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Caldera Collapse in the Galápagos Islands, 1968

The largest known collapse since 1912 followed a flank eruption and explosive volcanism within the caldera.

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Calderas are large, broadly circular volcanic depressions. They usually form by the collapse of overlying material into subsurface magma chambers that have been evacuated as by volcanic eruptions. Many ancient calderas have been found by geologic mapping, and more recent calderas, such as Crater Lake, Oregon, are topographic features common to many volcanic regions (*1*).

Few historic caldera collapses have been documented, however. The largely submarine collapse of Santorin, Greece, is believed to have produced tsunamis (seismic sea waves) that devastated the Minoan civilization about 1470 B.C., and similar waves from the famous 1883 collapse of Krakatoa, west of Java, killed 36,000 people (*1*). In June of 1968 the caldera floor of Volcán Fernandina, Galápagos Islands, subsided an estimated 300 meters. The volume of collapse was 1 to 2 km^3 which, although much smaller than Santorin or Krakatoa, is second in this century only to the 1912 Katmai (Alaska) collapse. Records of the Fernandina collapse were obtained by many remote sensing devices, by residents of the archipelago, and by field studies commencing 3 weeks after the start of the collapse. This article summarizes the present stage of our investigation of this event.

Setting

The Galápagos Islands, located on the equator some 1000 km west of Ecuador, are a group of basaltic shield volcanoes rising as much as 1,710 meters above the sea from a shallow submarine platform approximately 40,000 km^2 in area (*2*) (Fig. 1). Darwin's visit to the islands in 1835 has given them a biological fame that has overshadowed their geologic importance, for the group has been termed "one of the most active volcanic fields in the world" by Howel Williams (*3*) and "second to none in the magnitude of its recent volcanism" by A. R. McBirney (*4*). Although much activity goes unrecorded in this sparsely inhabited region, Richards lists 35 eruptions in the past 160 years (*5*). All these eruptions occurred on the western islands of Fernandina, Isabela, and Santiago (*6*), which cover an area roughly equivalent to that of the island of Hawaii.

The major shield volcanoes of the Galápagos have well-developed summit calderas, unusually steep flanks, and rows of volcanic vents that are concentric near the summit caldera and radial on the lower flanks (Fig. 2). These features are nowhere better illustrated than on Isla Fernandina, a single shield volcano on the western edge of the Galápagos platform. Its gentle outer slopes steepen (to 34°) as they approach the summit zone of concentric vents, where gentle slopes again prevail. This domal shape has been likened to an overturned soup plate, as contrasted with the overturned saucer shape of the better known Hawaiian shield volcanoes (*7*). At its summit, nearly 1500 meters above sea level, is an elliptical caldera measuring 4 by 6½ km across (Fig. 2). Prior undated collapses are recorded by benches at both ends of the caldera (Fig. 1), and in early 1968 the flat 7-km^2 floor of the caldera was 800 meters below the rim. Sailing vessels have reported at least 12 eruptions from this uninhabited island (*5*), and in 1958 lava flows from a summit eruption covered the floor and evaporated the lake shown in Fig. 2. In 1961 lava flowed to the sea from a vent at an elevation of approximately 400 meters on the southeast flank. No other activity was reported until 1968, but the island cannot be seen from inhabited parts of the archipelago, and even the 1958 eruption, when lava covered 15 km^2, was not witnessed by man (*5*). Summit visitors of recent years reported increasing fumarolic activity at the base of the caldera's west wall, as well as fumaroles on the east edge of the floor and along the southwest rim.

Petrologic reconnaissance suggests that the rocks of Fernandina are mainly tholeiitic basalts like those of the six coalesced shields of neighboring Isla Isabela (*4*). The oldest flows sampled for a paleomagnetic survey of the island showed normal polarity and are believed to be less than a million years old (*8*). Herron and Heirtzler (*9*) recognize an east-west axial zone of sea-floor spreading just north of the Galápagos, and they interpret a seismically active zone, which offsets this axis by 100 km, as an oceanic fracture zone extending southward through the seismically active area of the western Galápagos Islands.

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Chronology: 1968 Events

On 15 May a small earthquake (4.5 m_b, where m_b is the earthquake magnitude as determined from body wave characteristics by the U.S. Coast and Geodetic Survey) took place midway between the offset ends of the axial zones 300 km north of Fernandina. Additional seismic activity in the Galápagos region, together with major eruptive events, is shown chronologically in Fig. 3 (*10*).

Flank eruption. At 3 p.m. (*11*) on 21 May, witnesses on a Lindblad Tour vessel near Fernandina observed a small vapor cloud at an elevation of 600 meters on the east flank of the volcano. This position was roughly 5 km north-northwest of the 1961 eruption site and about 75 meters below the level of the caldera floor 6 km to the west. The cloud grew to a height of approximately 4 km, and lava fountained as high as 70 meters from several vents. Lava flows covered an estimated 10 km^2, and the activity was declining at 11 p.m. when the ship left the area (*12*). Two observers had noticed a similar vapor cloud several days earlier, suggesting previous activity, but their view of Fernandina was blocked by Isla Isabela. Visual searches of the east side of Fernandina on 25 May and 4 June revealed no further activity.

Precollapse seismicity. There were a few minor earthquakes in the Galápagos region near the end of May and 20 more (3.9 to 4.6 m_b) during the first week in June. After the last recognized earthquake in this group, there was an explosion inferred to have originated at Fernandina at 8:20 p.m. on 7 June. This event was recognized by H. Matheson in analysis of infrasonic (low-frequency atmospheric sound wave) recordings from Peru, but it was not heard by Galápagos residents and was too weak to be monitored by more distant microbarographs. Then followed three full days of apparent seismic quiet.

Clouds of 11 June. At 10:18 a.m. on 11 June there was a small (4.0 m_b) earthquake in the Galápagos, and the Pacific Missile Range hydrophones recorded *T* phases from four Galápagos events of increasing magnitude originating between 10:16 and 10:18. Shortly thereafter, a column of vapor was noticed above the Fernandina caldera by the crew of the fishing boat *San José*, which was anchored 35 km to the east in Urvina Bay. Observers at Academy Bay saw a large columnar vapor cloud over Fernandina at about 10:40, which spread laterally after reaching its full height of approximately 22 km (*13*). Its stem finally rose so that clear sky could be seen beneath it from Academy Bay, but a report from the *San José* suggests that eruption clouds remained low over the volcano and became darker as the afternoon wore on. No sounds were heard accompanying these events, but a strong atmospheric disturbance originating at 4:00 p.m. was recorded by South American infrasonic stations (*14*). Shortly afterward, a dark ash cloud was visible from Academy Bay; a picture taken at 4:30 by a Tiros satellite shows that the cloud was circular, 50 km in diameter, and centered over Fernandina. As seen from the ground (Fig. 4), its shape was like that described from many vulcanian eruptions since Pliny the Younger's classic account of the A.D. 79 eruption of Vesuvius. The cloud expanded radially outward at an altitude of approximately 24 km and at speeds of 80 km per hour. One witness

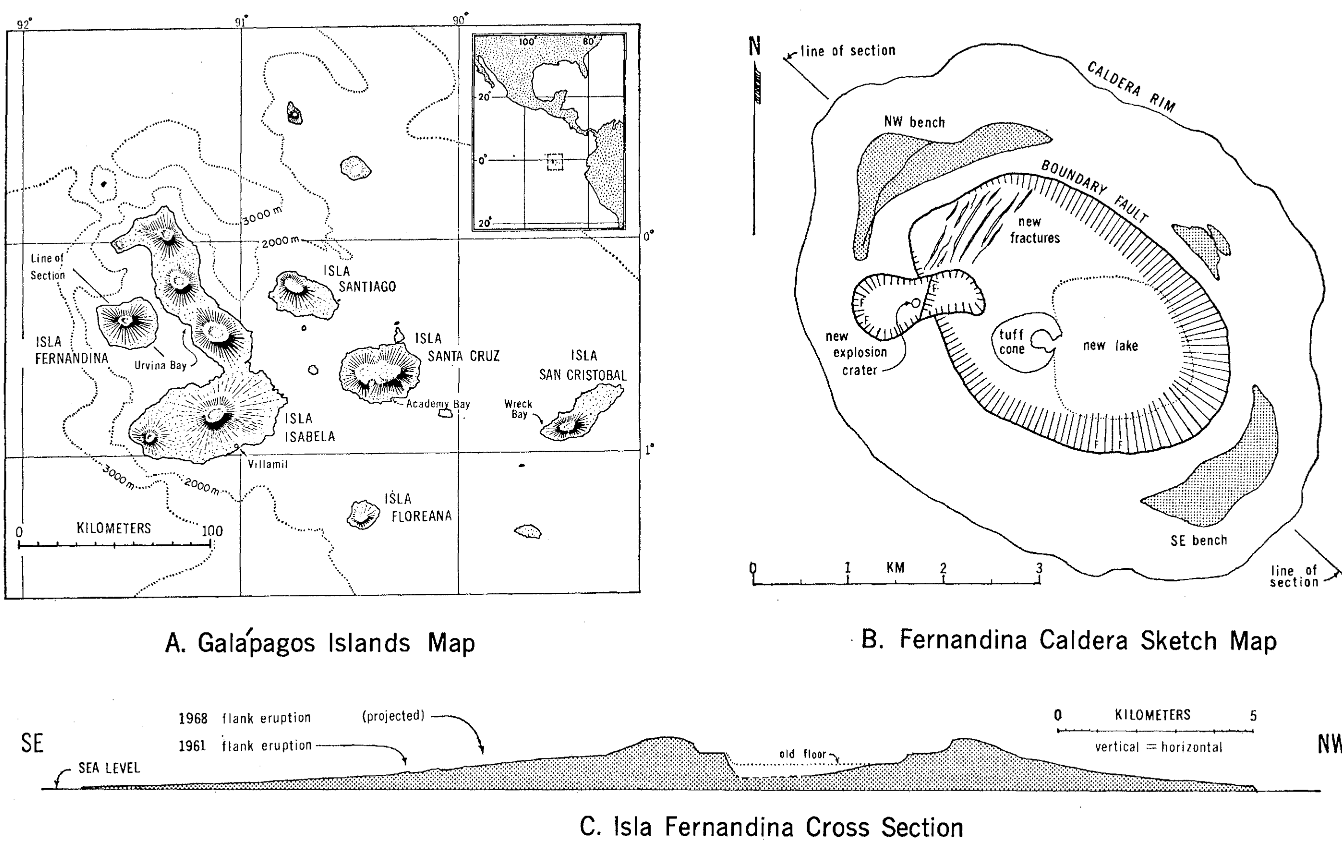


Fig 1. (A) Location map of the Galápagos Islands adapted from American Geographical Society map. (B and C) Caldera sketch map and volcano cross section from air and ground photographs, Hydrographic Office Chart 5931, and our own observations. Designations *F* on the sketch map indicate positions of the fumaroles discussed in text, and the length of hachures on the downthrown side of boundary faults is proportional to subsidence. There is no vertical exaggeration in the cross section.

noticed behavior of the cloud margin suggestive of cyclonic rotation.

Major explosion. At 5:08 p.m. a loud, deep boom originated at Fernandina and was later recorded at infrasonic stations from Bolivia to Alaska (*15*). To listeners 220 km to the east, the explosion sounded like a nearby dynamite blast. It lasted as long as 1 second and was followed in 5 to 8 seconds by a lesser blast. During the next 2 hours, sounds like distant gunfire were heard at intervals of roughly 1 to 5 minutes. However, the crew of the *San José* reportedly heard nothing, and residents of Isla Santa Cruz, 140 km from the volcano, described less loud noise than was reported from Wreck Bay, 60 km farther away. This phenomenon appears to be common in volcanic explosions; a similar situation occurred during the 1902 eruption of Mont Pelée, when explosions heard 240 km to windward were unheard only 20 km away (*16*).

By using infrasonic data from five stations in the Americas, Craine, Thomas, and Kuckertz calculated the energy coupled into the air wave by the major explosion as 10^{21} ergs, or equivalent to the rapid release of 1½ km^3 of gas (at atmospheric pressure) into the atmosphere (*17*). At 5:20 p.m. a recording barograph at Wreck Bay, 220 km east of the volcano, showed a positive deflection of 1.2 millibars, or roughly one-fifth the deflection observed 150 km from Krakatoa in 1883 (*18*). A drop in pressure, such as followed the initial pressure rise at Krakatoa, was not recorded at Wreck Bay.

Witnesses throughout the archipelago described an earthquake at about the time of the large explosion. Its intensity at Academy Bay was placed between III and IV on the modified Mercalli scale by Rolf Sievers of the Darwin Research Station. Smaller quakes followed. These observations, together with the absence of such accounts during later Fernandina quakes to magnitude 5.4, would indicate an event approaching magnitude 6. In our search of June seismic records, we recognized Galápagos quakes as small as 3.2, probably missed few greater than 4.4, and certainly missed none greater than 4.9; yet we find no evidence of any Galápagos seismicity around the time of this reported earthquake. We must conclude either that the air wave was responsible for the effects attributed to earthquake or that there was substantial air-to-ground coupling.

Eruption. The crew of the *San José* described a pink-red underside of the afternoon ash cloud over the volcano, and similar observations were made from Villamil and the highlands of Santa Cruz after dark (about 6:30 p.m.). The same localities provided additional evidence of eruptions during the evening in their reports of red flashes, each lasting several seconds and appearing as glossy, irregularly vertical streaks, perhaps kilometers in height, over the volcano. The major seismic swarm began in early evening.

Fig. 2. Air photograph mosaic of Fernandina caldera before 1968 collapse. Vertical photographs were taken by the U.S. Air Force in May 1947. The large lake was eliminated by a lava flow, which covered the caldera floor in 1958, but a new lake had formed at the northwest end before the 1968 collapse. Note concentric rows of vents that have fed recent black lava flows radially down the flanks of the volcano. Radial lines of vents can also be seen along the right side of the photograph.

Lightning. Over Fernandina, lightning was observed throughout the archipelago that evening, and all accounts emphasized the extraordinary thickness of the bolts. In marked contrast with the thin, irregular bolts illustrated by Anderson *et al.* at the Surtsey eruption (*19*), witnesses on Isla Santa Cruz reported straight-sided bolts that were perhaps 20 times the normal thickness and that pointed downward toward the volcano. Intervals between flashes averaged from 2 to 15 seconds, but the *San José* reported no interference with its radio reception.

Ashfall. During the afternoon, ashfall was limited to the vicinity of the volcano. From midnight to 8 p.m. of the next day, however, ashfall at Villamil, 85 km southeast of Fernandina, left a cover of 25 grams per square meter. During the ashfall, the men of the *San José* had difficulty breathing and many of the inhabitants of Villamil reported sore throats.

At about midnight the westbound ship *Port Nicholson* noticed a low bank of apparent cloud ahead lying in a northwesterly direction (*20*). At about 1:00 a.m. the ship entered the ashfall zone at a position 135 km distant and N 33°W from Fernandina. Minimum visibility of 500 meters was recorded at N 52°W of the volcano, and the ship did not emerge from the cloud until 9:30 a.m. on 12 June, when it was roughly 350 km west of Fernandina. Thin ash deposits, with drifts to 10 centimeters in depth, were left on the ship. This ash contains a few grains measuring 0.4 millimeter and consists largely of lithic and crystal fragments with a small proportion of juvenile basaltic glass (refractive index $N =$ 1.60). It is somewhat coarser than the Villamil sample, but both are quite fine-grained (76 to 88 percent by weight of sample grains were smaller than 44 micrometers) and well-sorted (Inman sorting coefficient $\sigma_\phi \leqslant 1.0$), suggesting the sedimentologic characteristics of loess (*21*). Ash collected on the northeast rim of the caldera 1 month after the eruption consisted largely of lithic fragments with a mean diameter of 2 millimeters; the ashfall measured 1.2 kilograms per square meter. Recent reports (*22*) suggest that ash and dust deposits are as much as 2 meters thick on the west rim.

The duration of the eruption is uncertain. Distant ashfall was not reported after 12 June, but unconfirmed reports from the *San José* indicated that ashfall, colored flashes, and lightning continued around the volcano for several days. The reports also indicated that venting began on 12 June from perhaps 30 localities along the north flanks of Sierra Negra and Cerro Azul, two volcanoes on Isabela 65 km south and southeast of Fernandina. This activity may have been vapor emission or only brush fires. A visual search by a party from the Charles Darwin Research Station revealed no evidence of eruptive activity on either Fernandina or Isabela from 18 to 20 June.

Seismic swarm. From early evening of 11 June, the frequency of earthquakes increased to a maximum on 19 June and then declined rapidly (Fig. 3). There were few earthquakes after 23 June, indicating that the major collapse took place within 12 days. On a global scale the earthquakes were not large: 16 were in the magnitude range 5.0 to 5.4, and none exceeded 5.4; by comparison, the 1968 worldwide epicenter determinations of the U.S. Coast and Geodetic Survey list 1013 earthquakes in the 5.0 to 5.4 range and 290 earthquakes greater than 5.4. Nevertheless, Galápagos tremors were large enough to be recorded around the world and were reported to the Coast and Geodetic Survey by 116 stations from all continents. The larger shocks were concentrated in the early part of the swarm, and thus the first 3 days, although containing only about 15 percent of the total number of earthquakes, accounted for nearly half of the seismic energy released. The Darwin Station party, led by Roger Perry, reached Fernandina on 19 June at the peak of the swarm, when more than 200 events per day were recorded at the Darwin Station seismograph 140 km to the east. They climbed to the north rim of the caldera, but dust clouds completely obscured the interior and they did not linger. Rockfall noise was continuous and seemed concentrated in the southern part of the caldera. During their descent they smelled sulfur fumes roughly halfway down the northeast flank, the only evidence of volcanic emanations noted, and they felt 56 individual tremors during a 6-hour period (*23*).

A striking regularity in the seismic activity was noted by this party, as well as by distant seismologists. Average time between earthquakes obviously decreased as the frequency increased, but on 14 June events greater than 4.5 m_b took place regularly every 6 hours; on 15 June, this interval dropped to 3 hours; on 17 June, to 2 hours; and on 19 June, to 60 to 90 minutes. No such regularity was apparent as the interval between large quakes increased to the end of the swarm. In addition, nearly all larger quakes were preceded within a few minutes by one or more foreshocks and were followed by a much longer period of quiet. This apparent absence of aftershocks is unusual (*24*).

We calculate the seismic energy of the swarm to be 5×10^{19} ergs (*25*). Since the potential energy of the collapse is much greater, some 10^{23} to 10^{24} ergs (*26*), we speculate that most of the earthquakes formed by frictional resistance of the collapsing block. The seismic history (Fig. 3) probably gives an accurate picture of the collapse chronology.

Late collapse activity. At 8:30 a.m. on 21 June, an Ecuadorian Air Force plane piloted by Captain F. E. Sevilla flew over the caldera. A dust cloud extended to an altitude of 3 km, but the flight took place during a lull in the seismic activity and during the morning, when rock avalanche activity was at a minimum. By that time the lake, formerly in the northwest end, had been shifted to the southeast end of the caldera by major collapse of the floor. No sign of fresh lava was seen, but a small puff of white vapor was present over the northwest floor and dust rose from avalanches down the oversteepened walls. Much the same situation prevailed at noon on 4 July, when the caldera was photographed by our group from a U.S. Air Force plane (see cover). During our flight the lower slopes were obscured by cloud, but the caldera and most of the circumferential belt of recent vents was clear. There was no evidence of new lava either around the circumferential belt or within the caldera. No further changes were apparent by 10 to 13 July when we were on the rim, or when the caldera was visited by other groups in November 1968 and February 1970.

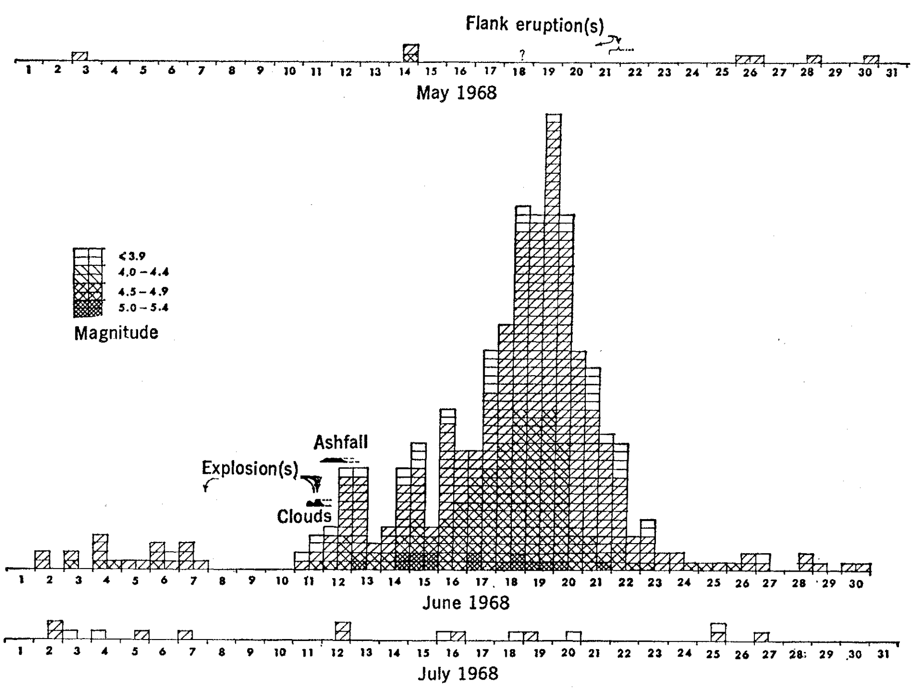


Fig. 3. Seismicity of Fernandina collapse (*10*). Each block represents an earthquake believed to have taken place in the Galápagos region during the (local) time interval shown.

Caldera Changes

The main visible result of the activity was the collapse of the caldera floor, the southeast part of which dropped approximately 300 meters. The main collapse took place along an elliptical boundary fault essentially coincident with that marking the last major (undated) collapse, which isolated the wide benches at both ends of the caldera (Figs. 1B and 2). Subsidence decreased to the northwest and was nil below the northwest bench. Near this northwest end, however, the floor is marked by a group of fractures that are aligned normal to the long axis of the caldera and that form a band of ½-km width at the crest of a monoclinal flexure on the caldera floor (Fig. 1B). The central third of the floor, between the fractures and the lake, is smooth, gently sloping, and apparently unbroken. The prominent central tuff cone, 700 meters in diameter and 110 meters above the floor, remained intact and showed no sign of fracturing. The floor now sags in the middle, as shown by the curvature of the northern lakeshore. Such a basining effect in calderas suggests an inward dip of the bounding faults (*1*, *27*, *28*).

Western block. A broadly elliptical area of ½ km^2, elongated east-west and crossing the main collapse fault on the west side of the floor, dropped as an independent block (Fig. 1B). The western part of this block, which included some of the old caldera wall, dropped an estimated 120 meters; the remaining eastern third dropped an estimated 50 to 150 meters more than the main floor, which adjoins it on three sides. Several ponds up to 100 meters across remained on the block in July, suggesting that part of the lake was trapped by subsidence of this block before the major collapse shifted the lake to the other end of the caldera. Steaming fumaroles that partly fed the ponds may, however, be responsible for much of the surface water. A part of this block had apparently been the site of previous collapse independent of the collapse of the main floor; before the 1968 collapse there was a cirquelike indentation in the wall there, and its floor was roughly 100 meters above the main caldera floor.

Fumaroles and vents. Ten to twenty vigorous fumaroles were seen on July mornings within the western block described above (Figs. 1B and 5). This area had previously been the site of sulfurous fumaroles, and 4 months before the collapse visitors noticed that the fumaroles were more active than in previous years and trees were dying in the vicinity. Five months after the collapse a Darwin Station party entered the caldera and reported continuing fumarolic activity in this area with the addition of sulfur deposits and fumes. They also reported new fumaroles, not visible in July, along approximately 200 meters of the south wall at the elevation of the former floor (Fig. 1B). Observers sailing east of Fernandina in 1969 reported puffs of cloud, possibly dust devils, above the south end of the caldera, and climbers found active fumaroles on the southwest rim in early 1970 (*29*).

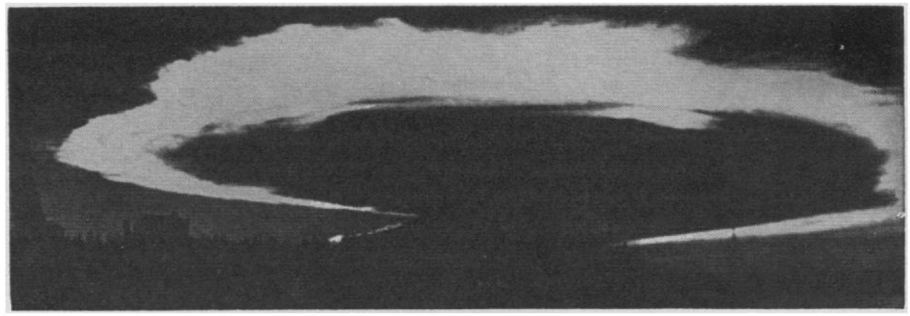


Fig. 4. Volcanic cloud backlighted by late afternoon sun at approximately 5:10 p.m. on 11 June 1968, within minutes of the explosion heard 220 km away and recorded by microbarographs throughout the hemisphere. At 4:30 the cloud was shown by Tiros satellite to be circular, 50 km in diameter, and centered over Fernandina. At the time of this photograph the cloud is estimated to be 175 km in diameter, at an elevation of 24 km, and expanding laterally at 80 km per hour. [Photograph from Academy Bay by J. Harte]

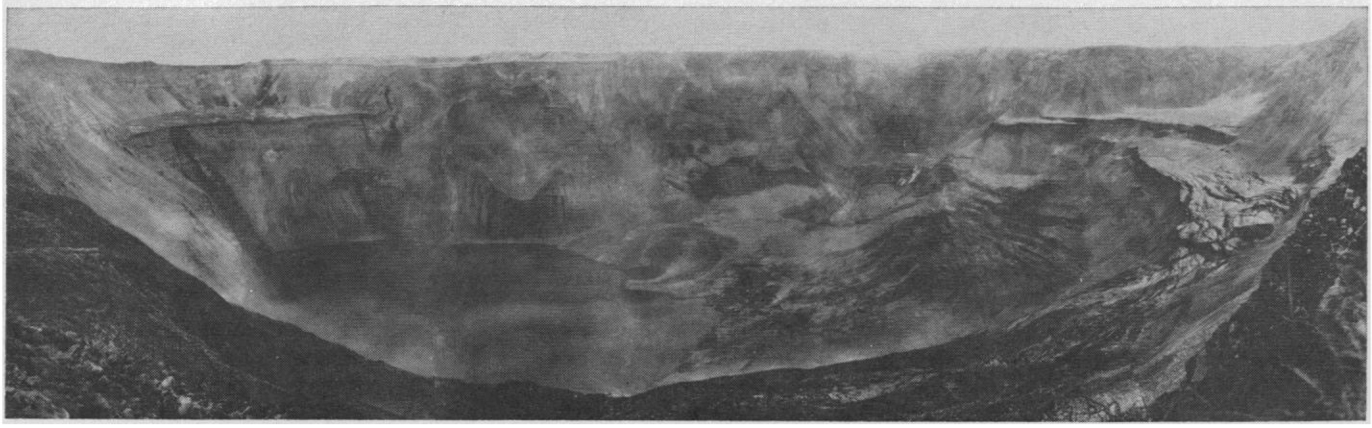
In July 1968, the most prominent fumarole, and the only one that produced visible vapor in the warm afternoons (when vapor did not condense as readily), issued from a new, low-rimmed explosion crater, which was 50 meters in diameter and was near the center of the western block (Fig. 1B). We surmise that the crater was formed during the explosive events of 11 June. Near this crater at the margin of the western block is a subdued depression of similar dimensions that may be the partly buried site of early explosive activity.

Rim fracturing. Surprisingly little of the caldera rim slid into the caldera, and numerous old slump terraces (Fig. 2) are still present. Of the 18-km perimeter, only 1 to 2 km along the western block had fallen by July, the new rim being less than 300 meters west of the old rim. The southwest wall along the adjacent 2 to 3 km has been largely stripped of debris, but the remaining three-quarters of the caldera wall shows little change in its upper half. New fractures are present on the rim ½ km from the edge; they increase in size and number approaching the edge, but new vertical displacements are generally much less than 1 meter. In places near the edge, however, the ground has been so severely jolted that large sod clumps have been thrown up, and underlying rocks weighing several kilograms have been violently moved to the surface. Approximately 90 meters of the southeast bench has caved into the caldera.

Rock avalanches. The lower slopes of most of the caldera and all of the southwest wall were oversteepened by the collapse. Loose rockfalls, each averaging about 2 minutes in duration, were a constant feature of our stay on the rim (Fig. 6), and they still persisted when the caldera was revisited 20 months later. During July mornings rockfalls could be heard only about three-quarters of the time, but they were continuous by noon; later in the afternoon it was often impossible to see across the caldera because of rockfall dust clouds. Evidently, slope stability decreased during the day as warming caused thermal expansion and evaporation of capillary water binding the rocks. Each afternoon there was a pall of brown dust above the caldera extending several tens of kilometers to leeward. Dust clouds continued to fill the caldera in February 1970, when there were approximately ten rockfalls per hour in the afternoons (*22*, *30*).

Earthquakes greatly intensified rock avalanching. We felt two small tremors while we were on the rim (4.0 m_b, intensity VI), after which the roar of increased avalanche activity was intense for 10 minutes, dust clouds completely filled the caldera, and avalanche activity did not decrease to normal for nearly an hour. Substantial dust deposits mantle the caldera floor (*31*), and thin deposits extend beyond the rim. These dust deposits consist of finely fragmented volcanic rock and might easily be mistaken for volcanic ash in later studies of this, or another, caldera.

Fig. 5. Fernandina caldera from northeast rim. The lower, postcollapse panorama (by T. Simkin, July 1968) was photographed from a position northwest of the upper, 1966 panorama (by P. A. Colinvaux). The lower panorama spans roughly 150°, but the scales of the two photographs are approximately the same to better illustrate the extent of the collapse.



Lake. After the 1958 eruption eliminated the large caldera lake, the surface of the new lava remained dry for at least 2 years. Then water began to accumulate at the northwest end and covered an estimated 1.2 to 1.4 km^2 to shallow depth before the collapse (*32*). After the collapse the lake had shifted to the other end of the caldera; it covered 2 km^2 and appeared to be deep. This substantial increase in lake volume was undoubtedly due to groundwater contributions as the 300-meter drop of the floor lowered the lake below the water table (*33*). Groundwater must have run into the lake simultaneously with the collapse and have stabilized quickly at the new level, for the level did not change perceptibly between 4 July and November (*34*). Numerous gullies were cut in dust and ash on the floor as the lake shifted position, providing a most unusual example of consequent drainage.

Some lake water may have been lost in phreatic explosions on 11 June, as in the Taal eruption in 1965 (*35*). Both the violence of the explosions, unusual in oceanic volcanoes, and the high proportion of lithic fragments in the ash suggest that water gained access to the vent (or vents) near the start of the eruption. As suggested by Stearns (*36*) for the phreatic explosions of Kilauea in 1924, groundwater may also have been able to percolate inward toward vents as underlying magma was withdrawn and as surface temperatures around vents were reduced.

Biology (37). Fresh lava flows of Fernandina's outer slope are barren, but inside the ring of circumferential vents that have fed these flows is a flattish summit bench covered with dense shrub vegetation. Increased rainfall at this elevation provides moisture, and a layered tuff unit, elsewhere covered by fresh flows, provides a footing for roots. In early 1968 vegetation continued down the caldera walls to the reed-fringed lake on the floor, and this unlikely oasis was the home of the largest population of pintail ducks in the archipelago (about 2000 adults). Land iguanas and other members of the remarkable Galápagos fauna were also present. The combined effects of heavy dust and ash coatings on the plants and root dislocation by collapse tremors have killed all vegetation on the caldera walls and for approximately 100 meters beyond the rim on the north and east sides. On the west side, where ash and dust deposition have been heaviest, some vegetation has been killed as far as 8 km from the rim (*22*). The 2000 ducks have not been found, but it is speculated that they may have contributed to the acoustic events of 11 June. The Darwin Station party found several dead and one near-dead iguana on the caldera floor 5 months after the collapse but noted that several types of birds had returned to the new lake.

Discussion

The Fernandina collapse differs from most historic caldera collapses in that the floor is not now largely under water and thus can be readily compared with precollapse photographs and measurements. The coherence of the subsided block and the restriction of most of the fracturing to within a kilometer of the elliptical boundary fault rule out all hypotheses involving explosive fragmentation of overlying material and its collapse as jumbled blocks. Similarly, the apparent absence of extruded lava within the caldera argues against the concept of cauldron subsidence in which magma moves up the cylindrical walls like liquid around a too small cork in a too full bottle. The seismic record indicates that collapse must have taken place as a series of short drops over a 12-day period. The regular decrease in time intervals between larger shocks suggests decreasing frictional resistance along the boundary fault, or it may be explained by the withdrawal of supporting magma. The rapid decline in seismic activity after 19 June may indicate bottoming on the floor of an irregular magma chamber, increased resistance from an inward-dipping boundary fault, or decrease in withdrawal of supporting magma.

The 1968 collapse was only the most recent of several such episodes on Fernandina, and vegetation within the caldera (*38*) suggests that at least 100 years had elapsed since previous subsidence along the same boundary fault. The 1968 collapse, like that at Kilauea in 1924 (*36*), took only a few weeks, whereas substantial subsidence continued for years following the 1883 eruption at Krakatoa (*1*) and the 1875 eruption at Askja, Iceland (*39*). Analogy with stoping patterns in mines indicates that rapid subsidence leads to en bloc settling of coherent blocks, but slower subsidence leads to breakup of the settling block (*40*).

Evacuation of a subsurface magma chamber is needed for a caldera collapse, and associated eruptions have often been responsible for this evacuation. The collapses at Askja, Krakatoa, Katmai, and others followed long dormant periods during which gas pressure increased in the differentiating magma chamber until it was finally relieved by the violent eruption of siliceous tephra. In collapses of this type the volume of collapse is often neatly balanced by the volume of extrusive products. At Fernandina, however, a long period of differentiation is precluded by the frequent recent eruptions and the basaltic composition of the juvenile ejecta in 1968. Furthermore, it is unlikely that the eruptions at and near the start of the Fernandina collapse produced a volume of magma equivalent to the collapse volume of 1 to 2 km^3.

We estimate the volume of the 21 May flow to be less than 0.1 km^3, and the 11 to 12 June ash volume (much of which was not juvenile) is also estimated to be of the order of 0.1 km^3 when recalculated as magma. Additional flank flows may have gone unseen, but historic lava eruptions at other volcanoes have seldom contributed as much as 1 km^3 in many weeks or months of violent activity (*41*). A likely place to look for the missing magma would be in a submarine flank eruption like the one believed to have withdrawn magma from Kilauea at the time of the 1924 collapse (*1*). Such eruptions have built a prominent ridge east of Hawaii (*42*), and a comparable ridge extends northwest from Fernandina. However, investigation by R. A. Norris of records from the Pacific SOFAR hydrophone network reveals no evidence of submarine eruptions during June 1968 (despite the recording of abundant *T* phases that can be correlated with the seismic record of the collapse). If submarine flows were associated with the Fernandina collapse, they displayed none of the characteristics recognized by Norris and Johnson for submarine volcanism elsewhere in the Pacific (*43*).

With recognized surface eruptive products insufficient to account for the missing magma and with no evidence for submarine eruptions, we conclude that magma was probably withdrawn below the surface. Downward retreat of magma is frequently observed in Hawaiian eruptions and has been invoked by Kuno (*44*), Macdonald (*28*), and others to explain imbalance between collapse volumes and extrusive products. However, it is difficult to say how far the magma went—whether it was withdrawn to great depths or whether it intruded the volcanic edifice near the surface.

Near-surface minor intrusions are commonly associated with ancient plutonic complexes comparable to the one now developing under Fernandina (*45*). Although we observed no indications of minor intrusions on Fernandina, their surface expression need not be obvious. The high magma level just before the collapse, shown by the May eruption, suggests analogy to the carefully monitored Kilauea pattern (*46*), in which slow feeding overfills a summit chamber and leads to rupture and drainage by eruptions and flank intrusions. Such intrusions low in the flanks of Fernandina could drain the

Fig. 6. Rock avalanches on the northwest wall of the caldera 1 month after the start of the collapse. [Photograph by T. Simkin]

chamber substantially and remove support for the caldera block. Furthermore, this transfer of magma to the flanks might expand the volcanic edifice so as to widen the inward-dipping fractures bounding the block and facilitate downward sliding (*1*). Once freed to descend, the block could act as a piston, accelerating the process by driving more magma into the flanks. If intrusions were concentrated in the southeast quadrant near the 1961 and 1968 flank eruptions, this might explain the maximum subsidence at that end of the caldera.

Although near-surface intrusion seems likely at Fernandina, some of the missing magma may well have been withdrawn at depth by regional tectonic movement. The association of volcanism with linear belts of crustal weakness is well known, and, in their recent interpretation of marine geophysical data, Herron and Heirtzler (*9*) suggest that the western Galápagos lie on an oceanic fracture zone. Seismic information suggests possible movement along that zone prior to the collapse; the 14 May earthquake, 300 km north of Fernandina along the zone, occurred within a week of the flank eruption (or eruptions) that preceded the collapse, and seismic activity in the eastern equatorial Pacific was unusually high during the month preceding the collapse (*47*). It may be that movement along the suspected fracture zone triggered the subsurface movement of magma that made room for the subsequent caldera collapse. If the reported simultaneous venting on Isabela was associated with the collapse of Fernandina 65 km to the north, then this evidence of deep interconnections between volcanoes would further support the suggestion that magma was withdrawn at depth.

Regardless of how or where magma was withdrawn, the major collapse was initiated by the violent explosive activity of 11 June, which followed a small earthquake ending 3 days of ominous seismic quiet. The presence of juvenile ejecta (along with abundant lithic fragments) indicates that the explosions had a magmatic as well as a phreatic component, and the air-wave calculations (*17*) indicate introduction of a large volume of gas into the atmosphere. Any withdrawal of magma prior to the collapse would have concentrated gas in the evacuated space and, by adding to preexisting structural support, this gas may have provided critical support for the overlying block (*48*). The large vapor cloud of 11 June may have consisted of this gas, which would have reached the surface after the 10:18 a.m. tremor. Release of gas, with consequent lowering of pressure in the magma chamber, would then have led to boiling of the remaining magma, which would have produced the later ash cloud and, with the removal of critical support for the block, the onset of the major collapse.

A cupola above the main chamber and along the main boundary fault would be expected to be the first locus of venting and collapse, as is believed to have been the case at Santorin (*1*), and we interpret the early independent collapse of Fernandina's western block in this way. As stress built, it was relieved by movement along the reactivated 10-km boundary fault, and intervals between movements became shorter as frictional resistance along that fault was reduced by fragmentation or inflation of the volcano. After 8 days the movement started to decline for one or several of the reasons listed above, and after 12 days it was all over except for minor readjustments. However, increasing fumarole and vent activity, together with lessons learned from other historic collapses, caution us that volcanic modifications of the Fernandina caldera are not yet complete.

Summary

The summit caldera of Isla Fernandina, a large, uninhabited basaltic shield volcano, was further enlarged by 1 to 2 km^3 in June 1968. A small quake and large vapor cloud on 11 June were followed 4 hours later by a remarkable volcanic ash cloud and, after another hour, by a major explosion recorded at infrasonic stations throughout the hemisphere. Seismic activity increased to a peak on 19 June, when more than 200 events per day were recorded by a seismograph 140 km away. Several hundred quakes were in the magnitude range 4.0 to 5.4 m_b, but few such events were recorded after 23 June. Unusual lightning accompanied the major cloud, and, during the evening of 11 June, distant observers reported red glow and flashes from the area. Fine ash fell that night and much of the next day to distances at least 350 km from the volcano.

The caldera floor, 7 km^2 in area, subsided in a series of short drops along a steep elliptical boundary fault coincident with that along which the preceding (undated) collapse occurred. Displacement increased from zero at the northwest end of the ellipse to approximately 300 meters at the southeast end, and slight basining of the floor was evident. Breakup of the floor was minor, and fracturing outside the ellipse was limited to a distance of ½ km from the rim. However, a part of the west caldera wall and floor—the site of precollapse fumarolic activity—dropped 50 to 150 meters as an independent ½-km^2 unit. This block contained the only new explosion crater and the only fumaroles visible 3 weeks after the start of the collapse. No evidence of fresh lava was seen within the caldera.

The present location of most of the displaced magma is unknown. The volumes of the only confirmed lava flow (21 May on the east flank of the volcano) and of the ash erupted from 11 to 12 June were both probably an order of magnitude smaller than the collapse. Some additional eruptive activity is suggested in mid-May and on 7 June by distant observations, but no evidence of associated submarine volcanism has been found by the SOFAR hydrophone network. The magma may have intruded the volcanic edifice because of high magma pressure, or it may have been withdrawn at depth by tectonic movements along a suspected oceanic fracture zone.

References and Notes

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6. Fernandina, Isabela, Santiago, and Santa Cruz are the names commonly used in the Galápagos; alternative names are (respectively) Narborough, Albermarle, James (or San Salvador), and Indefatigable.
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10. The U.S. Coast and Geodetic Survey located 259 events in the Galápagos region during

May, June, and July 1968. Study of records from several sensitive seismic stations has added 255 probable Galápagos tremors, 88 percent of which are less than magnitude 4.5. We believe the illustrated seismic pattern to be accurate for events of magnitude 4.5 or greater, but it no doubt misses many smaller shocks.
11. All times given are local times, which are 6 hours behind Greenwich Mean Time.
12. Measurements are from photographs and from estimates by Miguel Castro, who was present as a guide on the tour vessel and who had also witnessed the 1961 eruption of Fernandina.
13. A sequence of photographs figured by T. A. Jaggar [*Origin and Development of Craters, Memoir 21* (Geological Society of America, New York, 1947)], records the development of a similar cloud above Mauna Loa in 1916.
14. H. Matheson, personal communication.
15. This event was described as a stupendous explosion in the multimegaton range by V. H. Goerke of the Environmental Science Services Administration's infrasonic station in Colorado. He noted periods as long as 9 minutes and amplitudes of 20 to 40 dyne/cm^2 in his initial report (the first distant recognition of a Galápagos eruption) to the Smithsonian Center for Short-Lived Phenomena (SCSLP). The center immediately contacted the Galápagos by amateur radio; their communications were instrumental both in the confirmation, on 23 June, of the caldera collapse and in our later expedition.
16. T. A. Jaggar, *Volcano Lett. Hawaii, Volcano Res. Ass.* **149** (1927). See also F. A. Perret, *Volcanological Observations* (Carnegie Institution of Washington, Washington, D.C., 1950), pp. 96–97.
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23. Fourteen of these shocks (apparently those greater than 4.3 m_b) were large enough to send rockfalls down the insides of cinder cones on the volcano's flank, thereby producing dust clouds that would have appeared as vent activity to distant observers unaware of the associated tremors. Perry's account of this trip was *SCSLP Event Report 21* (1968) and a longer description by L. C. Saltos appeared in *El Commercio* of Quito on 3 July 1968, p. 1 (translated as *SCSLP Event Report 24*).
24. "An earthquake of consequence . . . is likely to be preceded by foreshocks, normally few in number and small in magnitude; and there is almost certain to be many aftershocks, gradually decreasing in frequency and magnitude" [C. F. Richter, *Elementary Seismology* (Freeman, San Francisco, 1958), p. 66]. In a caldera collapse, however, gravity alone is the driving force without the complex tectonic forces which cause overshooting and rebound after the main fracture movement.
25. This value is based on the relation $\log E = 5.8 + 2.4\ m_b$ given by C. F. Richter (*24*, p. 349). The largest 259 events listed by the U.S. Coast and Geodetic Survey account for 41×10^{18} ergs, and the 255 events recognized by us add only 5×10^{18} ergs. Still unrecognized small events are unlikely to bring the total to over 5×10^{19} ergs.
26. This range assumes an average drop of 150 meters for a block 7 km^2 in area and between 400 meters and 4 km thick. Although seismic sources may be only about 1 percent efficient [C. King, *J. Geophys. Res.* **74**, 1702 (19o9)], seismic energy remains at least three orders of magnitude below potential energy for this collapse.
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30. C. MacFarland was on the rim on 4 and 8 February 1970. Although rockfalls were less frequent than in 1969, several produced dust clouds that overspilled the caldera rim 20 months after the collapse.
31. Dust covers but does not obscure features such as the recent lava flow on the northwest bench (Figs. 2 and 5), and R. Perry (personal communication) reports that scrub trees in the central caldera have been buried. These observations, together with the frequency and persistence of rock avalanches, suggest that the dust and ash deposits on the caldera floor may be several meters thick.
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33. The water table in young basaltic islands is generally close to sea level but may be higher where dammed behind impervious dikes [H. T. Stearns, in *Hydrology*, O. E. Meinzer, Ed. (McGraw-Hill, New York, 1942), p. 678]. Probably feeder dikes for the vents ringing Fernandina caldera provide such a dam.
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37. This brief summary is based on the observations of R. I. Bowman (personal communication) and R. Perry (see *32* and *34*). A fuller account of biological changes, written by Bowman, is in preparation. The flora present in the caldera before the collapse have been listed by P. A. Colinvaux, E. K. Schofield, and I. L. Wiggins [*Science* **162**, 1144 (1968)].
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41. By comparison, 1.1 km^3 is the estimated total lava and tephra production during the first 3½ years of the Surtsey (Iceland) eruption [S. Thorarinsson, in *Surtsey Research Progress Report 4* (Surtsey Research Society, Reykjavik, 1968), pp. 143–148], and Kilauea has produced no more than about 4 km^3 within the last 150 years of historic flows [H. T. Stearns, *Geology of the State of Hawaii* (Pacific Books, Palo Alto, 1966), p. 139]. The 1783 Lakagigar (Iceland) eruption, "by far the largest lava eruption ever witnessed by man" [S. Thorarinsson, *Geol. Rundsch.* **57**, 708 (1968)], produced 10 km^3 of lava in 50 days.
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48. The largest magmatic gas pressures are in the range of 10^3 atmospheres [G. S. Gorshkov, *Bull. Volcanol.* **20**, 77 (1959)], which is equivalent to a lithostatic overburden of 4 km. Lower pressures could help support such a thickness if assisted by the chockstone effect of inward-dipping boundary faults at the block margins. The depth to the Fernandina chamber is unknown but may be comparable to the 2- to 4-km depth concluded by workers in Hawaii (see *46*) for the Kilauea reservoir.
49. We thank the Smithsonian Center for Short-lived Phenomena, the U.S. Air Force, and radio operators V. Bowers and F. Nelson for vital logistic support. We also thank the many eyewitnesses, correspondents, and others that have assisted our investigation, particularly the Angermeyers of Academy Bay, the members of the Darwin Station, and our companions on the volcano, R. I. Bowman and S. Simkin. We thank J. Filson, J. G. Moore, R. L. Smith, and H. G. Wilshire for reviewing the manuscript. This publication is authorized by the director, U.S. Geological Survey, and is contribution 113 of the Charles Darwin Foundation.