The Eruption of Krakatau

The explosions that obliterated most of the Indonesian island 100 years ago are only now beginning to be understood. The evidence is largely the volcanic deposits and the timing of air and sea waves

by Peter Francis and Stephen Self

One hundred years ago, on the morning of August 27, 1883, a series of intermittent volcanic explosions culminated in the paroxysmal blasts that accompanied the destruction of most of Krakatau, a small island in the Sunda Straits. Tsunamis ("tidal waves") set in motion by the eruption killed more than 30,000 people on the neighboring Indonesian islands of Java and Sumatra. The event attracted worldwide attention, and the ensuing scientific investigations made important contributions to the fledgling field of volcanology. Only now, however, is it becoming possible to explain some of the major events in the eruption sequence in terms of the underlying volcanic processes. Here we address three much-debated questions the eruption raises: What triggered it? Why were there so many violent explosions in the eruption sequence? What was the relation between the devastating tsunamis and the massive explosions?

When Krakatau erupted, the explosions were heard in central Australia, Manila, Sri Lanka and on Rodriguez Island, more than 5,000 kilometers away in the Indian Ocean. Lower-frequency atmospheric waves (at frequencies too low to be audible) were detected worldwide; barometers in Tokyo, 5,863 kilometers away, registered a pressure increase of 1.45 millibars. The sea waves generated by the eruption traveled not only across the Pacific but also across the Atlantic: they were detected by tide gauges in the Bay of Biscay, 17,000 kilometers away. The dust and gases injected into the atmosphere by the eruption produced spectacular sunsets worldwide for months afterward. The mean temperatures recorded in the Northern Hemisphere during the same period were from .5 to .8 degree Celsius lower than normal.

Krakatau's reputation as the classic volcanic eruption, however, is perhaps due as much to the date of its occurrence as to its violence. The eruption, which was one of the first to be the subject of intensive scientific investigation, came at a time in the Victorian era when science was followed by a large and enthusiastic audience. The eruption of the volcano Tambora on the Indonesian island of Sumbawa in 1815 attracted comparatively little attention even though it was much larger; Tambora is estimated to have ejected between 150 and 180 cubic kilometers of pumice and ash whereas Krakatau ejected 20 cubic kilometers. Moreover, the eruption of Tambora caused the death of more than 90,000 people either directly or as a result of tsunamis and an ensuing famine [see "The Year without a Summer," by Henry Stommel and Elizabeth Stommel; SCIENTIFIC AMERICAN, June, 1979]. At the time, however, no one made the connection between the unusually cold weather in Europe and North America in the summer of 1816 and the eruption of Tambora the year before, and the eruption has yet to be studied in detail.

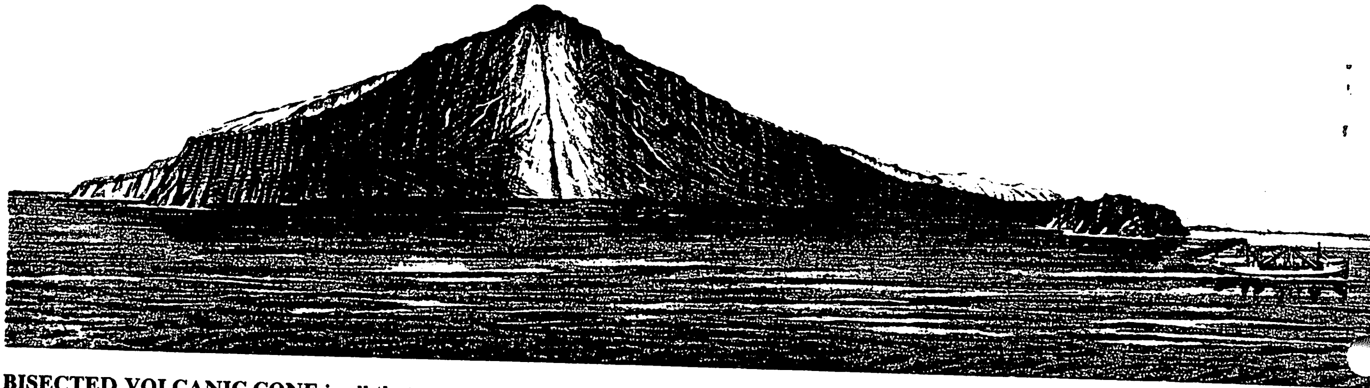
In contrast, both the Royal Society of London and the Dutch government, which was then the colonial administrator of the Indonesian islands, published lengthy reports about the eruption of Krakatau soon after it occurred. The Royal Society's report emphasized the worldwide atmospheric effects of the eruption. Of its 494 pages 312 were devoted to "the unusual optical phenomena of the atmosphere, 1883–6, including twilight effects, coronal appearances, sky haze, coloured suns and moons, etc." The report issued by the Dutch committee, led by Rogier D. M. Verbeek, a mining engineer and geologist, covers the geologic aspects of the eruption in greater detail. The members of the committee visited the scene of the eruption on October 15, 1883, and repeatedly thereafter. They mapped the new islands and the remnants of the old ones and measured the changed contours of the ocean bottom. Verbeek himself collected samples of the volcanic ejecta, which he and his team later examined under the microscope.

The conclusions Verbeek drew from this diverse evidence were for the most part remarkably prescient. For example, on the basis of depth soundings and measurements of the area of ashfall he made an estimate of the amount of material ejected by the volcano that has stood without substantial revision to this day. Finding that the rock specimens he had collected were magmatic rock rather than older rock, he correctly proposed that the old volcanic cone had not been blasted into the air but had foundered into the sea when the magma chamber underlying it was exhausted.

The full story of the eruption based on the accounts of witnesses makes compelling reading. Here we shall concentrate on those events of the eruption sequence that seem to be correlated with the emplacement of volcanic deposits, because it is on this correlation that reconstructions of what happened must be based.

The eruption sequence has been established largely from records kept by Dutch administrators living well above the shoreline in Sumatra and Java and in towns in the interior and from reports made by the officers on watch on ships passing through the Sunda Straits; several of the ships sailed near Krakatau during the most violent part of the eruption. The descriptions of the nature and stratigraphy of the volcanic deposits are based largely on a field study by one of us (Self) and Michael R. Rampino of the Goddard Institute for Space Studies of the National Aeronautics and Space Administration. We studied and sampled the deposits when we visited the island in 1979 in the course of a broader investigation into the atmospheric effects of volcanic eruptions.

Navigational charts of Krakatau and the surrounding areas of the Sunda Straits made before the eruption show that the island consisted of three volcanic cones aligned roughly northwest to southeast. The largest cone, Rakata, 813 meters high, was at the southern end of the chain. A lower cone, Danan, was in



BISECTED VOLCANIC CONE is all that remained of the island of Krakatau after the eruption of August 27, 1883. The island originally consisted of three volcanic cones aligned roughly northwest to southeast. The main vent of the 1883 eruption is thought to have lain between the two northernmost cones. Late in the eruption sequence two-thirds of the island foundered into the sea as the roof of the magma chamber underlying it collapsed. The northern face of the southern cone, Rakata, which was perched on the edge of the new caldera (the submarine depression formed by the collapse), was left virtually unsupported and subsequently slumped into the sea. Clearly visible are the interior structure of the old volcanic cone (including the rock whitened by hydrothermal alteration near the central vent), the feeder dikes (dark columns) leading down to the magma chamber and the alternating lava flows and ash layers that made up the cone. The layer of white pumice deposits laid down on both flanks of the cone is also visible in this chromolithograph from *Album of Krakatau.*

TWO NEW ISLANDS named Steers and Calmeyer in the Sunda Straits north of Krakatau consisted of deposits laid down on the floor of the straits that were exposed above sea level. The islands were created by successive pyroclastic flows: ground-hugging clouds of pumice and ash driven by gravity and fluidized by hot gases. The flows traveled an average of 15 kilometers from the vent, much of it through or over water. Hot material caused the explosive vaporization of seawater; some of the many large explosions late in the eruption sequence may have been such secondary explosions. This chromolithograph from *Album of Krakatau* shows a large secondary-explosion crater on Calmeyer. The crater closely resembles the craters formed by pyroclastic flows from Mount St. Helens that entered Spirit Lake. *Album of Krakatau* was published in 1886; the loosely packed deposits eroded quickly and the islands soon vanished below the surface.

the middle and a much lower one, Perbuwatan, was at the northern end. Lava flows around Perbuwatan showed that it had been active in the geologically recent past, and it is thought to have been the site of a pumice eruption in 1680. Two smaller islands near Krakatau—Sertung and Rakata Kecil (Little Rakata)—and the southern end of Krakatau itself were probably remnants of the rim of a submerged caldera: a large volcanic crater formed by collapse.

When Perbuwatan burst spectacularly into life with a series of deafening explosions on May 20, 1883, after nearly 200 years of inactivity, the eruption came as a surprise. Krakatau was uninhabited and was visited only occasionally by fishermen and woodcutters. Thus any small-scale activity that might have preceded its reawakening went unnoticed. There was a period of markedly increased seismic activity around the straits before the eruption, but at the time no link was made between this activity and Krakatau.

The May eruption of Perbuwatan was accompanied by explosions that could be heard more than 150 kilometers away. At the same distance atmospheric pressure waves of very long wavelength were energetic enough to stop clocks, rattle doors and windows and dislodge hanging lamps. Since the pressure waves were inaudible, their effects were often mistaken for those of earthquakes. Although some seismic activity was recorded during the climactic phase of the eruption in August, at this stage almost all the energy seems to have been transmitted through the air.

Perbuwatan continued to erupt intermittently throughout May, June and July, but the activity was relatively unimpressive. According to Captain Ferzenaar, a Dutch surveyor who visited Krakatau on August 11, trees were still standing, although they had been stripped of foliage by the falling ash. Ferzenaar noted that a layer of ash about 50 centimeters thick covered the island. Today only very limited outcrops of fine-to-medium-grained ash from this early phase of the eruption can be seen.

The relatively minor explosions continued into August and culminated in massive explosions on August 26 and 27. The scale of activity on these two days was so large that it has been difficult to piece together exactly what happened, and much detail is surely missing. No one within close range of the volcano survived. Reconstructions of the eruption sequence in this crucial period are based largely on instrument records and the volcanic deposits. The enormous explosions on August 27 generated air waves so powerful that they registered on a recording pressure gauge at the gasworks at Jakarta, which thereby preserved a record of their timing and relative amplitude. The timing and magnitude of the tsunamis were recorded by tide gauges along the straits.

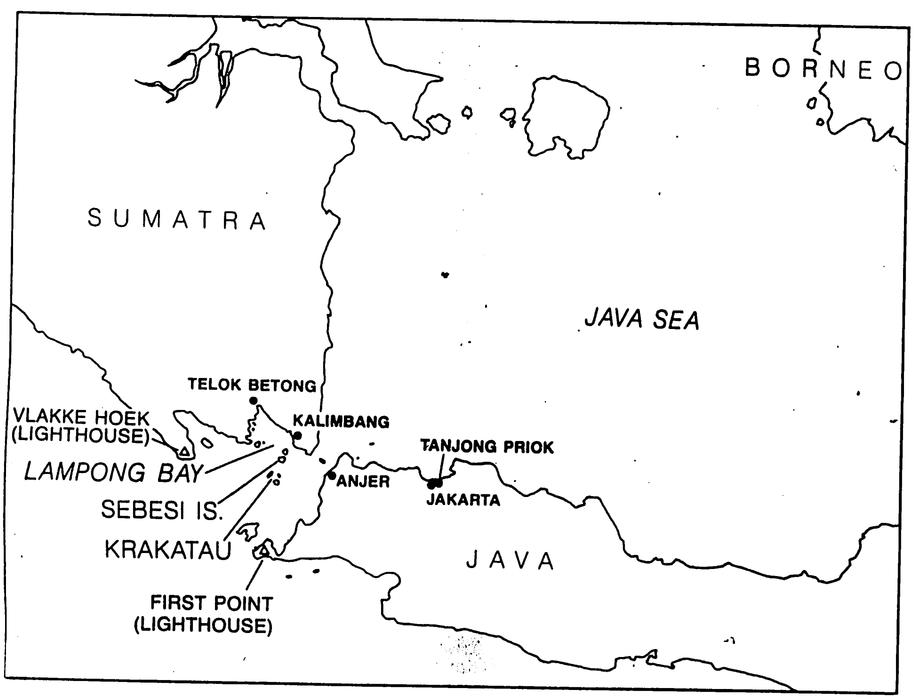
The climactic phase of the eruption can be divided into two stages on the basis of the nature and sequence of the deposited ash layers. Beginning at 1:00 P.M. on August 26 a series of explosions at intervals of about 10 minutes created a more or less sustained eruption column over the island that is reported to have reached a height of about 25 kilometers (82,000 feet). The explosions produced primarily air-fall material: pumice and ash carried upward in the atmosphere by a column of hot convecting gas. (Both pumice and ash are frothy glassy materials created by the chilling of vesiculating magma. The distinction between them is largely one of size; fragments smaller than two millimeters in diameter are generally called ash.)

Although pumice and ash deposits from this phase of the eruption accumulated to thicknesses of up to 20 meters on the islands of Sertung and Rakata Kecil and ships within 20 kilometers of the volcano reported heavy falls of ash accompanied by large pumice clasts (fragments) up to 10 centimeters in diameter, the heavy ashfall was limited in extent. Only a minor fall of ash was reported on Sumatra and on western Java.

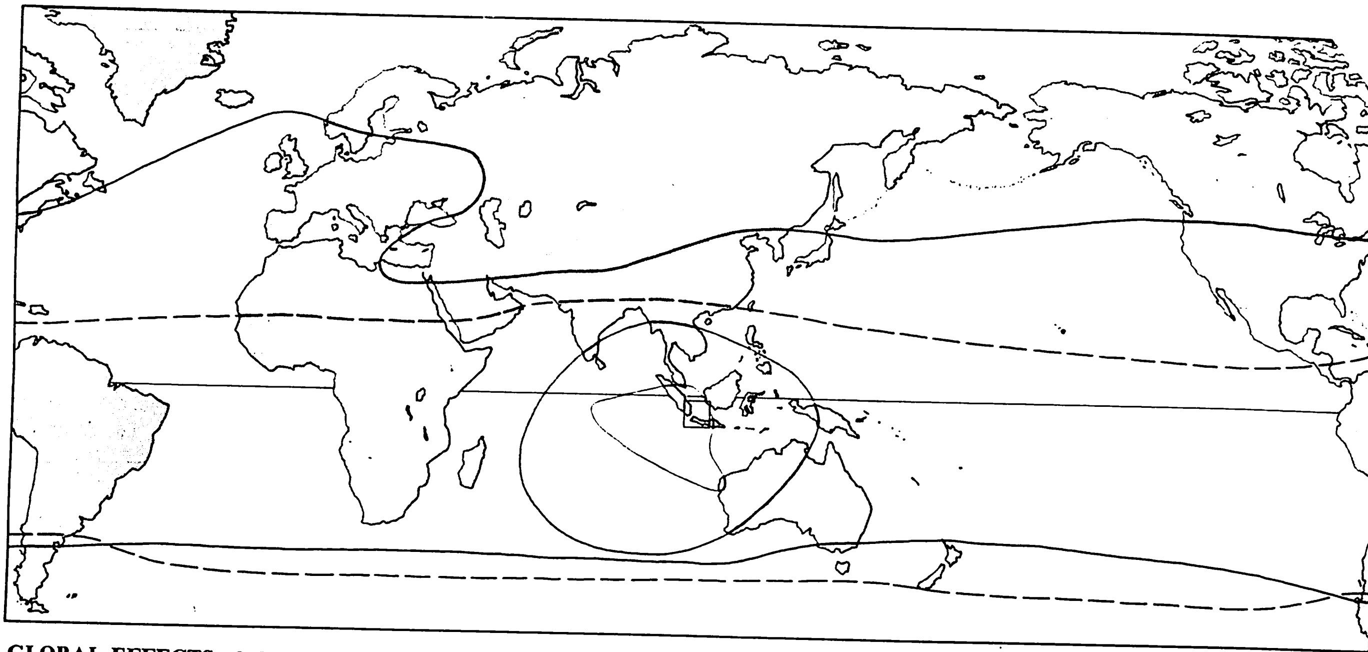
At 5:30 A.M. on August 27 the character of the eruption changed dramatically. In the course of the day there were many enormous explosions. The largest explosion, the one heard as far away as Rodriguez Island, came at 9:58 A.M.; it was associated with the largest tsunami, estimated to have crested at 40 meters, which caused most of the deaths on the neighboring coastlines.

During this period the explosions were characterized by the formation of pyroclastic flows as well as a sustained column of airborne material. The explosions of August 27 seem to have been paroxysmal rather than continuous. Each blast propelled a large amount of pumice and ash high into the air, perhaps as high as five kilometers. The aggregation of material was too dense and heavy to remain airborne for long, however, and most of it immediately fell back to the ground. There it formed incandescent, ground-hugging clouds, driven by gravity and fluidized by hot gases, that moved rapidly off the island and into the sea. A fraction of the ash was lofted much higher by convection currents set up in the atmosphere by local heating. The resulting ash cloud may have reached a height of about 40 kilometers. The ash from the towering cloud fell out over a wide area. The neighboring coastlines were plunged into darkness and ashfall was reported as far away as the Cocos Islands, 1,850 kilometers from Krakatau.

The pyroclastic flows laid down a dis-



KRAKATAU WAS A SMALL UNINHABITED ISLAND about 32 kilometers west of the narrowest part of the Sunda Straits between the Indonesian islands of Sumatra and Java. More than 30,000 people were killed by the eruption that obliterated most of the island. The majority were victims of the tsunamis that swept over the low-lying coastlines of the neighboring islands. Along the east side of Lampong Bay on the southern coast of Sumatra, however, some bodies were found buried in ash. Those people were probably killed by pyroclastic flows that had traveled more than 40 kilometers from Krakatau on the surface of the sea and yet were still lethally hot. The names on the map are locations mentioned in the graph of the eruption sequence on page 152. Modern names have been substituted for their 19th-century equivalents.



GLOBAL EFFECTS of the Krakatau eruption are plotted on this world map. Shown are the range within which ash fell out (*blue line*), the range within which the explosions were heard (*red line*) and the range within which atmospheric effects caused by the volcanic ash and aerosols injected into the upper atmosphere were reported before September 22, 1883 (*broken black line*), and by late in November (*solid black line*). Why the final explosions were so violent has not yet been explained. Ash from the eruption fell out over an area of 700,000 square kilometers, the largest range of ashfall ever produced by a volcanic eruption in historic times. The major explosions generated dense clouds of fine ash over the Sunda Straits that probably attenuated sound quite effectively. One of the consequences may have been that people living on the coastlines of Java and Sumatra, soon to be victims of the tsunamis generated by the eruption, did not hear the explosions that were heard by others as far away as central Australia. A study by the British physicist Rollo Russell of the path and travel time of the high cloud, based on reports of atmospheric effects, provided the first evidence for stratospheric circulation patterns.

tinctive deposit called ignimbrite; these deposits account for the largest fraction of the material erupted by Krakatau. Because the material in the pyroclastic flows was fluidized (given a low density and viscosity) by hot gases, it made extremely efficient use of the kinetic energy it acquired in falling from the height of the eruption column and so traveled long horizontal distances. Deposits of ignimbrite as thick as 40 meters were laid down as far as 15 kilometers from the primary vent, thought to have been between Danan and Perbuwatan.

The pyroclastic flows seem to have spread out preferentially to the north and northeast, covering the islands and the surrounding sea floor with a blanket of ignimbrite. The distribution was probably caused by the high cone of Rakata, which forced material from the collapsing eruption column northward. Reports of burns caused by hot ash from the area around Kalimbang in southern Sumatra provide evidence that some of the flows traveled to the northeast as far as 40 kilometers. It is clear that the injuries were due to horizontal flows rather than vertical ashfall because in one instance the survivors described hot gases and ash blowing up through the floorboards of a house.

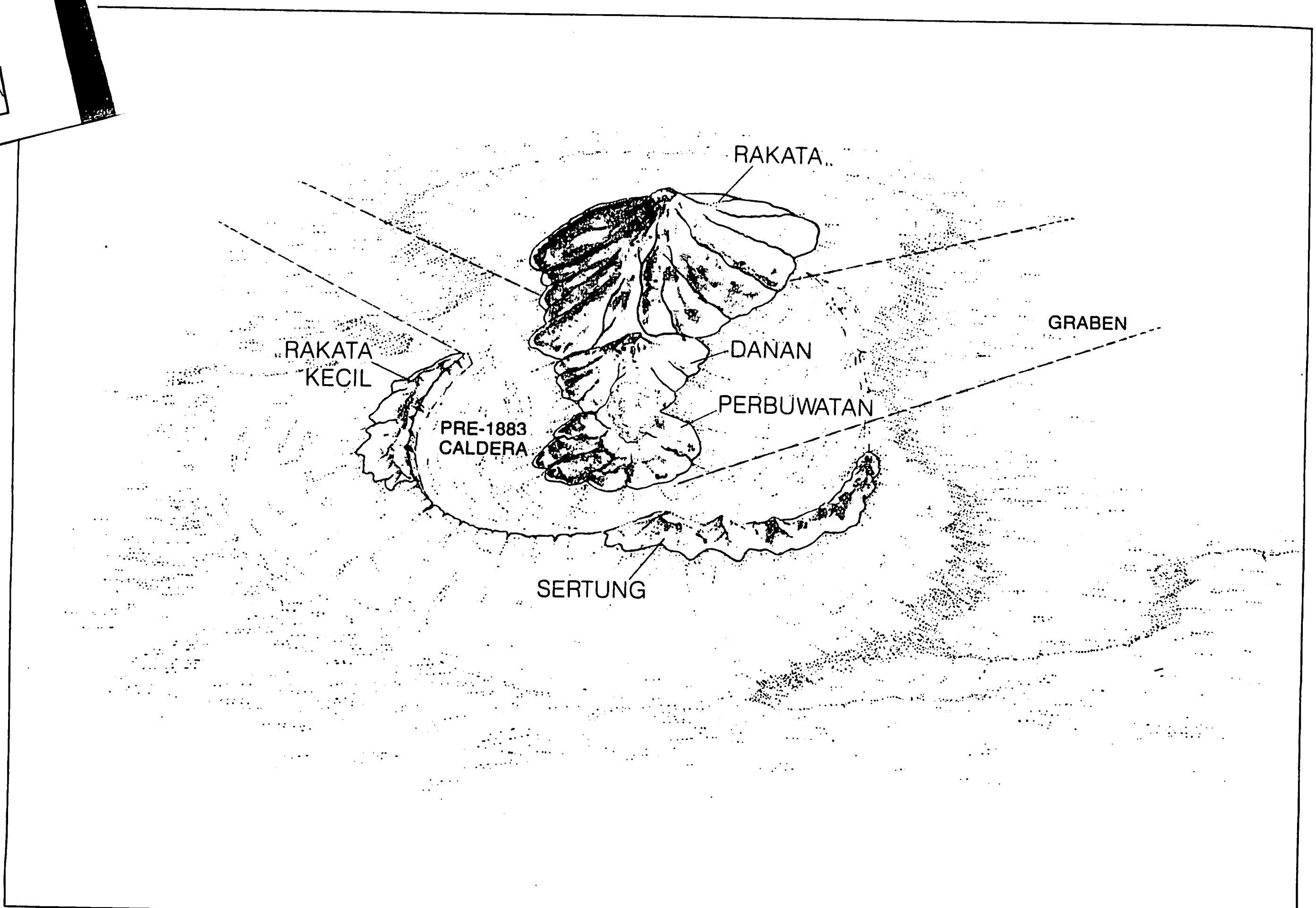
On August 28 the Dutch ship *Gouverneur-Generaal Loudon* attempted to sail from Telok Betong on Sumatra through the Sunda Straits north of Krakatau to Jakarta on Java. Parts of the straits had suddenly become too shallow to be navigable and were also blocked by floating islands of pumice. The ship was forced to deviate widely from its accustomed route, sailing west rather than east and finally passing south of Krakatau. The route the ship took roughly followed the outer edge of the ignimbrite that had been laid down on the floor of the sea.

The detailed hydrographic charts Verbeek's team of investigators made in mid-October record the topographic changes caused by the eruption. The northern two-thirds of the island of Krakatau had disappeared. The coastlines of Sertung and Rakata Kecil had been extended by as much as three kilometers by deposits of pumice and ash. Even the southern remnant of Krakatau was girdled by deposits of white ignimbrite. Most of the volcanic material, however, had gone into the sea. Parts of the Sunda Straits originally from 20 to 60 meters deep had been filled by ignimbrite. In the straits to the north of Krakatau ignimbrite exposed above sea level had formed two islands, later named Steers and Calmeyer.

A new caldera, 290 meters deep at its southern end, had formed within the older and now partially filled prehistoric caldera. The distribution of the pyroclastic-flow deposits of the southern and eastern flanks of Rakata suggests they were laid down before the caldera formed, indicating that the magma chamber collapsed relatively late in the eruption sequence. Most of the island foundered into the sea when the roof of the chamber collapsed, but the cone of Rakata was apparently left perched on the southern rim of the caldera, its northern face virtually unsupported. This side of the volcano then slumped into the sea, leaving behind a spectacularly bisected volcanic cone, all that remains of the island of Krakatau.

One reason little progress was made until recently toward understanding what happened at Krakatau is that little attention was given to the physical characteristics of the volcanic deposits, particularly those left by the pyroclastic flows. Verbeek studied the petrology of the deposits and C. E. Stehn (who visited the area in 1927 when the eruption of a new, still-underwater volcano inside the 1883 caldera became perceptible at the surface) studied their stratigraphy. Howel Williams of the University of California at Berkeley made an important contribution in 1941, when he pointed out that much of the exposed pumice had been emplaced by pyroclastic flows rather than by the fallout of airborne material. Only within the past 15 years, however, have volcanologists begun to realize the significance of the physical characteristics of volcanic deposits, such as grain size and internal structure. These characteristics of the Krakatau deposits were studied for the first time when one of us (Self) and Rampino visited the island in 1979.

In many respects it is hardly surprising that these aspects of the deposits had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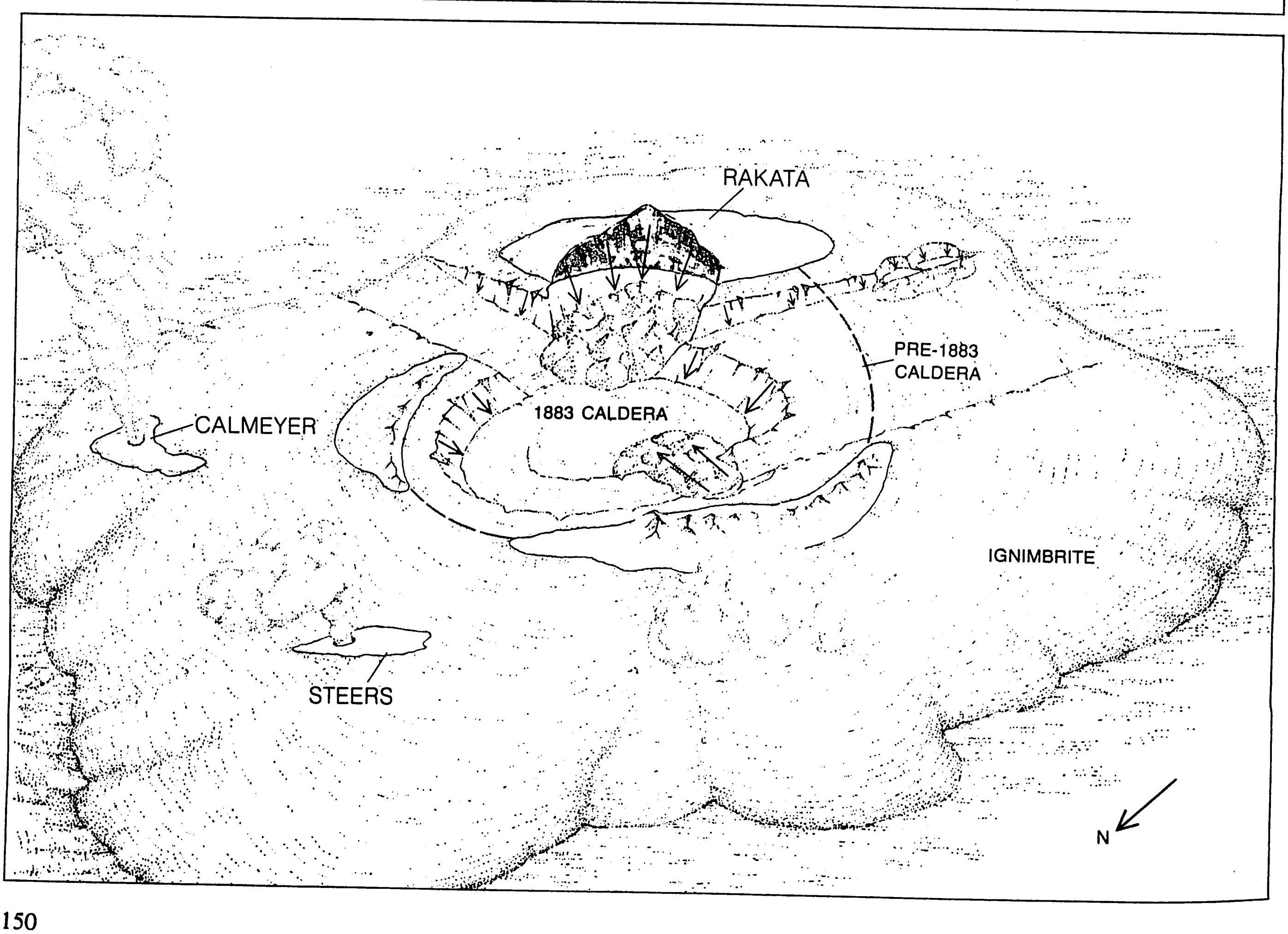
RAKATA
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not been examined before. Not only was most of the ignimbrite deposited in the sea but also the islands of ignimbrite, Steers and Calmeyer, were rapidly eroded and soon disappeared below the sea surface. The deposits that fell on the older islands were also rapidly eroded. Verbeek noted two months after the eruption that steep-sided gullies 40 meters deep had been cut into the deposits. The highly irregular topography was then enveloped in luxuriant and soon impenetrable vegetation. Today the deposits can be sampled only from boats at the bottom of crumbling sea cliffs. Yet it is on the physical characteristics of the deposits that many of the questions about the eruption turn.

Studies of the deposits provide the basis for our answer to the first question: What triggered the eruption? Major volcanic eruptions are caused by the sudden decompression of magma that is saturated or supersaturated with dissolved gases such as carbon dioxide and water vapor. The dissolved volatiles can be released in two ways. The pressure in the magma chamber may gradually increase as more volatiles come out of solution; when the pressure exceeds the strength of the overlying rock, the magma forces an opening to the surface. Alternatively, a tectonic process such as a landslide caused by an earthquake or movement along faults overlying the magma chamber may create an opening that causes instantaneous decompression. There is no evidence that any tectonic process was responsible for the eruption of Krakatau, and so an explanation must be sought in processes within the magma chamber itself.

Verbeek suggested that the final explosions began when seawater penetrated the magma chamber and reacted violently with the hot magma. This hypothesis was at one time widely accepted and was generalized to include the earlier explosions. Volcanic eruptions caused by the violent interaction of water and magma, called phreatomagmatic eruptions, do indeed take place either when magma heats and cracks rock close to an underground water table or when seawater somehow gains entry to the magma chamber. The mixture of groundwater or seawater and magma is highly explosive and usually gives rise to a distinctive deposit of very fine-grained and widely dispersed ash. The eruptions at Krakatau left rather different deposits that do not yield unequivocal evidence for this type of eruption.

The intrusion of large amounts of seawater could be expected to cool the magma, so that the ejecta, particularly the finer-grained ash, would cool faster in a phreatomagmatic eruption than it would in other types of eruptions. The field evidence at Krakatau is somewhat equivocal on this point. On the one hand, the early air-fall deposits on Rakata Kecil, only 2.3 kilometers from the postulated vent, were so hot that the glassy pumice fragments were soft enough to weld together in places. The nature of this deposit thus makes it unlikely that the ejecta had been cooled by contact with water.

On the other hand, George P. L. Walker of the University of Hawaii at Manoa has argued that the character of some of the ignimbrite deposits suggests the magma had been cooled by water. The centers of the larger pumice clasts are frothier than the peripheries. In addition the clasts have an exterior skin such as might be formed by sudden cooling. These characteristics suggest the clasts were originally hotter than the surrounding matrix of ash and cooled from the outside in. It is, however, possible that seawater either cooled the erupted material as it left the vent or chilled the ignimbrite as it was deposited. (Most of the deposits visible today are at sea level.)

The geologic evidence therefore does not indicate clearly that there was direct explosive contact between seawater and hot magma in the chamber or conduit of Krakatau. Since the vent was close to sea level, it nonetheless seems probable that there were minor phreatic explosions, which may not have involved direct contact between the water and the magma, late in the sequence, beginning perhaps on the evening of August 26. These explosions may have weakened the roof of the main magma-chamber, causing sudden decompression and the release of large volumes of vesiculating magma. We propose, however, that the interaction of water and magma was a contributory cause rather than the primary cause of the eruption.

The nature of the pumice fragments themselves points to a more likely triggering mechanism for the eruption. The frothy glass of the pumice includes a small number of mineral crystals that started to form in the magma chamber before the eruption. (When the magma cools relatively fast, glass is formed; slow cooling favors the formation of crystals.) The composition of a pumice and of any crystalline inclusions depends on the composition of the magma from which they formed. Magma ranges from basalt, a dark material relatively poor in silica, through andesite and dacite to rhyolite, a light gray material rich in silica. The lighter-colored magmas are called silicic; they form minerals with a high content of silica, such as quartz and feldspar. The darker magmas are called mafic; they form minerals rich in magnesium and iron, such as pyroxene.

Most of the Krakatau deposits consist of pale dacitic pumice that contains relatively few mineral crystals. Some of the deposits are strikingly different, however; streaks or bands of darker glass are intermixed with the lighter glass, and some clasts are entirely dark. The darker pumice also includes crystals with compositions different from those in the lighter pumice. Such mixed pumices are by no means rare in pyroclastic deposits. It has been suggested that they may be formed when hot basaltic magma intrudes into light rhyolitic or dacitic magma and the two mix.

The intrusion of fresh hot basaltic magma into the base of a chamber of dacitic magma may cause a violent convective overturn within the chamber. Silicic magmas tend to be less dense than more mafic magmas, largely because of the differences in their composition. Most dacitic magma chambers are thought to be stratified according to composition, with the most silicic magma at the top and the somewhat denser, more mafic material lower down. Such a system is stable. Stephen Sparks and Herbert Huppert of the University of Cambridge have suggested, however, that a pulse of hot basaltic magma that intrudes into the chamber may initiate convective overturn by superheating the adjacent layer, causing it to become less dense than the overlying silicic magma. A second possibility is that the hot basaltic magma initially rests quietly on the floor of the magma chamber and violent overturn takes place only when it cools. As the basaltic magma cools, volatiles come out of solution and crystals settle out, decreasing the density of the remaining liquid magma until it is lower than that of the overlying layers.

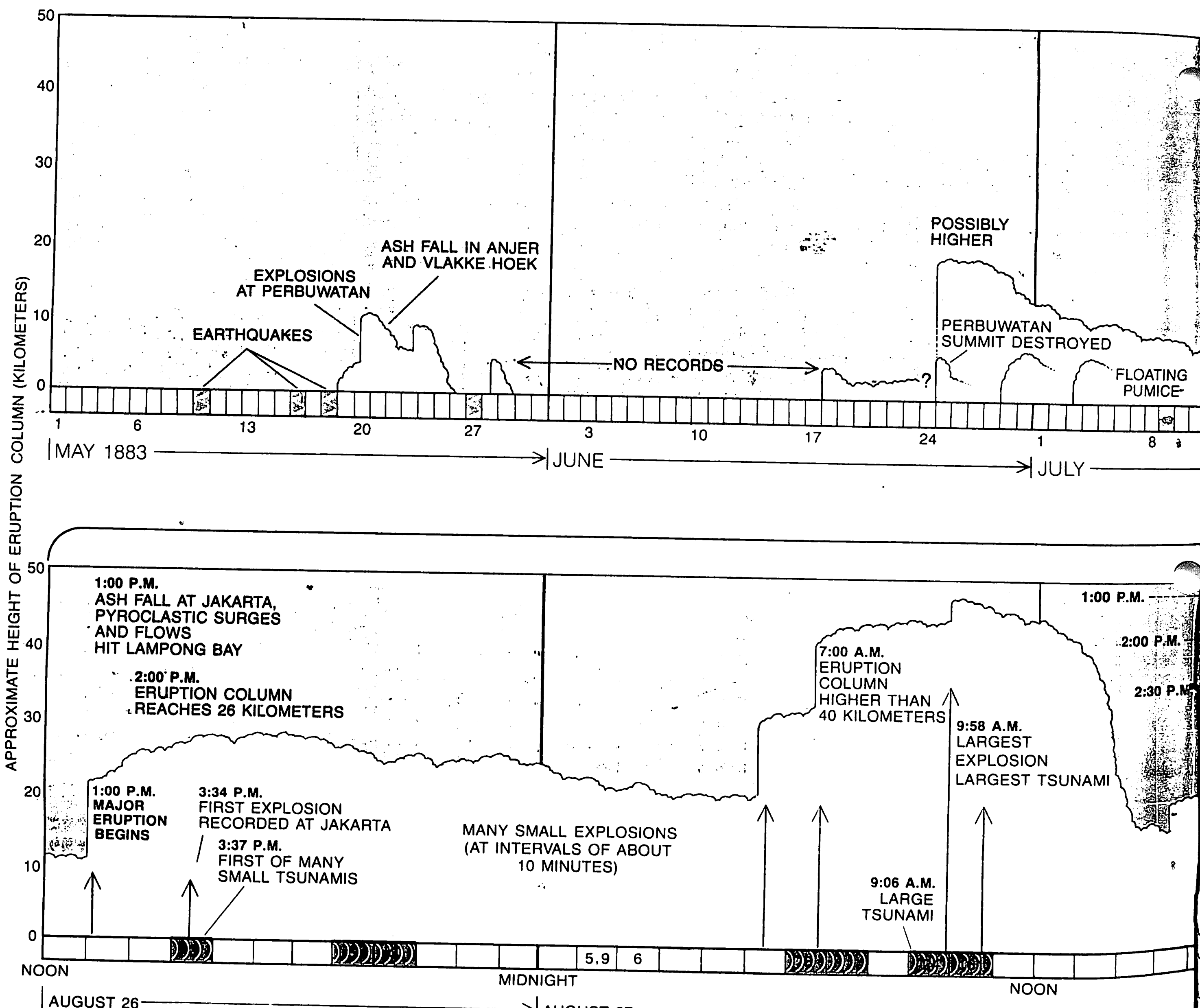
Why should convective overturn initi-

DRAWINGS OF KRAKATAU before and after the eruption are reconstructed from contemporary hydrographic charts. The island consisted of three volcanic cones: Rakata, Danan and Perbuwatan. The outlying islands Sertung and Rakata Kecil, and perhaps the southern edge of Krakatau itself, were remnants of the rim of a prehistoric caldera. Two submarine grabens (depressions) near the island indicate that the crust in the area was under extensional stress; this may have thinned the crust enough to accommodate the 1883 magma chamber. Most of the magma was ejected in the form of pyroclastic flows, which deposited on the sea floor a layer of ignimbrite (pumice fragments) as thick as 40 meters. The flows spread preferentially to the north and northeast, probably because the high cone of Rakata to the south acted as a barrier. The two new islands Steers and Calmeyer were areas of the ignimbrite exposed above sea level. Once the eruption had exhausted the supply of magma the chamber collapsed to form a new caldera and most of the island foundered into the sea. The 1883 caldera was probably elongate because the collapse followed the fault lines of the grabens. The drawings are not to scale.

ate an explosion? In general the eruption of basaltic magmas tends to be less explosive than that of more silicic magmas because they are less viscous and the bubbles of gas created by volatiles coming out of solution easily percolate through or effuse out of them, whereas the bubbles formed in more viscous silicic magmas are trapped there and cause explosive fragmentation of the magma when their internal pressure exceeds its strength. In an impressive series of laboratory experiments, however, J. Stewart Turner of the Research School of Earth Sciences of the Australian National University and Sparks and Huppert have demonstrated the importance of the volatile content of the newly introduced magma to the process of magma-chamber mixing. Fresh basaltic magma may be rich in volatiles kept in solution by the pressure at the depth at which the magma formed. Convective overturn carries the volatile-rich material to shallower levels in the chamber, where the ambient pressure is lower. As the magma rises, the volatiles rapidly come out of solution, the pressure within the magma chamber increases and an explosive eruption is likely to follow.

An important piece of historical evidence supporting the hypothesis that the eruption of Krakatau was caused by magma mixing came to light during the preparation of this article. On May 27, 1883, soon after the first explosions of Perbuwatan in May, a party of no fewer than 86, including the Dutch mining engineer J. Schuurman, visited Krakatau. Schuurman wrote a detailed account of his visit, noting that 60 centimeters of dark "ash" overlay 30 centimeters of lighter-colored "pumice." He also collected samples of the ejecta, which were later analyzed. The samples of pumice are similar in composition to the dacitic pumice ejected in the August explosions. The gray ash, however, is basaltic in composition. It seems likely, therefore, that a small amount of a basaltic magma was ejected in the early phase of the eruption, soon after an initial ejection of dacitic magma. This indicates that magmas of sharply contrasting composition underlay the volcano in May and lends further support to the hypothesis that the August explosions were caused by magma mixing following the intrusion of fresh pulses of basaltic magma.

Although it is impossible to prove

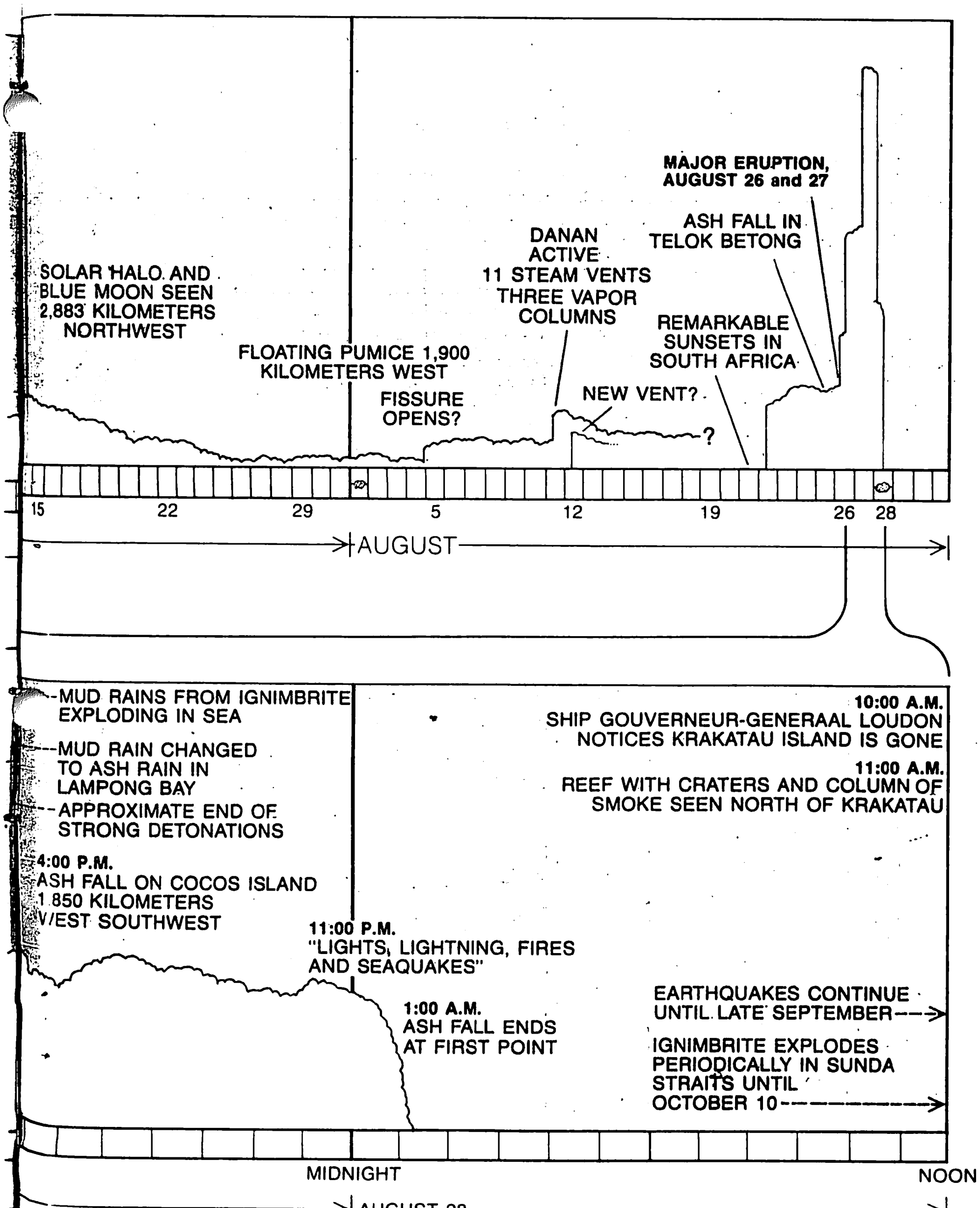


ERUPTION SEQUENCE OF KRAKATAU has been pieced together from many sources: diaries and notebooks kept by Dutch administrators and others living on the neighboring islands, logs kept by the officers on watch on ships in the Sunda Straits, events recorded by a pressure gauge at a gasworks in Jakarta and by tide gauges along the Sunda Straits and occasional observations made by people

that magma mixing actually caused the eruption of Krakatau, the laboratory experiments of Sparks and Huppert convincingly demonstrate that the mechanism is plausible. It has been proposed to account for other major eruptions, such as the 1875 eruption of Askja in Iceland and the 1902 eruption of Santa María in Guatemala, sites where similar mixed pumices have also been found. The magma-mixing hypothesis for the eruption of Krakatau nonetheless leaves one problem unsolved. Even if it is assumed that magma mixing initiated the eruption, it is still not clear why some of the explosions in the sequence were so extraordinarily violent.

The next question we address is why the eruption of Krakatau was accompanied by many separate explosions. One possibility is that some of the explosions were secondary ones caused by hot pyroclastic flows entering the sea. Little is known about what happens when a large pyroclastic flow comes in contact with seawater, because few examples have been documented. Does the flow displace the water and travel along the sea floor or does it travel over the surface? The answer seems to be a little of both, although exactly what happens probably depends on the characteristics of the flow.

As the flow enters the sea the denser underflow, consisting largely of pumice, fine-grained glassy material and fragments of older, nonvolcanic rock, may plunge into the water. The more diffuse turbulent upper layer, consisting largely of pumice and ash fluidized by hot gases, may temporarily have a bulk density less than that of seawater and may travel over the surface. As turbulence becomes less effective, the larger clasts begin to drop out and eventually the flow is depleted of solid material. Only a turbulent mass of gas and fine particles remains; such flows, still hot, probably hit Kalimbang on Lampong Bay.



as far away as South Africa. Numbers in colored boxes give the relative magnitude of the tsunamis. The relative magnitude of the explosions is indicated by the height of the arrows. Only a few of the many explosions that occurred in the course of the eruption sequence are shown.

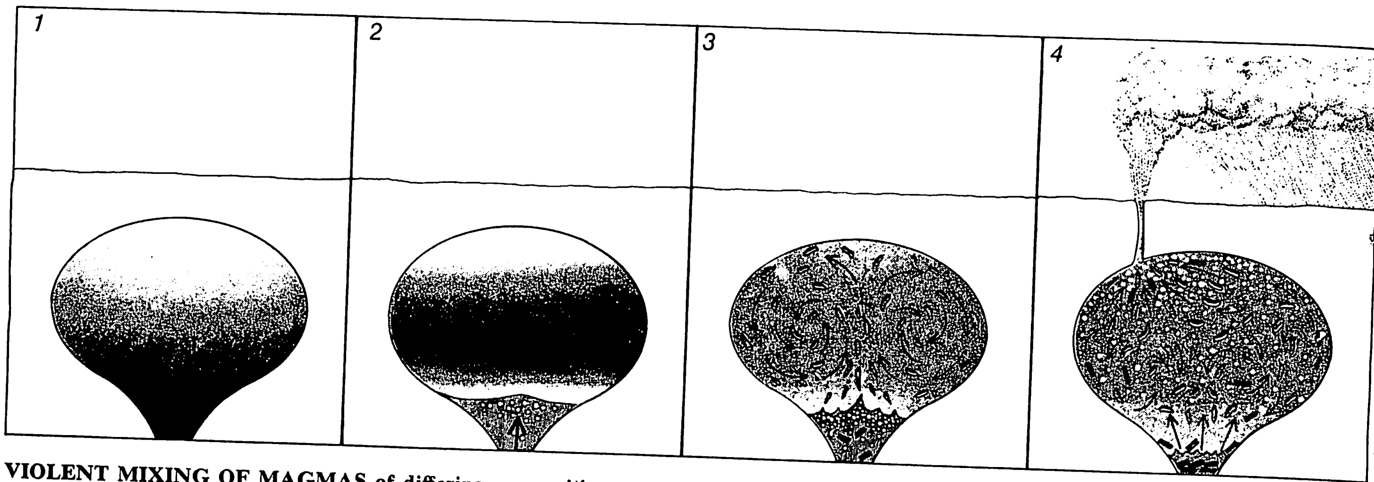
A pyroclastic flow deposited 6,000 years ago by the eruption of the volcano Koya on the Japanese island of Kyushu provides evidence that the interaction of hot ignimbrite with seawater may in some circumstances be as powerfully explosive as one might intuitively expect. On the basis of studies of these deposits Walker suggests that the explosions caused by flows entering the sea may lead to ashfall over many thousands of square kilometers. The distinctive feature of these ash deposits is that their thickness and their grain size vary little with distance from the source, a distribution that suggests the ash was generated by explosions of remarkable power.

The Rotoehu deposits erupted from the Okataina volcanic center in New Zealand some 50,000 years ago yield evidence that such ash deposits may also be crystal-poor. Walker argues that the crystals become separated from their parent pumice fragments by a natural grading process. As the flow moves toward the sea the denser crystals sink and the pumice dust is lofted. Further winnowing of the crystals from the dust accompanies the explosions that occur when the flow enters the sea, as powerful turbulent vortexes sifting through the cloud of ash created by the explosions carry away the lighter dust.

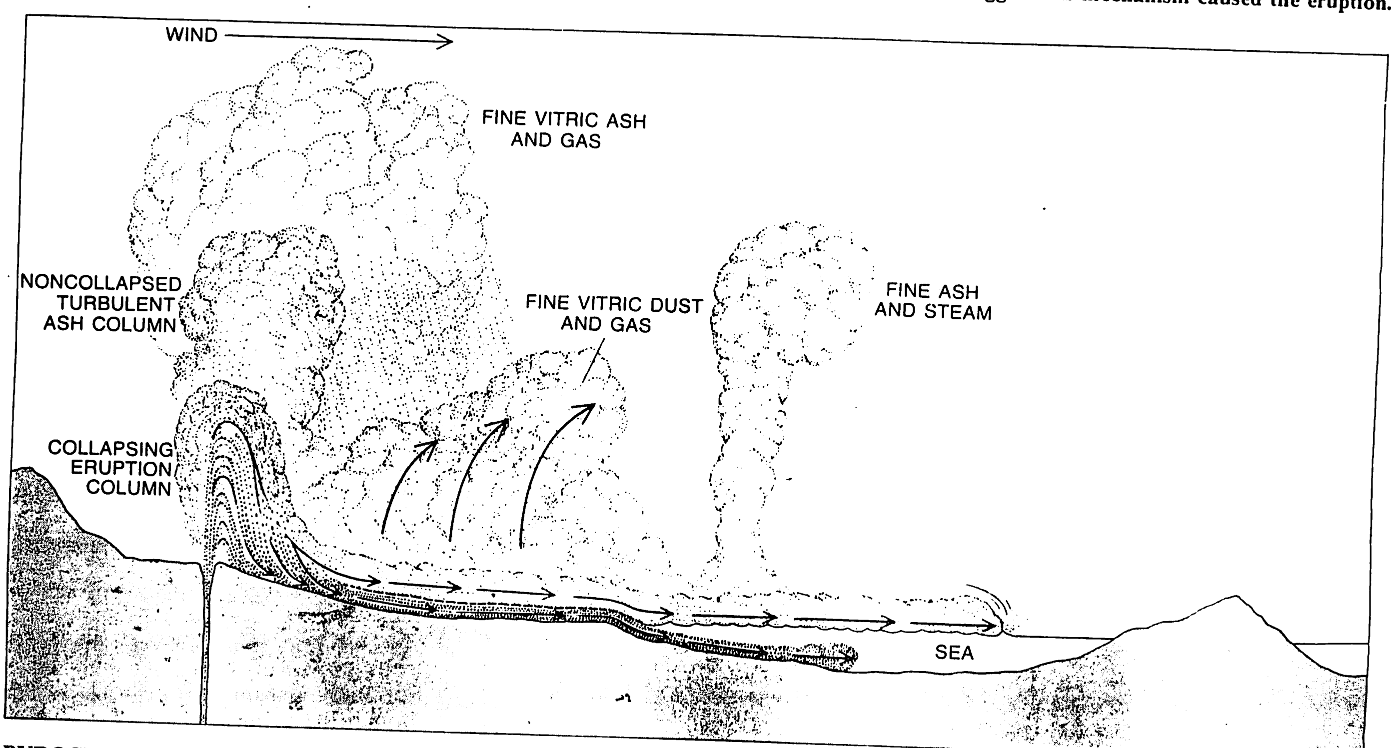
At this remove in time it is, of course, difficult to determine exactly what happened when the Krakatau pyroclastic flows entered the sea. Contemporary illustrations, however, clearly show large circular craters on Calmeyer, one of the two islands created by the deposition of ignimbrites. The craters strikingly resemble those made by the secondary explosions that occurred when pyroclastic flows erupted by Mount St. Helens in May, 1980, entered Spirit Lake. Moreover, Verbeek noted that the uppermost layers of ash on the island of Sebesi were extremely fine-grained and consisted almost entirely of glass. This fine crystal-poor ash may well have been the fallout from powerful secondary explosions. For these reasons we suggest that although the gigantic blasts at Krakatau up to 9:58 A.M. on August 27 were probably caused by the expulsion of the pulses of magma that generated the pyroclastic flows, at least some of the many powerful explosions in the eruption sequence were explosions caused by pyroclastic flows entering the sea.

It was the great tsunamis set in motion

by the eruption that wreaked the most havoc. Even though the tsunamis have been studied in detail by many investigators, their cause or causes remain a matter of debate. Tsunamis are generally caused by the sudden vertical movement of the sea floor, usually as the result of an earthquake. As late as the 1960's it was argued that the Krakatau tsunamis were caused by the similar mechanism of caldera formation. Discussion of this point has centered on the question of when and how quickly the roof of the magma chamber collapsed and on the question of whether the tsunamis were preceded by a lowering of the sea level, such as would be expected when water rushed in to fill the newly formed caldera. The question of the exact timing of the caldera collapse has not been settled, but it seems to have



VIOLENT MIXING OF MAGMAS of differing composition may have triggered the eruption of Krakatau. Magma ranges in composition from silica-poor basalt through andesite and dacite to silica-rich rhyolite. The less silica there is in the magma, the denser it tends to be. The mixture of dacitic magmas in the chamber of Krakatau may originally have been stratified according to density and therefore been stable (*1*). A pulse of fresh basaltic magma, hotter than the material already in the chamber and also rich in volatile substances, may have intruded into the bottom of the chamber, and at first it may have rested quietly on the chamber floor (*2*). The hot magma would superheat the layer of dacitic magma immediately above it, however, making that layer less dense than the overlying layers. At the same time, as the basaltic magma began to cool, crystals would settle out and volatiles would begin to come out of solution, making the basaltic magma itself less dense than the lower layers of dacitic magma. Either or both of these processes would cause violent convective overturning of the material in the chamber (*3*). As the volatile-rich basaltic magma rose to shallower levels of reduced ambient pressure, dissolved volatiles would rapidly come out of solution. The pressure within the chamber might therefore increase to the point where the magma would force its way to the surface and erupt (*4*). Mixed pumices found at Krakatau suggest this mechanism caused the eruption.



PYROCLASTIC FLOWS are masses of incandescent volcanic material fluidized (given a density and a viscosity lower than those of an aggregation of solid material) by hot gases. As the flow travels it segregates into a dense lower zone in which the flow is generally laminar and a light upper zone in which the flow is turbulent. When the flow reaches the sea, the denser material may plunge into the water, but the upper part of the flow may temporarily have a density less than that of seawater and therefore may travel on the surface. As the fluidization dissipates, the remaining material becomes denser and more of it enters the sea. The process continues until only a turbulent cloud of ash and steam is left. The hot material can cause secondary explosions as it sinks into the sea. It has been argued that the grading process that takes place within the flow itself and the winnowing of the ash by the secondary explosions produce a fine, crystal-poor ash that is distributed over a wide area by the secondary explosions. Rogier D. M. Verbeek reported finding deposits of this type near Krakatau.

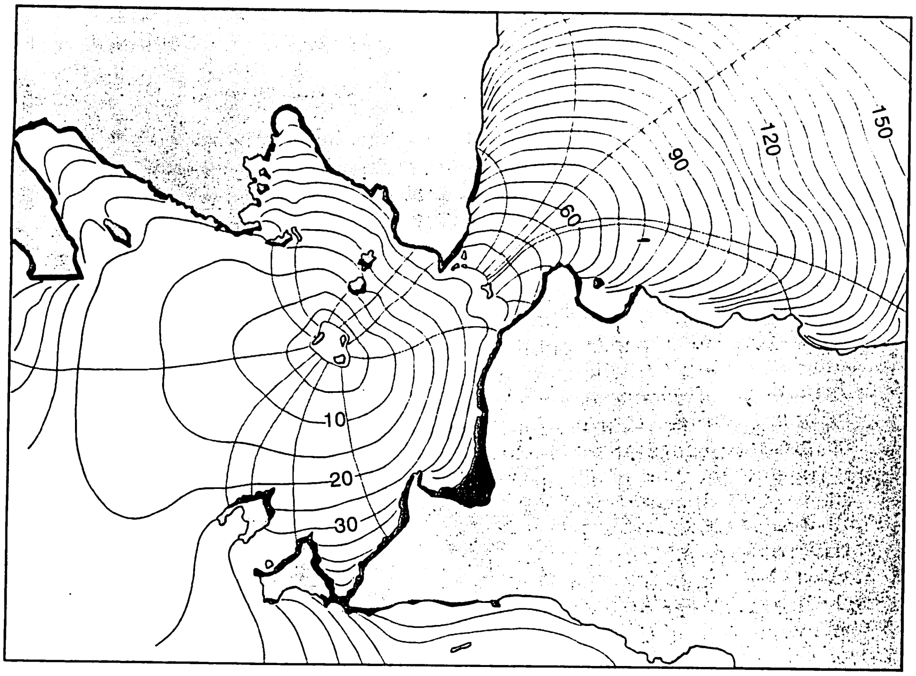
come late in the sequence, perhaps even after many major tsunamis. The evidence on the second question is also somewhat equivocal. At many points along the Sunda Straits the arrival of most of the tsunamis was marked by a rise in the sea level. A few retreats were also apparently recorded, however, and most of the tide gauges were so far away from Krakatau that an initial retreat may have been too small to register on them.

There are three alternative causes for the tsunamis. Some workers have suggested that submarine eruptions, which like a depth charge would create an outward-propagating water dome, may have caused some of the tsunamis. Verbeek suggested in 1884 that the largest tsunami was set in motion by the slumping of the northern half of the volcanic cone Rakata into the newly formed caldera. Verbeek also suggested that the sudden displacement of water by volcanic ejecta "falling" into the sea could have set the waves in motion. Given that many cubic kilometers of material entered the sea in the form of pyroclastic flows, this possibility seems to us the likeliest one.

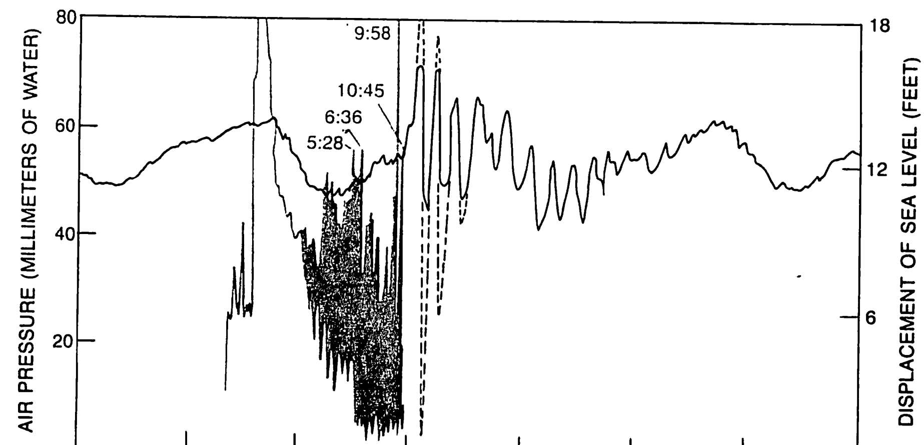
The correlation of the time of arrival of the waves at points along the Sunda Straits with events in the eruption sequence is critical to arguments about the origin of the sea waves. Establishing the chronology has been complicated by two problems. First, not all the tsunamis were true tsunamis, that is, waves that had traveled entirely by water. Second, it has proved difficult to synchronize the eruption sequence with the timing of the atmospheric disturbances recorded by the gasworks pressure gauge at Jakarta and sea waves recorded by the tide gauges along the straits.

Many of the sea waves, particularly those recorded at points far from the volcano, appear to have traveled extremely fast: at the speed of air waves rather than at speeds typical of sea waves. The velocity at which a wave moves through water is proportional to the depth of the water. More precisely, the velocity of the wave is equal to the square root of the acceleration of gravity multiplied by the depth of the water. The waves from Krakatau reached Honolulu in only 11 hours, a travel time that implies an average water depth of 17 kilometers. The average depth of the deep ocean is much less: about four kilometers. Furthermore, sea waves attributed to the eruption were observed in parts of the oceans where they could not reasonably be expected to appear; for example, waves were detected on the far side of island chains, a barrier through which they could not possibly have propagated.

These discrepancies came to light soon after the eruption but for many years were unexplained. In 1955, after microbarographs capable of registering small atmospheric pressure variations were developed, Maurice Ewing of the Lamont-Doherty Geological Observatory and Frank Press of the Massachusetts Institute of Technology were able to demonstrate that seismic waves through the solid earth can be coupled to the atmosphere. In 1967 David G. Harkrider of Brown University and Press showed that the long trains of pressure pulses set up in the atmosphere by nuclear explosions transfer some of



MAP OF TSUNAMI TRAVEL TIME is based on the times of arrival of the tsunamis recorded by tide gauges at various points along the Sunda Straits. The arrival times of the tsunamis were distinguished from those of the trains of secondary waves set up when the tsunamis entered the bays where most of the tide gauges were installed. Then the tsunamis were traced backward in time; their speed at each point in time was determined from the depth of the water through which they were then moving. Contour lines (*colored lines*) were derived from the paths and travel times of a number of tsunamis (*gray lines*), making it possible to find the travel time of a tsunami from Krakatau to any point on the coast. The inundated areas are in color.



PRESSURE AND TIDE GAUGES at Jakarta recorded the major explosions and the ensuing tsunamis on August 27, 1883. A pressure gauge at the gasworks (*color*) fortuitously recorded the arrival of the atmospheric pressure waves generated by the explosions. The broad peak in the trace on August 26 is unrelated to the eruption; it may have been caused by an increase in the pressure of the gas in the tank the gauge was monitoring. The tide gauge at Tanjong Priok (Jakarta's harbor) (*black*) recorded the arrival of the sea waves set in motion by the same explosions. Some of the waves were so high that they exceeded the range of the gauge. The broken-line peaks are estimates of the displacement in sea level based on various observations, such as the number of steps in a flight of stairs leading down to the harbor that were covered by water. The highest peak corresponds to the tsunami that arrived at Jakarta at 12:16 P.M. The peaks following it include secondary waves set up in the harbor and the straits by the tsunami.

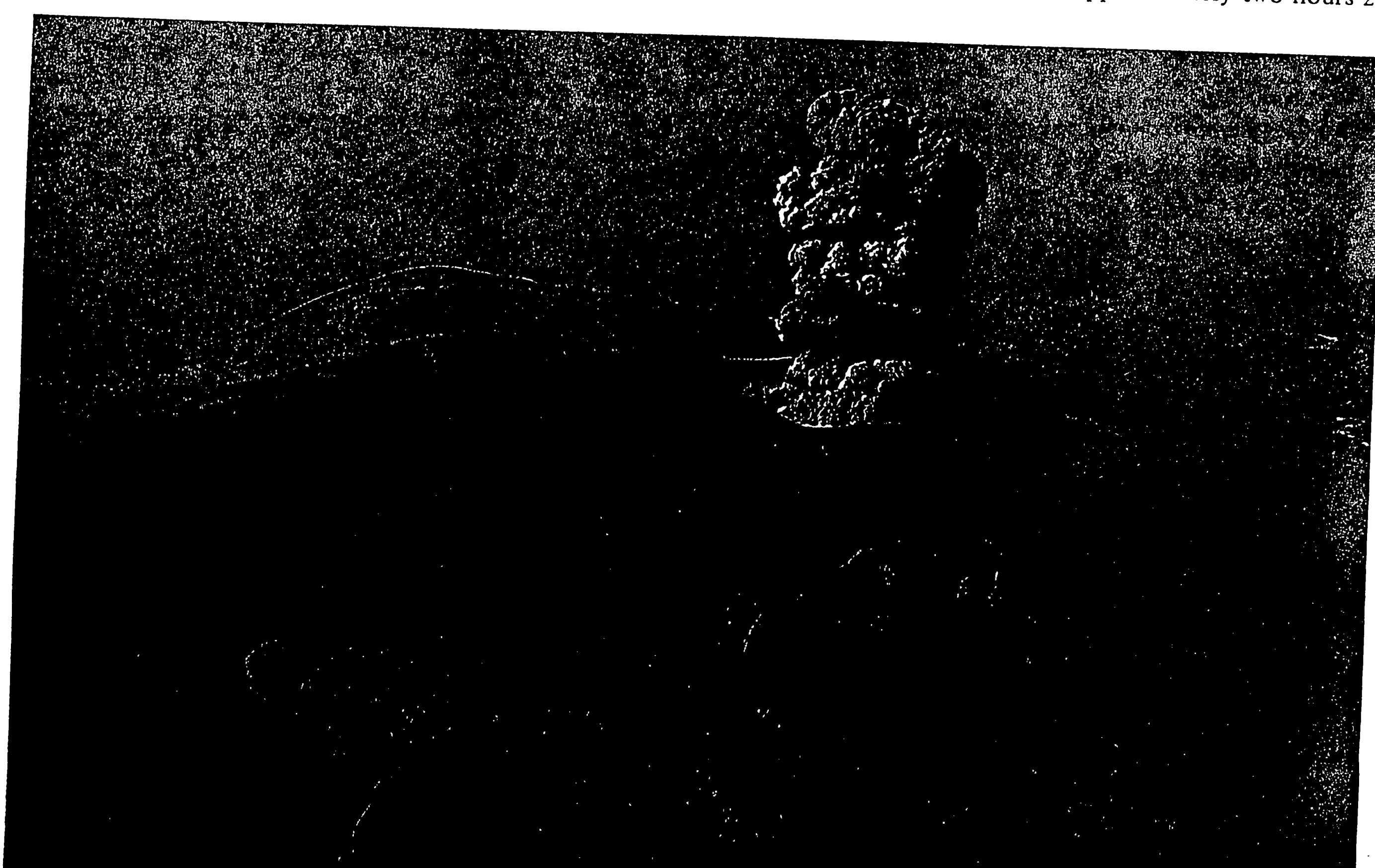
their energy to the ocean, causing sea waves in regions far from the explosion.

The coupling mechanism is complex; the amount of energy transferred depends strongly on resonance, that is, on the natural vibrational frequencies of the atmosphere and the ocean. Nevertheless, the general principle that governs the interaction can be stated simply: The ocean can be thought of as responding to alternating increases and decreases in atmospheric pressure in such a way as to maintain hydrostatic equilibrium. Increased atmospheric pressure causes the ocean to become shallower and decreased pressure causes it to become deeper, so that the weight of the ocean-atmosphere column above each unit area remains as nearly constant as possible. Harkrider and Press recognized the analogy between a nuclear explosion and a volcanic one and suggested that the same kind of phenomenon might explain the anomalous tsunamis that followed the eruption of Krakatau.

Much patient detective work was still needed to determine what caused the true tsunamis that inundated the coastlines along the Sunda Straits. The arrival of sea waves recorded by tide gauges at various points along the straits had to be distinguished from the arrival of secondary waves set up by the tsunamis within the enclosed bodies of water, such as bays, where most of the tide gauges were installed. Then the tsunamis had to be traced to their point of origin, taking into account refraction, or changes in velocity, caused by the varying depth of water in the straits. In 1981, I. Yokoyama of the Usu Volcano Observatory in Japan analyzed the refraction of the Krakatau waves and published a map of the travel time of the tsunamis. On the basis of the map he concluded that some of the minor tsunamis were probably caused by volcanic ejecta entering the sea but that the largest tsunami, which reached Jakarta at 12:16 P.M. on August 27, must have been caused by an underwater eruption.

John H. Latter of the New Zealand Department of Scientific and Industrial Research came to somewhat different conclusions in a paper published the same year. Latter set out to establish the chronology of events as accurately as possible from the records kept by both the pressure gauge at the Jakarta gasworks and the tide gauge in Jakarta's harbor. He calculated the times of explosions at Krakatau from the times of arrival of atmospheric pressure waves at Jakarta, taking into account the atmospheric travel time of eight minutes and the five-minute difference between Jakarta time and Krakatau time. He then showed on the basis of the timings of the explosions and the map of tsunami travel times worked out by Yokoyama, according to which the travel time for a tsunami traveling from Krakatau to Jakarta was two hours 25 minutes, that the chronometer on the tide gauge at Jakarta was inaccurate by three and a half minutes with respect to the pressure gauge. Having established the chronology of events, Latter was able to show that the arrival times of atmospheric waves and sea waves at Jakarta caused by some of the minor events of the eruption sequence were correlated.

In several instances, however, the sea wave could not be correlated with a matching atmospheric wave and thus with the explosive event that caused both. The largest atmospheric wave, caused by the massive explosion heard as far away as the Indian Ocean, reached Jakarta at 10:08 A.M. If the atmospheric travel time and other factors are taken into account, it must have been caused by an explosion taking place at Krakatau at 9:58 A.M. A large sea wave was recorded on the tide gauge at Jakarta at almost exactly the same time as the atmospheric pressure wave was recorded at the gasworks. Given that the travel time of a sea wave from Krakatau to Jakarta is approximately two hours 25



ANAK KRAKATAU ("Child of Krakatau") is a new volcanic cone that is building up in the caldera left by the 1883 eruption. It is at roughly the same site where Danan once stood. The new cone broke the surface of the sea late in January, 1928. Successive eruptions of Anak Krakatau have since largely filled the caldera left by the 1883 eruption with debris. The photograph was made by Maurice Krafft.

minutes and that Latter could find no evidence for an event taking place at Krakatau at about 7:40 A.M., he concluded that the large sea wave was caused by the coupling of the atmospheric wave to the water. The true tsunami caused by the explosion at 9:58 A.M., which had a much larger amplitude than the false tsunami, did not arrive at Jakarta until 12:16 P.M.

At this point the details of the timing become all-important. Given the sea-wave travel time, the large tsunami that arrived at 12:16 should have originated at Krakatau at about 9:45 A.M., that is, before the major explosion took place. Latter was confident of the accuracy of his meticulously checked timings, and he was certain there must be a causal link between the largest air and sea waves, and so he concluded that the tsunami originated not at Krakatau itself but rather at a point closer to Jakarta's harbor by a distance equivalent to the time discrepancy. He then used Yokoyama's map to show that the point of origin of the tsunami set in motion by the great explosion at 9:58 A.M. was 10 to 15 kilometers from Krakatau. This point corresponds roughly to the outermost edge of the newly formed island Calmeyer. Similar analyses of the timing of paired explosions and sea waves led Latter to conclude that at least three of the Krakatau tsunamis were probably caused by massive pyroclastic flows advancing into the sea, such as the flow that formed Calmeyer.

Although the Krakatau tsunamis are the largest tsunamis known to have been generated by pyroclastic flows, the same mechanism has been shown to be responsible for tsunamis following the eruption of other volcanoes. In 1980 Juergen Kienle and Samuel E. Swanson of the U.S. Geological Survey reported that the nine-meter tsunami that swept through English Bay in Alaska after the eruption of the volcano Augustine in 1976 was set in motion by a pyroclastic flow entering the bay.

Since the eruption of 1883 a new volcano, Anak Krakatau ("Child of Krakatau"), has been building up at a site roughly corresponding to the position of the old volcanic cone Danan. The new volcano was initially under water, but the cone emerged late in January, 1928. Since then successive eruptions have gradually filled the northern sector of the 1883 caldera with lava and pyroclastic flows. The focus of volcanic activity is shifting southward and may well be following the same fissure that determined the alignment of the volcanic cones on the original island. A large island, aligned like the old one northeast to southwest, may eventually develop. It seems that a new Krakatau is rising like the phoenix from the ashes of its own destruction.