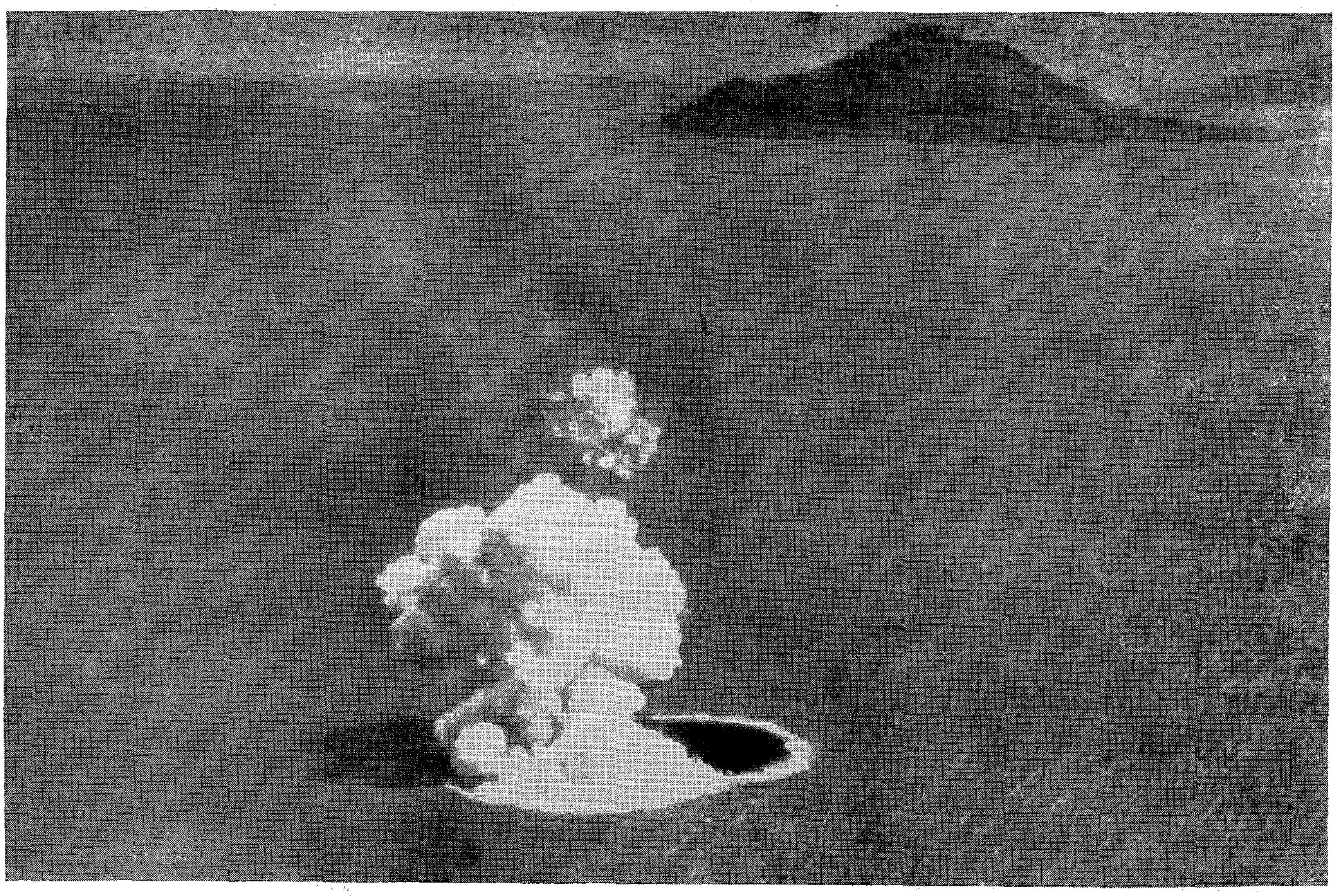


Krakatoa, the volcano that shook the world in 1883, still rumbles deep in its submarine crater.

VOLCANOES, ICE AND DESTRUCTIVE WAVES

by FRANK PRESS

THE NEWSPAPERS in recent months carried dispatches about the detonation of a hydrogen bomb in the megaton range. This was the largest man-made, or artificial, explosion ever achieved. Impressive as this was, however, one of nature's explosions still transcends all of man's attempts in this field to date—the explosion of the volcano Krakatoa which took place in the Sunda Strait on August 27, 1883. Not all of the phenomena associated with this explosion are understood even today, nearly 75 years later. Fortunately for modern students of Krakatoa phenomena, the data are readily available in the form of a detailed report prepared by a committee of the Royal Society appointed soon after the explosion.

Krakatoa lies almost in the middle of the Sunda Strait, a narrow, shallow body of water, with an average depth of about 200 feet, which ties the Indian Ocean to the China Sea. The volcano was in a period of relative inactivity prior to May, 1883. Gas and steam issued from a few scattered vents, but in May a new series of violent eruptions began. Typical of these eruptions, as the old books describe them, was a flaming region where the boiling lava poured down the sides, and a tremendous cloud of steam and volcanic ash that went high into the atmosphere, producing rain and severe electric storms in the vicinity of the volcano. Pumice and ash filled the Sunda Strait, and ships had difficulty cruising there. As the eruptions became more and more severe the strait was cloaked in darkness even in midday as clouds formed by a combination of steam, mud and water blotted out the sun. There was a rainfall of hot mud and soot which fell on the decks of nearby ships, until the crews had to use their sea pumps to play water on sails and decks to remove the hot sulphurous materials that came down from the sky.

It is only a matter of conjecture at this time as to why Krakatoa exploded the way it did. Volcanoes erupt in different ways. They erupt through fissures that occur in the earth, through which lava flows freely and forms plateaus such as we have in the Pacific Northwest. At the opposite extreme are the eruptions which result in cones with very steep sides, formed by falling cinders. Severe explosions are rarely associated with a volcano; in fact, Krakatoa represents the only known occurrence of a cataclysmic explosion in which a tremendous amount of energy was released almost instantaneously.

The reason why

Why this occurred at Krakatoa is not known. Conjecture has it that the ready access of sea water surrounding the island was responsible—not so much in forming superheated steam as it floated into vents and tissues, but in entering the crater and forming a cap by chilling and solidifying the lava. This did not stop the volcanic activity below, of course, which continued with the generation of steam and gas. Pressure was gradually built up, while the cap prevented its release. Then, at one stroke, the cap was impulsively blown out. The explosion was so tremendous that it almost entirely eviscerated the volcano, and it profoundly altered the surface and submarine topography in the surrounding region. A vast quantity of solid material was blown into the atmosphere, the coarse components falling locally, creating new banks and shoals in the Sunda Strait. The lighter material went into the atmosphere and formed clouds. These clouds were so extensive that at Batavia, more than 100 miles away, there was almost complete darkness at noon. The rain which fell was essentially a rain of mud—the drops consisting of 90 percent mud and 10 percent water. Associated with the mud-fall were severe electric storms. It was quite a frightening spectacle.

The fine dust went high into the atmosphere—so high as to reach air currents which disseminated the particles throughout the world. Unusual atmospheric optical effects appeared. Brilliant sunsets with unexpected hues, blue-colored moons, and rings and halos around the sun and moon were observed throughout the world.

The main loss of life which was connected with the eruption of Krakatoa resulted from destructive sea waves which were excited by the final explosion. Some 36,000 inhabitants of the adjacent coastal areas lost their lives in 100-foot waves that came without warning. (But, strangely enough, ships in the Sunda Strait close to the volcano were not harmed.)

As is the case with most tidal disturbances, it was the local effect of the coast line which funneled the destructive waves into certain areas. The Krakatoa tidal wave was not unlike the earthquake-generated sea waves which occasionally visit the coasts of South America and Japan. One theory has it that the earthquake initiates a submarine avalanche which runs down the continental slopes into the deep ocean, providing enough push to set the big tidal wave into motion.

California tidal wave

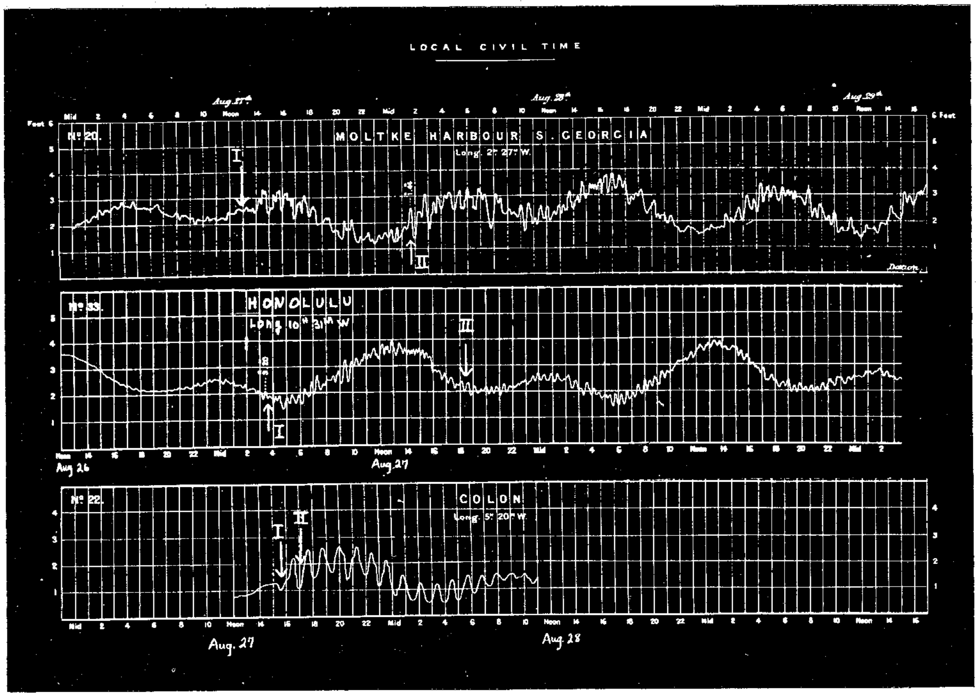
California is fortunate in not having tidal waves associated with its earthquakes—though this is not entirely true because, in 1812, one of our big earthquakes was accompanied by a tidal wave that may have reached a height of 50 feet at Ventura and at Gaviota, and about 30 to 35 feet at Santa Barbara. There was not much habitation in that area then, and the reports that we have are quite meager, but if it happened today, of course, tremendous destruction would occur.

Once excited, a tidal wave crosses the ocean at a very definite speed (given by the square root of gh, where g is the acceleration of gravity and h is the depth of the water). Tidal waves sometimes traverse the ocean many times. Earthquakes have been known to send them across the Pacific to another continent, where they are reflected and returned to the continent from which they started. These are by far the most destructive tidal waves.

Another variety is that associated with a storm. This is the kind of wave that did such damage on the East Coast last year, along with the Edna and Hazel hurricanes. This wave is associated with the low pressure area and the winds of the hurricane moving on the shore. When these arrive at a time of normal high tide, the excess above high tide produces an inundation on the coast line. This is not so much a wave coming in and going out as it is a general rise of the sea level that lasts from 6 to 24 hours.

The Krakatoa tidal wave was different. The explosion, the debris coming down, and its impact on the water—all of these together produced the tidal wave.

One of the most important features, scientifically, of the Krakatoa explosion was the sea wave which reached remote places throughout the world. These waves were only one or two feet high—too small to cause any damage—but of great significance because of their mechanism of propagation. Our knowledge of these comes from records made by tide gauges which were operating in important harbors. It is very important for shipping to measure the tides precisely so that ships can know the best time to come into harbor, the best

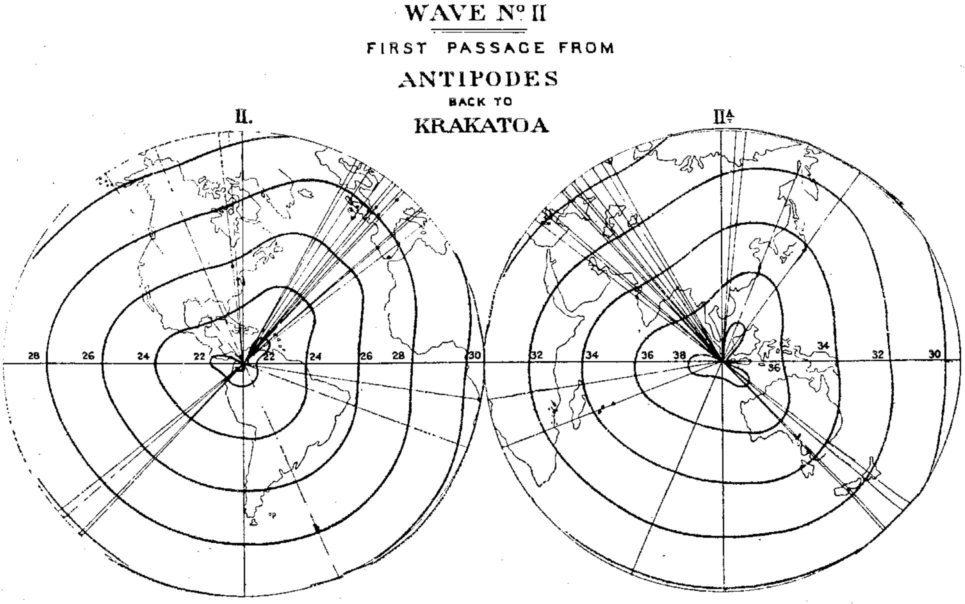


Tide gauge records from South Georgia, Honolulu and Colon showing Krakatoa sea waves superimposed on the normal tides. Arrows indicate arrival of first and second atmospheric waves.

time to tie up, and to sail. It was especially important, of course, in those days when so much depended on wind. Fortunately, the tide gauges of 1883 were sufficiently well designed to provide fairly good records of the Krakatoa waves. Thus we have instrumental data for the Krakatoa sea waves from such widely separated places as Honolulu, San Francisco, Colon, South Georgia and English Channel ports.

Another significant phenomenon associated with the explosion of Krakatoa was the atmospheric waves. We would expect an explosion of this sort to make a big sound—and it did; in fact, it was probably the biggest sound that was ever created, that we know of. It was as if there was an explosion in New York and the sound was heard in Los Angeles. Audible sounds, not unlike distant cannonading, were reported from as far as central Australia and India. The sub-audible atmospheric pressure pulse was detected by barographs on each of four passages around the earth. The fact that these early instruments were able to detect the wave after it had travelled some 75,000 miles testifies to the strength of the explosion.

One feature of the Krakatoa sea wave remained unexplained until very recently. The wave that reached the English Channel had to go around Africa and travel up the Atlantic Ocean. The wave that reached Colon had, further, to cross an effective barrier formed by the Antilles. The wave that came to San Francisco could not have gone by a direct route because of the barrier formed by the East Indies; in order to explain its arrival it was necessary to postulate a path involving a detour below Australia.



Atmospheric waves sent out by Krakatoa explosion made at least four passages around the earth. Diagram shows wave front of aerial disturbance after first passage through Antipodes. Times noted are in hours after zero hours, GCT, August 27, 1883.

Even if these unlikely paths are accepted, the observed travel times of the waves correspond to velocities that are inconsistent with the known depths of the ocean. Thus, the Krakatoa sea waves that reached widely separated parts of the world presented such a problem that most investigators came to doubt their connection with the explosion. The only explanation that could be offered was the unlikely one that local earthquakes, occurring coincidentally, produced the local sea waves. This basically untenable explanation of the Krakatoa sea waves remained with us until very recently.

Ice provides a clue

Oddly enough, it was work on ice that finally gave us a clue to the mechanism of propagation of the Krakatoa sea waves. Several years ago, together with colleagues at Columbia University and the Air Force Cambridge Research Center, I worked on ice—in the form of floating sheets, as it occurs in northern lakes or in the Arctic Ocean. Our interest in floating ice was stimulated by an Air Force problem—that of finding a method by which planes can determine the ice thickness in order to know whether it is safe to land or not. We thought of all sorts of fancy electronic schemes to use in the solution of the ice-landing problem, and in the very early days of this project we had some weirdly complicated contraptions—all of which were in sharp contrast to the simple solution found by a few Arctic pilots. They just bounce their planes off the ice without losing flying speed, then circle around and examine it. If the ice has a hole or a crack in it, they know it isn't thick enough. With the modern trend towards electronic methods, however, such a simple scheme never had a chance for wide adoption.

Our first serious approach to this problem involved the use of elastic waves transmitted through the ice. We conceived the idea of parachuting a small telemetering seismograph to the ice so that elastic waves excited by a small bomb could be detected in the airplane. We started experimenting directly on floating ice by exploding small charges and detecting the resultant elastic waves with small microphones—geophones—placed on the ice surface at distances of several thousand feet from the explosion. Explosions in the ice, or below it, gave the expected results of flexural vibrations which are characterized by a gradual variation of frequency and phase velocity with travel time.

To avoid the trouble of digging shot-holes in the ice, several tests were made in which the charges were detonated on the surface. Much to our surprise, the character of the resultant vibrations was profoundly altered. The geophones detected a train of constant frequency vibrations in which the phase velocity was equal to the speed of sound in air. In other words, we inadvertently demonstrated in this experiment that an explosion in the air can produce significant elastic waves in the ground of a special kind—in that the phase velocity of these waves in the ground is the speed of sound in the air.

Air wave and sea wave

So the tidal waves from the Krakatoa explosion were not tidal waves in the usual sense, but were excited by the great air wave as it swept across the ocean adjacent to the tide gauge stations. Indeed, a check on the arrival time of the Krakatoa air and sea waves at a number of widely separated locations shows that this is the only plausible mechanism.

Thus the ice work, completely unrelated, and performed for an entirely different purpose, provided the key to the unexplained sea wave from Krakatoa. Another clue was provided by an equally unrelated research project.

This part of our work began when the New York *Times* published a news dispatch concerning a disturbance which occurred on Lake Michigan on the morning of June 26, 1954. About a dozen people were fishing from docks in the vicinity of Chicago. The weather was clear at the time. Suddenly a wave appeared out of nowhere and swept seven people to their death.

This unique event was all the more peculiar since Lake Michigan is located in a non-seismic area and the weather was clear. Why should a destructive sea wave, with an amplitude of 10 feet, suddenly appear and wash all of these people into the lake?

A coupling mechanism

It occurred to us that this might be another example of the coupling mechanism we found in our ice studies, which so well explained the Krakatoa wave. We surmised that an atmospheric pressure disturbance swept across the lake with just the right velocity to excite a destructive sea wave, and an examination of the meteorological records showed this to be the case. A pressure pulse did indeed occur an hour before the accident, and its velocity was the critical one for this part of Lake Michigan—65 miles an hour. Fortunately, though atmospheric pressure disturbances occur frequently, very few travel with this high velocity.

We have seen how three apparently unrelated phenomena are tied together by a common mechanism. In one sense we have here an argument for broadness in science, for had we not known about the Krakatoa problem, our ice work could have been simply an interesting experiment, performed for a very special purpose. As it turned out—not only could the special purpose be satisfied, but a fundamental geophysical mechanism could be demonstrated.