CHAPTER I

INTRODUCTION

The term "boulder" has been defined as a sedimentary particle having a diameter (or intermediate axis) greater than 256 mm (Wentworth, 1922a). Unfortunately, the precision of terminology found in studies of fine sediment in a coastal setting is frequently absent in the literature dealing with coarse sediment, and the term "boulder" has been used rather loosely.

Langford-Smith and Hails (1966) discuss raised "boulder" beaches along the coast of New South Wales. Actual sediment size is indicated for only one of these beaches, however it appeared to by typical of the 13 sites mentioned. The "boulders" were found to be "variable in size, with a modal diameter of about four inches" [101.6 mm](Langford-Smith and Hails, 1966, p. 352). Although some particle diameters may have exceeded 256 mm, this beach could not be classified as a boulder beach in a strict sedimentological sense. Swan (1975) also refers to the raised beaches described by Langford-Smith and Hails as "boulder" beaches, but uses the more precise term "pebble" to describe the beach particles he studied. Relict boulder beaches are also mentioned by Langford-Smith and Thom (1969), but no indication is given as to the actual size of the sediment being so classified.

But, and perhaps more seriously, sediment coarser than cobble size is often completely disregarded in coastal studies (e.g., Bird, 1972; Shepard, 1963). It appears to be widely accepted that, "sediment composing beaches ranges from fine sand to cobblestones several centimeters in diameter" (Strahler and Strahler, 1978, p. 340). Indeed, Kirk (1980, p. 189) states that "mixed sand and gravel shores present the maximum range of particle sizes

to reworking by waves. . ."

However, some work on coastal boulders has been carried out. Kuenen (1947) considered the effect of water in faceting boulders in the shore zone, and Bartrum (1947) investigated the rounding of beach boulders. Shelley (1968) generated some interest in marine effects on boulders by examining the packing or fitting of boulders, and Hills (1970) discussed fitting, fretting, and imprisoned boulders. These studies examined boulders individually in a coastal context, but not as a sedimentary assemblage. Although boulders forming a raised beach at Boat Harbour, Port Stephens, New South Wales (see Langford-Smith and Thom, 1969, p. 580) were examined by Sussmilch and Clark (1928), the only previous investigation of a modern, active coastal assemblage of boulders appears to be an unpublished study by Eliot and Bradshaw (1975). In this study of a boulder "field" near Durras on the south coast of New South Wales, they found both lateral and transverse boulder-size grading. Longshore particle size decreased away from the headland, and up-beach particle size decreased landward. Cusps and spits formed by boulders were also noted in this work.

Langford-Smith and Thom (1969) reported that shingle and boulder beaches along the New South Wales coast are rare, often temporary, features. Bird (1972) refers to coarse-sediment beaches in Australia as pebble and cobble beaches, and he too believes them to be uncommon. This author, however, found 20 boulder beaches of substantial dimensions (approximately 100 m or longer) along the approximately 330 km length of the New South Wales coast between Myall Lakes and Jervis Bay. Thus, although boulder beaches may not be a common landform, they are not as scarce as previous writers have suggested.

Most of these boulder beaches are located along the flanks of headlands between the point of the headland and the embayment proper. For the purposes of this study, beaches so positioned will be referred to as "bay-side" beaches. Waves generally strike bay-side beaches obliquely, causing longshore variation in wave-energy expenditure. However, a few boulder beaches were found at the heads of embayments and these appeared to have become aligned to the approaching waves. Thus, wave-energy expenditure is probably fairly uniform along these beaches. None of these bay-head boulder beaches was included in this study. Field observations in the course of this work, however, have led the author to believe that because there is little longshore wave-energy variation, bay-head boulder beaches may have some sedimentary characteristics different to those of the studied bay-side beaches.

Although the bay-side boulder beaches are located adjacent to actively eroding cliffs, they are not backed by such cliffs. Thus it is clear that the boulders have been transported to their present position and the observed deposits are not coastal talus.

By investigating boulder size, shape, and roundness, beach form, sediment transport, and wave competence, this study seeks to demonstrate that wave-deposited boulders can and do form organized, sedimentologically unique coastal deposits, which may properly be termed beaches.

SELECTION OF STUDY AREAS

Five boulder beaches located along the central New South Wales coast between Myall Lakes and Jervis Bay were selected for detailed study of their sedimentological properties. These beaches, hereafter referred to as North Yacaaba, Copacabana, Bombo, Kiama, and Crookhaven (Figure 1), were chosen because only they satisfied the following criteria:-

1. Beach size: The beach must be at least 100 m in longshore length and 10 m wide at the narrowest point. These dimensions allow the examination of longshore and up-(down-) beach characteristics which would be more difficult to discern on a smaller boulder beach.
2. Sediment size: The mean size of the boulders (intermediate axis) over the entire beach must be 256 mm or greater (-8ϕ or less). This arbitrary size limit for boulders follows the Wentworth (1922a) classification of particle sizes. In order to satisfy this criterion, some beaches generally referred to as "boulder" beaches (*e.g.*, Langford-Smith and Hails, 1966) were excluded from study.
3. Permanency: The beach must not be a temporary feature exposed only by occasional storms. This was determined by observation, and questioning of local residents.
4. Natural State: To ensure that the beach form is the result of natural processes, the beach must show no evidence of human or animal disturbance or removal of sediment. This criterion excluded from study several boulder beaches. For example,

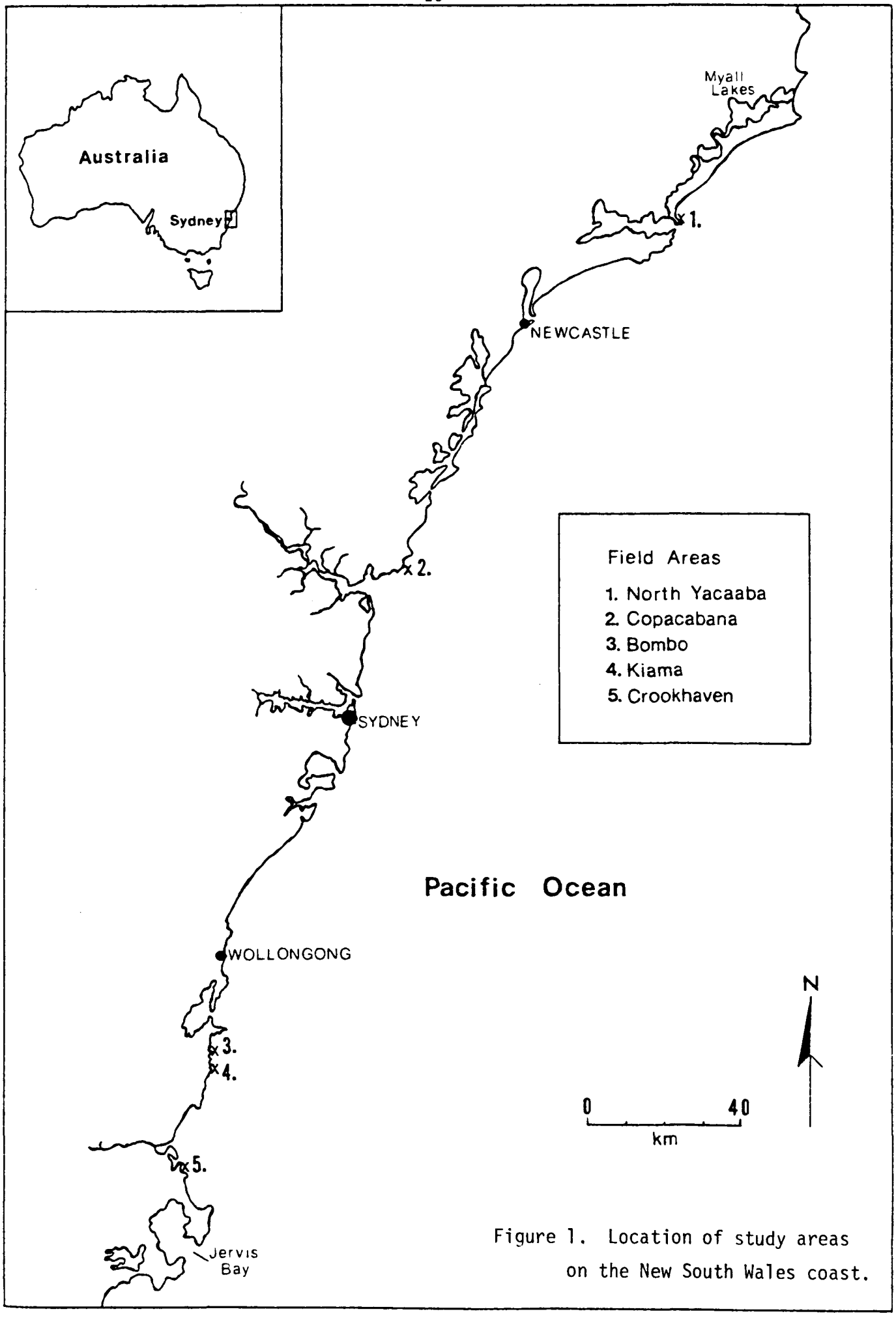

Figure 1. Location of study areas on the New South Wales coast.

Avalon Beach (northern Sydney) has had many boulders removed to be used as paving stones, and the boulder beach described by Sussmilch and Clark (1928) has had the landward section flattened.

5. Accessibility: It must be possible to gain access to the beach while carrying field equipment. Several boulder beaches sited from cliff tops could not be included in this study because access was too difficult.

STUDY AREAS

All five beaches are located in an area of similar meteorological conditions and uniform wave climate (Stone, 1969). In this east coast swell environment (Davies, 1964), southerly cyclonic depressions generate most of the waves. When these cyclones are located over the Tasman Sea, southerly storm waves are generated. Tropical cyclones can produce waves with a north-east to east approach, depending upon the southern extent of the cyclone. Various studies, however, have found that the predominant swell and storm waves approach this coast from a southerly direction (*e.g.*, Stone and Foster, 1967; Lawson and Abernethy, 1975).

North Yacaaba Boulder Beach

North Yacaaba boulder beach is located approximately 165 km along the coast north of Sydney on the north side of the north head (Yacaaba Head) of Port Stephens (Plate 1). Yacaaba Head is composed of Carboniferous Nerong Volcanics (Engel, 1962; Engel *et al.*, 1969), specifically andesite,

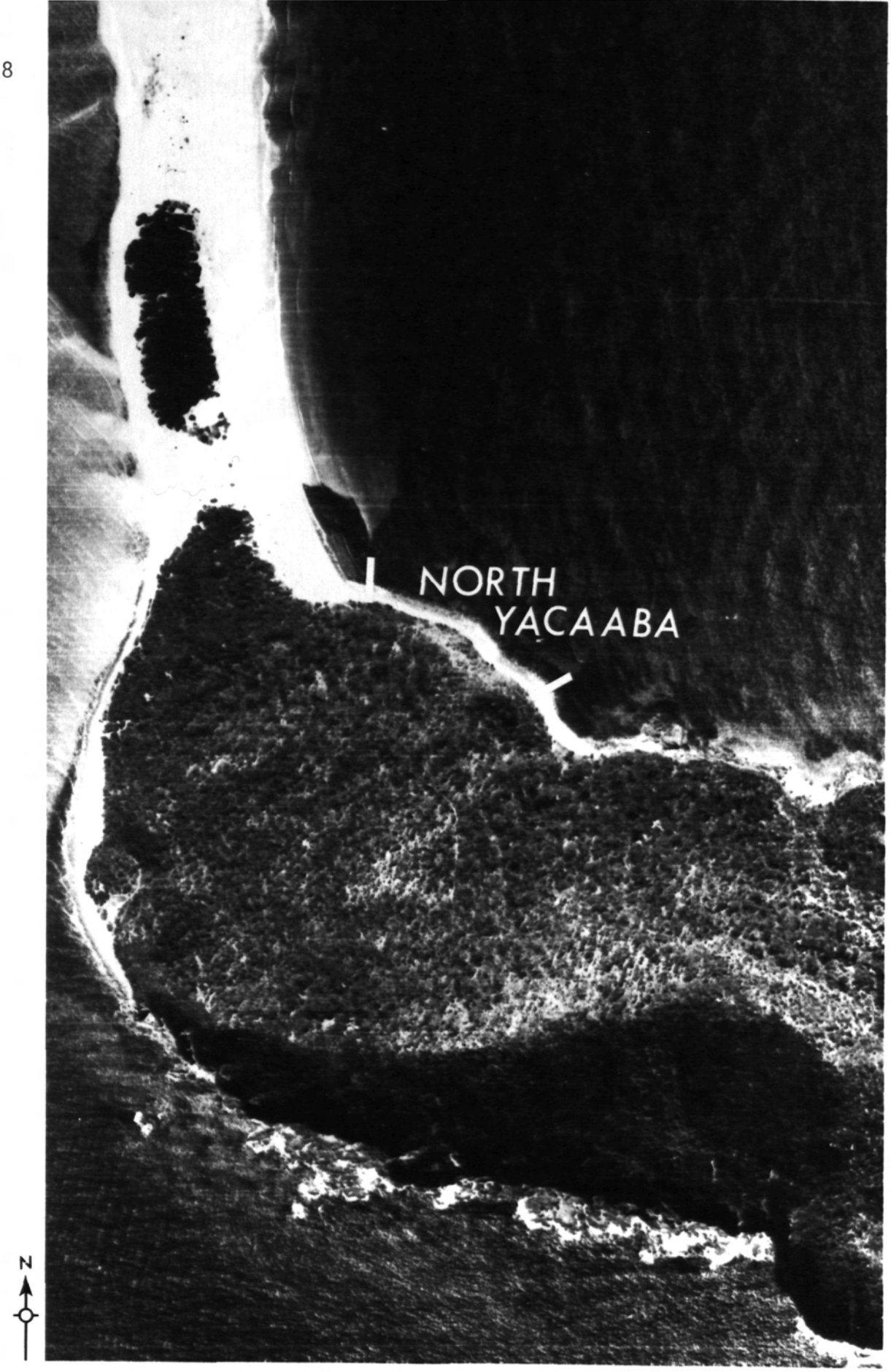

Plate 1. North Yacaaba boulder beach. Approximate scale 1:8000

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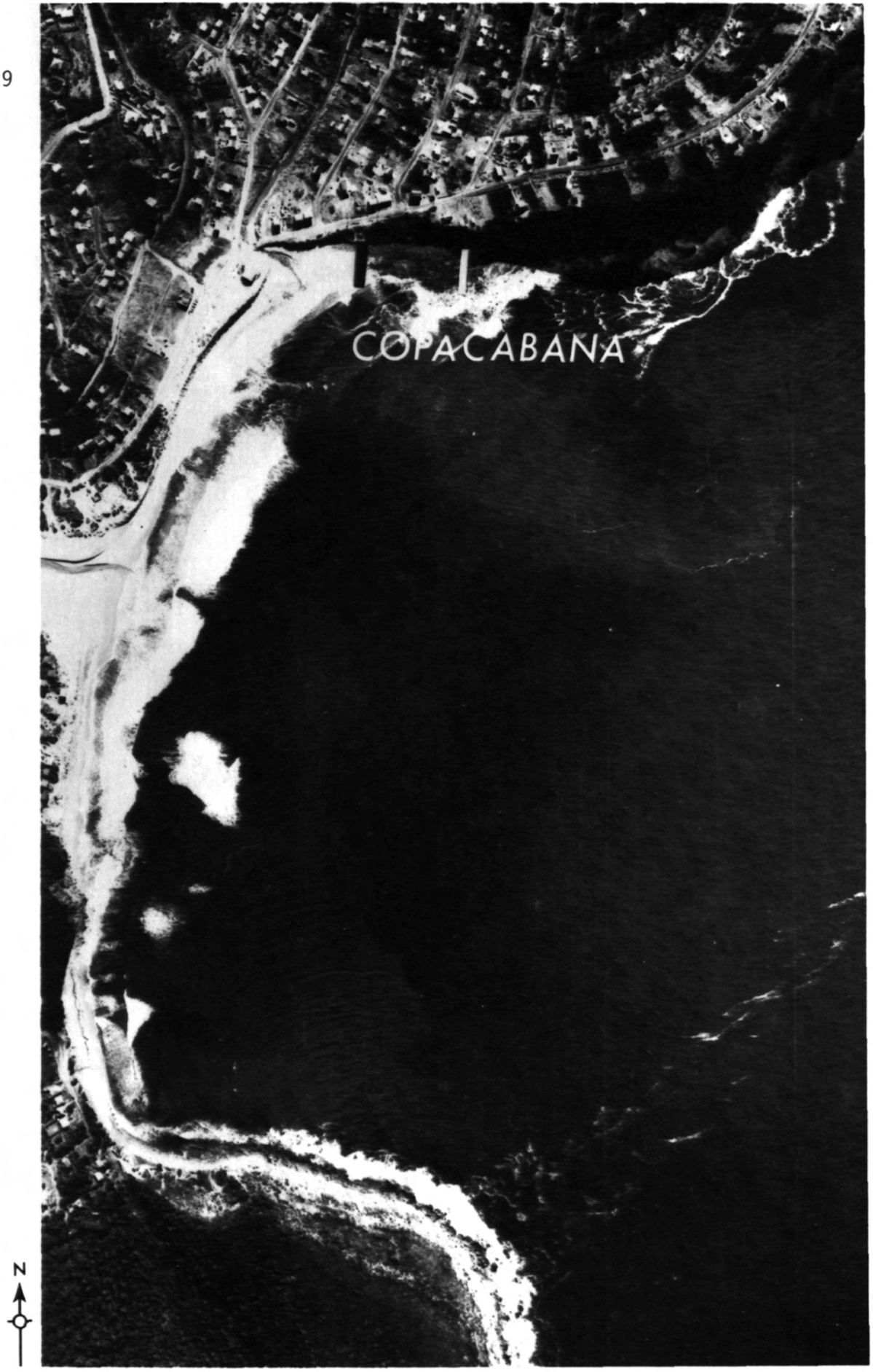

Plate 2. Copacabana boulder beach. Approximate scale 1:8000

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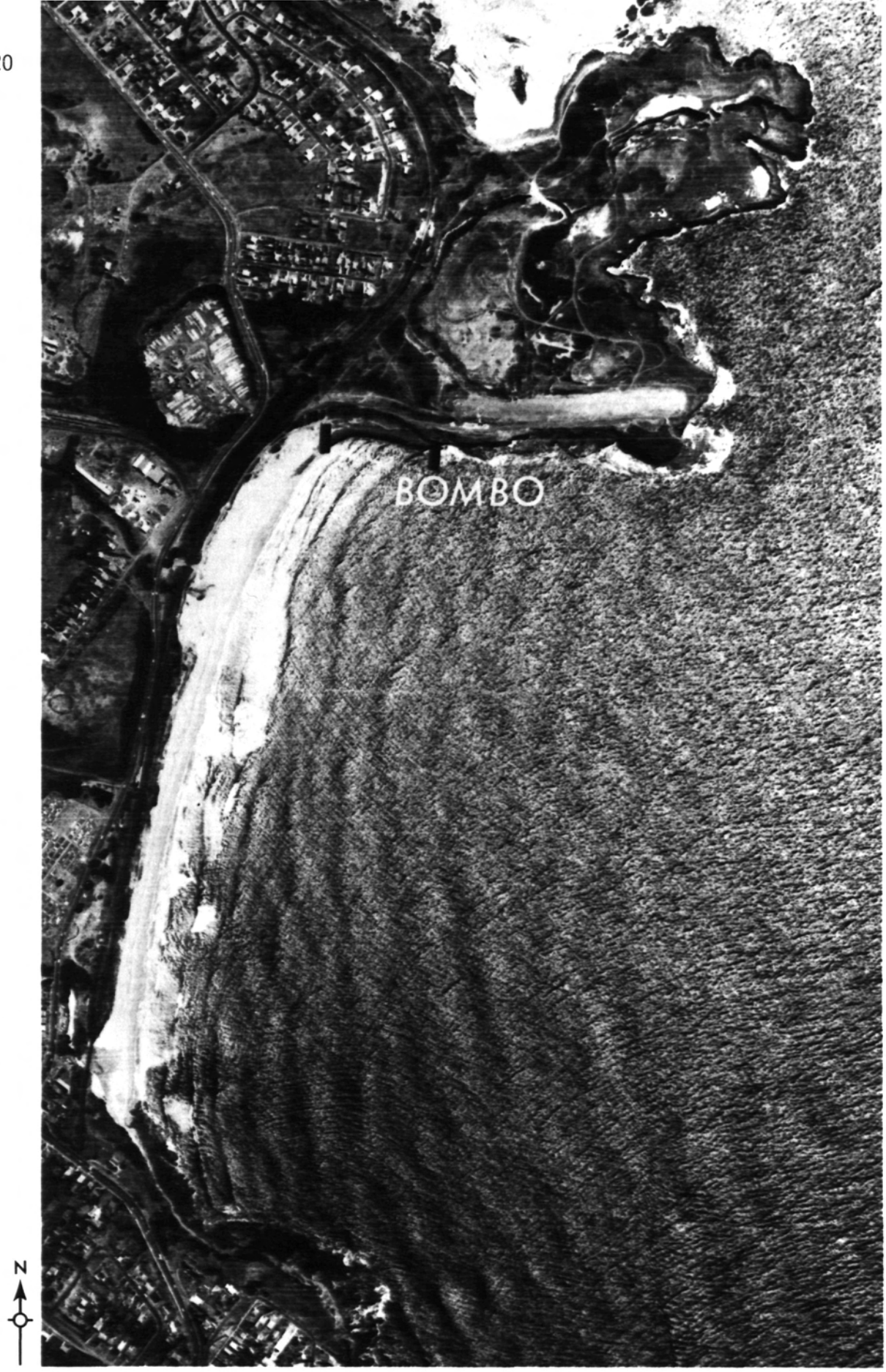

Plate 3. Bombo boulder beach. Approximate scale 1:8000

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Plate 4. Kiama boulder beach. Approximate scale 1:8000

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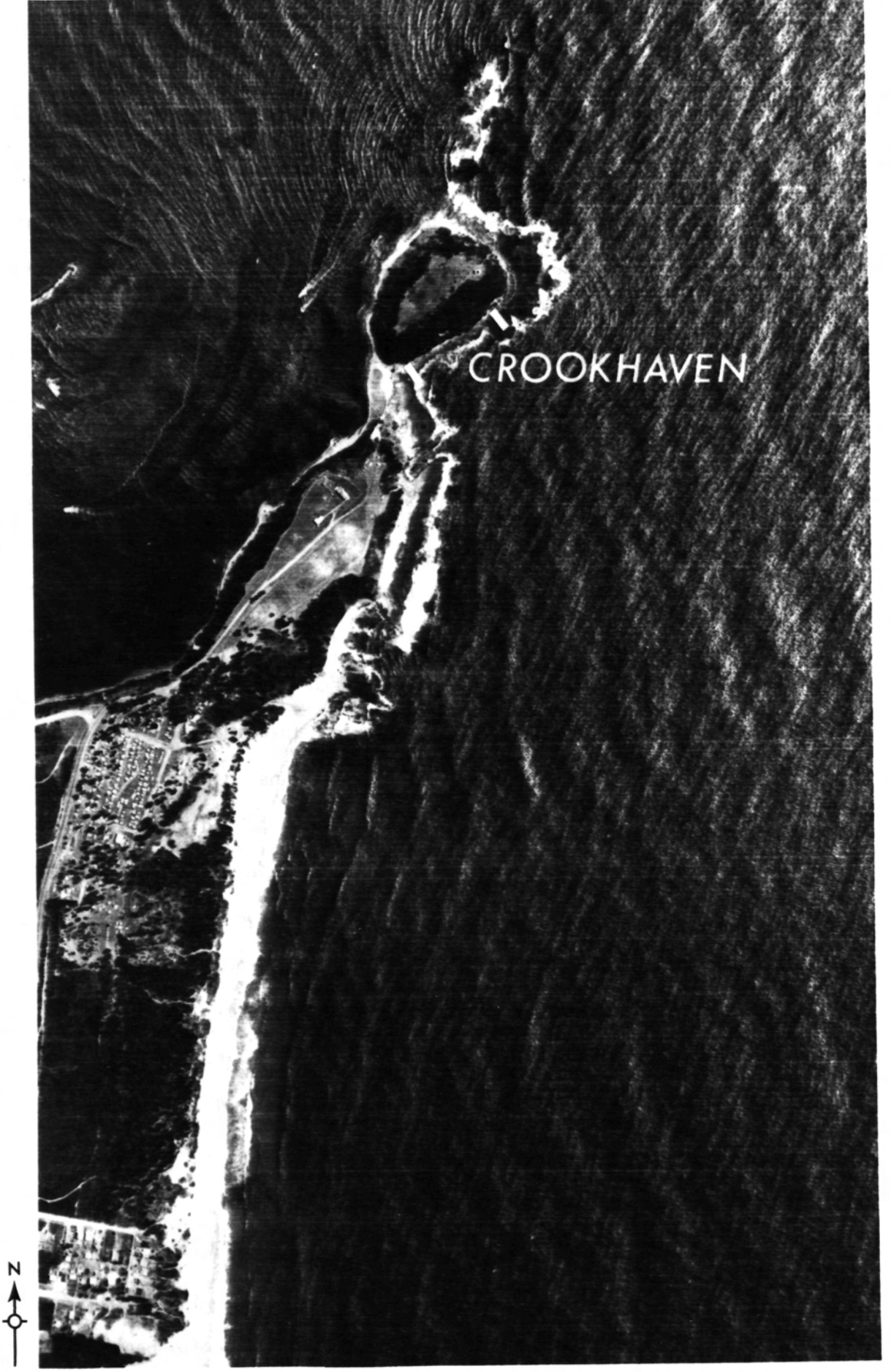

Plate 5. Crookhaven boulder beach. Approximate scale 1: 8000

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toscanite, and conglomerates (Sussmilch and Clark, 1928), and lithoidal toscanite occurs in proximity to the studied beach. The boulders forming the beach are of local origin, but the actual cliff source is almost totally degraded.

This north-facing beach is sheltered somewhat from open-ocean waves by a small offshore island (Cabbage Tree Island). Nevertheless, storm waves are of sufficient intensity to move and organize the boulders composing the beach. A bedrock outcrop occurs in the seaward portion of the beach near its centre.

Of the beaches studied, North Yacaaba has the greatest longshore length; 300 m. The narrowest width of this beach was found to be 17 m, with the average width close to 22 m. Seaward to landward profiles from the headland, mid, and embayment zones are presented in Figure 2. Mean foreshore slopes range between 7° and 10°, all profiles are backed by a degraded cliff, and no berm is present. From headland to embayment the tidal zone, approximately located by the upper limit of *Chamaesipho columna* (see page 44), includes progressively less of the boulder beach.

Although sand is associated with the beach (Plate 6), the boulder beach is not the result of recent exposure by storm waves. The supply of boulder-sized sediment to this beach appears to be extremely limited because the adjacent cliff, and major sediment source, is not being actively eroded under present-day conditions.

Copacabana Boulder Beach

Copabana boulder beach, 50 km north of Sydney, faces south and is exposed to the open ocean. This beach, as well as Bombo, Kiama, and

Figure 2a. Headland zone.

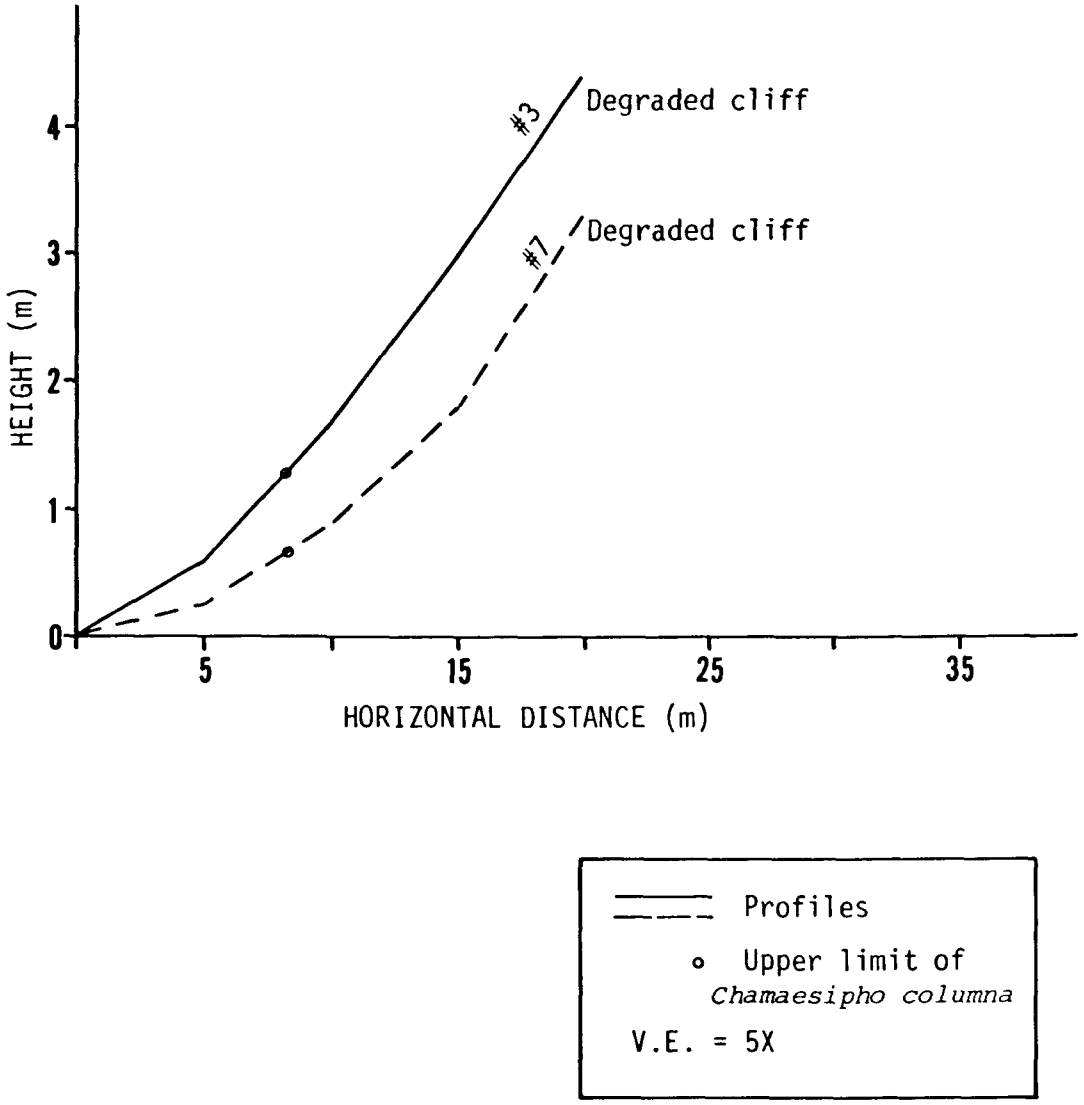


Figure 2. North Yacaaba boulder beach profiles numbered from headland to embayment, two per longshore beach zone.

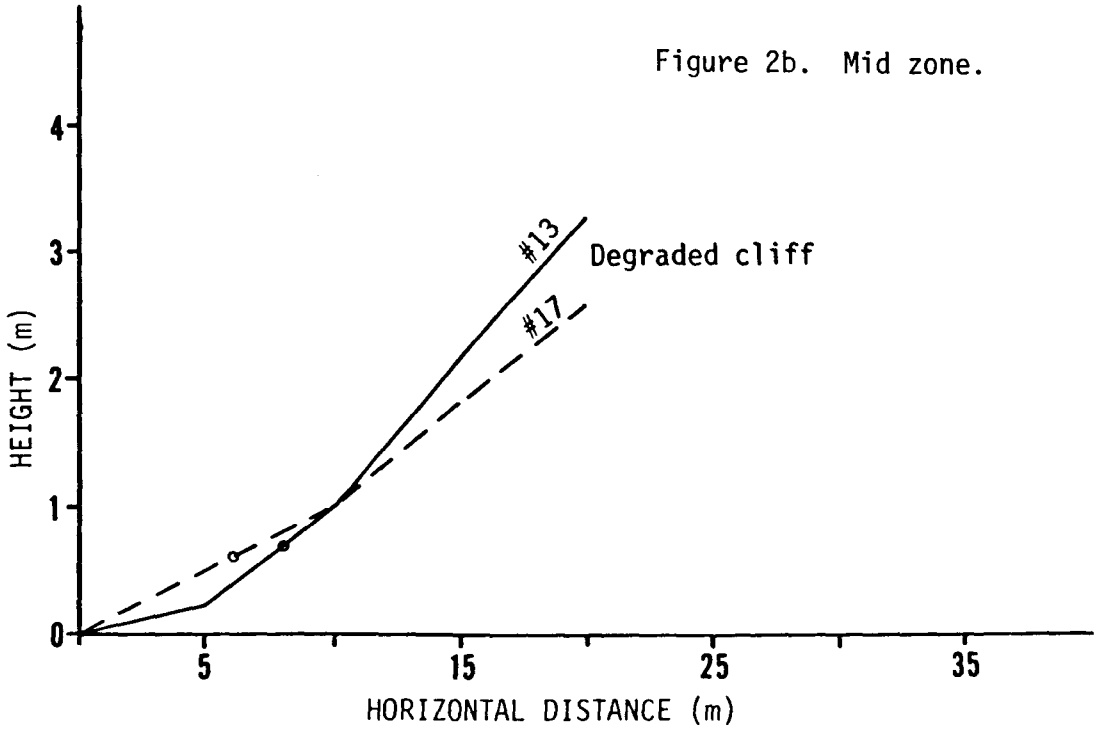


Figure 2b. Mid zone.

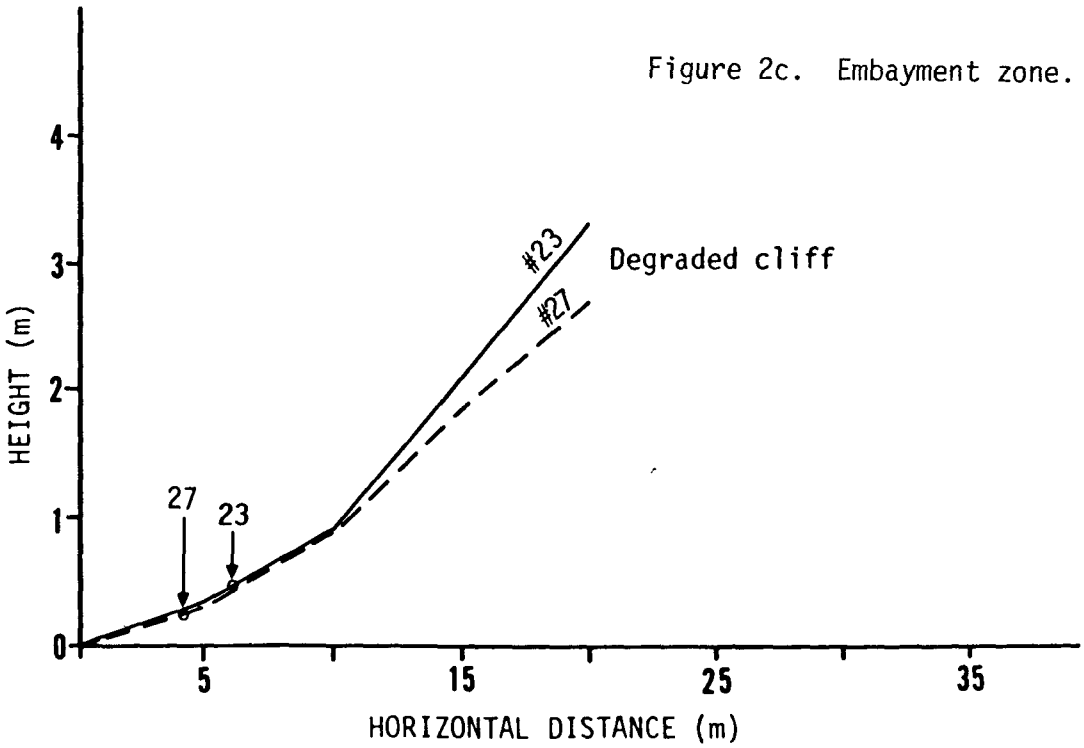


Figure 2c. Embayment zone.

Plate 6. North Yacaaba boulder beach.

Plate 7. Copacabana boulder beach showing imbrication and sand associated with boulders.

Crookhaven, are located in the broad structural unit known as the Sydney Basin. Tudibaring Head, the headland adjacent to, and the main sediment source for Copacabana beach (Plate 2) is composed of Gosford Formation Sandstone, which is part of the Triassic Narrabeen Group (McElroy *et al.*, 1969). This headland and the boulders on the beach correspond closely to the Mangrove and upper Ourimbah members. The Mangrove Sandstone tends to be well bedded with a pebbly base and yellow cavernous weathering. The lower portion of the Mangrove Sandstone is shaly sandstone and shale, and the Ourimbah Sandstone is fine to medium sandstone (McElroy *et al.*, 1969). Thus, the nature of the bedding in the cliff causes platy (disc-shaped) material to be liberated, greatly influencing the shape of sediment found on Copacabana boulder beach.

The longshore length of this beach is 150 m, narrowest width 17 m, and average width approximately 25 m. The mean foreshore angle varies between 7° and 12°. A shore platform underlies the headland zone which is backed by an active cliff. The mid zone is backed by a degraded cliff, and the embayment zone by a grassed rise. As can be seen from the profiles presented in Figure 3, no berm is present and the tidal zone changes little along this beach.

Sand is found with the boulders in the portion of the beach nearest the embayment, but the beach is not an ephemeral feature. Of the beaches studied, Copacabana exhibits the most consistent and pronounced imbrication, reflecting the predominance of disc-shaped sediment (Plate 7). After measuring and sampling of this beach were completed, some boulders in the seaward portion of the beach were removed to form a small breakwater and

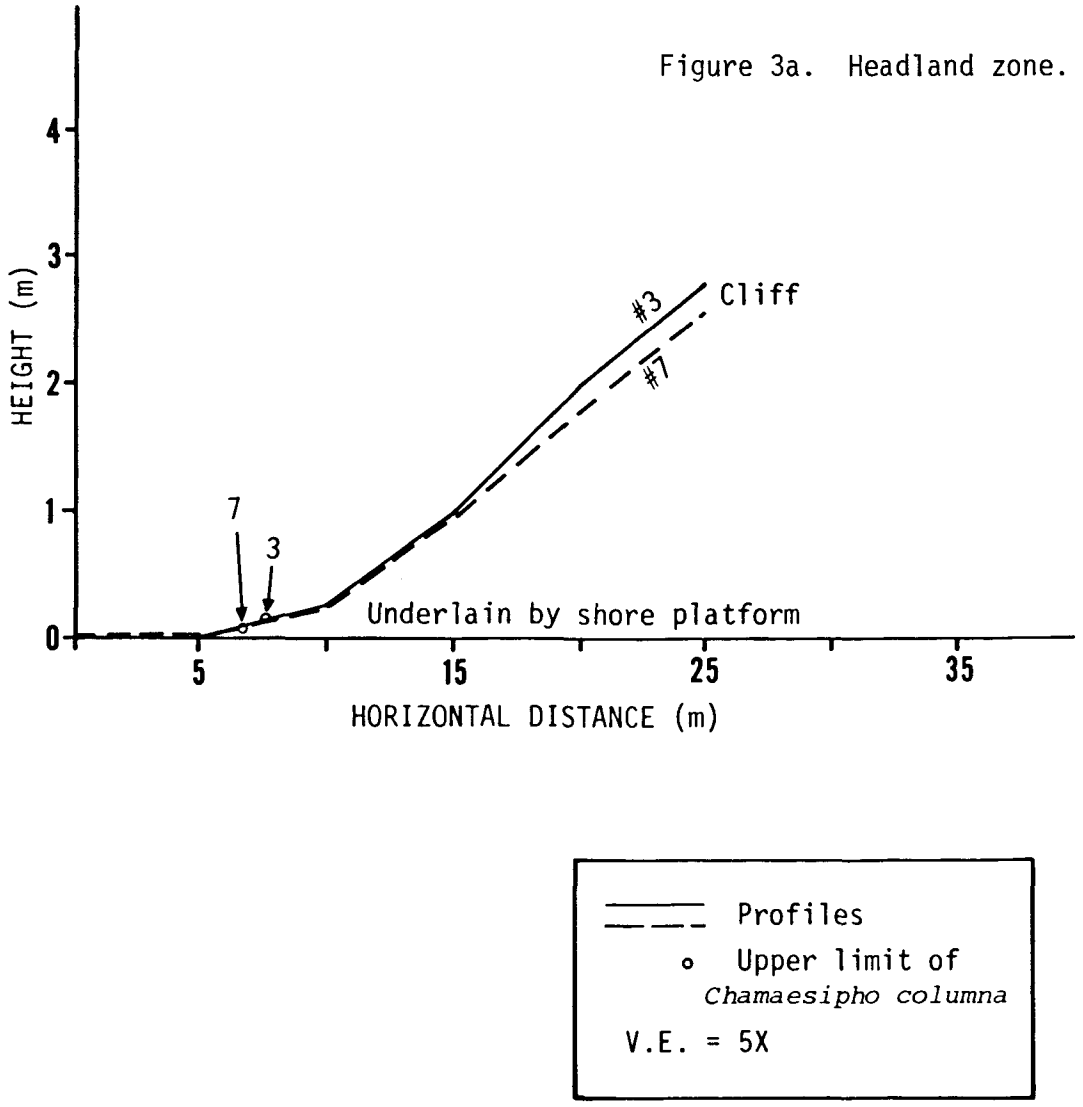


Figure 3. Copacabana boulder beach profiles numbered from headland to embayment, two per longshore beach zone.

Figure 3b. Mid zone.

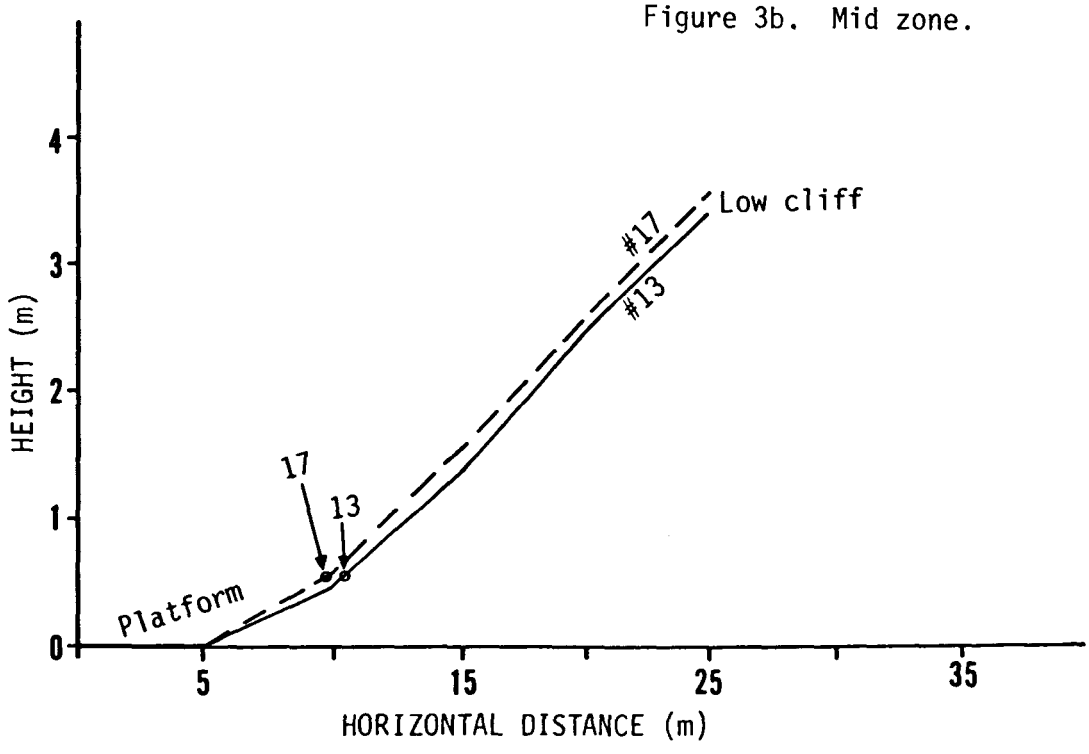
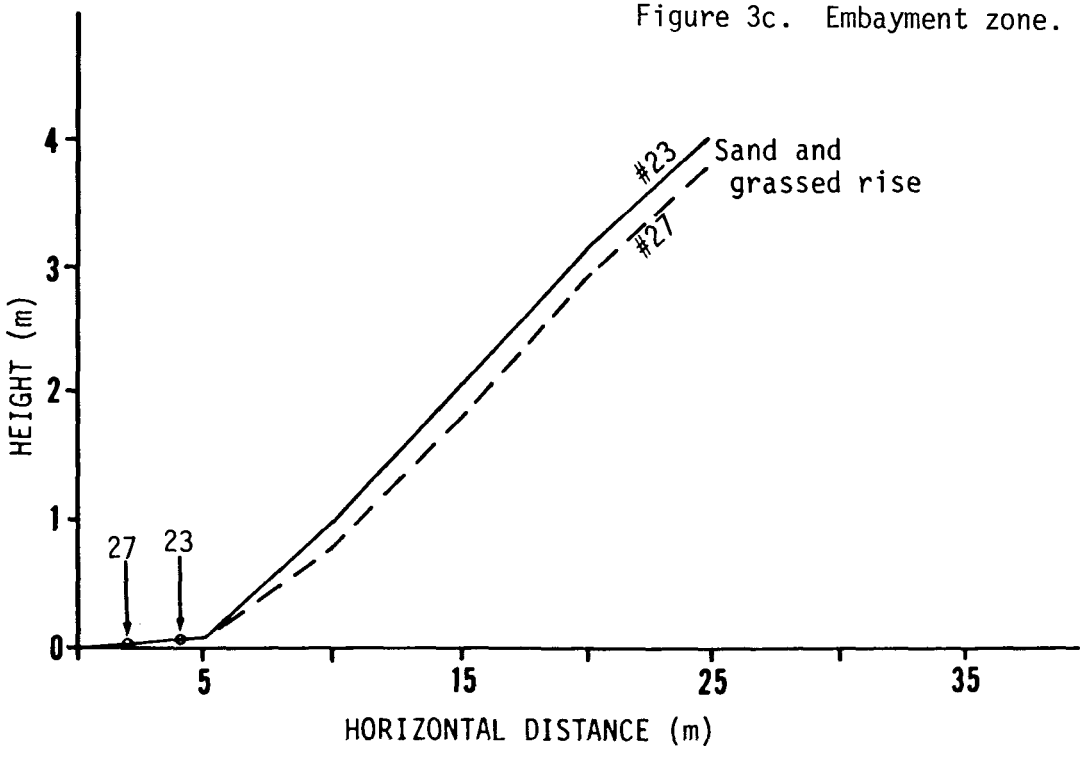


Figure 3c. Embayment zone.



swimming area. This disturbance had no effect on the present study, but renders the beach unsuitable for further research.

Bombo Boulder Beach

Bombo boulder beach is located about 95 km south of Sydney; it faces south and is exposed to the open ocean. Bombo headland and cliff (Plate 3) are composed of Bombo (also known as Bumbo) Latite, a member of the Geringong Volcanics, which are part of the Permian Shoalhaven Group. The latite is a medium-grained, medium-grey lava (Raam, 1969), and in this location exhibits striking columnar jointing. It is underlain by tuffaceous Kiama Sandstone which forms the shore platform. Many boulders which were originally rock refuse from a nearby latite quarry have been mixed by marine processes with naturally derived sandstone and latite boulders to form a boulder beach.

The shore platform forms a base for boulders near the headland while the other extremity of the beach is associated with and sometimes partially buried by a sand beach (Plate 8). The length of this beach, therefore, varies by several metres, depending on recent wave conditions. When measured and sampled in 1975, the boulder beach was 175 m long, which is probably near to its maximum length. The width averages 16 m, and the narrowest portion is 11 m wide. Bombo beach profiles (Figure 4) have mean foreshore angles ranging from 9° to 12°, and the headland zone is backed by an active cliff. No clear berm can be seen, however, a break in slope in the mid and embayment zones (see Figures 4b and 4c) indicates what, in the field, appears to be a berm feature.

Plate 8. Bombo boulder beach showing partial burial by sand in the portion of the boulder beach nearest the embayment. Wave approach can be seen to be oblique to most of the beach.

Plate 9. Kiama boulder beach showing oblique wave approach.

Figure 4a. Headland zone.

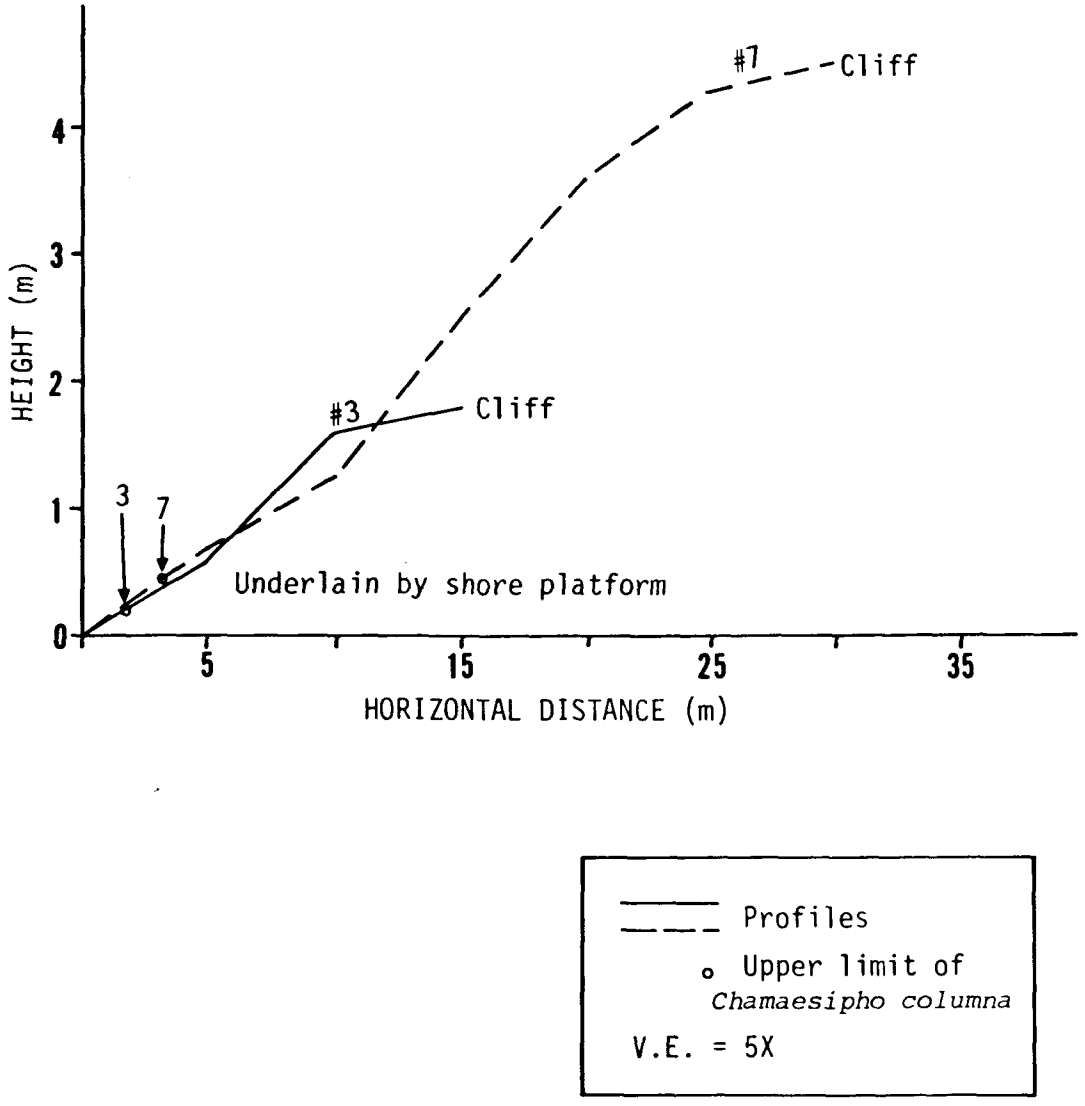


Figure 4. Bombo boulder beach profiles numbered from headland to embayment, two per longshore beach zone.

Figure 4b. Mid zone.

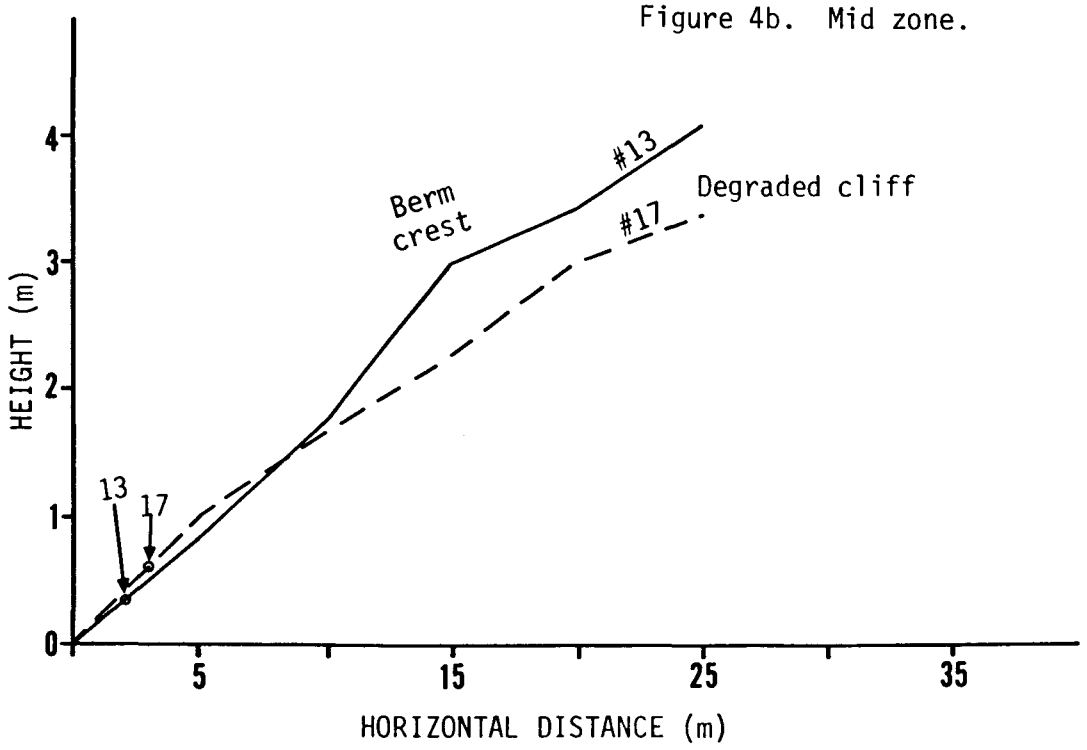
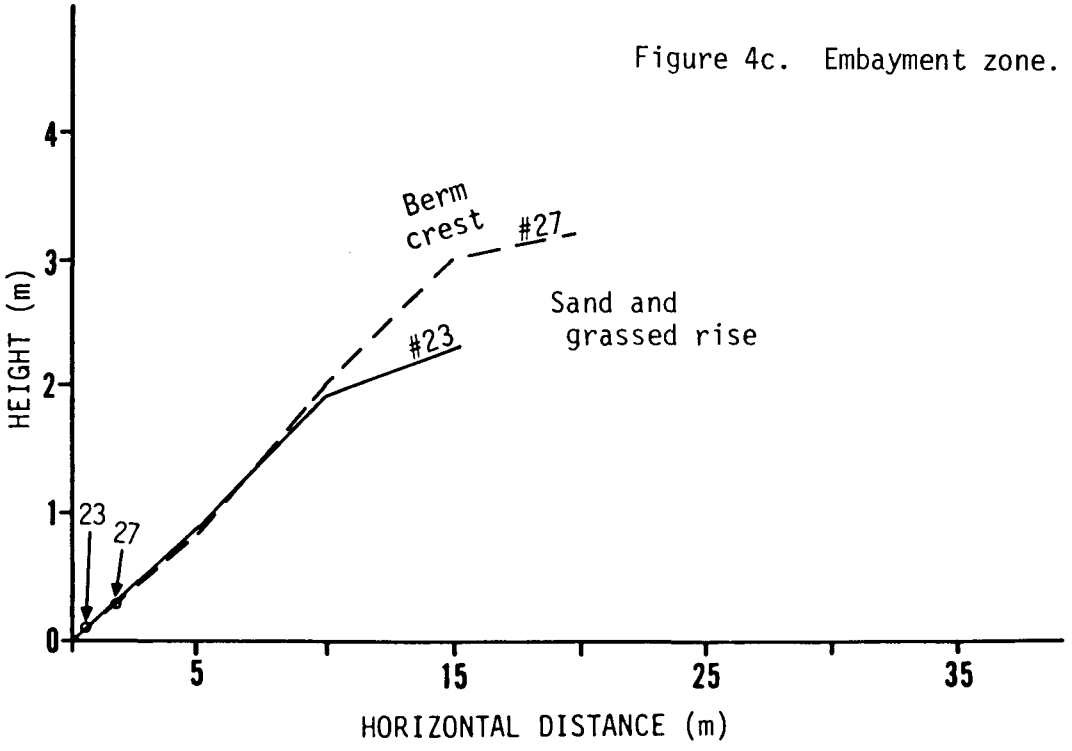


Figure 4c. Embayment zone.



Kiama Boulder Beach

Five kilometres south of Bombo boulder beach (100 km south of Sydney) is Kiama boulder beach which has a north-north-easterly exposure to the open ocean. Plate 4 shows the position of this beach which behaves as a sediment trap for material liberated from disintegrating cliffs extending approximately 1 km south. These cliffs are composed of Westley Park Sandstone (Branagan and Packham, 1970), the lowest member of the Geringong Volcanics. This formation is described as "shallow-water marine, highly fossiliferous, green-grey sandstones, with glacial erratics, minor siltstones and conglomerates" (Raam, 1969, p. 367). There are no massive joint patterns or distinct cleavage planes which might influence the shape and size of particles produced by these cliffs. A shore platform provides a base and protection from waves for one-third of this boulder beach, while the remainder is underlain by pebbles, cobbles, and boulders; no sand is present (Plate 9).

The length of the beach is 150 m and the width averages 23 m, with the minimum being 17 m. The profiles of Kiama boulder beach are illustrated in Figure 5. Mean foreshore slope ranges between 6° and 12°, a cliff backs only the headland zone, and each profile shows a berm. Lichen colonization, noted on the profiles, was observed on many boulders in the landward portion of this beach and will be discussed further in Chapter VII.

Crookhaven Boulder Beach

The most southerly beach selected for study is at Crookhaven Head, about 125 km south of Sydney. The headland (Plate 5) is composed of well-

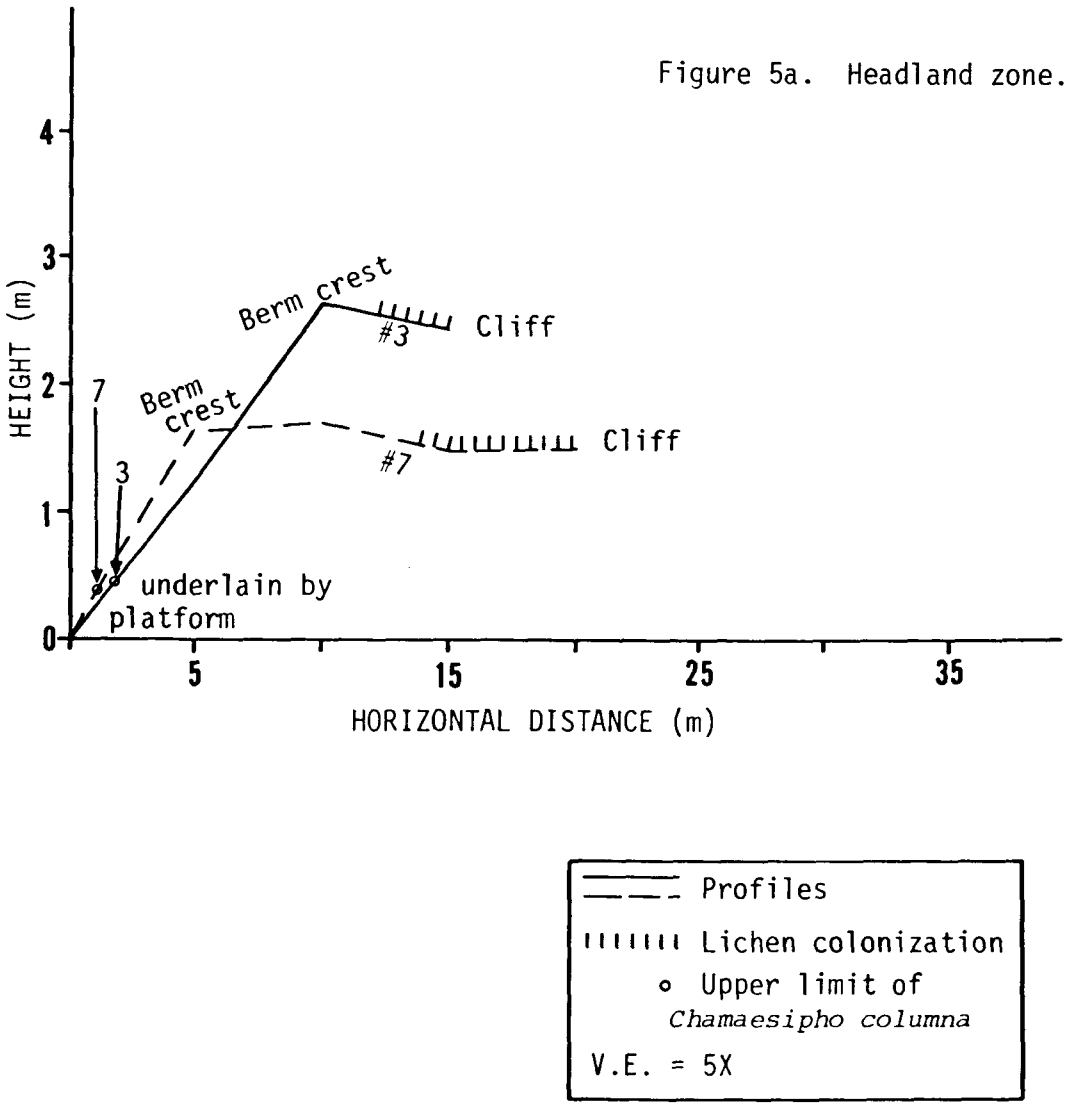


Figure 5. Kiama boulder beach profiles numbered from headland to embayment, two per longshore beach zone.

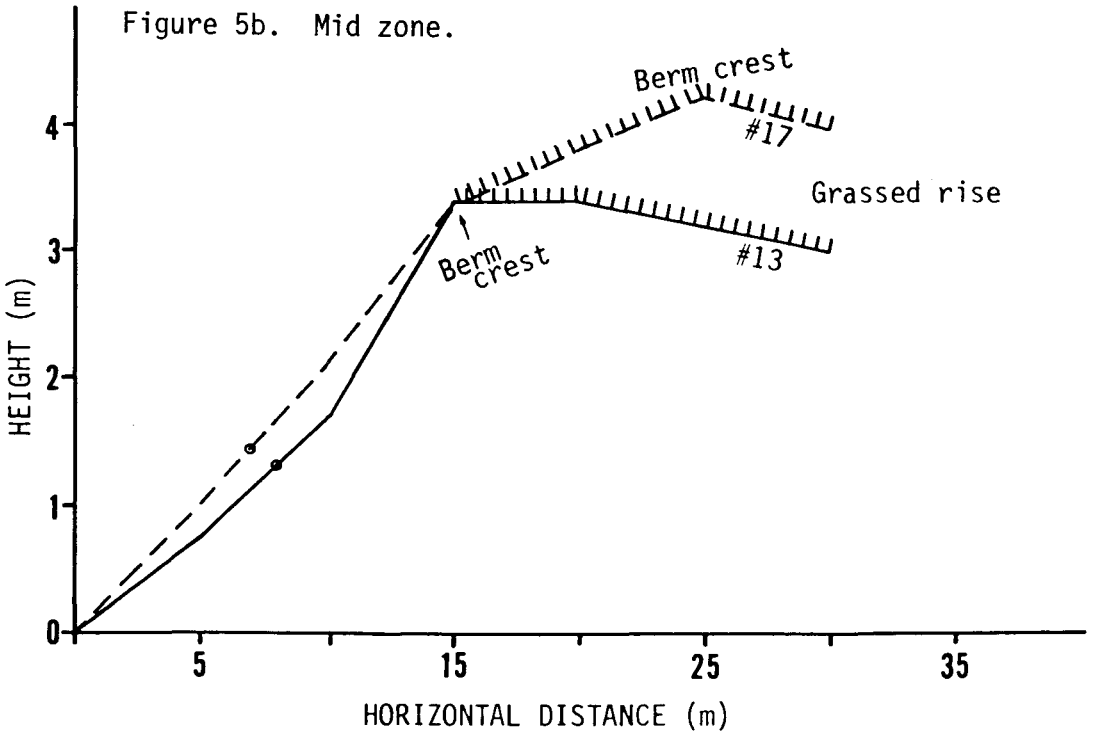


Figure 5b. Mid zone.
Berm crest
#17
Grassed rise
Berm crest
#13
HEIGHT (m)
0
1
2
3
4
5
15
25
35
HORIZONTAL DISTANCE (m)

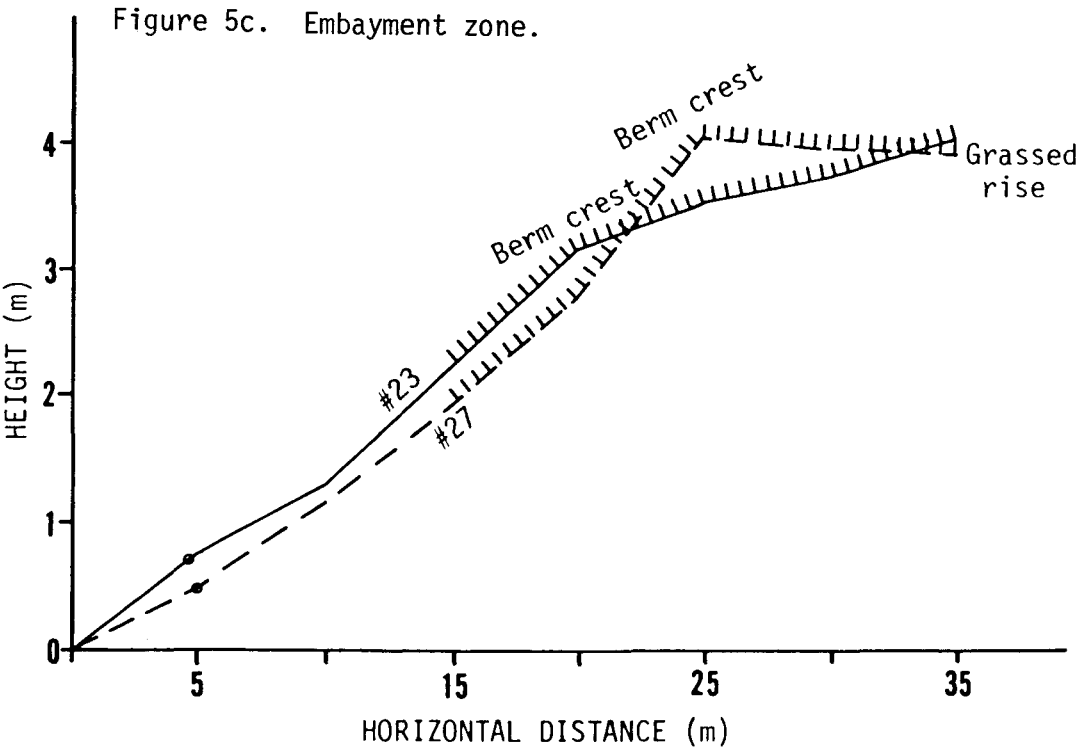


Figure 5c. Embayment zone.
Berm crest
Berm crest
Grassed rise
#23
#27
HEIGHT (m)
0
1
2
3
4
5
15
25
35
HORIZONTAL DISTANCE (m)

jointed sandstone and siltstone, and yields an abundant supply of large cubic blocks (reflecting the massive jointing pattern) to the boulder beach. This sandstone and siltstone is a lower member of the Permian Shoalhaven Group, and was considered by Nashar (1967) to be Wandrawandian Siltstone, a well-jointed silty sandstone with pebbly bands (McElroy *et al.*, 1969). More recently, it has been suggested by Gostin and Herbert (1973) that Crookhaven Head is composed of a member of the Conjola Sub Group.

Crookhaven beach is exposed to the open ocean and has an east-south-easterly aspect. No sand is associated with this beach, most of which is underlain by a shore platform (Plate 10). The longshore length is 150 m, average width is 24 m, and minimum width is 18 m. Figure 6 illustrates the profiles measured on Crookhaven beach, with the mean foreshore slope varying between 7° and 9°. No berm feature can be seen on this beach. The headland and mid zones are backed by a steep cliff while the embayment zone is backed by a low, degraded cliff, and all along this beach the tidal zone varies little. There is cavernous weathering of and lichen present on some landward boulders (discussed in Chapter VII).

Summary

In summary, Copacabana, Kiama, and Crookhaven boulder beaches are composed of various sandstones, whereas North Yacaaba and Bombo beaches consist mainly of volcanics. The joint configuration in the adjacent cliffs may be reflected in the size and shape of sediment supplied to each boulder beach; this is especially evident at Copacabana, where the cliff composed of thinly bedded sandstone produces disc-shaped boulders, and at Crookhaven, where large cubic blocks reflect the jointing pattern in the adjacent sandstone and siltstone cliff.

Plate 10. Crookhaven boulder beach.

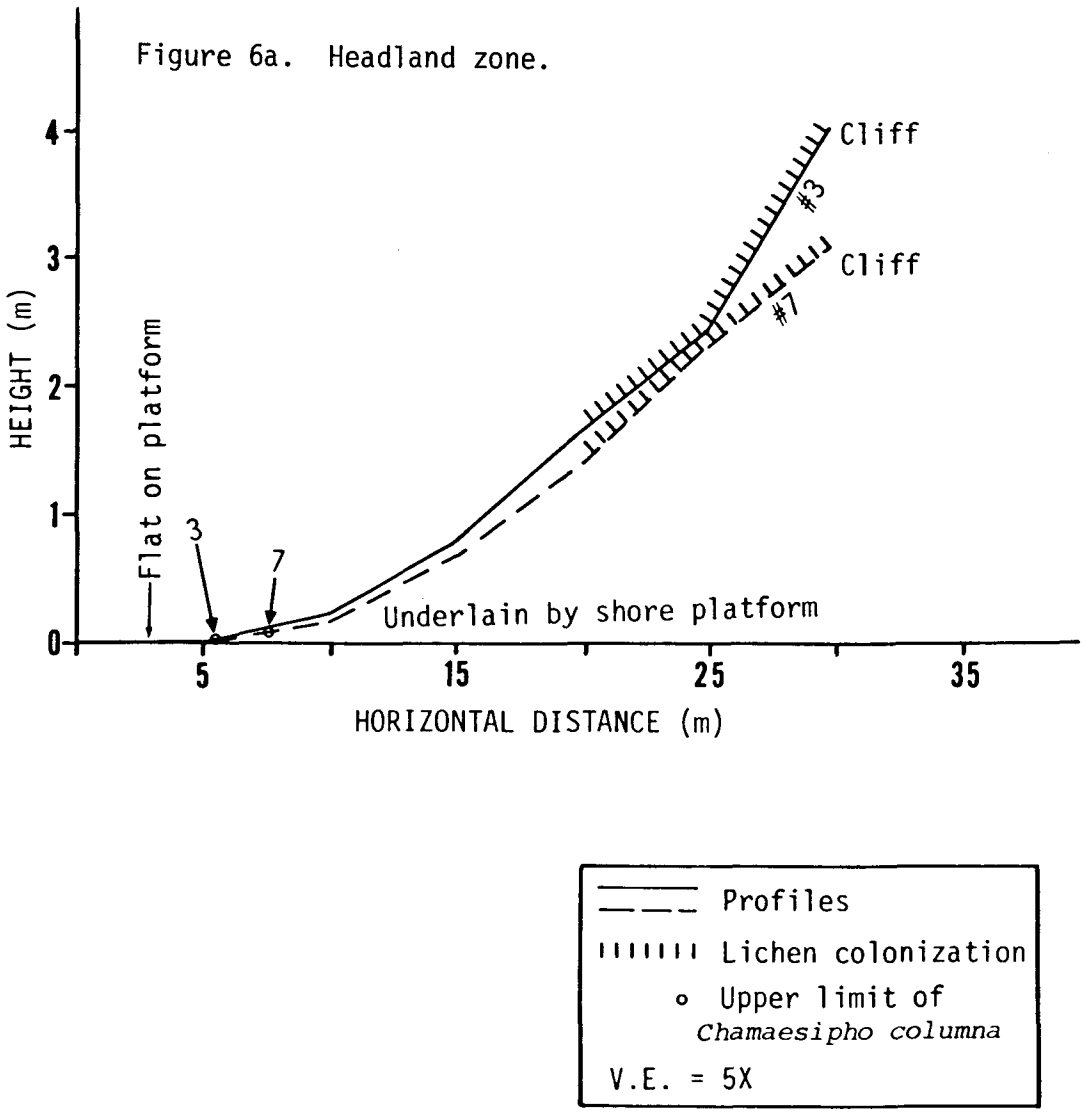


Figure 6. Crookhaven boulder beach profiles numbered from headland to embayment, two per longshore beach zone.

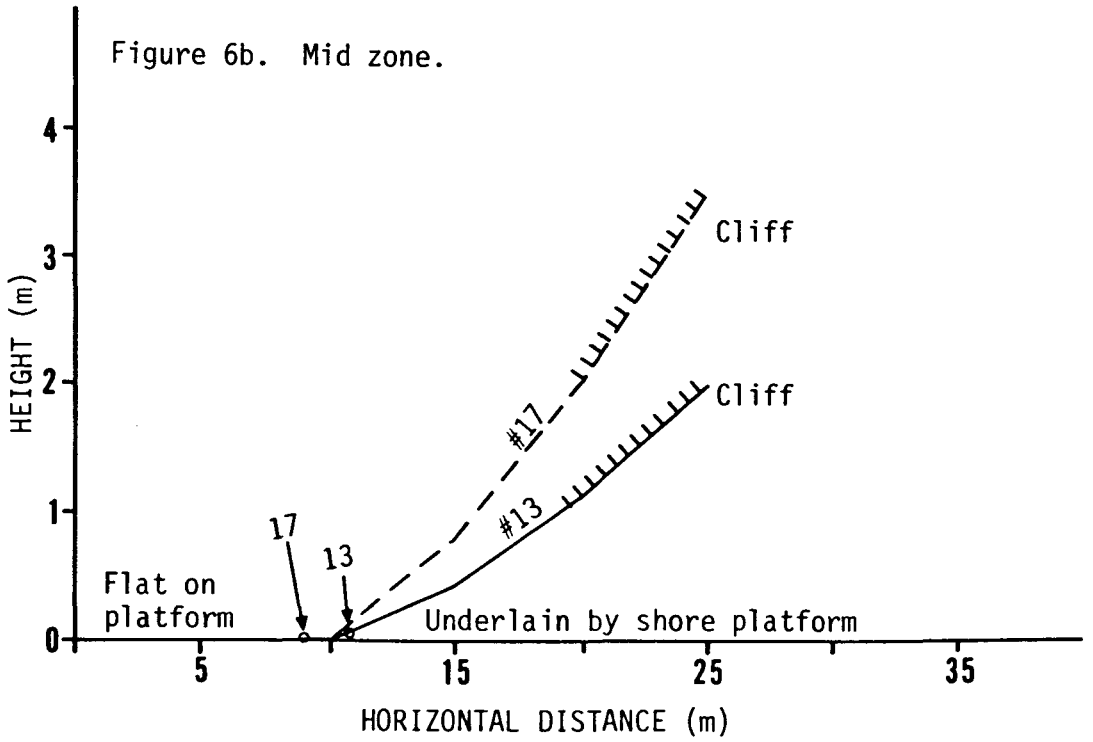


Figure 6b. Mid zone.
HEIGHT (m)
0
1
2
3
4
Cliff
Cliff
#17
#13
17
13
Flat on
platform
Underlain by shore platform
5
15
25
35
HORIZONTAL DISTANCE (m)

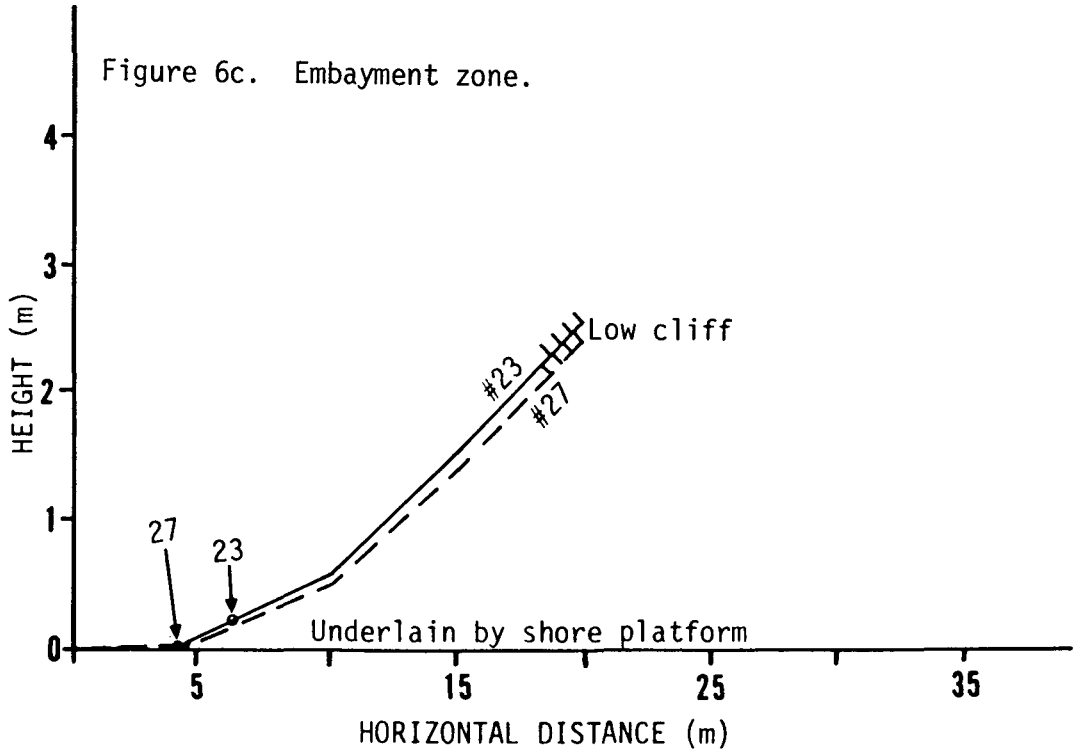


Figure 6c. Embayment zone.
HEIGHT (m)
0
1
2
3
4
Low cliff
#23
#27
27
23
Underlain by shore platform
5
15
25
35
HORIZONTAL DISTANCE (m)

Boulders are supplied in very limited quantities, if at all, to North Yacaaba beach, whereas there appears to be a steady input of fresh boulders at the other four beaches. On all five boulder beaches, sediment is of local origin, supplied mainly by the erosion of adjacent cliffs and possibly shore platforms (see Gill, 1971). Sand is associated with North Yacaaba, Copacabana, and Bombo beaches.

Since storm waves are the only waves competent to move the boulder-sized particles on the studied beaches, the profiles presented in Figures 2, 3, 4, 5, and 6 are storm-beach profiles. The mean foreshore slopes range between 6° and 12°, and the profile shape tends to be concave upward, a form considered indicative of high swash velocity (Dolan and Ferm, 1966). This concavity is particularly evident on Crookhaven, the beach which has the largest mean size of particles. Small-scale profile features (such as tidal ridges) were impossible to discern because of the great size of individual particles.

Because it was difficult and dangerous to obtain, no offshore information is included in the beach profiles. However, it is known that between Sydney and Jervis Bay, New South Wales, the nearshore profile is considered steep (Wright, 1976). Thus, the active nearshore zone is narrow and waves of high energy reach the studied beaches. Along this coast, "on the average only 3.4% of the incident wave power is dissipated before reaching the inshore zone. By contrast, friction-induced power expenditures over the low-gradient nearshore profiles fronting the coasts of Sergipe (Brazil), Santa Rosa Island (Florida, U.S.A.), Cape Henry to Cape Hatteras (U.S.A.), and Georgia (U.S.A.) average 29, 48, 58, and 84% respectively" (Wright, 1976, p. 633).

CHAPTER II

METHODS

FIELD METHODS

Sampling Technique

The unbiased selection of a representative sample of boulders from each beach is essential to the validity of this study. Because of the great size and weight of the material to be measured, a technique was needed which allowed the objective selection of each sample and its measurement *in situ*.

The most suitable sampling method was found to be a grid, similar to the system outlined by Krumbein (1953) and Wolman (1954). Columns were to be oriented normal to the low-water line, and rows parallel to the shore; one sample was to be taken from beneath each intersection point (Figure 7). Pacing was first attempted as a means of establishing this grid, but proved impracticable because the large sediment size made uniform pacing impossible. A grid of heavy rope was then constructed and samples taken at the intersection points of the rope grid when it was placed on the beach. This method too proved unsatisfactory because the rope grid was cumbersome and very difficult to lay over or move along the highly irregular surface of the boulder beach.

The third method attempted, and that eventually employed, was the most rigorous possible under the circumstances. A grid composed of approximately 30 profiles with an average of 10 sample points per profile was constructed for each beach using 30 m tapes. This was done by first measuring the length of each beach, and then locating the profiles at equal intervals along the beach. A tape was then stretched along each profile, and the sampling points located at fixed intervals along each profile. Since the tape was held taut

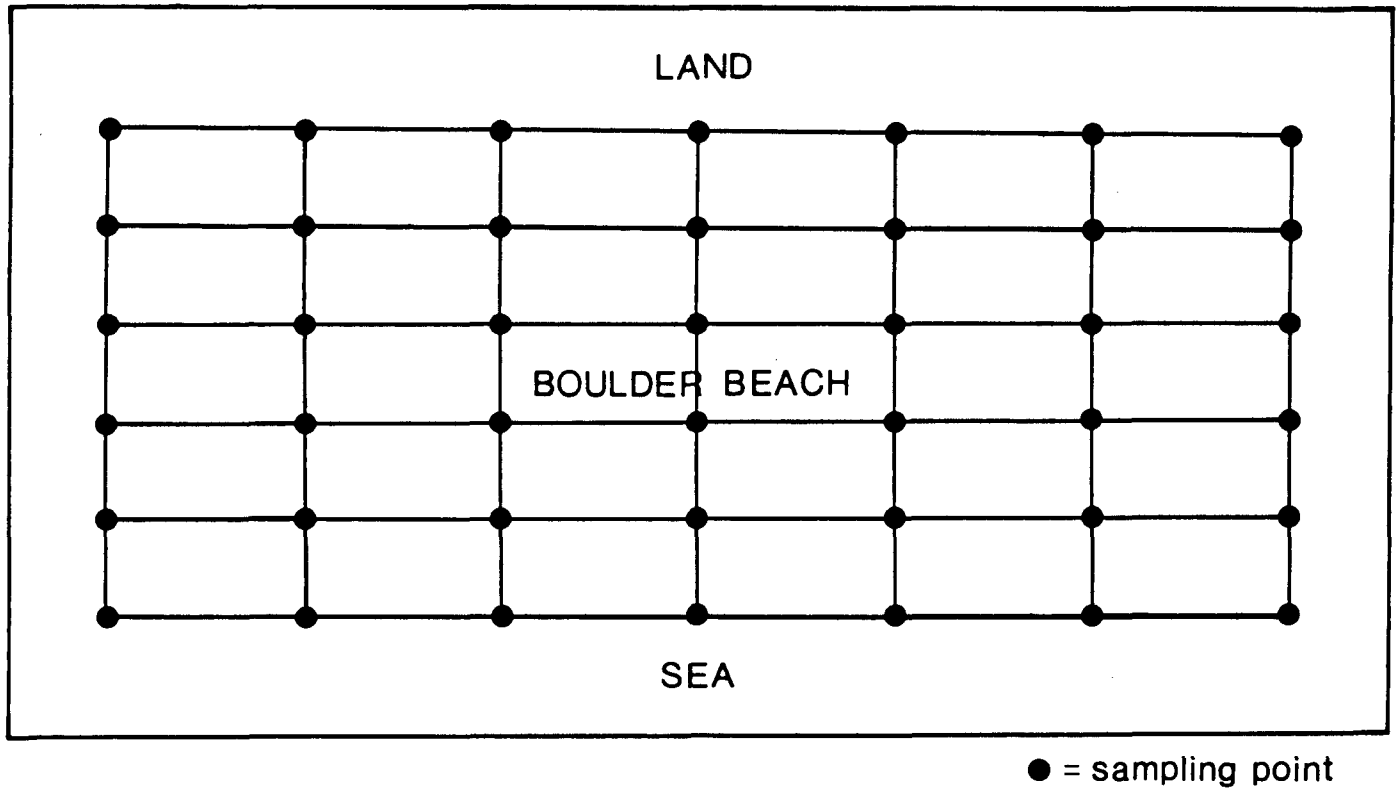


Figure 7. Grid for sampling boulder beaches.

at each end and placed over the beach, there was no foreknowledge of, or bias in, the location of sample points. This sampling method may be classified as "systematic point sampling" (Young, 1972, p. 145).

The mutually perpendicular long, intermediate, and short (A, B, and C) axes (Krumbein, 1941) of the particle beneath each sample point were measured to the nearest 0.5 cm with a linen tape measure. All particles at sample points were large enough to be measured in this fashion. At the same time, roundness of each sampled boulder was visually assessed. The grid position of each boulder was noted so that data could be analyzed by location. The basic data collected in this manner is included in Appendix VI.

All beaches were sampled to either their seaward limit or to the point where the beach was submerged at low tide. However, these beaches are surf beaches, consequently, low-water level at one beach on one day may not be equivalent to the low-water level on another day or on another beach. To facilitate valid between-beach comparisons, the establishment of a common height datum was essential.

The seaward portion of each studied beach supports *Chamaesipho columna*, a small, fixed barnacle which is a good "marker" species because its upper extent indicates the upper limit of the tidal zone (Dakin, 1973, p. 91). Therefore, when sampling, the position of the landward limit of the *Chamaesipho columna* zone was noted and plotted on the grid, thus providing a common environmental datum for the studied beaches.

For purposes of analysis, each beach was divided into three zones from sea to land (Figure 8). Thirds were chosen so that each zone would contain close to 100 measured boulders and because the tidal zone (as

Figure 8a. Up-beach zones.

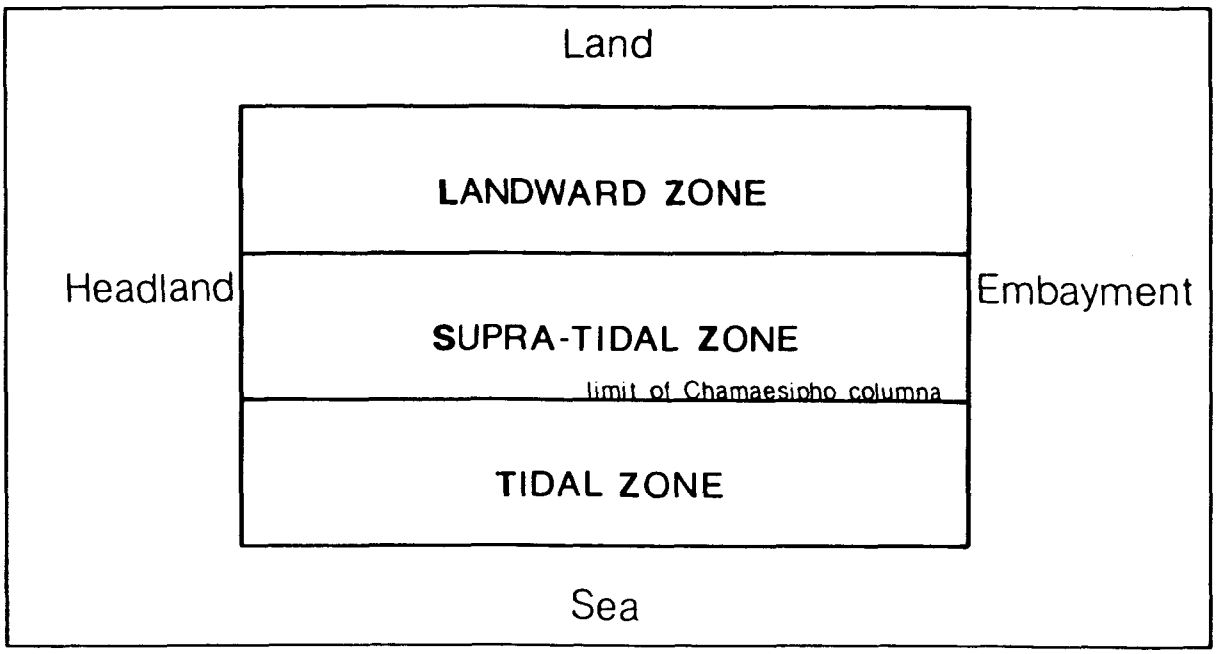


Figure 8b. Longshore zones.

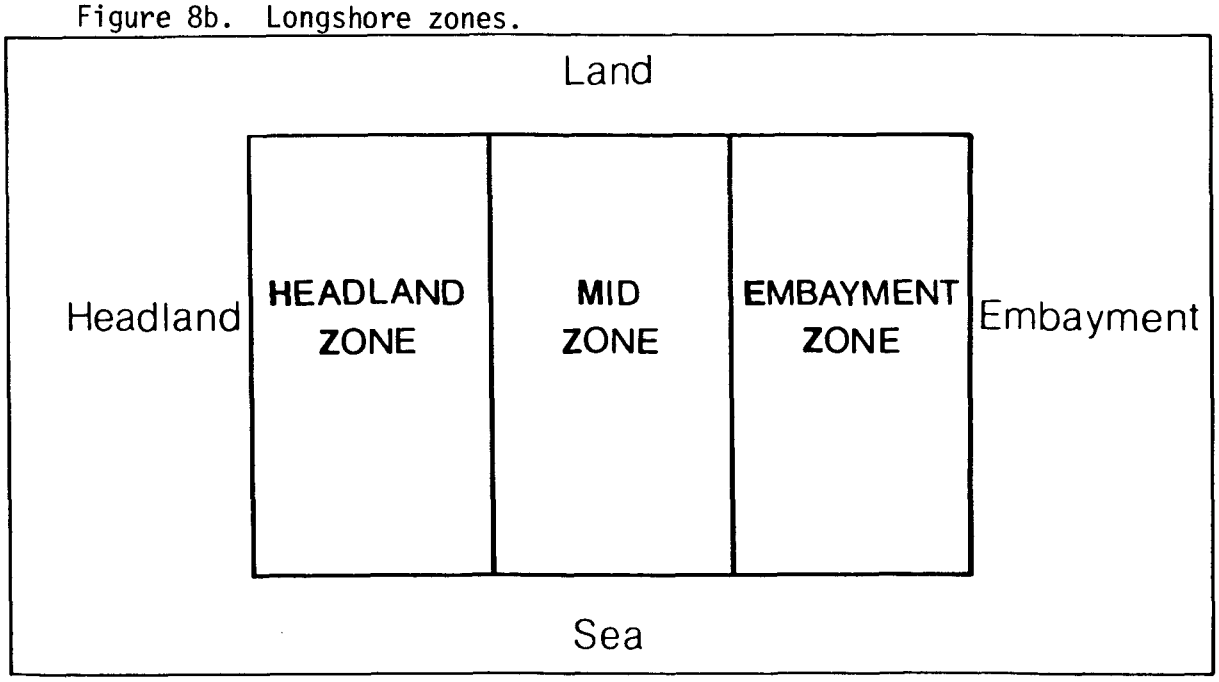


Figure 8. Zonal divisions of the studied boulder beaches.

indicated by the upper limit of the *Chamaesipho columna*) tended to occupy close to one-third of each beach. The tidal zone was considered as one unit and, if a berm were present, the upper two-thirds of the beach were divided at the crest. In the absence of a berm, the remaining area was equally divided. These three portions will be referred to as:

1) the tidal zone;
2) the supra-tidal zone;
3) the landward zone.

Each beach was also divided into three zones from headland to embayment. In this case, the division was simply into thirds, with each being referred to as:

1) the headland zone;
2) the mid zone;
3) the embayment zone.

Size Measurement

For each sampled particle, size, shape, sphericity, and roundness were assessed (values in Appendix VI). Sieve analysis is the most common method of obtaining size data for sedimentary material. Thus, when this technique is unsuitable, as is clearly the case in this study, it is highly desirable to collect size data in a form comparable to sieve analysis. Kellerhals and Bray (1971a, 1971b) have demonstrated that grid sampling is equivalent to bulk sieve analysis and that these two sampling methods are directly comparable.

Measurements of the B axis were used to indicate size and thus are equivalent to sieve measurement of size, since the B axis is the particle

dimension measured by sieving (*e.g.*, Bluck, 1967). These measurements were converted from centimetres to *phi* (ϕ) units ($\phi = -\log_2$ mm : Krumbein, 1934, 1936, 1938) to maintain consistency and to facilitate comparisons with other sedimentary studies in which *phi* units are commonly used.

Udden's scale of size terms (Udden, 1914), as adopted by Wentworth (1922a), was used to establish the lower mean grain-size limit for a boulder beach. According to the Wentworth class limits, boulders have a median diameter equal to or greater than 256 mm, which is equivalent to a *phi*-scale value of -8ϕ.

Shape Classification

> Because the shape of irregular objects cannot be conceived in absolute quantitative terms, all measurements of this parameter must be arbitrarily defined and their use must be comparative (Moss, 1962, p. 338).

Shape, a measure of the relation between the three axial dimensions of an object (Krumbein, 1939; Folk, 1974), can be described by various methods (see Carver, 1971), but the most widely used are those proposed by Zingg (1935) and by Sneed and Folk (1958). Both of these methods of classification describe the shape by using measurements of the A, B, and C axes because, although the particles are not triaxial ellipsoids, statistically they may be considered as such (Krumbein, 1941).

Sneed and Folk identify 10 shape classes; but this number of divisions is too large to allow valid statistics to be obtained with a sample size of about 100 (each beach zone). Consequently, the Zingg (1935) classification of shape, which contains only four classes, was employed. Using the Zingg classification also facilitated comparison of the results from this study

with those of Bluck (1967, 1969) who examined gravel beaches, and with the predictive shape research by Smalley (1966).

The Zingg shape classes were determined for each boulder by the ratios of the B and A axes, and the C and B axes as follows:

	B/A	C/B
SPHERE	> 2/3	> 2/3
DISC	> 2/3	≤ 2/3
ROD	≤ 2/3	> 2/3
BLADE	≤ 2/3	≤ 2/3

This method of shape classification provides a simple and objective measure of form, but since the resulting categories are nominal, statistical analysis is limited.

Another shape index was calculated for each sampled boulder. This index indicates the extent to which a particle approaches an oblate or prolate spheroid (Williams, 1965) and is found in the following manner:

If $\frac{B^2}{AC} > 1$, the ellipsoid is tending to be oblate;

If $\frac{B^2}{AC} < 1$, the ellipsoid is tending to be prolate.

(A = A axis, B = B axis, C = C axis)

Although this index has been criticized by Dobkins and Folk (1970), it is used in this study to give an indication of shape tendency, and to investigate the proposition that coarse material subjected to wave action tends to become oblate (Russell, 1939; Blatt, 1959).

Sphericity Measurement

Sphericity is a quantitative statement of how nearly equal are the three dimensions of an object (Folk, 1974), and is geometrically interdependent with shape (Whalley, 1972). A measure of sphericity may indicate settling velocity because when volume and density are constant, a sphere has the least surface area of any shape and, hence, the greatest settling velocity. Sphericity measurements may also be related to transport probability because particles with great surface area:volume ratios (*i.e.* low sphericity) are most easily entrained. Various indices of sphericity have been developed (*e.g.*, Wentworth, 1922b; Wadell, 1934; Corey, 1949).

Folk (1955) introduced an index of sphericity which Sneed and Folk (1958, p.118) termed "maximum projection sphericity", and defined in the following way:

$$\frac{\text{Maximum projection area of sphere of same volume as the particle}}{\text{Maximum projection area of the particle}}$$

which reduces to $(C^2/AB)^{1/3}$, where A = length of A axis, B = length of B axis, and C = length of C axis. In addition to settling velocity sensitivity, this sphericity measure has been found to correlate well with bed-load movement. "For rolling velocity, the correlation coefficient with maximum projection sphericity is 0.86 . . ." (Sneed and Folk, 1958, p. 123). Because of its possible relation to the behavioural characteristics of boulders, the maximum projection sphericity (ψ_p) was calculated for each boulder sampled in this study.

Roundness Assessment

Roundness refers to the degree of smoothness of corners and edges of a clastic fragment, and is a property distinct from shape or sphericity. Various methods have been developed to assess roundness through both laboratory measurement of particles (Wentworth, 1919; Wadell, 1932) and visual comparison (Russell and Taylor, 1937; Krumbein, 1941, Powers, 1953). Visual comparison charts illustrate the various roundness classes, and each particle is compared with images of defined roundness, and the roundness value of the most closely corresponding illustration is assigned to the particle.

Since roundness values in this study had to be determined in the field, visual comparison was the most efficient method. Nine roundness classes were suggested by Krumbein (1941) and presented as silhouettes. These silhouettes, however, were too simple to accurately assess values of three-dimensional forms, and the numerous classes representing slight roundness changes resulted in a time-consuming, and not always consistent, decision as to which value to assign.

Powers' visual roundness chart (Powers, 1953, p. 118) displays artificial images with their roundness determined by Wadell's (1932) method (which is the ratio of the average radius of curvature of the edges or corners of the sample to the radius of curvature of the maximum inscribed sphere). Only six roundness classes are used, and three-dimensional models of both high and low sphericity particles are displayed for each class. Thus, this method of roundness classification eliminated most of the disadvantages of the Krumbein visual comparison method, and the Powers'

visual roundness chart, reproduced at a larger scale by Folk (1968), was used to assess roundness in this study.

Powers' six roundness grades are defined so that the class limits approximate a $\sqrt{2}$ geometric scale. Folk (1955) assigned *rho* (ρ) values to these class limits in order to simplify computations, just as Krumbein (1934, 1936, 1938) developed the *phi* scale for grain size.

All assessments of roundness were made by the author, so that values are consistent within this study. Although another operator might assign different absolute values, the relative values would remain. To ensure consistency, 100 sampled boulders were marked and reassessed one month after the initial roundness evaluation. There was so little difference between the two sets of roundness values that a statistical test was not necessary to establish that the readings were consistent.

Sedimentary Variation With Depth

Because of the great size of the individual particles, only the surface sediment of each boulder beach could be investigated. Where boulders were resting on shore platforms and sediment depth generally of only a few boulders, surface measurements appeared to be representative of underlying particles. However, where sediment depth is greater, surface particles may differ from those found deeper in the beach. Perhaps, as has been observed in fluvial studies, larger particles may be preferentially deposited at the surface (Leopold *et al.*, 1964, pp. 209-215), and also, smaller particles could filter through the large interstices of the surface beach boulders and become buried. Bluck (1967) excavated a number of trench sections across three gravel beaches in South Wales,

and found that particles within the beach tended to be smaller and more spherical than those at the surface. Thus, since the sedimentary properties of particles deep within the boulder beaches may be unlike those which were measured, in this study the discussion of boulder-beach sedimentology is confined to the beach surface.

Measurement of Beach Slope

The beach slope was surveyed by using an Abney level and two ranging poles. On each beach, the angles of six of the 30 sampling profiles numbered from headland to embayment (two profiles per longshore beach zone, see figures 2, 3, 4, 5, and 6) were measured, with stations along each profile being located at 5 m intervals (see Young, 1972, pp. 114-147). Both ranging poles were kept vertical (see Abrahams and Melville, 1975) with the aid of a "Survey Chief" attached to each pole. This device is essentially a small spirit level which indicates whether or not the ranging pole is in a vertical position.

When the beach is composed of boulders, the measurement of beach slope presents a special set of problems due mainly to the great variations in micro-relief caused by the size of the boulders. In this study, therefore, to ensure that both poles were placed at relatively similar depths in the boulder beach, a 5 m cord was attached to each pole and held taut (Figure 9). The bottom 50 cm of each pole were divided into measured lengths which were numbered. The height of the cord was equal on the two poles, and was varied within the numbered section according to the size of the boulders. This method, combined with reasonable judgement, helped to eliminate situations of grossly unrepresentative slope measurements (Figure 10).

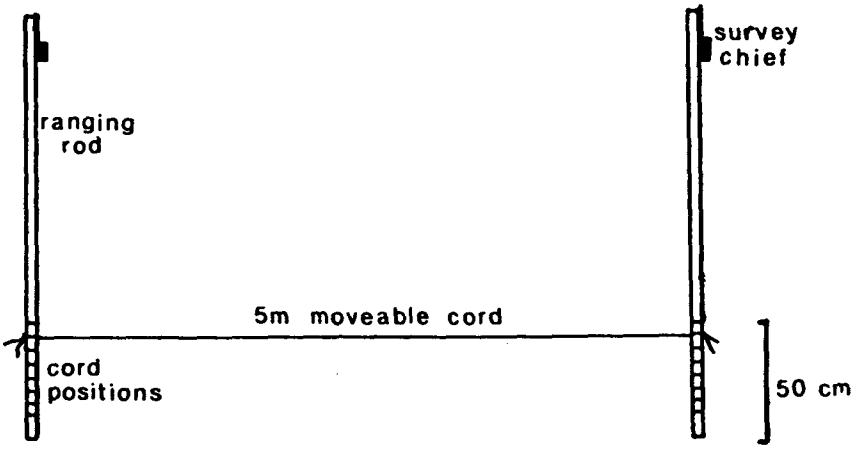


Figure 9. Beach angle measurement apparatus.

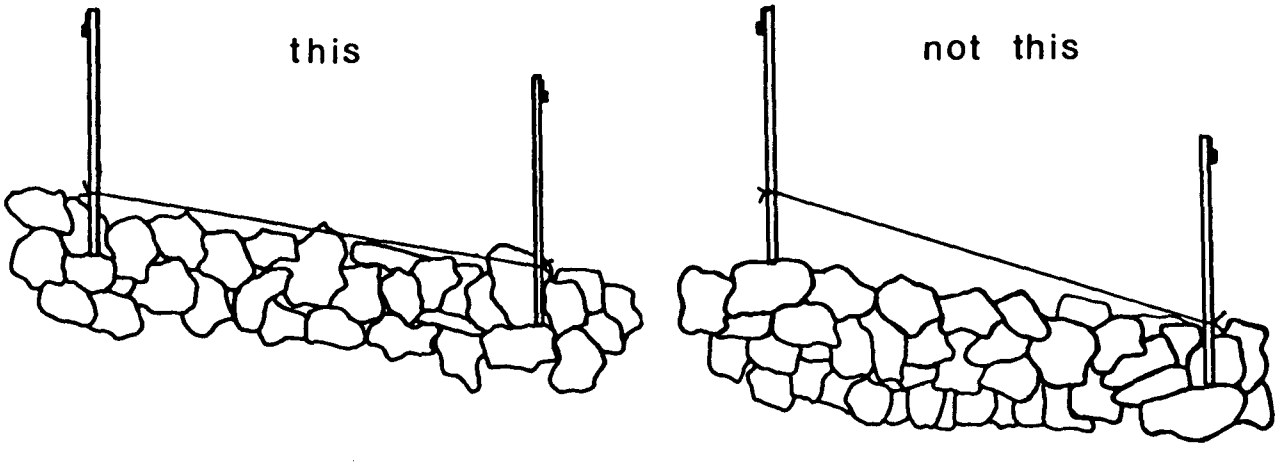


Figure 10. Use of beach angle measurement apparatus.

Monitoring of Boulder Movement

Kiama boulder beach was chosen for the monitoring of boulder movement because of all the studied beaches it is the least accessible and it is not adjacent to a beach suitable for recreation. For these reasons there was little chance of human interference with the marked boulders.

Three hundred boulders at the intersection points of a grid surveyed from a fixed bedrock position were marked and measured on Kiama beach so that any movement could be documented. Profiles were indicated by numerals and the grid points by letters (Figure 11). For example, profile 1 consisted of grid points labelled as 1a, 1b, 1c, . . . 1j, and this identification code was painted on each boulder. The paint was applied in such a fashion that even if a boulder were completely overturned, evidence of labelling would be visible. The A, B, and C axes of each marked boulder were measured and its position on the beach carefully noted. Two colours were used and alternated from profile to profile so that adjacent profiles were marked in different colours. This aided in the identification of transported boulders when abrasion had obscured the original markings. Boulders strewn across the platform adjacent to the studied boulder beach, and occupying the northern edge of a small boulder beach south of the studied beach (Figure 11) were painted with blue paint, a colour not used in the marking of Kiama boulder beach.

Initially, outdoor cement paint was used to mark the boulders, but even during periods of calm seas, the paint in the tidal zone would fade and be worn, often beyond recognition, in approximately 40 days. Late in the study, it was found that marine paint was more durable, but monthly maintenance of the marked grid remained essential.

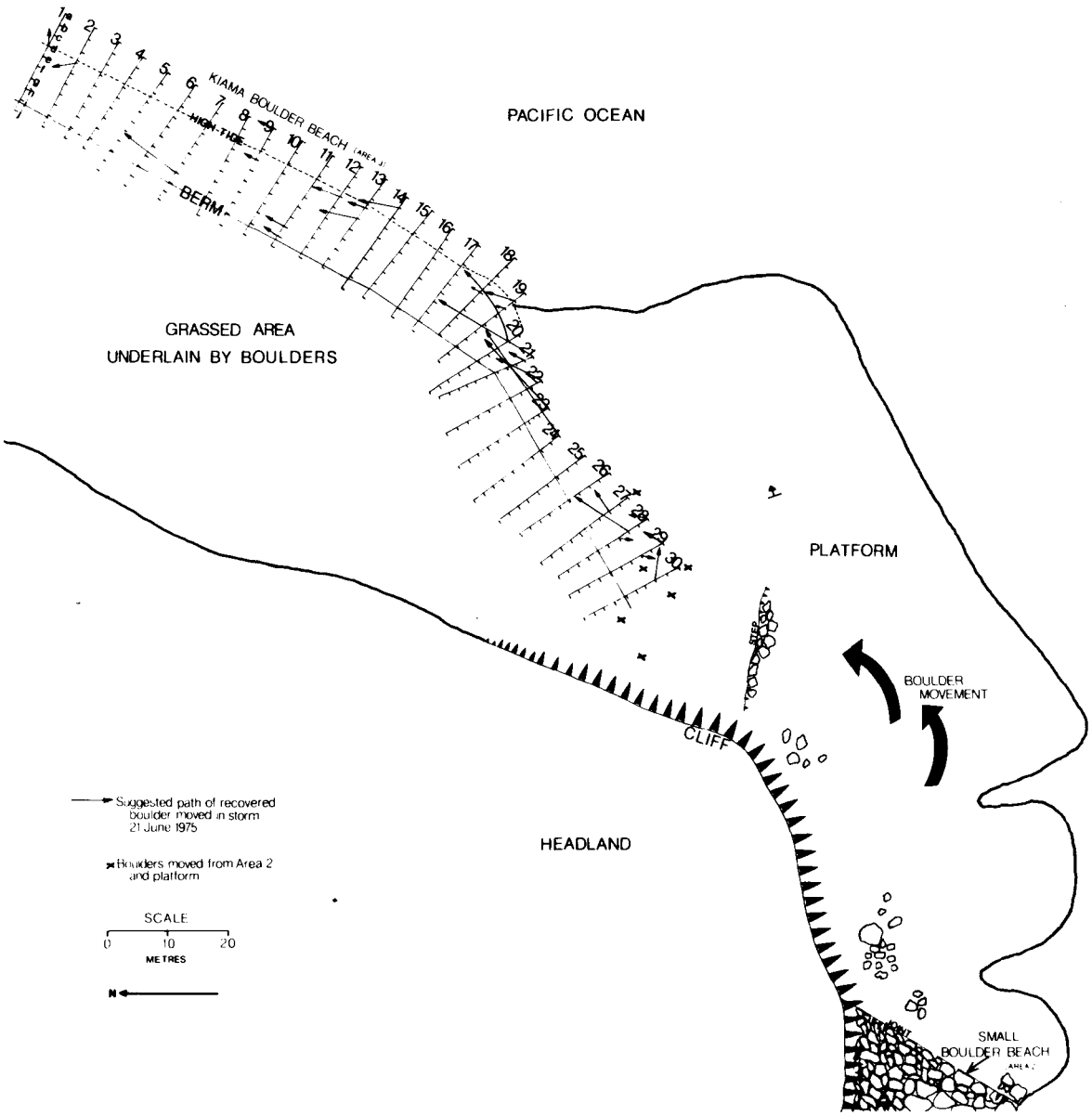


Figure 11. Field surveyed map of Kiama boulder beach showing profiles, sample points, and boulder movement.

Once a month and after every major storm during the two year period, June 1975 - July 1977, the beach was examined for evidence of boulder movement. Since the position of each marked boulder was known, the number of transported boulders could be readily ascertained. If the moved boulder was found, the distance and direction of the movement were measured. When a marked boulder was removed from its grid-point position, the boulder in its place at the grid point was marked and measured, so at all times a complete grid of 300 boulders of known size and position was maintained. Thus, the axial measurements, former positon, distance moved, and, when possible, distance moved and direction of movement were recorded for each boulder that was transported from its original grid-point position during the study.

WAVE-REFRACTION DIAGRAMS

Direct measurement of wave-energy expenditure on the boulder beaches was impossible. In a situation where boulder-sized sediment is being transported, it is likely that recording equipment would be destroyed. Therefore, wave-refraction diagrams (see Appendix I) were prepared to illustrate the *relative* energy expenditure and direction of wave approach on the five studied boulder beaches under different deep-water wave conditions. Royal Australian Navy Hydrographic Charts #808, #809, and #1070 were used to determine the bottom configuration and provide data for the construction of wave-refraction diagrams for the beaches. Additional information at a larger scale was available for Copacabana beach (Short, 1967) and Bombo beach (Stone and Gordon, 1970).

The actual construction of the wave-refraction diagrams was by the

wave-front method (Wiegel, 1964, pp. 150-179). Since the available data do not warrant sophisticated analysis, this method was chosen, and because the wave crests are actually drawn they can be compared with field observations and air photographs, ensuring a realistic portrayal of the wave behaviour. All wave crests were first drawn in deep water with the waves approaching from the north-east, east, and south-east. Where data were available, crests were then extended into shallow water. A more detailed discussion of the wave-refraction diagrams is found in Appendix I.

QUANTITATIVE METHODS

All basic data were placed on computer cards with the data for each boulder recorded on a single card. These data include the X and Y coordinates indicating the exact position of the boulder in the sampling grid of the beach, the lengths of the A. B, and C axes, roundness (ρ class), shape (Zingg class), maximum projection sphericity (ψ_p), beach zone from headland to embayment in which the boulder was located, and beach zone from sea to land in which the boulder was located. The cards were grouped according to beach (see Appendix VI).

Because each boulder was represented by a separate card, information could be added as it was acquired. On Kiama beach (the beach monitored for movement), when a boulder was transported out of the grid to be replaced by another, the appropriate card was removed from the beach group and a new card was inserted, keeping the beach-grid record up-to-date. The moved boulder's card was marked with the date of movement, and then added to the group of cards representing transported boulders.

Following established convention, size-frequency curves were prepared with *phi* units on the abscissa, and the measure of frequency on the ordinate. Graphic methods have been employed in this study for illustrative purposes only, since all descriptive statistics have been found by the method of moments (Croxton, 1953; Chappell, 1967; Friedman, 1967; Davis and Ehrlich, 1970). The actual formulae employed may be found in *Statistical Package for the Social Sciences* (Nie *et al.*, 1975, pp. 183-185).

Descriptive Statistics

Since the mean is sensitive to the entire distribution, it is used in this study as the measure of central tendency for the interval and ratio level data (Pettijohn *et al.*, 1972; Briggs, 1977). Although often employed, the median is not a suitable measure of central tendency for skewed distributions (Folk, 1974). "The best measure of overall average size is the mean as computed by the method of moments" (Folk, 1966, pp. 80-81).

Roundness classes were determined in the field using the Powers method, so although the data are representative of a continuous scale, they are grouped into six categories, and the median is used as the measure of central tendency.

Following convention, the standard deviation is used as the measure of sorting. Sorting is not a statistical term, and "dispersal" better describes the standard deviation measure (Spencer, 1963). Since moment standard deviation has been employed, a sorting classification based on this statistic (Friedman, 1962) was used as a rough guide in assessing the sorting values found in this study (Table 1).

"Skewness is the tendency of a distribution to depart from a symmetrical form" (Croxton, 1953, p. 93). A positive (right) skewness value indicates graphic clustering to the left of the mean with a tail to the right. A negative (left) skewness value indicates graphic clustering to the right of the mean with a tail to the left. When the skewness value is zero, the distribution is symmetrical. In sedimentary studies, skewness is considered to be environment sensitive - that is, diagnostic of depositional environment (Friedman, 1961) - and a high degree of skewness may indicate the presence of more than one population (Folk and Ward, 1957; Spencer, 1963).

TABLE 1

GENETIC SORTING CLASSIFICATION BASED ON ϕ STANDARD DEVIATION*

Sorting Interval	Sorting Destination
0.50-0.80	Moderately well sorted
0.80-1.40	Moderately sorted
1.40-2.00	Poorly sorted
2.00-2.60	Very poorly sorted
>2.60	Extremely poorly sorted

*after Friedman, 1962, p. 750.

Kurtosis compares the spread in the centre of the distribution to the spread in the tails. In this study, when skewness and kurtosis are both zero, the distribution is normal. Kurtosis can measure bimodality in some instances (Darlington, 1970) but not in others (Hildebrand, 1971). Even the capacity of Kurtosis to measure "peakedness" is questionable since "almost any distribution may have a negative kurtosis value" (Chissom, 1970, p. 22).

Kurtosis has been used as an aid in the interpretation of sediment genesis (Folk and Ward, 1957), but only in conjunction with skewness. Friedman (1961, p. 517) also plots skewness against kurtosis, but indicates that kurtosis "provides a second dimension for the plot, but is not diagnostic of depositional environment." In this study, kurtosis was calculated for the distributions of size, roundness, and sphericity, however, this statistic did not appear to provide any additional information about the

distributions. Given the problems in statistically interpreting kurtosis, and the fact that kurtosis did not appear to be useful in distinguishing between different depositional environments either within or between the studied beaches, the results for this statistic will not be discussed.

Trend Surface Analysis

Trend surface mapping is an appropriate method for the presentation of the boulder beach data because the discrete point samples are taken from a continuous surface (see Norcliffe, 1969). The contour maps obtained from trend surface analysis of size, shape, sphericity, and roundness of boulders on each studied beach provide a visual demonstration of the amount and direction of systematic variations. Meaningful and compact illustration of the dominant trends was the primary object of the analyses. However, since trend surfaces can be considered as "response surfaces" (Chorley and Haggett, 1965, p. 47), process can be inferred.

Trend surfaces were calculated and plotted by computer using the "Fortran IV and Map Program for Computation and Plotting of Trend Surfaces for Degrees 1 Through 6" (O'Leary *et al.*, 1966). The significant order was obtained by the application of the F test, and unless the term of order (K + 1) significantly improved the fit, it was dropped, and the fitting rested at order K (Chayes, 1970, p. 1273). In most cases, the significant order was quite low. Where higher orders were found to be significant, the complexity of the surface obscured its descriptive value, so a lower order is presented (see Robinson, 1970). The degree of explanation is statistically significant ($\alpha = 0.05$) for all trend-surface diagrams presented in this study.

The upper limit of the *Chamaesipho columna* (tidal zone) is indicated on each map. Therefore, the trend surface contour maps (diagrams) are directly comparable because they all contain a common reference point. To further enhance their comparability, regardless of actual beach orientation, the maps are presented with the headland zone (high wave-energy zone) to the left, as in Figure 12.

Each trend surface diagram, therefore, is a regularized and comparable representation of each beach, derived from the data collected in a grid pattern. It must be remembered, however, that these diagrams mould an irregularly shaped beach into a rectangle and a false impression of the beach may result (Figure 13).

Non-Parametric Statistics

Since all the sedimentary properties measured in this study (size, shape, sphericity, and roundness) were found to have non-normal distributions, non-parametric statistical tests were employed. A 0.05 level of statistical significance was used for every test. The following non-parametric statistical tests were utilized:-

1) Spearman rank correlation;
2) Kruskal-Wallis one-way analysis of variance;
3) Kolmogorov-Smirnov two-sample test.

These tests and their applications are discussed in Appendix II.

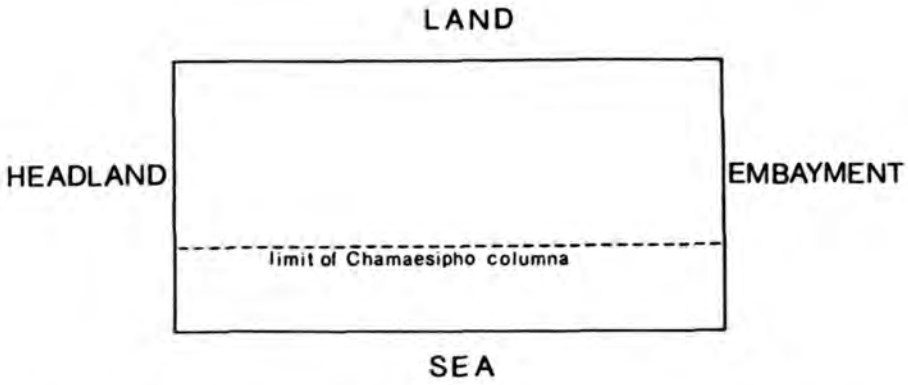


Figure 12. Boulder beach with regularized features.

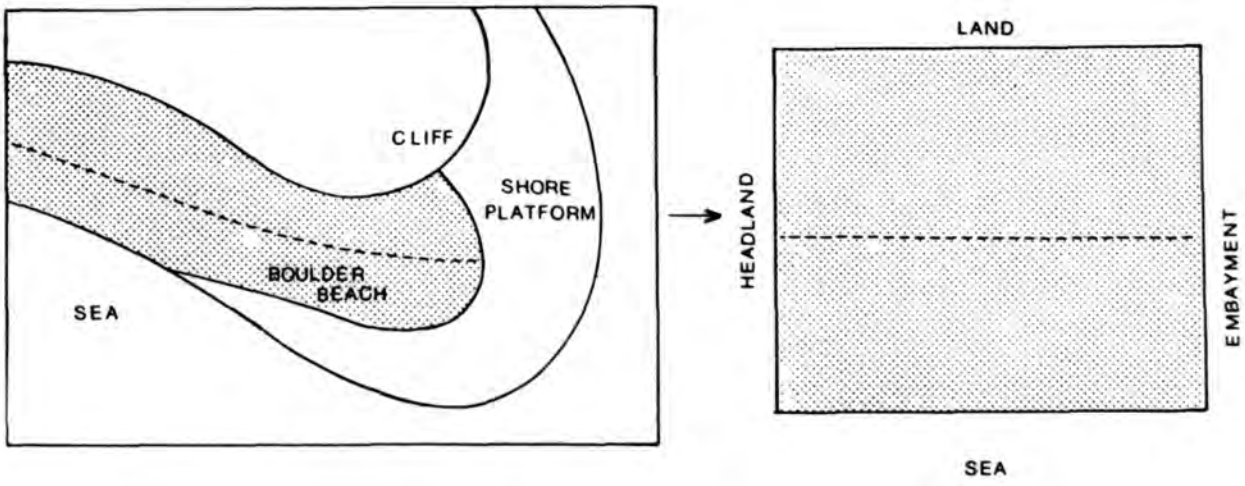


Figure 13. Regularization of Copacabana boulder beach.