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ZOOLOGICAL EXPEDITIONS TO THE KRAKATAU ISLANDS, 1984 AND 1985: GENERAL INTRODUCTION

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[Plates 1–14]

CONTENTS

This paper is a general introduction to a series of papers reporting the results of the 1984 and 1985 Zoological Expeditions to the Krakataus.

The geological history, history of human habitation, climate, morphology and vegetation of the archipelago are outlined. Previous zoological expeditions are noted, and the coverage and methods used in the 1984 and 1985 expeditions are provided.

The biogeographical significance of the archipelago for studies of ecosystem succession, colonization and island biogeography is briefly discussed.

1. INTRODUCTION

This work serves as an introductory background to a series of papers reporting and discussing the results of zoological expeditions to the Krakatau (Krakatoa) Islands in the Sunda Strait, about 44 km from Java and Sumatra (figure 1 and figure 30, plate 14), in September 1984 and August 1985. The expeditions were conceived and organized by the senior author from the Department of Zoology at La Trobe University, with the cooperation of Dr S. Adisoemarto, Bogor Zoological Museum, Lembaga Biologi Nasional – Lembaga Ilmu Pengetahuan Indonesia (L.B.N.–L.I.P.I.), Indonesia, and Professor D. Sastrapradja, the Deputy Director of L.I.P.I.

Biological interest in the Krakataus concerns two nested long-term natural experiments.

The first of these was initiated by the famous cataclysmic eruption of 1883, which is believed to have eliminated the biota of Rakata, the remnant of Krakatau, and of the adjacent islands Sertung and Panjang (figure 2). Botanical and zoological surveys have been made at intervals since 1883 in an attempt to monitor the reassembly of a tropical monsoon forest community on these islands from a zero base-line, a process that has been described by Richards (1952) as the most spectacular recorded example of a primary xerosere.

Brattstrom (1963) studied primary succession on a part of the oceanic San Benedicto island, west of Mexico, which had been devastated by volcanic activity. Investigations have also been made of the bird fauna on islands off New Guinea from which the entire biota is believed to have been extirpated by volcanic eruptions in 1888 (Ritter Island) and about two centuries ago (Long Island) (Diamond 1981), and on islands near them that were defaunated by a tsunami generated by the explosion of Ritter Island (Diamond 1974).

There have been several studies of the recolonization of tropical forest ecosystems through secondary succession after severe disturbance such as volcanic activity, fire and clear-felling, and because the rate of destruction of tropical forests is of increasing concern such studies may conceivably have practical value in possible future reinstatement programmes. The Krakataus, however, represent the only opportunity ever provided by tropical marine islands from which the entire biota has been eradicated to monitor the natural reassemblage of this ecosystem from the beginning.

Because the sterilized areas were separated by some 44 km of sea from the major sources of recolonization (Java and Sumatra), there was also the opportunity to study the dispersal abilities of various segments of the source land biota as well as the order in which they successfully colonized. Although the marine barrier is not great, it has undoubtedly affected both the nature of the reassembled biota and the timing of successful colonizations by its constituents.

The recolonization of the islands has also become a classical case study in island

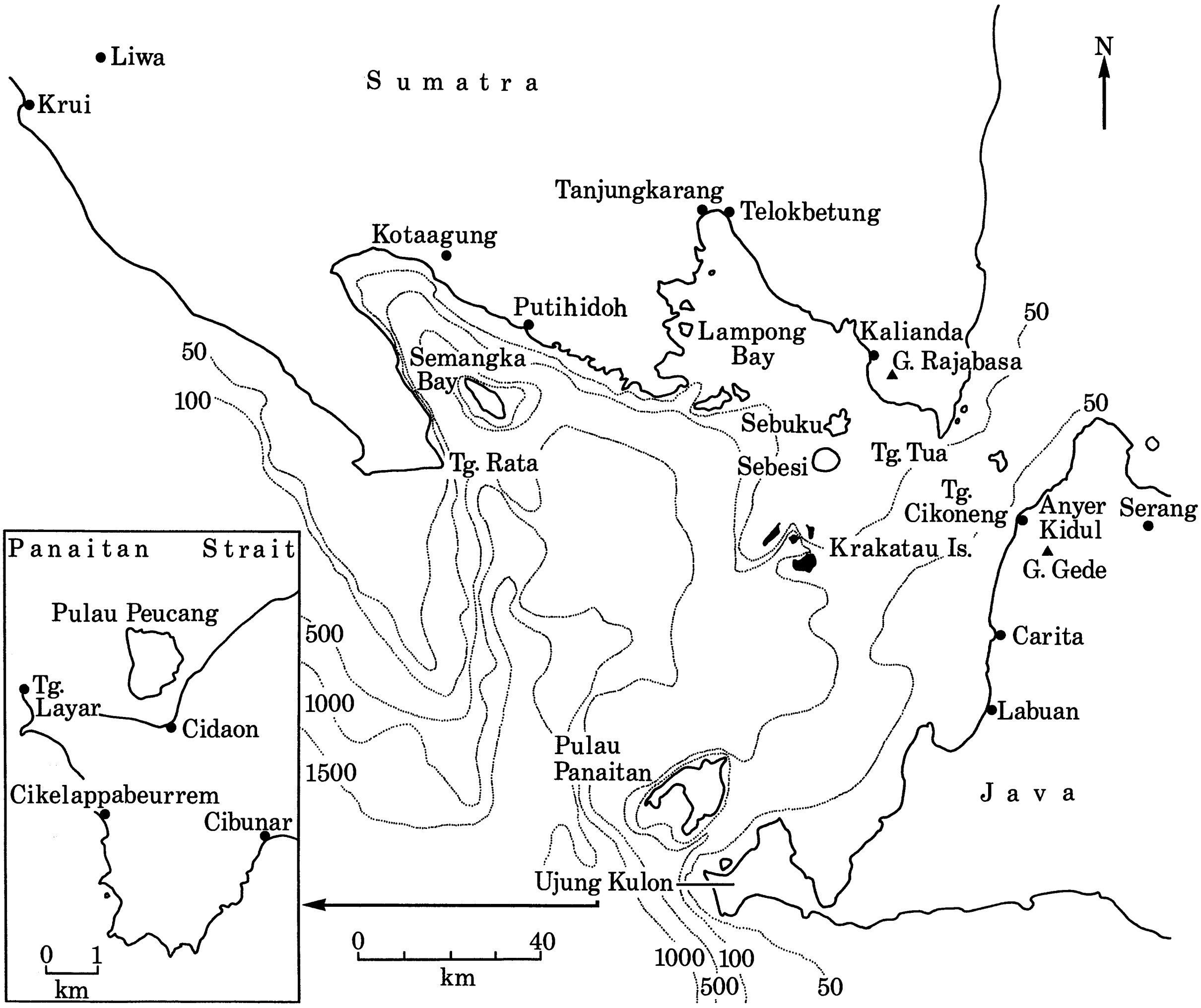

FIGURE 1. Sunda Strait showing the Krakataus and places mentioned in the text. Bathymetry in metres.

biogeography. Before the much smaller-scale experimental studies of Simberloff & Wilson (1970) on artificially defaunated mangrove islets off Florida had been made, the Krakatau case was used by MacArthur & Wilson (1963, 1967) as a test of their stochastic model of immigration and extinction processes and the achievement of a dynamic equilibrium on islands. Their belief that the bird fauna had reached equilibrium after 25–36 years (1908–1919), at a time when land plant species numbers were still rising, has been quoted in several biogeography texts.

The emergence in 1930 of a fourth island of the group (Anak Krakatau: 'Krakatau's Child') (figure 2) was the beginning of the second long-term natural experiment. Anak Krakatau's colonization by animals and plants, although from quite close sources (the other islands were from 3 to 5 km distant), to some extent provided a 'replay' of the processes that had taken place on the older islands some 50 years earlier. There was thus an opportunity to check on earlier conclusions and to improve on and correct shortcomings of the frequency of surveys and monitoring techniques of earlier biologists.

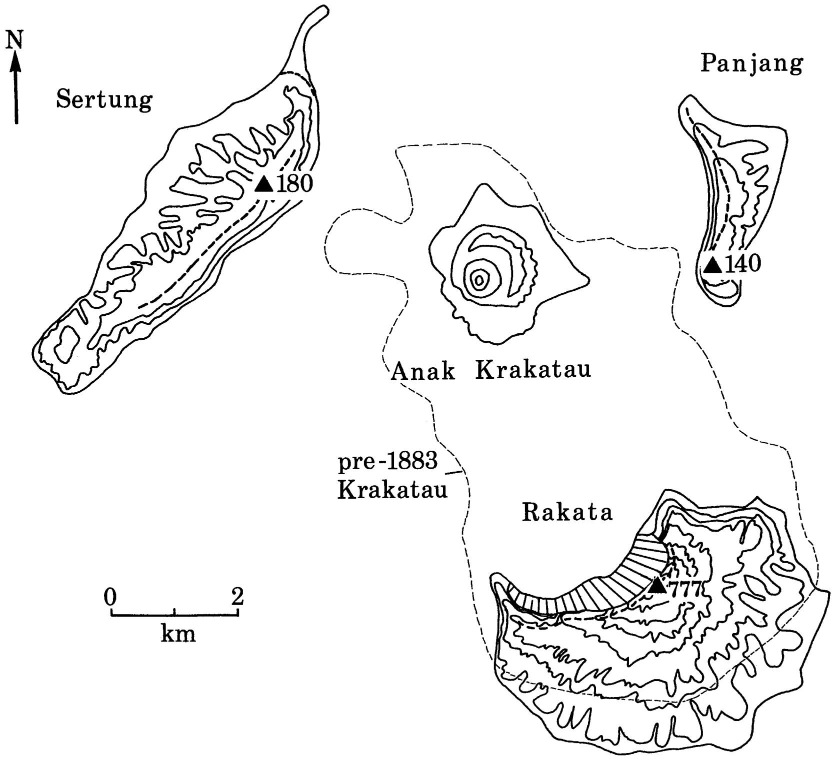

FIGURE 2. The Krakatau archipelago in 1985 with outline of pre-1883 Krakatau Is. (dashed). The lowest contour is 50 m, the next 100 m and subsequent contours are at 100 m intervals. Contours and heights are approximate and show the general forms of the islands rather than accurate topographic details.

Virgin volcanic islands in Long's crater lake, some 3 km from their nearest source biota, have also been investigated (Bassot & Ball 1972; Diamond 1977; Ball & Glucksman 1981), but Surtsey, 35 km from Iceland and 20 km from the nearest large island of the Westman Group in the cold temperate North Atlantic, is the only virgin marine island to have been regularly monitored since its inception, in 1963 (Lindroth *et al.* 1973; Magnusson & Fridricksson 1974; Kristinsson 1974; Fridricksson 1975; Olafsson 1978; Fridricksson 1982; Henriksson & Henriksson 1982; Olafsson 1982). Although to a large extent ignored by biologists for the first 50 years because its frequent eruptions have set back the succession (see §3*f*), Anak Krakatau is of interest in providing a comparison between early colonization processes in the tropics, from rich source areas, with those observed on Surtsey in the cold temperate region and with a relatively depauperate source (Thornton 1984).

The archipelago is geomorphologically dynamic (Bird & Rosengren 1984; Rosengren 1985), and the effects of physical changes on the biota, and on the rate of successional turnover, are also of considerable interest (Bush 1986*b*). Finally, as Bush (1986*a*) has noted, the archipelago's discrete, definable, tropical biota provides a rare opportunity for ecological studies, particularly of plant–animal interactions.

2. History of the archipelago

(a) Geological antecedents

Sunda Strait and the Krakataus lie on a convergent plate margin between the Indoaustralian and Eurasian plates, about 120 km above the Benioff zone. The chemical composition of the magma of Krakatau has been shown to differ from that of typical island arc volcanoes and Nishimura *et al.* (1985) conclude that a northeast–southwest chain of volcanoes in Sunda Strait, including Rajabasa, Sebesi, Krakatau and Panaitan (figure 1), represents a peculiar type of volcanism. The strait bestrides a discontinuity in the Sunda arc, and may represent a boundary between two segments of subducting lithosphere. The underthrust of the Indoaustralian plate abruptly changes in this region from frontal and relatively slow, deeply dipping subduction (Java trench) to oblique and relatively fast, shallow dipping subduction (Sumatra trench). Moreover, the distribution of shallow earthquake epicentres and the different fault patterns and contrasting directions of lateral movements on either side of the strait have led geologists to conclude that it represents a major tectonic break, with extension in the south and convergence in the north. The geological setting has been described as a wrench–fault system and ascribed to a clockwise rotation of Sumatra, round an axis located in Sunda Strait, at the rate of 5–10° Ma^{-1} for the past 2 Ma (Ninkovich 1976, 1979; Nishimura *et al.* 1985).

De Neve (1985*a*), reviewing historical evidence relating to the eruption of volcanoes in the Sunda Strait region, regards Chinese records dating from the 3rd century A.D. as being the first recorded account of activity from Krakatau. He supports the contention of Judd (1889) that the *Pustaka Raja* (Javanese *Book of Kings*) offers evidence of a major eruption in 416 A.D., when a mountain, Kapi, located near the present site of the archipelago, 'with a tremendous roar burst into pieces and sunk into the deepest of the earth'. The narrative continues 'the water of the sea rose and inundated the land' resulting in great loss of life and property. This can be interpreted as referring to one or more tsunamis of similar if not greater magnitude than those of 1883 (see §2*c*). As Judd pointed out, it also records a major volcanic eruption; moreover, the reference to sinking 'into the deepest of the earth' may also signify a caldera-forming event that may have contributed to the tsunami.

Rakata, Sertung and Panjang are believed to represent remnants, what Judd (1884) describes as the 'basal-wreck', of a stratovolcano, 'Ancient Krakatau', some 11 km in diameter and 2 km high (figure 3*a*). This is thought to have exploded and collapsed (Verbeek 1884, 1885), perhaps in prehistoric times but possibly more recently as recorded in the Javanese chronicles above, leaving three major fragments and a small islet, Polish Hat, around the rim of its submerged, 7 km diameter central caldera (figure 3*b*). Volcanic activity was renewed and there are records of seven eruptive episodes between the 9th and 16th centuries inclusive, when Krakatau was considered as the 'fire mountain' of the Cailendra dynasty of Java (de Neve 1985*a*). During this period or earlier the basaltic cone of Rakata was built to a height of at least 800 m, and two smaller andesitic islands, Danan (450 m) and Perbuatan (120 m), developed in the caldera in line with and to the north of Rakata (figure 3*c*). Continued volcanism led to the coalescence of these three islands to form the single large island of Krakatau, about 9 km long and 5 km wide (figure 3*d*, dashed line in figure 2).

The *Pustaka Raja* states that the inundation of the fifth century extended from Mount Gede (in west Java) to Mount Rajabasa (in Sumatra) (figure 1) and continues 'After the water

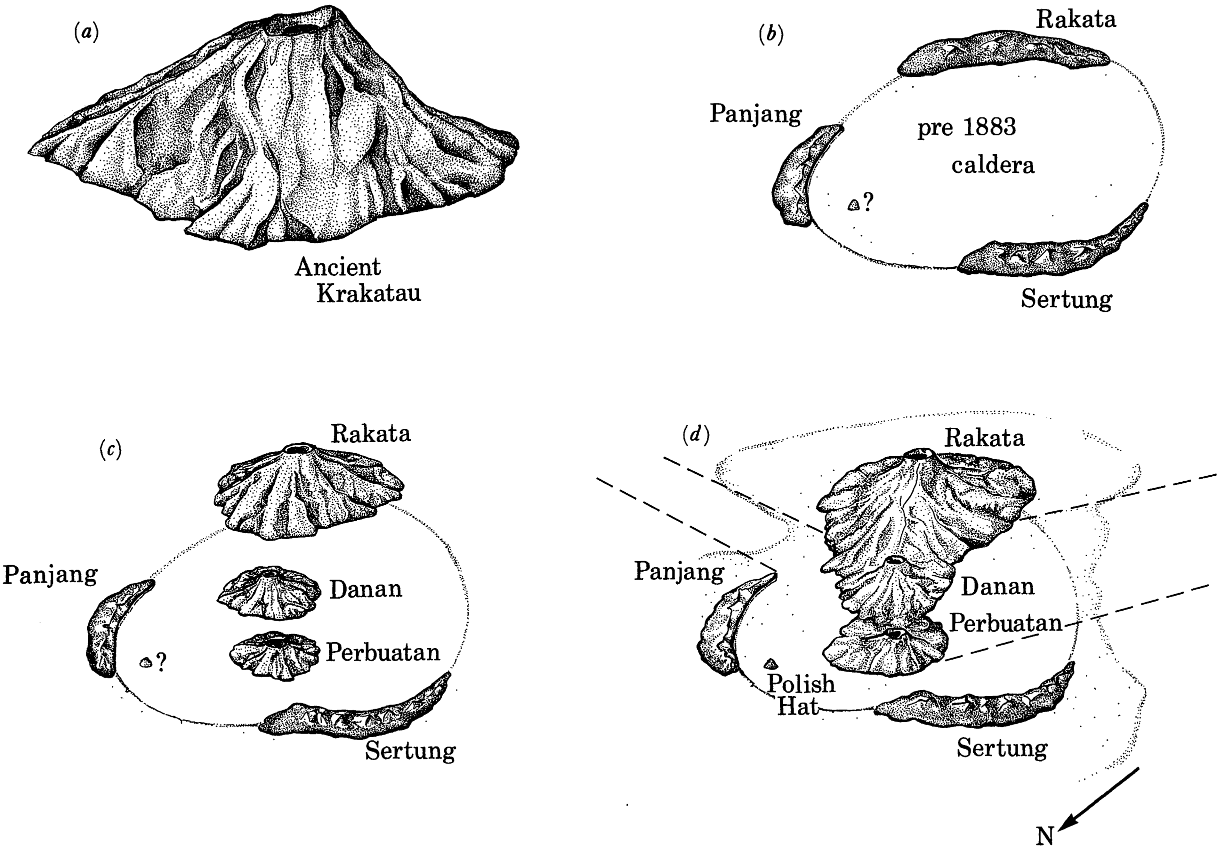

FIGURE 3. Summary of geological events (*a–d*) leading to the formation of Krakatau Is. (see text). Not to scale; view from northwest. Partly after Francis & Self (1983).

subsided the mountain Kapi and the surrounding land became sea and the island of Java (the Sanskrit Jawadwipa, which comprises central and south Sumatra and Java) divided into two parts... This is the origin of the separation of Sumatra and Java'. As Judd (1889) points out, this can be interpreted as describing the origin of Sunda Strait as a result of events associated with volcanicity at a site close to the present site of the Krakataus, and de Neve (1985*a*) notes that there is no record of a navigable passage connecting the Java Sea and Indian Ocean until a report by the Arabian navigator Yakut in 1175. We have not seen comments from other geologists on the probable accuracy of this speculative account of the strait's origin and we make no further comment ourselves.

(*b*) *Pre*-1883 *Krakatau*

Very little is known about the biota of Krakatau before the 1883 eruption, apart from the molluscs. Five species of land snail were recorded (von Martens 1867); these were all large, and undoubtedly a much more extensive fauna, including micro-molluscs, existed.

Timber and sulphur were regularly obtained from the well-forested island in the 17th century, and indeed in 1620 the Dutch East India Company established a naval station there and later set up a shipyard on the island. In the year following May 1680 flows of andesite lava issued from the northernmost volcano, Perbuatan, in what was probably a period of

Strombolian-type activity; as the resident human population was harvesting and selling a pepper crop in March 1681 (de Neve 1985*a*), however, this eruptive period could not have included extensive pyroclastic emissions.

No volcanic activity was recorded during the next two centuries. In January 1771, Cook, in *H.M.S. Endeavour*, had seen a village and cultivation on the island (Beaglehole 1963), and in 1780, after the death of Cook, the captains of *H.M.S. Resolution* and *H.M.S. Discovery*, learning that Dutch ships regularly obtained water from the island, anchored on Krakatau's northeast side, where some of the crews went ashore, finding a stream, a village, clearings for rice growing, and a hot-spring (Cook & King 1784). Simkin & Fiske (1983) quote van Breugel as recording in 1787 that the island was still inhabited but was no longer a source of pepper, and Horsburgh stated in 1809 that the villagers were raising goats and poultry and growing fruit (van den Berg 1884). The island was described in 1854 as 'shaded from the foot up to the summit in forest trees', and this is confirmed by Stehn's finding, in the 1920s, of carbonized wood 5 cm thick under the deep stratum of pumice still covering the summit (Docters van Leeuwen 1936). A small penal colony was situated on the group at about this time. When Verbeek visited the islands in 1880 (Verbeek 1885) they were deserted except for occasional fishermen and woodcutters, and covered in dense vegetation (average annual rainfall is over 2600 mm) except near the craters of the 1680–1681 eruptions of Perbuatan where the lava flows were barren. Van Gestel, however, who visited the island in May 1883, reported, in an exaggerated account of events (Simkin & Fiske 1983), seeing pig tracks.

(*c*) *The events of* 1883

Details of the eruption of 1883 and its effects have been fully documented in the Royal Society report (Symons 1888) and by Verbeek (1885) and Simkin & Fiske (1983); summaries have been provided by Simkin & Fiske (1982) and Woolley & Bishop (1983).

In May, 1883, Krakatau again became active after two centuries of dormancy, the activity at first appearing in the northern, Perbuatan volcano. In subsequent months the number of active vents increased and extended to Danan, until on the 26 and 27 of August activity reached a climax. A tsunami was produced late on the 26, and three on the 27, when there was a series of four violent explosions, the penultimate one, at 10h00, being audible in South Australia, Perth, Colombo, and Rodriguez 4800 km distant. This was one of the greatest natural explosions ever recorded, and the tsunami it generated beached ships as far away as Sri Lanka and caused temporary changes in sea level that were detectable in New Zealand, Alaska and the English Channel. In some of the bays and gulfs on the shores of Sunda Strait the wave reached a height of over 30 m and travelled at speeds of up to 90 km h^{-1} penetrating as far as 11 km inland, obliterating 165 coastal villages and towns and killing more than 36000 people.

A cloud of fine volcanic dust rose some 50–80 km into the stratosphere and circled the earth in the jet streams several times. The resulting unusual atmospheric effects, seen in various parts of the world (Symons 1888) were caused by very fine ash and sulphate aerosols generated by the eruption (Rampino & Self 1982, 1984). Weather conditions cooler than normal prevailed in the northern hemisphere for more than a year as a result of a reduction in the amount of solar radiation reaching the earth (Kimball 1918), and mean temperatures were from 0.5 to 0.8 °C lower than normal for several months (Francis & Self 1983). The volume of material ejected is now believed to have been 18–21 km^3, representing 9–10 km^3 of dense rock (Self &

Rampino 1981), and it is thought the tsunamis were generated by several cubic kilometres of pyroclastic flows entering the sea as a result of collapse of the eruption column following large-volume explosions driven by magmatic gases (Self & Rampino 1981, 1982; Francis & Self 1983; but see also Yokoyama 1981, 1982). The northern half of the Rakata cone, together with the northern two thirds of the island, collapsed and slid into the depleted magma chamber, creating a submarine caldera (figure 4); this event is associated with the final, most devastating tsunami.

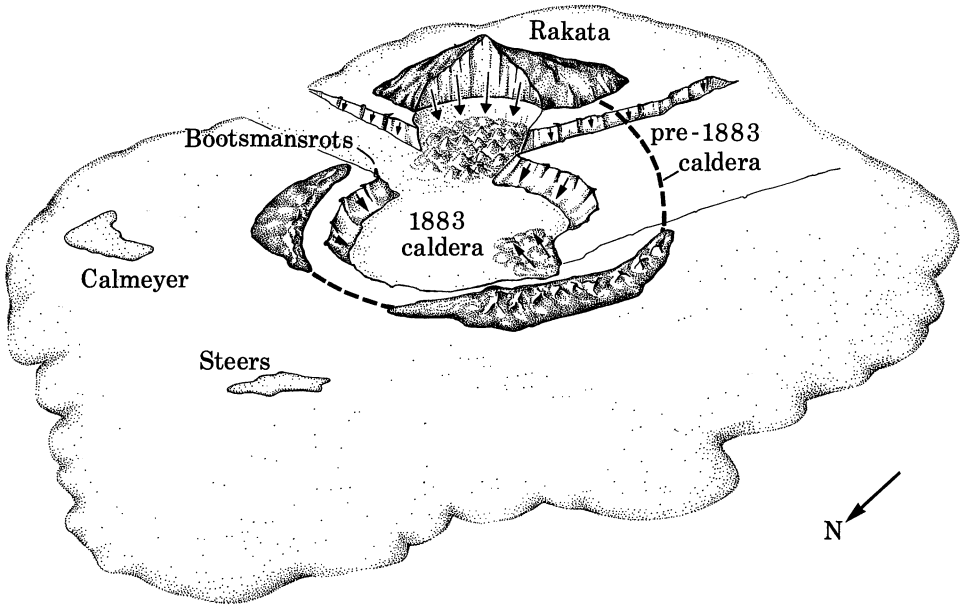

FIGURE 4. Aftermath of the 1883 eruption of Krakatau Is. (same view as figure 3) showing 1883 caldera within ancient caldera, undersea deposition of volcanic emissions, Calmeyer and Steers Islands (later eroded), enlargement of Sertung and Panjang, and remnant of Rakata volcano left as Rakata Is. (see text). Not to scale; modified from Francis & Self (1983).

In the aftermath, the northern two thirds of Krakatau, including the volcanoes Perbuatan and Danan and the northern half of the Rakata volcano, were seen to have disappeared, along with the small islet Polish Hat, and the submarine caldera that now existed in their place was over 200 m deep and covered an area of about 28 km^2. Krakatau's southernmost remnant was left as an approximate half-cone of the Rakata volcano and a nearly perpendicular arc of cliff from the 800 m summit to the sea provided an almost sagittal geological section through it. Sertung and Panjang were enlarged considerably (Sertung to about three times its former size) by glowing ash and pumice, which reached a depth of at least 50 m. The south and west coasts of Rakata were extended seawards almost 1 km and here the ash layer was 60–75 m thick in places (although probably much shallower on the steep slopes). A small rock pinnacle, Bootsmansrots, was left just exposed above sea level, a remnant of Krakatau representing part of the northeast rim of the newly formed caldera (figure 4).

The general opinion now appears to be that life was extirpated from the Krakatau group by this cataclysm, but opposing views have been advanced. Backer, who visited the islands in 1908, argued that some roots, seeds, spores and soil organisms may have survived either in protected crevices or on the more sheltered southeast side of Rakata, and that on the steep higher southern slopes the ash would not have settled deeply (Backer 1929). He also argued that monsoon rains in September and October 1883 may have assisted survival, and criticized the failure of early expeditions to make the crucial observations on the upper slopes of Rakata necessary to prove complete sterilization. Scharff (1925) had expressed similar views. Ernst (1934) and Docters van Leeuwen (1936) advanced strong counter-arguments, and the matter was the subject of considerable international debate (Anon. 1929; Turrill 1935; van Steenis 1938, 1952). Subsequent surveys by biologists, however, have shown that the nature of succession since 1883 indicates that sterilization was very probably complete (Bristowe 1931; Dammerman 1948; Richards 1952; Richards 1982).

Carbonized wood up to 5 cm diameter was found beneath pumice deposits at the summit of Rakata (Docters van Leeuwen 1936), and is also now being exposed in the basal 1883 deposits on eroding coastlines. Händl (see next section) found unburnt tree trunks and other parts of plants beneath layers of ashes and pumice when digging a well at Händl's Bay (Backer 1929). Docters van Leeuwen (1936), dismissing Backer's use of Händl's find as evidence that not all vegetation was destroyed by the eruption, argued that the trunks were covered by only some 3 m of pumice and were sited where sea existed in 1883, and agreed with Van Steenis (1930) that they represented new vegetation, which had been buried superficially by landslides and floods. In 1985 we found incompletely carbonized logs up to 30 cm in diameter protruding from what appeared to be undisturbed, original basal 1883 pumice deposits resting on pre-1883 lava flows and ash (figures 8 and 9, plate 1) at the south end of Turtle Beach. The pumice extended some 10 m above the plant remains.

In the light of this recent discovery the question remains open, but even if some plant life survived it is unlikely to have had a significant effect on the succession, although it would have biogeographical importance, and the long-term survival of animals, without available food, is even less likely. The geologist Verbeek visited the islands in October 1883, and believed all life had been destroyed: the ash was still too hot for bare feet and rainwater turned into steam as it trickled into crevices (Verbeek 1885). Backer's conclusion that 'the Krakatoa problem ... is of no importance at all for botanical science' is now generally regarded as an unjustified exaggeration.

The three islands Rakata, Sertung and Panjang are now covered in forest; over 260 species of vascular plants having been found on Rakata from 1979 to 1983 (Richards 1986).

(*d*) *The birth of Anak Krakatau*

In 1927 signs of volcanic activity were seen in the sea between the sites previously occupied by the main vents of the Danan and Perbuatan volcanoes, which had been responsible for the major activity at the time of the 1883 cataclysm. A succession of three new islands appeared as a result of a series of submarine eruptions 185 m below the surface, but were soon destroyed by marine erosion and submarine sliding (de Neve 1985*b*). The fourth, which emerged on 12 August 1930, 47 years after Krakatau's eruption, was not eroded, and was named Anak Krakatau IV. By the following year it was 47 m high with a crater some 700 m in diameter, and ten years after its emergence it had a height of 125 m and a crater, now open to the sea, 680 m in diameter. The crater became closed off from the sea in 1952 when the island suffered what was probably a sterilizing eruption (van Borssum Waalkes 1960). Lava flows first appeared from 1960 to 1963, thus ensuring the island's permanence by providing a rampart in the south and west against the prevailing currents. Eruptions have occurred fairly regularly since that time, at intervals of about 2–3 years, the last being in 1982. The island is now

195 m high and 2 km in diameter, and is still active; only the northeast coast and north and east cuspate forelands are vegetated, the succession being at an early stage, with *Casuarina equisetifolia* the dominant tree. Some 61 vascular plants were recorded from the island in 1981 (Partomihardjo 1983) and about 66 in 1983 (Richards 1986).

(*e*) *Human influence since* 1883

In 1915 Mr J. Händl was granted a concession to work volcanic products on the islands, making bricks from the pumice. He, and a retinue of family and servants, were present on the southeastern shore of Rakata (Händl's Bay), from 1916 for about four years (Docters van Leeuwen 1936; Backer 1929). He built a house, sank a well, introduced such exotic plants as banana, coconut, mango, cassava, pineapple, chilli and rice and accompanying weeds, and kept fowl, geese and pigs. He received visitors, and guided several scientists to the summit by a southeastern route. Docters van Leeuwen believed 17 plants found on Rakata in 1920 were the result of introductions during Händl's sojourn. By 1929 only the well and five of the exotic plants, which had not spread, remained. Recognizable banana and coconut plantings still remain but are now overgrown by secondary forest.

There is some evidence that before 1906 a party of surveyors inhabited Sertung for a time (Ernst 1908). In 1951 a cottage, small clearing and cultivated garden containing ten species of cultivated plants and several weeds, were found near the junction of the spit and the island proper; they were destroyed by the October 1952 eruption of Anak Krakatau, although *Musa*, *Carica* and *Lantana* plants were sprouting again a month later (van Borssum Waalkes 1960). A group of large coconut trees (some felled) now exist in this area.

From August 1896 to January 1897 a survey team lived on Panjang and was supplied from Java twice a month. A small observation post and signal station was established in the north of the island in 1927 at the location shown on figure 27, plate 11, and was manned until 1935 and from 1937 to 1940 to report the emergence and growth of Anak Krakatau (G. A. de Neve, personal communication). Two concrete wells, an observation bunker, concrete survey post, flourishing mango tree and large coconut palms are now the only visible evidence of this visit.

There have been no other permanent inhabitants of the archipelago.

Zwarte Hoek and South Bay on Rakata, and the eastern shore of the Sertung spit, are frequently visited by fishermen, who have made a few small clearings and set up fish drying racks, and Hoogerwerf (1953) stated that people from Sebesi practiced some shifting cultivation on Rakata. Small parties of tourists now visit the islands about weekly in the dry season (May–October) but usually only for a few hours; they land on the east foreland of Anak Krakatau and some climb from there to the crater. Pumice-collectors visit various places on the islands periodically, removing larger pieces of pumice, and some timber has been removed from Anak Krakatau, South Bay on Rakata, and Sertung. Germinating coconuts and casuarinas are also removed, and at Zwarte Hoek, Rakata, an extensive area of shallow pits is evidence of land-crab collecting. A Chinese shrine was found about half way up the eastern face of Anak Krakatau's outer cone in 1984, but had been removed a year later. An automatic solar-powered seismic monitoring device is installed on the outer rim of Anak Krakatau in the south, above the site of its breach by lava flows.

In December 1933 a dog was seen near the southeast shore of Rakata, and was still present four months later (Dammerman 1948). It is possible that there is a viable population of wild pigs on Panjang (tracks and wallows are common), but we found no sign of other feral animals.

The Krakataus, together with the Ujung Kulon Wildlife Reserve, were designated the Ujung Kulon National Park in 1925, and are under the control of P.H.P.A. (Department of Forestry and National Parks, Indonesia).

3. The present environment of the archipelago

(a) *Hydro-oceanographic conditions of Sunda Strait*

Available data concerning the hydro-oceanographic conditions of the Sunda Strait are summarized by Birowo (1985). The Sunda Strait (figure 1) is a funnel-shaped seaway connecting the Indian Ocean with the Java Sea and is the principal link between these two water bodies. In the northeast, the strait is less than 25 km wide between Java's Fourth Point (Anyer Kidul) and Tanjung Tua in southeastern Sumatra and has an irregular bottom topography with a maximum depth of about 80 m. The strait opens to the southwest to be over 100 km wide between Java's First Point (Tanjung Layar) and Tanjung Rata in southwestern Sumatra. A narrow shelf, averaging 45 m depth, extends 40 km south from Tg. Rata before the bottom falls steeply to a depth in excess of 1500 m (figure 1). This deeper basin extends towards Semangka Bay, but in the centre of the strait the depth decreases rapidly and around the Krakatau Islands the average depth is 50–100 m. One of the deepest points in the centre of the Sunda Strait is the submarine floor of the caldera 3 km northwest of Rakata, which is over 200 m deep.

Wave and sea conditions in the Sunda Strait are determined by swell generated in the Indian Ocean and by the seasonal reversal of monsoon winds that is characteristic of western Indonesia. The direction from which swell arrives at the western entrance to the Sunda Strait is predominantly between northwest–southwest from November to March, and south–southeast from April to October (Anon. 1949). This swell is refracted through the western entrance and approaches the Krakataus from the southwest. Observations from Rakata during September 1984 recorded a wave period of 5–8 s passing Zwarte Hoek, and similar regular long swells were noted approaching the southern coast of Sertung. Strong surf is generated along the southern and western coast of Sertung and the coast of Rakata between Zwarte Hoek and Händl's Bay and prohibits boat landing at any time, and waves also break heavily along the south coast of Panjang. On the exposed western coast of Anak Krakatau, because of the extremely steep offshore profile, waves surge against the lava cliffs without surf-crest development.

Short-period seas develop in the eastern Sunda Strait during strong wind episodes, especially during the northwestern monsoon. These can develop steep and erosive waves on the normally sheltered eastern and northern coasts of the Krakatau islands.

The flow of water through the strait is considered to be small and of the order of 0.5×10^6 m^3 s^{-1} (Wyrtki 1961). For the greater part of the year (February–November) this flow is towards the southwest from the Java Sea, with surface-current velocities of 0.38–0.65 m s^{-1}, but in November the flow reverses for a period of 2–3 months with a weak northeasterly stream rarely in excess of 0.25 m s^{-1}. Despite the wider opening at the southwest of the strait, the available evidence from salinity and surface-current measurements suggests that the influence of the Indian Ocean on surface-water movements is relatively weak, because of the surface sea-level gradient that exists from north to south (Birowo 1985).

(*b*) *Climate*

No long-term climatic observations are available for the Krakatau Islands, and analysis of climate must be based on records from stations on the nearby coasts of Java and Sumatra, and records for the years 1929 and 1930 on Panjang and Rakata.

Mean annual temperature at Tanjungkarang (figures 1 and 5) at the head of Lampung Bay, Sumatra, 65 km north of the Krakataus (10 year average, 1961–1970) is 26.4 °C, the monthly means varying by less than 1.0 °C around this. Mean maximum and minimum temperatures ate 31.4 °C and 21.6 °C respectively. Precipitation along the coast of south Sumatra increases from east to west. At Telukbetung and Kalianda on the southeast of Sumatra average annual precipitation is 2111 mm and 2201 mm respectively, and totals increase to 2791 mm at Kotaagung and 3157 mm at Putihidoh, both stations around Semangka Bay. On the west Java coast, rainfall increases from 1875 mm at Serang, 2216 at Anyer Kidul, to 4262 mm at Labuan. The annual mean for Java's First Point over a period of 40 years was 3249 mm, and Hoogerwerf (1971), in reference to Ujung Kulon, notes that 'while many years have a pronounced dry season, in others the season barely differs from the wet south-west monsoon season and in June–September exceptionally heavy rains fall almost daily'. It is likely therefore that the annual precipitation at sea level in the Krakataus is between 2500 and 3200 mm (figure 5).

Temperature and rainfall data for Panjang in 1929 recorded by Stehn (van Baren 1931), have been illustrated according to Gaussen's system (Tagawa *et al.* 1985) and the resulting climate diagram is reproduced here as figure 6. Dammerman (1948) provides a table (reproduced as table 1) giving rainfall data also for Rakata in 1929 and 1930. In 1929 the dry

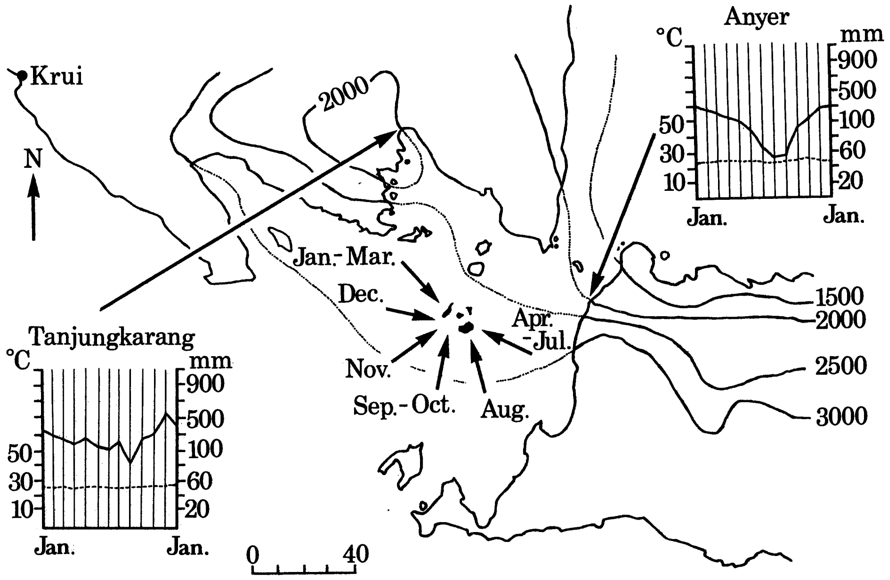

FIGURE 5. Mean annual rainfall map of Sunda Strait from 1941–1975 data. Isohyets in millimetres; short arrows show approximate direction of wind resultant for months indicated. Mean annual temperature and rainfall charts from January to January for places indicated by long arrows.

season, as a result of the east monsoon, was from May to October, and driest from July to September when only 88–90 mm of rain fell on the two islands (3–4 % of the annual rainfall). As Hoogerwerf noted, however, the dry season in the Sunda Strait area is by no means predictable: 1930 was wetter than 1929 and the dry season was much less pronounced. On Rakata, 9 % of the annual rainfall in 1930 fell from July to September, over twice the percentage of the preceding year. More recently, in 1982, November was exceptionally dry, the northwest monsoon being very late. In 1929 the northwest monsoon brought heavy rains to the islands from November to April, 85 % of the annual rainfall, with 77 % in the period November to March. Local variation is evident in the February 1929 figures, Panjang receiving twice the precipitation of Rakata. Monthly temperatures were fairly constant on Panjang in 1929, at around 28 °C (26.9 °C in July and December to 28.7 °C in October).

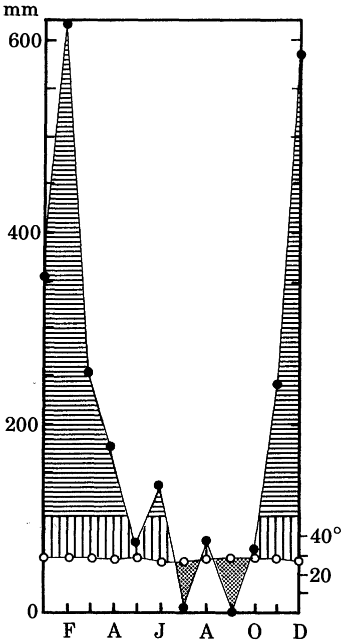

FIGURE 6. Climatic diagram for Panjang, 1929. From Tagawa *et al.* (1985).

The rainfall and wind régime of the Sunda Strait (figure 5) is dominated by a monsoonal wind reversal. There are four monsoon seasons although two of these are short transitional periods. The main monsoon periods are the wet northwest monsoon, which is effective from late November to February, and the southeast monsoon, which dominates the weather pattern from April to October. Strongest winds occur during the northwest monsoon. Winds swing from west–southwest in November and December to be westerly in January and northwesterly in February, averaging 15 knots† but rising at times to 25 knots. March winds are variable but becoming more southerly, and by June–July a southeasterly airflow is dominant, persisting until October. Rainfall distribution is related to winds and shows a distinct seasonality although, as Hoogerwerf noted, substantial rainfall can occur in any month. June–September are the driest months although monthly mean precipitation for each of these is in the order of

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† 1 knot ≈ 0.514 m s^{-1}.

TABLE 1. MONTHLY RAINFALL (IN MILLIMETRES) ON PANJANG AND RAKATA

(After Dammerman (1948), p. 197.)

	Panjang	Rakata	
	1929	1929	1930
Jan.	357	210	230
Feb.	620	266	354
Mar.	267	267	463
Apl	178	179	225
May	72	72	422
Jun.	138	138	112
Jly	9	9	168
Aug.	79	81	67
Sep.	0	0	61
Oct.	68	68	281
Nov.	245	245	341
Dec.	589	612	384
Total	2620	2145	3117

TABLE 2. CLIMATIC PARAMETERS FOR SUNDA STRAIT

evaporation/millimetres per day[a]

Jan.	Feb.	Mar.	Apl	May	Jun.	Jly	Aug.	Sep.	Oct.	Nov.	Dec.
3	3	2	2	2	3	3	3	3	3	2	3

total cloudiness (tenths)[a]

Jan.	Feb.	Mar.	Apl	May	Jun.	Jly	Aug.	Sep.	Oct.	Nov.	Dec.
7	7	7	7	6	6	5	5	5	7	7	7

mean number of rainy days[b]

	Jan.	Feb.	Mar.	Apl	May	Jun.	Jly	Aug.	Sep.	Oct.	Nov.	Dec.	year
Telukbetung	18.4	17.2	16.4	13.4	11.4	10.0	9.3	10.0	9.2	10.0	12.0	16.0	153.3
Anyerkidul	20.1	17.0	13.6	11.2	10.0	7.9	5.8	6.3	5.3	8.1	11.7	18.2	135.2
Labuan	13.7	13.0	9.5	7.7	8.7	4.8	2.2	5.9	6.6	10.3	9.3	12.3	104.0

[a] Unspecified localities from Hastenrath & Lamb (1979).
[b] From Boerema (1925).

70–120 mm. Rainfall in each of the wettest months of the northwest monsoon (December to February) is in excess of 200 mm.

Other climatic parameters for Sunda Strait are summarized in table 2.

(c) *Rakata*

Rakata (sometimes called Krakatau, or Rakata Besar), the only island of the group that is a remnant of Krakatau (figures 2–4), is easily the highest (777 m) and largest (11.5 km^2), and has received the most attention from biologists (see §4 and table 3).

(i) *Physical features*

Rakata is a high, steep island, deeply dissected by a radial gully system and almost entirely bounded by eroding cliffs (figure 7, and figure 10, plate 2). Small areas of sandy lowland near Zwarte Hoek on the northwest coast, and at Owl Bay and Händl's Bay on the southeast, are the only places where boat landings may be made. As with Panjang and Sertung, the configuration of the island is determined by residual pre-1883 terrain, and by the dissection of the thick blanket of pumice tuff that buried the existing topography during the 1883 eruptions.

The older rocks underlie the steep summit cone, are exposed in the floors of the gullies at high levels, and underpin the scarps flanking the dominant terrain feature of the island, the precipitous northwesterly facing cliff (figures 12 and 13, plates 3 and 4). Rising 777 m above sea level, this huge cliff traces the line of fracture developed by the final collapse of the volcanic edifice and the formation of the submarine caldera, and exposes an impressive section through the interbedded lavas and pyroclastics of the former Krakatau volcano. The cliff has been modified since then by rockfalls, at times generated by earthquakes, and by accumulation of boulder screes and fans at the waterline. Several rockfall chutes have developed along gullies in the cliff face and the screes are concentrated at the base of these. Because of the steep submarine slope that fronts much of the cliff, many rockfalls cascade from the lower parts of the face and plunge directly into deep water, resulting in a smooth profile free from cliff base rubble (figure 12, plate 3).

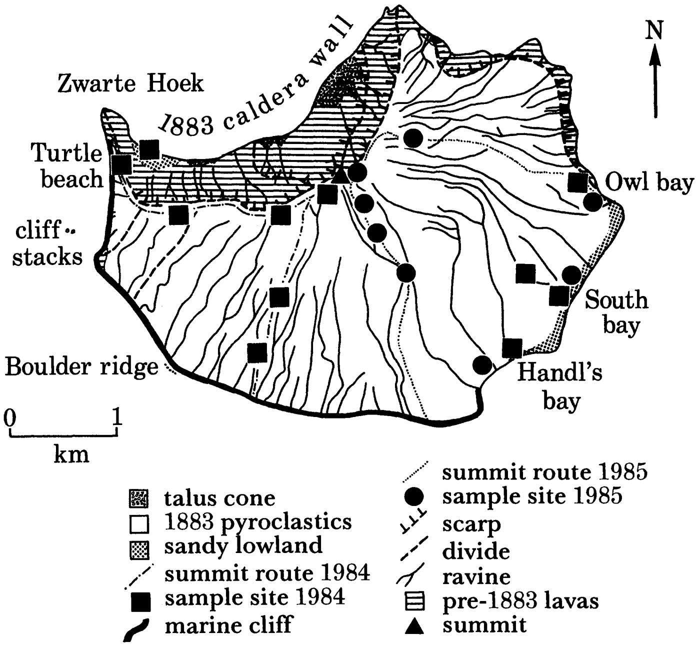

FIGURE 7. Rakata, 1985, showing localities mentioned in text and routes of summit climbs in 1984 and 1985.

Outcrop of the pre-1883 lavas extends along the eastern coast of Rakata to Owl Bay. The cliffs here are less precipitous, as lava is exposed only at the base, and there are sectors of steep coast with vegetation overhanging to the waterline. Gullies initiated in the overlying pyroclastics terminate in steep, narrow gutters, and there are sectors with narrow sand beaches. The contact between the 1883 eruptive products (including carbonized wood fragments in the lower strata) and the older lavas, descends to sea level where it is clearly exposed just north of Owl Bay. From Owl Bay to Händl's Bay the coast is fringed by a low sandy terrace, partly built by coalescing downwash fans from the southern slopes of Rakata. Most of the seaward edge of this terrace is now eroding, and a low cliff is formed as waves undercut the mature *Barringtonia* communities. The retreating coast is becoming fringed with boulders that are exposed below the sandy terrace and accumulate in the surf zone.

The southern and western coast of Rakata is dominated by high, almost vertical marine cliffs cut in the 1883 pumice deposits, the cliff crest forming an abrupt junction where it truncates descending spurs. Rapid rates of recession are indicated by the presence of hanging valleys (figure 10, plate 2) and by the straight line form of the coastal segments. A basal section of the 1883 deposits (including logs and large branches) overlying older lava flows, is exposed on a small promontory on the western coast of Rakata. The older flows form the base of two cliff stacks that lie 400 m offshore to the north of this (figure 11, plate 2). Comparison of aerial photographs taken in 1946 with preliminary field maps derived during the 1984–85 expeditions, indicates considerable recession of all the soft rock coasts of Rakata since 1883. This has been greatest on the western and southern coasts, where the unconsolidated materials are exposed to strong wave action from southerly and westerly swells. Despite high rates of sediment production from cliff wasting, much of the sediment is buoyant pumice fragments that float away and do not build wide protective beaches at the cliff foot. Wave action thus sweeps across beaches, rapidly dispersing fans and collapsed cliff blocks and maintaining a persistent rate of cliff retreat. Offshore, the seafloor is bouldery, and in September 1984, an emerged boulder ridge some 120 m long, 20 m wide and rising to 1.5 m above the high-water mark was noted 40 m offshore. The ridge contained large, tightly packed boulders over 30 cm in diameter and appeared to be due to localized tectonic uplift of the seafloor rather than of storm-wave origin.

The outline of the gully system of Rakata (as on Panjang and Sertung) was initiated in the first months and years after the 1883 eruption, before the establishment of a dense and protective vegetation cover. Paintings and photographs in Verbeek (1885) and Docters van Leeuwen (1936) show gully systems already well established less than 3 years after the eruption with dissection tens of metres deep. Rates of gully dissection have diminished as the channel floors have excavated down to the resistant pre-1883 lavas, but gully deepening, widening, headward erosion, interfluve breaching and channel capture continue to occur. Tributary gullies typically head in an amphitheatre with vertical or overhanging walls against the intervening interfluve and make the ascent (and descent) of the mountain hazardous. A rapid rate of slope wash is indicated on the steeper pumice covered slopes by the number of uprooted trees and by the accumulation of debris behind temporary log or rock dams on the gully floor. The upper slopes are the least stable for several reasons: they have an initial steepness imposed by the pre-1883 terrain slope, impermeable older lavas lie close to the surface and give rise to high water tables allowing seepage into gully sides, and there is a substantial input of moisture from fog drip which maintains a permanently wet soil state.

(ii) *Vegetation*

About 260 species of higher plants are now known to occur on Rakata (Richards 1986). Apart from the huge north-facing cliff scar, which supports *Casuarina equisetifolia*, the island is covered in secondary growth from shore to summit. Whittaker *et al.* (1984) and Tagawa *et al.* (1985) provide accounts of the present vegetation.

The coastal forests consist of the typical *Barringtonia* formation, including *Barringtonia asiatica*, a strictly coastal tree, and *Hibiscus tiliaceus*, *Terminalia catappa*, *Morinda citrifolia* and *Pandanus tectorius*, and on non-eroding beaches the shade-intolerant *Ipomoea pes-caprae* creates a ground cover extending into the *Barringtonia* formation a little way. On the lower slopes, Tagawa's group found the forest to be dominated by *Terminalia catappa*, with *Calophyllum inophyllum*, *Neonauclea calycina*, *Morinda citrifolia* and *Ficus septica* as common species. They also recognized

FIGURE 8. Uncarbonized logs buried under 1883 eruptive materials, southwest Rakata coast.

FIGURE 9. Detail of site of figure 1, showing log between pre-1883 and 1883 eruptive layers. Tape is extended 40 cm.

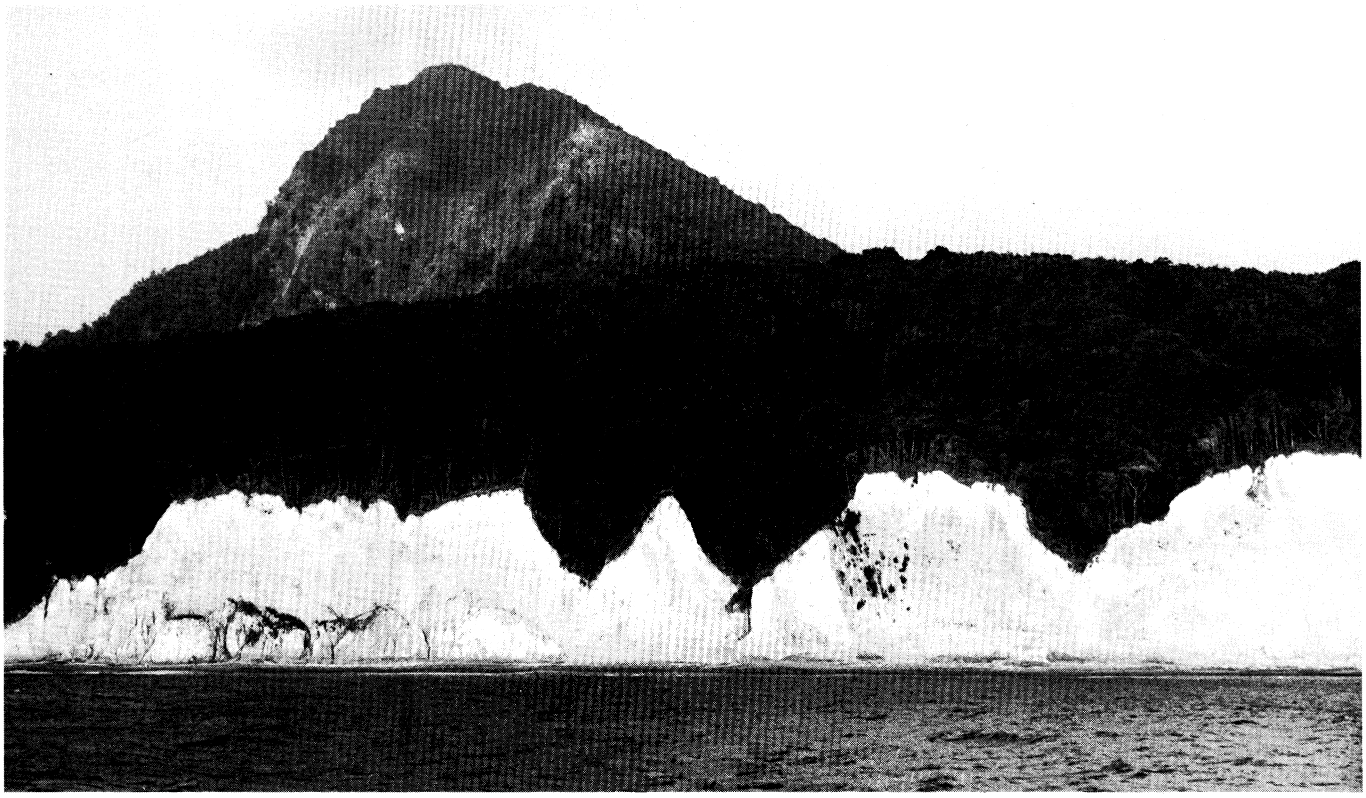

Figure 10. Cliffs cut in 1883 pumice, Turtle Beach, Rakata.

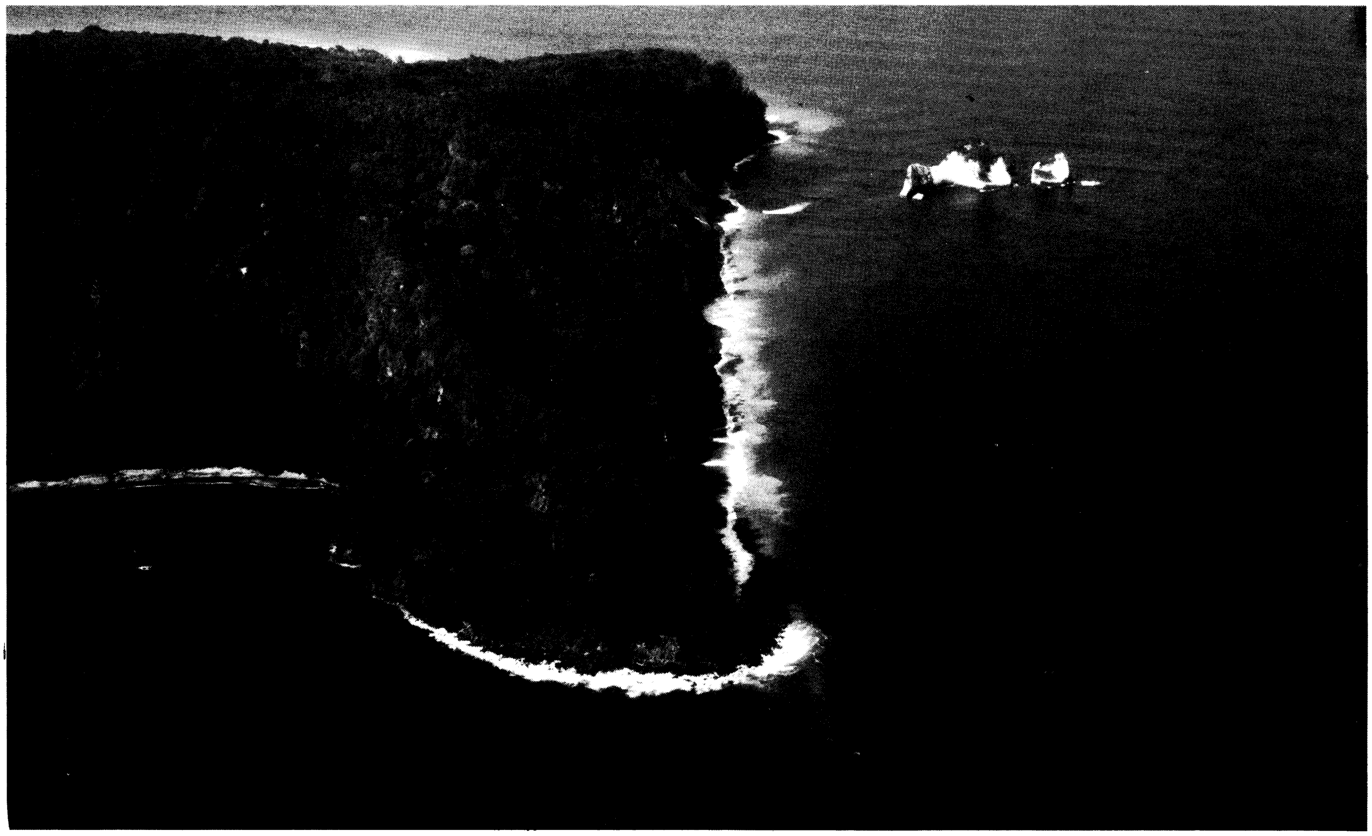

Figure 11. Zwarte Hoek, Turtle Beach, and the two cliff stacks off the west coast of Rakata.

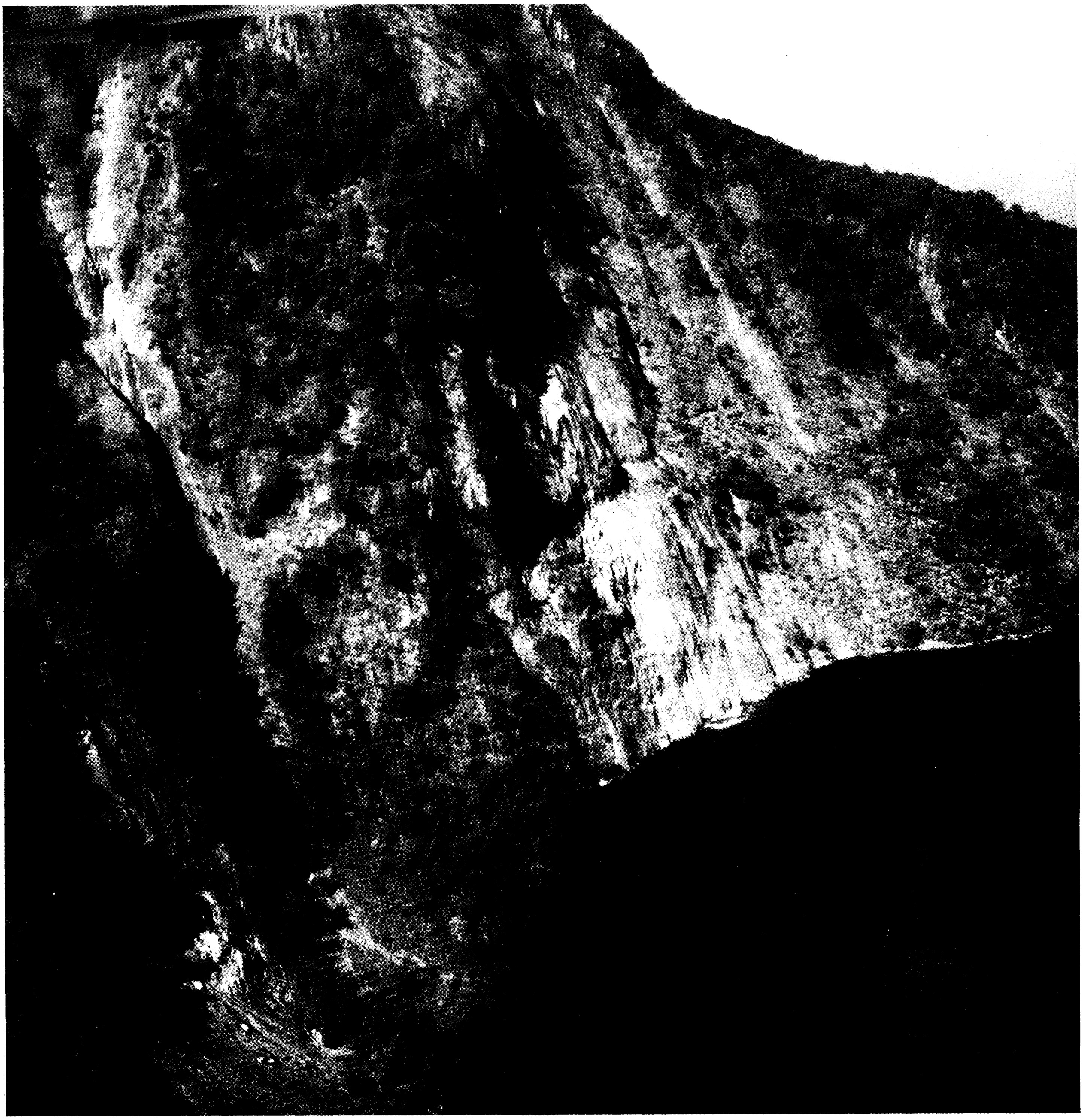

FIGURE 12. The great northern cliff of Rakata, resulting from 1883 caldera collapse.

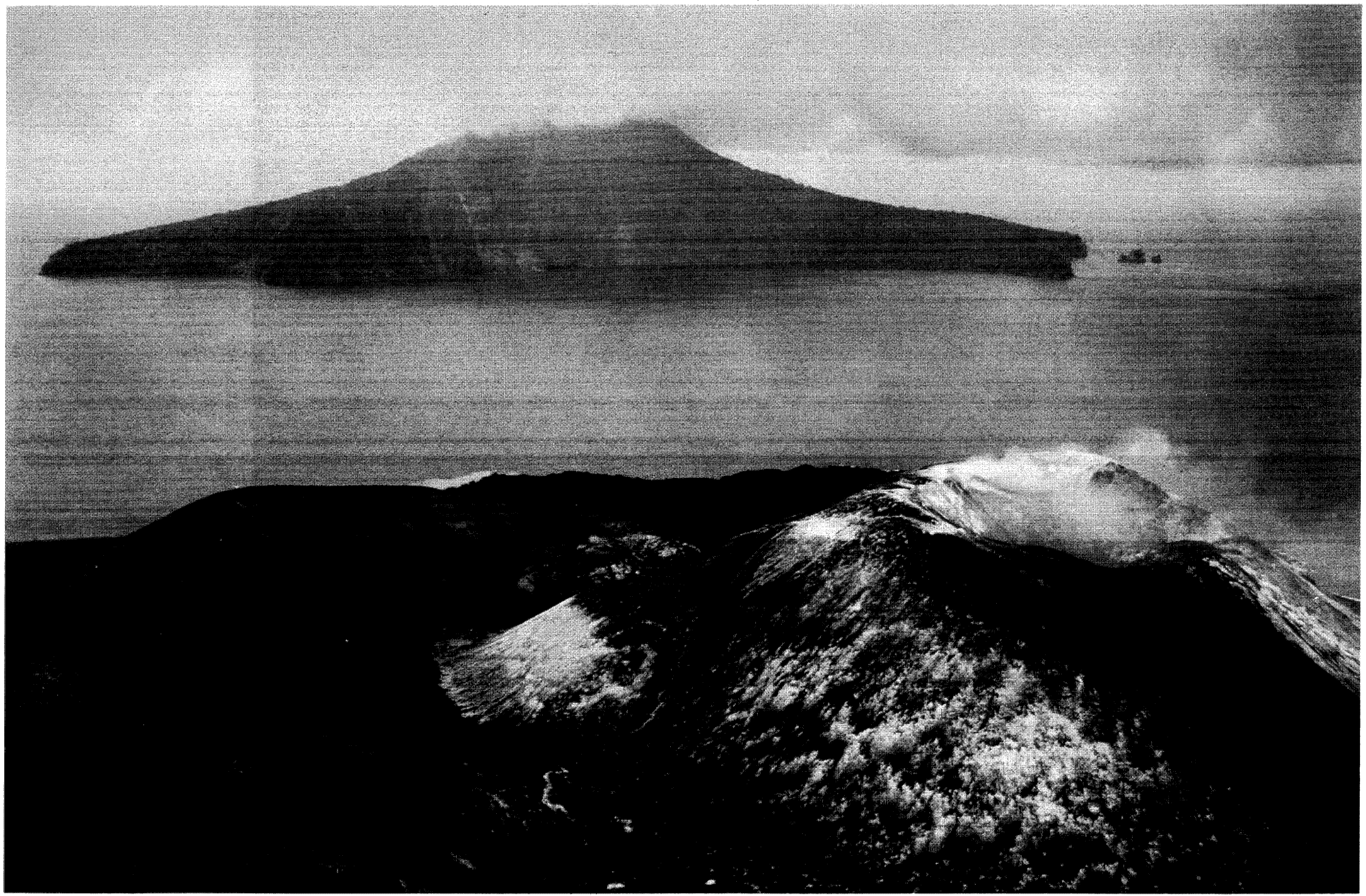

FIGURE 13. Rakata, from north; Anak Krakatau in foreground.

a *Terminalia–Timonius compressicaulis* co-dominant forest type at low elevations, with the *Timonius* forming an even canopy beneath the emergent layer of *Terminalia*, and believed this to be transitional forest from a *Terminalia* to a *Timonius* forest, *Timonius* forest itself not yet being recognized on Rakata.

Most of the forest on Rakata, from 30 m to about 550–600 m, is *Neonauclea* tropical monsoon 'secondary' forest, dominated by the single species *Neonauclea calycina*, and such forest is unique to Rakata in the Krakataus. Bush and Whittaker (1986) noted very large trees of *Ficus pubinervis*, up to 5 m girth at breast height, and, inland of the south coast, an area with very large trees at low density with a sparse ground flora, which they regard as the closest approach to primary forest found on the islands. The undergrowth is generally characterized by such species as *Leea sambucina*, *Leucosyke capitellata* and *Villebrunea rubescens*, with *Cyrtandra sandei* in ravines under the *Neonauclea* canopy. Above about 550 m Whittaker and his colleagues found the character of this forest to change gradually to a more mixed, mossy forest with species of *Ficus* included in the canopy. The summit is now covered in stunted *Schefflera polybotrya* scrub, including *V. rubescens*, *L. capitellata* and *Ficus ribes*, with small areas of *Saccharum spontaneum* in places of tree fall or ground disturbance, including the summit itself.

Flenley's 1979 expedition found that relative humidity rose by about 5% per 200 m altitude above about 200 m, to saturation near the summit. The lapse rate of air temperature at 13h00 was 0.9 °C 100 m^{-1} elevation, which corresponded to a lapse rate of average annual air temperature of 0.8 °C 100 m^{-1} estimated from soil temperatures taken at a depth of 75 cm, suggesting that altitudinal gradients of temperature and humidity persist throughout the year. They also found altitudinal changes in the soils. Sodium concentration is negatively correlated with altitude (and distance from the shore), and at heights above 500 m there is a better developed organic horizon, the organics being black and well decomposed but mixed with fibrous material (Whittaker *et al.* 1984). Cloud, which usually envelops the heights above about 500 m in the late afternoons, even in the dry season, and clears in the morning, results in very high humidities and moist conditions in the summit area, where a 'moss forest' with festooning epiphytic mosses such as *Floribunda floribunda* occurs at a much lower elevation than on adjacent 'continental' areas, a possible example of the 'Massenerhebung effect' (Forster 1982; but see Bush 1986*b*). Forster found that the composition of the moss flora changed with altitude and ascribed this to changes in relative humidity. Bush (1986*b*) believes the dwarfing noticeable in the summit area cannot be ascribed to edaphic conditions or wind or drought stress, but that the increased nocturnal and diurnal temperature range or reduced insolation as a result of cloud cover may be involved.

Such altitudinal environmental variation is of course unique on the archipelago and may also be reflected in the distribution of components of the fauna of Rakata. Diamond (1972), for example, showed that for islands in the southwest Pacific each 300 m of elevation enriches an island's avifauna by 2.7% of that at sea level.

The summit was first reached in 1908 and until the 1980s was climbed from the southeast; it is also possible to climb along a narrow ridge of partly consolidated ash above the northern cliff face from a gully on the western side of Zwarte Hoek. These were the routes of the summit climbs we made in 1984 and 1985.

There is no permanent freshwater on the island.

(*d*) *Sertung*

Known to the Dutch as Verlaten, Sertung (figure 14) is the second largest island of the group (area 7.9 km^2) and much lower (at 182 m) than Rakata, with no prominent peak. It is approximately 8 km long and almost 2 km at its widest point.

(i) *The main body of the island*

After the 1883 eruption, the island had increased in area by almost three times as a result of the accumulation of pyroclastics. These completely buried the pre-existing terrain and extended the southwestern margin of the island over 3 km seaward. Further to the west, the seafloor was shallowed by up to 40 m and the line of surf break was as much as 5 km seaward of the pre-1883 line. The pyroclastic fall and flow units are at least 70 m thick (and possibly thicker in the central part of the island), and initially formed a plateau surface sloping gently to the west from a divide close to and parallel with the eastern coast (figure 17, plate 6). This surface has now been deeply dissected by a network of gullies (figure 15, plate 5), with wide, planar interfluves terminating as near-vertical marine cliffs. Deep V-shaped gullies descend to sea level along the western coastline, but along the south, the continuing rapid rate of retreat results in high hanging valleys and truncated spurs (figure 15, plate 5). Comparison of early post-eruption maps of Sertung (Verbeek 1885; Symons 1888; Stehn 1929) with more recent aerial photographs and field surveys, shows that the western and southern coasts have receded by up to 2.5 km. In places this coast must now be close to the pre-1883 island coastline.

The eastern margin of Sertung is a more stable coast consisting of a steep forested coastal slope with the pre-1883 lavas outcropping as a basal cliff. This coast was little changed by the eruption, the bulk of the ejected material being emplaced on the western sector of the island.

The main body of the island is a dissected upland plateau covered in tropical monsoon rainforest, and some 140 species of higher plants have been recorded in recent years (Richards 1986).

Beaches on the more sheltered east coast carry a rich *Ipomoea pes-caprae* association, but typical coastal communities are absent from the rapidly eroding southwestern shores, the cliff tops carrying forest species (Bush & Whittaker 1986). Both Tagawa and Bush & Whittaker found the forest at the northern high point of the island to be dominated by *Timonius compressicaulis*, and although *Neonauclea calycina* is present, no *Neonauclea* forest has been found on the island. Young trees of *Dysoxylum gaudichaudianum*† also occur in the *Timonius* forest. *D. gaudichaudianum* is the only possibly primary forest tree on the archipelago and is found on all islands but Anak Krakatau (Tagawa *et al.* 1985). Bush (1986*b*), however, points out that this species is not a primary emergent, but a middle canopy tree, which thus must be shade tolerant to some degree; it may be seen regenerating under *Timonius* canopy. The deciduous *T. catappa* is characteristic of the forest just inland of the coast (Bush & Whittaker 1986) usually with *Ficus fulva*, *T. compressicaulis*, *C. inophyllum* and *Hernania peltata*, and in the southeast are areas with *D. gaudichaudianum* and *Ficus retusa* forming the canopy, with some *T. catappa*. Tagawa and his colleagues found an area of *Dysoxylum* forest at an altitude of 50 m in northern Sertung, and at 15 m, some 500 m to the west of this, the forest had *Dysoxylum* and *Terminalia catappa* as

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† Previously identified as *D. caulostachyum* (Whittaker *et al.* 1984; Tagawa *et al.* 1985; Bush 1986*b*).

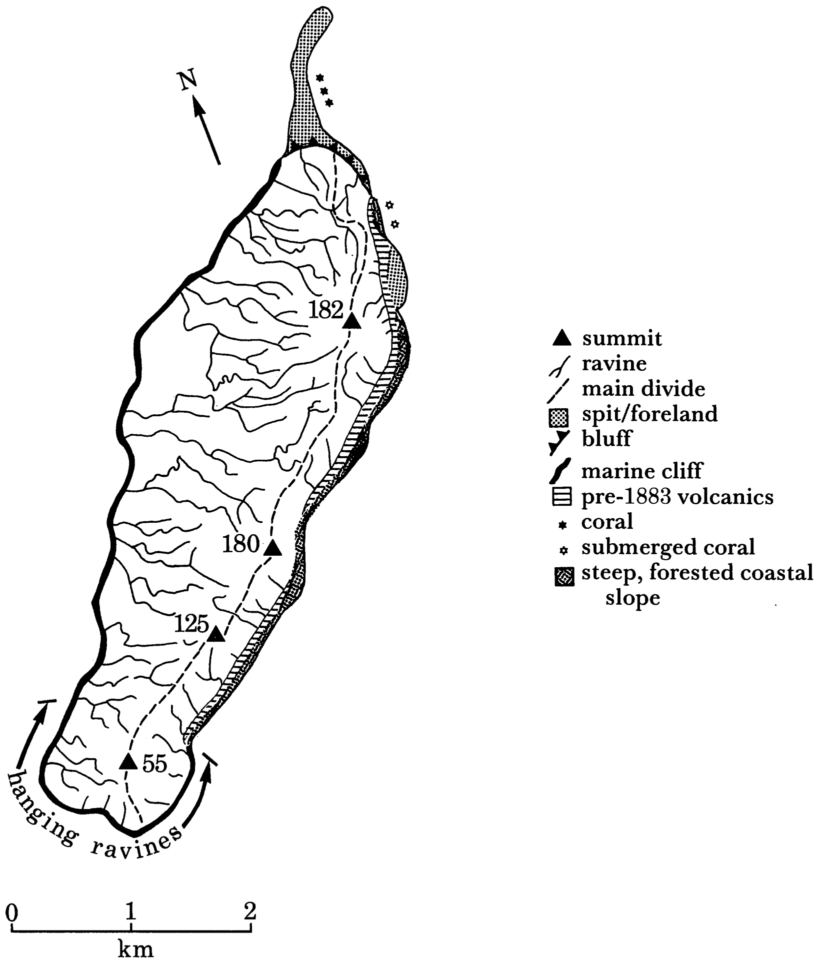

FIGURE 14. Sertung, 1985, showing localities mentioned in text.

co-dominants, with *Gnetum gnemon* characteristic of the shrub layer. Bush & Whittaker found the ridge and east-facing slopes bearing *Dysoxylum* forest, with a rather dense ground flora including *G. gnemon.*

There is a small freshwater spring at the base of a high cliff near the northeast coast about 1 km south of the junction between the spit and the main island, and Stehn (1929) reported another in the southeast.

(ii) *The northern spit*

At the northern end of Sertung, a gently curving sand-spit (figure 17, plate 6) is a dynamic remnant of a much larger feature that developed quickly after the 1883 eruption (Rosengren 1985). A well-defined bluff marks the proximal end of the spit, indicating that in the first few years after the eruption a sea cliff was eroded here into the pumice that blanketed the island. By 1906, the spit had developed as a broad sandy lowland, vegetated by *I. pes-caprae* and *Barringtonia* formations and with 'forest-like' patches of *Casuarina.* At the southeastern end a mangrove-fringed lagoon had been enclosed by spit growth, and by 1919 a second lagoon had developed at the distal end of the spit (Stehn 1929). By 1929 a *Casuarina* woodland covered the spit, but 2 years later, after heavy damage by Anak Krakatau's 1930 eruptive emergence, this had evidently disappeared and been replaced by a 'mixed forest' (Docters van Leeuwen 1936). Aerial photographs in 1946 show the spit to have been 4 km long, but it had narrowed because of substantial loss of material from the western coast, and the lagoons were gone. Shortly after, it was breached, and the longer detached northern sector was dispersed by wave action. The spit is now only 1 km long, averages less than 100 m wide, and the axis lies over 1 km east of the 1908 position and 600 m east of the 1946 position. The southern remnant of the spit has migrated eastward owing to rapid recession of the western coast (figure 16, plate 6), partly balanced by progradation along the eastern coast (figure 18, plate 7). Rosengren & Suwardi (1985) measured rates of erosion (west coast) and accretion (east coast) over a 6 month period in 1981–82 as high as 2.5 m per month and 2.0 m per month respectively, but in the interval between October 1984 and September 1985, erosion was predominant on both coasts. The spit may soon be breached again at its narrowest point as there was evidence in 1985 that complete overwash had recently taken place.

Erosion, overwash and saltwater intrusions have greatly modified the vegetation of the spit since Docters van Leeuwen's description, and it has reverted to the early successional stage, *Casuarina* woodland. The spit is now, and may have been held for some time, at an early stage of vegetational succession dominated by *Casuarina equisetifolia*, with *Hibiscus tiliaceus* as understorey, and *Ipomoea pes-caprae*, *Ischaemum muticum* and *Spinifex littoralis* as ground cover. The *I. pes-caprae* association is vigorous and extensive on the accreting eastern beach (figure 18, plate 7), but erosion on the west coast (figure 16, plate 6), has not permitted its establishment. Because of the erosional régimes, the subaerial life of any part of the spit cannot have been greater than 10–20 years; it would have been prevented from proceeding beyond the *Casuarina* stage by the time constraints imposed by the rate of physical turnover. The spit is now being substantially reduced in area as casuarinas fall into the sea on the western side at a rate in excess of the establishment of new communities on the east.

The spit is clearly demarcated from the main island, not only by the well-defined bluff, but also by its vegetation, and the sharp contrast between the *Casuarina* forest of the spit and the adjacent secondary monsoon forest (figure 17, plate 6) has captured the attention of several expeditions, ours included. Sertung is thus a successional composite, offering an early successional stage for study for a long period of time, contiguous with a much later stage, and in this the island is unique on the Krakataus.

(*e*) *Panjang*

Panjang is a translation of the Dutch *Lang* (or vice versa), and the island is also known, inappropriately, as Rakata Kecil (Small Rakata). It has also been referred to, quite incorrectly, as Danan, with which pre-1883 volcano of Krakatau it has had no association.

The island has received very much less attention from expeditions before the 1980s than have Rakata and Sertung (see §4), only Bristowe (1931) and Dammerman (1948), of the zoologists, spending more than a day there (table 3). It is about the same height (142 m) as Sertung, and is the second smallest of the islands in area (2.7 km^2), being approximately 3 km long and 1.5 km at its widest point (figure 21).

Like Sertung, Panjang is also blanketed by 1883 deposits that built the island to a height of approximately 140 m with a high ridge on the side closest to the 1883 eruption centres with a dissected plateau sloping away from this (figure 19, plate 7). An escarpment some 80 m high thus lies 100 m inland and parallel to the west coast. There is extensive and accessible exposure

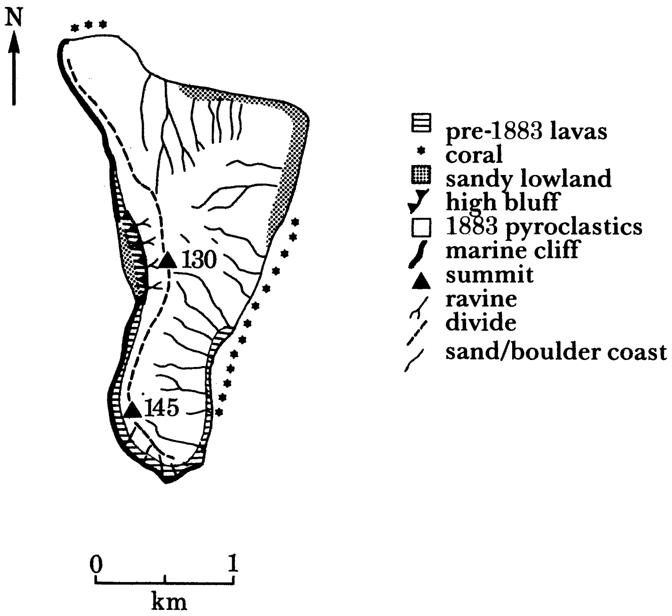

FIGURE 21. Panjang, 1985, showing localities mentioned in text.

of pre-1883 lavas on Panjang, extending along the western coast and around the south of the island to the eastern coast. A broad reef of coral has developed along the eastern and northern margins of Panjang, the growth presumably all post-dating the 1883 eruption which almost certainly would have destroyed existing coral communities (live corals also occur in the bay north of Zwarte Hoek at Rakata and east of Sertung). Panjang lacks the extensive high-cliffed shorelines in 1883 pumice that are such a dominant feature of the coastlines of Rakata and Sertung, and much of the northern (figure 20, plate 8) and eastern coast is fringed by a low sandy terrace built by deposition at the mouths of the numerous ravines that descend towards this coast. In most places, however, this terrace is cliffed at the seaward edge and is being cut back by wave action. This reflects the reduced rate of sediment supply as many gullies have cut back to the central divide exposing less erodeable lavas, and the development of a closed forest canopy has slowed the rate of surface wash.

The pre-1883 lavas that form the cliffed coasts around the southwestern margin of Panjang are strongly fractured. Wave action has etched out weathered zones along vertical fractures, causing collapse of large blocks, which in several places have enlarged and coalesced into narrow elongated clefts or caves. These are sufficiently dry and sheltered to provide bat roosts on the western coast.

In 1982 163 species of vascular plants were found on Panjang by Suriaatmadja (1985) and from 1979 to 1983 approximately 120 species of higher plants were recorded from Panjang by the Hull University expeditions (Bush 1986).

Just inland from the landing beach on the northeast coast the vegetation is mixed *Terminalia* forest, and *Casuarina–Dysoxylum* forest with *Hibiscus tiliaceus* was found at 45 m on steep gully cliffs in northern Panjang (Tagawa *et al.* 1985). In this region also, at the top of the escarpment (70 m) and along the ridge, there is *Dysoxylum* forest, Bush & Whittaker noting specimens up to 33 m high, with *T. compressicaulis* and *Ficus tomentosa* reaching 12 m, an open understorey, and a ground flora dominated by pteridophytes. In the southern part of the island, at 100–125 m above sea level, are *Timonius–Terminalia* and *Timonius–Neonauclea* associations. Tagawa and his colleagues believe that *Timonius* forest, like the *Neonauclea* forest on Rakata, will change in time to *Dysoxylum* forest. Casuarinas grow on Panjang's steep rocky coastal slopes, as they do on Rakata's northern cliff, and Bush & Whittaker (1986) point out that *C. equisetifolia* is more characteristic of disturbed ground than a strictly coastal species; it is found, for example, on the recent volcanic cone within the crater of Mount Rinjani on Lombok.

Suriaatmadja's group made three transects from the coast (two from the east, one from the west) inland for about 0.5–0.7 km. The most striking result of the survey was that no herbaceous species were present from 1 to 20 m elevation, and from 20 to 50 m a *Piper* association occurred. The main differences between this survey and that of Tagawa's group, so far as forest tree species are concerned, is the finding by Suriaatmadja of *Hernandia peltata* as an important dominant from 1 to 50 m, particularly from 1 to 20 m, and the fact that in Suriaatmadja's survey *Timonius compressicaulis* was not found, even at the highest elevations (50–100 m) sampled. Tagawa and his colleagues draw attention to the differences in forest types between Rakata, Sertung and Panjang (Tagawa *et al.* 1985). *Dysoxylum* forest is absent from Rakata, *Neonauclea* forest absent from Sertung and Panjang. They explain these differences by the fact that *Neonauclea calycina*, a heliophilous species, colonized Rakata before 1905, well before the first record of *Dysoxylum* on the island (1979), whereas *N. calycina* was not found on Panjang until 1929 and was then quickly followed by *Dysoxylum* (1932), the closed canopy of which may have prevented invasion by *N. calycina*. Thus Tagawa and his colleagues suggest that the relative timing of the arrival of dominants on the individual islands has determined the type of forest they support today.

Bush (1986*b*) points out that on Sertung the area most seriously damaged by Anak Krakatau's 1930 eruption is now dominated by *Dysoxylum*, and the areas most affected by the 1952 and 1953 eruptions include those now dominated by *T. compressicaulis*. He believes that the differential effects of Anak Krakatau's volcanic activity may be an important factor controlling the distribution of *N. calycina*, *Dysoxylum* and *T. compressicaulis* on the archipelago, and thus the striking differences between the forest types on Rakata and those on Sertung and Panjang. Richards (1986) also cites this as one reason, along with area and physical diversity, for the lower floral diversity on Sertung and Panjang than on Rakata (see also §6*c*), and notes that *Dysoxylum* forest should be regarded not as primary forest but as another transitional community; the species, probably '*r*-dispersed' and with rapid growth, may be an opportunistic colonizer of disturbed areas. He also believes the *Neonauclea* and *Timonius* forests are successional stages that will probably not be entirely superseded as long as volcanic disturbances continue.

A spring, difficult of access, high on the southern coastal bluff, was reported by Stehn (1929).

(*f*) *Anak Krakatau*

Stages in the topographic and volcanological growth of Anak Krakatau since its emergence in 1930 have been monitored closely by various official mapping agencies in Indonesia (Stehn 1929; Neumann van Padang 1951; Sumartadipura 1985; de Neve 1985). The island is an active volcano developed approximately within the Rakata-Danan-Perbuatan lineament. It is now 195 m high with an area of 2.35 km^2, and a diameter of approximately 2 km (figure 22 and figure 25, plate 9).

Four principal topographic zones are evident, each reflecting a particular stage in the

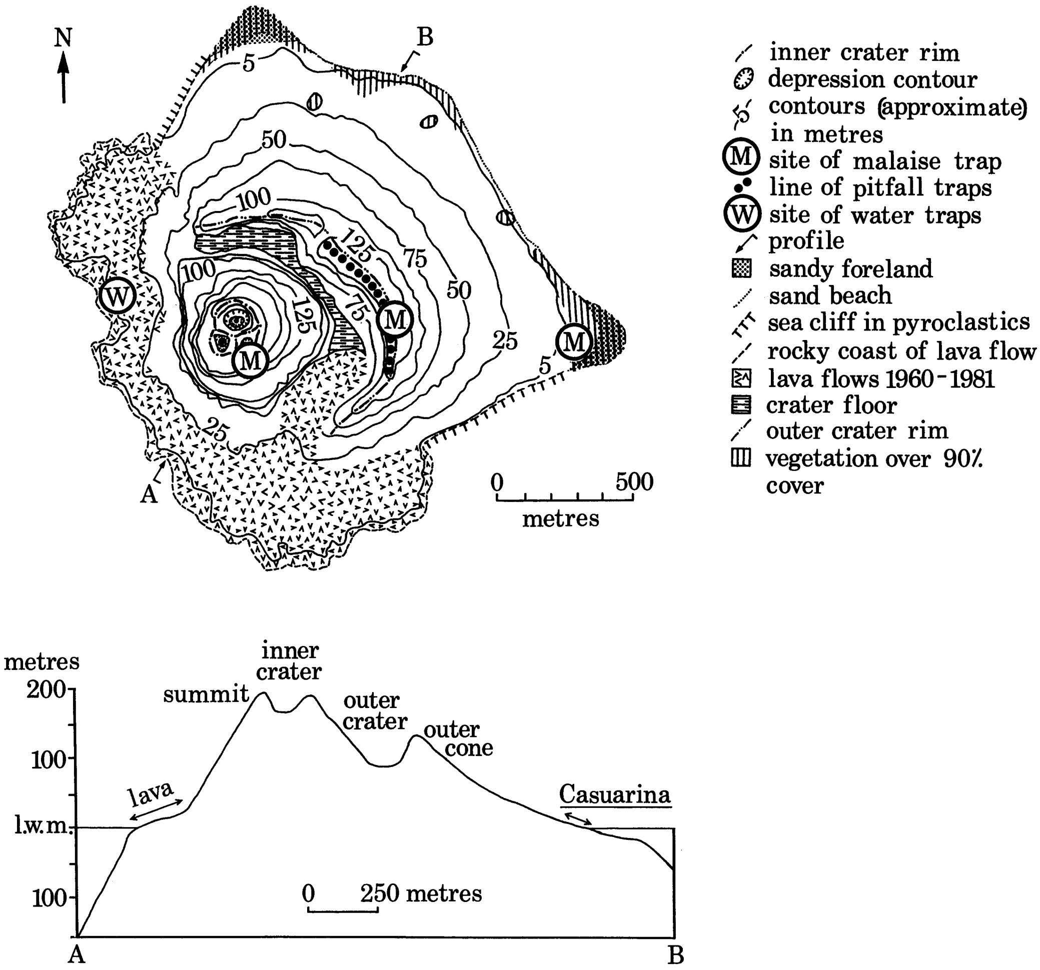

Figure 22. Anak Krakatau, 1985, showing line of transect and features mentioned in text.

growth of the island and each subject to different geomorphological and volcanological processes. These zones are (i) the older outer cone, (ii) the active inner cone, (iii) the lava flows, and (iv) the sandy forelands.

(i) *The older outer cone*

From the emergence of Anak Krakatau IV in August 1930, until 1952, explosive volcanic activity produced a tephra cone up to 1.5 km in diameter and 150 m in height. The cone was markedly asymmetrical with a high crescent-shaped rim on the north and east partly enclosing a crater that frequently opened to the sea on the low southwestern side (figure 23*a*). Development of the southwestern rim was inhibited by submarine sliding on the steep caldera slope, by breaching by storm-wave activity, and by the migration of the centre of volcanic activity towards the southwest (Sumartadipura 1985). From late 1938 until 1952, an equilibrium was reached between the constructive processes of volcanism producing tephra materials to build the island, and the destructive processes of marine erosion that eroded the crater edge and the exposed flanks of the cone (figure 23*b*). Hence the size and shape of the island remained steady over that time. The crater sloped steeply to the sea on all sides and an

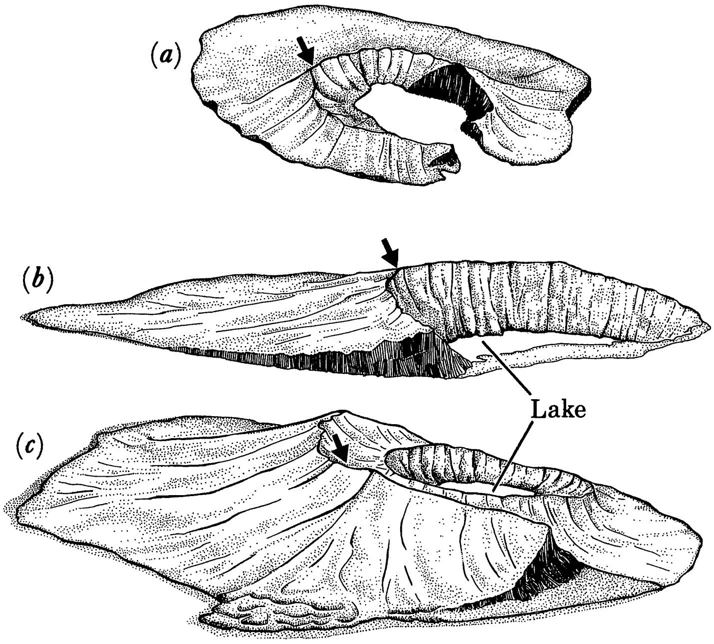

FIGURE 23. The changing form of Anak Krakatau before the first lava flows. Drawings from oblique aerial photographs taken from the west. Arrows identify the same point on each drawing. (*a*), 1931 (cone height *ca.* 50 m); (*b*) early 1952 (cone height *ca.* 130 m); (*c*) 27 Oct. 1952, after major eruption (height of outer cone *ca.* 150 m, inner cone 70 m). Not to scale. Adapted from Bird & Rosengren (1984).

incised radial gully system delivered material to build narrow beaches. Cliffed coastlines developed on all sides but slumping of the crater slopes and accumulations of beach material increased, so that by 1950 a small lobate foreland had developed on the northern margin of the cone. Although very small, it constituted the only stable lowland terrain on the island.

The gradual shift of the eruption centre towards the southwest and the development of the inner cone reduced the accession of tephra to the outer cone and halted its upward growth. Gully incision on the flanks of the cone increased and a second foreland developed on the eastern flank of the cone. Both of these forelands have been extended as described below.

(ii) *The inner cone*

A series of major tephra eruptions, commencing in October 1952 and continuing intermittently until September 1953 (de Neve 1985*b*), closed the breach in the old crater and built a new circular cone 500 m in diameter and overlapping the outer cone on its southeastern rim (figure 23*c*). For several years the floor of the new cone remained at sea level enclosing a crater lake until this was filled by lava flows and further tephra eruptions in 1960–63. Subsequently, this inner cone has built to almost 200 m in height with multiple eruption craters at the summit. In 1985 there were three summit craters (figure 24), the two southern craters being partly rubble filled and the northern crater being flat-floored and veneered with firm dry mud.

(iii) *Lava flows*

The first lava flows were a vitric andesite extruded from the inner cone of Anak Krakatau between late 1960 and early 1963. This flow breached the southern wall of the inner cone and

FIGURE 15. Sertung, from south.

FIGURE 16. Sertung spit, eroding western coast.

FIGURE 17. Sertung, from north. Arrows show line of marked vegetation change at proximal end of spit.

FIGURE 18. Sertung spit, prograding eastern coast, with beach cover of *Ipomoea pes-caprae* and *Casuarina equisetifolia* forest.

FIGURE 19. Panjang, from north, Rakata beyond. Arrows show coral off northern point; cross, approximate position of observation post established in 1927.

FIGURE 20. Panjang from northeast, Rakata and Anak Krakatau beyond.

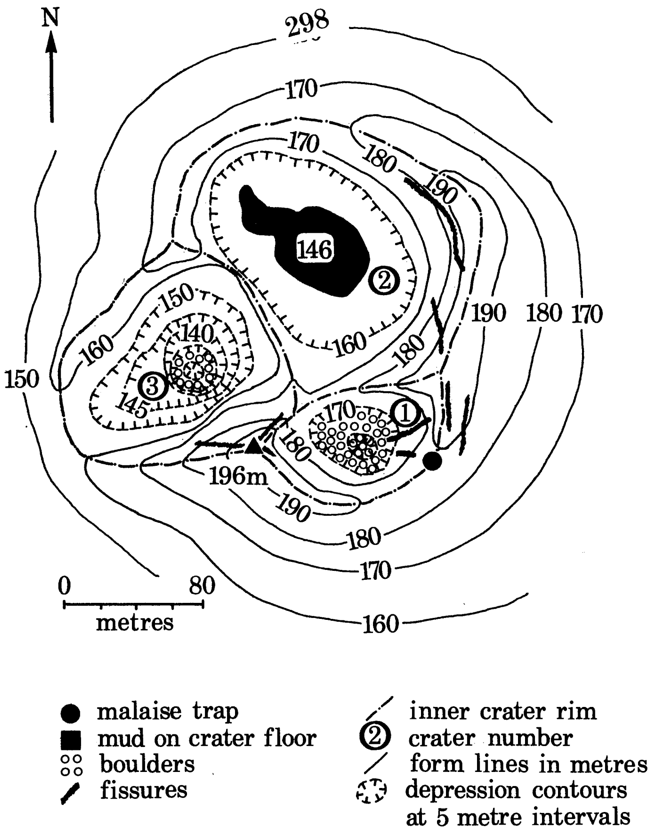

Figure 24. Summit craters, Anak Krakatau, 1985.

built a crescent-shaped rampart into the sea, thus providing the first buttress against wave erosion of this side of the island. Further lava flows were erupted in 1972–73, 1975, 1979 and 1980, the later flows being more basaltic in composition (Effendi *et al.* 1985). These flows now extend around almost 50 % of the coastline of Anak Krakatau and provide a broad and effective shield against wave erosion of the inner cone (figure 26, plate 10).

The lavas are typical aa flows with a very rough rubble covered surface. The 1979–80 flows are deeply fractured and surfaced with loose angular fragments. Numerous spines and spiky crags of twisted lava project above the general surface level, and there are many overhangs, deep crevices and small caverns produced by contortion of the cooling lava. The older flow surfaces are less rough as they have been partly buried by later ash eruptions and many of the irregularities have been infilled.

(iv) *Forelands*

Two prominent lobate projections have developed on the northern and eastern margins of the outer cone providing the most extensive lowland surface on the island (figure 22). The forelands are composite features being partly built by coalescing fans developed at the mouth of gullies and partly extended by coastal deposition as cuspate spits. On the outer cone, flanking the lava flows, eroding tephra cliffs 12 m high are deeply incised by V-shaped gullies that debouch alluvial fans directly on to the beach. These provide sediment that is moved northwards and built into beaches to nourish the growth of the protruding forelands.

Vegetation

Most of the 20 species found as seedlings near the beach in 1932, two years after the island's emergence, were not present in 1949 (Docters van Leeuwen 1936; van Borssum Waalkes 1960). Of this early pioneer stage, only *Barringtonia asiatica*, *Ipomoea pes-caprae*, *Canavalia maritima*, *Erythrina variegata*, *Pandanus tectorius*, *Calophyllum inophyllum* and *Cocos nucifera* survived the first two decades. Six species were newly recorded in 1949, most notably *Casuarina equisetifolia* (first seen from the air in 1947), *Saccharum spontaneum* and *Spinifex littoralis*, and some casuarinas were already 7 m in height. The *Saccharum* occurred as scattered clumps on the ash slopes, and a single fern specimen (*Nephrolepis* sp.) was seen. Eruptions almost annually between 1932 and 1949, when there were no botanical surveys, had probably severely damaged the vegetation, setting back the successional process.

Van Borssum Waalkes (1960) found the vegetation in 1951 was still limited to a strip behind the beach in the east and north. On the east *Spinifex* dominated, with *Ipomoea* and *Ischaemum*, and there were scattered woody plants and *Saccharum*. The casuarinas on the northern part were now about 10 m high. A patch of *Imperata cylindrica* occurred near the eastern shore with pandanus shrubs, *Saccharum* and several newly recorded herbs. The *Saccharum* extended up the slopes to about 25 m, and in gullies small ferns such as *Nephrolepis hirsutula* and *Pityogramma calomelanos* occurred up to about 50 m altitude. *Cassytha filiformis* was fairly common as a parasite of *I. pes-caprae* and *C. maritima*. *Barringtonia asiatica* was not found.

A month after the 1952 eruption only the skeletons of large casuarinas emerged from the blanket of ash that covered the island to depths of 3.0–5.0 m on the slopes of the new cone and up to 0.5 m at the coast; van Borssum Waalkes could find no living plants, although seeds and fruits of coastal plants such as *Barringtonia*, *Pandanus* and *Terminalia* had already been washed up on the beach. It is likely that the vegetation was eradicated in 1952, and another damaging eruption occurred in 1953.

The island was visited by several groups of botanists from 1979 to 1982 (Partomihardjo 1983; Suzuki 1984; Whittaker *et al.* 1984; Partomihardjo *et al.* 1985; Tagawa *et al.* 1985; Bush *et al.* 1986). In spite of almost a score of eruptions in the three decades since 1952 (Siswowidjoyo 1985), that in 1972–73 being very severe, some 66 species of vascular plants were present in 1983 (Barker & Richards 1986). Vegetation covers only about 17 ha†, approximately 7% of the island's area, and is largely confined to alluvial fan deposits and beach deposits of reworked volcanic material on the northern and eastern forelands and the intervening coastal strip (figure 25, plate 9). The upper slopes, eroding ash deposits and lava fields are very sparsely vegetated. Partomihardjo (1983) advances several explanations for the more rapid colonization of Anak Krakatau since 1952 than in the first two decades of its existence: some propagules may have survived the 1952 eruption and subsequent recovery would not then be reliant on oversea dispersal alone; the eruptions since the early 1960s have produced lava flows rather than pyroclastics alone so that physical disturbance was more limited; and the cuspate forelands, which support most of the vegetation, have become significant land form features only in the past 25 years.

An *I. pes-caprae* community on the non-eroding northeast shores includes the herbs *C. maritima*, *Vigna marina*, *Thuaria involuta* and *C. filiformis*, young specimens of the woody *C. inophyllum*, *B. asiatica*, *Terminalia catappa* and *Desmodium umbellatum*, and *C. equisetifolia.*

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† 1 hectare = 10^4 m^2.

Behind the beach community a *Casuarina* association is developed as a forest on the eastern foreland, with some casuarinas 35 m in height (figure 27, plate 11). This has completely replaced a dense *alang alang* (*Imperata cylindrica*) grassland that existed in 1971 (Tagawa *et al.* 1985). In places there is a shrubby understory, including *C. umbellatum*, *Timonius compressicaulis* and *Premna corymbosa*, but in general this forest has a simple structure. Areas opened by tree-fall are filled by *Hibiscus tiliaceus* scrub. A few specimens of the figs *Ficus fulva* and *Ficus septica* were fruiting in 1985, and were almost 20 m in height. Several open glades surrounded by tall trees are carpeted by the grass *Ischaemum muticum*.

The northern foreland is different in character (figure 28, plate 12), being mostly covered by *alang alang* grassland, including the leafless parasite *C. filiformis*, *S. spontaneum* and some casuarinas, with a narrow fringe of *I. muticum* and *I. pes-caprae* on the coast. It is evidently now at a stage similar to that reached by the eastern foreland over a decade earlier.

The ash slopes at nearshore lower elevations support clumps of *S. spontaneum* (which also occurs on the forelands), along with a few *C. equisetifolia*, the creepers *I. pes-caprae* and *C. maritima*, and the grass *I. muticum*, but at higher elevations the accompanying species are gradually lost, and only *S. spontaneum* occurs, in scattered patches gradually thinning up to 120 m elevation on the northern and to 20 m on the eastern slopes of the outer cone. Suzuki (1984) analysed the ability of this pioneer species to colonize unstable ash slopes and the ability of rhizomes to withstand repeated accumulation of volcanic ash to a depth of 60 cm.

On lava flows that are ash covered, such as that of 1973, the ferns *P. calomelanos* and *N. tomentosa* occur, along with some *alang alang*, *S. spontaneum*, *Melastoma affine* and *F. fulva*, the two ferns being pioneers on the flows. A *Nephrolepis* species is a lava pioneer on Hawaii and another follows bryophytes and lichens on Sakurajima volcano (Tagawa *et al.* 1985). Young flows, those near the crater, and those without an ash substrate for plants are barren.

4. PREVIOUS SURVEYS

Although botanical surveys were made soon after the 1883 eruption and have continued fairly regularly until recent times, the first systematic faunal survey of the islands was not made until 1908, 25 years after Krakatau's eruption (Jacobson 1909) (table 3). Subsequent systematic surveys of the fauna were made in 1919–1922, 1924, and 1929–1933 (Dammerman 1948). Unfortunately, previous zoologists have provided little or no details of their survey methods. On Dammerman's expeditions light trapping and the sifting of litter were done, methods not specified by Jacobson. Dammerman, however, was interested in earthworms and is likely to have particularly sampled the soil fauna. The birds were again surveyed in 1951 (Hoogerwerf 1953), other animal groups in 1982 (Yukawa *et al.* 1984; Ibkar-Kramadibrata *et al.* 1986), but no further comprehensive zoological surveys were attempted until recently. Thus the early pioneer phase of colonization by animals was not systematically monitored and until the expeditions of the 1980s complete data on faunal reassemblage was confined to the second quarter of the century since the eruption.

Flenley & Richards (1982), Whittaker *et al.* (1984) and Thornton (1984) have summarized the course of colonization and redevelopment of the biota as known before 1979, and the first two works report the results of the 1979 Krakatoa Centenary Expedition (Hull University and Bogor Herbarium), which made a botanical survey of Rakata, and discuss vegetational succession on the group and the colonization of plants in relation to biogeographical theory.

Table 3. Island coverage in days by zoological expeditions since 1883

(*x*, A few hours; *, zoologist-days.)

year	month	zoologists	Rakata	Sertung	Panjang	Anak Krakatau	total
1888	Nov.	Sluiter (corals)	?	?	?	?	—
1889	Jly	Sluiter (corals)	—	—	—	—	—
1889	?	Strubell (molluscs)	*x*	—	—	—	—
1908	May	Jacobson	3	*x*	*x*	—	3
1919	Apl	Bartels, Sunier (birds)	3	2	*x*	—	5
1919	Oct.	Dammerman	*x*	*x*	—	—	—
1919	Dec.	Dammerman, Groenewege	5	3	—	—	8
1920	Apl	Dammerman	4	3	—	—	7
1920	Sep.	Dammerman, Siebers (birds)	4	3	—	—	7
1921	Apl	Dammerman	—	1	—	—	1
1921	Oct.	Dammerman	1	2	—	—	3
1922	Jan.	Dammerman	2	—	—	—	2
1919–22			*19*	*14*	*x*	—	*33*
1924	Jly	Dammerman	2	1	—	—	3
1928	Feb.	Dammerman	2	—	—	—	2
1929	May	Dammerman	1	1	—	—	2
1930	Jly	Dammerman	1	1	—	—	2
1931	Feb.	Bristowe (spiders)	*x*	—	4	1	5
1932	Nov.	Dammerman	2	1	1	*x*	4
1933	Jan.	Dammerman	1	2	2	*x*	5
1933	Apl/May	Dammerman	4	1	—	—	5
1933	Oct.	Dammerman	2	3	2	*x*	7
1933	Dec.	Dammerman	2	2	1	—	5
1934	Apl	Dammerman	3	1	—	*x*	4
1928–34			*18*	*12*	*10*	*1+*	*41*
1939	Aug.	Dammerman	—	*x*	—	1	—
1951	Oct.	Hoogerwerf* (birds)	10	*x*	*x*	*x*	10
1952	Nov.	Hoogerwerf* (birds)	—	*x*	—	*x*	1
1982	Jly	Ibkar-Kramadibrata *et al.**	—	—	15	25	40
1982	Jly, Aug.	Yamane*	7	6	4	2	19
1982	Oct., Nov.	Yukawa *et al.**	15	15	9	9	48
1982	Nov.	Thornton* (Psocoptera)	1	1	1	*x*	3
1983	Sep., Oct.	Thornton* (Psocoptera)	4	—	—	*x*	4
1984	Sep.	Thornton *et al.**	119	26	16	37	198
1985	Aug.	Thornton *et al.**	39	18	21	49	127
1982–85*			*185*	*66*	*66*	*122*	*439*

The report of the 1982 Kagoshima University Expedition to the Krakataus (Tagawa 1984), which includes studies on both plants (Tagawa *et al.* 1985) and animals (Abe 1984; Evenhuis & Yukawa 1986; Iwamoto 1986; Kanmiya & Yukawa 1985; Yamane 1983; Yamane & Tomiyama 1986; Yukawa 1983, 1984*a–c*, 1986; Yukawa *et al.* 1984; Yukawa & Yamane 1985), is also highly relevant to the present work, as is the botanical report of Partomihardjo (1983). A second botanical expedition by Hull University and the Bogor Herbarium, done in 1982, is reported upon by Bush & Richards (1986).

Because Anak Krakatau's biota was very largely destroyed by eruptions in 1952 (van Borssum Waalkes 1954, 1960) and the vegetation again very severely damaged in 1972, it is effectively no more than about three decades old. Barker & Richards (1982) studied the vegetation of the eastern foreland in 1979 and recorded 49 species of vascular plants, and Partomihardjo (1983) recorded 62 species of vascular plants present in 1982. Bush (1986*b*) found 66 species in 1983. Hoogerwerf (1953) listed four non-migrant birds seen on Anak Krakatau in 1951, but did not believe any were permanent inhabitants of the island even before the 1952 eruption. Until our 1984 and 1985 expeditions the only zoological surveys of Anak Krakatau since 1952 were in 1982 by the Japanese and Indonesian teams and in 1982 and 1983 by Thornton (Psocoptera), and did not cover the birds.

5. The 1984 and 1985 expeditions

(a) *Aims*

The main object of our 1984 and 1985 expeditions was to provide a faunal datum line for the archipelago for as many animal groups as possible for comparison with past and future surveys, and in particular to complement the work of the Kagoshima University group in 1982 by making thorough specialist surveys of birds, reptiles, land molluscs and insect groups not covered by that expedition. Using the data obtained, with the results of the Japanese expedition and the ornithological survey of Hoogerwerf, a reassessment of the biogeographical significance of the Krakataus' fauna over a wide range of animal groups in the light of the equilibrium theory of island biogeography is attempted.

Geomorphological interest in the Krakataus centres on the nature of shoreline change and on the response of the different volcanic materials to processes of slope development and rate of weathering and valley development. In coastal geomorphology the principal research aims were to extend and revise maps of coastal geomorphology compiled during previous visits, and to sample and map the distribution of volcanic and beach materials.

(b) *Coverage*

(i) *Coverage in* 1984

The 1984 expedition, from 24 August to 28 September comprised 27 biologists, a geomorphologist, a photographer and three cooks. There were specialists in birds (4), reptiles (2), land molluscs (3), land arthropods (15), plants (2) and conservation (1).

To sample the possible source faunas on either side of Sunda Strait and to minimize collecting pressure on the Krakataus at any one time, we intended to give equal coverage to an area in Barisan Selatan National Park, Sumatra; the western, hilly region of the Ujung Kulon peninsula, Ujung Kulon National Park, on Java; and the Krakatau Islands (figure 1). Three teams were formed with the intention that each should work for the same period of time in each study area, the teams changing twice so that each area would receive equivalent attention. For bureaucratic and logistic reasons, this plan had to be modified, the Sumatran coverage being drastically curtailed. Coverage of the study areas was thus uneven, the Krakataus receiving greater coverage than the Ujung Kulon peninsula and Barisan Selatan National Park together (table 4).

Table 5 shows the 'field ratio' of the 1984 expedition, i.e. the ratio of effective days in the field to the total time spent on the expedition. This ratio, 50%, is evidently about what may be expected for a tropical expedition.

Because of the difficulties mentioned above, work in the Barisan Selatan National Park on Sumatra was limited to 4 days at Kubuperahu, at 700 m elevation, some 8 km west of the village of Liwa, and some insect collecting and study of coastal geomorphology near the village of Krui on the west coast (figure 1). The Kubuperahu site was a river valley and adjacent

Table 4. Coverage of study areas in man-days of field work, 1984 and 1985

	1984	1985	total
southern Sumatra	33	—	33
west Java			
Ujung Kulon	158	—	158
Carita area	12	11	23
	170	*11*	*181*
Krakatau Islands			
Rakata	139	43	182
Sertung (north)	30	20	50
Panjang (north)	18	23	41
Anak Krakatau	43	54	97
	230	*140*	*370*

Table 5. 'Field ratios' of expeditions

(Units: collector-days.)

	total expedition (*A*)	waiting, administration	travel	sick	collecting (*B*)	*B*/*A* (%)
1984	867	192	198	44	433	50
1985	239	54	33	1	151	63
total	1106	246	231	45	584	53

north-facing hillside of disturbed secondary rain forest where there was some selective logging, and where Siamang (*Hylobates syndactylus*) were common.

On Java, preliminary, familiarizing collecting in some groups was done around the village of Carita (figure 1) and the adjacent foothills, in agricultural land and greatly disturbed secondary forest.

At Ujung Kulon (figure 1), together with the Krakataus constituting the Ujung Kulon National Park and containing the only population of the Javan Rhinoceros, collecting was concentrated at Pulau Peucang, Cidaon, Cibunar, Gunung Payung, and the west coast south to Cikalappabeurrem. There was some shifting cultivation here before 1883, but since the tsumanis of that year, which inundated low-lying areas and overwashed the peninsula's narrow neck, the area (some 300 km^2) has been undisturbed wilderness and uninhabited except by park guides on Pulau Peucang.

All islands of the Krakatau group were sampled; their coverage is set out in table 4. Rakata, easily the largest and highest island, received by far the most attention in 1984. The coverage of Anak Krakatau's small vegetated area in that year was probably adequate, that of Sertung and Panjang inadequate.

(ii) *Coverage in* 1985

The 1985 expedition, from 10 August to 31 August comprised ten biologists, a geomorphologist and a cook. The biologists included were specialists in bats (1), birds (1) reptiles (2) land arthropods (5) and bacteria (1).

Table 5 shows the 'field ratio' of the 1985 expedition, which, at 63%, is a good one. Coverage of the islands was intentionally uneven (table 4), this time Anak Krakatau receiving the most attention.

(*c*) *Survey methods*

We believe it is important to report our methods in some detail so that, in contrast to the present situation, workers in the future can make comparisons in a context of known survey methods.

(i) *Geomorphology*

In 1984 details of nearshore topography of Anak Krakatau and Sertung were mapped by echo-sounding traverses from boats. Foot traverses were made around all of Anak Krakatau, all accessible parts of Rakata (approximately 75%), and the northern section of Sertung. Observations and photographs of other coastal sectors were made from boats and during an aerial survey.

A theodolite traverse was done across Anak Krakatau in 1985. This commenced at a point on the eastern coast midway between the two sandy forelands, crossed the outer cone, traversed the rim of the inner cone to the highest point on the island, and descended to the lava flow coast on the western side near the southern gravel beach (figure 22). Measurements were also made along the southern shore of Anak Krakatau to determine cliff height, depth of gully incision, tephra stratigraphy, and amount of cliff recession since 1981. A theodolite traverse was done around Sertung spit to supplement the compass and pace survey of 1984, and a similar traverse was commenced around the southern coast of Rakata from Owl Bay to Turtle Beach south of Zwarte Hoek. A high resolution echo sounder was used to chart seafloor profiles in 1985.

(ii) *Bacteria*

In 1984, soil samples (four collections at each site, 5 cm below the surface) were taken on Rakata at Zwarte Hoek, at heights of 250 and 500 m on the west ridge, and at the summit. Samples on Anak Krakatau were taken on the east foreland beach and the summit crater, and on Sertung on the northern spit 50 m inland from the east coast. On the Ujung Kulon peninsula, samples were taken at Cibunar near the coast, and on the summit of Gunung Payung (480 m).

In 1985, samples (five collections) were taken at 13 sites along a north–south transect of Anak Krakatau, which passed over the summit crater (see §3 and figure 22). On Sertung, five samples were taken along an east–west transect of the spit, and two from the adjacent forest to the south. Samples were also taken at two sites in Carita village, west Java.

Rectal swabs were taken in 1985 from 81 individuals of 13 species of vertebrate; 23 of these individuals were taken at Carita, west Java, and 58 on the Krakatau Islands.

(iii) *Terrestrial arthropods*

The extent and nature of active collecting at various study sites in 1984 are shown in table 6.

Arthropods were collected by direct search under bark, logs and rocks, by pole pruning and by beating, sweeping, netting and extraction from litter with Winkler apparatus. Individual entomologists tended to specialize in one or more of these methods and used them consistently at all collecting sites.

The extent of trapping in 1984 at the various study sites is shown in table 7. Light traps (both UV and white lights), water traps, fruit baits, pitfall traps and Malaise traps were employed. The light traps were simple 6 W fluorescent lights suspended against a white sheet 2 m above

Table 6. Insect collecting at various study sites in 1984

(In collector-hours, except L, Winkler apparatus litter extractions.)

	B	S	N	DS	DA	W	total collector-hours	L
Carita (west Java)	37	—	—	—	—	7	44	—
Sumatra								
Tanjung Karang	4	—	—	—	—	—	4	—
Penang (coast)	1	—	—	—	—	—	1	—
Liwa river area	21	—	9	3	—	—	33	2
Liwa hill	23	—	9	2	1	—	35	—
Krui	2	—	—	—	—	—	2	—
Belimbing/Tempang	21	—	—	—	—	—	21	—
							96	
Ujung Kulon (west Java)								
Pulau Peucang	31	42	7	13	1	11	105	1
Cibunar	12	3	—	—	1	14	30	1
Gunung Payung summit	16	3	1	4	2	8	34	—
Cidaon	6	—	—	4	—	7	17	—
Cikalappabeurrem coast	4	11	—	12	—	—	27	—
							213	
Krakataus								
Rakata Zwarte Hoek	13	13	9	17	1	25	78	2
Rakata West Ridge 250 m	19	2	—	8	—	9	38	1
Rakata summit	8	3	6	3	—	9	29	1
Rakata South Bay	8	—	—	3	—	7	18	—
Rakata Owl Bay	6	6	—	—	—	—	12	—
Rakata south slope	12	—	—	—	—	—	12	—
Panjang	19	9	—	6	—	6	40	1
Sertung	11	12	—	8	—	13	44	1
Anak Krakatau	16	19	2	7	—	14	58	1
							329	

B, Beating; DA, damage assessment; DS, direct search; L, litter sample; N, netting; S, sweeping; W, wood investigation.

Table 7. Extent, in days, of various methods of insect trapping in 1984 at main study sites

	light	pitfall	water	Malaise
Sumatra				
Liwa river area	31 Aug. 1, 5, 7 Sep.	5 Sep.	5 Sep.	—
Liwa hill	6 Sep.	6 Sep.	6 Sep.	—
Ujung Kulon				
Pulau Peucang	10–15 Sep.	13–15 Sep.	—	31 Aug., 4 Sep.
Cibunar	12, 13 Sep.	—	—	—
Gunung Payung summit	12 Sep.	12–13 Sep.	—	12–13 Sep.
Cidaon	15 Sep.	15 Sep.	—	—
Ciramea, west coast	19 Sep.	—	—	—
Krakataus				
Rakata Zwarte Hoek	9–21 Sep.	—	—	—
Rakata 250 m	18 Sep.	6–22 Sep.	19–22 Sep.	6–22 Sep.
Rakata summit	18 Sep.	4–19 Sep.	—	4–19 Sep.
Panjang	—	—	—	—
Anak Krakatau (southwest)	—	—	21–23 Sep.	—

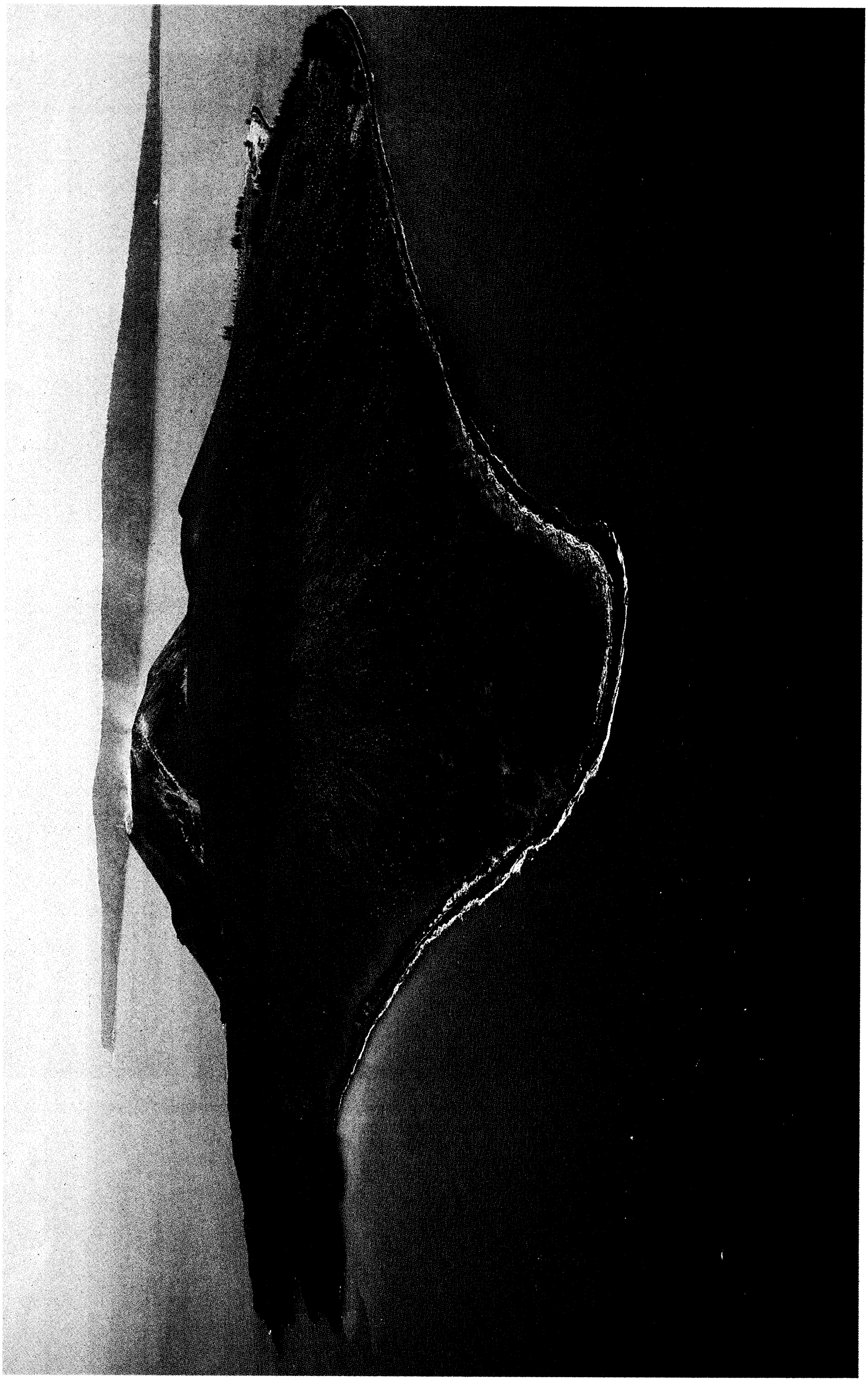

FIGURE 25. Anak Krakatau, from east.

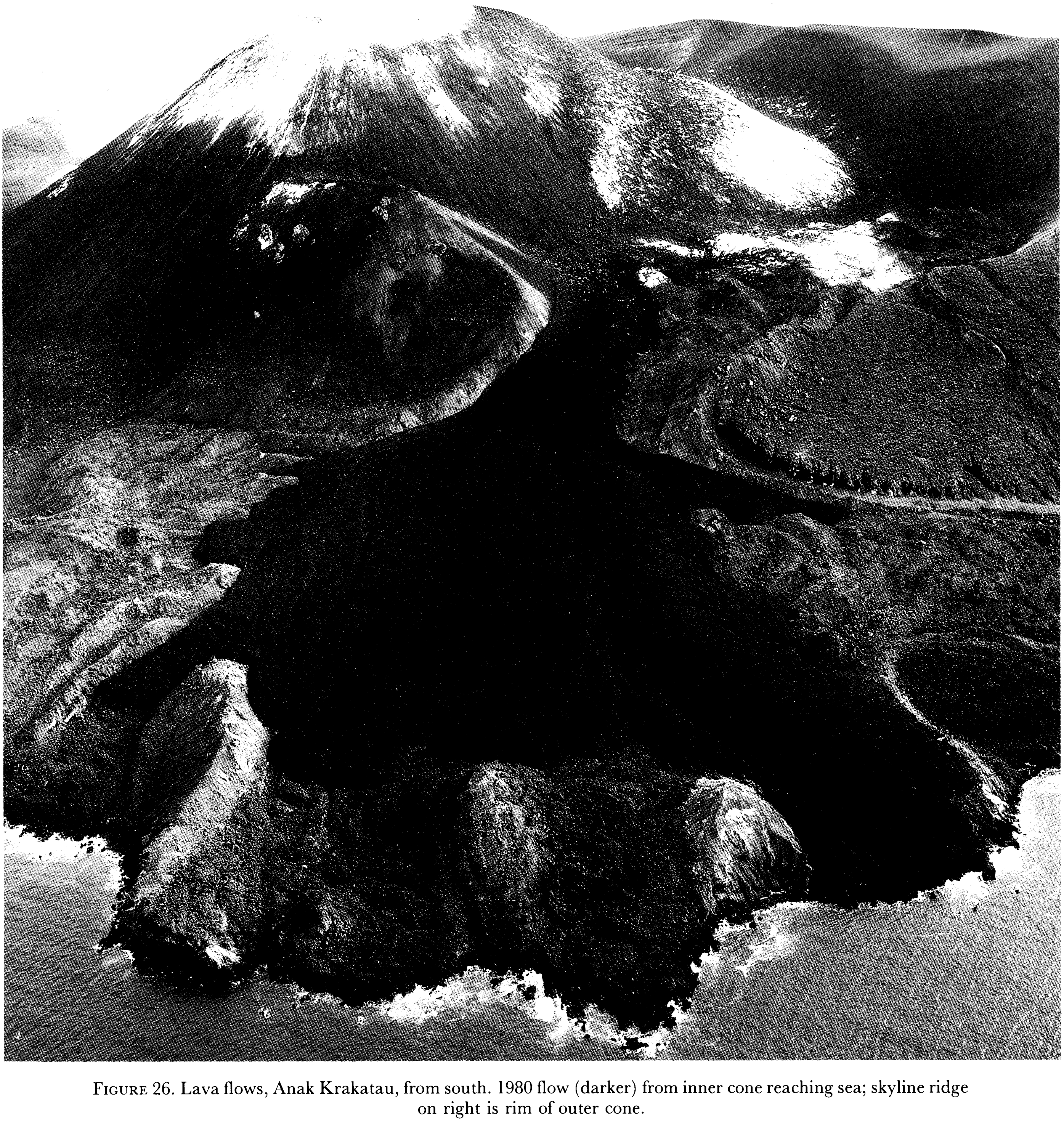

FIGURE 26. Lava flows, Anak Krakatau, from south. 1980 flow (darker) from inner cone reaching sea; skyline ridge on right is rim of outer cone.

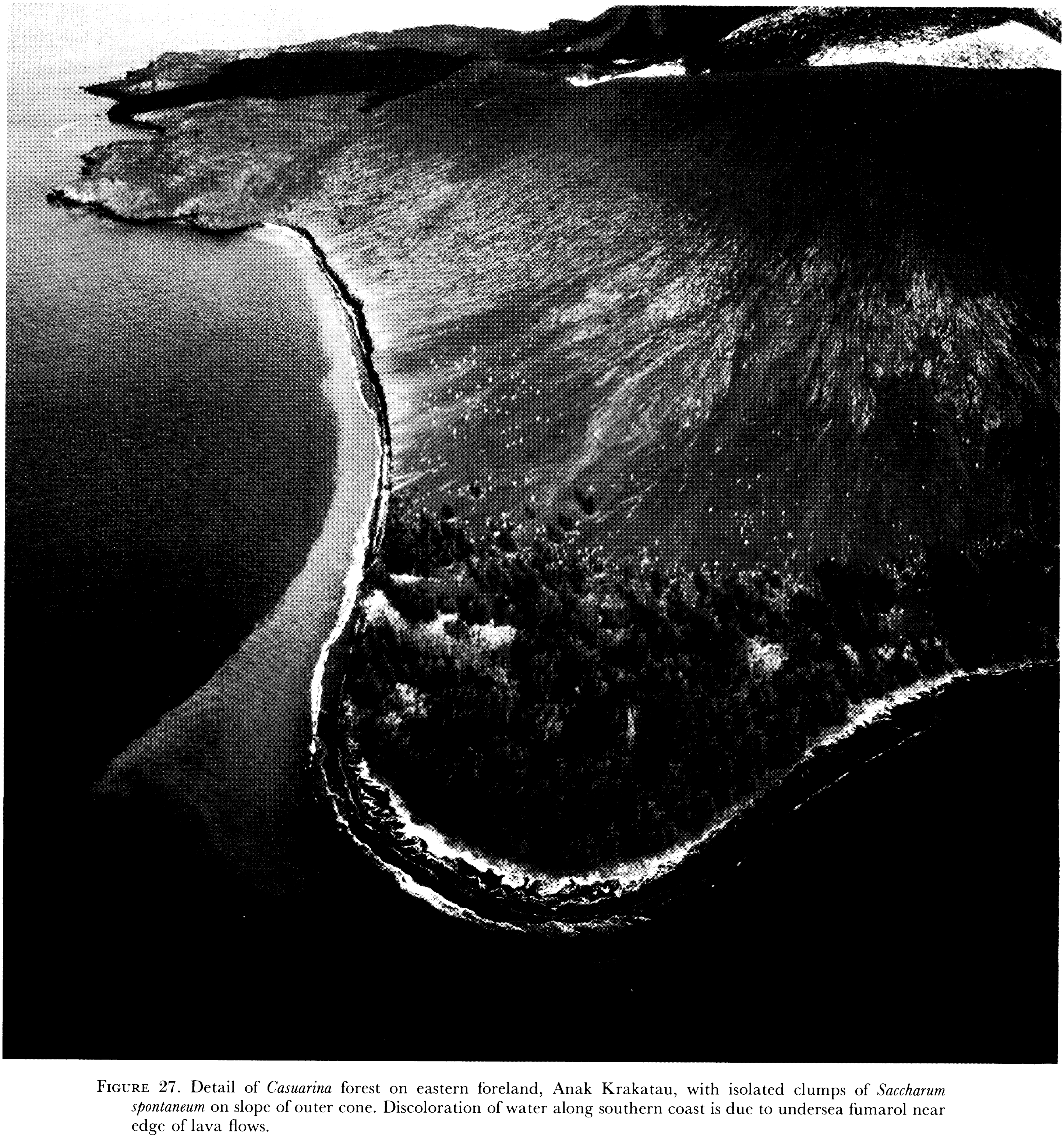

FIGURE 27. Detail of *Casuarina* forest on eastern foreland, Anak Krakatau, with isolated clumps of *Saccharum spontaneum* on slope of outer cone. Discoloration of water along southern coast is due to undersea fumarol near edge of lava flows.

FIGURE 28. Detail of northern foreland, Anak Krakatau, with a broad zone of *Ischaemum muticum* grassland, scattered casuarinas, and clumps of *S. spontaneum* on slope of outer cone.

Figure 29. Ash-covered lava flows on west coast, Anak Krakatau. Arrow shows site of 1985 water traps.

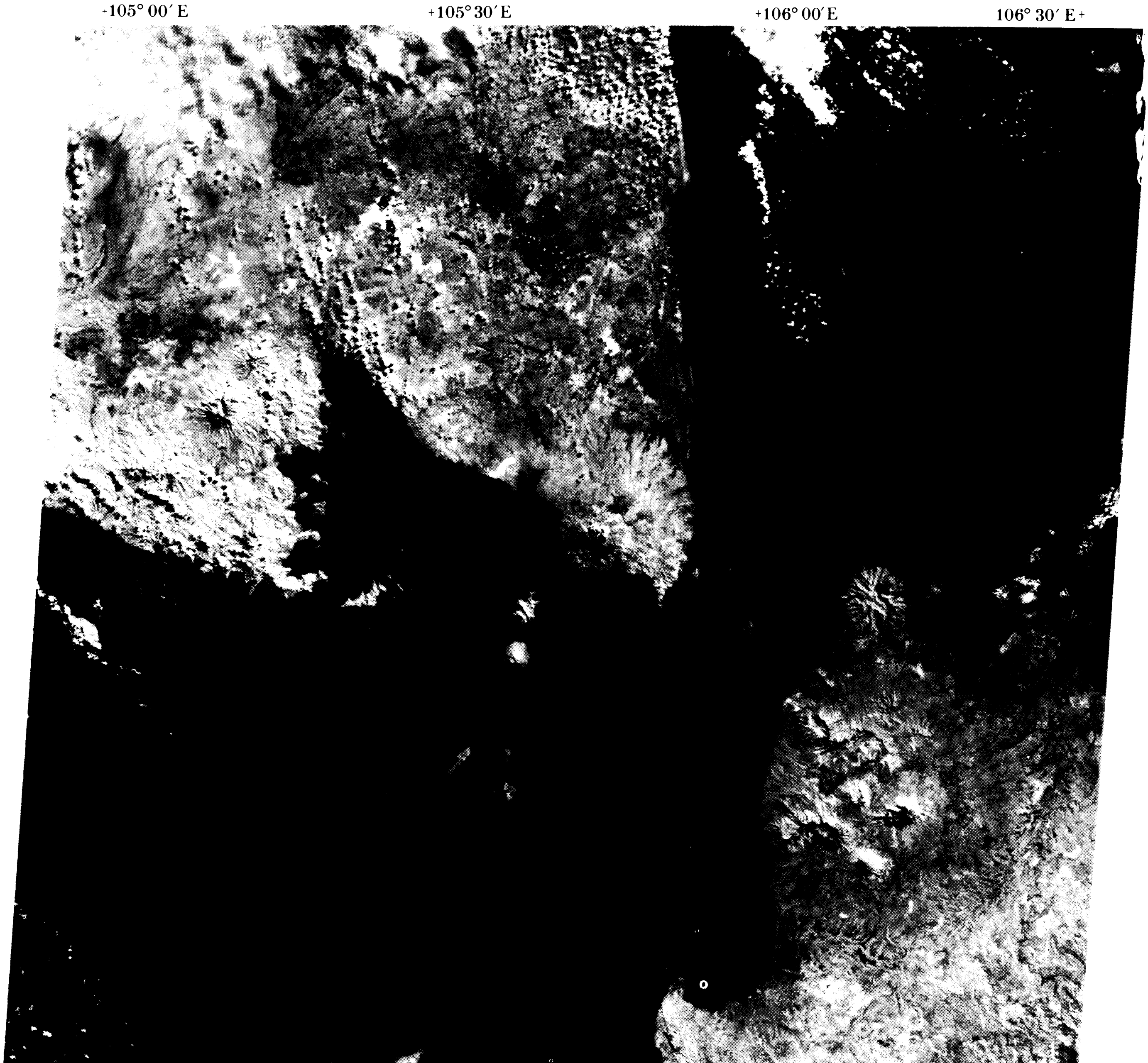

FIGURE 30. Satellite image of northern Sunda Strait showing Gunung Rajabasa on the southern promontory of Sumatra, and to the south the islands of Sebuku and Sebesi, and the Krakatau islands. The Sertung spit and Anak Krakatau, which lack cover by broad-leaved vegetation, do not appear on this image (see §6*d*). Landsat, Band 7, 19 June 1983.

ground level, insects being collected from the sheet from dusk until 23h00. Insects were also caught at camp lights. Water traps consisted of white or yellow plastic trays, 24 cm × 24 cm, containing seawater mixed with a little seawater soap. Pitfall traps were plastic cups sunk in the ground. Flooding was a problem on the Krakataus in early September. The Malaise traps were set up with cyanide bottles; ants invaded the Rakata trap at 250 m in late September.

In 1985 the range of techniques employed in 1984 was again utilized, with greater emphasis on 'passive techniques' such as Malaise traps, which this time were provided with alcohol bottles.

Sertung and Panjang, and the southern side of Rakata were somewhat undersampled in 1984. In 1985 sampling on Sertung and Panjang was more concentrated and comprehensive, and more time was spent on the southern side of Rakata than in 1984. Collections at various heights on southern Rakata, from sea-level to the summit (see §3 and figure 7), were made by direct search, beating, netting, sweeping and light-trapping, and a Malaise trap was operated near the shore at Owl Bay.

Most effort in 1985 was directed towards making a substantial collection of arthropods from Anak Krakatau. The vegetated areas were comprehensively sampled by the above techniques and pitfall traps, and a Malaise trap was sited in the *Casuarina* area of the east foreland (figure 22) for 6 days. Malaise traps were also operated on the rim of the outer cone (150 m) for 9 days and on the inner cone on the southeast rim of Crater 1 at 187 m for 4 days (see §3, and figures 22 and 24). Strong, gusty winds necessitated anchoring of the traps and occasional repairs and re-erections. A series of 50 pitfall traps was laid out along the rim of the outer cone (figure 22), and monitored for 9 days. A series of water traps was set up in ash-covered lava on the barren western side of the island near sea-level (figure 22 and figure 29, plate 13). Two patterns of water trap were used: white plastic 'pot' containers (19 cm × 19 cm) of low UV reflectance, at ground level, and the same mounted on posts at *ca.* 1.5 m above the ground. The water traps were monitored daily for 10 days.

(iv) *Soil nematodes*

Soil samples for nematodes were made only in 1985. Samples were taken on Java from the township of Labuan, the village of Carita, and the forest behind Carita (figure 1). On the Krakataus, samples were taken on Anak Krakatau (under *Casuarina*, *Ipomoea* and *Saccharum*, and on the transect across the island (figure 22)); northeast Panjang (forest); Sertung (along a transect across the ecotone from the spit to the forest); and Rakata (under *Ipomoea* on the shore and at 400, 550 and 777 m during the summit climb (see §3 and figure 7)).

(v) *Land molluscs*

Three specialist collectors of land molluscs were present only in 1984, and all islands were explored, but south Sertung, south Panjang and much of west Rakata were not investigated.

(vi) *Reptiles*

Three reptile specialists were present in 1984, two in 1985. All islands were covered, but again southern Sertung, southern Panjang and most of west Rakata were not covered.

(vii) *Birds*

In 1984 all four islands were surveyed for birds. Coverage was opportunistic to some degree, and although all major vegetation types on all islands were visited, the extent and intensity of survey was not proportional to extent of the habitats. Thus, for example, Panjang was undersampled in comparison with the much smaller vegetated area of Anak Krakatau (table 8).

TABLE 8. DURATION AND INTENSITY OF BIRD SURVEY METHODS AT STUDY SITES ON THE KRAKATAU ISLANDS IN 1984

(Visual survey in man-hours, figures in parentheses are additional hours spotlighting; mist-netting in square metres of net multiplied by number of rain-free hours for which nets were set; sound recording in hours.)

island	site	visual survey	mist-netting	recording
Rakata	Zwarte Hoek	48 (6)	3446	—
	West Ridge to 250 m	42 (4)	1011	—
	West Ridge 250–777 m	25	—	—
	South Bay	34 (4)	1456	1
	total	149 (14)	5913	1
Sertung		38	260	—
Panjang (north)		17	284	—
Anak Krakatau		47 (5)	2272	2
Bootsmansrots		0.3	—	—
total		251.3 (19)	8729	3

The four ornithologists in 1984 worked in pairs, and species that were identified from observation alone were confirmed by at least two ornithologists. Three of the ornithologists had previously worked in southeast Asia (Indonesia and Malaysia).

Mist-netting was undertaken on all islands in 1984 but was opportunistic. Most of the nets were 12 m × 3 m with a 32 mm diagonal mesh size; 9 m nets were erected in dense vegetation, and on Anak Krakatau the 18 m nets were used in open areas. All birds captured were identified and the moult in the right wing scored; many were also weighed and measured and some photographed. All but 8 of over 100 individuals captured were released within 2 h of capture. Of the eight retained, one had died in the net, one was found injured on the beach, and the remainder were needed for confirmation of identifications and were later matched to skins in the collection of the Ornithology Department of the Museum Zoologicum Bogoriense.

The dawn chorus was recorded for 1 h at South Bay on Rakata and for 2 h on Anak Krakatau. Recordings were used to confirm the presence of the Lesser Coucal on Anak Krakatau.

In 1985 methods were basically the same as in 1984; however, there was only one ornithologist on the 1985 expedition in contrast to the four in 1984. A tape-recorder was used more extensively to record calls and songs as well as to play tape loops of sounds of species that might be expected to occur. Mist-netting (table 9) was less extensively used than in the previous year, and a greater attempt was made to visit all habitats (table 10). Previous familiarity with Krakatau birds meant that many more species could be identified by call alone than was possible in 1984. Fruit pigeons were the only birds whose calls caused identification problems. On Anak Krakatau the number of pairs of birds was estimated by recording the number of singing birds along a transect of the coastal strip of vegetation.

Table 9. Location and extent of bird mist-netting on the Krakatau Islands in 1985

(Mist-netting measured as in table 8.)

island	site	date	duration	m^2 h	total
Anak Krakatau	East Foreland	13 Aug. 85	16h00–18h30	150	390
		14 Aug. 85	06h30–10h30	240	
Panjang	northwest (Bunker Ridge)	16 Aug. 85	12h30–18h30	216	504
		17 Aug. 85	05h30–13h30	288	
Sertung	spit	18 Aug. 85	09h45–18h30	315	(699)
		19 Aug. 85	06h13–10h10	144	
		18 Aug. 85	10h30–18h30	240	
	ecotone/*Dysoxylum*	18 Aug. 85	11h06–17h10	216	(558)
		19 Aug. 85	06h30–09h45	117	
	Dysoxylum	18 Aug. 85	12h00–17h00	150	
		19 Aug. 85	07h00–09h30	75	
			Sertung total		1257
Rakata	South Bay	22 Aug. 85	15h00–17h00	144	144
total					2295

Table 10. Duration and intensity of bird survey methods in 1985 at study sites

(Units as in table 8.)

island	site	visual survey	recording	mist-netting
Rakata	Owl Bay	12	—	—
	South Bay	3	—	144
	eastern ascent	4	—	—
	summit	10	—	—
	southern descent	3	—	—
	Händl's Bay	0.4	—	—
	total	32.4	—	144
Sertung	spit	6	—	699
	northern forest	7	1	558
	total	13	1	1257
Panjang	north	2	—	—
	northwest	15 (2)	1	504
	central west	11 (2)	—	—
	total	28 (4)	1	504
Anak Krakatau		32 (1)	3	390
total Krakataus		105.4 (5)	5	2295

(viii) *Mammals*

Bats were captured in 1984 in mist-nets and harp traps. The mist-nets were those used for birds, and were simply left up overnight. The collapsible harp traps were a modification of the design by Tidemann & Woodside (1978), and had a collision area of 4.5 m^2. They were left in continuous operation at Zwarte Hoek on Rakata. The 1984 expedition did not include a bat specialist.

In 1985 a bat specialist was included in the expedition, and three lightweight portable harp traps (Tidemann & Woodside 1978) and an ultrasound detector were used. Most attention was paid to Rakata (eight man-days), particularly the southeast coast and Zwarte Hoek areas. Two man-days were spent on Sertung and four on Panjang, mostly in the north and on the west coast, where several bat caves were discovered. Three man-days were spent in the small vegetated area of Anak Krakatau, and the ultrasound detector was extensively employed in an attempt to detect insectivorous species.

Elliott traps were set for rats in 1985 only. Twenty-five traps were set at the following locations: Anak Krakatau (six nights); north Sertung (one night); north Panjang (one night); Owl Bay, Rakata (five nights); South Bay, Rakata (one night); Carita village, west Java (three nights).

6. BIOGEOGRAPHICAL CONSIDERATIONS

(a) *The biogeographical significance of the Krakataus*

The Krakatau Islands have significance for students of biotic succession and those interested in the equilibrium theory of island biogeography (see §1).

As a case study in vegetational primary succession, the archipelago has been treated by Richards (1952), Whittaker *et al.* (1984) and Tagawa *et al.* (1985). Dammerman (1948) analysed his own and previous studies up to 1934 for the course of faunal succession.

MacArthur & Wilson (1967) analysed the data on recolonization of the Krakataus by plants and land birds up to 1934 in the light of their equilibrium theory of island biogeography, evidently being unaware of surveys of these groups made in 1951–52 (van Borssum Waalkes 1960; Hoogerwerf 1953). They drew attention to an evident paradox, the birds apparently having reached equilibrium numbers by 1908–1919, although land plant species numbers were clearly far from equilibrium at this time. The results of the 1951–52 surveys, and subsequent ones since 1978 (Flenley & Richards 1982; Tagawa 1984; Bush & Richards 1986; and our expeditions), may now be considered together with the data available to Macarthur & Wilson. Whittaker *et al.* (1984) made such an assessment in the case of the flora of Rakata and found some evidence of a dynamic equilibrium, which they believed may represent the end of the penultimate phase in the development of the island's flora and the beginning of a slow progression towards 'primary' forest. Richards (1986), however, reassessing the situation after the Hull University survey of 1983 and the work of Tagawa's group in 1982, concluded that since 1934 species have been added at the rate of about three every two years. Although about 70 species have been replaced in this time, immigration is exceeding extinction and an equilibrium has certainly not been reached. In a later paper of this series a similar reassessment of the bird data will be made.

The vast majority of studies concerning island biogeography have concerned animals, and more particularly vertebrates, with a major emphasis on birds. The opportunity is presented by the Krakatau case to examine other groups of animals also (for example ants, butterflies, reptiles and bats) over the same period of 100 years in the same developing ecosystem, and to compare such parameters as immigration, extinction and turnover rates for various segments of the fauna. We may be able to determine, for example, whether or not it is possible for one component of a fauna to reach equilibrium while others are still growing in species numbers, and to recognize inter-relationships between the colonization parameters of different components of the biota.

We also hope that our surveys will be of value to future reassessments over the next century, so that this important natural experiment may be monitored to its conclusion.

(*b*) *Problems of intersurvey comparisons*

(i) *Differing extent, intensity and completeness of surveys*

Whittaker *et al.* (1984) have drawn attention to the difficulties involved in comparisons between botanical surveys of different lengths at varying time intervals and of different intensities and geographical coverage. These problems are exacerbated when coverage and survey methods and intensity have not been explicitly stated, and considerable caution is necessary in interpreting differences between surveys.

All the above factors also obfuscate comparisons between faunal surveys, which on the Krakataus have been rather less frequent than botanical ones, particularly in the crucial first few decades after 1883. Some problems are increased in the case of animal surveys. Taxonomic uncertainties, always a problem with tropical forest plants, may constitute a more important source of error in the case of some animal groups such as insects and spiders, which are often still incompletely known in tropical areas. Incompleteness of surveys is obviously an even more likely source of error in the case of animals than it is in plants; mobility of animals and their often secretive habits mean that they must be actively collected or trapped. Differences in trapping or collecting techniques may thus result in differences between faunal inventories that constitute a large component of pseudoturnover (see below).

For example, in 1984, although we employed specialist harp traps for bats, no bat specialist was present. In 1985 a bat specialist was included in the expedition, and ultrasound detection was used as well as harp traps. Collecting techniques for bats have not been detailed by previous zoological expeditions, but it is certain that harp traps and acoustic methods would not have been used. The observed increase in species number in 1985 over 1984 (5 in 1984; 11 in 1985) is almost certainly due to differences in coverage, survey techniques and expertise between the two surveys. The increase in number of species of bats recorded in 1984 over the number recorded in the 1930–34 period is therefore almost certainly a misrepresentation, and to a considerable extent is due to the use of more sophisticated trapping techniques in the 1980s.

The above example is an extreme one, but the problem also exists for other groups of animals. Mist-netting is not mentioned in reports of previous surveys, and although methods are not stated, it is likely that bird surveys were made by sight and sound only, with specimens being obtained by shotgun. Mist-netting is an important technique for the detection of retiring, secretive or silent bird species, and for collecting the smaller fruit bats. The use of Elliott traps for rats, and water traps, light traps, Malaise traps and pitfall traps for arthropods, are further examples of techniques used in 1984 and 1985 that are not specified in the reports of previous surveys, although in those cases for which the date of a technique's general introduction into field studies is known, a reasonable guess can be made concerning its use.

Most of the previous surveys (see §4 and table 3) have concentrated on Rakata and Sertung, which were the first islands to be granted protected status, whereas in 1984 and 1985 an attempt was made to cover all four islands. Correction for this difference in coverage can be made of course by using only that subset of our data corresponding to the island coverage of previous workers (see also §6*c*).

(ii) *Pseudoturnover and cryptoturnover*

Observed changes in species complement from one survey to the next may accurately reflect real, i.e. actual, changes due to immigrations and extinctions in the intersurvey interval, or they may include components of what has been termed pseudoturnover: changes in faunal composition that are apparent rather than real. Pseudoturnover has two components.

An incomplete survey may result in falsely recorded extinctions when compared with a more thorough previous one, and thus also to falsely recorded cases of immigration in a more thorough subsequent survey. Differences in the extent and intensity of surveys and in survey methods used therefore will result in pseudoturnover, the extent of which is often difficult to assess.

Another component of pseudoturnover involves recording, as presences, species that are not true components of the fauna but merely transients. The extent of this error may be reduced by applying criteria by which presences (and therefore immigrants and extinctions) may be defined. Such criteria have been suggested by Lynch & Johnson (1974) (see also Jones & Diamond 1976) for birds, and by Simberloff & Wilson (1970) and Simberloff (1976, 1978) for arthropods in relatively short-term studies on experimentally defaunated mangrove islets. The criteria clearly must differ between animal groups which, for example, may have differing lengths of breeding cycles, and for different island situations, as well as in their retrospective application to previous surveys. Previous bird workers on the Krakataus, for example, have separately identified migrants and residents, and have noted evidence of breeding, as we have, although the necessarily short visits may have missed the breeding season of many species. In practical terms, if all the breeding criteria of residence suggested by Lynch & Johnson were strictly applied, many species recorded consistently in all surveys over a decade or more in the period of Dammerman's surveys would fail to qualify and much data would become valueless. The extent of this component of pseudoturnover obviously will vary between animal groups: for example, land molluscs are much less likely to be transients than are shore birds or fruit bats. Clearly, common sense must also be applied and, most importantly, the criteria applied must be explicitly stated and all biological data recorded.

Cryptoturnover (Lynch & Johnson 1974), as the name suggests, is actual change in species complement that is unrecorded because it is not observed; species may invade and become extinct within the intersurvey interval. Thus, particularly in the case of surveys taken at long intervals, the observed figure will be an underestimate of actual turnover. Jones & Diamond (1976), as a result of annual surveys of birds of the California Channel Islands, estimated that the 'in-and-out effect' caused estimates of turnover as a result of surveys made several decades apart to be underestimates of the true value by about an order of magnitude. In studying the recolonization of defaunated Florida mangrove islets by arthropods, Simberloff (1969) estimated the proportion of unobserved extinctions to be from 33 to 75 % of total extinctions, but Gilroy (1975) showed theoretically that this was too pessimistic and that only about 17 % of total extinctions were not monitored. Where periodic devastating eruptions have occurred, for example as a result of Anak Krakatau's activity from 1930, whole colonizing episodes may have been nullified and thus been unrecorded. Simberloff (1978) outlined a method of estimating the amount of cryptoturnover by comparing the average times to first appearance of species on a number of defaunated mangrove islets (taken to be a sample of the distribution of intervals between invasions) with the species' generation times. Successful application of this method to the Krakatau situation is unlikely, given the very large time intervals between surveys.

(iii) *Effect of grouping several surveys*

Dammerman and his colleagues made several surveys from 1919 to 1934 (see §4 and table 3), most of which were evidently general faunal surveys, but some (e.g. April 1919, September 1920) included specialist ornithologists. The surveys varied in length from 1 to 8 days. Dammerman (1948) therefore consolidated these into two major survey periods: 1919–1922 and 1928–1934, and MacArthur & Wilson (1967) followed this convention in their analysis of the data. The succeeding survey, of birds only, was in 1951 by Hoogerwerf, who also made a very short visit in 1952.

Jones & Diamond (1976) have pointed out that the effect of consolidating several years' data into one survey period (e.g. Dammerman's second period) for comparison with a single survey (e.g. that of Hoogerwerf) is to overestimate extinctions but to underestimate immigrations, and these tend to cancel. In succeeding papers of this series we shall usually treat our 1984 and 1985 surveys as one when comparing our data with those of the 1928–34 Dammerman expeditions or, in the case of birds, those of the 1951–52 visits by Hoogerwerf. We shall also generally follow previous authors in consolidating the Dammerman surveys into two periods.

(*c*) *Differing successional histories of Rakata, Sertung and Panjang*

Bush (1986*b*) and Richards (1986) both draw attention to the possibly major effects that the regular activity of Anak Krakatau has had on the vegetation of Sertung and Panjang, in contrast to the minimal effects on Rakata. Indeed, they believe that this may be an important cause both of the differing forest types now present on the islands, and the lower floral diversities of Sertung and Panjang.

Eruptions in 1930 and 1952 are known to have very severely affected the flora of Sertung, and both Sertung and Panjang were badly damaged by the 1952 eruption, which was followed by another damaging episode in 1953. The ash-fall on north Panjang and on Sertung reached depths of 0.7 and 1.5 m respectively (Bush (1986*b*), citing de Neve), and both Hoogerwerf (1953) and van Borssum Waalkes (1954, 1960) described the damage to vegetation. Assessment of damage has not been made in the case of other eruptive events, but the vegetational successions on these islands are younger, less developed and much less diverse than the Rakata forests, and Richards records a significant decline in observed species numbers on Sertung and Panjang since about 1930. He believes that succession on these islands has probably been set back to such a degree that Rakata is the only island of the group to which the equilibrium model can now be usefully applied.

(*d*) *The biogeographical significance of Anak Krakatau and the Sertung spit*

The birth, development and volcanic activity of Anak Krakatau over the past half century have several important implications for any considerations of the biogeography of the archipelago.

Most obviously, the island's existence and growth has increased the total area available on the archipelago for colonization. However, the setbacks to plant colonization and succession by its repeated eruptions have resulted in only some 7% of its area now being vegetated, so that the additional area of available habitat for most animals is small.

Anak Krakatau's eruptions have not only undoubtedly very significantly affected the successional processes on the island itself, but there is evidence that succession on the other islands, particularly Sertung and Panjang, may also have been set back (see §6*c*), although the southern slopes of Rakata (the majority of the island) appear to have been relatively unaffected, being sheltered by the huge northern scarp.

The youth of Anak Krakatau's biota, at least 47 years and more probably some 68 years (because of its possibly self-sterilizing eruption of 1952) younger than the biota of the other islands, means that early stages of colonization and succession, which were inadequately monitored (at least zoologically) on the other islands in the first few decades after 1883, may be reexamined. Here it must be borne in mind, of course, that Anak Krakatau is very much nearer possible sources, the other islands, than were they at a similar stage of their biotic history. The pool of potential immigrants to Anak Krakatau present on the remaining islands, moreover, is, at any one time, a selected subset of the mainland pool: those species that have already successfully colonized the archipelago from the mainland and therefore have high probabilities of immigration to Anak Krakatau.

The highly mobile, ever-young spit of land on the north of Sertung (see §3*d*(ii) above) also offers a stage of succession earlier than that obtaining on the rest of Sertung and on Rakata and Panjang, and the biota has probably been held at this stage for several decades because of the rate of physical turnover of the spit itself. In this instance the area concerned is contiguous with the later successional stage present on the main body of Sertung.

The Sertung spit may not persist for long, but for a considerable period yet the succession on Anak Krakatau will be out of phase with and at an earlier stage than that on the other islands, where the successional process, in general, will have proceeded beyond the stage obtaining on Anak Krakatau. Thus, theoretically, Anak Krakatau, and probably for a shorter time the Sertung spit, could act as ecological refuges for species typical of early successional stages (such as grassland) whose optimal habitat on the other islands is declining or has been extirpated by succession, providing that the species concerned are able to persist on the other islands until their optimal stage of succession becomes available on Anak Krakatau or the spit. The continuing provision of such successional refuges would result in the postponement of the extinction of the species concerned from the archipelago.

The presence of earlier successional stages on Anak Krakatau and the spit will also provide, for potential mainland colonists, habitats that would have been closed on the archipelago as a result of succession had Anak Krakatau not emerged or the spit been formed. Theoretically, this could extend or revive the possibility of establishment by species of the mainland pool whose optimal habitats develop in the earlier seral stages of vegetation, and could re-open or prolong a successional 'window' on the archipelago for such immigrant mainland species. Because of the distances involved, however, this is likely to be of less significance than the delay in extinction mentioned above, and the net result should be to reduce turnover and delay the achievement of biotic equilibrium on the archipelago as a whole.

These implications will be further discussed in subsequent papers in relation to particular groups of animals.

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Plates 9 and 10 were printed by George Over Limited, Rugby, U.K.

FIGURE 8. Uncarbonized logs buried under 1883 eruptive materials, southwest Rakata coast.

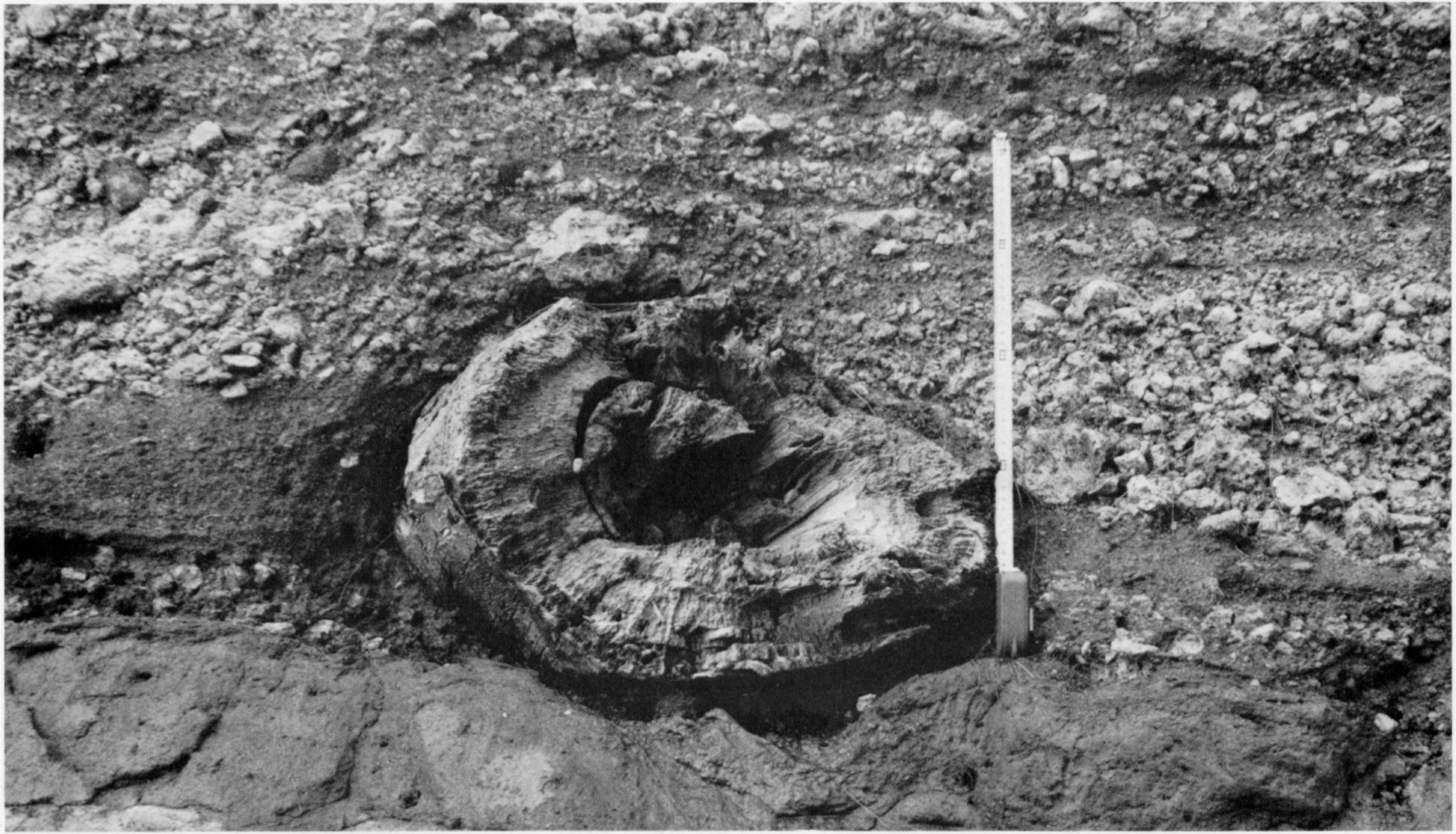

FIGURE 9. Detail of site of figure 1, showing log between pre-1883 and 1883 eruptive layers. Tape is extended 40 cm.

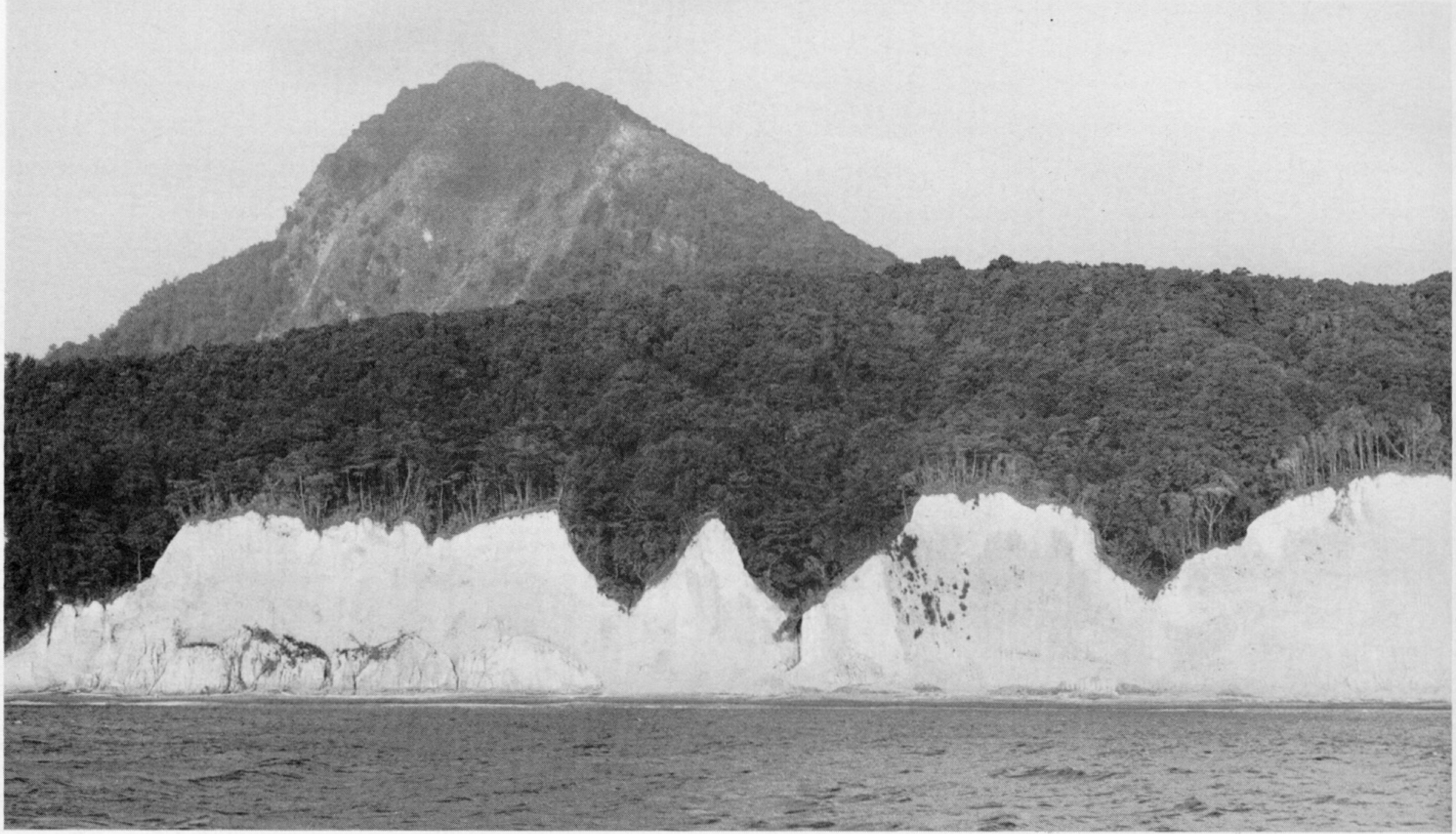

FIGURE 10. Cliffs cut in 1883 pumice, Turtle Beach, Rakata.

FIGURE 11. Zwarte Hoek, Turtle Beach, and the two cliff stacks off the west coast of Rakata.

FIGURE 12. The great northern cliff of Rakata, resulting from 1883 caldera collapse.

FIGURE 13. Rakata, from north; Anak Krakatau in foreground.

FIGURE 15. Sertung, from south.

FIGURE 16. Sertung spit, eroding western coast.

FIGURE 17. Sertung, from north. Arrows show line of marked vegetation change at proximal end of spit.

FIGURE 18. Sertung spit, prograding eastern coast, with beach cover of *Ipomoea pes-caprae* and *Casuarina equisetifolia* forest.

FIGURE 19. Panjang, from north, Rakata beyond. Arrows show coral off northern point; cross, approximate position of observation post established in 1927.

FIGURE 20. Panjang from northeast, Rakata and Anak Krakatau beyond.

Figure 25. Anak Krakatau, from east.

FIGURE 26. Lava flows, Anak Krakatau, from south. 1980 flow (darker) from inner cone reaching sea; skyline ridge on right is rim of outer cone.

FIGURE 27. Detail of *Casuarina* forest on eastern foreland, Anak Krakatau, with isolated clumps of *Saccharum spontaneum* on slope of outer cone. Discoloration of water along southern coast is due to undersea fumarol near edge of lava flows.

FIGURE 28. Detail of northern foreland, Anak Krakatau, with a broad zone of *Ischaemum muticum* grassland, scattered casuarinas, and clumps of *S. spontaneum* on slope of outer cone.

FIGURE 29. Ash-covered lava flows on west coast, Anak Krakatau. Arrow shows site of 1985 water traps.

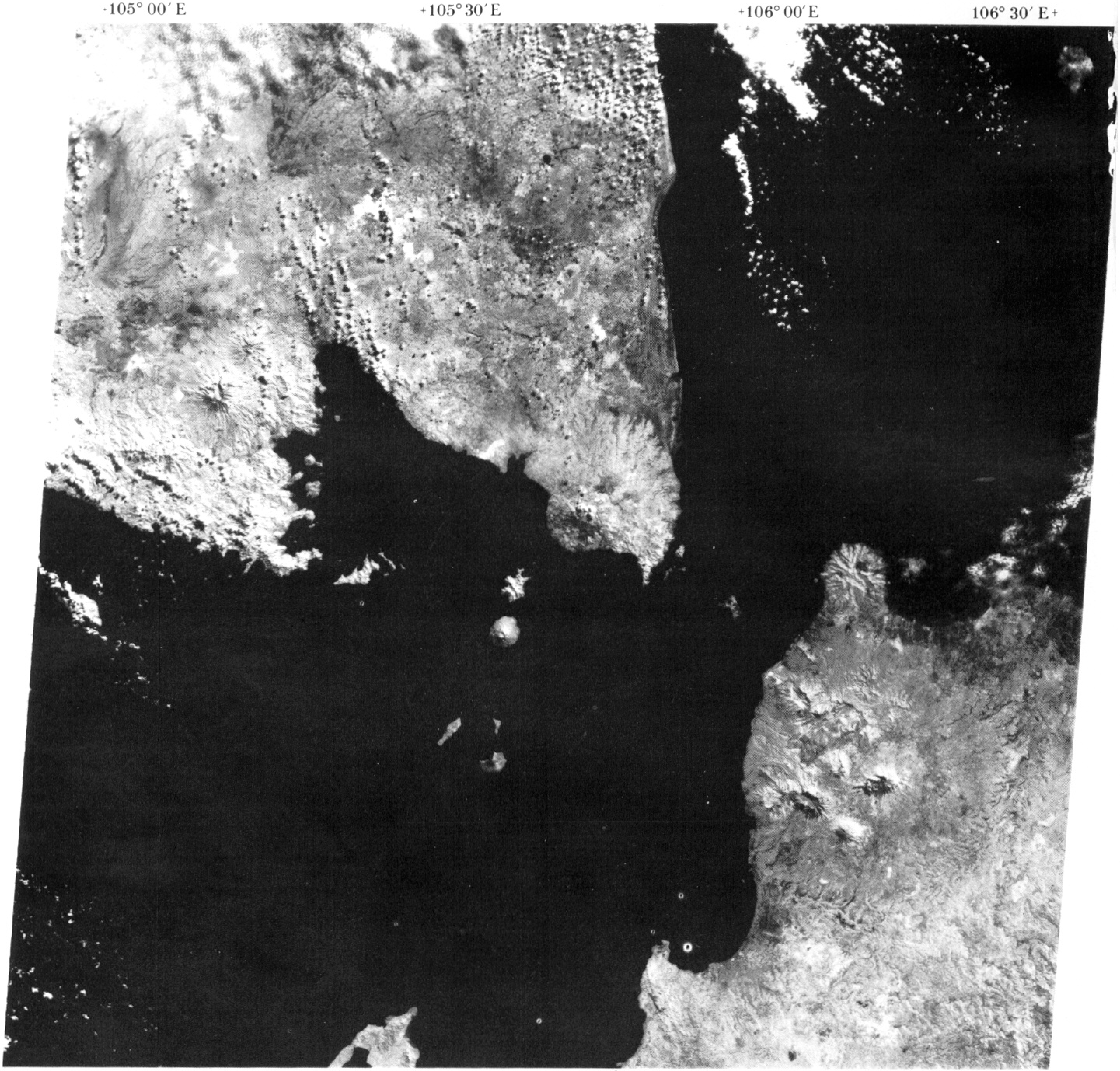

FIGURE 30. Satellite image of northern Sunda Strait showing Gunung Rajabasa on the southern promontory of Sumatra, and to the south the islands of Sebuku and Sebesi, and the Krakatau islands. The Sertung spit and Anak Krakatau, which lack cover by broad-leaved vegetation, do not appear on this image (see §6*d*). Landsat, Band 7, 19 June 1983.