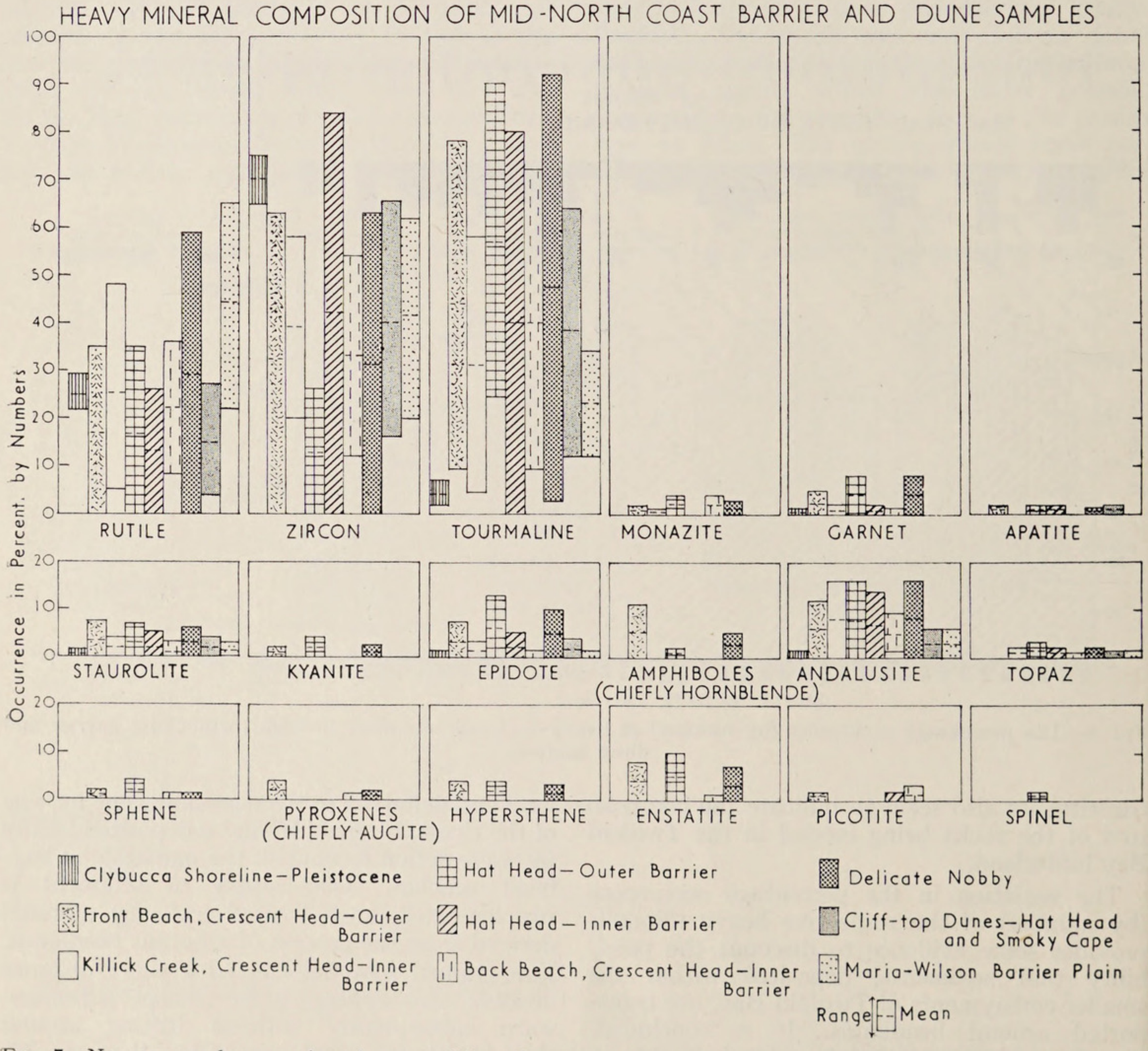



FIG. 7—Non-opaque heavy mineral composition of some barrier and dune samples collected on the Mid-North Coast.

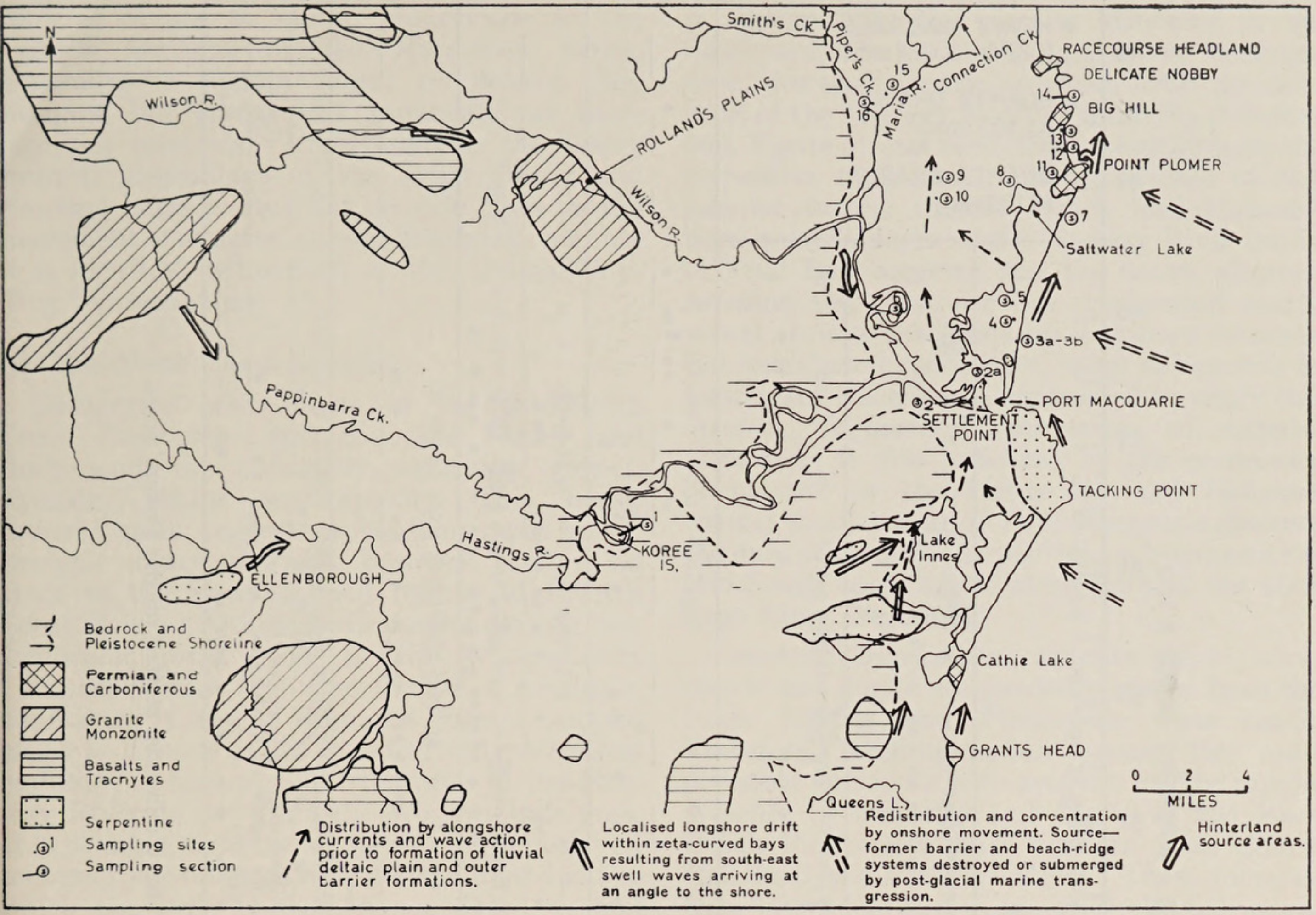



FIG. 8—Postulated sources of heavy minerals identified on the Mid-North Coast.

well rounded minerals collected from the other two study areas (Plates 1A–1C ; 1G–1I). Both Twofold Bay and Broken Bay are fairly well sheltered from wave action compared with the arcuate bays on the exposed Mid-North Coast, but even so, the Broken Bay minerals, except those of the Patonga barrier, are well rounded compared with the Boyd Town samples. The slightly lower values of the Patonga samples indicate that the material carried into Brisk Bay by Patonga Creek has travelled a relatively short distance from its source. In general, the roundness values reflect the polygenetic history of most of the Broken Bay minerals.

(*b*) *Broken Bay Samples :*

The analyses of Broken Bay samples provide some interesting information. Although hypersthene occurs in relatively few samples, its presence warrants some comment. Hypersthene is one of the least persistent minerals in the geologic column, and it is generally found in sediments derived from nearby hypersthene-bearing rocks, such as gabbros, norites, dolerites, basalts, andesites, and volcanic tuffs. According to David (ed. W. R. Browne, *op. cit.*), the Chocolate Shales of the Middle Narrabeen Series are usually regarded as redistributed fine basic tuff with a large admixture of purely clastic material. On the other hand, he states that the Hawkesbury Series is thought to be entirely free from volcanic material, though the Upper Wianamatta Stage is characterized by a large proportion of calcareous sandstone which is tuffaceous. Therefore, it seems that the hypersthene is being derived from such rocks in the Broken Bay hinterland since it has been identified in nearshore sediments collected by the writer from Brisk Bay. The mineral has been traced in four Holocene samples, but it is absent from the Umina-Woy Woy Pleistocene (?) barrier sands. The fact that hypersthene is not very resistant to abrasion is also supported by the results of Culey's (1933) mineralogical study of the Narrabeen Series ; only one hypersthene grain was identified in samples collected at the Entrance, Tuggerah.

The contention that volcanic material is being weathered in the vicinity of Broken Bay is also supported by the appearance of titan-augite in a few samples. The presence of picotite is not considered particularly significant because the

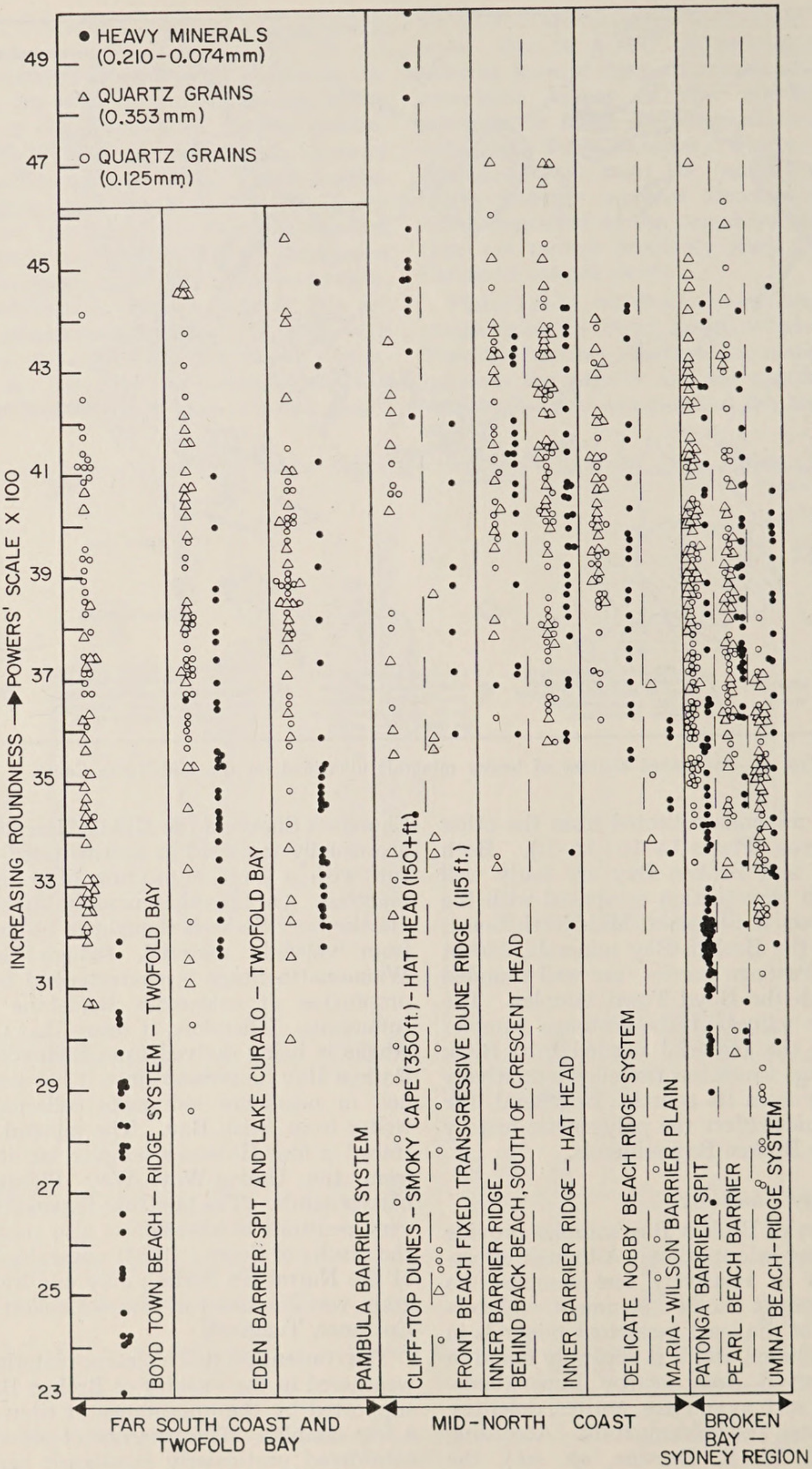



Fig. 9—Roundness values of quartz and heavy minerals, plotted on the Powers' scale.

mineral occurs in minor proportions in the various horizons of the Narrabeen Series. Staurolite is seldom found in Broken Bay samples, but garnet and andalusite are more common minerals. Unfortunately, the heavy mineral assemblage of the Pearl Beach and Patonga barriers does not provide clues on the movement of material around headlands, because it is identical with that of the Umina-Woy-Woy barrier system.

(*c*) *Mid-North Coast Samples :*

Distinctive constituents of the Mid-North Coast Pleistocene and Holocene barrier and dune sands are andalusite, staurolite, garnet, kyanite, zoisite and epidote. This heavy mineral suite suggests a medium-grade metamorphic source of which, however, there is no trace in the areas drained by the Mid-North Coast rivers. Although sillimanite-bearing metamorphic rocks occur in the Wongwibinda Complex (Binns, 1965), north-east of Armidale, sillimanite is absent from the coastal samples either because of its low chemical and mechanical stability, or because the tributaries of the Macleay River do not drain the Wongwibinda area. It is possible, therefore, firstly, that the observed metamorphic minerals were derived from a source which has been entirely removed by erosion. Secondly, they were eroded from cliffs and headlands, or delivered to the coast by rivers, outside the region thus necessitating the longshore movement of material around headlands and over considerable distances. Thirdly, the minerals were deposited as rivers extended their courses across the emerged continental shelf during Pleistocene low stands of sea level and were reworked and transported shoreward by wave action during subsequent marine transgressions. Fourthly, they were derived from a metamorphic source that was submerged during the post-glacial and earlier Pleistocene marine transgressions.

A similar heavy mineral assemblage to that of the coastal sands has been identified in bed load samples collected from the Hastings River, and Stockyard Creek which predominantly drains a serpentine rock area in the Macleay River catchment (Lindsay, 1963). However, the metamorphic minerals in the samples from Settlement Point on the Hastings River (Numbers 2–2a, in Figures 3 and 8) may have moved upstream from offshore because the river is tidal at this locality.

The presence of picotite in the river sands is also of some interest since as a detrital mineral it is of very restricted occurrence. Therefore it appears that the picotite identified in the Stockyard Creek samples, and those collected near Sherwood Bridge upstream from the tidal limit of the Macleay River at Aldavilla (Number 306, Figure 3), has been derived locally from the serpentine rock area. The occurrence of this mineral in the modern beach and Holocene barrier sands north of the Macleay River outlet in Trial Bay suggests that the heavy minerals reaching the coast are not transported southwards around headlands by longshore currents, but nearshore experiments, using radioactive or fluorescent tracer sand, are needed to verify this opinion. A northerly movement of material alongshore is also indicated by the occurrence of picotite in the Pleistocene and Holocene coastal sands north of Port Macquarie because the only other major serpentine rock areas on the Mid-North Coast are located south of the Hastings River (Figure 8).

Enstatite, hypersthene, kyanite, spinel, hornblende and augite are generally absent from the Inner Barrier and Pleistocene dune sands. Therefore, aeolian action seems the most plausible explanation to account for the unique presence of enstatite and augite in the Back Beach Pleistocene sands between Race Course Headland and Crescent Head. These minerals have been identified in samples collected within three feet of the surface of the barrier. The reason why they should be transported from the adjacent Outer Barrier on this section of the Mid-North Coast and not elsewhere is still a problem that has to be resolved.

The persistence of certain heavy minerals in the Mid-North Coast sediments appears to be determined by either their chemical or mechanical stability. For example, staurolite has an extremely low stability to weathering index compared with zircon and tourmaline and therefore its occurrence is attributed to its resistance to abrasion. Despite its relatively high position in the Order of Persistence Table (5B), biotite however appears to be an unstable mineral since it is absent from all the samples that have been analyzed, including the Holocene barrier sands and fluviatile sediments.

According to Baker (1962) though, differences in stability of any particular mineral undoubtedly exist in different areas according to variations in climate, topography and vegetation. Allen (1948), on the other hand, stated that the resistance of minerals to weathering depends upon the particular variety of the mineral in question. Dryden and Dryden (1946) in their study of the comparative rates of weathering of common heavy minerals *in situ* discovered that garnet is the least resistant to chemical alteration, even though most other workers list this mineral as highly stable.

It is generally accepted that the mechanical stability of minerals like tourmaline, rutile and zircon, for example, is controlled largely by their physical properties. Figure 9 shows that the heavy accumulates in the Mid-North Coast barrier and dune sands are composed of fairly well rounded minerals, and there is little difference between the values of Pleistocene and Holocene samples. This evidence partly supports the view put forward here that the minerals have been derived from ancient sediments and they have inherited their properties. Some minerals of course, can be derived locally and abraded in the surf zone before being redeposited as beach concentrates, but this seems unlikely on the Mid-North Coast because the mineralogical composition of the coastal sands differs from that of the adjacent bedrock headlands. Even so, the evidence does not entirely exclude the possibility that some minerals may have been derived from a source now submerged.

Contrary to the statements in some publications (Gardner, *op. cit.*; Beasley, *op. cit.*), the writer's analyses show that heavy minerals can be transported beyond the limit of high water mark. Although wave action is the initial cause of concentrating stable heavy minerals, the complementary effects of wind action seem to have been under-estimated (Hails, 1964). The mineral composition of Pleistocene and Holocene dune and barrier (and also modern beach) sands is basically similar, and the average weight per cent of heavy minerals in dune samples is 2·16 compared with 1·78 in barrier sands. Furthermore, the weight per cent of heavy minerals in the cliff-top dunes does not vary appreciably, irrespective of height above mean sea level and distance from immediate source areas. Specific gravity values of the different minerals in the dunes range from 2·98 to 5·18 and their hardness values (Mohs scale) range from 5 to 8 (Table 5A).

There appear to be two main reasons to account for the differences in the concentration of heavy minerals (by weight) in the Pleistocene and Holocene sands (Table 6). Firstly, there may have been low sediment yields from the river catchments in the past because of reduced erosion and slow weathering, or there were few heavy minerals offshore to be reworked and redeposited by wave action as the Pleistocene barriers were established. Also, nearshore processes may have controlled deposition only in certain areas. Secondly, ephemeral barriers existing off the present coast during periods of lower sea level, may have been partly eroded or destroyed before complete submergence during the late Holocene transgression. This process could have provided large supplies of sand for the construction of the Holocene Outer Barriers. However, temporary shorelines may not have existed immediately before the formation of the Inner Barrier. Undoubtedly, slight fluctuations in sea level and variations in local wave and wind regimes have controlled the concentration of heavy minerals since the major barriers were established (Hails, *op. cit.*).

Based on the accumulated evidence reported here, the writer has shown in Figure 8, the possible areas and sources from which some of the identified minerals have been derived. The closed arrows indicate the directions in which the minerals were transported to an embayed coast before the formation of the barriers and the deltaic plains. Dominant south-easterly swell waves, that arrived at an angle to the shore, undoubtedly moved some material northwards alongshore, and heavy minerals could have been

TABLE 5A

*Specific Gravity and Hardness Values of Heavy Minerals Identified in Cliff-top Dunes*

(Hardness values on Mohs scale)

| Mineral | Specific Gravity | Hardness |
|---|---|---|
| Andalusite . . . . | 3·16–3·20 | 7·5 |
| Epidote . . . . | 3·25–3·50 | 6–7 |
| Ilmenite . . . . | 4·50–5·00 | 5–6 |
| Leucoxene . . . . | 3·50–4·50 | — |
| Magnetite . . . . | 5·17–5·18 | 5·5–6·5 |
| Piedmontite . . | 3·45–3·50 | 6·5 |
| Rutile . . . . | 4·18–4·25 | 6·0–6·5 |
| Staurolite . . . . | 3·65–3·77 | 7·0–7·5 |
| Topaz . . . . | 3·51–3·61 | 8·0 |
| Tourmaline . . | 2·98–3·20 | 7·0–7·5 |
| Zircon . . . . | 4·20–4·86 | 7·5 |

TABLE 5B

*Order of Persistence of Heavy Minerals in the Geologic Column*

(Least persistent minerals are listed first. Minerals marked * occur in cliff-top dunes.) Table based on that of Pettijohn (1941). Read down columns

| | | |
|---|---|---|
| Olivine | Topaz* | Apatite |
| Actinolite | Andalusite* | Biotite |
| Diopside | Hornblende | Garnet |
| Hypersthene | Epidote* | Monazite |
| Sillimanite | Kyanite | Tourmaline* |
| Augite | Staurolite* | Zircon* |
| Zoisite* (epidote group) | Magnetite* | Rutile |
| Sphene | Ilmenite* | Anatase |

TABLE 6

*Range and Average Percentage Concentration by Weight of Heavy Minerals in Pleistocene and Holocene Sediments*

| Area/Location | Environment | Age | Heavy Mineral Concentration | |
|---|---|---|---|---|
| | | | Range | Average Percentage |
| Twofold Bay : | | | | |
| Eden . . . . . . | Barrier spit | Holocene | 0·1– 1·2 | 0·25 |
| Boyd Town . . . . | Barrier beach ridges | Holocene | 0·4–14·0 | 2·70 |
| Whale Beach . . | Barrier spit | Holocene | 0·2– 8·0 | 4·06 |
| South Coast : | | | | |
| Pambula . . . . | Barrier spit | Holocene | 0·2– 4·6 | 0·96 |
| Broken Bay : | | | | |
| Pearl Beach . . | Barrier beach | Holocene | 0·1–44·0 | 8·37 |
| Umina-Woy Woy . . | Barrier beach ridges | Holocene | 0·1–14·6 | 3·45 |
| | | (?) Pleistocene | 0·6–22·0 | 2·74 |
| Patonga Beach . . | Barrier spit | Holocene | | |
| | (ridges) | | 0·1– 7·0 | 0·28 |
| | (swales) | | 0·1– 3·0 | 0·23 |
| | (foredune) | | 0·2– 1·8 | 0·49 |
| | (random bores) | | 0·1–56·0 | 6·81 |
| | Grand total | | 0·1–56·0 | 1·45 |
| Patonga Offshore . . | Neritic | Holocene | 0·1– 2·0 | 0·44 |
| Mid-North Coast : | | | | |
| Delicate Nobby . . | Barrier ridges | Holocene on Pleistocene | 0·2–13·0 | 2·05 |
| Back Beach . . . . | Inner barrier | Pleistocene | 0·4– 6·6 | 2·30 |
| Killick Creek . . . . | Inner barrier | Pleistocene | 0·2–15·0 | 4·13 |
| Front Beach . . . . | Outer barrier | Holocene | 0·1– 7·6 | 1·14 |
| Hat Head . . . . | Outer barrier | Holocene | 0·2– 2·0 | 0·58 |
| Hat Head . . . . | Inner barrier | Pleistocene | 0·1– 5·2 | 0·76 |
| Hat Head . . . . | Cliff-top dunes | Pleistocene | 0·4– 2·4 | 1·50 |
| Smoky Cape . . . . | Cliff-top dunes | Pleistocene | 0·8– 7·8 | 3·56 |
| Front Beach . . . . | Transgressive dunes | Pleistocene | 0·2– 1·4 | 0·91 |
| Clybucca shoreline . . | Beach ridges | Pleistocene | 18–50·6 | 32·62 |

concentrated locally as waves were refracted around promontories, as indicated by the dashed arrows. However, the longshore movement of material was incidental to that moved onshore (open dashed arrows). The open arrows in Figure 8 show the most probable direction of longshore drift in the modern arcuate bays.

## Summary and Conclusions

Locally derived titan-augite and diopsidic augite are the distinctive constituents of South Coast sediments. The occurrence of hypersthene in the Broken Bay barrier samples seems to indicate a volcanic rock source in the Patonga Creek catchment.

All the Mid-North Coast minerals are polygenetic because they have been derived from various sources, and have survived several phases of rock formation and weathering.

Andalusite, staurolite, garnet, kyanite and epidote are the most distinctive constituents of the Mid-North Coast sands and suggest a medium-grade metamorphic source of which there is no trace in the area drained by the Mid-North Coast rivers. It is therefore possible, firstly, that the minerals were derived from a source which has been entirely removed by erosion ; secondly, from other regions by being transported alongshore ; and thirdly, from offshore.

The picotite in the beach and barrier sands north of the Hastings and Macleay Rivers has been derived from the sepentine rocks in the Hastings River basin and from the small outcrops near Stockyard Creek.

The percentage occurrence (by number) of the common detrital minerals in the Pleistocene and Holocene barrier and dune sands does not vary appreciably. The most common detrital minerals on the Mid-North Coast and in Broken Bay are rutile, zircon, tourmaline and the opaques. Hornblende, the pyroxenes, and members of the epidote group are the most common minerals on the South Coast. Most minerals in the dunes on the Mid-North Coast were probably derived from neighbouring barrier and beach sands. The mineralogical composition of the cliff-top dunes reflects the strength and transporting power of wind.

The sub-angular minerals derived from the various catchments on the South Coast are not rounded appreciably by abrasion in the surf zone before being deposited as beach concentrates in the small embayments. Twofold Bay sediments are comparatively angular compared with those of the other two study areas. There is little difference between the roundness values of the Pleistocene and Holocene heavy minerals on the Mid-North Coast mainly because the minerals are polygenetic.

A possible sequence of events which led to the concentration of heavy minerals in the Holocene beach and dune deposits was the :

(i) formation and establishment of barriers a short distance from the coast ;

(ii) complete or partial destruction of those barriers during a rise in sea level ;

(iii) redeposition of heavy minerals along a newly established shoreline ;

(iv) modification of that shoreline by aeolian action and storm waves.

Finally, should coastal erosion cause foredune or beach ridge destruction, heavy minerals may become concentrated as the lighter quartz grains are removed. If erosion is followed immediately by a period of shoreline progradation, the minerals will be preserved as a concentrated deposit.

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## Explanation of Plates

Plates 1A-1C Heavy minerals in

A. Hat Head cliff-top dune samples. (×58.)
B. Smoky Cape cliff-top dune samples. (×36.)
C. Front Beach transgressive dune samples. (×36.)

1. Piedmontite. 5. Leucoxene.
2. Zircon. 6. Magnetite.
3. Rutile. 7. Andalusite
4. Tourmaline. 8. Ilmenite.

Plates 1D-1'I' Heavy minerals in

D. Boyd Town beach ridge system. (×36.)
*A—Amphibole. T/Aug—Titan-augite.
E—Epidote. P—Pyroxene.
H—Hornblende.

E. Whale Beach barrier. (×36.)
M—Magnetite.

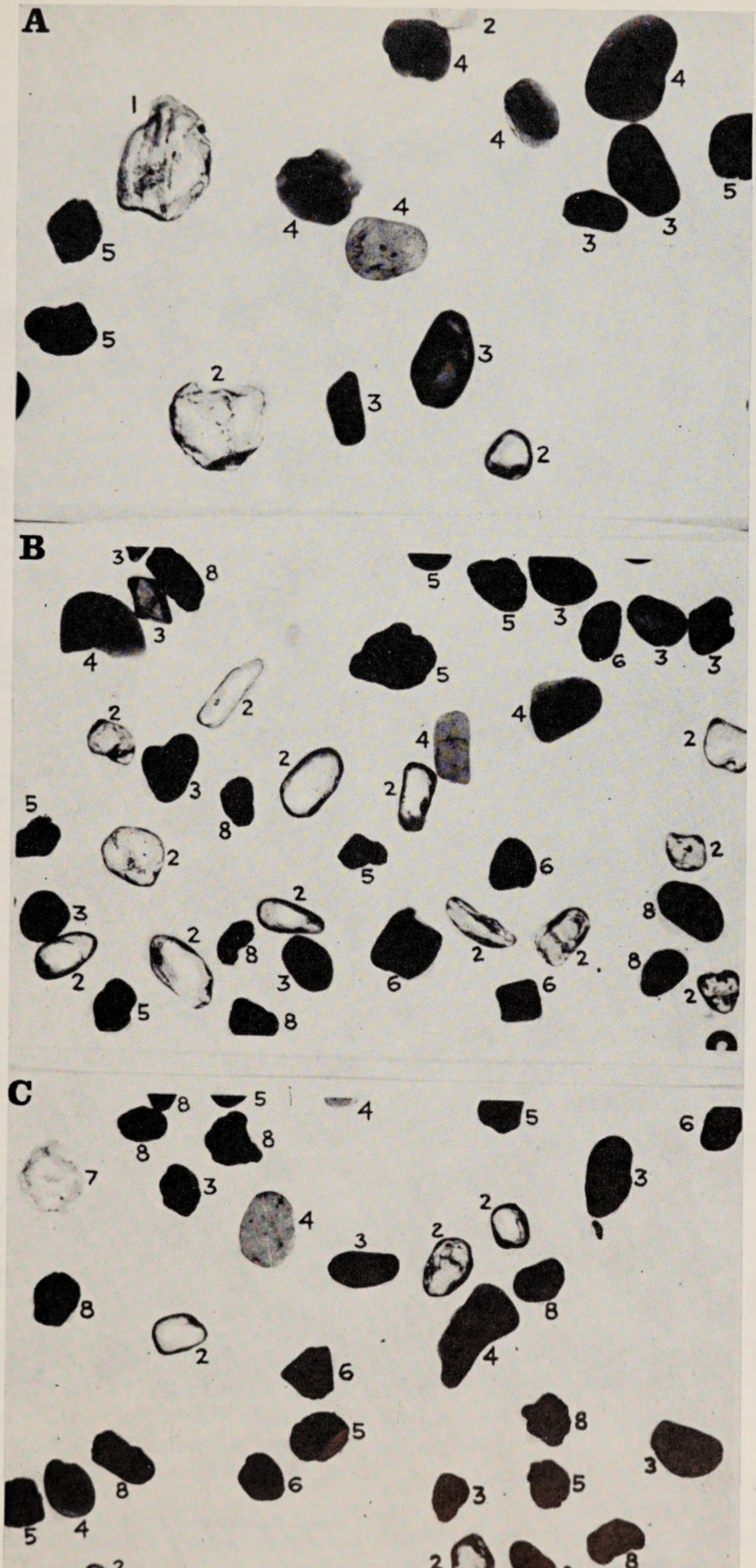
F. Pambula barrier spit. (×58.)

G. Number 3*a*–3*b*, Fig. 3, north of Port Macquarie.
An—Andalusite. T—Tourmaline.

H. Patonga barrier spit, Broken Bay. (×36.)
R—Rutile. Z—Zircon.

'I'. Macleay River—Sherwood Bridge. (×36.)
T—Topaz.

* Same symbols as for D'I' unless shown otherwise.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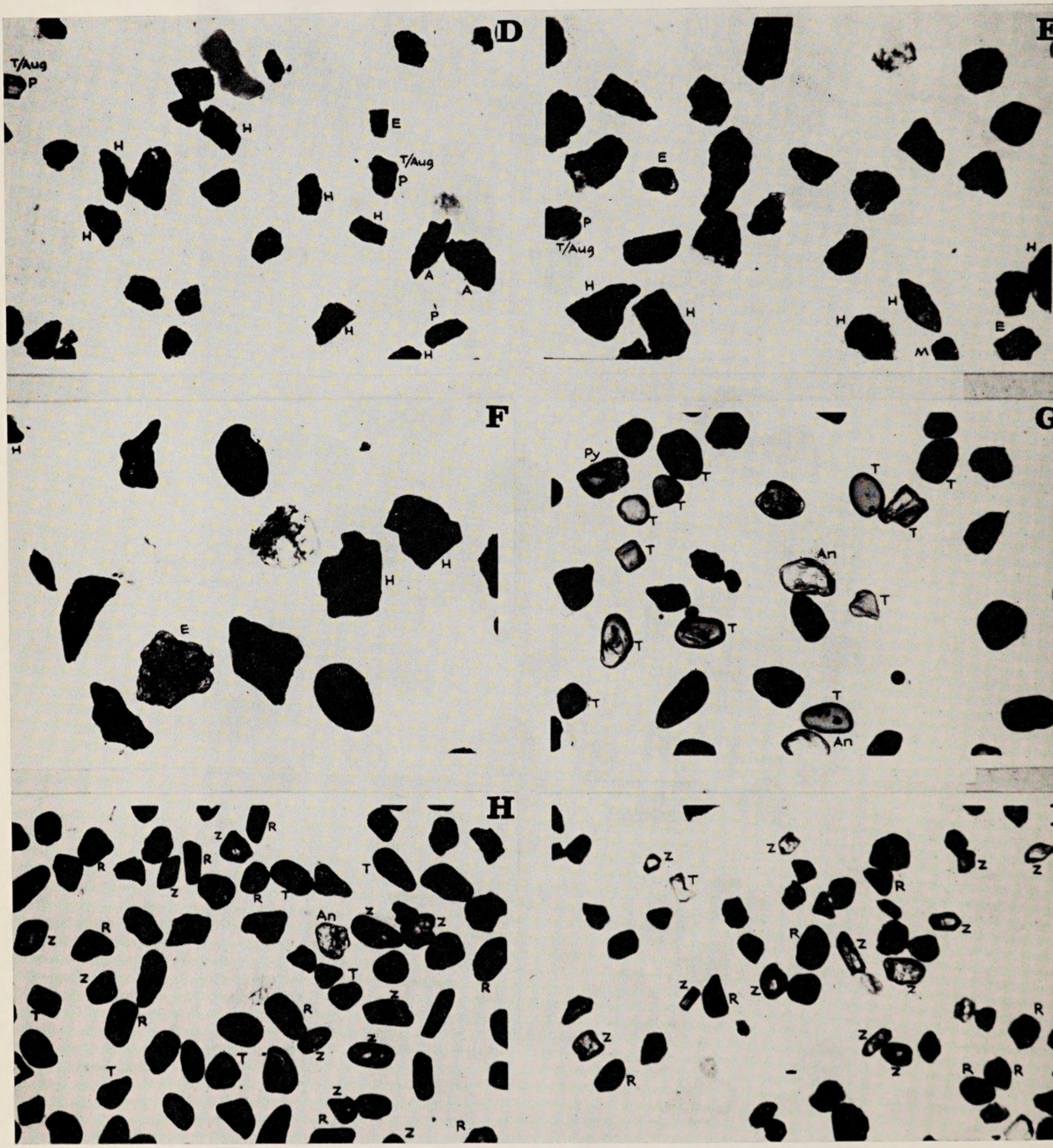
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