paper, and the finest possible emulsion grain in order that magnification may be used. The best photographs for geological use, however, depend upon the nature of the terrane to be studied; in coarse-textured terrane of high relief where the structural anomalies are of large size, one can usually employ shorter focal length photos than in the flat-lands under discussion here. As stated above, the widely used $8\frac{1}{2}$ inch focus lens has produced most of the photographs available today. It is practically at the limit of usefulness for stereoscopic study of strike and dip in the flat lands. A longer focus would be better in those regions. Any undertaking with the great possibilities of aerial photographic exploration and mapping will not be handicapped by lack of proper photographs for long.

In addition to evaluating the significance of the larger features, geologists will probably always be searching for signs of bedding and other features up to the limit of visibility of the photographs. Professional photogrammetrists could no doubt do a much better job of estimating dips and strikes than the photogeologists; but the surveying work, the time and the effort necessary to do it, and the possibility of confusion arising in the recognition of bedding would make the undertaking prohibitively expensive for geological exploration. The photogeologist can work many times as fast. Any new improvements in quality of photographs and in the variety of photographs available in oil-bearing regions will be to the benefit of exploration companies and photographers, as well as to geologists.

PHOTO-INTERPRETATION OF CORAL REEFS

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INTRODUCTION

THERE can be few branches of geology where aerial photographs are more useful than in the study of coral reefs. Because reefs are either partly or wholly submerged, most reefs can only be visited in parts, and many reefs are entirely inaccessible. The first more comprehensive studies of aerial photographs of restricted coral reef groups were made in the East Indies by *Umgrove* (1928, 1929) and in the Great Barrier Reef of Queensland by *Stephenson* et al. (1931); but both used aerial photos as a check on ground observations and not as independent sources of information.

During World War II the coral reefs of the western Pacific area, including those of Indonesia, New Guinea and northern Australia were extensively photographed from the air. An almost inexhaustible source of information on coral reef structures is thus now available. Subsequently there have appeared a number of coral reef studies in which extensive use has been made of aerial photographs (*Nugent*, 1946, 1948; *Tracey, Ladd* and *Hoffmeister* 1948, *Fairbridge* and *Teichert* 1947, 1948; *Teichert*, 1947; *Fairbridge*, 1948, 1950 b) and one which is entirely based on photo-interpretation (*Teichert* and *Fairbridge*, 1948). Some future possibilities in this direction were outlined to the Great Barrier Reef Committee by *Fairbridge* (reported on by *Steers*, 1945).

REQUIREMENTS FOR CORAL REEF PHOTOGRAPHY

The photography of coral reefs poses special problems, mainly because of the fact that some of the features to be photographed and interpreted are situated in the surf zone or below sea-level.

For detailed determination of reef features the scale of verticals should not be less than 1/5,000, while 1/3,000 is preferable in many cases. The photographs should have the normal lateral 60% overlap for stereoscopic examination and they must be taken at low tide.

Very low altitude, large scale obliques are needed to interpret special sections of the reef edge, negro-heads and coral heads, to demonstrate if black shadows on the reef flat are sea-weeds or coral, and so on. High, small scale obliques are useful for general orientation purposes.

If at all possible, photographs should be taken in calm weather. Verticals should be obtained either early or late in the day in order to avoid glare and reflected light, and to obtain shadows from such features as negro-heads and coral heads to aid in determining their height.

If the range of the tide be known, valuable figures for heights of various reef parts, slope gradients, size of negro-heads and so on can be obtained, if verticals taken both at high and at low tide are available.

PHOTO-INTERPRETATION OF CORAL REEF FEATURES

(A) OUTER PART OF REEF

(i) *Lithothamnion rim.* This is the upper seaward part of the reef where dead coral is heavily overgrown with limestone deposited by algae (see section by *Marshall*, 1931). This zone is a foot or more higher than the average level of the reef platform behind it and remains, therefore, emerged for a somewhat longer period, depending on range and rapidity of change of tides. It is mostly

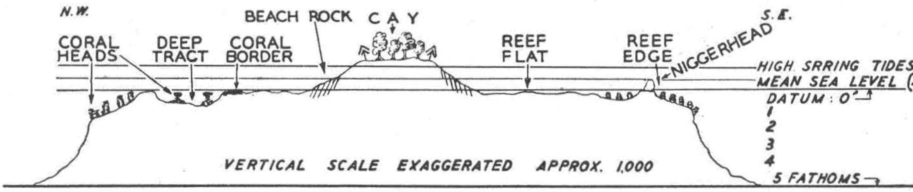

FIG. 1. Diagrammatic cross section through a typical coral reef and island of sand-cay type (Green Island, in the lagoon of the Great Barrier Reef, Queensland), showing relationship of coral features to the tide height.

recognizable by a line of small breakers at the time of about mean sea-level. At high tide it is completely submerged, at low tide it is above sea-level (Figures 2, 4, 5, 9). In exceptional areas there is a series of little terraces rimmed by low walls of *Lithothamnion* (see ground photos: *Stearns*, 1941), which appear in a scalloped pattern from the air.

(ii) The *living coral zone* is the zone of active lateral growth of all reef types and shows up well on photographs taken in reasonably calm weather. This zone extends from about low-tide level down to 25–40 feet, and appears on photos as a dark belt limited on the reef side by the lighter colored (sand covered) reef flat. The outside of the coral zone is somewhat irregular, but is usually distinctly marked off from the coral-free deeper water (Figures 2 and 8).

(iii) *Chutes* are radial surge channels cut through the outer edge of a reef. They dissect the outer edge of the reef platform, the *Lithothamnion* rim and the upper part of the living coral zone, and reach down to as much as 30 feet below low tide (see diagrams or ground photos: *Kuenen*, 1933; *Tracey* et al., 1948; *Ladd*, 1950). On photographs they show up as dark, radial, somewhat irregular, sometimes anastomosing lines of varying length, merging downward in the darkness of the deep water and separated by *Lithothamnion*-covered buttresses (Figure 2).

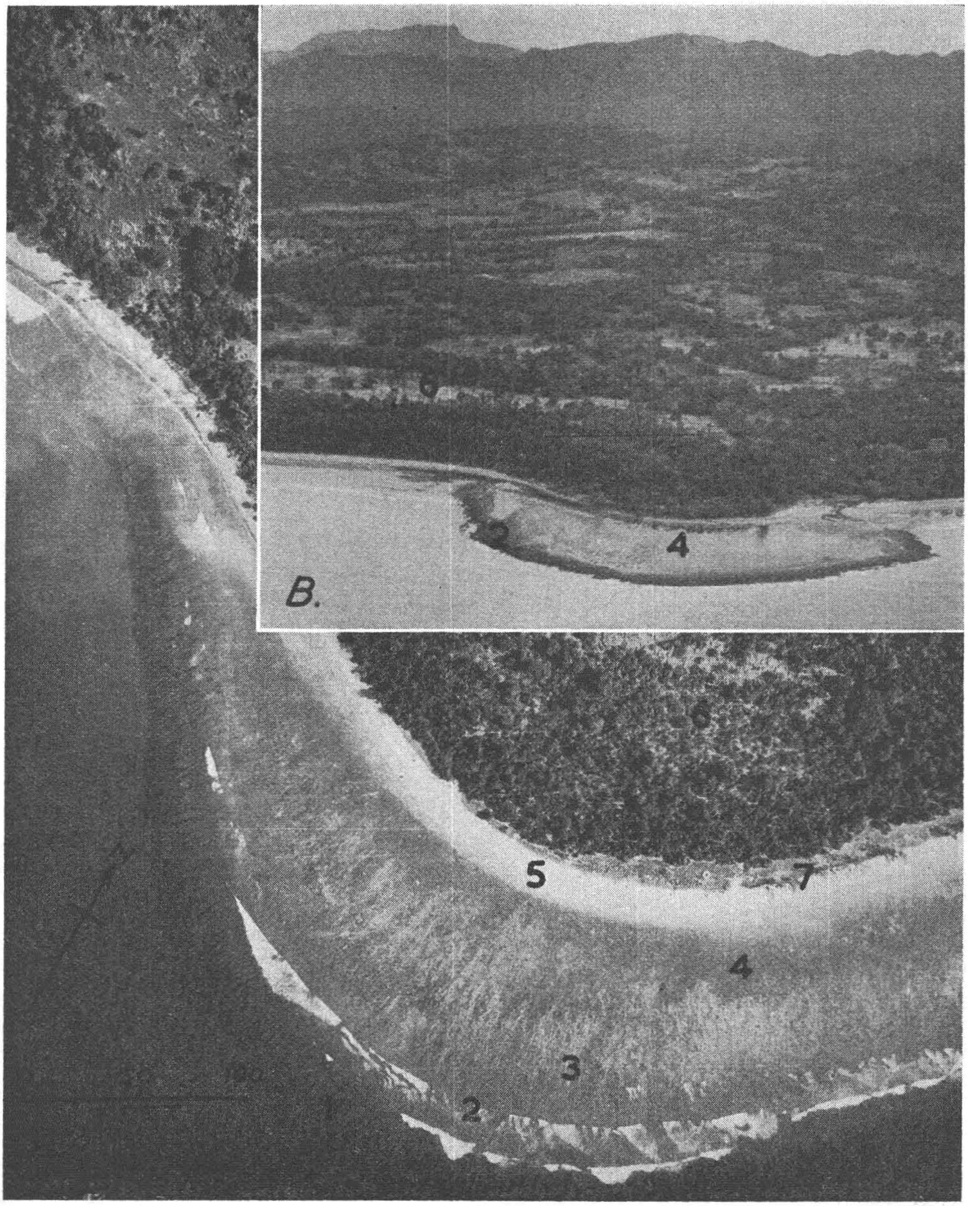

FIG. 2. Simple fringing reef on the south coast of Timor (East Indies). A: vertical, taken at high tide, at Cape Meti Boot, showing chutes (1), waves breaking *over* the *Lithothamnion* rim (2), radial pattern in shingle waves (3), slightly deeper inner part of reef-flat (4, weed covered), and broad sandy beach (5); Savannah to sub-tropical vegetation inland (6), with *Casuarina* fringe along shore (7). B: oblique of similar reef in same area, but taken during low tide, showing waves breaking outside the exposed *Lithothamnion* rim (2) and shallow film of water on reef surface (4).

(iv) *Negro-heads* are coral masses, sometimes many feet in diameter which are thrown up onto the edge of the reef platform by exceptional storms or hurricanes. They are not generally recognizable on small vertical photographs, but may show up on pictures taken from sufficiently low altitude (Figure 3) and still better on low obliques (Figure 9).

(v) *Radial* or *Trickle zone*. This is found forming an outer or peripheral belt of many platform reefs. It appears on photographs as a belt merging with, and sloping gently back some hundreds of feet from the *Lithothamnion* rim, conspicuously characterized by striations perpendicular to the outer margin of the reef (Figure 5). On the ground the trickle zone appears as a maze of low clumps of dead coral or coral boulders with sand between. In aerial view the arrangement is remarkably regular, the sand being drawn out into strands between the coral patches.

(B) INNER MARGIN OF BARRIER AND ATOLL REEFS

(i) *Sanded or mottled zone*. From the Radial Zone the reef surface slopes gradually down or drops in steps towards the interior. Here, the surface is covered with coral sand, algal crusts and coral pools and, with the exception of the latter, details are usually hard to interpret. On verticals it has a mottled appearance, greyish and white shades merging into each other. Its features and margins are usually ill-defined. (Figures 3, 4, 5, 6).

(ii) *Coral pools* are depressions in the surface of the sanded zone, with rims of coral growth and usually a sandy bottom. On photographs they appear as white patches with well defined dark edges (Figures 4, 5).

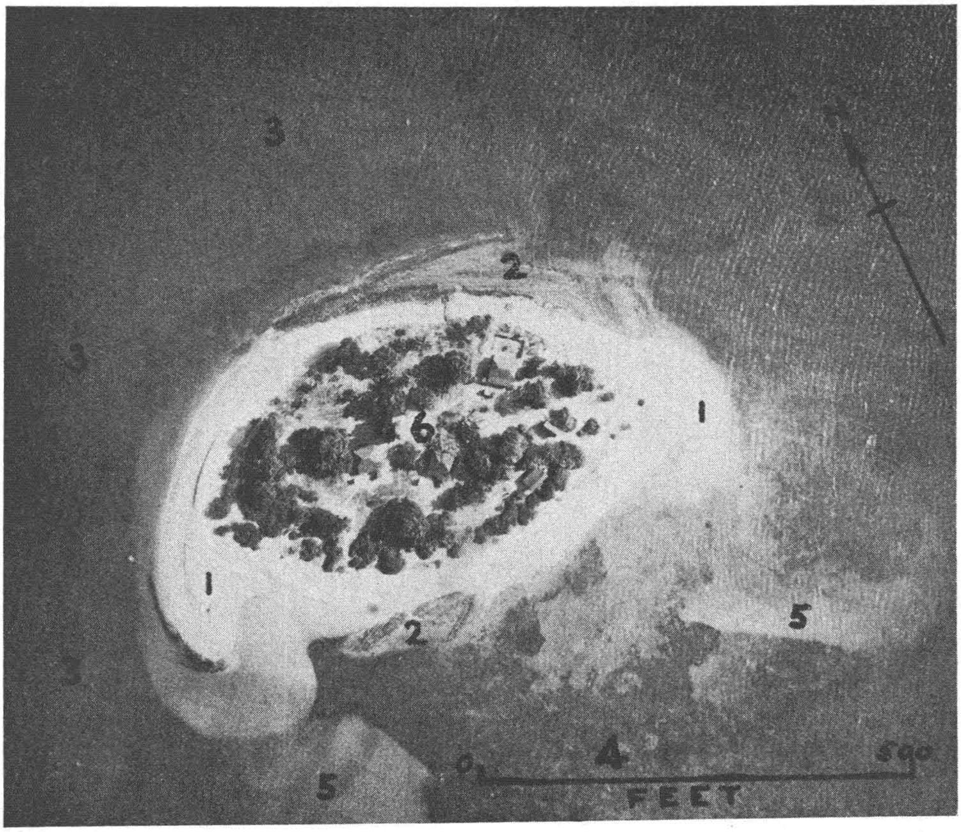

FIG. 3. Sand-cay (Low Isles, Great Barrier Reef), vertical at high tide, showing oval sand accumulation with small sand spits (1) building at each end; pattern of beach-rock (2) indicates former extent of beaches. On seaward side, numerous small negroheads (3) mark reef margin-("Boulder zone") while reef flat is mottled by small seaweed (4) and low sand banks (5). Cay is crowned by semi-tropical trees and lighthouse buildings (6).

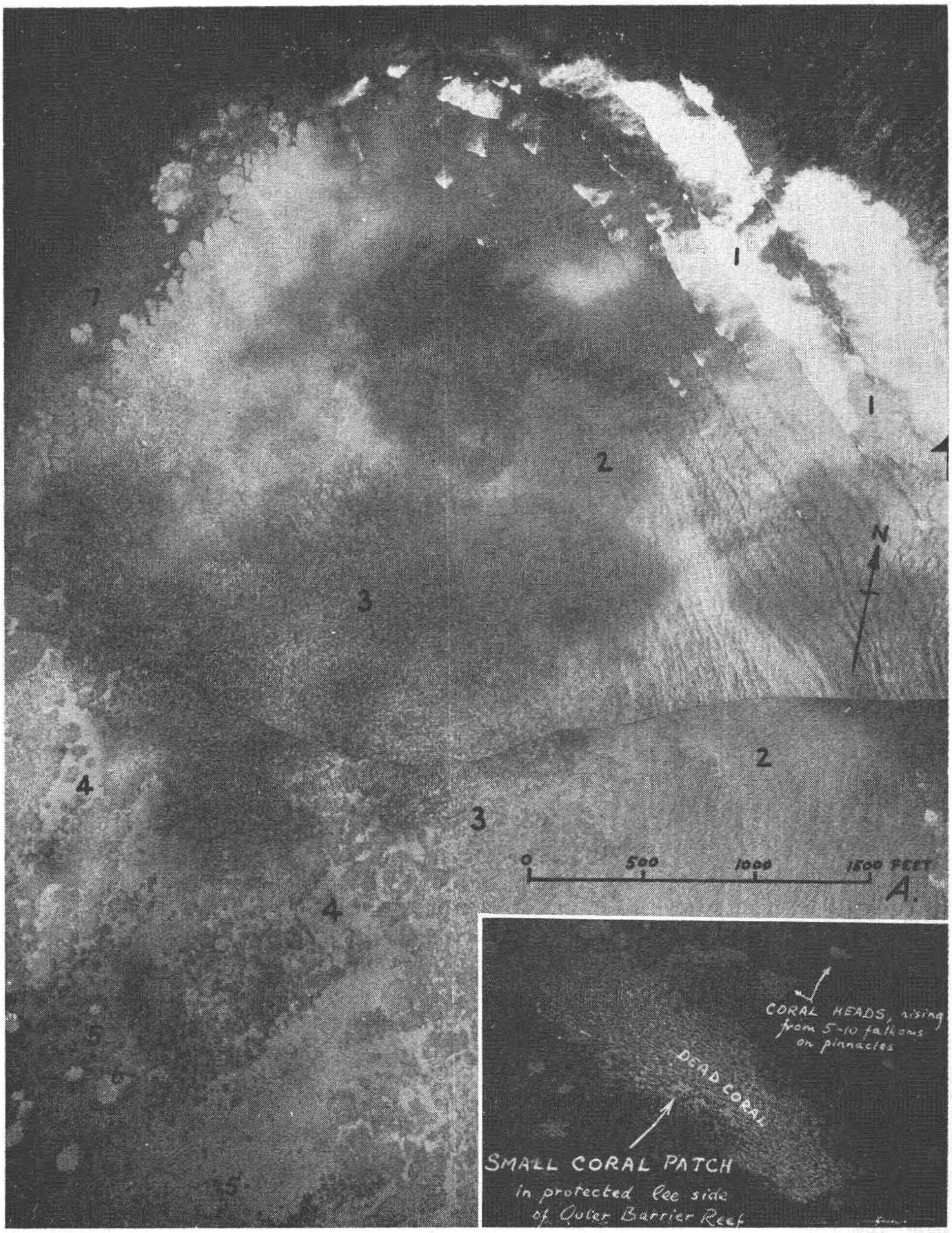

FIG. 4. Outer barrier type in Great Barrier Reef of Queensland (near Ribbon Reef). A: shows vertical of north end (slightly marred by cloud shadows) with heavy surf (top right) breaking over *Lithothamnion* rim (1) during high tide; ripples gradually die out over the radial zone (2), and the mottled zone (3) to the interior shows pattern of sea-weed and growing coral (black) forming fringe to coral pools with pale sand floors (4); from deepening water (to the lower left) rise living coral heads (5), which are white on their "mushroom" tops where they have become exposed and killed (6); at the north end of the reef (top) there is calm water (7), dropping steeply away in one of the cross-channels through the barrier—note the "cauliflower" pattern of the living coral fringe, overhanging the deep water Inset B: shows detail (oblique) of a small coral patch on the inner (lee) side of the reef.

(iii) *Coral heads* are isolated small coral masses growing up from greater depth to the vicinity of low tide level. They appear as light patches of somewhat irregular outline against a dark background (Figure 4), because the bottom on which they grow is not as a rule visible on aerial photographs. Coral heads in shallow-water may appear as grey and black against a white background (sand floor).

(iv) *Dead coral areas* have lost the fresh outline of living clumps and are usually partly enveloped or buried by white sand. They appear, therefore, as mottled patches, although in the tidal zone the sand may be arranged in parallel strips, at right angle to the reef edge (Figure 4).

(v) *Coral patches* are larger masses of coral growing up to the vicinity of tide level. Their surface is made up of irregularly distributed coral heads separated by sandy patches, giving it a somewhat irregularly reticulate appearance. The coral here appears dark (Figure 4).

(vi) *Lagoons and Pseudo-lagoons.* Deep lagoon floors (of 20 fathoms depth or so) appear dark as a rule, but the sea is generally calm and coral heads (even if they do not break the surface) may be seen rising "like cauliflowers" from the dark floor (See *Emery*, 1948). The smaller lagoons of atollons or faros (called "velus"—*Gardner*, 1903) are generally nearly covered with rising coral heads. Lagoon margins generally shallow very gently, as seen by the lightening shades as the sandy floor shows up. Pseudo-lagoons are mostly extra-large pools on platform reefs and often show a rich coral growth all over the floor in 3–4 fathoms.

(c) SPECIAL FEATURES OF ISLAND-REEFS, REEF PLATFORMS AND ATOLL RIMS

(i) *Sand cays.* Careful study of tide marks and search for signs of vegetation will usually reveal whether a particular sand cay is a transient sand bank or a permanent feature and whether it is submerged at high tide (Figure 7) or has an island nucleus (Figure 3). Many cays terminate in sand spits from which the predominating direction of currents and wind at the time of photography may be deduced. Such spits may, however, be transient and changing features (Figure 3).

(ii) *Beach rock* is solidified beach sand and is formed in the intertidal zone. On coral sand beaches it is easily recognized in photographs because of its dark color. As a rule it shows distinct lineation parallel to or slightly oblique to the beach, and often radial jointing as well (Figures 3, 7). Observations on beach rock give evidence as to the tidal range and also about the state of the tide at the time of photography. (For typical pictures of beach rock see also *Teichert* and *Fairbridge*, 1948, p. 234, 239, 240; *Tracey* et al. 1948, pl. 8.)

(iii) *Emerged coral platforms, benches, or "promenades"* show up clearly in verticals and obliques taken at low tide (Figure 6). They appear as dark marginal belts, often with a jagged outer edge, and may display the "basset" edges of formerly steeply bedded coralline debris, now consolidated and truncated by erosion (see *Stephenson* et al., 1931).

(iv) *Ramparts, breastworks,* and *shingle waves.* These represent coral debris thrown up by the waves and accumulating on the reef platform. Ramparts are ridges, a few feet high, of asymmetrical cross section, with a gently sloping outer and a steep inner flank. The latter shows up well on verticals (Figure 6) and a fresh rampart looks rather like an arrested wave. Occasionally fresh ramparts may be thrown up to a greater height forming steep-sided ridges known as breastworks (Figure 6). Older ramparts further inward on the reef platform may be marked by a rim of vegetation, such as mangrove. Thinner sheets of

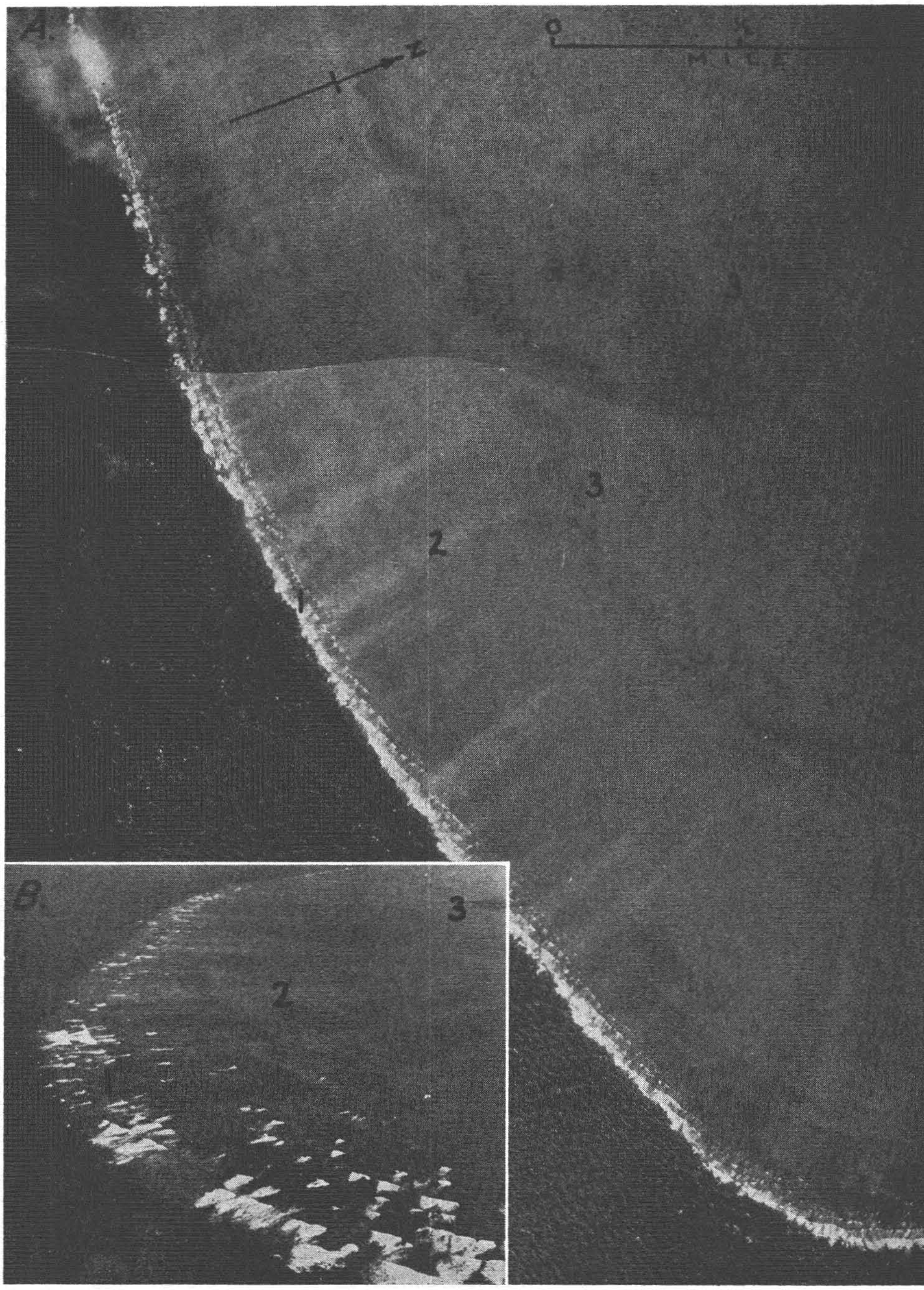

FIG. 5. Large platform reef, characteristic of the inner lagoon of the Great Barrier Reef. A: vertical of Batt Reef, at mid-tide, showing waves breaking on edge of *Lithothamnion* rim (1). Radial or trickle zone is marked by both radial and concentric pattern of successive shingle waves (2). Rather sharp margin to the interior with mottled or sanded zone (3), probably represents limit of infilling of old lagoon. Black spots and patterns here indicate pools lined by living coral and floored with sand (4). B: oblique of same reef, showing similar features, but at high tide.

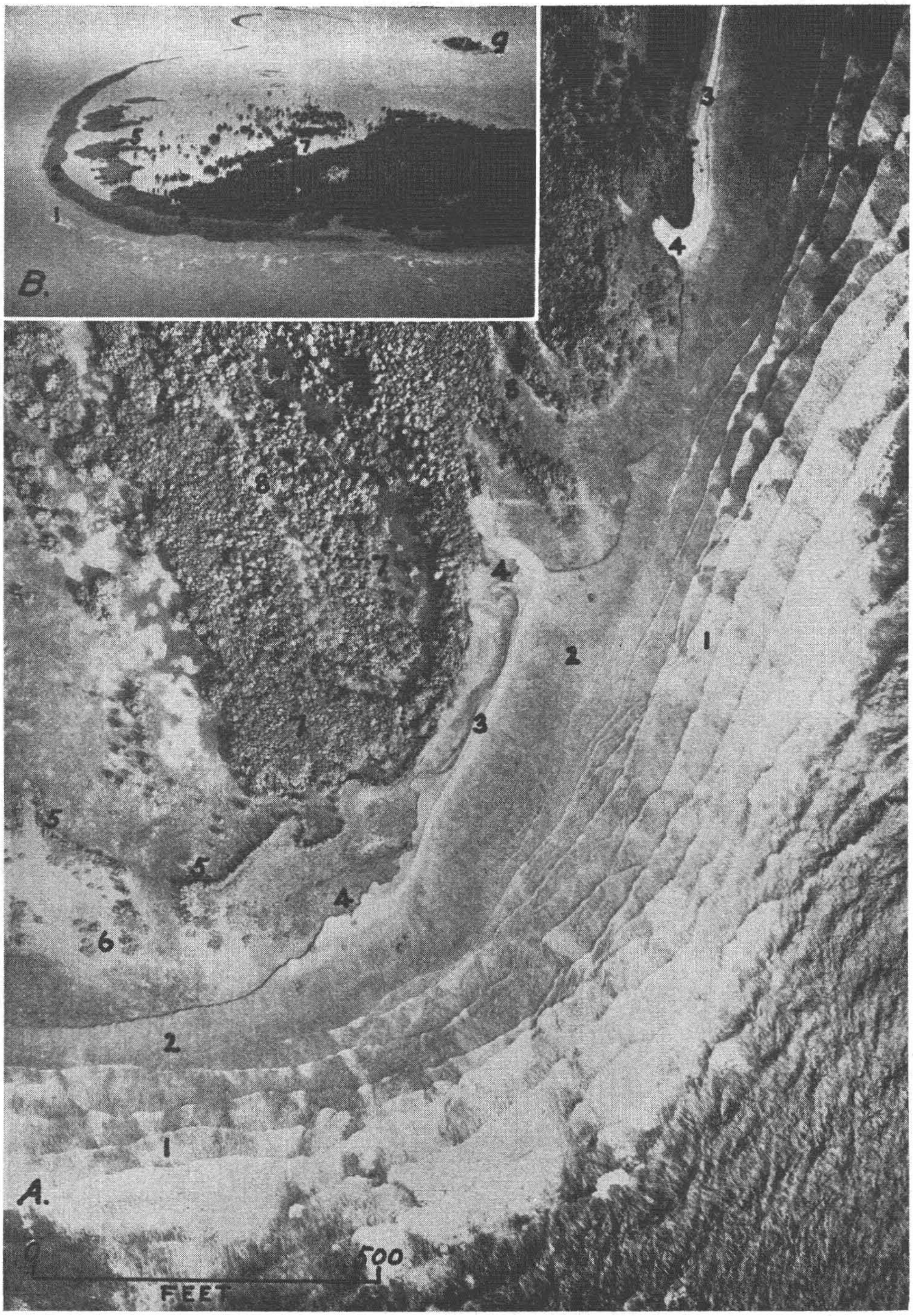

FIG. 6. Low-wooded island-reef (in the Great Barrier Reef Lagoon). A: vertical of Low Isles, taken at mid-tide showing breakers over reef margin (1) and washing against a fairly youthful shingle rampart (2), radially patterned, with steep inner edge), which in two places is crowned by a very new shingle breastwork (3, white), less than 10 years old, and exhibits incuring horns at each end (4); older shingle rampart inside is rimmed by growth of young *Rhizophora* mangrove trees (5); isolated mottling on outer side of older rampart is due to the low *Avicennia* mangrove bushes (6); fully grown *Rhizophora* form a swamp (7) on the reef flat within (dark patches indicate deeper pools where mangrove have died and rotted away); lineation in mangrove swamp is due to old ridges of coral shingle (8). Inset B: oblique of Low Isles taken at mid-tide, showing emerged ramparts (2), to the interior of which are older ramparts (5), mangrove (6) and sand-cay (9). For vertical view of (9) see Fig. 3.

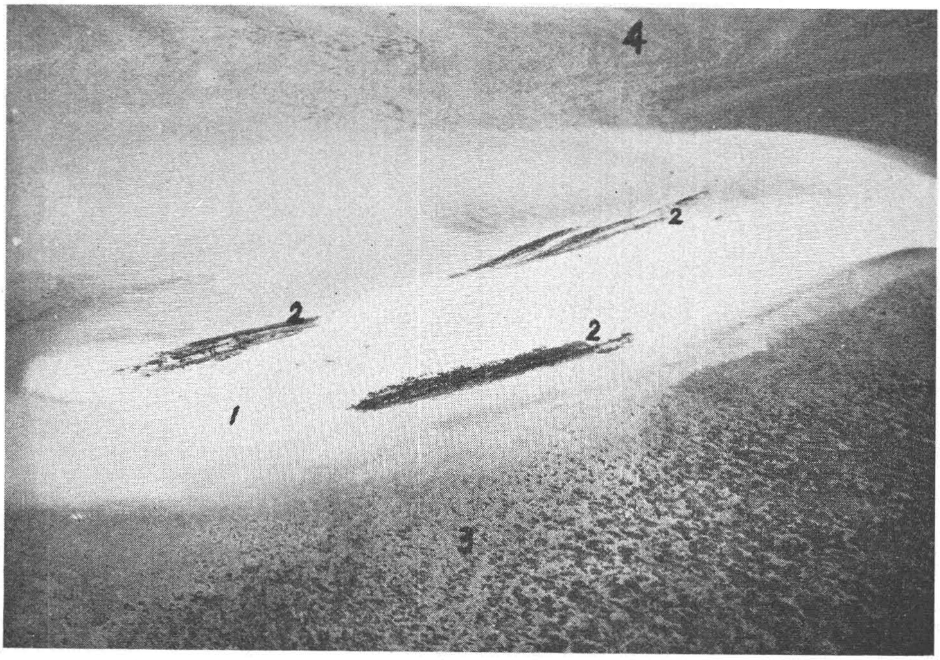

FIG. 7. Sand cay (2) which is probably submerged at high tide. *Lithothamnion* rim (1). Radial jointing beach rock (3). Beach rock showing parallel or oblique lineation (4).

FIG. 8. Atollon or Faro (i.e. secondary atoll) on the margin of a compound atoll; Taroepa Besar, on the margin of the Tijger Atoll, East Indies. Oblique, showing living coral margin and shingle waves (2) near outer part of reef, overlain on the inner part by successive banks of sand (3) in broad, low ripples, culminating in long sandy spit-like cay (4). Fairly shallow sandy floored atoll on lagoon (5, called "levu" in the Laccadives—*Gardner*, 1903) marked by dark spots on growing coral heads (6). Note canoe-like pattern of small reefs in distance (7), oriented in line with the currents entering and leaving the central lagoon on the compound atoll.

coral shingle with no well marked inner (reefward) boundary are known as shingle invasions or shingle waves and may be recognized as dark grey belts with somewhat irregular jagged inner edges (Figure 8). Sometimes they form shingle spits or "hammer heads" (Figure 9). In places a number of successive shingle invasions may be distinguished (*Teichert* and *Fairbridge*, 1948, p. 235). All these features are entirely submerged during the highest tides and some are below mean sea-level.

(v) *Beach ridges* of coral shingle are mostly above high tide level and are not regularly submerged. They are not a common feature of coral islands. Where

FIG. 9. Simple, island-less atoll. Seringapatam Reef on the Sahul Shelf, Northern Australia. Oblique at mid-tide showing negro-heads (1) scattered along *Lithothamnion* rim, and two large "hammerhead" shingle spits (2). Lagoon in distance (3).

they are present, they are usually easily distinguished from ramparts by their more even configuration. They are more symmetrical and straight or gently curved, following the general trend of the shore, not its minor irregularities (*Teichert* 1947, pl. 7, *Fairbridge*, 1948).

(vi) *Moats* are depressions of the reef flats slightly below tide level, on the inner side of ramparts and breast-works (see ground pictures in *Stephenson et al.* 1931; *Fairbridge* and *Teichert*, 1947). They usually have a scattered growth of coral which may show up as dark patches in photographs (Figure 6).

(vii) *Seaweeds* cover parts of many reef flats. Such areas appear rather uniformly colored dark grey, with somewhat diffuse and irregular boundaries (Figures 2, 3, 4). They may be difficult to distinguish from thin coral shingle sheets, except that the latter have the tendency to be arranged in a radial pattern, while the weed tends to fan out in V-shape from the outer margin.

(D) RAISED CORAL REEFS

Raised fringing reefs are easy to recognize because they are structures that are superimposed on the topography of the island to which they belong. They often show pot-holes and other karst features (see *Fairbridge*, 1950a, Figure 4, *Nugent*, 1948). As a rule there is also a noticeable difference in drainage, vegetation, habitation and agricultural patterns between the coral rock and island core (Figure 10). Even in tropical areas the raised reefs are often rather dry, owing to Karst drainage. *Kuenen's* (1933) block diagram of Kisar Island (Figure 11), made without the help of aerial photographs, serves to illustrate in a diagrammatic way the features shown in oblique and vertical views on Figure 10.

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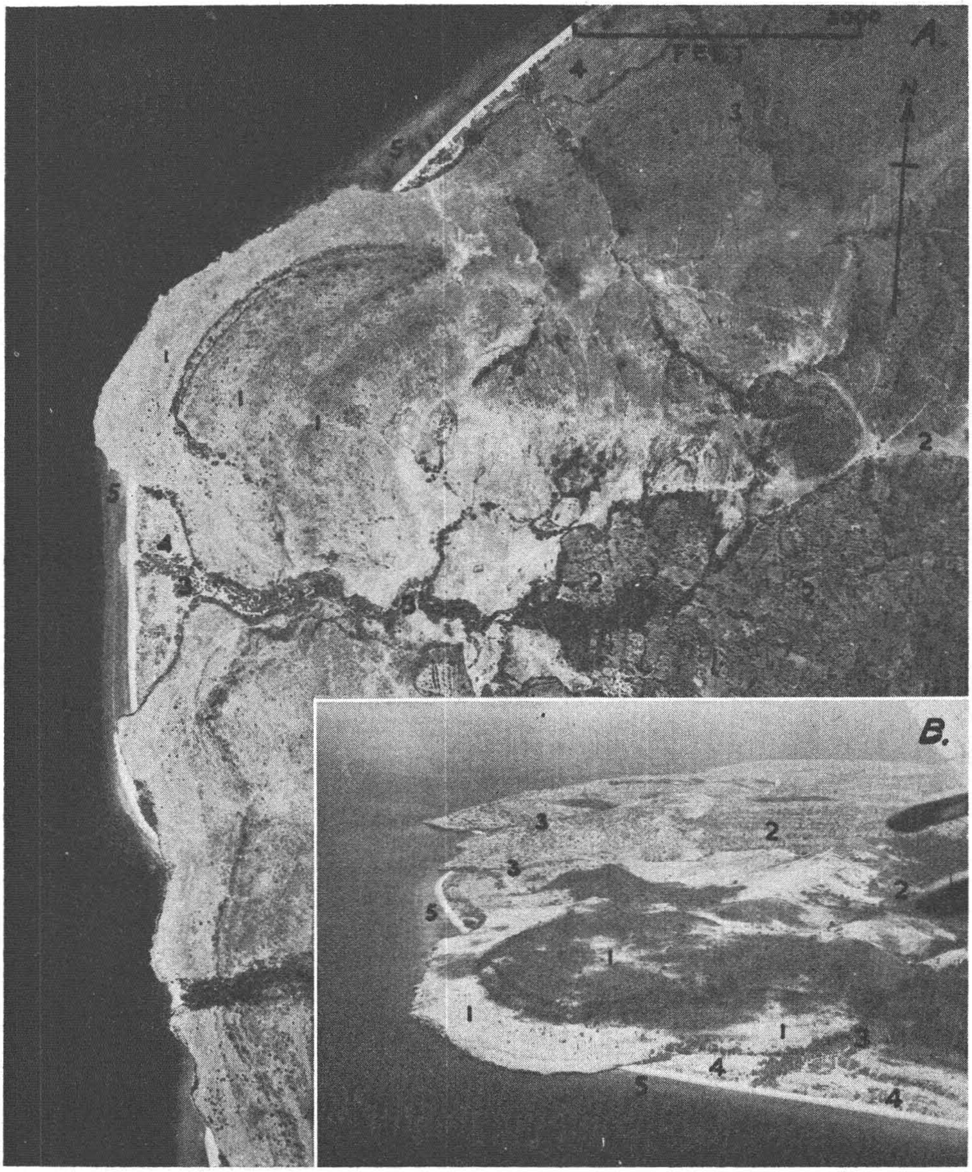

FIG. 10. Elevated coral terraces (probably of Pleistocene age) fringing an old volcanic island. Kisar Island, East Indies. A: vertical photo showing rather barren coral limestone terraces (1) resting unconformably on the eroded and folded core of pyroclastic rocks (2). Superimposed streams (3) cut through the resistant limestone "rim" of the island and have eroded much of the core below the level of the rim. The mouths of these streams were drowned probably during the Flandrian (early Recent) transgression, and filled with sediment (4), which is now exposed owing to the mid-Recent eustatic drop in sea-level of 10 feet. A contemporary reef (5) forms a modern outer fringe. Inset B: Same locality, oblique, showing terraced nature of raised coral limestone "rim" and low country inland, drained by the superimposed rivers (dark shadows over hills are due to clouds).

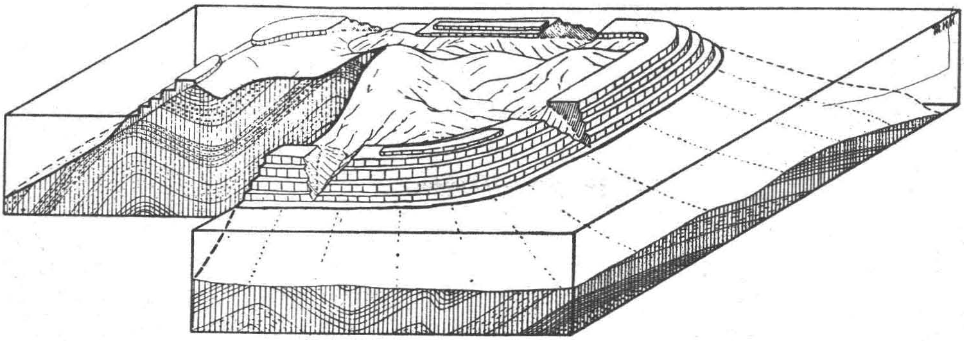

FIG. 11. Block diagram (by *Kuenen*, 1933) showing the nature of the old dissected core of Kisar Island (see air photos, fig. 9), its "rim" of coral limestone terraces, and its superimposed drainage.

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