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STEAM BLAST VOLCANIC ERUPTIONS

A study of Mount Pelée in Martinique as type volcano

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TABLE OF CONTENTS

ERRATA

Page 41, at bottom, insert "are" for "is".
Page 42, middle, "rescue" for "recue".
Page 45, near top, location "94" for location "14".
Page 117, near bottom, "as" for "at".

TABLE OF FIGURES

ABSTRACT

The investigation is concerned with the author's expedition to Martinique and St. Vincent in 1902 and comparison of the experience of investigators and sufferers with that of others in so-called "explosive" eruptions. The Hawaiian mechanism is reviewed with special reference to rifts, underground water, intrusion furnace, wedge rupture, and lowering of magma. These features of structure are applied to Martinique, St. Vincent, Kilauea, Tarawera, Sakurajima, Katmai, Taal and Tomboro as a series of steam blasts old and new. The comparison is found to be applicable and the analogy with Hawaii considered as fundamentally magmatic for gas and basaltic slag, brings out the contrast that lies in steam eruptions. For all volcanoes they are believed features of ground water and of collapse. Ground water stimulates lava eruptions.

The Pelée disaster at St. Pierre May 8, 1902, followed by a dacite dome with spines, which renewed activity in 1929, is examined for paroxysms of downblast. These are distinguished sharply from the Carib migratory upblasts along valley fissures which are not uncommon elsewhere. The valleys are on rifts recognized as deep fumaroles. The Ghyben-Herzberg laws of ground water are applicable. Geyser rhythm was followed by Pelée, Soufrière of St. Vincent, and Kilauea in their sequence of paroxysms. Structure sections are drawn to scale, and the structural reactions of intrusion, rifts, boiler, gas effervescence, heat, and timing are thus outlined. The bearing of this machinery on volcanism in general, on world ignisepta and on reaction of magma is suggested. It is contended that steamblast is a climax of eruption in the water zone and should be sharply delimited from the rising and intrusion of fundamental earth magma, and from the high pressure water reactions of ocean bottoms. Rising magma is considered an age-long elevatory force along volcanic lines, modified by cyclical yielding. Compared with oceanic volcanism continental irruption in sediments is a separate science in experimental field geophysics. Every locality supramarine or submarine of warm ground and steep thermal gradient is a subject for volcanology, if pulsating ground water is critically, thermally and chemically measured.

Authors are referred to herein by names and dates in parentheses, as listed in the appendices.

ACKNOWLEDGMENTS

For field experience of 1902 and 1936 in the Caribbee Islands the author is indebted to Harvard University and the late Alexander Agassiz, to the National Geographic Society, to the Royal Society of London, and to the United States Navy for transportation.

For companionship in the field and much assistance he is grateful to T. M. MacDonald and the late R. T. Hill, E. O. Hovey, G. C. Curtis and Tempest Anderson. For help on the ground water problem he thanks H. S. Palmer, H. T. Stearns, C. F. Tolman, M. Carson, G. Duncan, C. K. Wentworth, R. H. Finch, H. A. Powers, G. Macdonald, and G. Giacometti, all in the Territory of Hawaii.

He is under obligation to hospitable people in the Antilles, and to the authors of books on the Caribbee eruptions of 1902 and 1929, and on the Montserrat earthquakes of 1935.

INTRODUCTION

Earlier Reports of the Hawaiian Volcano Observatory

The First Report of this series announced foundation of the Hawaiian Volcano Observatory by the Massachusetts Institute of Technology (Jaggar 1912). The Second Report discussed seasonal cycles of lava rising (Wood 1917). The Third Report mapped and described a large volume of pyroclastic formations on the Island Hawaii (Wentworth 1938). The present Fourth Report makes critical comparison of Hawaiian steam blast eruption with that of other volcanoes, notably Mount Pelée.

The data of rhythmic rising, sinking, arresting or exploding of the Hawaiian lava column are in the writer's Memoir on "Craters" (1947), and in his paper on crater seismometry (1920). The data on volatiles are in his "Magmatic Gases" (1940), including therein the Caribbee volcanoes and others.

Observation of Explosive Eruptions

It is difficult for a volcanologist to obtain first hand experience of the phenomena of paroxysmal steam blast eruption. Few of those who have written accounts of such eruption were actually in the field at the moment of primal outbreak. Assistant Volcanologist Finch furnished unusual record from the crater edge in Kilauea in 1924 (Jaggar 1947, 214). In the Caribbees in 1902 local residents were in the field as careful observers and were often seriously wounded. The writer's experience of actual observation in Martinique and St. Vincent May to July, 1902, in the midst of repeated steam blasts, followed by a second visit 33 years later, concerned an area of maximum tragedy where many close observers survived, and the physiological symptoms in the wounded revealed pure steam.

Until the Kilauea record of 1924 was made, no interpretation of Pelée yet published satisfied the writer. Access to seawater requires global exploration. A bursting boiler is not made by pouring water on the fire: confinement is a first essential for steam pressure. Poisonous mixtures of carbon and sulphur oxides with hydrogen, nitrogen and chlorine released from hot magma do not yield odorless expanding high pressure steam. Confined lava gas in a basalt cupola is not hissing steam. Hawaiian experience with fundamental magma finds both magma and its gases uniform, and the steam explosion phase a distinct phenomenon.

In view of the large number of volcanoes that have a steam explosion phase almost odorless and non-asphyxiating, this essay is devised to assemble descriptions of observers and reviewers, partly new to science, duly classified, and submit the results to synoptic analysis. The subject concerns the most catastrophic aspect of volcanism, and the most fundamental one where the deep oceans are concerned.

Visible magma before or after a cataclysm, in relation to a cycle, has come under the author's observation in ten volcanoes, and forty years of observed eruptions in Hawaii have exhibited steam blasts once, and magma gas efflux with contiguous water vapor frequently.

In this Report are shown some of the 115 personal narratives, which have been reviewed in relation to rift system, boiler action, and magmatic gases of Pelée in 1902 and 1929. The Caribbee eruptions of 1902 yielded rich documentation of personal report. No such autobiography of wounded victims exists for eruptions like Tomboro or Tarawera. The rough and ready surgeon, constructor, sea captain, policeman or mechanic has furnished useful data for science in trying to explain St. Pierre, and this includes women who made their report and died.

The Explosion Problem in Volcanology

The writer uses Pelée as the basis for comparison of explosive eruptions. St. Pierre was suddenly destroyed by a blast that rushed down, while observers on high ground saw blue sky and horizon across the profile of the crater rim. Apparently a horizontal crocodile had opened its jaws and vomited steam in a narrow sector that included the stricken city. No writer of the period covered these facts with explanatory map showing that mouth. Figures 16, 34, and 37 herein show that a rift under a gorge can conceal the mechanism of its eruptive heavings over migratory steam jets, and that a plexus of engulfment, geyser water and frothing magma requires recognition of ground water laws and hidden faults. For Geology the Pelée problem needs study of water pressure under ocean trenches, of magmatic release in presence of that pressure, and of magmatic differentiation on water vapor contact.

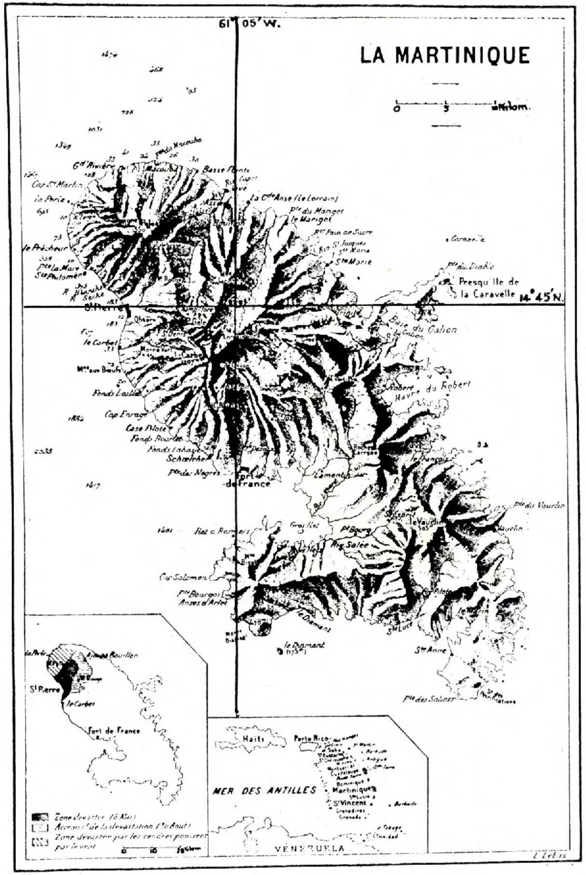


FIGURE 1. *Map of Martinique* (after Lacroix). Base for Figure 2.

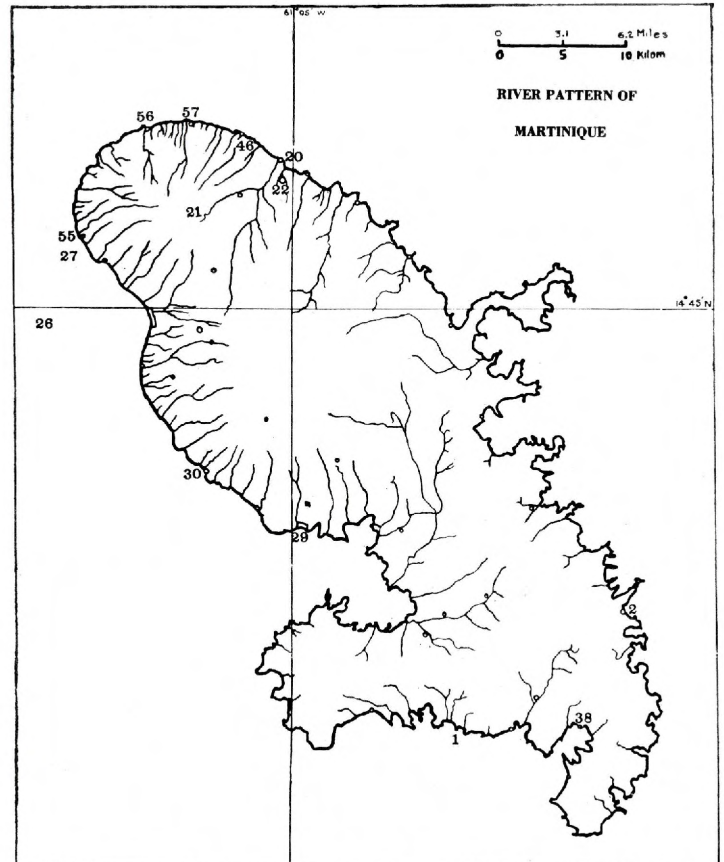


FIGURE 2. *Location map of Martinique.* Position numbers on this map locate more distant observers than can be indicated on Figure 4. Shows straight-line embayment Prêchur-St. Pierre. Compare Figure. 1.

I. ERUPTIONS OF PELEE

General Statement

Arnold Hague, the geologist of the Yellowstone, frequently said that the volcanic lavas and breccias of the West Indies and of Mount Pelée and Soufrière are like those of the Rocky Mountains. If the Cordilleran volcanoes are Pacific in quality, certainly the Caribbean ones are. The Carib volcanoes in May 1902 set the pace in stimulating volcanology.

Pelée at the north end of Martinique made a violent steam blast down on St. Pierre about 8 a.m. May 8, 1902. Soufrière of St. Vincent, 102 miles south, had erupted the day before, and Pelée itself for 2 weeks had been exploding and throwing out its crater lake. St. Pierre was totally destroyed, and eruptions continued at intervals culminating August 30, 1902. Then for two years a lava plug rose in a dome, with a central higher pencil, over the crater.

The problem for physicists was why the blasts rushed down the slopes instead of up, why they seemed to be pure steam loaded with powdered rock, and what their relation was to the rising lava plug. About 26,000 people were killed at St. Pierre May 8, about 2000 in August, and several hundred had been killed May 7 in St. Vincent.

The disaster recalled Pompeii and seemed to have no parallel in the story of ordinary volcanoes. American, French and British geologists wrote books about it, notably Heilprin, Hovey, Kennan, Lacroix, Anderson and Flett. (See bibliography).

Sequence of Paroxysmal Eruptions of Pelee 1902

Lacroix (1902) presents a table showing general falls of ash in the paroxysmal eruptions beginning May 2-3, 1902, and ending August 30. This table is notable in showing a decline of distance reached by ash fall after the St. Pierre disaster of May 8; fall of lapilli in all the eruptions excepting May 2 to 3; greater depth of ash in the range up to 10 kilometers May 20 and 26 than on May 8; but otherwise the eruption of May 8 reached farther with its ash than any other eruption of the series. Locations refer to numbers on the appropriate maps herewith: Figures 2 and 4 show drainage pattern for Martinique, and Figures 1 and 3 (after Lacroix) show place names and relief. The progressively denser drainage pattern northward to Pelée has importance. Lapilli fell even at Trois Rivières, location 1, and Vauclin, location 2, 25 to 31 miles southeast of Pelée, May 8 and May 20.

The series of dates listed as paroxysmal are: May 2 to 3, May 8, May 17, May 20, May 26, June 6, July 9, August 30.

The writer summarizes quotations from persons who suffered from paroxysmal eruption which bear on such questions as concealed eccentric deep vents or radial rift, on emission of liquid water or liquid mud, and on pure steam as paroxysmal gas. His papers on structural development of cones (1938) and on contrast

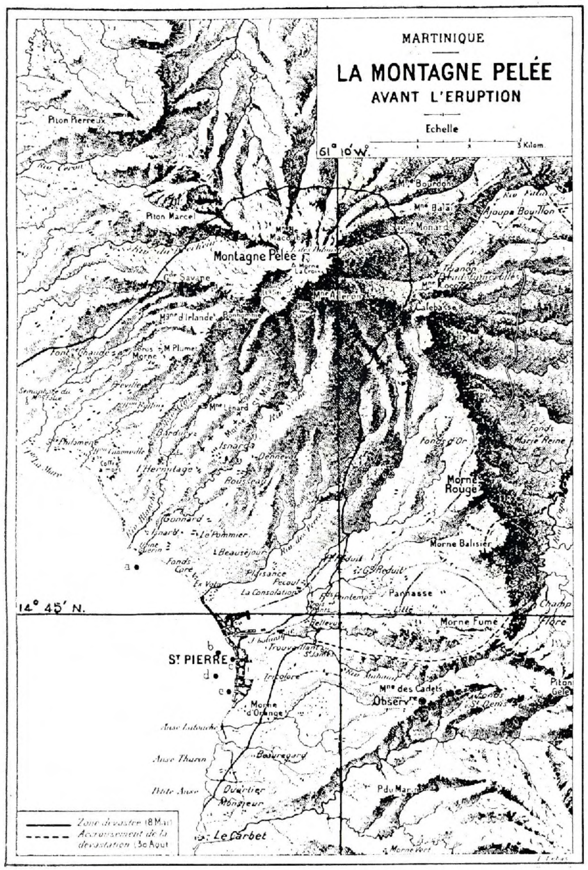


FIGURE 3. *Map of Mount Pelée* (after Lacroix). Base for Figure 4. Black line outlines area devastated May 8.

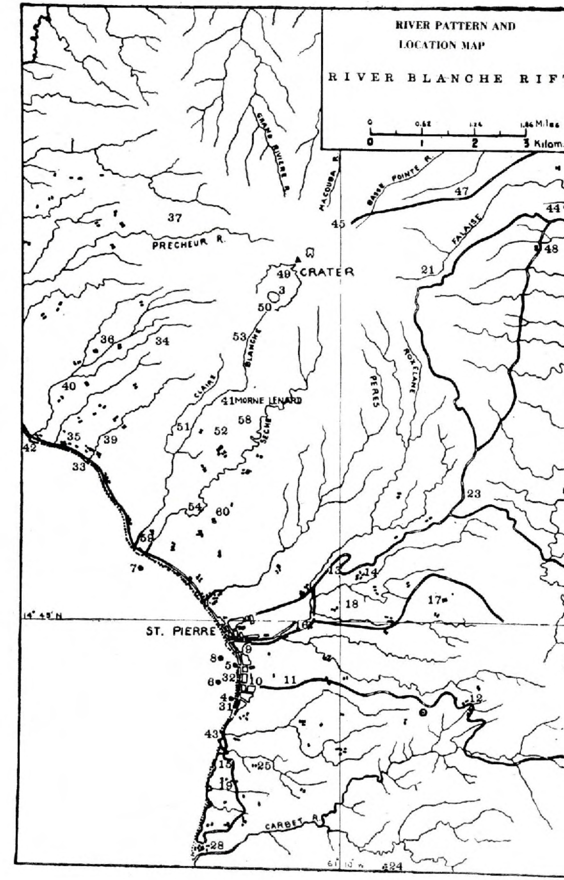


FIGURE 4. *Location map of River Blanche rift.* Indicates radial rivers around Pelée, parallel rift rivers of southwest group, and locations numbered in text. Compare Figure 3.

between magmatic gases and steam blast engulfment (1924) have accented the concept that circular pits extend into radial linear rifts or concentric ones, that magma essentially intrusive at volcanoes rises up dike chasms, that carbonic, sulphurous, and hydrogen gases are the exothermic agents, and that water or steam is oxidation or contamination.

Pelee Crater before Eruption

Reporters named in the following pages are generally those listed by Lacroix (1902).

June 4, 1900, two small new fumaroles in Etang Sec, location 3, destroyed foliage spanning areas of 60 to 100 feet. May 8, 1901, a year before disaster there was new steam in the southeast part of the Etang Sec floor and several fumaroles. March 23, 1902, the basin of Etang Sec (the crater) was sending up vapors at several points and smelling strongly of hydrogen sulphide. April 2, steam rose from the upper valley of Rivière Blanche. April 25, the crater was filling with water, a bowl half a mile in diameter with a new cinder cone near the eastern wall, trees were covered with black volcanic dust from the throwing up of ash, and a film of cinder floated on the water. April 27, from the verge could be heard the tumultuous movement of boiling liquid, vapor shot up in big volutes, water spouted in cascades from the margin of the crater and poured into the lake at the base of the walls with a temperature of 37° C. In the upper River Blanche downhill from the crater notch a jet of water a meter in diameter emerged as a steaming cascade from a fissure in the bottom of the valley giving excessive volume to River Blanche. April 28, the crater lake submerged trees around the margins, with leaves reddened and branches whitened and water as deep as a big tree is high.

The crater had been an oval basin 2600 feet in diameter with a "Dry Pond" inside, an open notch southwest, an andesite dike or plug northeast; the mountain summit, 4200 feet high, was called Morne La Croix. The inner walls were precipitous to an uneven plain of the Etang 1,000 feet wide and 2,300 feet in elevation. Hovey listed several hard-rock intrusive plugs. There was a small summit plateau northeast of the high peak, occupied occasionally by a shallow puddle called the "Lac des Palmistes," and northwest of this stands the Macouba ring-ridge or "somma," overhanging a gulch at the source of the River Precheur.

An important feature was the high escarpment extending from location 35 (Fig. 4) to the crater, a straight ridge bounding the area that was devastated. That area was a flat plain sloping gently to the sea at St. Pierre. Another ridge bounded this plain on the east, and a cliff hemmed in the city. The south slope of Pelée was an amphitheatre opening toward St. Pierre, the mountain sloping 28° and the plain 9°.

Preliminaries and Eruption of May 3

With continuous jets from the crater at the end of April and the fall of ash over the country, hydrogen sulphide was so strong between Precheur and St. Pierre that people wore wet handkerchiefs, horses stopped and snorted, and some of them died of suffocation. The sulphurous odors had been perceived for 3 months. Earthquake shocks on April 23 made dishes fall from city shelves. The ash fall spread from crater to city between April 25 and May 1.

May 2 to 3 a marked eruption occurred. At 8:00 a.m. May 2 three large balls of compact grayish cauliflower clouds poured out of the crater in clear weather, and this was renewed densely at noon. At 2:00 a.m. May 3 stones were hurled out of the crater with detonations, and a heavy fall of ash reached even to Fort de France. About this time there was transition from hydrogen sulphide to sulphur dioxide, but hydrogen sulphide was necessary for the poisoning observed as carried in the ash. The sea was covered in patches with dead birds, others lay asphyxiated on the roads, the cattle suffered, while poultry, pigeons, and little birds cowered in fear in their shelters.

In St. Pierre the morning of May 3 the volcano was hidden, muffled detonations were heard, there was a rain of ash, people could hardly see the ocean, wheels were muffled by the dust in the streets, furniture became dusty with ash, shops closed, and houses were barred up in order to keep out the rock powder. The eruption of 2 a.m. was a definite paroxysmal primary explosion, (Lacroix 1902) and could not have failed to eliminate Etang Sec, the shallow crater lake. This fact was missed in the confusion of greater events.

Floods of all the Rivers

Landes reported that the River Blanche on May 5 was developing a unique torrent of boiling mud and water that migrated 3 miles in 3 minutes from crater to ocean, carrying just after midday blocks of rock estimated to weigh 50 tons each. It buried the sugar mill at the mouth of the river leaving a little of its smokestock like a post projecting from a desert of black mud. There was no trembling felt, thickness of mud exceeded 100 feet, and the coast line was extended outward by the new delta. A white seething mass migrated down the mountain along the plain between the Rivers Blanche and Seche, marking its course with a thick cloud of white smoke, while the summit fissures vomited out intermittently yellow and black powder, with greater force than ever. At location 41 a new branch appeared later on. It all appeared to be an avalanche of boiling matter travelling a mile a minute. When the flood plunged into the sea the ocean withdrew 300 feet, a yacht capsized 500 feet from the shore, and people retreated quietly before the return wave.

Precheur River overflowed on both May 5 and May 6, carrying with mud and water enormous masses of rock. Soundings opposite its mouth increased from 3 to 25 feet (Fig. 2 and 4). The River Peres overflowed its banks, and at 7 p.m. May 6 the flood increased in muddiness until it was a torrent carrying trees and giant boulders; this lasted until 10 p.m. and the bridge was buried. Roxelane River at St. Pierre overflowed at the same time, and great quantities of dead fish were observed opposite its mouth. This river began flooding at

2:00 a.m. May 7, and at its point of entrance into the sea an enormous cavity had been cut where the vegetable and mineral debris disappeared; the current reappeared a little beyond at the surface of the sea.

Across the island, Capot River, location 20, became black with mud May 6 to 7, and 150 kilograms of dead and torpid fish were taken from the irrigating canal at Vivé. The Falaise River, location 21, was peculiar in sending down hot water which steamed all the way to the point of confluence with Capot River. Basse-Pointe River, location 46, on May 8 at 3:00 a.m. preceding the St. Pierre disaster by 5 hours made a terrific flood carrying enormous trees and rocks; it swept away 20 houses and littered Basse-Pointe town with gravel and mud.

The Grand-Rivière, location 56, May 8 at 4:00 a.m. rose 10 feet, flooded the shore road with mud thick as syrup, and carried boulders more than 10 feet in diameter.

The major eruption that destroyed St. Pierre occurred about 7:50 a.m. May 8. All the floods above enumerated, beginning with the flooded crater and meter-thick jet in the River Blanche in April, were timed for the week immediately preceding the cataclysmic steam blast. Their directions from the volcanic center were east, northeast, northwest, west, southwest, and south. There was no flood at Carbet, location 28, but just as much rainfall.

PAREL wrote from the north end of St. Pierre on the day of the St. Vincent catastrophe, May 7:

"Since four o'clock in the morning when awakened by loud detonations I have been watching a pyrotechnic display; at one moment a fiery crescent gliding over the surface of the Pelée crater, at the next long, perpendicular gushes of flame piercing the column of smoke, and then a fringe of fire encircling the dense clouds rolling above the furnace of the crater. Two glowing craters from which fires issue as if from blast furnaces were visible during half an hour, the one on the right a little above the other." (Compare Calder in Eruptions of Soufrière).

"I distinguished clearly four kinds of noises; first the claps of thunder which followed the lightnings at intervals of 20 seconds; then the muffled detonations of the volcano like cannon; third the continuous rumbling of the crater; and then last the deep noise of the swelling waters of all the torrents which take their source upon the mountain, generated by an overflow such as has never yet been seen. This immense rising of thirty streams at once, without one drop of water having fallen on the sea coast, gives some idea of the cataracts which must pour down upon the summit from the storm-clouds gathered around the crater. When day lighted up the roadstead of St. Pierre, as far as the eye could reach it was covered with floating islets, spoils of the mountains, the forests and the fields, with trunks of gigantic trees, pumice stone, wreckage of every sort, discharged by the overflowing torrents."

In comparing with Martinique the St. Vincent rainy spell that began with the eruptions, Anderson and Flett (1903) refer to the absence of any torrential downpours in Martinique in the months of May and June, and to the fact of less surface erosion on Pelée than on Soufrière.

Critical details of volcanic flood action from underground water, in relation to authors, and to rifts, will be discussed under Critical Discussion.

Observers in St. Pierre Harbor May 8

Without repeating the harrowing details of suffocation by ash, and wreckage of ships and city by fire, wind, and wave, the following is a bare outline of actual observation of persons at the locations numbered on the map. Details may be found in the books by Heilprin, Kennan and Lacroix.

Prudent, location 4, machinist from a wrecked steamship, noted a sea wave similar to that of May 5, at 11 p.m. May 7; a preliminary jet of vapor 7:15 a.m. May 8 from the mountain toward city; half an hour later an enormous violet-colored mass directed toward St. Pierre, hugged the mountain slope, overwhelmed the ship, and darkness followed immediately; houses burned, rum factories exploded, trees were stripped of leaves, hot mud fell, followed by warm ashes, flesh was scalded only on exposed surfaces, clothing was not burned but an under jersey rotted; almost everyone on the ship was killed or mortally wounded; it was piled with hot ashes, bumped the bottom, and was swept by waves; sea water was not heated, and he smelled no odor.

Sainte, location 5, mate of a dismantled and swamped schooner, saw a black cloud emerging from the mountain about 700 feet below the summit, with indescribable noise, the cloud prolonging itself the whole length of the gorge of the Rivière Blanche and shooting toward St. Pierre which it reached in 45 seconds. The ship was dismantled and swamped before it was touched by volcanic ashes, and the scalding avalanche came through portholes after the men had taken refuge in the cabin. The cloud was hot with a faint sulphurous odor, the sea was not hot, and all noise ceased after the cloud went by. A fall of boiling mud began 5 minutes after the ash cloud. The river Roxelane overflowed after the catastrophe and rushed into the sea carrying corpses, trees, and debris. Sailor Octave, at the same location 5, saw the dark cloud coming from the same point where the avalanche of mud had emerged May 5, and noted a tidal wave sweeping over the quay after the eruption.

Freeman, location 6, succeeded in running his half-wrecked steamship Roddam out of the harbor. He reported a violent detonation, the mountain splitting from summit to base, a flashing flame shooting upward, a gush of black cloud rushing downward unfolding itself along the slope of the mountain, advancing like a whirlwind, overcoming all obstacles (at sea level spreading out like a fan) and reaching the city in 1½ minutes. Extraordinarily dense darkness followed. There was time enough to see small boats overturned, the Roraima thrown on its side, and the Grappler, at location 7, sunken instantly at its anchorage. Of a crew of 46 on the Roddam, 26 were killed; 120 tons of ash were removed.

Scott, location 8, mate of SS Roraima, in clear weather, saw Pelée sending up enormous puffs of smoke pushed seaward by a southeast wind; suddenly a cloud emerged with a terrific crack like a revolver shot, hugged the slope, leaped over the ridges, a mass of luminous flames, smoke, and ashes. The smokestack went over, steel masts were cut off at the deck, and the ship took fire. Burning cinders fell, followed by hot stones that hissed in the sea; their fall on deck was muffled by a thick layer of ash; then burning mud fell, resembling thin cement, sticking to everything and plastering Scott's face even though his head was covered with a tarpaulin; a sailor was plastered so that he could not hear, there was danger of pulling off the skin with the dried cement, and scalp under the hair was badly burned by the scalding mud.

CLARA KING and MARGARITE STOKES, location 8, were passengers interviewed by the author in hospital. Mrs. Stokes, Margarite, a boy, and a baby girl, with Clara, the nurse, saw the mountain sending up puffs but were reassured by officers. Suddenly the steward rushed past shouting, "Close the cabin door, the volcano is coming." Mrs. Stokes slammed the door; a terrific explosion came which nearly burst the ear drums, the vessel lifted high and sank down, and all were thrown off their feet by the shock, and huddled crouching in one corner of the cabin. Hot moist ashes poured in through a broken skylight in inky darkness. Next came suffocation, relieved by the door bursting open and air rushing in. When a little light came Mrs. Stokes and the little boy were plastered black, the baby girl was dying, the nurse and Margarite were in great pain. A heap of hot mud collected on the floor, and as the young girl put her hand down to raise herself, it was plunged to the elbow in scalding hot sand. They were taken to the deck where they remained from 8:30 a.m. until 3 p.m., and the mother, boy and baby died. The whole city was one mass of roaring flames, and every now and then more ashes fell and burned the victims. The Roddam coming near with uncontrollable rudder, could back up but not go forward, and nearly sank their ship. Twenty-two persons were rescued by a French gunboat.

The physical effects were: clothing not burned in the least, yet third degree burns on the flesh underneath; hot mud in the burns which had to be cleaned out of the wounds; flesh described as "rather steamed than roasted." In answer to 38 carefully prepared questions, Miss King replied by topics; the mountain appeared gray, mostly white below and black above, with smoke rolling toward the left; the weather was very calm except for the blast, and later there was a good breeze, fresh air, a sunny day, and no thunder or lightning; the only smell was from the gray dust, described as "like gunpowder." There was no smell of burnt vegetation; the witness was in the cabin during the actual explosion and saw no flames or red hot stuff, heard no suggestion of gas explosion, and did not know what set fire to the steamer; the ashes came in boiling, spattering splashes like "moist marl;" no pieces of rock fell, and the cabin accumulations were wet sand, as was the grit in the wounds. Before the blast there had been falling dust, but no difficulty in breathing; the sun was brownish red as the darkness dissipated; the ship's bow was pointed seaward, she heeled over to the left and reacted to the right; the stern toward the city caught fire first, the bow later. There was no rumbling, and the blast itself was like a terrific clap of rattling thunder all at once, and then no more; there was no noise before or after. The witness saw no living people in the city, but later in the day men were seen on a raft. Dr. E. G. W. Deane, graduate of Aberdeen University, testified that Miss King was severely burned on knee, arm and hand and would never be a strong woman, and that Miss Stokes had severe burns on head, hands and arms, she would be disfigured on one ear, there was no injury to the vital organs, but hands and arms would be incapacitated for manual labor.

Observers in St. Pierre City May 8

Prisoner Cyparis, location 9, had burns so deep on back, legs, and feet that blood oozed from them; wounds looked as though made by hot steam. This was in spite of the fact that the prison was under cliff shelter, and the cell a masonry dungeon with only a grated aperture over an iron door, and a ventilation chimney. He heard outcries and felt heat, it grew dark, hot air mixed with fine ashes came through the grating and burned him; intense heat lasted only a moment, he smelled nothing but his own burned flesh; scalding ashes continued longer, coming in without noticeable blast. His shirt was unburned though his back was scalded under it; his jug of water was not heated.

Compere, location 10 under the cliff in the open air, noticed violent wind from the north, the garden trees were uprooted, it became dark, and he found himself burned on exposed surfaces; a great quantity of cinders made a noise on iron roof and penetrated rooms; neighbors died, whereas Compère saved his life by quickly taking refuge in his house; after 20 minutes the roof burst into flames, and he noticed his flannel vest on a wall taking fire spontaneously; he took flight eastward with bleeding legs, observing corpses on the road near Trouvaillant, location 11; the city was all in flames, and the ground was hot with fallen ash; he heard no uproar and experienced only momentary heat and lack of air. He took refuge at Fonds St. Dénis, location 12.

Observers outside of St. Pierre, May 8

Lasserre and Simonut, location 13, saw a black cloud coming with a "galloping sound," it overturned their carriage and swept across the summit of Grande Reduit, location 14. They were stunned, bruised, and burned; two persons 30 feet behind them were killed; 30 feet up the hill ahead of them the blast left no trace at all. They smelled "smoke from lava," did not realize their serious injury, the carriage showed no burning, and their scalds under uninjured clothing were like those of a steam discharge from an exploding boiler. After the blast, pumice pebbles of nut-size fell; darkness lasted from 8:30 to 9:30 a.m. followed by warm rain for a quarter of an hour. They were on the extreme edge of the blast and were badly scalded but were able to walk to Morne Rouge, location 23.

Lesage, location 15, saw a mass of fire surrounded by a large globular black cloud which rushed into the sea. It reached him in 2 minutes, rolled him along the earth for 10 feet, and covered him with semi-liquid scalding mud like mortar; mouth and nostrils full of hot cinders impeded breathing.

Taudilas, location 16, was thrown down by a violent wind, covered with hot mud, and badly scalded. Clerc, high location 17, saw the great cloud of black smoke start at Etang Sec, make a rending, roaring sound, and hug the earth like a flock of sheep directed toward St. Pierre. He was looking down on it from the east and could see the horizon above this cloud; he noted lightnings and a city explosion. The time occupied was 2-3 minutes, and the speed between 90 and 135 miles an hour. At location 18 it set fire to buildings and at location 19 it scorched the coconut palms. He returned to Vivé, location 20 (Fig. 2) which place he believed in danger from the Falaise Crater, location 21, and from floods of the Capot River.

ARNOUX, location 17, was a scientific observer; he saw a wave-like puff followed 2 seconds later by the cloud which took less than 3 seconds to reach Carbet and swelled up into the zenith. It seemed as though the crater had opened along its entire length; there were electric sparks, and the ears were deafened. A terrific upward wind arose, the sunlight went out, stones up to 1 inch in diameter fell, then a rain of mud; a fiery whirlwind over St. Pierre rose 1300 feet and lasted 2 or 3 minutes.

THIERRY, location 23, also a scientist, saw a series of columns of fume appearing to represent little craters along the Rivière Blanche; he counted six columns below the upper crater, which his eyes had just reached to count "seven," when a fountain of rocks was projected 200 feet above the top of the mountain; then the cascade took the direction of the seashore, leaping over the ridges between the Blanche gorge and the city. He heard the detonation and saw enormous rocks shooting along with terrific speed, leaving a black trail outlined against the interior whiteness of the cloud. After the local violent wind and mud fall he looked toward the crater and saw it clear, estimating that the murderous downblast lasted less than 2 minutes. FATHER MARY at the same location thought the rocket-like bursts were caused by uprushes of mud and steam from the ground, over which the discharge was moving. He was 1400 feet above sea level, and the upper surface of the cloud was level "looking as if all Martinique were sliding into the sea."

ALTEROCHE, high location 24, saw upright vapor column over the gorge, but the summit of Pelée was distinct. The downrush reached Carbet, location 28, in less than a minute, while the blue sky was unobscured over crater and summit. The downblast was preceded by a fire column enveloping Carbet quickly, stopping and rising under a reaction of wind from the south. At Morne Vert, location 24, the cloud of darkness went over with falls of stone, sulphurous mud, and dry ash for an hour, clearing to a twilight at 10 a.m.

MRS. DUJON, location 25, reported detonation, lightning discharge of a smoking mass from an opening in the mountain, which reached the city in an instant, then expanded over the ocean and swelled up.

BERTE, sea location 26, (Fig. 2) reported that at 7:25 a.m. a dozen men in a canoe from Precheur, location 55, were headed south opposite Morne Folie, location 27, when struck by the northern edge of the downblast. The boat capsized, seven were drowned, five reached shore. The station was destroyed with 800 natives of Precheur. Hot mud fell in enormous drops, and a hurricane of fire followed the ridge crest downhill. Berté on the cableship 5 miles west of the city saw what looked like two gigantic flashes of lightning traversing the air, Pelée to St. Pierre. The shore line appeared on fire, and the slope of the mountain was red as though it had melted. There was no atmospheric disturbance at the ship, and no odor, but the barometer fell 0.12 inch.

MAUCONDUIT, location 28, saw a sheaf of flames at the volcano, followed suddenly by an advancing spout of smoke that obscured the city. A very violent south wind dissipated the smoke, and everything started to catch fire at the same moment. He thought a fiery spout over the city exhausted the air.

OBSERVERS IN RESCUE PARTIES

PAREL, location 29, reported a violent thunder storm in Fort de France at 4 a.m. May 8; at 8 a.m. thunder pealed, it grew darker, there was noise like hailstones, three times the sea receded several hundred meters, and an ash fall lasted a quarter of an hour.

On a rescue ship at 3 p.m. the Rivière Blanche was in full flood and vaporing, St. Pierre was a smoking ruin without life, and dying victims were found near Carbet. A witness reported a sudden vertical discharge with detonation at 7:50 a.m.; a horizontal spout detached itself, bearing on St. Pierre in a regular curve, before which everything went down and everything took fire. Rainy squalls from two sides of the blasted sector assisted in sharp demarcation of the immense area.

LUBIN, landing at location 31, said bodies in houses were charred, those outside were distended by gases but not burned. The streets were full of red-hot coals. Position of the population showed unexpected overwhelming and no panic preceded destruction. Carbet showed the effect of water waves.

THE PERIOD FOLLOWING MAY 8

ALTEROCHE, location 24, on the night following the great blast, made the first observation of fiery glow clouds migrating down the rift in three streaks, several to the minute, and even out to sea. The first appeared to be the River Blanche, the second near location 33, the third beyond Sainte-Philomène, location 35. The last two were small. All came into view when nightfall revealed them, below several luminous points arranged in a semi-circle at the summit; the crater appeared to vomit fiery torrents that reached the sea with lightning-like rapidity, and the Rivière Blanche torrent even advanced into the sea and remained luminous for several hundred meters. The phenomenon lasted until 1 a.m. when the summit fire darkened and the streams gradually ceased. During the evening there were five or six downward jets per minute; as they diminished the intervals were several minutes long. This was a time of complete absence of lava dome in the crater.

WILL, a Royal Mail ship's surgeon, examined St. Pierre May 11. Pelée sent up a fume cloud, and a stream of hot mud rushed down the gorge sending up huge volumes of steam where it passed into the ocean. The city showed tornado effects and burning, but nowhere was ash deeper than an inch. Bodies had been buried under fallen and burning roofs. Clocks had stopped at 7:50. Death did not appear to have been instantaneous; it was occasioned mostly by dust suffocation and intense heat.

Parel saw the eruption of May 20 from Fort de France, location 29, with the usual advancing cloud and darkness, followed by ash with some light stones as large as an egg. The May 8 blast was re-enacted in the same places; the walls remaining in St. Pierre were knocked down by a second fiery whirlwind, and a tidal wave ravaged Carbet.

The author visited St. Pierre on May 21 and found more complete burial and devastation than Dr. Will reported for May 11, but otherwise conditions were similar and were as his published papers describe them. All this period and the later eruptions are described by the authors of that time, and listed hereafter.

Review of Eruption Pelee, May 8

Steam, hydrogen sulphide, and warm water gushed up anew around the sides of the crater pond at the end of April. An immense jet of warm water spouted from a fissure under the source valley of the River Blanche. Ashfall followed from the crater source, steam becoming explosive; between April 25 and May 1, with increase of poisonous hydrogen sulphide gas, the ash spread beyond St. Pierre, and presumably crater pond and bottom were engulfed. Crater lakes can not remain static when the same crater is flinging up giant cauliflower clouds for a week. Steam blast eruption begins with engulfment; yet Landes found no incongruity in saving the crater lake for the flood of May 5.

Beginning May 2, increasingly large explosions culminated in rocketing of stones out of the crater at 2:00 a.m. May 3, presumably illuminated. There were detonations; heavy ash fall reached Fort de France bay.

May 5, 6, 7, and 8 beginning with Precheur River and River Blanche, 30 radial streams around Pelée burst into flood overflows, the larger ones carrying trees and giant boulders and building out deltas; the River Blanche took the lead on May 5 with boiling mud carrying 50-ton boulders and travelling a mile a minute, while the summit crater was throwing up powdered ash. Attention was too much concetrated on the confluent delta of Rivers Claire, Blanche, and Sèche where human lives were lost and a large sugar mill was destroyed in a suburb of St. Pierre, while the flood destruction straight across the mountain at Basse-Pointe was sweeping away the greater part of a town. The River Blanche flood was considered erroneously the ejection of the crater lake, in disregard of the eruptions of May 2-3.

Accompanying the floods on May 5 of both the River Blanche system and Precheur River, and despite the enormous delta displacement, the ocean suddenly lowered. On April 22 the submarine cable had been broken (April 23 was the earthquake day) in the Dominica Channel in the afternoon, it had broken 1.75 miles west of St. Pierre the afternoon of May 3, and it was broken 16 miles WSW from Mount Pelée at 7:30 a.m. May 5, just 4½ hours before the terrific flood of River Blanche. The southward cable from St. Pierre to St. Lucia was ruptured in the evening of May 6 when there were floods of the southwestern rivers. Other cables were ruptured at 2:54 p.m. on May 7 in four places from 5 to 24 miles west and north of the crater of Soufrière near St. Vincent simultaneously with the eruption and flood of that volcano. Finally, there were other ruptures of the Martinique cables on May 8 at 8:02 a.m. at St. Pierre itself, at a point 12 miles SW of Pelée, and 14 miles NW from that volcano, 50 minutes before the great cataclysm. There was another rupture near St. Vincent Sept. 18, 1902, between the September explosions of Soufrière. All of this cable breaking cannot be disconnected from the eruptive events. (Fig. 24.)

Disturbance of sea bottom was dismissed as superficial submarine landslip, and as not being movement on fault planes or volcanic rifts. There seems to have been no publication of the possibility of radial rift systems and ground water setting the dates for these events, with the aid of the magmatic furnace. Yet the feathery rill etching of the landscape on the ash mud, and Lacroix's photograph, like Waimangu, of the Soufrière geyser of St. Vincent in its crater lake, almost duplicate the effects of the Rotomahana-Tarawera eruption in the hot-spring and lake district of New Zealand—a type case of a rift eruption through underground water.

Finally, on May 5 in the gulch of the River Blanche a hot mud eruption seemed to travel 3 miles in 3 minutes on a flat grade carrying 50-ton boulders. This is impossible unless the volcanic crack vomiting water and debris opened progressively from crater to shore in that 3 minutes. Every structural evidence favors ejection of ground water as part of the gradual development of a coming boiler explosion.

The survivors of May 8 in St. Pierre reported a preliminary jet of vapor toward the city, then the horizontal blast, the fall of hot mud, steam burns, almost no odor, a rending of the mountain from top to bottom, a series of clouds prolonged the whole length of the River Blanche, and a rolling downhill of a horizontal tornado that unfolded itself along the slope of the mountain reaching the city in 2 minutes and fanning out over the sea. It then developed into a vertical tornado over exploding rum storage and rum factories. It carried with it scalding hot dust and incandescent pumice pebbles. The nearest ship sank instantly at its mooring, and the more distant ones were dismasted, swamped, and set on fire. The order of events was (1) blast, (2) hot cloud, (3) hot mud. There was no time to make mud out of rain. The noise was a single violent crackling of deafening intensity. There is lack of agreement about rough seas, but apparently they ended with the first blast.

The scalding of flesh was beneath unburned clothing, and only one case suggests acid decomposition of underclothes. Hot pebbles and wind set fire to inflammables. Men subjected to this died. There was for others momentary suffocation immediately relieved by a counter current of fresh air from the south. City and ships took fire in a hundred places at once, and rum in casks and tanks exploded and distributed an inflammable fluid. Persons nearest the mountain reported hot mud falling in enormous drops, and farther away hot, boiling, spattering splashes, which all suggests a more violent repetition of the water ejection like that of May 5, and water-clogging of steam along the whole length of the Blanche rift when the mountain heaved. The tidal wave recalled May 5 to a sailor who saw both eruptions, and seamen called May 5 a mud eruption.

Under the shelter of the cliff in the city two witnesses were burned by hot air mixed with fine ashes, the intense heat lasted only a moment, very hot cinders were left on the ground, and deaths were from shock and breathing hot rock powder. At the east edge of the blast there was a hot tornado that scalded without igniting, and only scattered were the pumice pebbles. At the south limit of the blast (and also on the ships), victims were enveloped in semi-liquid mud, and at Carbet some were less burned.

Outside of the blast area from the eastern heights, the perspective was different; the cloud that rolled down, starting at the crater, hugged the earth with its cauliflower-topped surface resembling a flock of sheep, and the ocean horizon remained in full view above it. There is no indication that a tall "pine-tree" cloud stood above the crater though there is difference of opinion. A tall cloud eventually rose high over the whole rift belt as seen from distant places. (Figs. 13-14). The reports from these eastern heights tend to make the duration of the blast from rift to Carbet only a few seconds, whereas the estimates for observers on ships and shore was 2-3 minutes. This is a serious discrepancy.

Here again explicit statements made the rift open along the whole Blanche valley with seven columns of fume appearing to represent little craters, and recall the mud flow of May 5. The fountain of stones rocketed not only over the crater wall but across the ridge southeast of the River Blanche towards the city. The same observer saw on the sides of the explosion, when the middle of the sector was drowned under fume, "enormous rocks shooting" horizontally, leaving a black trail outlined against the interior whiteness of the cloud. A change of color from interior of cloud to periphery was also noted from the Carbet direction, as a mass of fire surrounded by a large globular black cloud. This was a view end on.

On the eastern heights electric sparks were seen in the cloud, and over the city was seen a migratory whirlwind of fire 1300 feet high (Finch, 1935). As the outward-spreading mushroom of dust cloud in the zenith darkened the sky a terrific convectional upward wind was followed by falls of pebbles, mud and rain. Even at the end of the blast the crater was clear and throwing up the ordinary fume. There are various accounts to the effect that the return wind stopped the outblast, or that the outblast spread like a fan on the ocean and stopped suddenly, changing its motion to an upward swelling. The sudden beginning and stopping of the blast proper are like a boiler explosion generating convectional indraft.

From the high montain east of Carbet, Pelée was described as showing blue sky above the crater during the downblast, though there had been a vertical column over it half an hour earlier. The account from Beaurégard Plantation, location 25, just outside the end of the blasts at the south, that the expulsion was "from an opening in the mountain with lightning rapidity," of a dense mass streaked with lightning and almost instantly reaching the city, checks remarkably with the accounts from the eastern heights. This is singularly at variance with the accounts by sailors in the harbor which gave the steam blast 2 or 3 minutes to reach its destination and gave them time for considerable maneuver of protection.

It leads to the query, could there have been a minute or two of slower flow down the Blanche valley as the rift split open after the fashion of May 5, with a preliminary clot of boiling water, mud, and boulders, and all of this under a haze not transparent when seen from the heights? Then came the instantaneous or 3-second cannon shot, clearly seen from the heights, opening the rift more profoundly to the steam boiler, and possibly even blocked on the side of the incipient magma dome under the crater (Fig. 16), so that the exceptional down-blast was literally bent to its downjetting course by the configuration of the rift, as a lifting lid in the bottom of Blanche valley. Such duplex mechanism agrees with (1903) Anderson and Flett, who saw Pelée July 9. (See preliminaries of August 30.)

Lacroix and others are reasonable in denying that the paroxysmal early eruptions could rely on gravity alone to roll the steam blast sufficiently rapidly downhill. All have interpreted the accounts as meaning the crater only, for the source of the blast. Jaggar's statements (1902), based on study of St. Vincent were that backfall at the crater cushioned the upjet into the topography of the notch, and so forced the weakening upflow into a downward deflection. Russell and Hovey (1902) echoed this; Kennan (1902) favored back-wall reflection. In the words of Anderson and Flett this was the "crateral avalanche" at St. Vincent, but it was an avalanche of backfall from the air.

This does not apply if the hillside observers at Pelée are correct in saying that the initial air over the rift and over the crater was clear. Furthermore, when we study critically the wording of the observers, they say the blast came from the mountain, but the assumption that they meant the crater is not justified. Few believed the bottom of the valley could split open along the old solfataras and hot springs and morne domes, but the observers said that it did just that (Figs. 13, 14, 34, 36, 29, 32). These were ancient eruption sources, many of them alive, even though the bottom was full of mud and stones that would leave small scar. It was at the places of the largest accumulations of big boulders, vent fillers, that Lacroix and Hovey were later to find persistent deep fumaroles. Hill mapped and photographed a lower crater in the River Blanche gorge 2000 feet below the summit.

This division of the event into a preliminary mud flood and an instantaneous boiler explosion agrees with the valuable account of the nearest observers of all, struggling in the ocean water midway between the Blanche and the Precheur. The hot mud burned them, fell in large quantities and big blobs, and the hurricane of fire followed the crest of the mountain to Morne Folie, location 27, and killed 800 people. No meteoric rainfall could develop in that space of time. To them (Figs. 4, 3) the crest of the mountain was the big scarp of the Gros Morne of Pelée, location 34, so that the lateral reach of the blast included the hot springs above Morne Folie, the village of Sainte Philomène, location 35, and everything across the great plain of sugar fields to Bellevue, location 16.

Possibly deep down athwart the mountain there are dike rifts extending from above the crater to the mouth of River Blanche, and others through the mountain from Fontaine Chaude, location 36, to the fumaroles of the Falaise, location 21. There may be cracks parallel to the Precheur-Somma escarpment, location 37. A radially cracked dome is not limited to single fractures.

Similarly the cable ship at sea saw two gigantic flashes traversing the air from the summit of Pelée to the city, leaving the slope of the mountain looking as though it were red hot, not merely the crater. Again an observer of Carbet saw an immense sheaf of flames starting out of the volcano before the spout of smoke advanced to the city. Exactly the same observation August 30 at Carbet was made by a different observer (Renaudineau hereafter). The violent south wind fanned the fire in St. Pierre. Someone in Carbet described to Parel two separate events, a mass hurling itself upward and then a spout detaching itself and beating its way downward to the harbor. This was not a summit pine-tree cloud. If by "crater" this observer meant the split-open rift, we would get the immense mass of mud and water (called "mud-smoke" by Kennan) hurling itself up from the rift as the latter split its way open, and then the boiler explosion downward. "High" from Carbet might still be below observers at Morne Rouge, elevation 2000 feet.

The ocean receded several times all the way to Fort de France; after the eruption the River Blanche was rushing madly into the sea with a crest of vapor, so that clearly the eruption did no final drying up of the water; the remainder of the daylight hours on May 8 were taken up with humane activities of rescue, and the mountain was unreported.

The tidal waves of both May 8 and May 5 are not satisfactorily disposed of as mere thrusts of blast or delta mud. The rupturing of cables, the opening of the rift, and the apportionate fault movement under the sea are quite sufficient material for a seismic source, and it must be remembered that the volcanic edifice is much larger below sea level than above it, and the volcanic rift does not stop at sea level (Fig. 16). A rift opening in depth under the sea readjusts salt water pressure inland under fresh. Felt earthquakes are not necessary evidence. There were similar seismic waves with all the paroxysmal eruptions. Only sensitive seismometers would record the earth motion. At Kilauea a rift crack 10 miles long in December, 1919, opened down the mountain flank to make five principal vents in 10 days, with almost no felt earthquakes.

The report from the hills east of Carbet (Altéroche) the night following the disaster is of great importance: it described a luminous arc (Calder, Soufrière May 6-7) at the crater, probably trajectories of glowing stones, and three fiery torrents pouring down the course of the rift to the sea for most of the night, at intervals from 10 seconds to 4 minutes, and shooting along with lightning rapidity.

The eruptive activity between May 8 and May 20 continued but was little observed. It distributed ash over the country, especially May 17, 4:00 to 8:00 p.m., registered by Lacroix as a paroxysmal eruption only in his table of ash fall, and noticed at Marin, location 38. The ash at Fort de France on this date was measured on U. S. cruiser Cincinnati as equivalent to half a ton per acre. This eruption was almost contemporaneous with the outbreak of May 18 at St. Vincent; that of May 20 initiated a new phase (Fig. 21.)

The importance of the view of the mountain after dark by the Abbe Altéroche on May 8, 12 hours after St. Pierre was destroyed, is that it gives the first description of "nuées ardentes." Not only did the fiery streams follow exactly the belts of known solfataras or hot springs of the Rivers Claire and Blanche, the River Canonville, location 39, and the River Lamare, location 40, but they shot down five or six to the minute with speeds like meteors and "a fairy-like ethereal aspect;" and shot out over the sea still luminous to about a fifth of a mile across the water. This might have come up through the water.

Here was definite description of nocturnal luminosity not electric, and the speed as a stream agrees closely with Lande's (Lacroix 1904) account of the flood of May 5 in daylight, carrying enormous boulders, "a white seething mass under a thick cloud of white smoke, and at the foot of Morne Lénard, location 41, a new branch that threw out lava, all seeming to be boiling mud and water travelling a mile a minute." We have already seen that such speed could only be progressive opening of a spouting crack, and that the water could not possibly have been the April crater lake, which was no longer there. This downblast of high noon in brilliant daylight probably had incandescence in its fragments, transported on a mud surface.

The great disaster of 8:00 a.m. May 8 may have been divided between two sources, a floodlike rush down the valley of finite speed, and an outward explosion of instantaneous quality oblique from the middle of the same valley. "Fire" was seen in the middle of the blast, stones and black smoke around its edges.

Assembling the preliminary floods of all the streams, the May 5 flood, the May 8 blast, and the May 8 fiery downjets at night even carried out over or under the sea, the events are consistent with a heaving volcanic structure. The sequence is: (1) rift splitting outward from a central shaft, (2) deep magma wedging open the rift, (3) ground water, with its hydroviscosity lowered by heating, dropping down into the void, (4) steam expansion establishing rhythm, (5) release of pressure on magma heating its gases and swelling it to pumice and heaving the rift wider open. Finally, (6) the magma column rises under the crater, and the negative pulsations of the rhythm cause the dropping, heating, and preparing for ejection of internal avalanches of wall rock under both rift and crater, and excess of liquid water is ejected through the rift followed by incandescent effervescence.

The rapidly congealed but still incandescent pumice is itself crushed and eroded in the deep mixture, and some of the wall sill rock is internally engulfed. A volcano naturally heaves open ragged sectors bounded by cracks radial from the crater, breaking the cone where valley grooves make the mountain weakest, just as a man notches a stick with a knife in order to break it. Similar five-point star rupture is the radial breakage on top of an asphalt road-swelling, made by an upthrusting subjacent root, or the back side of armor plate penetrated by a capped projectile.

All volcanoes have old belts that are kept open and weakened by solfataric action. Moreover these rot the rock and become valleys. The "Fontaine Chaude" and the "Whitened River" got their names from hot springs and solfataras. These locations have deep carbonic acid, carbon monoxide, hydrogen, sulphur, air, and underground water as shown by investigations and analyses of the Geophysical Laboratory, the Martinique observatories, and Hovey (1908).

Returning to fire streams coursing down the southwestern gulches of Pelée, on the evening of May 8, 1902, when there was no carapace over a magma dome to make the crater the source, streams considered as true "nuées ardentes," or intense, prolonged, and rapid "Gluhwolken:"

How could so astonishing a thing happen as the cracking open of valleys over and over again, through all the paroxysmal eruptions and all of the "nuées ardentes" of Lacroix, Perret, and the observers at Santa Maria in Guatemala, and some of those in Java, (Merapi), without someone finding the cracks?

The answer is as follows: both Lacroix (1904) and Perret (1935) described and figured the scars as ridges; Lacroix (1908) and Hovey (1908) described deep solfataras in Rivers Claire-Blanche progressively hotter craterward. Not one of these crackings could possibly happen without immediately filling itself up. And Lacroix published an illustration of mud flows coming up through the scars. Even lava craters bury up their vents, (Fig. 15), and flank vents leave nothing identifiable. Perret and Jaggar both found this so at Sakurajima. The only place at Pelée definitely a fissure everyone acknowledged to be such; this was the notch where the ash-charged steam jets always began at the head of River Blanche, in the line of summit and magma dome, itself lengthened into an unseen dike below. Morne La Croix, the summit crag, is an old dike on this line. Santa Maria in Guatemala also had notch and dome, was indubitably a flank crater, and vented downblasts. This same dike at Pelée may have executed subterranean effervescences (like lava fountains) with each heaving open of the crack, especially in the later nuées. Perret's experience with carbon monoxide suggests that all the later migratory jettings after the dome and spine became established were from such magmatic effervescence, especially as the 1929 eruption had no paroxysmal beginning. All this depends on the extent to which the ground water table remained in contact with the eruptive system by some such mechanism as the Morey (1938)-Goranson (1931) water absorption and pressure increment.

The generally accepted transition in time, between the paroxysmal eruptions ending with August 30, 1902, and the later "nuée ardente" eruptions characterized by the rising and crumbling of the andesite spine probably also marked the end of a succession of major geyser explosions of ground water, and the gradual domination thereafter of lava fountains mixed with water, (curves Fig. 21). The constant element in a geyser curve is the temperature-pressure ratio where the water volume increases as the ground-water chamber enlarges by collapse (Jaggar 1898.)

Preliminaries of Pelee Eruption August 30

The eruptions of May 17, May 20 (described by Parel above), May 26, June 6, and July 9 were like the eruption of May 8 and were described by Lacroix (1904), by American naval officers, by Kennan (1902), Heilprin (1903) and Jaccaci (1902), by Hovey (1902), Curtis (1902), Jaggar (1902, 1904), Hill (1902), and Russell (1902), by Flett and Anderson (1903), and need no repetition here, except for the following July 9 data. They exhibited more river floods, increase of the inner fragmental heap to a cumulo-dome, increase of fiery incandescence to visibility in daytime, and increasing evidence of glow clouds, migrating as successive upjets, from crater to ocean along River Blanche. Migrating upjets are not identical with downblasts.

The eruption of July 9, seen from a sloop off Carbet by Anderson and Flett (1903), had a duplex quality which recalls Prudent's observation May 8 of a preliminary downblast at 7:15 a.m., 35 minutes before the St. Pierre catastrophe. July 9 produced a crateral bulbous cloud at 7:40 p.m., and 40 minutes later a red-hot avalanche. The first cloud "rolled and tumbled, squirted and seethed, for quite a perceptible time." Then it "began to move with greater and greater speed down the hillside" till it struck the sea, when it stopped rather rapidly. The second explosion was much larger; after red-hot stones were projected a mile from the crater, suddenly a yellow-red glare occurred with a snarling growl. A red-hot avalanche rose from the cleft in the hillside, poured into the sea, billowy like a cascade in a mountain brook, and then its ash-bearing cloud swelled forward with tremendous velocity, but "the mist and steam did not allow us to see very clearly how the fiery avalanche arose." These authors state the avalanches move faster the flatter the slope: "the idea of a blast is also essential." They are forced to the heavy gas emulsion notion, without understanding the speed.

The pair of blasts indicated in several of the paroxysms is explained if the first cloud were simply a mud geyser splitting its way at increasing speed down the rift to the sea. The second cloud was the freed vapor with incandescent debris. The cessation product was superheated steam up the whole rift followed along the lower rift and stream bed by boiling water. Such boiling water was sweeping down the River Blanche and photographed by the author July 10. This order of progress agrees with the floods preceding paroxysms, the internal steam ejecting water before gas, and agrees with the later glow clouds accompanying magmatic risings of the spine.

The eruption of August 30 was critically studied by Heilprin (1903) and

FIGURE 5. *Pelée flank southwest, 3:10 p.m., May 21, 1902.* By Jaggar, from U. S. S. Potomac, showing valleys Claire and Blanche and initiation of the deltas, later merged. Conspicuous was the "crater chasm filled with huge crusty blocks, and steam rising from the midst of the pile." Also the crack-like appearance of Blanche valley with steam jets in a line, measured as trending N 53° E. From this Jaggar gained the impression that gas-melting among the fragments of the dome might make mobile the matter of the spine.

FIGURE 6. *Pelée flank with new dome and glowing crack across dome. June 28, 1902.* By Jaggar, drawn from sloop "Minerva" opposite Carbet Grande Anse, showing new volcanic delta of Rivers Sèche and Blanche, also St. Pierre and Carbet, and the dome growth since May 21, see Figure 5.

recorded by French officials in the absence of Professor Lacroix. Heilprin climbed to the summit of Pelée the afternoon of the eruption day and was at the edge of the destruction zone northeast when the paroxysm occurred.

The writer was in the field May 21 to July 16, he has had ample opportunity for comparing notes, and it is evident that from May 8 to July 9 the eruptions were increasingly magmatic, and that after May 20 they were decreasingly powerful as boiler explosions and flood makers. Crateral incandescence and migratory nuée incandescence along River Blanche increased. The steam blasts were notably quiet July 15 to August 13. None of the greater eruptions was so strikingly heralded by fiery premonitory signs as that of August 30, in the events following July 14.

August 15-20: As seen from Morne Rouge, location 23, luminosity increased at the crater, the cumulo-dome (Figs. 5, 6) grew in size and incandescence and sent avalanches into River Blanche valley, while the rumbling crater sent up cauliflower ash clouds vertically.

August 21-24: The most intense migratory clouds of the entire eruptive period of Pelée occurred apart from the downblasts of grand paroxysms. The activity of August 21 was seen from Carbet and hills southeast and east of St. Pierre as endless, immense, travelling clouds from 10:00 a.m. to 3:00 p.m. from crater to ocean, and in the evening an enormous quantity of material spread down the valley of the River Blanche to form at its mouth a new point of land several meters high. All peaks north of the Blanche were covered with fresh white ash. Active fumaroles in the River Blanche formed in the next two days, and upward jets from the crater continued. On August 24 an earthquake was felt all over Martinique, 6 days before the climax, just as the April 23 shock had been 9 days before the May 2 outbreak.

August 25-29: Intense eruptions increased. At 10:00 a.m. August 25 large mushroom clouds were overturned to the north; rumblings became loud detonations at 8:00 p.m. along with rockets and fireworks of electric discharge; at 10:00 p.m. from the midst of flames that rose high above the crater incandescent material was projected east and south 200 meters so that the people of Morne Rouge cried out "the mountain is splitting" and some took flight: August 26 at 1:00 a.m. the eruption increased with earthquakes, and the volcano appeared to be a huge conflagration full of explosives. At 7:30 a.m. Pelée cleared of clouds, and from Morne Rouge the new cinder peak (which had been glimpsed August 16, 18, and 25) had changed its appearance by enlargement west. Columns of black smoke shot up to a prodigious height with hissing, crackling, and powerful detonation. Fiery stones fell toward the Roxelane source. At noon with decrease of summit eruption fused matter travelled to the sea as migratory clouds. August 27-28: The eruption continued with enormous quantities of incandescent blocks migrating down River Blanche and decrease of rumbling. August 29: At 7:00 a.m. a new downflow migrated southwest, and from 7:00 p.m. to midnight concussions of rumbling made loose objects jump (compare Sakurajima, and Calder at Soufrière), and fiery electrical phenomena were intense.

In all this quoted description there is no mention of flood, though the whole valley steamed and a new point of land was built out. Volcanic floods probably occurred, mud eruptions below, ash eruptions above. No one was observing.

August 30 was destined to extend destruction to Morne Rouge in the evening at 8:45 p.m. The preparation for this was as follows:

Between 5:00 and 6:00 a.m. August 30 there was a lull; at noon a big migratory cloud down the River Blanche was accompanied by a vertical eruption at the crater many thousand feet high. From Morne Vert, location 24, the downward movement appeared like an advancing wall which bent northwest to Point la Mare, location 42, on leaving the Blanche and then spread out to St. Pierre. At 1:50 p.m. a rain of muddy water fell at Morne Rouge.

There was some flight from Morne Rouge, but when we read of this growing intensity for 15 days it is incomprehensible that Morne Rouge was not evacuated officially.

Paroxysmal Eruption Pelee August 30

At Carbet, location 28, 8:45 p.m., Brigadier Renaudineau of the military guards described what he saw; ("Guérin Plantation" means the mouth of River Blanche):

"We saw an enormous flow of fire emerge from the crater and descend rapidly toward Guerin Plantation. The whole mountain between the crater and the mouth of the River Blanche seemed for one long minute a vast brazier of fire. (Compare Fig. 13-14). The people fled but we decided to stop and watch. The fire rolled down the west flank of the mountain like an overflowing river; suddenly a sheet of flame was thrown up to a height we estimated at three miles; then after spreading over the whole region between the Guerin plantation and Latouche Cove, location 43, at the south end of St. Pierre, and in the Morne Rouge direction, it began to come down." [Note the duplex quality.]

"Up to this time there had been no strong rumbling, but now we heard a violent detonation, a brutal crash, and then a frightful column of flames was projected from the crater with violence emerging from the earlier spout of fire, and headed for St. Pierre; we saw it at Latouche Cove, then it was only 500 meters away from us; we fled to the house. There we saw above us a red cloud shot through with lightning; the volcano and the thunder rumbled together, but big stones began to fall, some as big as my fists; we sheltered ourselves in the house which was full of people, closing the windows. But the ash blinded and suffocated us, and we had to open them. We stayed there about 30 minutes; stones were still falling mixed with ash and a muddy rain. There were very brilliant flashes of lightning."

At Morne Rouge, location 23, Police Captain Arnuel (who later died from the effects) reported:

"There were three successive eruptions. During the first I was in the police office which I closed tight. Before the second eruption the house had caught fire and I took refuge in the jail which was not burning. In crossing to this building I felt boiling water on my legs; it was the cinder through which I was walking that burnt me. The jail did not take fire until the third squall came that struck Morne Rouge. Then I went out and was burned once more."

It will be observed that Morne Rouge, location 23, took fire. Ajoupa-Bouillon, location 44, did not.

Also at Morne Rouge, an educated French girl, Miss Martin-d' Harcourt, 17 years old, with mother and brother, were among the wounded in Fort de France hospital, and she was so seriously wounded that she died the next day. Her account was:

The family at Morne Rouge had retired for the night, not being able to stand the strain which the roaring of the volcano imposed upon them any longer, and firmly secured the house, closing everything. Shortly after 9:00 p.m. August 30 a dull detonation was heard, and the outer shutter was torn open. Instantly the hot blast entered and seemed luminous or electric in character. Refuge was sought under the beds, and mattresses were hauled down to cover protruding feet. Just as in the case of the inmate of a house at Ajoupa-Bouillon, Miss Martin-d' Harcourt at this time, thinking that the storm had passed, opened the outside door only to admit a second and stronger blast to which she nearly succumbed. All experienced extreme difficulty in breathing but the sensation of choking was only momentary. Sulphurous odors were strongly perceptible. This house escaped destruction owing to superior construction.

Other cases at Morne Rouge were the following: Mr. LUCILE was in a house facing the volcano, and when the blast came the door burst open violently, the tornado invaded the room and Mr. Lucile was thrust back while trying to keep the door from opening and was jammed behind it against the wall. Another man in the room was killed instantly, and the woman servant was cruelly burned. Mr. Lucile was not injured and was able to go back and seek help at Fonds Saint-Dénis, location 12.

The widow MARTIN was in a house facing the volcano. With the first blast she was burned on the back by ash from a window that burst open on the side of the blast. She had just prepared to flee toward a neighboring room holding in her arms two children, 4 and 5 years old; her body protected them and they were only lightly burned. Madam Martin was badly burned in returning to the window to close it at the instant when a second blast arrived. She was badly burned on arms and hands, lightly on the breast, and had blisters impregnated with black ash in nose, mouth, and ears. She could talk and did not complain of any great throat trouble, but she died September 4 from a pulmonary complication.

Madam PENROSE was in a house with seven other women and it was very hot and difficult to breathe. The house was closed and they were very little burned by the gas and ashes that came through the curtains. Two of her companions were not burned at all. After the eruption she fled in panic with Miss Aline across country. The ashes burnt their feet so that they had to stop and tie boards under their soles.

AVENEL, at Morne Rouge, had been engaged as a porter, observed the danger, urged flight and was called a coward. He fled and after running several minutes took refuge under a breadfruit tree and dug down into the soil. The eruption passed over him and he was unhurt. The next morning he returned to Morne Rouge and found the house burned and its inhabitants carbonized.

The American geologist, HEILPRIN, on August 30 climbed the volcano by the northeast spur, location 45, about noon. Close to the summit a fusillade of falling stones forced retreat; from a high spur the roar of the volcano was terrific, the summit plateau was bombarded, and the steam column was a furious swirling mass towering miles above the summit. It swept up in curls and festoons of white, yellow and almost black, boiling with ash in majestic cauliflower clouds that rose on all sides to join with the central column (compare Sakurajima Fig. 20).

"The entire crater was working, bottom as well as summit of the inner cone with great vigor. Diameter of the column was not less than 1500 feet, and its rate of ascent from 1½ to 2 miles a minute, and considerably greater at the initiation of every new eruption. When we reached the lower slope we were covered with ash and mud, and stones of all sizes had fallen close to us. The falling ash was not warm. There were a few peals of thunder but we observed no lightning. Even when I was within 400 feet of the steam column, I noticed no rise of temperature, detected only a feeble taint of sulphur, and no atmospheric disturbance suggested a suctional whirl." This was 8 hours before the culmination.

At a plantation east of Basse-Pointe, location 46, in the final August 30 eruption, there was little to be seen over the summit of Pelée; Heilprin reported a flash of lightning and a dull thud ("dull detonation" of Miss d' Harcourt) summoned the people into the open air. The volcano was distantly growling, there were electrical flashes, a great pattering of pumice sounded like a hailstorm, with fragments at first an inch or more in size followed by others like peas and then like sand. These were angular bits of andesites or trachytes white and gray in color. The fall lasted over an hour, the ash felt warm, and all motion in the atmosphere ceased. For more than an hour the southwest was glowing fiery red from the burning of Morne Rouge. After 1:00 a.m. August 31 there was another fall of cinders. That forenoon Heilprin visited the ruins of Ajoupa-Bouillon, location 44, where houses were laid flat with the ground, trees were overturned with butts toward the crater, and boards were penetrated by pieces of wood that had been shot through them. This had happened also to Morne Balai, location 47, and Morne Capot, location 48, farther east. Cattle and horses were lying on their backs with legs rigidly extended and a few still living had raw flesh protruding from tightened hides and were wandering about in a dazed condition. Some houses had collapsed over their occupants. In one house they heard moaning and found a woman 30 years old, groaning in agony in one corner of a dark room, her flesh terribly burned and hanging in places from the bones. She called incessantly for water and died shortly thereafter. Other houses presented similar heartrending scenes, with writhing bodies, cries of pain and flies swarming everywhere amid an almost unbearable odor.

One negro less burned than the others, stated that he had been struck by the hot blast at the moment of opening the door and instantly the fiery air enveloped him. He felt the sensation of choking without air to breathe and noticed no gas except a feeble sulphurous odor. His flesh was as if baked and steamed, with raw, red masses appearing where there was no longer skin, but the clothing had remained untouched. Where the cottages had doors and windows that were kept firmly closed, there was little or no injury done. Nothing had been set on fire in the surroundings of Ajoupa-Bouillon. There appeared to have been a series of downblasts of steam following rapidly on one another.

Review of Pelee Eruption August 30

The fortnight preceding this eruption produced the most intense migratory clouds without counting such grand paroxysms as May 8 and Aug. 30. An amazing rush of material into the ocean the entire afternoon and evening of Aug. 21 built up an extended flood delta containing giant boulders. The River Blanche had been found a rushing torrent after May 8, May 20, and July 9, and it was intensely steaming after Aug. 21.

Flames, incandescence, and a splitting mountain impressed the Morne Rouge observers during the last week. The new "cinder peak" piled up into the skyline and again we find a record of apparently fused matter travelling to the sea carrying enormous masses of incandescent blocks. This suggests flood with hot mud carrying the 50-ton boulders which Hovey attributed to the August 30 eruption, just as similar giant blocks had gone to the shore May 5. The noises were now hissing, cracklings, detonations, and concussions.

Lacroix did not question the volcanic flood of Pelée May 5. Yet so much were Lacroix, Hovey and Perret impressed by rainfall, that unlike Curtis, they seemed to neglect the fact that all the streams of Martinique and St. Vincent are normal rivers fed with ground water springs, in turn representing a high-level water table and also perched water, marked in ordinary times by crater lakes. When thermal expansion is added to the Ghyben-Herzberg deep lens (Fig. 22) of fresh water over salt in such porous volcanic islands, reducing the water viscosity and starting deep boiling alternating with cold seepage, there are more ground water springs, not less. It doesn't matter if they are partly salt, except to introduce chlorides. Rainwater seepage plays less part than before, not more. Surface rainwater has no chance in a red hot crater. As to its breaking up a cumulo-dome of live lava at 900° or 1200° C., (Perret 1935) that is inconceivable because of Hawaiian experience, where incandescent domes have received with no effect, 20 inches of rain in 48 hours.

Finch (1930) has disposed of volcanic steam making any important addition to crateral rainfall: the thunder storms of July 9 (Jaggar 1904) developed after the eruption at lower levels than the eruption cloud; the floods came mostly before the eruptions. Any rock joint or fault that bore springs or solfataras in any valley of Pelée or Soufrière before the eruptions necessarily received added water when central magma was heaving the cones through months and years. There is good reason from the crateral measurements to believe that initially Soufrière collapsed and Pelée heaved: Soufrière represented engulfment, Pelée represented correlative tumefaction. Soufrière had little flood. Pelée had floods while paroxysms endured.

In the afternoon of August 30 a rain of muddy water fell at Morne Rouge and the same afternoon Heilprin's party was plastered with falling mud on the northeast slope. Then in the great night eruption the observer at Carbet saw the whole mountain a fiery furnace from crater to ocean with the fire rolling down like an overflowing river. This was a mud gush through the rift carrying on its surface a rain of incandescent fragments from the crater, and the ring of wall-crack around the crateral lava column was shooting up its incandescent material vertically as in St. Vincent May 7. Here also a fiery avalanche from the backfall detached itself from the upjets and headed not only for St. Pierre but also in northeast and southeast directions.

The accounts of the sufferers in Morne Rouge are more like St. Vincent than St. Pierre. The gushes came in successive squalls, and people were caught by opening the windows between squalls. The scalding and suffocation and violent outblast were like those south and southeast of Soufrière, and the blast was like a tornado in that wooden splinters penetrated boards and palm trees. The crateral column of steam, sand, and fragments was enormously high.

This is quite different from May 8, when the Morne Rouge observers could look over the top of the blast descending on St. Pierre, and the observer at Morne Vert could see blue sky behind the summit of Pelée.

The writer has had experiences of severe scalds which may be compared with those that by repetition killed Police Captain Arnuel as described by himself above, feeling "like boiling water on his legs."

At Lassen on the shore of Boiling Lake, a hot springs pool, I walked too close to the edge on a mud-flat and my unshod ankle sank into it. I did not know I was scalded. Later the skin came off in strips. The foot under a low shoe was uninjured. The second occasion was on Mauna Kea when I unscrewed an automobile radiator cap after a long climb: the vent exploded in my face, a jet of water and steam. I felt no great inconvenience, but was under treatment for a week with badly swollen cheek, eyes and temple. I cite these experiences as showing how little it takes to scald human flesh, so that steam-blast needs no sulphur or superheat to kill a man, even without much initial agony. The power to kill in these volcanoes demanded nothing superlative in the eruption; all it required was a downward direction.

Tarawera and Pelée were geysers, even when phenomenally maxima. At Pelée there is no proof whether August 30 or May 8 was the greater eruption. The curves of Figure 21 imply marked decline after May 20th. The steepness of the line May 3-20 marks concentrated energy around May 8. From April 23 to December 16 in the external edifice a steam water boiler was cooling a mass of rising slag, and the pressure of the ages dominated both. Compared to the globe, the whole structure is small. In the world of steam-blasts, the geyser transitions up from the Yellowstone to New Zealand and on to Pelée are important. Water access to magma, on a globe with seventy-two percent ocean surfaces, extended into a bulky ground water body under hundreds of river deltas, is a major process.

ERUPTIONS OF SOUFRIERE

General Statement

Soufrière volcano in St. Vincent, about 102 miles south of Pelée, initiated the eruptions of 1902 by tremendous upblasts and downblasts of steam in the early afternoon of May 7, 18 hours before the Pelée calamity. The effects on

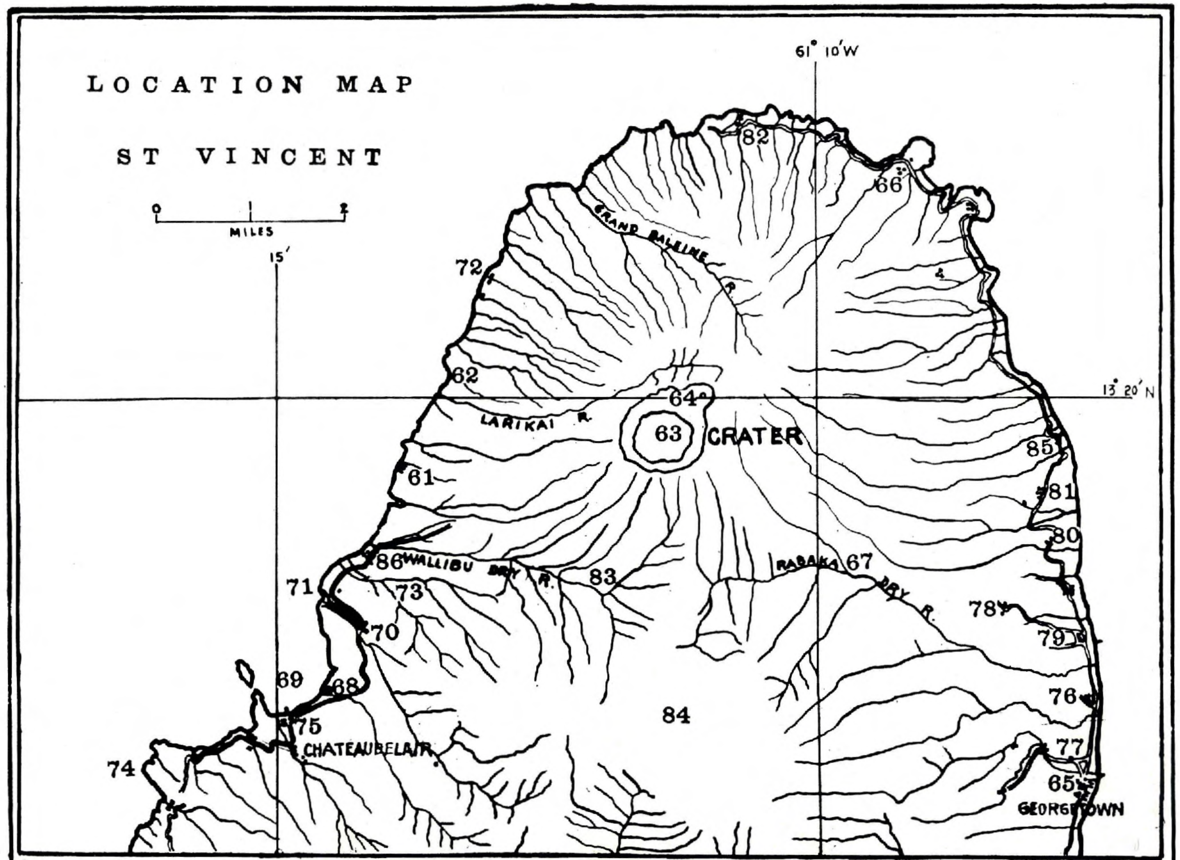


FIGURE 7. *Location map of St. Vincent.* Showing west rift embayment, numbered locations, eccentric crater. Compare Figure 18.

landscape and people were nearly the same. The secondary explosion effects of stream water on incandescent ash were immense, fed by volcanic pumping as well as rainfall. Important western habitations were quickly deserted, and the structural facts about Morne Ronde, (Fig. 7) location 61, and Larikai, location 62, are probably not recoverable. The main narrative has been admirably assembled by Anderson and Flett. (1903, 1908).

In the following pages are gathered personal reports of wounded persons and others who bore witness to the phenomena, questioned by the author, especially of May 7. These statements, with the map, show in what measure Soufrière was like Pelée. In the sequel appears discussion of the distinctive features of Soufrière and of comparative theoretical explanations. (Figures 21, 18).

Narrative of Soufriere Eruption, May 7

The following is a competent account by Dr. Will of the British Army, of what he thought happened after taking personal narrative of nearly 200 wounded people and discussing the eruption with scientific men.

To arrive at some definite conclusion as to the cause of intense burns and asphyxia by ashes and the loss of 1600 lives, it will be necessary to consider briefly the phenomena observed.

Soufrière Mountain is the northern portion of a north-south volcanic range, dividing the island into the Windward (east) and Leeward districts. The volcano consists of two craters; the date of origin of the older, location 63, is unknown, and the small new crater, location 64, not active in 1902, is supposed to have come into existence during the eruption in 1812. The accounts of the 1812 eruption show events like those of 1902. The craters are separated by a narrow saddle-ridge and are approximately 3000 feet above sea-level. The larger "old" crater was occupied by a crater lake.

For some months prior to the date of the eruption rumbling noises had been heard in the mountain. On May 6 these noises became more continuous and louder, and on the afternoon of that day a huge vertical column of steam was ejected with a noise like the report of a cannon. Explosions, with discharge of vapor, occurred during the night, and on the morning of May 7 black material was seen to be thrown up at each discharge, some of it falling back again into the crater. These discharges occurred intermittently, but with increasing violence until about 1:00 p.m., when they became continuous with the roar of a mighty torrent, and a mushroom-shaped cloud of black smoke, intersected in every direction by electrical flashes, rose many thousands of feet into the sky. This mushroom-shaped cloud seems to have divided into two parts, one passing to the windward (east) over the sea, and the other leeward.

About 2:00 p.m. large stones fell to the windward side and the cloud which passed in that direction returned to a certain extent towards the crater, probably drawn by convection or explosion vacuum. This will account for the condition of the windows observed in Georgetown, location 5, where all the glass was broken in on the windward side, that on the side next the crater had sustained little damage.

The volcano seems to have reached its acme of violence about 2:30 p.m., and about 3:00 o'clock the wave of hot air and ashes overtook the inhabitants of the eastern district between Georgetown and Owia, location 66, killing about 1600 people, and thousands of domestic animals, while most of the survivors were burned. The inhabitants of the leeward district had been alarmed by the explosions of the previous night and most sought safety in flight before the fatal stage of the eruption was reached, hence few human lives were lost there, but everything in the way of livestock was killed and buried by mud and ashes.

Leeward or Western Estates

Calder at Chateaubelair, location 75, midnight May 6-7, reported the volcano summit making long flashes of deep-red fire traveling from the top downward in a circular track, trajectories like a blacksmith's heap of air-blown coal. A rattling clatter followed, dying to a rumble. Very dark heavy smoke rose. Other explosions with little flame occurred May 7 in early morning, followed by a heavy explosion at 10 a.m. with dense smoke rising rapidly and earthquake; fire increased and vibration became very severe. At the height of eruption, 1:30 p.m. the column 2 miles high became lighter colored with bulbs like brain convolutions and sideways spreading into ostrich plumes. Hot half-melted stones fell, some a half pound in weight, and fine light dust carried sulphurous fume. The volcano grumbled throughout the night. The afternoon retreat southward of refugees met complete darkness, a thunder storm igniting dry grass, and the relief of a steady breeze from the south. In the morning of May 8 ash of leaden color obscured all vegetation several inches deep.

On May 8 darkness returned 9-10 a.m. with sulphurous smell and unbearable heat and pressure on the ear drums. "Sulphurous" apparently meant hydrogen sulphide May 7, and sulphur dioxide replaced it May 8 to judge from the medical evidence. A thunder storm and rain dispelled the darkness. At 2:15 p.m. another eruption with fire belched from the crater, and eruptive matter coursed down each deep ravine accompanied by white vapor, while heavy stones crashed through roofs. Ash was several feet deep, the coastline completely changed, dead goats and pigs were strewn along the shoreline, and a large new fissure on the side of the volcano was reported.

May 9: after explosions and downrushes, at 7:15 a.m., boiling mud reached the beach at Richmond Mill, location 70, while heavy black discharge rose high from the crater. The mud made a new promontory of slate-colored ash. At 10:35 a.m., a very dense rising of steamy smoke north of Richmond was thought to be "another heavy overflow" of steaming mud from the crater. These conditions dwindling, the crater smoke becoming steamy and the eruption had quieted May 11.

MacDonald (1902) at Richmond, location 68, more than 4 miles southwest of the crater center reported the boundary of total destruction a line trending NW-SE between locations 70-71 and locations 68-69. White steam shot up at the crater with detonation 2:40 p.m. May 6, fire reflection was seen 4:35 p.m., thick smoke rose from the foot of the mountain on the right at 5:15 p.m., completely clearing in a half hour, but renewing at 6 p.m. and becoming an enormous vertical column of noiseless white vapor a half hour thereafter. Darkness revealed a thin red sparkling line between vapor column and crater rim and there were explosions with loud noise at intervals of 2 hours during the night.

May 7: at 6:15 a.m. there was a short column of dense black stuff that seemed heavier as it quickly subsided back into the crater, apparently a mud geyser from the crater lake. At 7:45 a.m. a column of vapor rose in one minute 30,000 feet, or eight times the height of the mountain. In the late forenoon the eruption became continuous, trajectories of heavy black material fell outward from the white column, some discharges were from location 64 northeast of the main crater, and vapor rose from points westward in the direction of Morne Ronde, location 61. The main column changed from white to light gray. At noon vapor jets appeared to extend the crater toward the left, and with great rumblings "dark, blacker upheavals occurred, as if the side of the crater toward Morne Ronde broke away and the crater enlarged in that direction," suggesting the opening of a radial rift along one of the gorges. At 12:35, the slope appeared to have formed into fissures, vapor rose from small vents and at 12:50 p.m. there was enormous outburst there involving the whole front of the mountain. Next came a shift of activity with stones thrown out thousands of feet toward the right in the direction of locations 83 and 84. Black and white gushes followed east and west until at 2 p.m. retreat in boats became necessary before an advancing enormous purple and reddish curtain. The observer moved from location 68 through location 69 to location 71, where the sea was peppered with falling stones, maximum size one cubic inch, increasing in a short time to the size of a fist. The race within the curtain of falling ash was to a beach between locations 74 and 75. Mouths and throats became very dry. It looked as though a submarine eruption were taking place advancing southward toward Chateaubelair. It seemed to Macdonald a "question of how much area the volcanic forces would require of St. Vincent to give themselves a proper vent." Lightning and thunder were terrific, noises inland sounded as though land of the island were breaking up as well as the sea bottom. Earthquake shocks occurred all night, and 18 inches of dust covered the country 3 miles southwest from Chateaubelair. Then came the declining days of the eruption as described by Calder.

Negroes in a boat north of location 71, May 7, at 2 p.m. were struck by the cloud curtain as by a strong breeze coming over the rippled water with a hissing sound from hot sand that made steam. It became pitch dark, hot, and sulphurous, and they dived to escape suffocation from the burning sand and gas. They dived repeatedly until the air cleared and the heat diminished; no rain or scalding mud fell. The hair was full of dry sand, making burns over the ears. They were in the outer south edge of the cloud, for on adjacent land 40 feet of red hot sand was deposited in a few minutes.

Other men in boats saw the beach cloud pour down the northwest valleys, location 72, sinking a boat and drowning the people. The stream-like torrents of ash, however, were denser at Wallibu, location 73. The curtain-like side of the cloud consisted of gentle eddies at the side of a downrushing torrent of ash.

Windward or eastern Estates

A summary of events on the east side indicates that the destruction of life began at Langley Park, location 76, and extended to the north. Mount Bentinck, location 77, and Georgetown, location 65, escaped. North of Langley all animals and men in the fields were killed. At Lot Fourteen, location 78, persons shut tightly in a rum cellar survived. At Rabaka, location 79, 50 persons were firmly shut in a room, felt intense heat and smelled strong and irritating sulphur odor, but all survived. The black cloud rolled over the house, there was darkness, a fall of stones was heard on the roof. A flash occurred as the cloud struck the sea, when it seemed to return and a suffocating feeling was experienced in the room. At Orange Hill, location 80, some 150 people crowded into a large masonry cellar with the door held open, and about 37 were killed around the door and in an outside passageway on the uphill side. The rest were saved. People in lighter buildings were killed, roofs collapsed and the corpses were found buried in sand. At Turema, location 81, everyone died except two who shut themselves in a tightly closed room.

In Overland, location 85, there was loss of life. A survivor reported that when they saw the black cloud coming down, it was red at first, but changed into black before it passed overhead, with heat and vivid lightnings. The air smelt of sulphur, throats were dry and parched, some burst into spasmodic coughing from sulphuric acid and fine dust in the air. They cried out for water until suffocation silenced them. Several fell dead, for others the air began to clear, there was a cool breeze from the sea that saved them. A flash off the sea was seen when the cloud reached the shore. A man, with shirt sleeves rolled up, had arms burned by hot mud or ash which came down with the cloud, but the skin under his clothing was uninjured.

Fancy Estate, location 82, 3 miles from the crater to the north, had a fall of stones about 2 p.m., and the people all collected in a large iron-roofed building. Dark clouds poured over the sea east and west and seemed to join at the north until the falling matter enveloped the building, producing darkness and a feeling of suffocation. In a few minutes there was glimmering light, the village houses had been demolished by falling matter and lightning, and their people were found either dead or fearfully scorched. The large building was of stone and all who were in it were saved. The dust did not set anything on fire and burns appeared to be scalds. There seemed to be damage by lightning to buildings, trees, and animals.

At Owia, location 66, pebbles fell at 1:00 p.m., hot liquid mud 1:30 to 1:45

p.m. with the rotten-egg smell of sulphuretted hydrogen lasting a half-hour. It became dark with suffocating heat; water was thrown about the house to make breathing possible, and no one was killed. The ridges northeast of the crater apparently sheltered the northeast corner of the island where destruction was less than in the devastation tract.

Southern avalanche

Flett and Anderson report an avalanche of dust, sand, and stones south of the crater. This occurred notably in the upper Wallibu Dry River, location 83, the upper Rabaka Dry River, location 67; and on both sides of the Morne Garou mountains, location 84; it filled the valleys to depths of more than 100 feet with sand, stones, scoria and burnt timber, and in places flowed as sand or mud "glaciers." The likeness to a glacier with arched back was cited also by Hovey. In the Rabaka this avalanche front was left more than a mile from the sea. The trees were swept along by it. No evidence was found to prove what form the avalanche discharge took from the crater or what was its path. Trees were flung down straight away from the crater. Evidence indicates that this was an avalanche of backfall from the high column, as shown by MacDonald's citation of "black outburst with showers of stones to windward" and towards locations 83 and 84, coupled with a large black mud geyser through the site of the crater lake, directed somewhat southward by the inclination of the rifle-barrel of the crater shaft.

Dr. Will made surgical report as follows:

"Of the 194 cases admitted to hospitals in St. Vincent 56 were men, 98 women, and 40 children under 14 years of age. The 191 severe burns were characterized mostly by the extent of the areas implicated. Subcutaneous tissues were affected in only 5 cases of ankles and fingers. All the cases had adherent fine dust. There was a remarkable absence of shock, always a sequel of intense burns in Europeans. Total number of deaths was 80, of which 79 were due to burns, one direct impact on scalp of large stone, wound septic and development of tetanus. Cause of death by burns mostly exhaustion from septic wounds of large surface. A few died from pneumonia and pleurisy, and four from tetanus."

Evidence showed that every person who left shelter during the wave of hot ashes was killed in a few minutes, that inhaling the ashes, etc., caused a feeling as if the windpipe was being compressed, and that this feeling was less acute while the sufferers held in their breath. Burns were caused by hot dust falling on exposed parts causing vesication and the destruction of the skin, but not at a sufficiently high temperature to ignite clothing or thatched roofs of houses. Many houses were burned, ignited by what the natives called "fire stones." None of the burns presented appearance characteristic of lightning, and depth of tissues destroyed was greater than that usually found in burns by steam.

The 1600 deaths in St. Vincent by the eruption were almost entirely due to asphyxia by hot ashes and heated air, the latter being probably somewhat deficient of oxygen. The cloud of dust was highly charged with electricity, and some deaths outside of houses may have been caused by lightning, and a few, especially children, were killed by falling stones. There was some sulphur dioxide with the hot dust and there may have been a little hydrochloric gas, but except in one or two of the elderly patients, there were no signs of tracheal or bronchial irritation. There is no evidence of carburetted hydrogen, carbon monoxide, or carbon dioxide; had these gases been the cause of death, it is inconceivable that anyone could have survived and moreover, death would have been more sudden.

In all the houses there was a very large quantity of excessively fine dust, which had penetrated through the thatch and the most minute crevices. In the manager's house at Langley Park Estate, location 76, with close-fitting doors and windows this fine dust lay on the floors to a depth of three inches (June 15) and adhered to the plaster of the walls to a thickness of 3/8 inch. In this house there had been 31 people, 28 of whom died during the fatal afternoon and night of May 7.

Lacroix states that there were no cases of injured eyeballs, and the nature of the scaldings was identical with a case cited of wounding from a boiler explosion. This appears to apply to both Martinique and St. Vincent.

Later eruptions of Soufriere

On May 8 at the time of the Martinique disaster there was a fog of falling ash in St. Vincent and the Soufrière crater had been steadily erupting, with rain, lightning, and thunder at 10 a.m.; in the afternoon there was an increase so that steaming torrents erroneously called "molten lava" were sending up "clouds of white vapor" from streams rushing down "each deep ravine," with noises from the mountain, probably internal avalanches. All of this may be interpreted as primary water eruption.

At about 8 a.m. May 9, the volcano shot out material which was carried in a cloud over Georgetown, location 65, and its neighborhood, causing not only alarm, but compelling the people by families to seek shelter in other districts. There was a stream of boiling mud down the Wallibu, heat, darkness and suffocation at Chateaubelair, and falls of stones to the east. Discharges of dark vapor from the valleys caused local report of valley fissures, and each discharge was accompanied by lightning and thunder.

MacDonald reported that between Wallibu, location 86, and Larikai, location 62, there was found afterwards down-faulting of shoreline back for 600 feet just where the old chart shows a straight embayment, and the flat land seemed raised 40 or 50 feet, terminating in abrupt vertical bluffs at the sea.

The eruptions of Soufrière were on May 7, May 18, September 3, September 21, September 24, October 16, 1902; March 23 to March 30, 1903. This sequence is expressed on the curve of Figure 21 as it parallels Pelée for a geyser succession. The eruptions of May 7 and May 18 preceded and followed corresponding outbreaks of Pelée; that of September 3 followed the August 30 eruption in Martinique. The others were times of glow-clouds and spine development at Pelée: Soufrière made declining steam blasts, and geyser jets of black mud in its crater.

The crater water surface was 350 feet below west rim before the eruption, 1600 feet on May 31.

The eruption of Soufrière September 3 was seen even at Fort de France by Heilprin, in Martinique, in competition with small eruptions of Pelée, as follows:

"Far out to sea southward vivid flashes of lightning were illuminating a corner of the heavens. They followed swiftly upon one another, and zig-zagged across broad stretches of a practically cloudless sky. As evening advanced the flashes became more and more brilliant. To about every twelfth or fifteenth flash from Soufrière, Pelée responded with one blinding flash, so intense as to seem to open the heavens. A green sky appeared in the flash, and for a fraction of time the eye was paralyzed and saw nothing."

This contest continued for 3 hours, Pelée gradually increasing the number of her responding flashes. Shortly after 1:00 a.m. a great red light in the south announced the culmination for Soufrière. The eruption was more intense than on May 7, but observers had moved away on St. Vincent. About 5:00 a.m. September 4 the ash cloud of Soufrière advanced upon Martinique from the south; by 7:00 a.m. it passed over Fort de France, and at 8:00 o'clock the sun was covered and remained so until 3:00 p.m. The canopy overhead was like the Pelée cloud of June 6 but it was less dense and moved more slowly. As on June 6 there was lowering of temperature, and Heilprin detected no sulphur smell.

Review of Eruptions Soufriere

If we consider serially the items of the foregoing we find that the eruption of Soufrière May 7 made a noise like artillery, the rumble was like a roar of rushing water, the burial of cattle to leeward (west) was by mud, and an avalanche of mud and hot water came down Rabaka valley to windward. Observation showed inclined showers of stones eastward, a purplish curtain with electrical flashes and noise westward, and some uproar inland. Just as on Pelée, eruptions through the crater were in progress for many hours before the grand paroxysm of May 7, and there was no evidence May 7 that the crater lake had been preserved for expulsion as a unit. On the western sea-water the arrival of the curtain with falling sand had sulphurous and stifling heat, possibly carbon gases, without rain or scalding mud at the edge of the cloud. A reaction of clear air came, but the cloud in the interior was a downrushing torrent of red-hot debris. There were twirling vortical spirals in the face of the cloud, which extended 8 miles from the shore west. Farther south there was a shower of mud.

At the east, life in the fields was destroyed but in strongly enclosed rooms was preserved. The downrushing cloud had irritating sulphur odor, was red at first, changing to black, and the ash carried sulphuric acid. A flash discharge occurred when the cloud reached the water, and at the north end of the island two such clouds east and west seemed to join over the ocean, in plan like two lobster claws. Weak houses were demolished by wind, falling matter, and lightning, the lightning effects especially at the northeast, where also hydrogen sulphide was smelled. Wounds as at Pelée were scalds and asphyxiations by dust, clothing protecting skin. At the east, noise like a rushing river was heard.

Large stones fell through the roofs: immediately south of the crater in the upper valleys an avalanche of stones, sand, and dust fell. The oncoming eastern blasts were in pulsations, just as was reported at Morne Rouge in Martinique, leading people to open windows for air, and to get caught by a later pulse. Some stones at eastern plantations were red hot, and here as in Martinique incandescent pebbles and wind were sources of conflagration. The streams of black downblast followed valleys, and the effect of contact with ocean seemed like an explosion. This was more generally reported at the east shore of St. Vincent. It was not reported northwest nor west where boats were overwhelmed, nor was it reported in Martinique. It may have been a localized combination of charcoal gas from the burnt forest mixed with air, ignited by an electrical discharge from the water. There were wounds of stone impact, and notably little sign of gas poisoning, bronchial irritation among survivors, or injury to the eyes.

The later eruptions of Soufrière led to suspicion of dark vapor discharged from fissures in the bottom of valleys, all eruptions were accompanied by localized lightning and thunder. One report of a competent witness suggested that flat land back of Morne Ronde was raised 40 or 50 feet, but there was unquestioned downfaulting of the shore line between Wallibu and Larikai which made the remaining shore land appear higher. The later observation of Soufrière crater itself showed its bottom pool giving vent to mud geyser eruptions that rose above the crater lip. The September eruption of Soufrière was seen at Martinique, its dust covered the sun there, and there seemed to be electrical flashes from Pelée sympathetic with those from Soufrière. The whole series of recorded paroxysmal Soufrière dates accorded approximately (within one to three days) with Pelée dates. There was imperfect record for both volcanoes.

COMPARISON OF PELEE WITH SOUFRIERE

Comparative theoretical explanations

Publication has been insufficient of the seismic prelude at Soufrière or of the weeks of eruptive prelude at Pelée. It is important that May 3, 5, and 8 were a consistently increasing sequence at Pelée, and that events of May 6, 7, 8, and 9 at Soufrière rose consistently to a peak and declined. Soufrière was in full eruption when St. Pierre was destroyed.

In both volcanoes an important mechanism was the rupture of the under earth for 100 miles, the conflict between suddenly released magmatic heat and underground water, and the disruption by superheated steam, of two local edifices.

These two craters were themselves connected with local lateral ruptures that showed very little, and these in turn promptly obscured themselves under thick deposits of debris. MacDonald's account indicates strong lateral disruption of Soufrière. Incidentally liquid underground water became involved in the obstructing of vents, not only at the crater lake in each case but at cracks away from the circular shafts. There were left a crater lake and a magma dome; the crater centers may not be given the credit for the whole cataclysm, for the Caribbee ridge is the larger feature.

The two incidents of May 7 and May 8 are like the downblasts of Tomboro, Kilauea in 1790 (and on a small scale 1924), San Jorge in 1580 and 1808 in the Azores, Sakurajima in 1914, Taal in 1911, Tarawera in 1886, Galounggoung in its prehistoric eruptions, Katmai in 1912, and many other volcanoes.

Tremendous avalanches from glaciers or mountain sides in high mountains displace the air in front of them and flatten out villages. If such air, so disturbed by an avalanche of hot rocks previously discharged 10,000 feet vertically, is subjected to the slightest tangential friction of wind, great convectional tornadoes of migratory character are inevitable.

If such avalanche backfall is from a trajectory, given direction by some inclination away from the vertical, while backfall from simultaneous vertical jets impinges upon it and on the mountain slope, the moving volutes will be flattened out to a horizontally expanding smoke ring downward encircling a volcanic cone, impelled by a central upblast.

Backfall restrained by upjet is called "cushioning." Volcanoes are not thus symmetrical; their flanks are dissected with irregular guiding gulches, and the rifle barrels of interior fill of craters are apt to be inclined at several angles, along the wall crack between funnel and plug. (Figs. 16, 17, 18.)

If sectors of the inverted bowl of the mountain are radially cracked free and lifted in the center, and the central shaft is plugged with rising magma, expanding gas finds a way out through the sectoral cracks. If the sectoral cracks are zigzag in plan and have dip in section, the vapor is an inclined jet as in Figures 29 and 30, where the jet is not only away from the crater at 40°, but also away from St. Pierre. If, at another bend in the rift, the dip were in the opposite direction, an inclined blast at 40° might be toward St. Pierre. It would depend on how the sector heaved. (Such would be a jet from the gorge in Figure 30 up and inclined to the right.)

If in San Jorge in the Azores (Lacroix, 1904) the lava flows began by rifting the mountain flank as in Hawaii—they had begun when the people were burned by downblast—then a steam blast could be directed by lava deflection, through the open rift downhill from the lava vent. This probably happened at the Hakamagoshi downblast at Sakurajima, and may also have occurred May 8 at St. Pierre (Fig. 16) if a central lava plug had already risen and blocked the discharges of steam to a radial direction into the River Blanche crack.

The Soufrière has not been surveyed geologically to the same extent as Pelée, and there is no mapping of hot springs or solfataras in the western side valleys to indicate a rift down the Larikai gorge, the Wallibu, or along the depressions northeast and south. There were warm fresh waters under the beaches. The behavior on May 7, with downflowing clouds northwest, northeast, southeast, and southwest, suggests mostly a straight upblast, and the lateral distribution of avalanche effects by cushioning in accordance with the topography.

There may be a movable fault sector between Wallibu and Larikai with rifts on both sides which were heaved open. The smooth shore indentation suggests it as at Waipio, Hawaii. That region of St. Vincent received rumblings and earthquakes, the population was driven away sooner, and the shoreline down-faulting was different from anywhere else.

The devastation, however, was mostly radially symmetrical about a central crater lake that was lowered. As reviewed in this paper the devastation by most of Pelée's paroxysms was unsymmetrical about the middle of River Blanche as center, as if by comparison Soufrière had expended itself upon Wallibu and Chateaubelair.

If central mechanism had been at work on Pelée, there was no reason for it to confine destruction to a sector bilaterally symmetrical to the River Blanche rift. The growth of a lava dome in the crater extending the Pelée destruction on August 30 is not comparable with Soufrière, which had no lava dome at any time, but instead had a profound well. Pelée on August 30 continued to blast St. Pierre. It appears that Pelée shot its blasts bilaterally from a rift, and Soufrière shot hers centrally and radially.

The chart of St. Vincent, British Surveys of 1863 and 1889 (U.S. Hydrographic Office No. 1279) has a striking feature in a south-trending ridge of old agglomerates adjacent to the volcano, which is the divide between east and west valleys, Rabaka Dry River and Wallibu Dry River. The Langley Park river at the east and the Wallibu River on the west, lie south of the two "dry" rivers, and are smaller.

"Dry" is a strange name for these rivers as they are the largest drainage channels of the north end of St. Vincent (Fig. 7). The "Sèche" River preserves a similar tradition on Martinique. They are known to be locally erratic and subject to waterless spells alternating with flood. The consequent branches on the Soufrière cone slope are quite normal, but drainages of the southern branches in the Morne Garou mountains are partly radial from the old Morne Garou and partly deflected at the divide into four rectangular subsequent headwater branches and their tributaries.

The Morne Garou peaks enclose a basin at elevation about 2000 feet, densely wooded, and presumably well watered. The aerial avalanches of past eruptions must have piled quantities of incandescent debris on this divide and dried up normal waters to produce the Carib Indian name of "dry river." If a good contour map were made of the topography, some stream robbery from eruption to eruption might be traced in relation to the structure, and light thrown on normal springs of the older and newer volcanic peaks.

COMPARISON OF PELEE WITH KILAUEA

Steam Blast eruption Kilauea 1924

References to the Kilauea steam blasts of May 1924 are in the bibliography and are well known to geologists. The crater in that month lost about 250 times as much material as could be accounted for in visible ash. The time sequence indicated a submarine lava flow draining the crateral lava column, and so fracturing the well by collapse as to let in ground water under the choked funnel. The boiling of this started and maintained geyser eruptions of pure steam.

The eruptions selected for comparison with the Caribbee Islands, besides Hawaii, are steam blasts probably accompanied by mud flow in relatively wet places of springs, lakes, and fumaroles. Kilauea differs from these in that ground water is far below the surface, and so there was no hint of eruption of liquid water, making mud, as there certainly was at Pelée, and probably so at Rotomahana, Sakurajima, Katmai, Taal, and in many of the Netherlands Indies volcanoes.

Periodically volcanic edifices rupture and magma lowers. Volcanoes have radial rifts, ground water complications, and phreatic geyser eruptions, all of which conceal evidence. The mud flows are concealed by ash. The rifts are concealed by both. The geyser transition in time may be mistaken for normal magma-gas eruption.

Kilauea in 1924 exhibits measured major steam blast eruption that was accompanied by crateral collapse, lava subsidence, rift breakage, and pure steam from ground water different from previous magma-gas. But this volcano did not inaugurate these things for the first time. They were foreshadowed by the exceptional quality of the Vesuvius eruptions of 1872 and 1906 and followed by the explosions of Vesuvius in 1944. With many other volcanoes, they clinched the argument for a fundamental principle: namely, that phreatic eruption is in some way part of a structural rhythm of the interplay between magma and ground water, which recurs in most, if not all, volcanoes more or less periodically. The Morey and Goranson water reactions with magma may initiate all eruptions. The clue is pure steam smelled without asphyxiation by some observers. Perret was exposed in 1906 to a direct downblast from Vesuvius, and smelled nothing. Observers at Kilauea removed gas masks on the leeward edge of the pit during the steamblast period where in lava time they would have been partly suffocated with sulphurous gas; instead they smelled pure laundry steam. Finally in the Caribbee eruptions we have heard the evidence of scalded victims.

Recurrent lowering of intrusive lava is often unperceived and collapsing rifts are also unperceived; ground water inrush to incandescent cavities over surging lava is evidenced by geyser action and is apt to be misinterpreted as being wholly magmatic.

The following supplements previous writings about Kilauea in 1924, by exhibiting the nature of its mortal injury from steamblast, the sequences of history and a summary of the mechanism, in comparison with Pelée. Physiology and psychology of human reaction to volcanic eruption is a part of experimental geology, just as is the use of thermometers.

Physiological Effects

The steam blast eruption at Kilauea culminated in the explosions of Sunday morning, May 18, which caused the loss of one life. About 10:30 a.m., Truman

A. TAYLOR of Pahala, a young plantation man, approached the northeast rim of Halemaumau to take photographs. He had been warned 20 minutes before by the seismologist Mr. Finch, in charge of the observatory, that an explosion was imminent on the basis of geyser intervals. A terrific explosion took place, a dense colud of dust rose vertically out of the pit bringing with it thousands of red-hot blocks of lava and tons of smaller debris and dust (Figs. 9-10). Probably within 45 seconds these rocks were showering down in the vicinity of Taylor, who had reached a place southeast of Halemaumau about 1800 feet from the old rim. A boulder weighing about 80 pounds crushed both of his legs.

Some of his friends who were farther from the pit succeeded in reaching an automobile they had left nearby with the engine running. They waited a few moments for Taylor, but small rocks soon began to fall through the top of the car. One rock, weighing about a pound, was hurled through the body of the car. Miss Bradfield, one of the occupants, experienced a blow on the left shoulder while in the car. The blow paralyzed her arm for a short time. She thought she had been hit with a rock, and that the rock was hot was shown by the melted rubber of her raincoat on a serge coat below.

The following is the account of Taylor's recue by R. H. FINCH, volcanologist in charge:

"About 15 minutes after the explosion that began at 11:09 A.M. on May 18, 1924, the observatory party assembled where the road crosses the sand spit and found that Taylor was missing. We (Dranga and his father, W. O. Clark and myself) organized a searching party to cover the area southeast of Halemaumau. Taylor about 11:45 A.M., was located by his calling for help. The injuries noted were one foot missing, the other dangling, and burns on the back of the neck. A tourniquet was applied. An automobile seat from Dranga's car was brought to be used as a litter. Owing to its shortness it was augmented by a raincoat. While we were carrying him out another explosion (11:55 a.m.) started. Personal safety prompted us to put Taylor down behind the pillar that marked the end of the road and watch for rocks. When I apologized to Taylor for leaving him thus exposed he commented "At a time like this it is everybody for himself." When no more rocks were coming in our direction he was carried to the car which had been prevented from coming farther by large boulders in the road. Taylor died under amputation at Hilo Hospital later."

"I noted burns only on the back of his neck. He was found face down and covered with ash. Judging by his ability to call out and carry on conversation his lungs were not seriously injured. The Taylor case was discussed with Dr. John K. Cullen of the Kilauea Military Camp in 1941, and he was of the opinion that Taylor's burns were due to the accumulation of hot ash. Dr. Cullen stated that it was easily possible to receive third degree burns without the clothing being charred. The charring point of most cloth is about 375° to 400° F. His comment on a nurse's statement 'flesh peeled off to the bones,' was that the skin and some tissue came away and more clearly showed the outline of some bones. He ruled out the possibility of the burns being due to hot gas, stating that if the gas were hot enough to produce the burns observed his death would have been almost instantaneous from blocking of the lungs. The burns would also have been more general. Vegetation was scorched by some of the explosions beyond where Taylor was found."

The REV. MR. HAIL at Asama, Japan, was killed in the same way, by a barrage of stones.

KILAUEA STEAM BLAST SEQUENCES

The vital feature of the following is the sequence NE to SW or the reverse for the NE extension or the SW extension, from the crater, of the shore-to-shore rift that splits the mountain, location 87 (Fig. 8).

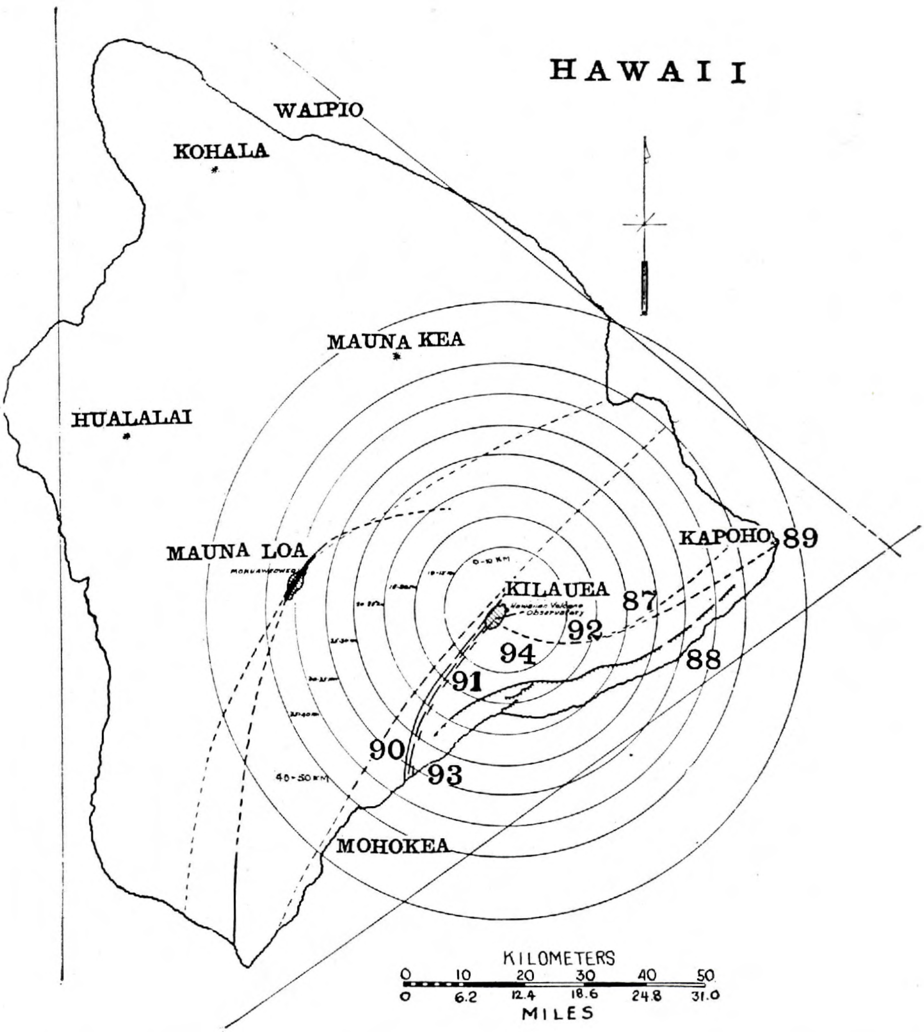


FIGURE 8. *Location map of Island of Hawaii.* Showing rift embayments, numbered locations. Kilauea and Mauna Loa rifts transverse to the WNW line of the Hawaiian Islands.

1790 produced a great engulfment, downblasts killing natives, a mixture of steamblast and lava, extension of steamblast to NE rift, recovery to 1823 leaving black Kilauea floor, birth of Halemaumau, and outflow graben sank 1823 SW on rift. Probably 1780-1790, there were Puna rift overflows NE, as historically reported (location 88).

1924 produced great engulfment, pure steamblasts after extensive overflow crateral and from SW rift, after extension of overflow also to NE rift (where there are ancient steamblast boulders of perhaps 1790); and after shoreline graben subsided NE, that inaugurated the crateral engulfment, although 30 miles away, (location 89).

The outflow location contemporaneous with engulfment is unknown in both 1790 and 1924, and in both is probably submarine: presumably 1790 SW, 1924 NE. 1790 made SW rift explosions near the sea (location 90), 1924 NE rift downbreak near the sea. In both, the agent was mostly steam from ground water. In both, killing men occurred by lateral barrage of stones and dust. In 1924 carefully studied, the phenomena were closely similar to Pelée (and Bandaisan), totally different from sulphur-carbon lava-gas ejection. In both Kilauea and Pelée the process utilized flank rifts extending under sea. In both it was demonstrated that crateral engulfment below ground water probably follows lava withdrawal. In both, lava returned to crater when explosion ended. In both the gases from lava fountains were totally different from the superheated steam of engulfment; the gases with pumice, making the solfataric rift gushing for Pelée, lava-lake fountains making the gushing for Kilauea, whereas the engulfment crisis produced explosion steam (nearly pure water).

Tabulated data of the two steamblast crises are as follows:

1780 to 1800 KILAUEA

On the rift across the mountain from shore to shore through the crater, the mountain was split from NE to SW; in the following sequence:

1. Crateral lava
2. Outflows NE
3. Crateral lava
4. Crateral collapse
5. Steam blast from crater
6. Steam blast with graben collapse from rift SW, location 90-93
7. Crateral lava recovery.

1914 to 1934 KILAUEA

On the rift across the mountain from shore to shore through the crater the mountain was split from SW to NE; in the following sequence:

1. Crateral lava
2. Outflows SW, location 91
3. Crateral lava
4. Outflows NE, location 92
5. Crateral lava
6. Crateral collapse
7. Graben collapse at shore NE, location 89
8. Steam blast from crater
9. Crateral lava recovery for ten years.

The only known sequent event after 1790 on the flank rift was 33 years later when there was a graben collapse with earthquakes and outflow to the sea SW (location 90-93). There is no record of Kilauea 1800 to 1820.

The next sequent event after 1924 on flank rift was 14 years later when graben earthquakes occurred on the flank NE (location 92-94). This may quite possibly lead, with 19 years more to outflows on the NE rift about 1957, which is a critical cyclical time for several studied analogies.

The 1790 recovery by uprising lava in the northeast then was from a preceding crisis over a century earlier that had ended NE, and 1790 began NE.

The 1924 recovery was from the 1790 crisis that had ended SW and 1924 began SW. Now the coming century is recovering, (the earthquake downfaulting of 1938, location 14) from the 1924 crisis that ended NE; and 1938 begins NE, as though the lava outflow vent of 1924 under the sea NE were backing up along the rift towards the crater to fill the rift faults, left as empty graben fissures by the 1924 submarine outflow, after crater and mountain had slumped (Wilson, 1935).

Critical features of volcano mechanism

The highly critical features of this typical mechanism for volcanoes, are:

(1) Intrusive magma on rift through volcano.
(2) Lowering magma in rift to admit ground water.
(3) Sharp distinction between lava-gas and steam explosion.
(4) Submarine or subterranean magma escape, essential to crateral collapse.
(5) Crateral collapse essential to crater plugging by debris.
(6) In a lava-flow volcano, rhythmic sequence alternates crateral lava and flank outflow.
(7) In an intrusive andesite volcano, this rhythmic sequence is limited to unmeasured and usually unobserved elevation events, tilting events, seismic events, and solfataric events.
(8) In a lava-flow volcano, the lava fountaining or effervescing openly, reveals hydrogen, carbon dioxide, nitrogen-group gases and sulphur oxides as reacting exothermically, with a small amount of water vapor as one of numerous oxidation products, but not remotely indicating any steam-boiler effects.
(9) In an intrusive andesite volcano, the magma effervescence is a complete mystery, working very slowly subterraneously as intrusion, making seismic, tectonic, and solfataric events that go unmeasured during long periods of fumarole simmering on a scale in the underworld enormously larger than the individual volcano or crater. The individual crater is one of many pin-pricks on fault rifts, in a volcanic system, and the system elects its vents across hundred-mile spaces along a thousand-mile dike swarm in the earth's crust which in geology is known as a "chain of volcanic islands," or "volcanic mountains." Its rhythmic sequences under tidal stress may be just as real as those of Kilauea, but they require a precision laboratory in the field.

In a lava-flow volcano the aberrant steam blast events depend on submarine or subterranean magma escape, crateral collapse, ground water inrush and plugging by collapse. The rhythm of a supercycle of steam blast is dependent on the rise and fall of magma in the whole volcano system, in relation to the water table. This rhythm in lava volcanoes like Vesuvius or Kilauea may be 33 years or 132 years, without being regular. There are, however, traces of rhythm, in basaltic lava eruptions.

Not so for the andesite, trachyte or soda-rhyolite types of volcano. The intrusive viscosities, temperatures, and gas reactions are unknown. Continental assimilation is present; measurement of ground motion and water table is needed, and rhythm may exist in larger time intervals and distances, hence the Krakataus, Bandaisans, and Katmais of history.

If we grant fundamental olivine basalt, however, and much contamination by assimilation, there may be intrusive fluidity, shore to shore rifting, definite lava-gas, submarine escape of magma, subterranean collapse making water reactions, and plugging of a ground water steam boiler, to act as precipitating cause for the St. Vincent-Martinique sequences along 100 miles of the Carib volcanic system.

Submarine outflow in deep water gives no sign. Submarine fault slipping breaks cables. The cables were broken in the Caribbees. Hydrogen sulphide and sulphurous acid were introductory features. Radial rifting was much discussed, with high temperature solfataras and migrating upblast along gulches down toward the mouths. The deposits mask the cracks just as at the famous "Valley" west of Katmai. There was enlargement of both Caribbee craters. Ground water floods, "pure" steam, rhythmic plugging, and release through months, a bursting boiler effect, curves of phreatic decline and magmatic increase, characterized two years.

With a century of intrusive stress of accumulation, and submarine or longitudinal rupture suddenly setting the date for crateral collapse, there is a parallel between the Pelée-Soufrière events and the steam blast events of Kilauea. At Tarawera, Katmai, and Bandaisan, there are distances from neighboring volcanoes such as those separating centers in the Caribbean. For Bandaisan and Nyamlagira being inland does not prevent their deep magmas from lowering suddenly. Sudden lowering is a first essential of Hawaiian magma, sudden lowering happened at Crater Lake. A stress opening voids is a fundamental fact of volcanism: it need not yield submarine outflowing, it may be terrestrial inflow to a deep tensional rupture.

Comparison of rift eruptions

It is of interest in comparison with Figures 19 and 20, to show some instructive photographs (Figs. 9 and 10) taken by Maehara about 11:00 a.m. May 18, 1924 from the high west cliff of Kilauea crater. These pictures were made with the camera recording that culminating blast of the explosive eruption of Halemaumau that killed Truman Taylor. The subject is Halemaumau, a collapsing pit, 2000 feet in diameter, about a mile from the camera, after 8 days of explosive action by means of geyser blasts of steam that had increased in intervals from 2 hours to 8 hours apart. Thus it was possible for Mr. Finch to warn Mr. Taylor that an explosion was due in the forenoon, and neglect of the warning cost Mr. Taylor his life.

The photograph shows upblasts from the wall crack, or peripheral contact between the fill of fallen debris and the wall of the oval pit. Nearly pure steam was coming up in boiler explosions. Its direction was controlled by whatever rifle barrels the contact of fill and wall created. As ordinarily the Halemaumau funnel slopes inward, (60° beneath the upper 200 feet of steeper wall) and the greater length of the ellipse is NE-SW, the two end walls being vertical, it was natural for the explosions to be guided under the talus to

FIGURE 9. *Halemaumau explosive eruption May 18, 1924, from west bluff of Kilauea crater.* By Maehara. Left-hand detail of an 8x10 inch photograph. Explosion of 11 a.m. when Truman Taylor was overwhelmed. (A) Cauliflowers. (C) Cascade and vortical billow. (E) Cleft in upjects made by obstacle below.

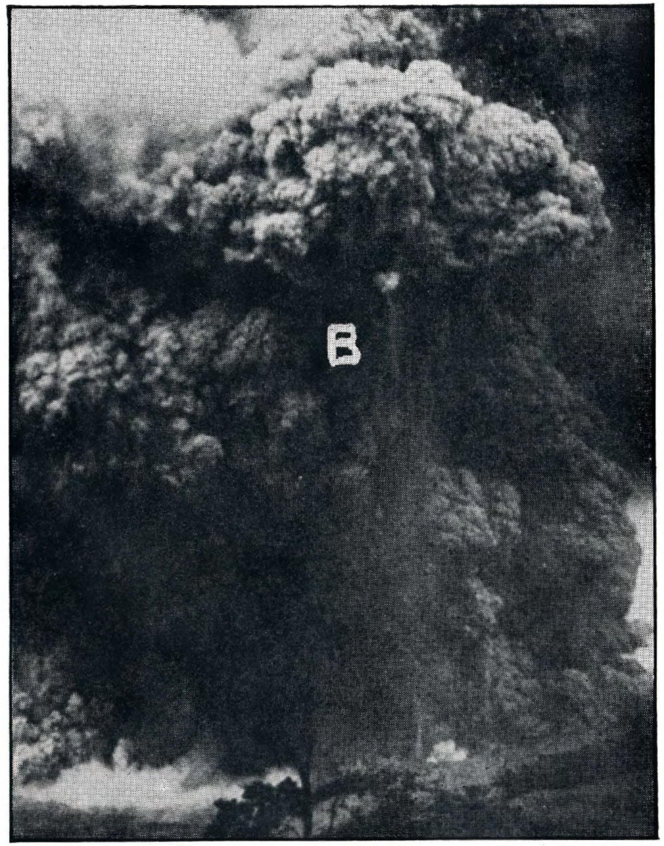


FIGURE 10. *Same negative, right-hand detail.* (B) Upblast and cauliflower head emerging from north bay of Halemaumau, showing white dust from boulder falls. Kilauea May 18, 1924, by Maehara.

FIGURE 12. *"Ship's prow" stage of opening Pelée rift December 16, 1902* (after Lacroix). With mud-rush in front, forward-springing jets, migratory column not yet at sea-front. Elephant trunk upblast and compression cushions comparable to Halemaumau, Figure 11, vertical striations and clefts, always greater hardness of cauliflowers at front as the rift split open and vomited mud, steam and glow-clouds, the rate of migration being the rate of temporary heaving open from crater to shore.

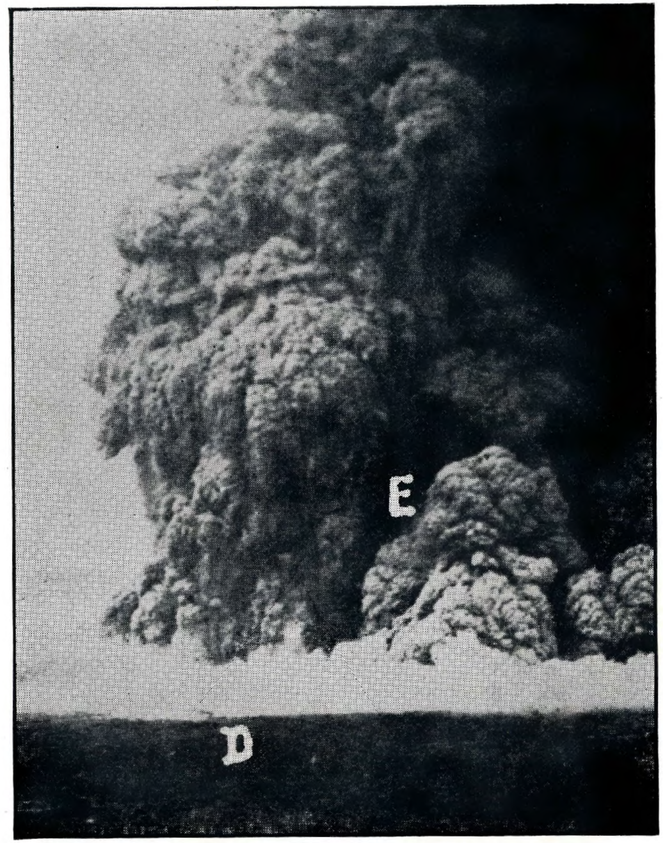


FIGURE 11. *Halemaumau explosive eruption May 18, 1924, by Maehara.* Left-hand detail of a second negative of an explosion a few minutes after that of Figure 9, showing now whitened dusty surfaces from earlier ashfall steaming. Vertical striation of column, cleft (E) as in Figure 9 at same place, and "elephant trunk" upblast (D) at site of cascade (C) of Figure 9. The vertical striations and clefts reflect obstructing vent protuberances of hard rock. These are plainly seen in the Sakurajima and Pelée photographs.

barrages northwestward and southeastward for the larger blocks. Mr. Taylor was under the southeastward barrage.

The photographs are taken looking somewhat east of south so that the northwestern barrages would be at the right of the picture, and a portion of the eastward barrages show on the left side of the picture of Figure 9. At A there is a remarkable cluster of sprouting cauliflower of even texture crowded against the vertical north wall. At B in Figure 10 there is a superbly symmetrical upblast with its single cushion or cauliflower head. At C there is a fine example of outward barrages in a series of cascades of big boulders pounding down away from the lip of the pit; this cascade rolls up a vortical pillow at its front, that is spreading out over the ground in an enlarging semicircle.

Figure 11 is a second picture taken a few minutes later, showing a new upblast D at the site of the previous cascade and instructive in exhibiting the vertical striation of column, the cauliflower head, and the compression cushions of successive cauliflowers above. All around the base is the whitened dusty surface that had been occupied by the overlapping cascades of falling materials of Figure 9. A subject of peculiar interest in both Figures 9 and 11 is the chasm of black void E to the right of the cascades and of the later upblast, clearly representing a division between two rifle barrels created by some resistant inner buttress separating two steam jets up the inner wall.

Comparing upblast B and D (Figs. 10 and 11) and the overlapping cushions above D with the streaming vertical lines and compression cushions of Sakurajima and Pelée, Figures 20 and 19, it will be seen that the detail of uprush, and scale of the cauliflowers, is larger in the Sakurajima-Pelée pictures than in those of Kilauea. The Kilauea camera is much closer to the subject by 2 or 3 miles.

Another picture taken by Lacroix in the River Blanche on December 16 (Fig. 12) before the jets had migrated all the way to the sea, is extraordinarily like Figure 11, D of Kilauea. Here is a higher locality in the process of the splitting open of the River Blanche rift, the jets strictly vertical back of the front, the front like the prow of a ship as the rift opens, and the compression cushions of cauliflower still relatively small as in the Kilauea picture. The prow is the forward-springing jet, where the narrow crack is in process of extending. Again the hard outlines and size of expansion are in ratio, according to the distance of migration along the bottom of the valley from the crater, the jets from the crater being soft and steamy, those from the expended Lénard crater being large and hard at the top, soft and columnar at the bottom, while those at the lower end of the migration are in small hard columns and a small hard pile of cauliflower heads. (See Lacroix, 1904, Pl. IX).

This picture exhibits the path of the opening crack, for the subsequent jets represented by Figure 19 followed the far side of the V-shaped flood plain, and it is evident that the crack followed the right bank of that triangular plain to the sea. The identity in character between the Kilauea upblast (Fig. 11) unquestionably rising from a pit, and that of Pelée (Fig. 12) supposedly rising

FIGURE 14. *Rift belt cumulus of Perret.* First stage of two photographs of Pelée January 7, 1930 from Parnasse, Location 17, almost same line of direction as Figure 13, jets up from bottom of River Blanche, harder cauliflowers at the front, backward springing jets under crater, time four minutes after first emission. His second picture developed left-hand cauliflower wtih compression cushions and torus below, and upward expansion to 13,000 feet elevation in a few seconds, greatly exceeding height of soft anvil-cloud over crater.

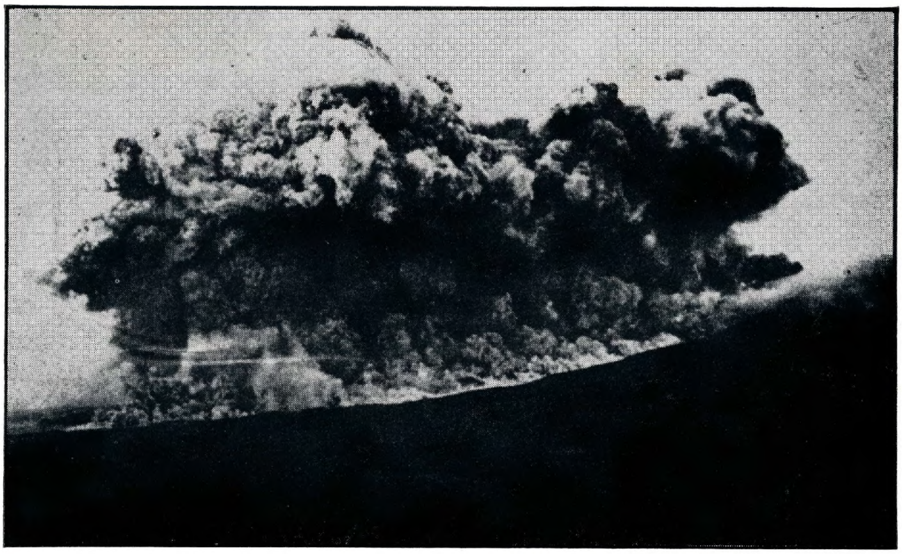


FIGURE 13. *Rift belt cumulus of Locroix.* Tenth stage of twelve photographs of Pelée January 25, 1903 from Observatory, Figure 3, Morne des Cadets, successive jets down River Blanche valley from lava dome and spine to the sea, higher columns at the front, lower columns at the crater, height about 7600 feet, spine summit black above white cloud at extreme right.

from a torrential emulsion, carries its own evidence that requires for Pelée a pit or crack.

The final argument for a line of blasts up a crack the length of the River Blanche valley from crater to Morne Lénard appears by a comparison of Perret's nearer photograph (Fig. 14) from Parnasse January 7, 1930, and Lacroix's photograph (Fig. 13) from his observatory at Morne des Cadets, on January 25, 1903, almost in the same line of sight. In both cases the eruptions started at the lava dome; Perret's photograph is 4 minutes after the eruptive start; in the serial pictures, not here reproduced, both cameras make the maximum development above the Morne Lénard crater, with superb cushioned upblasts above that region. The greatest height of hard cauliflowers eventually stood above that intermediate vent. In both pictures the entire line of columnar upblasts show columns nearly vertical over the Lénard locality and fanning right and left from that locality, with an ending at the crater. In Perret's pictures there is vast upward shooting of backward springing jets towards the crater.

Again the harder cauliflowers are towards the left and softening ones towards the right, and the linear overhang of the long series of cauliflower heads above migratory upblasts from the valley exhibit a valley crack.

Speeds of translation bear no relation to anything that an avalanche could do on that flat slope (see profile Fig. 16) and the appearance of the migration in the serial pictures of the monographs, indicates a series of vortical heads with source jets at right angles to the ground, according as the ground profile is steep on the upper mountain or flat in the lower valley. When we find the blast fanning from that vast depression above Morne Lénard ("Russell's crater," 1902), which in the photographs resembles a chasm in River Claire (just as does the Falaise gorge), and appeared to be a similar chasm in River Blanche 1902-1903, (before the filling up of later dates), it is incredible in these "gluhwolken" that anything resembling a cannon shot down the valley, from the dome as a gun barrel, can have occurred. Nothing but a cannon shot could achieve the recorded speeds, except the progressive opening of a crack.

In Figure 15 a Mauna Loa rift is shown vomiting up true basaltic lava flows. The openings of 1919 and 1926 are indicated. The rift belt 2 miles wide buries itself under its pumices, lavas, and solfataras. Ash is absent. This picture was taken on April 18, 1926 at 7:20 a.m. by a photographer of the 11th Photo Section U.S.A.C. from an airplane over the Puu o Keokeo section of the southwest rift while in eruption. The lower flow along the rift cascades down a pit on the crack itself as the mountain swells open. This is a common occurrence on Kilauea and Mauna Loa rifts, and the observers have watched the cracks open, yielding first white vapor, then lava. They open from the crater region seaward. Such heaving open, over lava, is seismically quiet after the rift is once opened, and migration of outflow proceeds downhill during hours, days and weeks. (See Volcano Letter 476, April-June 1942, for backward springing lava fountains, page 6, on Mauna Loa rift spurting centripetally towards summit crater, just as in Perret's upblasts on Mount Pelée).

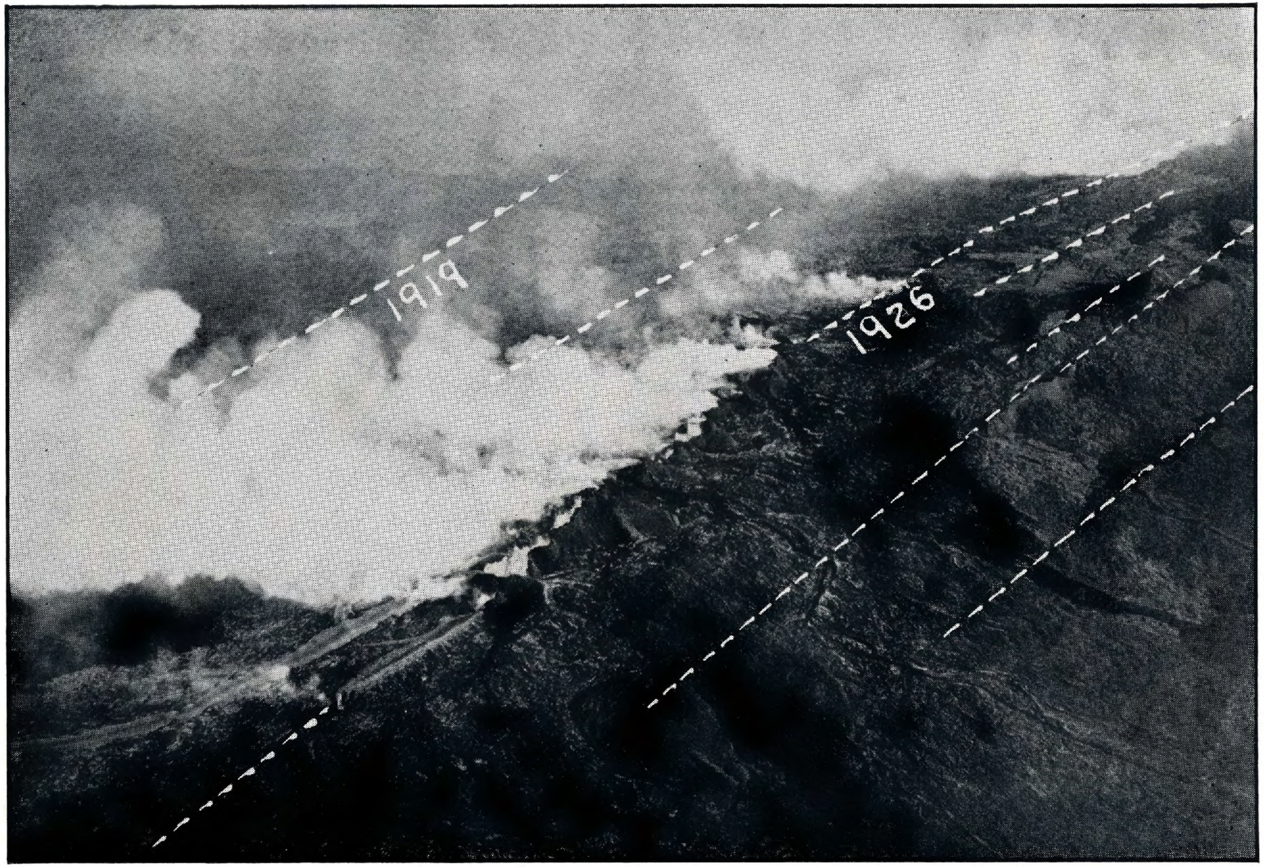


FIGURE 15. *Mauna Loa southwest rift, Hawaii 1926.* Photograph from airplane, U. S. Air Service 11th Photo Section by permission. April 18, 1926. Looking northwest shows basaltic lava flowing along rift and cascading into rift wells. Line of basaltic pumice cones 50 to 75 feet high. Old rift cones of 1919 in background: of unrecorded date in foreground. Rift belt two miles wide with convergence of cracks toward summit crater outside of picture at the right.

The mechanism of such a rift in a steeper cone, with a lava dome near the peak, and deep water admixture dominant as out-blast maker, can be imagined. Each pulsation of geyser pressure opens the active fissure to the outrush of water, fragments, and steam. The resistance to opening is least near the top of the crateral notch. The sectoral weight closing fissures is at a maximum wherever mountain and ocean (for a volcano extends far under sea) present the most resistant section to expansion components of boiling water in an underground chamber of purely hypothetical shape. This again is dependent on the hypothetical shape of the deep magma dike. Effervescence of magma heating the water is in turn dependent on the pressure release that the expansion lift accomplishes. Size of chamber and consequent volume of restored cold water are dependent on evacuation of solid matter at each pulsation of what is called "eruption." Finally erupted matter filling valleys and deltas weighs down on land and sea bottom, with new internal magma compensating whatever is lost by transport to a distance. This and the new lava structure make the mountain heavier and bulkier than before, just as does the Mauna Loa outflow of basalt: and the enlarged water chamber probably contains an added weight of slowly intruded magma. The eruptive pulsations are short as at Tarawera or Sakurajima, more prolonged as at Pelée or Krakatau, in accordance with the speed with which the deep magma fills spaces and congeals to seal off water.

A difference between Sakurajima and Pelée, conspicuous in the history of the two eruptions, 1914 and 1902, is that Sakurajima lava poured immediately from the flank rift low down: Pelée lava immediately, but more slowly, piled up in the crater at the upper end of the rift, beginning as a heap of lava bombs that fell back from upjets. The upjets of steam from Sakurajima were on the uprift side of the outflow. The upjets of water and steam from Pelée were on the downrift side of the piled outflow.

The diagram of this is expressed by two true-scale sections in the rift plane showing the apparent structures. Figure 16, Pelée with its spine-bearing dome (D), its water (W), and its steam (S): Figure 17, Sakurajima with its lava flows (L) and its steam (S). (Compare Soufrière, Figure 18, where the magma status was invisible, and the jets are steam up the wall crack, and backfall strikes the slopes.)

The eccentric craters of escaping magma are conspicuous in both volcanoes. There were eccentric vents of steam eruption in Soufrière. The cause of deflection to the side of the center is resistance and weight of old central dikes. This dike was Morne La Croix (M) at Pelée, and it was the summit crater plug at Sakurajima. The wedge fracture in the plane of the rift section achieves a maximum opening halfway down the mountain. One half of the section is eruptive at Pelée, with a stiffer andesite that finds the path of least resistance by splitting along the River Blanche on one side of the summit only. Santa Maria (Sapper 1927) in Guatemala has done the same thing. The split achieves, in Pelée, the maximum opening at Etang Sec, where D now is, just below the top of the mountain: the top is cemented by the old plug Morne La Croix, M.

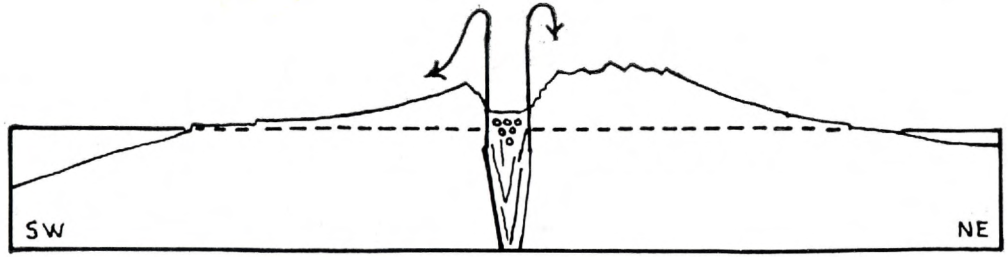


FIGURE 18. *Profile of Soufrière, St. Vincent, May 31, 1902 from Wallibu to Sandy Bay.* Survey by Jaggar Volcano Letter 359. Drawn to true proportions from chart. Shows engulfing crater fill, wall-crack explosions, backfall from cushioning, notable eccentric position of crater on a rift away from central heaping of mountain. Elevated benches, which on the east are 60 and 200 feet above sea-level. Ocean depths 530 fathoms normal to shore west whither the section is bent, 125 fathoms east. This is steeper than Pelée Figure 16. Crater bottom 2550 feet below summit, 1660 feet below rim, 1285 feet above sea-level. Diameter crater rim 4870 feet.

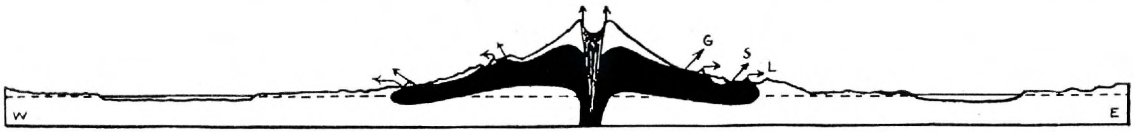


FIGURE 17. *Profile of Sakurajima from Hakamagoshi to Seto along rift of 1914.* Drawn to true proportions from chart on line N 66° E. Arrows when inclined are cauliflower gas ejection, horizontal ones are lava flows. Obstructing crater fill shown, magma forced off bilaterally Seto strait east, Kagoshima strait west. (S) steam. (L) lava flow.

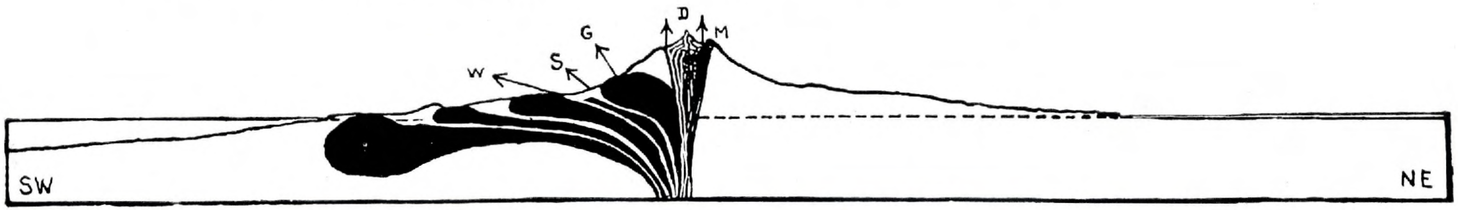


FIGURE 16. *Profile of Pelée along rift of 1902 and 1929 from River Blanche to Basse-Pointe.* Drawn to true proportions from contour chart. Subsidiary cone is Morne St. Martin below east fork of River Blanche. Morne Lénard is under the arrow marked (W). Crater section shows obstructing old andesite fill with wall-crack explosions and new dome. Rift opening of the eruption is on SW radius only in the plane of the paper. Knife-blade wedges of magma force the geyser explosions to flat angles of trajectory. (M) Morne La Croix. (D) dome. (G) gas. (S) steam. (W) water. Shows steeper submarine slope on the west 300 fathoms, compared with 30 fathoms on the east. Compare bilateral symmetry of Sakurajima Figure 17.

The tapering crack below is the River Blanche line of ancient solfataras. The section explains itself: the magma dike in the plane of the section bends outward underground, somewhat as the later spine curved outward above ground. This outward bend directs a sub-horizontal blast of steam and water rising along the dike expansions of the lava column. Mostly the 40-degree gash is easier to open (nuées ardentes), for emission of water and steam. Extreme paroxysms opened the lower gash against gravity, and sent out the downblasts. The lower gashes on opposite sides of the mountain vented the lava at Sakurajima, while steam usually emerged higher up the slopes. The rounded balloon-like extensions of magma are dike intrusions in the rift plane of the paper. (Figs. 16, 17).

This is merely a conceptual structure, drawn from comparison of these two volcanoes. It illustrates underground dip of rifle barrels. Figures 29 to 32 in the River Blanche, and photographs in Figures 34 to 36 show how various the dips may be at different times and angles of view, even within a few minutes, as the mountain blocks readjust themselves. In Figures 16 and 17 the letter G over an arrow, for volcanic gas, might have been written over any of the extrusive openings as applicable to nuées ardentes, but gas admixture is here taken for granted.

The glassy froth called pumice in dacitic and andesitic volcanoes is the equivalent of the vesiculated glassy fountains in basaltic volcanoes. Mauna Loa and Kilauea in their magmatic eruptions build cones and cups of basaltic pumice, the "thread-lace scoria" of Dana. Moreover the pahoehoe lava flows of the top region of Mauna Loa are commonly pumiceous all over their glistening sherry-colored surfaces, showing that floods of excessively gas-charged magma have poured forth. If the gas in viscous dacite of Mount Pelée discharges the magma up the cracks more violently that it does in the fluent Hawaiian foams, the "nuées ardentes" may result. Siliceous pumice was an abundant product in Katmai, Krakatau, Pelée, and Sakurajima in the form of ejected boulders, often making floating fields on the sea.

COMPARISON OF PELEE WITH SAKURAJIMA AND KATMAI

Pelee and Sakurajima

Figure 20 shows the two columns of Sakurajima (the eastern one beyond the mountain top) as seen from Kagoshima at 10:40 a.m. January 12, 1914, less than an hour after the outbreak, with a suggestion of pure white steam rising from the summit crater, and an immensely powerful upblast, with steaming jets all around the base, rising from the slope of farm land back of Hakamagoshi. It is not possible to distinguish any vents. The cushioning effect of successive billows over the upblast is clearly seen, also the expansion in size of each billow as it rises higher, and the succession of steam cushions from the central vent imprisoned under the arch of the western eruption. On the right side near the base may be seen the trajectories of boulders. In view of the exploration of this ground by numerous careful observers immediately after the explosion,

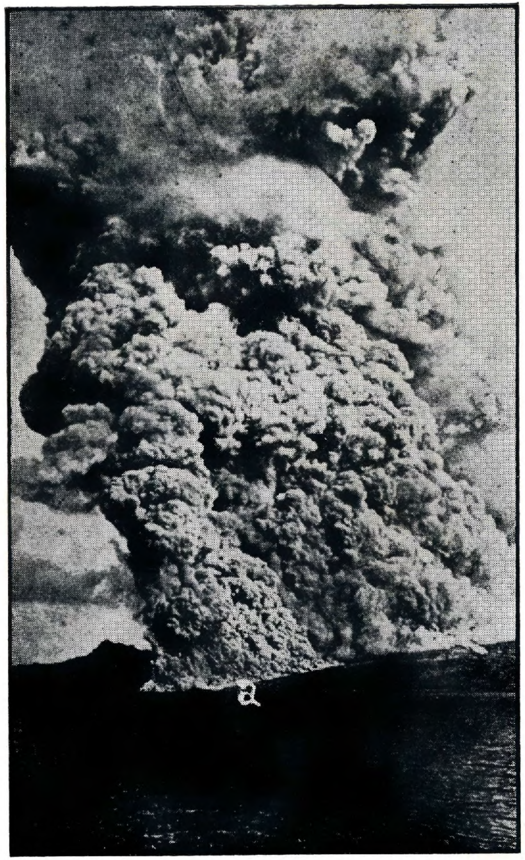


FIGURE 19. *Migratory cauliflower explosions down River Blanche rift on Pelée December 16, 1902 (after Lacroix).* At moment of reaching the sea. Three distinct lateral pediments possibly mud-gush. Compression cushions. Softening clouds craterwards. Resembles Figure 20 as equally a flank eruption through debris covering a rift. Point (a) appears to be final opening of migratory splitting of mountain.

FIGURE 20. *Sakurajima outbreak 10:40 a.m. January 12, 1914 as seen from Kagoshima (after Koto).* Shows summit steam, distant cauliflowers on east flank, west flank cauliflowers in foreground, compression cushions and boulder trajectories. Transverse rift erupting, explosions from opposite radial fractures that became lava sources next day.

it is clear that the holes through which these explosions came in a radial line left no great engulfment pit and represented a relatively small radial crack in the mountain (for small pits see Perret, 1914, table XXXXVIII.)

The famous picture by Lacroix (Fig. 19) of the migratory cloud of December 16, 1902, at River Blanche on Mount Pelée, at the moment that it reached the sea on the delta of the combined rivers is also shown. The current accepted explanation of this cloud with its upjetting blast, compression cushions, and extension pedestal right and left, like the fissure-made Sakurajima upjet, is that it is superficially downrushing along the slope of the valley from the soft white billows on the right, that it can carry 50-ton boulders horizontally by gas expansions, that it contains no liquid water (see the tongue of overflow on the land), and that the cauliflower hardness of outline on the delta at the left, where there are no collision obstructions, is occasioned by an emulsion ball of explosive gas-charged lava, generated by the lava dome 3 miles up the valley, the cauliflowers growing progressively more energetic rolling from the dome to the sea.

By this wrong explanation nothing is coming up through the ground at the point a in Figure 19, where there is a sharp upblast with five expanding cushions vertically above; and nothing through a crack in the ground in the valley above. The migration of the hard cauliflowers from crater notch to sea was at the rate of three-fourths of a mile per minute. Such explanation is now replaced by migratory upjets along a fissure.

The blasts stopped at the sea, for no apparent reason, and did not steam up the sea water. Some stopped at a point two-thirds of the way to the sea, the junction of Rivers Claire and Blanche, the location of many and deep fumaroles adjacent to Morne Lénard. By Lacroix's statement, there were two topographic units that arrested the nuées ardentes, which would correspond to an upper crack from crater notch down River Blanche, and an echelon crack, offset to the northwest from the other, from Morne Lénard down River Claire valley (under the combined deltas) to the ocean, and under the ocean. Ocean water is a condenser, and was a quencher for rising rift froth and steam.

Some blasts of the paroxysmal type shot over the ocean, and some may have had such exceptional power that they opened the submarine rift and exploded through sea water.

We have on the Pelée slope the following sensible evidence by the experience of numerous persons landing there, photographing, collecting gases, noting dates, hours and speeds, listing cycles of ejection and collecting specimens; others made notes from a distance. Others were wounded and died, but left valuable record as result of the experiment of dwelling near the mountain throughout a cataclysmal crisis.

This evidence is:

(1) A crater pool in a valley amphitheatre became steamily explosive around its edges.
(2) This increased to fragment-flinging and distributing ash.

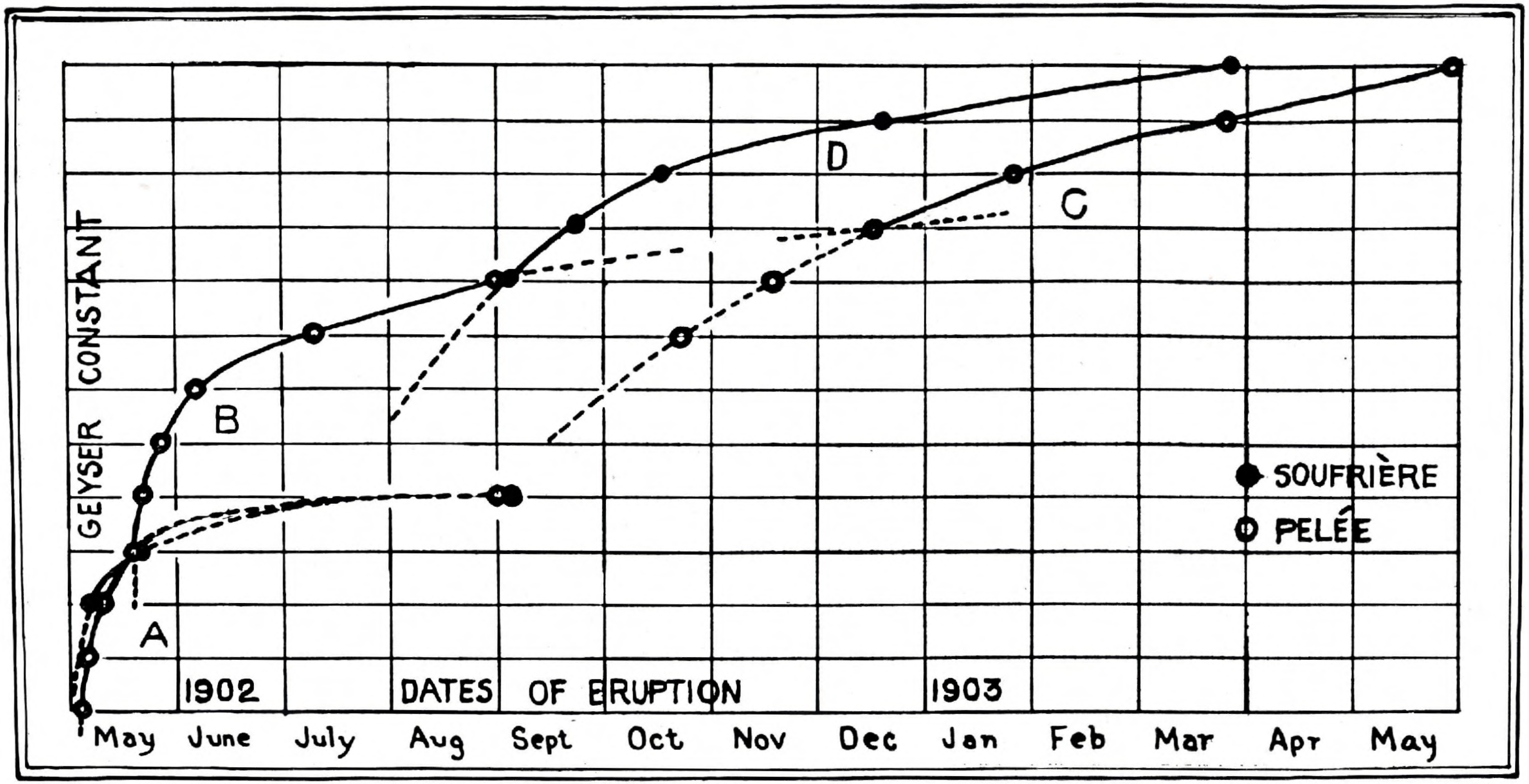


FIGURE 21. *Curves of Carib sequence 1902-1903.* (A) Major paroxysms Pelée and Soufrière. (B) Paroxysms of Pelée after May 17. (C) Nuées ardentes of Pelée. (D) Minor eruptions of Soufrière. The "constant" on the ordinate is heat supply.

(3) This extended down the valley through the valley springs as a rapid hot volcanic mud flood, after the shallow crater lake had been destroyed days before. The crater exploded dry, and the Lénard crater distorted the flood. Speed is explained by migratory opening of crack under tension.

(4) This crack under tension suddenly yielded excessively to water boiling in a clogged geyser chamber over magma. This chamber had received the same release of ground water as (3), but deflected downward, and the water was heated to sudden boiling emission at the St. Pierre destruction.

(5) The same evening incandescent magma explosion products showered on the surface of liquid mud, both rising through the Pelée-Lénard rifts, making forking fiery streams along the opening rifts from crater to sea, the first observation of "nuées ardentes."

(6) For a year there followed a succession of geyser cycles of water and steam represented by curves which, considered as a single curve (see Fig. 38), has inflections for Pelée breaking it into (Fig. 21):
   (A) Parabolic sequence boiler paroxysms May to September.
   (B) Parabolic sequence increasingly magmatic May 17 to December 16.
   (C) Parabolic sequence to the close of eruptions October 1902, into 1904.

The constant interval on the ordinate stands for "other things being equal," chiefly water pressure and magmatic heat supply. The increasing intervals stand for an increasingly bulky geyser chamber filled with cold water.

The December 16 photograph of Figure 19 compared with Sakurajima, appears to exhibit analogy. There was no question but that the Sakurajima upblasts came up through crevices in the solid crust of the earth. As Pelée had to reckon with rift, ground water, and magma, there is no question but that the upblast at the mouth of the River Blanche came up through crevices in the solid crust of the earth. (Fig. 16.)

The scars, as bouldery ridges, were found after these migratory upblasts from crater to sea by Lacroix and Perret, mud flood came up the scars tapering craterward as photographed by Lacroix and mud flood was observed by Perret rushing down from the crater itself at a time when the magma dome was collapsing.

Pelee and Katmai

The "high sand level" (of Fenner at Katmai in 1923) as seen by all observers in the palpitating hot sand emulsion of the sides of the combined southwest valleys of Pelée, makes the accumulations of the River Blanche a parallel to the Valley of Ten Thousand Smokes, and both deep and shallow fumaroles were identified afterwards in both places. In both cases the ejections were up through cracks now mostly buried under the deposit, and there was in each a subsidiary crater of complex cracking, namely Novarupta and Lénard: the differences lay in the extent to which ground water participated, in the relative steepness, in the placing of the cumulo dome, and in the characteristic gases. (See Theoretical Conclusions for the accent on fluorine in Pelée rocks and Katmai fumaroles).

The main Katmai crater in its engulfment was more like Soufrière; the Alaskan "Valley" had its "Novarupta" dome where the Lénard vent ought to be. If Pelée had had its new dome at Lénard, and the big St. Vincent engulfment at Etang Sec instead of 100 miles away, it would be more like Katmai. Katmai was a plexus of big cones as was the Carib chain.

Participation by water and mud is essential for the utilization of ground water physically in processes of so-called "mixed eruption." There is nothing remarkable, if mud came first, and hot gas with incandescent ash followed, and as final product came soft, hot, dry incandescent quicksand. Steam can appear red hot.

The function of a temporary black mud volcanic geyser like Soufrière, Waimangu (Grange 1937) or Anak Krakatau (Stehn 1929) is to clear a way for oncoming dry steam and then self-exploding pumice, not to mention internal avalanche matter of rock wall gravel and boulders. These things are all coming up from craters on rift systems, not flowing down as an avalanche across country from a central crater. It is possible to envisage a mechanism, like a geyser basin on a deeper scale, where normal hot springs feeding a river give place to dry explosion, and then return to vigorous mud-making flow after the explosion is over. Geysers begin with water and end with super-heated steam. An ending with glowing dust at these volcanoes destroys all trace of preliminary water within each eruptive episode.

Pelée, Sakurajima and Katmai "Smokes" have revealed that radial rifts as eruption centers conceal themselves with their own ejecta. Soufrière, Katmai Mountain and Taal evacuate their crater cauldrons by subsiding magma and geyser eruption. Kilauea radial rift exhibits magma subsiding from its caldera, and the cauldron following with geyser eruption. Etna, Mauna Loa and Kilauea radial rifts show magma concealing its aligned vents with outflows. Pelée peak, Santa Maria flank and Tarumai show magma concealing its crater with heaped up andesite. Pelée, Soufrière and Montserrat have deep radial erosion trenches disguising radial rifts, and eroding heaped up andesite. Tarawera was an ancient Katmai in a geyser land, Krakatau an ancient Soufrière engulfed in sea water, and there restoring itself by heaping up andesite in Anak Krakatau; Bandaisan was an inland Santa Maria which disrupted its flank and may yet renew action, and Tomboro was a shoreline Krakatau waiting like Soufrière before revealing its intrusive plug.

COMPARISON OF PELEE WITH TOMBORO

Sumbawa Island 1815

The eruption of April 1815 on Sumbawa Island had all the character of a steam blast of first magnitude producing black darkness, whirlwinds, floating pumice, rise of sea level, subsidence of the land, and inrush rather than outrush of a tidal wave, which accompanied the phenomena of land subsidence. It culminated in November. There was engulfment of the crateral area; 4000 feet of loss of summit elevation was reported. The fiery streams of incandescent blocks and ash, misnamed "lava," flowed down gulches and mountain slopes. Unidentified water and mud crusted with incandescent fallen matter gave the character of liquid flow to these deposits. There were no lava flows. Many glowing downfalls elsewhere are now known, where showers of crateral material pepper the surface of erupted mud, as at Mount Pelée.

There is the same reason in the structure of Tomboro to suspect vesiculate pumiceous tumefaction rupturing the mountain radially as in the Caribbean volcanoes. This is an elevation mechanism. There was reaction with underground water to generate steam pressure ejecting mud, and as Tomboro is a peninsula mostly surrounded by sea water in a region of abundant rainfall and porous rocks, the Ghyben-Herzberg deep lens exists under the water table.

Stehn (1929) has shown that the principal happening at Krakatau in 1883 was a large engulfment. The same thing occurred in the 1924 and 1790 eruptions of Kilauea. Williams (1942) has shown collapse for Crater Lake. The great calderas are engulfments, and the internal lowering of magma to flow out or enter a sub-caldera void is an ordinary process of magmatic adjustment amid the tensional crackings of ignisepta.

The computations of large bulks in cubic miles of supposed ejecta, are wrong. They were computed from supposed continuity of discharge or from the cubical bulk of enlarged crateral space. Obviously this crateral space was evacuated mostly by matter dropped inside the earth, and paroxysms are not continuous. The measurement that led to these large figures was not based on thickness of residual ash, for most of that was immeasurable and in the ocean. The computation Finch in Hawaii 1924 showed the ratio of ejecta to inclusa to be 1 to 250 for the explosions of Kilauea in May.

The Tomboro ejecta were in moderate volume, as also those of the Caribbees, Krakatau and Katmai. In these places Heilprin, Verbeek, Judd, and Griggs have made excessive estimates of volume ejected as did Verbeek and Junghuhn for Tomboro. All such estimates become more reliable if they are called "volume engulfed."

Explosive Fragmentation

The discussions of Heilprin, Lacroix, Perret, and others on whether magma explodes so as to keep particles apart, and make them angular or rounded by mutual attrition so as to flow as emulsions, appear unnecessary.

The first thing that happens is internal downbreak and avalanching of old wells. The second is the mixture of this with rising and heating water. The third is pumiceous foaming internally of intensely gassy and liquid magma. The fourth is the utilization of this magmatic furnace to boil and expel a mud geyser. The fifth is the expulsion of mixed gas, steam, pumice, avalanche fragments, and underground engulfed material. This keeps on, with recurrence of mud ejection, and in basaltic volcanoes may become mingled with burning gas and lava fountaining. In andesitic ones stiffening of magma by gas release makes it tend to plug orifices. Mud ejection followed by excessive heat will solidify as ash.

The visible products are "vulcanian" clouds making a large spectacle from small cracks. Pumiceous expansion of bombs after they reach the air doubtless takes place, and accounts for "horsetail jets" from the sides of vertical ash blasts (see Sakurajima blast near the base, Figure 20). The products are mixed, but the gas lift does not handle 50-ton boulders. These are avalanche blocks, and for far transport they depend on mudflow. Eight and 10-ton blocks may be hurled several thousand feet. The principal grinding mechanism to produce fragmentation is engulfment avalanching, mostly unseen. As the fault-block adjustments go on internally for a long time, this crushing machine extends in depth indefinitely, and supplies much heterogeneous material.

WORLDWIDE STEAM BLAST ERUPTIONS

Caribbee Islands

The paroxysmal eruptions of Pelée in Martinique and Soufrière in St. Vincent 1902 have been reviewed in relation to the actual experiences of victims and observers. The succession of eruptions has been plotted as a curve, indicating a rhythmic increase of interval along with decrease of steam energy and increase of magma plugging.

Next the principles of structural volcanology developed at the Hawaiian Volcano Observatory have been compared with the Antilles. These principles involve sharp contrast between a magmatic furnace of reacting gases, and the steam of phreatic eruption. Confined and basal ground water, directly held up by salt water, are realities surrounding rising magma. Every volcano has rifts leading from a greater linear system. Crateral magma sinks as well as rises. In its lowered condition it is intrusive magma.

Magmatic gas, rift system, phreatic explosion, intrusive magma and lava lowering have been suggested for Pelée, and the conception of the linear igniseptum and the radial rift is found applicable to the Caribbee chain and the River Blanche.

Lowering of magma disrupts rifts and the opening of voids generates ground water explosion and release of magmatic pressure. The result in the Antilles was intense water-mud eruptions that were profoundly volcanic. The result of paroxysmal steam rupture of radial rifts in Pelée was a series of upright, inclined, and downward blasts, complicated with mud eruptions that opened flank rifts just as Hawaiian lava opens flank rifts.

Soufrière in St. Vincent was connected along the igniseptum with Pelée. The greater Soufrière paroxysm came on the day preceding the St. Pierre disaster, and both volcanoes together followed a sympathetic schedule that has been plotted as curves to the end of 1902. The under-earth was ruptured along a deep rift belt for 100 miles and made conflict between released magmatic heat and underground water. The two craters were extended into invisible radial ruptures which were buried under debris in gulches. These valleys are called by Friendlaender (1916) "verwerfungs thaler," or fault valleys.

Avalanching from the air with backfall on the mountain was more in evidence at Soufrière than in Pelée, except for the August 30 eruption of the latter.

There is evidence of fault sectors from the Soufrière crater outward to the western shore and possibly southward to the valley of the Rabaka, as in Pelée.

There were floods of the Rabaka just before the major paroxysm, not due to ejection of the crater lake.

Kilauea

The Kilauea steam blast eruption of 1924 killed a man by impact of falling rocks and the shock of scalding burns. A review of the Kilauea steam blasts of 1790 and 1924 indicates that the earlier eruption had steam mixed with magma, whereas the latter was almost pure steam. In both, killing of men occurred by lateral barrage of stones and scalding-hot dust. In both, crateral engulfment followed withdrawal of lava, and lava returned when explosion ended.

The prelude to the 1924 eruption was a sequence of outflows (1) from high levels on Mauna Loa, (2) to emission at crateral level in Kilauea, (3) then from southwest Kilauea flank vents at high levels, (4) from northeast flank rift vents at lower levels, (5) finally down-faulting of rift blocks at sea level. Combined summit crateral collapse and vertical steam blasts followed, as the magma of the pit lowered below the water table, and flowed out under the ocean.

There is evidence of 11-year, 33-year, 66-year and 132-year cycles in the upwelling and downsinking of magma under the island of Hawaii through 200 years of human record. This shows geometrical symmetry with reference to the volcanoes involved. There is a sharp distinction between lava-gas risings and fallings, and the rare steam explosion phenomena more than a century apart.

The latter appear to be the integrated results of a number of the smaller cycles, whereby the magma is above the water-table level most of the time, but during about 66 years appears to be executing a major lift in the crevices of the volcanic system, followed in a similar period by a major depression below ground water level, causing an explosive crisis. It is possible that gradation of water contact controls all sudden eruptions, including lava gushings.

The total interval of 132 years between major steam-blast events appears to have been noticed in Italy and Japan as well as in Hawaii and possibly applies to magmatic stresses that produce tilting, elevation and earthquake, as well as to those that produce eruption. The cycles in Hawaii have been reviewed by Brown, Jaggar, Emerson, Finch and Wood, with reference to tidal controls. (Jaggar bibliography 1947).

Measurable alternations of visible rising and falling basalt in Hawaii make rhythmic sequences. These in the volcanoes of viscous dacite magma would be measurable only as changing events of elevation of the ground, tilt, small seisms, and solfataric temperatures and chemistry. The rhythmic sequences in the Antilles may be just as real as in Hawaii, but they require a field laboratory of high precision, and continuous experimental studies of geophysical and oceanologic change.

Tarawera

Tarawera volcano and Rotomahana Lake in 1886 developed a sudden eruption along 9 miles of rift, from old rhyolite volcanoes to a geyser basin, all in one June night, with pasty basaltic lava bombs, transitions from ash to mud, and destruction of 140 people buried under 75 feet of mud. The eruption was preceded by marginal lake floodings. There was incandescence and steam blast engulfments along the lake-basin chasm so that Rotomahana lake was greatly lowered, recovering during years to large size.

This eruption was like Katmai or Taal and showed the possibility of violent steam blasts along any volcanic rift country, in any geyser belt over intrusive magma. This would apply to many places in Japan, or to Geyserville, California; Drakesbad at Lassen, or to the Yellowstone Park.

Waimangu geyser was left as a mud volcano at the southwest end of the Tarawera rift. Excelsior at Yellowstone was such a geyser. The San Francisco earthquake by a suitable branch rift might have started steam-blast eruption at Geyserville. The Cinder Cone at Lassen is a recent magma gush that might have been explosive at Boiling Lake. Tarawera was no more known to be an active volcano than was Bandaisan or Katmai. Mount Rainier, Haleakala, or Fujiyama are competent to erupt.

The entire Taupo belt of New Zealand is an almost ideal location for magmatic geophysics and geochemistry of solfataric volcanism. It is somewhat dangerous (hence worthy of study), as proved by Ngauruhoe, Waimangu, Tarawera, Rotorua Lake, and White Island. Its cyclical subterranean routine is unknown. A large geophysical center on Lake Taupo might solve by experiment fundamental problems of rift action, underground water, magma sounding, cycles of rupture, and tumefaction.

The variety of action and accessibility are greater than in the Caribbees, everything is more accessible by telephone and motor car than at volcanoes in Alaska, scientific centers are near, and the climate is good. It is an opportunity for a new John Milne.

Sakurajima

The Sakurajima eruption of 1914 stood out as an eruption expected and prepared for, its cycle estimated, its vicinity geodetically measured, its counterpart recorded historically, its population trained to expect it, so that they moved with little loss of life.

The Sakurajima steam blasts were notable in leading to a major world-shaking earthquake that released rapid magma in the evenings of January 12 and 13, 1914. It is not known whether water emission occurred for the island was evacuated. The island was lifted, but the shoreline of the bay lowered. The land had been rising during preceding years. There were eastern and western lava mouths on the same transverse rift, the summit part of the rift remaining mostly closed. There was downblast from the western rift. Probably hydrochloric acid was dominant and there was little sulphur. A sequence of eruptive dates occurred comparable to the Caribbees: it has not been plotted.

Comparison with Pelée showed analogy between the flank upjets of Sakurajima and those of River Blanche, an agreement if the latter came up the rift there and not down from the crateral notch. Whatever shot down from the Pelée flank rift, selected a crack of inclined throat, and this crack was Hill's "lower solfatara" of Pelée, that opened only over the stress of exceptional paroxysms. Like the "lava lid" of Lassen, it was probable that this throat is actuated by an internal magma tongue beside the column under the cumulo-dome. Orifices were concealed by deep beds of ash, and in Sakurajima by overlying lava. (See Figures 16, 17.)

Comparison of Sakurajima with Kilauea explosions from Halemaumau in 1924 shows the same upblasts crowned with cauliflower heads, the same trajectories outward of boulders, and the cushions in succession retarded and flattened by upper vortical heads resisting those puffed up below. Similar also is the platform of dust and outrolling horizontal curling cylinders about the base of the column, from backfall and from overwelling the lip of vent. These details in the Pelée nuées at sea level imply a valley-mouth vent. The obscuring of Sakurajima vents by lava ejecta is comparable with the Mauna Loa rifts.

KATMAI

Katmai in 1912 was like Tarawera and the Antilles in disrupting several volcanoes simultaneously and in occurring where eruption was unknown to the present generation. It was remarkable for its distance from habitations. It caused the collapse of Katmai crater and the filling of an adjacent radial valley. Here an intensely siliceous magma dome oozed up where rift collapse had previously made steam blast. This procedure was like Pelée. There were left hundreds of large fumaroles rich in steam charged with chlorine and fluorine. There was probably water of ejection at the beginning, there was certainly mud flow at the end. There was deep seismic action of world-shaking violence for 4 months, reaching highest intensity at the end of the period.

The sequence appears to have been pre-eruption uplift, subterranean magma drainage, explosive valley mud-flow, Novarupta steam blast and valley ash, collapse of Katmai and other cones, an unrecorded geyser rhythm of explosions, increasingly oxidized ash ejections, maximum hydrogen sulphide about the large cones, assimilation of deep sediments to acidify the magma, Katmai mud-flow, rising incandescent rhyolite streaked with basalt, increased seismicity, involvement of subterranean salt water; the rising lava next closed off the water-explosion chambers, finally intrusion replaced extrusion, and both earthquakes and steam dwindled through a decade. The whole was on a 1500-mile line of sympathetic volcanism mostly unobserved.

The Herzberg lens of fresh water over salt probably exists under the Alaska Peninsula with its rivers, abundant rainfall and big glaciers, and its long igniseptum following the edge of the coastal plain of Bering Sea. Also there are oil and coal-bearing marine strata, well known to carry salt water in other regions, and the volcanic belt is obviously fissured deeply. The lakes exhibit the water-table surface.

The Katmai group of eruptions extended into the Carboniferous rocks south of the Bering Sea Quarternary, was on a gigantic scale in both time and space, involving at least five volcanic centers across an area 20 miles in diameter, and shattered the highlands of the Alaskan peninsula for half a year or more, leaving its enormous steam jets by thousands to belch poisonous gas indefinitely, while avalanches, floods, glacier disruptions, rock faultings, and quakes kept the land tottering and unstable and inaccessible for 2 years.

Thorough exploration was not begun until the third year, and was continued for 5 years before the facts were known. No one as dweller among the volcanoes actually saw the eruptions as Pelée or Vesuvius was seen. It was a wilderness. The Aleutian belt has had other such eruptions at Pavlof, Aniakchak, Akutan, Shishaldin, Bogoslof, Gareloi and Seguam, where the nearest natives were many miles away. A similar unstudied crisis in 1899, but seismic in quality, had occurred in granite mountains amid glaciers near Yakutat in southeast Alaska, surveyed later by geologists.

Katmai is in the middle of an arc of igneous matter joining the high granites of Mount McKinley with the active effusions of the Aleutian islands. It is probably the finest existing geographic type of linear transition from basic volcanism to siliceous continental plutonism. This chain needs a geophysical laboratory.

Taal

Taal was a mud-steam and magma eruption at sea level, possibly more muddy because it was at sea level. It was on a seismically rupturing dike rift like the others. It was seismically associated with the Palawan tectonic line, with graben down faulting at sea shore as on Kilauea in 1924, and with similar crater-cone collapse and probable land tumefaction and submarine outflow. A laboratory was later established there by the Jesuit Fathers of the Manila observatory.

Tomboro

In comparing steam blasts with Tomboro, the ancient big disturbance at the Sanggar peninsular in 1815, said to have lost one-third of the height of a 14,000-foot volcano, the reports here demonstrate an example of gross error in computing bulks. Sir Stamford Raffles, however, the English governor, ordered an investigation that revealed the same quality of happenings in the earth crust that distinguished all the later steam blasts.

Van Rheden (1918) made a modern geologic study of Tomboro and discovered that the 1815 eruption produced leucite tephrite like that of Vesuvius. There was an underlying basalt dome capped with a cone of mixed eruption. This is true of most continental steam blast volcanoes. In Pelée the mixed-eruption cone is of quartzose andesite, in Soufrière of hypersthene andesite bearing olivine.

In the Caribbees there are transitions not only from basaltic foundation to andesitic cap, but also along the chain from basaltic south to quartzose north. The implication as Tempest Anderson suggested is increased assimilation of siliceous sediments in one direction, as well as increased assimilation in the history of a single island. It would be of interest to know what are the geologic transitions near Sumbawa. There is probably such transition in the Aleutians from basalt in the ocean to rhyolite at Katmai, from oceanic to continental, from free-flowing to viscous, from deep magma to an assimilate.

The events of Tomboro were prolonged over years, the crater was unvisited, the crisis lasting 4 months as in the others, with whirlwinds, darkness, fire, glow-covered mud streams, pumice in great quantity, sea movement, land subsidence, crateral engulfment on a vast scale, physical effects at great distances, seismic disturbance, water spurts, endless ash fall, and no record of actual sequences such as might have been rhythmic on the rifts. We do not know where the rifts were. Forty-seven thousand persons died from a variety of causes. It may be assumed there was the usual sequence of accumulated pressure, rupture, lowered water, magma drainage, magma effervescence, seismic disruption, mixed ejection, rhythmic cooling and boiling, viscous upflow, water exclusion, and final solidification.

One feature of Tomboro is of interest today. This volcano has been inactive in recent years. Clouds gathered over the summit 3 years before the 1815 cataclysm (April 5, 1815 to July 15, 1816). It is 132 years on November 10, 1948 since the maximum of the great outbreak. About 132 years has proved a critical interval at Sakurajima, Asama, Mihara, Kilauea (Wood 1917) and at Messina under Etna.

CRITICAL DISCUSSION OF THE CARIBBEE STEAM BLASTS

Magmatic, Mixed, and Phreatic Eruption

It is desirable to picture clearly that these three are related to the symmetry of disruption of a conduit on the one hand; and to the admission of perched, confined, or basal ground water under hydrostatic pressure, on the other.

The fracturing of a conduit in a cone if regarded upward from below, envisages a dike fissure wedging open as an inverted V section, and leading into a crateral circular shaft. All volcanic wells are dike systems in the depths. All craters lead downward to rifts, large or small: large in the chain, small in the edifice, and the two not necessarily parallel. Owing to the weight of the mountain, all taper upward in a cone, for weight of sectors closes surface fissures.

Rising or falling of magma is frictionally straining the walls. Frictional strain or breakage on a dike wall makes multiple parallel fractures; rising magma within a cylindrical wall makes multiple radial or concentric fractures.

If magma is sinking, concentric dike breakage dominates; if it is rising it may lift concentric horsts within funnel sheets (inverted-cone sheets), or strain open radial cracks. (See Anderson's diagram in the Mull memoir, Bailey, 1924.)

Recurrent intrusion produces radial dikes, ring dikes, and funnel sheets. Recurrent withdrawal seals radial and funnel joints, but opens ring joints and parallel fractures by collapse toward the evacuating magma chamber; and supplies large rock blocks.

Such collapse within the water table opens wells and channels not present before, with downward and inward circulation. Whereas a hot magma with chilled selvage mantle seals off water; a lowered magma with collapse talus lets in water *pari passu* with release of vesiculation heat and foaming. If viscosity of water diminishes with rising temperature and viscosity of magma diminishes with added water, "mixed eruption" occurs.

This is the cross section for any central magma body: a tapering funnel fracture upward over rising paste, where the well opening downward is an inverted funnel section; a fracture parallel to walls thus creates engulfment around sinking paste. Paste friction or drag exists in both cases, and the pre-existent shaft always widens downward below the surface funnel, whether dike or circular pit. Add the invariable directional extension of pit into rift and the usual sea of underground fresh water pressing inward somewhere above or below sea level, and a structure section is formed that must be confronted by anyone explaining Pelée or Vesuvius. Existing publications do not always recognize the structural rift and the ocean of basal water.

There is an *a priori* condition, of sudden change, that sets the date April 8 for Vesuvius (1906), May 8 for Pelée (1902). In both cases the crater started to cave in; in Pelée the liquid water started to boil up. In Vesuvius magma was at the very top and went down; the liquid water was not visible. In Pelée the magma was invisible, but suddenly moved, ruptured rock, and in the depths frothed into siliceous pumice flung up by steam that ejected water through the collapsing crater. In Vesuvius the magma froth flowed out along with collapse and boiler explosions: in Pelée the boiler explosions were needed to release the stiffer magma froth which rose and monopolized the structure as collapse ended. In Vesuvius the north-south rift was definite: in Pelée the northeast-southwest rift was definite to Lacroix, his associates, and other investigators of the paroxysmal period, and was not parallel to the chain of islands. In both, the ocean of basal water was definite. The widening and extension, downward and longitudinally, of the unseen structural rifts of cone and chain, and the geyser timing of the basal water, released to heating by magma volatiles, are features of certainty, not of theory. There is no possibility that the two percent of gas in andesite lava made the great weight of water vapor for many months that caused the hot floods and steam blasts destroying St. Pierre and Morne Rouge.

Rifts and basal water may not be neglected. First consideration is here given the meeting of magma with structure, thermal timing, actual experience of gas constitution, and insistence on transition or separation between bursting boiler and magmatic gas. Tempest Anderson (1908) recognized rift structure for Soufrière and Pelée: "the two volcanoes are at the ends of two branches of one common passage" dividing at great depth. He stated clearly assimilation for the Pelée magma. Ability to avoid excessive assimilation of water and of foreign rocks with an impervious vitreous skin keeps basaltic volcanoes relatively pure and uncontaminated, within a basaltic perilith.

Hawaii Island is fundamental type of Structure and Sequence

There are four features of the Hawaiian volcano process and structure that the studies of the last quarter-century have revealed as fundamental to volcanism.

These are:

(1) Gases. Magma vesiculating yields flaming hydrogen and carbon-sulphur gases totally different perceptually from pure water-vapor or de-oxygenated air.

(2) Dike Rifts. All volcanoes are founded on dikes, and these in turn are underlain by profound elongate dike-rift systems. The dikes of local crater and edifice, fractures extending into flank breakage, are transverse in direction to the main deep rift system of the volcanic chain, possibly an échelon relation. That is, tension of deeper rift may make oblique overlap ruptures in upper accumulations. The dike complexes are competent to make water-confining boxes.

(3) Ground Water. The catastrophic-paroxysmal eruptions of steam are not due to age-long accumulation and restraint of magma. They are phenomena of basal fresh ground water subcraterally confined. One mechanism of confinement heating is lava lowering below ground water, frictional fractures of conduit walls for opening waterways, and co-ordinate fractures and collapse of crater-pit walls to choke the opening. Lava lowering above ground water makes collapse but not explosion. Boiler explosion requires sealing of valves, for which sudden lava lowering sets a date by avalanche clogging, and sealed valves start geyser intervals. The logical steam path of enforced valve opening is through the fracture system of crateral dikes and debris plugs. There is explosion debris from rifts on both flanks of Kilauea mountain, as well as around the central well. The steam explosion episodes known are aberrant, various in intensity, and distinctly accordant with lowering and engulfment.

(4) Magma. On the other hand, magma rising in dike or well is systematic, reasonably rhythmical, and self heating with gas from solution, sealing its wall contacts against meteoric or vadose water. Magma rising is slow, magma sinking is fast. Magma rising is adjusted intrusively to an edifice that it lifts open. Magma sinking at a conduit is sudden and variable, owing to internal or external lava drainage. Always the weight of edifice is opposing magmatic lift. Always magmatic lift is thrusting up volcano accumulations of the ages. Atmospheric, hydrospheric, rock-tidal and cosmic rhythms are imposed on rising magma. Rupture limit or strength of larger structure operates sinking magma (lower rift system wedges open, and higher liquid or frothing intrusions lower to the magma's fluo-static level of the moment).

Ground Water in Hawaii

Many years of study for drilling wells have determined the occurrence of ground water in a basaltic island to exhibit six types of structures holding up perched water, two holding basal water, and one holding confined water. Perched and basal ground water are well known, but confined water is distinctly characteristic of volcanic belts. The foundation is basaltic in both Martinique and Hawaii.

The surface of basal water in Hawaii is shallow in the permeable rocks of the coastal plains and deeper in the island interiors, the water lens supplying artesian wells if restrained by buried contact clays of the coastal plains. It floats on a deep concavity in heavier salt water.

The perched superficial water is held above the basal water table by igneous sills, ash beds, soil, alluvium, or sometimes by ice in the high mountains, and occasionally by dense lava flows. Ash and alluvium are the commonest bottoms of such water recovered by tunnels on such surfaces.

Stearns (1935-1940) describes confined water in Hawaii as occurring

"in compartments of porous lava between dikes. Such water extends to considerable depth below sea-level in most places and is usually resting on impermeable intrusive dike-rock and is not floating on sea-water" (Fig. 23).

Dike complexes revealed by erosion where they had been the feeders of volcanic extrusion are apt to lie in groups of dikes intersecting in V structure or box structure and are prolific as water containers. Saturated dike complexes connected with subterranean drainage of valleys buried by impermeable alluvium, whose sources reach into the mountainous rainy belt, may become catchment basins even for artesian water. Geikie (1897), in many British cases, has shown that old craters were left full of coarse agglomerates in the depths. This is initially porous to the passage of water. Extensive ancient river agglomerates are similarly porous, and lavas are apt to have porous joints, rift faults, and vesicular sponge structure. The old sections of crater regions in Hawaii show extensive dike complexes. Assuming such dike complexes holding confined water under all rainy belts of volcanoes, we may have along such lines of volcanic mountains as the Caribbee islands a large store of underground fresh water even high above the basal water table.

The presence under all porous oceanic volcanic islands of the Ghyben-Herzberg lens of fresh water, floating within a concave basin of salt water, needs recognition. The salty foundation of ground water is a subterranean extension of the ocean from both sides of the island. It furnishes an upholding hydrostatic pressure not dependent on any rainfall and not equivalent to the dry under earth which exists locally under the interior deserts of the great continents, but not under interior lacustrine areas. The latter (central Africa) have the same properties as the ocean.

If a volcanic ridge rising above sea level is split longitudinally under a row of volcanoes, and a single volcano rifts itself radially or diametrally on a dike branch of this split, and a rising magma wedge suddenly applies vapor pressure in the depths, then not only has a well been suddenly dug below the water table, but an "air-lift" pump has been applied to foam up the water.

Dr. Chester K. Wentworth (1941) discussed before the Engineering Association of Hawaii as recorded in their weekly bulletin Vol. XIV No. 39 for Sept. 19, 1941, the practical application of the Ghyben-Herzberg theory. For every foot of head above sea level there are 40 feet of fresh water below sea level. Thus if the artesian head were 40 feet, there would be 1600 feet of fresh water stored under the island of Oahu below sea level.

The lens of fresh water above sea level is referred to as "top storage;" the lens of fresh water below sea level as "bottom storage." A drop of a foot in artesian level should be reflected by a decrease of 40 feet in bottom storage, or a rise of the lower surface of the lower lens by that amount. Such a decrease of 40 feet in bottom storage represents an enormous volume of water. Where does this immense quantity of water go if the artesian level is slightly lowered?

The answer lies in a "lag" in balance between top and bottom storage. It is as though there were two reservoirs—one small (top storage) and one forty times as deep (bottom storage)—interconnected through a small pipe. Owing to the inadequacy of the connecting link, any change in water level in the small tank is not immediately

reflected by a similar change in bottom water surface in the large tank. The adjustment may take days, weeks, months or even years, according to the volume of water involved.
The inadequacy of the connecting link in our simile represents the unknown quantity of frictional resistance in our aquifer. This resistance is believed to prohibit quick passage of the vast volume of water involved in a strictly theoretical interpretation of the Ghyben-Herzberg theory. Under the operation of this lag, top and bottom storage are probably never in balance. The extent of this imbalance is the most important hydrologic problem of the Honolulu Board of Water Supply.

Applying this to volcanoes, in a disrupting steam blast the bottom forty would be used first to lower by one the top accumulation of rainwater drainage. If convectional rainfall accompanies eruption, a steam boiler might have forty units of fresh water to use for one unit of ground water accretion, with lag diminished by ruptures. If bottom water were used in large volumes reversing the waste by artesian wells, the groundwater head would be pulled down slowly, but the rainwater accretion would partly compensate this. Steam blast interval would utilize the lag of the compensatory head: if the geyser interval between steamblasts increases, this would represent Wentworth's increasing lag applied to a catastrophic discharge reversing the mechanism of a lowering artesian head.

From Tolman (1938) we get the accompanying figure 22 and the following principles. Ground water percolates outward laterally from rainfall and mingles with sea water at the shore. Fresh water can be found slightly above mean sea level. Salt water under an island extends across the island but not at sea level. The lens of fresh water resting upon salt water inside the island is doubly convex with its deeper convexity downward, and roughly forty times as deep as the upward convexity is high. The depth through fresh water to the deeply depressed

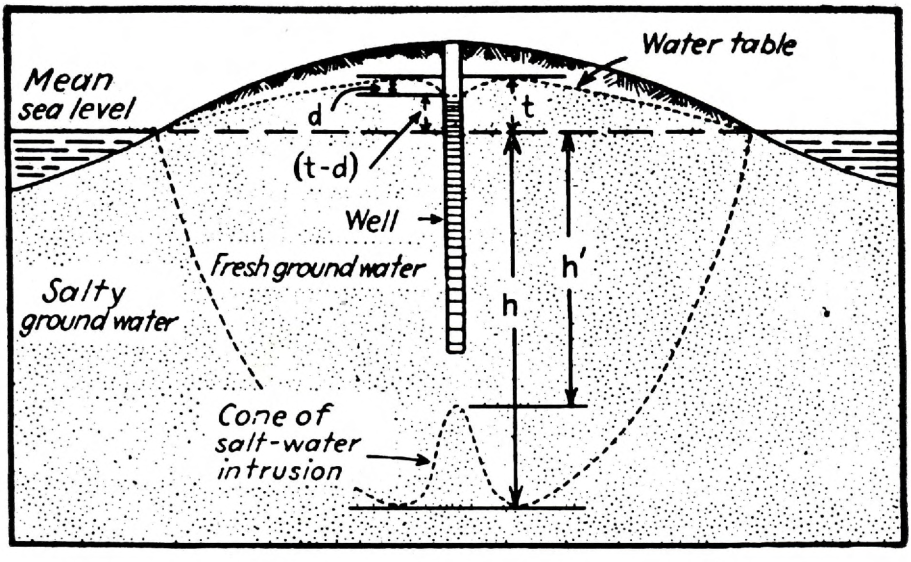


FIGURE 22. *Diagram cross-section of Herzberg lens of fresh ground-water under a volcanic island (after Tolman).* Dotted line showing fresh water lower limit is drawn to one-fifth the vertical scale of height of water-table above sea-level. Effects of pumping down a well-surface.

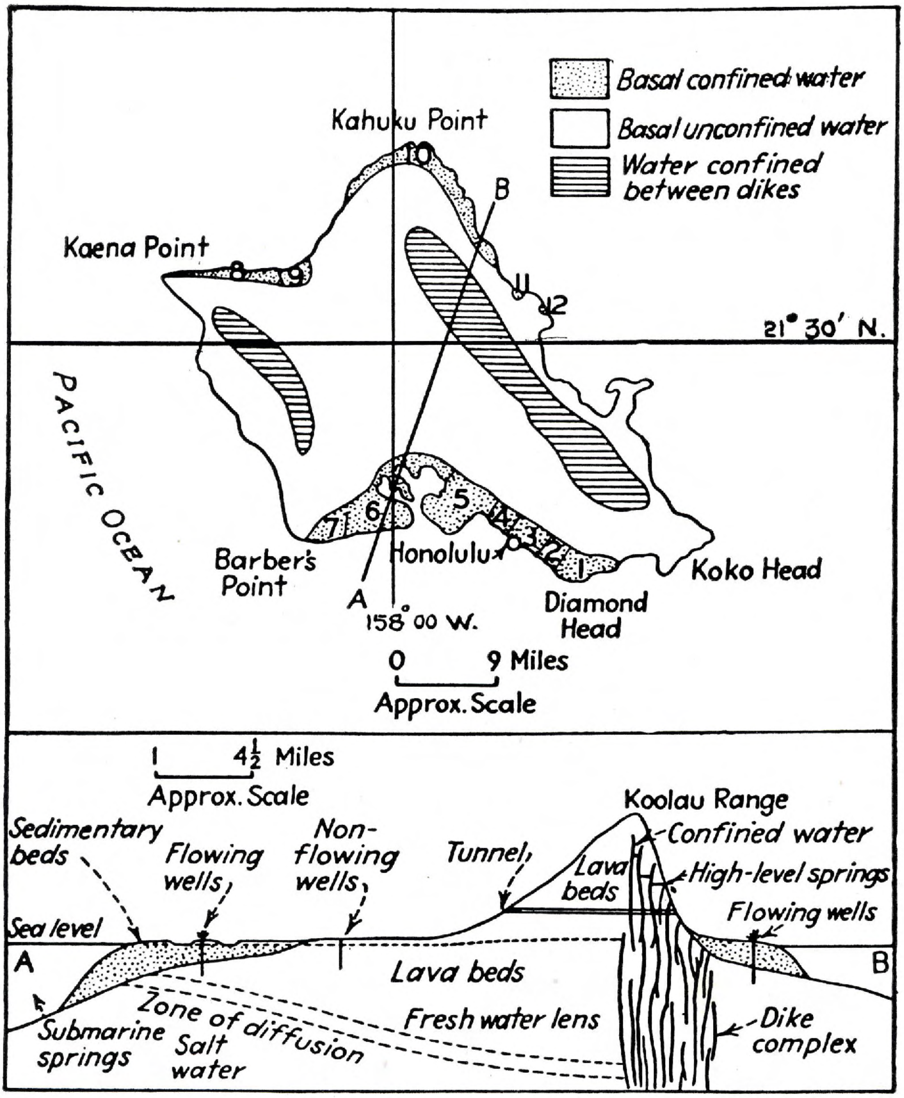


FIGURE 23. *Map and exaggerated cross-section of underground water in Oahu, Hawaii (after Tolman).* Especially shows confined water on a dike-rift system, as actually discovered by a tunnel driven artificially.

salt water is a function of the difference between water densities and the height of water table above sea level. The simple formula involved giving the depth of fresh ground water in relation to a pumped well is illustrated by figure 22. The dotted line showing the boundary of fresh water in cross-section has the distance below sea level drawn to one-fifth the vertical scale of the distance of water table above sea level: the downward convexity should be five times deeper than is shown.

In Hawaii the specific gravity of salt water is 1.024 making the thickness, h, of fresh ground water plano-convexity downward below sea level, 41.66 times t, the height of water table. However, h is also the height of the balancing column of outside sea water that holds up h+t, the total column of fresh water. If 1.0 is the specific gravity of fresh water and s that of sea water, then:

$$\mathbf{h + t = h\,s}$$

$$\mathbf{h = t\ \ (s - 1)}$$

If a well or a crater acts as a pump, as shown by the well in the figure, where d= drawdown, and we substitute t - d for t, and substitute h′ for h where h′ is the depth below sea level of the top of a cone of salt water intrusion occasioned by the depression cone of pumping, the equation becomes:

$$\mathbf{h' = \frac{t - d}{s - 1}}$$

From this equation the depth of fresh water can be computed for every foot of drawdown. When h′ equals depth of well below sea level, salt water will enter the system.

If the well shown is considered a diagrammatic volcano acting as a steam-pressure pump, the plane of the paper may be considered a transverse rift across the Caribbee or Aleutian or Hawaiian ridge, and the capacity of a crater formed through any point on the water table from summit to shore, to deplete fresh water, may be calculated. The important point in the volcanic problem is that an oceanic hydrostatic pressure is always present down to the magma source, however low and flat may be the lens of the fresh water table, and the deeper water can supply chlorine.

In Hawaii the steepness of curvature of the water table varies inversely with the permeability of the water-bearing material, so that where the lavas are extremely permeable, the depth of the interior fresh water basin below sea level may be small.

Where ground water is confined between dikes of impermeable fine-grained basalt, the pervious vesicular basalt of the ancient lava flows between the dikes stores great quantities of water, registering pressures of 65 pounds to the square inch, and for a tunnel driven through mountains back of Honolulu, the water level stands 900 feet above sea level, and is computed to represent a body of confined water extending down to sea level or below (Fig. 23). This figure is modified after Stearns for the cross section of Oahu where the Waiahole tunnel has been excavated. It gives a clear picture of such up-to-date knowledge as exists concerning coastal plain artesian beds, the tunnel, and the longitudinal dike complex known to underlie the northeastern volcanic ridge of this island. The island is a part of the NW-SE ridge of the Hawaiian chain, so that this section might be used for any oceanic ridge built by volcanoes made of permeable vesicular lavas, pumices or agglomerates, and such ridges generally are in wet climates. Galapagos is notably dry, and possibly is notably free from steam blast, but nevertheless ocean water should underlie these islands. For the Katmai country, heavy rains and lakes characterize the entire Aleutian belt, and the Taupo district of New Zealand is wet.

Summary of Volcanologic Questions in Hawaii

The writer approaches any steam eruption in any volcano with five questions:

(1.) Where were the magmatic gases shown?

(2.) Where does the rift system lead?

(3.) What made the boiler explosion?

(4.) Where was the intrusive magma?

(5.) What set the date for the event?

If the Kilauea explosive eruption of 1924 is used as a model, with due allowance for difference from continental types, we get the following answers:

(1.) Magmatic gas fountains appeared in 1924 January and July, the liquid lava lowered to explosion throughout May, the explosion was pure steam, lateral rift exhibited sequences to submarine eruption of lava, and to backfill of the lava within the rift from the explosion month to the July magmatic inflow.

(2.) The rift system led from sea level to sea level through and across the cone and its sink crater, with bend in plan at the crater, (Fig. 8). It certainly extends under the sea, and somewhere in depth connects by forking with Mauna Loa, and through the deep Hawaiian crust fracture to the other islands in the chain.

(3.) The timing was perfect for the seismic rift rupture observed at sea level, the inflow of ground water during sub-crateral lava evacuation, rhythmic intervals of geyser quality increasing during pit collapse, enlargement of pit, debris floor steaming, then debris floor invaded by backed-up lava, and cessation. All agreed with the conception of rhythmic collapse-damming of an aspirating water-supplied steam boiler, with the water replacements cold.

(4.) Intrusive magma had shown itself present by rising and falling in the pit from 1914 to January 1924, the risings dominating but slow, the sinkings fast. Magma intrusion visibly had split the south end of the rift open to flank outflow in 1919-1920, the northeast end 1922-24, and had overflowed the crater floor of mountain top 1918-21. Throughout it had, by geodetic proof, lifted the mountain and injected dikes to 1921, lowered it 1922-24 during the explosive crisis, and left it lower by from 3 and 14 feet at outer crater and inner pit edges. Magma ejection after the explosive crisis changed to shorter-lived, hotter, more intense, and more gaseous annual eruptions distributed between Kilauea and Mauna Loa.

(5). The dates set for progressive lava-subsidence in Kilauea pit until the great explosions, were rhythmic (Jaggar, 1947, diagrams), and deepening in effect, 1916, 1919, 1922-23, and 1924: only the last and deepest lacked visible

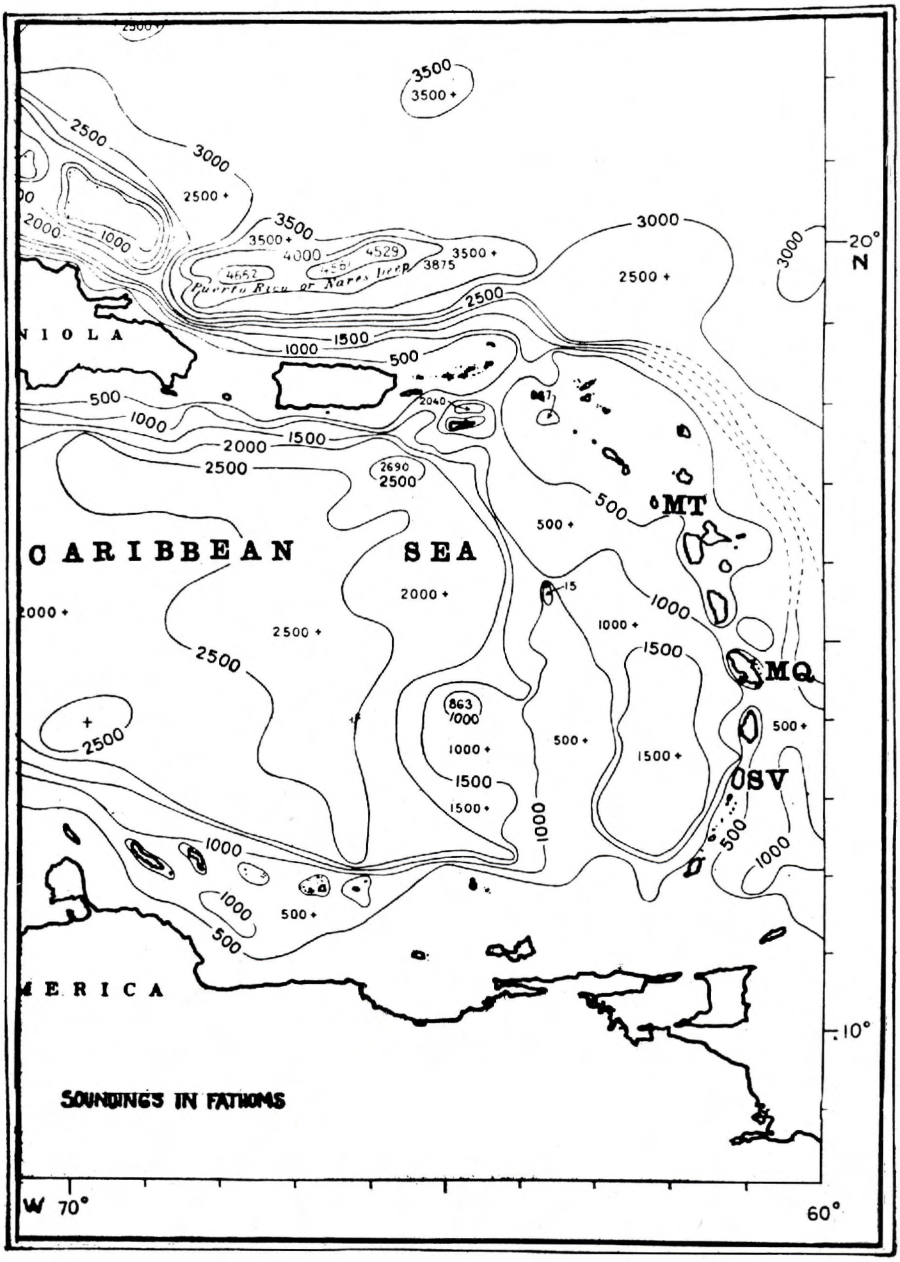


FIGURE 24. *Chart of soundings in fathoms, Eastern Caribbean Sea.* (MT) Montserrat. (MQ) Martinique. (SV) St. Vincent.

surface outflow, and produced geyser explosions and final gigantic engulfment, but the engulfments in series enlarged the pit. Mountain tumescence to 1919, and repeated outflow to 1924, suggested rift split and radial inflow to rift from crater tube. The sequence and seismic events indicated rift split to shoreline, and submarine flow of lava accompanying crateral steam-blast. Reactions of observed surface splitting, by observed magma, definitely set dates at Kilauea. The same may be said of Vesuvius and Sakurajima where, as in Hawaii, flank rifts were not concealed by rivers, and both produced flank outflow. On Pelée and Soufrière, flank rifts were overlaid by sediment-filled valleys, and if flank outflow occurred it was totally submarine, just as at Kilauea the flank outflow of 1924 was totally submarine. Chemically the Carib magma was competent to make flank outflow, heated by more hydrogen (Jaggar 1940) than Hawaii.

Hawaiian Questions applied to Pelee

If we imagine the Kilauea sequence happening where the surface rifts are sealed deeper, with basaltic magma rising and falling underground, and splitting its way with seismic and elevatory accompaniments, irrupting in deep fissures instead of erupting through surface craters and their rifts, we may get, by explosion, chains of volcano accumulations like most of the volcanic belts of the world.

The Caribbee islands are so constituted, on the western margin of an arcuate continental sedimentary uplift connecting North and South America at the eastern border of the Caribbean basin. It is like the inside slope of the end of an elliptical bathtub (Fig. 24). The floor of this basin has sunk and ruptured its curved contact with this partially submerged Barbadian isthmus, which narrows the West Indian extension of North America in a sweeping curve through Barbados to the Trinidad extension of South America (Fig. 24).

The line of volcanoes old and new encircles a deep cup of the eastern Caribbean with convexity of mapped curvature toward an Atlantic coastal plain of continental matter (Fig. 1, inset), just as the similar Aleutian curve is convex toward the Pacific (Fig. 25), with the volcanoes on the inner Bering Sea side of an extension of the continental Alaskan Peninsula out toward Asia. The Bering Sea coastal plain (Smith 1939, Pl. 1) extends widening to Iliamna Lake.

Figure 25 is too important a line of volcanism on the globe from Katmai to Krakatau in a succession of arcs to pass without notice. The volcanoes cluster to a maximum of height and intrusive import from Borneo to Iliamna, with concentrations in the middle region, Japan-Kurile-Kamchatka. There is a succession of straight fractures *en échelon* on the globe, hooked westward from Palawan to Attu: they are progressively longer Taiwan, Chosen, Sakhalin, Kamchatka and Alaska to Mt. McKinley. Murray (1945) accents the perfect circularity of the Aleutian arc. The igneous ignisepta are older and deeper than any mountain foldings. Considered collectively as a great-circle deep rupture, where the *échelon* cracks have joined by cross fissuring—a major joint made up of minor *échelon* joints (Woodworth, 1896)—this igneous feature of primitive fracture of the sphere may even extend beyond Sumatra to Keeling, St. Paul, and Kerguelen. The Java-Sumatra arc cuts across it. Lunar fractures may be comparable.

Whatever the meaning of curves in plan, there is no question but that both Caribbees and Aleutians are arcuate fracture belts up which volcanic magma has risen and piled up linear accumulations, with deep water irregularly distributed on both sides of the ridge. In detail the slope of old Cretaceous and Tertiary sediments appears to dip flatter on the side of the greater ocean, as though the active volcanic igniseptum were built up over a belt of sinking on the side of the smaller sea, and there acquired a Quaternary coastal plain. The Guatemalan line of active volcanoes in a continent borders a downfaulted coastal plain on its western aspect, again with arcuate curvature convex toward the larger ocean, but with a history of uplift on the continent.

Both Carib and Aleutian arcs differ from the Hawaiian arc, which is without continental connection. This agrees with the uniform basic quality of Hawaiian magma, representative of no contamination by contact with the concentrated silica and alumina of continental sediments.

In applying to Martinique and St. Vincent, for their eruptions of 1902, the five questions concerning magmatic gas, rift system, boiler explosion, intrusive magma and precipitating cause of eruption dates, we find solfataric gases, a linear rift, gigantic boiler explosions, exuding magma, and some rhythmic dates. The mountain rifts (River Blanche and possibly Morne Ronde) are not parallel to the igniseptum.

The following keeps the Hawaiian order by number:

(1) Caribbee gases: Magmatic motion developed excessively, far below both islands in April 1902, generated release of pressure and gas heating by inrush into dike chasms, split new chasms longitudinally making many small earthquakes and a few which were felt for 100 miles from St. Vincent and Martinique, and jostled down old material into the new vesiculated magma that was travelling the subterranean *échelon* of cracks. Magma stress is unceasing and gases are emitted during vesiculation and consequent liquefaction; gaseous heat-giving reactions aid the melting, and the blue fume associated with "nuées ardentes" was composed of the deep sulphurous and carbonaceous gases.

(2) Caribbee rifts: Rumbling accompanied by quaking rupture of radial rifts over the magmatic swelling frightened the Carib natives on a line through Soufrière crater southwest to northeast and in gulches of Mount Pelée opened waterways radially, especially the River Blanche named for generations of men the white stream or milky river, Rivière Laiteuse. So named because of solfataric openings in its bottom, just as White Island in New Zealand was named for the gleam of sulphur.

In contrast to the north-south trend (Fig. 24) of the line joining St. Vincent and Martinique (the tangent to the middle point of the circular arc of the Caribbees, Figs. 1 (inset map) and 24, the ancient rifts athwart both Pelée and Soufrière, determined by connecting old local craters, and also connecting lines along fault scarps, appear to trend about N. 53° E. There is just such a series of transverse NE.-SW. structural lines athwart the Hawaiian chain, on which lie localized active rifts and submarine fault scarps.

Supposing parallelism of deep cracks this direction for Pelée connects Rivers Blanche and Falaise on opposite sides of the mountain, and also connects the Sainte Philomène escarpment across the crater to the Basse-Pointe ridge. Supposing similar parallelism of features at Soufrière, this direction connects Wallibu through the Somma escarpment to Owia Point, and also connects the Chateau Belair embayment through old and new craters with Espagnol Point (Fig. 7). These shoreline irregularities may be induced by the underlying dike complex, and dikes are in the northeast crater walls of both Pelée and Soufrière.

(3) Caribbee boiler: Water rose in crater lakes and was added to streams, over intrusive displacement. By the tumescent opening of rift cracks the lenticular bodies of downpressing basal ground water dropped into the cracks. The higher reservoirs of dike-confined water under the volcanoes, at greater pressure drained downward. Heating lowered water viscosity. This was the signal for boiler explosions and selection of paths upward of least resistance to steam and water, and the process by ejection and cold replacement fixed times for geyser rhythm. (Jaggar 1898.)

(4) Caribbee intrusive magma: Intrusive magma was now ready to vesiculate to pumice on release of pressure and to become extrusive. Mixing with water promoted its liquefaction, cooling determined its rigefaction, and combined water and release of magmatic heat were set to create geyser rhythm so long as water was available, the geyser interval being controlled by increasing size of cold-water fillings as explosive evacuation enlarged subterranean chambers. Water was indefinitely available, and salt water introduced chlorine.

Magma became increasingly apparent as an incandescent dome in Pelée, making spines by upflow from July 1902 onward; and thereafter brilliant glow increased to the time of maximum upflow, and the "nuées ardentes" that gushed up from the bottom of River Blanche exhibited some incandescent matter, so that they were spoken of as "gluhwolken" or glow clouds. The glow clouds of Pelée are the equivalent of the flaming basaltic pumice fountains of Mauna Loa, but most of the Carib incandescence, liquidity, and flaming appear to exhaust themselves underground.

(5) Caribbee timing: This mechanism might have been recorded by geophysical observatories had any such laboratories existed between January of 1901 and May of 1902. Magma stress seismometrically and chemically measured about craters and solfataras would furnish data for a period of magma strain upsetting the rift belts. It is assumed the future will accumulate many world eruption diagrams of quantitative data.

By geyser rhythm is meant heaving open a way for downrush of cold water, heating of the water with a rising furnace of gas and magma, ejecting liquid water above, and starting periodicity of jetting of water, steam and magma. There is short-lived ejection of water in such eruptions.

Setting dates by scientific forecast demands experience of chemical tests of erupted gases and their humidity, correlation with seismic measurement of the magma column itself, and measurement of ground water height. Knowledge of historic intervals builds up reliable cycles. Experimental skill with automatic instruments wired to a safe distance was the life ambition of the late Frank Alvord Perret, for many years observer at Mount Pelée.

The August and December culminations of Pelée in 1902 exhibited gradual increase of glow clouds, the first leading to a grand paroxysm from the crater with radial destruction that originated at the River Blanche rift. The December gush came from the rift itself in the bottom of the valley.

The accompanying curves of Figure 21 plotting intervals for the paroxysmal eruptions of Pelée and Soufrière indicate increasing intervals and sympathetic dates. Accumulation on the ordinate is treated as a constant ratio of boiler volume to heat supply: if both increase in like proportion this geyser constant produces equal intervals on the abscissa. If boiler volume gains or heat supply decreases, the intervals should increase in due proportion. The curve flattens out when eruptive interval becomes infinity, and water and pressure quench geyser action. The River Blanche eruption of December 16, 1902 (Figure 19) fell into the curve satisfactorily; the plat was drawn in September and a December date predicted. Successive curves have increasing radius.

This was a crude setting of dates after geyser action had begun. Setting of date for structural strain over age-long pressing of intrusives is based on geophysics as in meteorological forecasting.

Contamination

Volcanic eruptions in continental regions are assimilative, and assume contact solution and absorption. Assimilation extends to rock, to crateral concentrations like sulphur and selenium, to fresh and salt water and to air.

Rapid assimilation of minerals and of water at times of intense gas vesiculation and heat was suggested by Fenner (1923) for Novarupta, near Katmai. This process as seen by Perret (1935) at Pelée in 1930 may produce little change in erupted specimens, if old rocks and new magma are alike. The writer (Jaggar, 1947, Pl. 7b and p. 122) by observing gas melting has seen assimilation at Kilauea and Mauna Loa, all the material being basalt.

The doctrine of contamination extends into the greater sub-volcano intrusions. There were several volcanoes erupting with Katmai, where distant more basic Bogoslof magma on the same chain just before had been rising and falling. The solfatara of Dominica and the St. Vincent (Anderson and Flett 1903) volcano on the Carib chain were actively destructive of human life with hydrogen sulphide and steam just before the Pelée crisis of 1902-05; and Montserrat (MacGregor 1938) on the same chain had a solfataric earthquake crisis just after the Pelée eruption of 1929-33 (Perret 1935). St. Vincent in 1902 continued its culminations sympathetic with Pelée during May, autumn, and the following spring (Anderson and Flett 1908).

Lacroix recognizes the Carib volcanic synchronism, but gives magmatic independence to acid Pelée and basic Soufrière. Anderson (1908) gives credit to assimilation. Fenner is constrained to a superficial origin (glacial boulders) to get *schlieren* of basic inclusions in the Valley of Smokes, believing the deep magma of Novarupta to be independently and fundamentally acid. He reverses normal syntexis. Rhyolite at its lower temperature does not ordinarily melt basalt, but diabase embays and resorbs quartz inclusions. (Jaggar 1898).

This insistence on fundamental acidity for a single vent, when the larger terrestrial feature is the chain of vents and the profound magmatic unit is the long plexus of intrusive dikes under that chain, takes no account of rapid and far-reaching intrusive rearrangements possible within the ignisept.

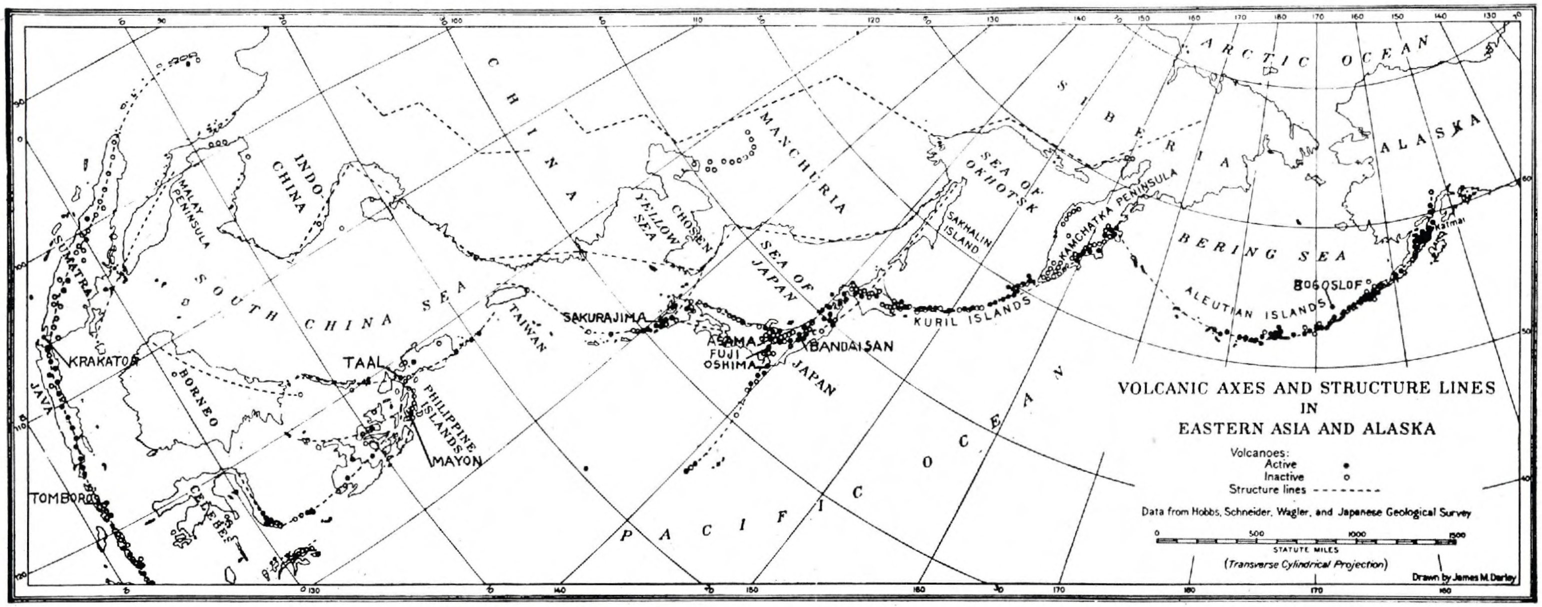


FIGURE 25. *Map of Pacific volcanic arcs (after Griggs, with additions).* Valuable transverse cylindrical projection, by J. M. Darley, expressing four arc intersections on the line from Katmai to Krakatau with land emergence on each, of Kamchatka, Hokkaido, Kyushu and Taiwan. Borneo ends the Taal-Palawan arc, and Alaska ends the Aleutian arc. Volcano locations indicated.

This term is the author's (Jaggar 1947, 410-12) designation (igniseptum, ignisepta, igniseptal, ignisept) for deep and large primitive magmatic fillings, from batholiths below to dikes above, along the earth's greater linear volcanic features (Figs. 24, 25). Examples are the Cordillera, the African Rift, the Caribbees, the Aleutian-Alaska and Asiatic arcs, the Hawaiian chain, New Zealand-Tonga, and the linear igneous roots of the orogens. Ignisepta are mostly today vertical partitions in the primitive crust between continental high and oceanic low, exclusively so in the pristine globe. To the author's vision they widen downward to the core, and they rock rib the globe with their frozen contacts.

The individual mountain has no magmatic independence, and continental volcanology recognizes fundamental basalt and its igniseptal differentiates by assimilation. Continental volcanology is a fraction of world volcanology encompassing all present-day intrusion. There are old basalts and old sediments under all continental chains. The probability favors living basic magma medially at some depth, and geologic history exhibits old basic magma subjacent and peripheral, along the volcanic chains (see Tomboro).

A volcano is a tiny pustule of the deep feature, and the continental surface is infected with sial and alkalinity. Light weight matter of the ocean deeps (Ewing 1938, Hess 1938) is probably primitive sial. Novarupta, and the similar Pelée, Santorin, and Santa Maria dome tumuli are in a variety of ways contaminate. The mechanism, and such a place of eruption engulfment, may be studied as a precious index laboratory of how the unseen intrusion engulfment works and achieves assimilation.

Engulfment and lowering of magma are common. Explosion is uncommon, though attributed to a variety of physical processes, such as Hawaiian lava fountains, paroxysmal steam blast, "nuées ardentes," gas ignition, avalanche sliding, and phreatic release from engulfment clogging. Volcanoes do not blow off their tops, and lowering of magma may not show at all after a vent is plugged and a void is left beneath the plug, for the fissures are small. Krakatau (Stehn 1929) in 1883 was structurally an engulfment.

The grouping of paroxysmal steam blast with "nuées ardentes" in disregard of dike rifts, eruptive floods, groundwater, rhythmic timing of eruption intervals, and of intrusion drainage of lowering magma; and in disregard of the self concealment of submarine eruption, valley fissures and of internal magmatic liquidity, have tended to keep the Carib events obscure. The notion that magma only rises is mistaken. Pelée magma was competent to lower while the plug stuck, and did so when initiating eruption in 1902 and 1929.

Rhyolitic and andesitic foams stream as lava flows if the gas release, gas content, and the gas heating are right. Sakurajima proves this. Perret (1935) shows that Pelée lava is liquid subterraneously: Grange finds liquid basalt traces within Tarawera crater. This the author maintained for the debris heap of breadcrust bombs in Pelée in 1902. Both Wada and the author picked up vesicular basaltic-andesite fragments at Bandaisan, apparently contemporaneous intrusive lava. The pumices and breadcrust bombs are believed to be contemporaneous intrusive lavas of any eruption. Mauna Loa basaltic pumice cones are of lowest viscosity, Kilauea lava lakes next, and Bogoslof cumulo-domes of stiffest lava.

The underlying lava of Soufrière and Pelée and Montserrat is possibly liquid and engaged in irruption all the time, and in unseen submarine eruption as flows part of the time, just as in Hawaii. The unseen submarine eruption encounters less resistance of accumulated weight of edifice. Occasionally intrusive irruption in the Carib igniseptum penetrates a dike fissure as a branch above sea level contiguous to an old crateral solfatara.

Penetration by wedge splitting makes earthquakes. Earthquakes are mostly microscopic, and seismograph as microscope must be craterally placed. Multiple penetration lifts contours and tilts the ground, but no one in the Carib country has measured these tilts. In the deeper parts of the ridge intrusive bosses and sheets are penetrating, rupturing, stoping, assimilating. The fluid is basaltic, but its upper assimilates are siliceous and high floating. When a deeper longitudinal dike splits, or a low lateral sill penetrates between strata and lifts, the higher branches lower suddenly to supply the intrusive fillings.

A dike NE.-SW. deep under the Wallibu-to-Crater line in St. Vincent, or the River Blanche line of solfataras in Martinique, its fissure totally concealed within the deposits of valley bottoms, suddenly lowers and drags its wall with it. The date was set by large yielding, and by deep intrusion penetration elsewhere a hundred miles away, or ten miles down. A yielding of a millimeter amplitude along 100 miles, is considerable volume displacement. An ancient crater pit on the dike line has weak bottom, concentrically jointed, softened by water. Probably there are several high radial dikes, all secure and rigid before the yielding, with water-tight glassy selvages. There is a typical one on the wall of Soufrière crater photographed by Hovey, Anderson and the writer. The medial liquid lava portions withdraw, the glued wall contacts rupture off slabs, the crateral lake bottom collapses, and from an upward-pressing system of fills, the plexus suddenly becomes a down-sucking system of voids, bottomed by sputtering incandescence, laterally invaded by springs, overhead choked by collapse, the water viscosity lowered by heat, the lava viscosity lowered by water.

This is not one circular crater well, it is primarily a dike complex, topographically completely concealed. Hence Hovey's comment on central conduit, "if there is one." When the Mull (Bailey 1924) ring dikes, longitudinal dikes, and cone-sheets were under an active caldera, they were not visible on the landscape above. The geology of Mull today after erosion locates no cylindrical small central well. Not one concentric dike is visible on Mauna Loa in Hawaii, but concentric cracks are there. A mile down, probably Halemaumau pit is a longitudinal dike along its rift. The same invisibility applies to the four classes of groundwater: perched, confined, basal and submarine.

Small earthquakes testify to the dike locations; a net of seismographs reveals the earthquakes; tremors are more numerous on lowering of pit lava than on rising. The epicenters are not at the pit. The deep centers are at the subterranean split that is draining the pit. Earthquakes near Haleakala 90 miles away accompany magma movement at Mauna Loa.

Withdrawal is evidenced at a crater pit if engulfment initiates steam blast. It is possible for upward wedging of deep magma in a vertical crack, directly under crater, to open a void and admit groundwater. In this case the acts of irruption and eruption are identical. Irruption under Pelée may produce lowering under Soufrière. In such case the intrusive rush of basaltic igniseptal magma from Soufrière toward Pelée had time enough during the months, from first earthquakes to final eruptions, to do a large amount of assimilation of the Fenner type. And "ribbon lavas" were present at Pelée. Tempest Anderson suggested such migration as very deep.

With initiation of downrush or engulfment there is released a whole series of expansive reactions, physical and chemical. Consequently a time is set for steam blast eruption (a "breaking forth." When the same process wedged open the void for permitting intrusion, an earthquake time was set for magma-gas irruption, a "breaking in.") Reported absence of earthquakes is meaningless; it takes a magnifying seismograph at the crater itself to reveal them, as abundantly proved in Italy, Japan, Java, and Hawaii.

The sudden reactions are: water inrush, internal avalanching, steam generation, pressure withdrawal, magma-gas release and its oxidation, air insuck, increased heat by gas reaction from the vesiculating and fountaining magma, the Morey effect of water liquefying magma, liquefaction of a pumice foam by vesiculation, immense expansion and foaming up by this process, and then the Goranson effect in the crater cumulo-dome itself—sudden freezing with the transition from liquid to stiff sinter: the central pencils will be the rigid product of gas-expansion cooling over liquid: the marginal envelope or "carapace" will be the viscidifying and freezing mantle: and the place of maximum gas escape will be the "wall-crack," the contact zone between crumbling and engulfing perilith and outermost glassy shell of the inner lava cylinder, or dike.

This at Pelée is the *"rainure,"* (location 49, Fig. 4) the "spiral valley," the depression around the fragmental cone, the "wall-valley," the horse-shoe gulch around the "cumulodome;" leading to the "cleft," location 50, "gash," "notch," *"Terre fendue,"* "flank chasm," "V-shaped gorge" or *"échancrure"* that was directed toward the rows of deep solfataras that persisted for years in the bottom of River Blanche at Pelée, and possibly in the Larikai gulch at St. Vincent, near Morne Ronde (see the MacDonald account). Both Hovey and Lacroix acknowledged the River Blanche fumaroles as primary and the whole thing is simply a dike system all the way out to the broken cables under the sea.

Radial Cracks at Pelee as Sources of Water and Steam

Hovey found in 1908 a quarter of a mile of radial deep-seated fumaroles, graded hotter towards the crater to 305° C., the spur west of River Blanche, location 51, at elevation 1200 feet, next to River Claire. Lacroix (1908) for about the same elevation, maps a similar radial series, location 52, on both sides of east fork of River Blanche at temperature maxima of 400° to 500°, between the hills Lénard and St. Martin, for a distance of three quarters of a mile, and 1 to 2 miles from the crater center (see Fig. 3). They are chasms choked with big boulders. He calls these of profound origin, and Hovey speaks of his (6 years after the eruption he camped and cooked with them) as "true fumaroles, connecting through deep fissures with the internal heat of the earth." Hovey remarks that the fumaroles highest in temperature are also highest in position, "a mile from the central conduit of the volcano, if there is one." This "if" is acknowledgement that he suspected lateral extension of conduits from crater to radial rift. Lacroix objects to lateral extension but acknowledges doubt, and in his later memoir (1908) lists the River Blanche fumarole temperatures as graded hotter toward the crater for years until 1906. The River Claire crack may have been the 1851 vent (Jaggar 1903), the rift becoming multiple in 1902.

Hovey in 1908 measured 515° C. in the glowing summit crack of the cumulodome, location 3, near 4444 feet in elevation, giving off pure steam "like a Russian bath," with no odor. Directly in line with his River Blanche deep fumaroles and 2.75 miles to northeast, Lacroix maps three *"pseudofumerolles"* on the north bank of River Falaise, location 21, at the east foot of the steeper slope of the ancient volcano cone of Pelée.

It so happens that the Claire-Blanche deep fumaroles are where the "lower crater" of Pelée was much discussed by R. T. Hill and believed in by the American investigators at Martinique in May, 1902, supposedly near where the 1851 eruption occurred. The Falaise fumaroles are where the unquestioned "Falaise crater" of May belched up great yellow clouds of fume, and Varian (Kennan, 1902, 164) drew his impressive sketch showing great round holes in line in the bottom of this terrific gorge. Hovey later, after eruption fillings and in a lull between paroxysms, dismissed this too easily as superficial. Heilprin (1908, 1924) after a revisitation in 1906 shows a photograph, taken on the actual bottom of this gorge, which makes it look like a crack, and Lacroix shows others with cylindrical scars of wells. Russell, Hill, Kennan, Jaccaci, Jaggar, Curtis, and Hovey had no question of the rift in bottom of River Blanche extending into the old Pelée summit dike of Morne La Croix, when we studied it in May 1902 during the paroxysms, and Lacroix at that time argued for it. (Lacroix, 1902).

Finally on October 25, 1904, Lacroix records "the reappearance of a fumarole in the lower valley of River Blanche at the same time that light activity was renewed at the crateral dome" (1908). This seems (to him) to indicate for this fumarole "a profound origin."

The wide rift belts of many thin dike-cracks become concealed in hard-basalt Hawaii (Fig. 15); like them "deep fumaroles" in debris-filled valleys of ash-covered Martinique, are proof of normal active rift belts on the flank of Pelée competent to produce phreatic and vulcanian explosion of an unusual migratory type, well recorded at Tarawera, Santa Maria, Sakurajima, and Katmai, and probably known in Java. Vulcanian eruption through a narrow chasm can make a terrific display, just as can Mauna Loa "fire-fountains."

Volcanic Stream Floods

Perret's and Heilprin's "water of volcanic origin," and the "erupted water" of Curtis as hereafter quoted, agree with the common sense of the natives in considering the paroxysmal floods volcanic, and obvious for the paroxysmal period. The floods came in the earliest days of the Pelée eruption, ended with the appearance of the dome and spine and glow in July, did not recur in the following year of nuées ardentes," and were conspicuous at St. Vincent in the Rabaka an hour before the first crisis, and in the Wallibu for 2 or 3 days following.

The natives associated the floods, not only of the Blanche, but of all the radial rivers of Pelée, with the eruptions. The flood maxima were on days different from those of the great eruptive convections that made thunder storms. When scientists insisted on cloudburst origins, which Kennan called "steam and dust condensed and mixed" (see Finch, 1930, who objects to this), the natives said that the floods came out of the ground under a clear sky, that such were unknown before the eruptions, and that a rainstorm would affect all the gorges, and not one at a time as noticed. Parel allowed himself to be persuaded of meteorological origin, in spite of

> "the deep noise of the swelling water, of all the torrents which take their source upon the mountain, generated by overflows such as have never yet been seen. This immense rising of thirty streams at once, without one drop of rain having fallen on the sea coast . . ."

—all this was written by Parel in St. Pierre the day before the disaster.

The Blanche flood of May 5 was attributed to the crater-lake although the crater was eviscerated 2 days before. It was the Blanche river-bed product also, where were Hovey's and Lacroix's deep fissures, and where on April 27 before the disaster, at the crater floor margin "water spouted in cascades at the base of the walls" and "a jet of hot water a meter in diameter emerged as a cascade at the bottom of a fissure" in the river bed, well down the valley from the V gateway and the lake rampart, location 53; this, before the eruptions, was the underground outlet for Etang Sec and principal source of River Blanche water. Both lake margin and river bed were vomiting up deep water.

The flood of May 5 was a rift heaving and opening, accompanied by lake bed subsidence as in St. Vincent. If the River Blanche springs could open by release of steamboiler pressure, so could those of the River Precheur with source in the somma ring crack, and of the River Falaise with source at the summit cone in the solfataras of that name. Curtis's (1902) interpretation, as "erupted water," applies equally to the Wallibu, and to the Larikai and Rabaka Rivers in St. Vincent, and is accordant with volcanoes elsewhere in Java, Alaska, Central America, and New Zealand. There were submarine offshore cable disturbances in St. Vincent as in Martinique. Curtis is in agreement with the natives, and with Hill and Heilprin.

If denuding an ash covering could induce all mud floods by cloud-burst, why was this great flood period confined principally to the paroxysmal eruption period, not extended to the adjacent Carbet mountains, and not repeated in the 2 following years of "nuée ardente" eruptions, possibly even hotter for meteorological convection? Finch (1930) has cast doubt on volcanic steam as a rain-maker, but believes volcanic convection a powerful precipitant of meteoric rain.

Both Pelée and Soufrière had radial old dike rifts full of confined water, these heaved open over the profound basal water steam pressure, and emitted liquid water with engulfment dirt in the first year of paroxysmal eruption. Eruptive heaving became an established mechanism.

The heaving of a volcanic mountain does not throw out a crater lake, it drops it down. Crater-lake water is high level water, confined within dike barriers. The water drops down toward basal water level, and like the basal water becomes involved in the steam boiler, with the crater or fissure walls above caving in and choking the funnel.

The eruption has to heave the mountain and clear away obstructing liquid water, heave again and clear openings for steam pulsation against engulfing debris, adopt a boiler mechanism, clogged above, and aspirated by spring action below, which sets dates for repeated cooling and geyser rhythm; and it uses for its conduit the dike rift to which the mountain and the crater well are details. Engulfment debris is one ash maker. The dike rift is the magma bringer, and the magma is no respecter of islands or shore lines nor of flat features on the crust of the globe. It is guided to a crater only if that crater is the path of least resistance. Active solfataras are open paths within dike systems. Hence subaerial eruption. Submarine eruption may offer less resistance but requires equipment to detect it.

The Caribbees have had submarine eruptions unperceived; submarine eruptions are not explosive; and submarine lava-flow might have accompanied the events of 1902, for there was no geophysical measurement to find out. Submarine lava foam with instantly frozen skin of heat-confining glass may be highly mobile.

The cable companies made soundings, and cables were repeatedly ruptured, and the eruptions made tidal waves. These were accountd for by submarine landslips, but faulting was more probable. One main break was straight in line with River Blanche rift, 12 miles out to sea southwest from Pelée, another was 14 miles northwest.

Sapper (1927) calls attention to many cases apart from the ejection of crater lakes, where water floods have accompanied and preceded volcanic eruptions. At volcanoes of Java and Sumatra, Celebes, the Canary Islands, Kamchatka, Vesuvius and Etna, Guatemala, Nicaragua, and Costa Rica, and some places in Spain and Italy associated with earthquakes, there have been mud eruptions of ground water. The following is a free translation of the summary furnished by Lacroix (1904) for the critical mud eruption of Pelée 1902:

"In the night of May 4-5 the River Blanche overflowed; violet detonations were heard at the crater where the sky was shot with lightnings; the ash fell at Macouba. At 9:00 a.m. Pelée was calm; at 10:00 a.m. detonations were heard, the River Blanche became a furious torrent; at 12:45 p.m. a violent mud eruption was seen at the crater, the dam of the Etang Sec burst, an enormous smoking mass of thick mud and big blocks of rock showered the vegetation that covers the mountain slopes, vomited into the upper valley of the Blanche and flooded the delta at its mouth, destroying the Guérin sugar mill and making the first 25 victims of the eruption. A small tidal wave accompanied the entrance of this flood into the sea, was propagated to St. Pierre, but the cable lying offshore southwest opposite the Rivière Blanche and 16 miles from the crater had been broken at 7:47 a.m. All the northern rivers now began to have floods during the next few days."

The detail of sequence for the other Pelée gorges is unknown as most of them were abandoned by inhabitants. The Roxelane and Pères Rivers had floods before May 7. On May 7 the Roxelane was normal while the River Pères, draining the Pelée slope more directly, had a tumultuous flood with a sinkhole at its mouth: both headed in the same region so far as rainfall was concerned. After August 30 the River Pères had been widened at its mouth. Not so the Roxelane, which drained the older mountains.

That the individual rivers on the volcano had their own spring sources was shown by the River Sèche remaining totally dry May 5 and May 6 when the adjoining River Blanche, heading in the same rainfall region, made floods. Yet on May 7 River Sèche had a flood.

Hovey and Curtis on June 24 were in heavy rain at the crater and on returning across the River Sèche, location 54, found 18 inches of yellow muddy water replacing the 3 inches of their upward trip. The heavy eruption "was sending enormous clouds of dust-laden steam down the gorge of the Blanche to a point below the so-called lower crater." With a thunderous noise a wall of hot water more than 10 feet high swept by them in the Sèche. The roar was like a railroad train, and the water dashing from side to side of the narrow gorge caused the ground to shake like a ship with racing propeller. The water was black as ink with volcanic ash carrying erupted boulders 5 feet in diameter. Curtis wrote *"this I interpreted as erupted water,* and this process is *the most satisfactory explanation I have yet found for the great mud flows* which have deluged the lower slope of Pelée." Heilprin unquestioningly calls the floods "torrents of volcanic water deluging and destroying towns and villages."

The River Canonville, location 39, had violent floods May 6 and May 7 and was uninhabited thereafter. The River Lamare, which heads close to the crater, had numerous unobserved floods, deposited 15 or 20 feet of new delta, and must have had very hot water in the big eruptions.

The River Precheur, location 55, which heads against the somma ridge of the crater, became muddy after May 5; floods increased May 6 and 7, the banks fell in, houses were crushed by cinders, and on May 8, at night, during the same hours that Father Altéroche reported tremendous fiery streams, the Precheur had a flood that carried away 12 houses and destroyed others with large boulders and undermining trenches. Thereafter there were unobserved floods, ravines were extended, the flood plain was widened and the destruction became complete.

The Grande River, location 56, had several destructive floods. A big one occurred at 4:00 a.m. May 8 burying houses and road, sending forward a mud wall 10 feet high that carried boulders 10 feet in diameter. Other known floods were May 11, May 19, June 6, June 17, and June 22. The Macouba River, location 57, built a huge new delta with big boulders.

Basse Pointe River, location 46, wrought damage in a larger town with floods increasing in their destructive effects. These floods were better recorded than the others. At 3:00 a.m. May 8, the day of the St. Pierre catastrophe, this river overflowed overwhelmingly carrying into the sea big trees and boulders; 20 houses on the river bank were transported, all the streets of the town were obstructed by mud and rock fragments.

On May 17 at Basse Pointe at 1:10 p.m. the mud covered the bridge in a new flood; floating matter passed over the surface of the bridge; by 5:00 p.m. the river resumed its normal level. More than 2 feet of deposit was added. An eruption of Pelée came 4 hours after this flood, from 4:00 p.m. to 8:00 p.m., when there was a fall of ash over the whole island even to Mount Vauclin, far south. Just as the flood of May 8 had preceded the maximum of eruption by 5 hours, so did this flood by the same interval of time, as though the water pressure systematically took effect in advance of the gas escape.

The next notable flood of Basse Pointe River again occurred preceding a violent eruption of Pelée, considered by some even stronger than that of May 8; this was the outbreak at 5:20 a.m. May 20 which destroyed the second stories of the St. Pierre houses that had resisted the earlier eruptions. The Basse Pointe flood was 17 hours before the outbreak, at 12:30 p.m. May 19, more violent than the preceding floods, just as was the eruption. On the right bank of the stream a house above the bridge was floated away to the ocean like a ship. Below the bridge the river dug a wide trench right through the town and swept away 40 houses. Six feet of new material was deposited in the bed of the river enclosing boulders of several cubic yards bulk as well as big trunks of trees: the bed of the river was now entirely above the highest part of the bridge, which was disrupted. Many stones fell at Basse Pointe during the eruption of May 20.

4:00 p m. at Basse Pointe May 20 there was recurrence of floods, and others 2:00 a.m.-4:30 a.m. May 21; 4:30 a.m. and at 11:00 a.m. May 22, midnight May 24-25, and 10:30 p.m. May 25, when a new trench was dug through the town on one of the streets 8 feet deep, and 3 feet more of river bed was added above the bridge level. This last flood preceded the eruptions of 8:00 a.m. and 8:00 p.m. May 26, which caused the flight of Heilprin and Kennan from Vivé. The later floods preceded eruptions by a longer interval than in the eruptions of May 8 and May 17.

In confirmation of this continuance of major Basse Pointe floods, anticipating contiguous eruptions by longer and longer intervals, and spread out also among minor floods, the paroxysmal eruption of June 6 was preceded 6 days by a flood of the Basse Pointe River May 31, at noon, with mud near 50° C., and the river bed was built up 31 inches.

The next powerful eruption was that of July 9 and there were small Basse Pointe floods June 8, June 16, and June 17 in the morning; but on June 17 at

5:00 p.m. the most tremendous Basse Point flood of all devastated the town where but few persons remained. These had barely time enough to save themselves when they saw sweeping through the town a colossal mass of muddy water 16 feet high and 150 feet wide carrying trees and rocks. The temperature of the water was about 40° C., and it so displaced the air in front of it, in rushing down the valley, as to make a dense cloud of dust, twigs and leaves. The flood came with a roar against two masonry houses that in less than a second were undermined, lifted 15 feet into the air and fell in ruins into the torrent. Two others followed. Then an electric plant and its outhouse on a slight eminence had all its doors broken in, the far wall pushed out, the near wall transported by the flood. Any strong houses resisting the shock of the flood were quite uninhabitable with from 5 to 10 feet of mud on their floors. Twenty-two houses were carried away and some 35 demolished or buried. Boulders so large were hurled against houses as to shove them along intact.

In like manner the great eruption of August 30 was preceded by Basse Pointe floods of July 14 and August 9, and river and town were filled still deeper with debris after the whole settlement was evacuated. The details of all floods could not be learned, but there were more September 3 and September 10; that of the 3rd (the day of the St. Vincent eruption) was reported hot.

The effect on the shoreline at Basse Pointe was greater than anywhere else. Not only was the shore line built out 650 feet, but a sand bar was built across a bay west of Basse Pointe so as to separate a pond from the sea. The whole north coast of Martinique had been added to by new beaches at the foot of the cliff between Basse Pointe and Grand Rivière. All this kind of construction extended to Vivé and the mouth of the Capot River, location 20 (Fig. 2), there shutting off another bay with a sand bar, and this river is supplied by the notorious Falaise Gorge, location 21, believed to be a subsidiary crater in June, and taking its rise in hot solfataras at the immediate east base of the original upper cone of Pelée.

Volcanic Floods and Rainfall

Lacroix (1904, p. 421 and following) discusses secondary explosions and torrents of mud which were in perpetual conflict with the red hot deposits of the glow-clouds. Hovey, Curtis and the writer were impressed with this conflict, making high jets of secondary explosion. Perret (1935, pp. 27, 37, 51, 81, 103) accepts the glow-cloud as always an avalanche down the valley, variously modified with rainfall, torrents, and forward springing jets. He discusses "distilled" waters of volcanic origin. To him the St. Pierre disaster was a glow-cloud. The nuée ardente has entered the science as one thing, yet Perret and Lacroix are at great pains to demonstrate its modifications, and always to attribute water to rainfall. The presence of the ground water table continuous to ocean water as a bedrock filling is nowhere mentioned, yet Lacroix repeatedly saw jets of water and streams of mud on the deep rift of Pelée, and Perret makes much of hot stones tossed about by a rushing torrent, and rain water reacting with the hot lava dome.

FIGURE 26. *Boulder near sea, Sèche-Blanche plain of Pelée 1902 (after Hovey).* Block 30 feet long, 200 yards from beach, mud transport from a Pelée vent. White circle encloses a man.

FIGURE 27. *Boulder of Montrose, California, December 31, 1933 (after Tolman).* Transport by mud flood. White circle encloses a man.

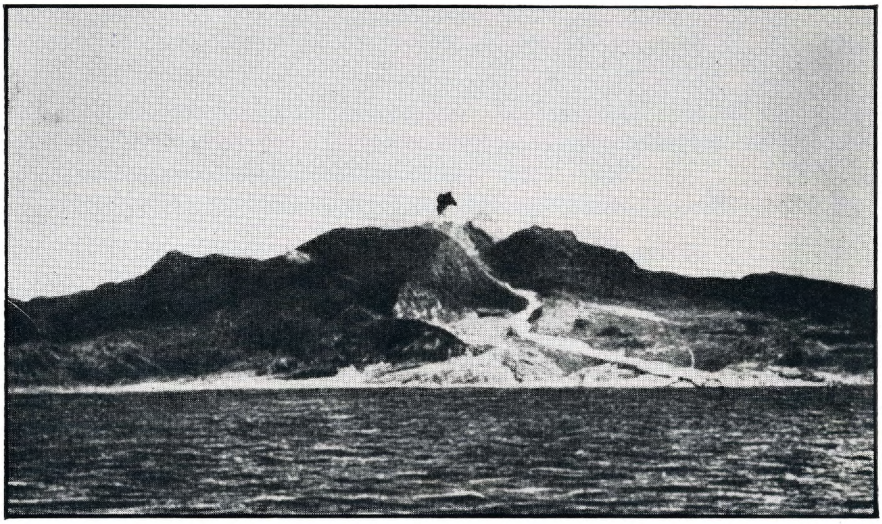


FIGURE 28. *Nuée scar, showing on the right boulder field of Figure 26, River Blanche (after Lacroix).* Volcano Pelée, volcanic delta of rivers Claire, Blanche and Sèche, 1902.

Curtis (1902) and the writer had no question of ground water spring sources in river beds, actuated by volcanic pressure at times of eruption. The writers above cited did not question deep cracks in the bottoms of Rivers Blanche and Séche. All observers were impressed by secondary phenomena of running water contacting hot deposits. The present paper insists on the deep cracks and the ground water as primary essentials.

Illustrations of Boulder Transport

When it comes to boulders, I reproduce here in three figures the following: A boulder 30 feet long of light gray andesite, near the seacoast, location 59, in the Séche-Blanche deposits was photographed by Hovey in June 1902 about 200 yards from the beach (Fig. 26). A boulder of similar size was illustrated by Tolman (Fig. 27) from the Montrose flood in southern California December 31, 1933, a torrent that displaced houses, occasioned by destruction of mountain vegetation releasing flood waters after forest fires, and illustrating what only mud floods can do (apart from glacial transport). Figure 28 is a retouched photograph published by Lacroix (1904, Fig. 70) of the boulder field at the mouth of rivers Claire, Blanche, and Séche showing the scar of a nuèe ardente immediately after its passage in November 1902.

These scars are also reported by Perret (1935) who says that the nuées ardentes produced the characteristic sound of a splashing liquid audible as far as the field station, and that they were veritable streams of fire by night; the entire valley glowed red for hours after their passage. He speaks of the extreme angularity of lava blocks in block flows; and at the base of Morne Lénard figures hard conglomerate scored by passing rocks, much like glacial scour. Such scour by mud flows carrying boulders is also well known. Perret says of this scar photograph that the nuée ardente deposits boulders and ash along its course, and the net result of its passage is a ridge. The active nuées roll the larger and heavier fragments, press down and slide on the ground, and there is a gouging process which leaves a trough with a cross section similar to a W, with a central ridge like the medial moraine of a glacier. The cause of the central ridge is "entirely unexplained" (Perret).

The advancing front of a nuée reveals a diagonally upward and forward jetting, which Perret calls "forward-springing jets." He writes that a small nuée ardente reaching Morne Lénard seems diffuse, when there arises "as from a hidden crater" a regenerated cloud with densely compressed convolutions, and a new lease of life which he attributes to collision. The causes are no longer unexplained, for ridge and transport, if we admit a rift progressively opening.

The only parallels to transport of a boulder (Hovey) 30x24x22 feet are in glaciers or on torrential mountain floods. Perret (1935) figures even larger Pelée boulders. No mass of gas could roll these boulders 3 miles on the slope (Figure 16) shown. They could, however, be transported by upward-vomiting mud at the subsidiary craters at the base of Morne Lénard and other places along the rift as the rifts slightly opened to emit upjets and induce flood transport from the crateral dome avalanches all the way to the sea.

Excessive flood apparently initiated the paroxysmal eruptions; minor floods accompanied some or all of the nuées, and the subterranean dip of the fault-plane, or magma gaps of Fig. 16, probably affected an inclined upward jet in the southward direction to bring about a cushioned trajectory downward in the peculiar cataclysm tornadoes of the several southward blasts. All of Perret's comments and his difficulties, appear to justify the rift and flood accompaniment of Peléan eruptions.

Illustrations of Inclined Blasts

Nuées ardentes of the nonparoxysmic phase of the eruptions definitely do not make blasts downward, and on the contrary migrate while making remarkable blasts upward the whole length of the River Blanche, with the cauliflower clouds sometimes showing gigantic "forward-springing jets."

Four tracings from photographs are reproduced here as follows: Figure 29: a 41-degree upjet apparently southwestward from the bottom of River Claire photographed by Jaggar opposite River Pères the afternoon of July 6, 1902, with a sharply delineated source in the bottom of the valley, just where similar jets were photographed by others. Figure 30: a 45-degree upjet apparently westward from the bottoms of both Rivers Blanche and Claire photographed by Hovey from the steamer Madiana, opposite Coffre à Mort, the afternoon of July 6, 1902 probably a few seconds earlier than that of Figure 29, and the same jet, nearly at right angles to Jaggar's line of sight. It shows the thick fan cone of the combined deltas, a structure due to erosion and sediment of flood water, and not a nuée ridge piled up as upbuilt track of the scar represented in Figure 28. The photograph shows what would be expected if the rift vomited waters principally near Morne Lénard. Figure 31 illustrates the nuée ardente at maximum on the River Claire side of Morne Lénard, a 37-degree angle of upjet, taken by Perret at St. Pierre February 9, 1930. This shows how the 1930 eruption duplicated the rift conditions of 1902-03. Figure 32: Jet of same type taken for Heilprin (1903, 266) from steamer June 5, 1902, with a still flatter angle of trajectory (25 degrees): camera position about same as for Figure 29. (See photographs Figures 34 Jaggar, 35 Hovey, 36 Perret).

Suggested Explanation of Glow Clouds

On the basis of quoted experiences of Pelée and Soufrière, and the sequent processes, the writer ventures to explain migratory glow clouds of volcanic matter that he saw in action rolling down the River Blanche in July 1902. This was after magma had increased the size of the crateral dome, a spine had appeared, and a glowing crack had heaved open athwart the dome as shown by the black line across its southwestern aspect in Figure 6 of June 28 as drawn by the writer from the sea opposite Carbet.

More than a month before, when American geologists first saw the smoking heap of boulders on May 21 in the crater bottom (Fig. 5), which, by July 6, had increased to an andesite dome and pushed up its core to develop the spine (Jaggar 1904) and downblasts shown in the birdseye sketch (Fig. 33), there was no mention in the writer's May notes of downrushing cauliflower clouds filling the bottom of the River Blanche valley beyond what the sketch shows. There was, however, on May 21-22 a steaming vent in the bottom of River Blanche next to Morne Lénard, called by the natives a crater or "soufrière," and not doubted as being a vent. U.S. Geologist R. T. Hill even thought it the main source of the St. Pierre blast, Hovey and Curtis called this locality "Russell's Crater" after I. C. Russell who was with us and was impressed by it, and Kennan and Heilprin discussed it.

In my sketches of May 21 when we cruised along the shore in the U.S.S. Potomac, I labelled the V-shaped gorge that opened from the crater into the River Blanche a "great rift in the mountain side and steam jets in continuation of same line below like a fracture N 53 E". (Fig. 33).

The notes on the crater described it as emerging from the fog at 3:10 p.m. and steaming, a "chasm filled with huge crusted blocks of rock, and steam rising from the midst of the pile. Apparently an open rent. Cloud-burst flood drainage, mud flows and digitate gulches."

When on July 4 I climbed from the mouth of the River Sèche and kept up the spur south of the gorge, location 60, which by then was 800 feet deep, earthy breccias were seen at the side, and there were at least four thick andesite sheets in the great north wall of the crater dipping 7° to the northeast under

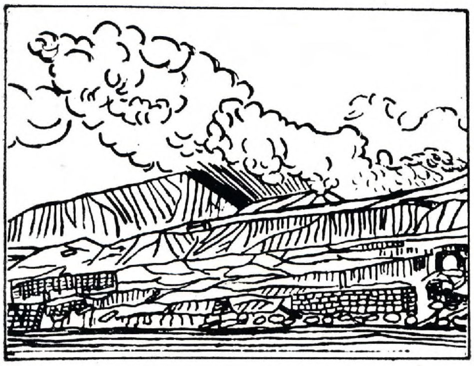


FIGURE 29. *Upjet from River Claire at Morne Lénard, after Jaggar.* July 6, 1902 from Fonds Coré. Compare Figures 16 and 34, for position see Figure 3.

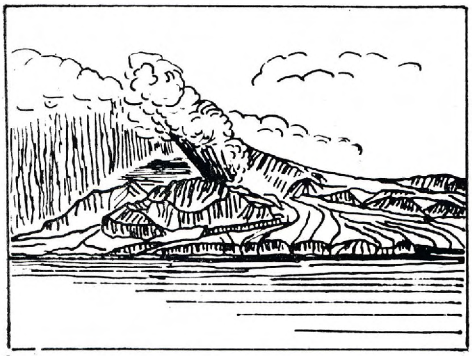


FIGURE 30. *Same upjet as Figure 29, from ship opposite Coffre à Mort, (after Hovey).* July 6, 1902, compare Figure 35.

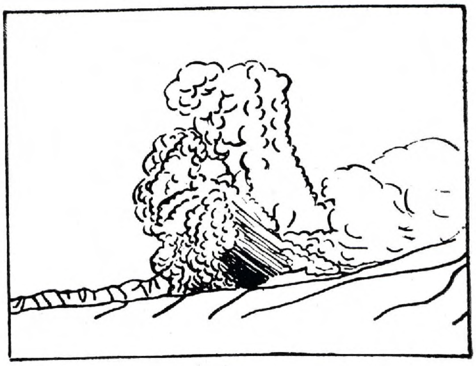


FIGURE 31. *Flatter upjet at same place February 9, 1930 (after Perret).* Duplicates conditions of 1902. Photo from St. Pierre. Compare Figure 36.

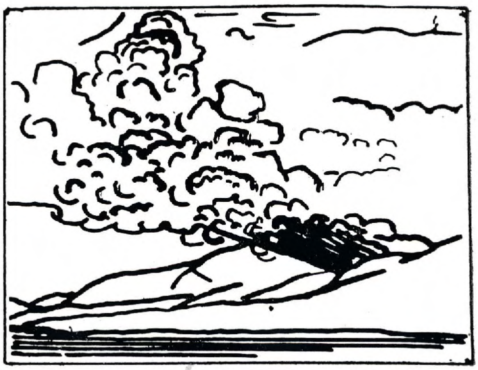


FIGURE 32. *Still flatter upjet at same place June 5, 1902 (after Heilprin).* From Fonds Coré position, see Figure 3.

higher agglomerates. I paced off a baseline and dictated a compass survey of the crater position.

At this time cauliflower clouds seemed to roll down the bottom of the valley of the River Blanche starting in avalanches from the cone and acquiring in a manner then totally unexplained an increase of uprising energy, an increase of cauliflower energy at the base of each forward moving volute, as though a new jet were springing up out of the ground at each point reached, and this extended even seaward from Morne Lénard in the bottom of the valley.

These phenomena of forward-springing and of renewed energy have been described by Lacroix for the winter of 1902-1903 and by Perret for the eruption of 1930 ("regeneration as from a hidden crater"), and both described the very narrow raised track of debris with an inner medial slight ridge along the middle of the bottom of the Blanche valley as seen immediately after the passage of a glow cloud. Perret describes two small creases lengthwise of this ridgelet, a double U, indicating that the ridge is triple. This linear scar immediately after eruption in the flat-topped volcanic flood plain of the bottoms of the valleys is destroyed by the rains, floods, winds, and subsequent eruptions, but Lacroix exhibits a retouched photograph (our Fig. 28) showing the definiteness of the glow cloud mole-hill.

This is explained by these authors as the product of a unique Peléan globule of energized magma emulsion that rolls down the valley boiling up with ever-renewed energy. It is energized by shock of obstacles and does not reach maximum until at a point down the slope remote from the crater. Sometimes it reaches the sea, sometimes it stops at Morne Lénard. Ingenuity was required to account for clouds shooting up in a line of sources from crater to shore, with increased cauliflower energy in the lower valley and the whole line producing a wall of boiling ash sharply delimited against a linear horizontal cumulus overhanging above. The linear cumulus in the upper region follows in plan the course of the valley below (Figs. 13-14). The line of scar in the bottom of the valley is supposed to be the tenuous contact of self-propelling cloud with the ground. The source is supposed to be sudden rupture in the carapace of the dome, jetting its gases downward. "Unexplained" high gas tension, high incandescence and mass of solid matter, produced "only" by an orifice in the shell of the summit dome was believed to distinguish Pelée as different from Vesuvius.

Heilprin and Mercalli combatted this explanation and thought Lacroix had over-accented the "nuées ardentes." But Heilprin's explanation as "the overloaded part of a volcanic steam explosion," and Mercalli's as a "simple avalanche of fragmentary lava overcharged with steam" do not account for linear scar and progressive jetting. The paroxysmal eruptions of major intensity are partly different in underground origin from "nuées ardentes," and are much more sudden and cushioned boiler explosions. The migrating glow clouds do have progressive rift openings under the deposits of the valley, the wedge splitting or heaving open of an unseen crack, small but energetic like a succession of rifle barrels that leaves the scar above described. This crack is nothing more than the radial rift belt of Pelée, on the line of which are the River Claire, River Blanche, and Falaise solfataras, and the spring sources of the Basse Pointe river. Offset échelon members of the same rift system are the great Philomène scarp, the Claire and Blanche solfataras, the V-shaped gateway, the main ancient rupture of Etang Sec and Morne La Croix, and the Basse Pointe gorge to the northeast.

In regard to the gigantic blasts downward and horizontally that destroyed St. Pierre and Sainte Philomène again and again, both backed by cliffs bounding a graben sector, with radial modification of August 30 assisted by the dome filling, it can be shown that at least one of these great explosions (August 30) utilized the rift system for a vertical jet, 5 miles high, principally over the crater, and highly complicated with liquid water from very profound depths. These two features, phreatic water and depth, give character to Lacroix's dis-

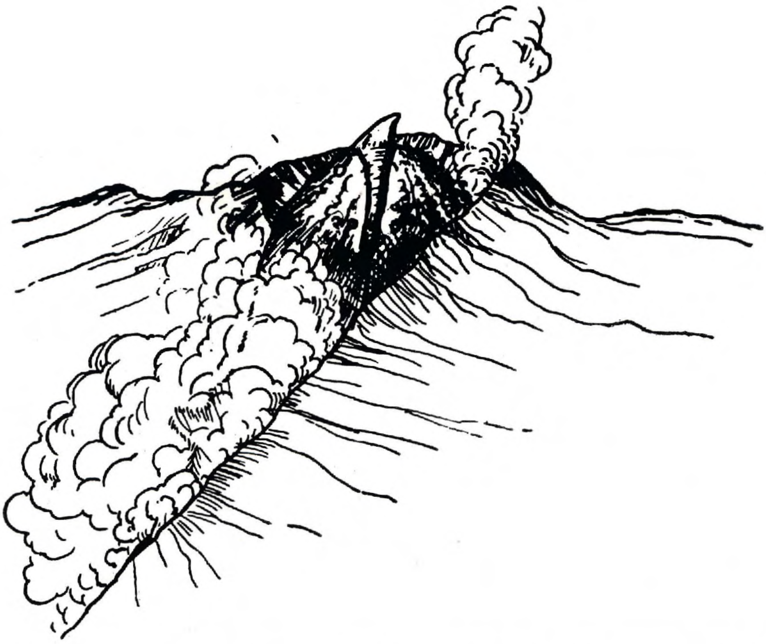


FIGURE 33. *Bird's eye sketch of dome and spine July 6, 1902.* By Jaggar drawn from St. Pierre, to elucidate photographs of Pelée taken during a clear spell in the morning. This was the first recorded appearance of a spine, and this spine was destroyed in the August 30th eruption.

tinction separating the paroxysmal eruption period. There is a possibility that the curve mounted in intensity as well as interval up to August 30, and that in flattening from October to December (Figure 21) explosive intensity decreased and magmatic upflow increased to replace steam with mixed gases.

It is difficult to evaluate the part played by ground water in the initial culmination of the 1929 renewal of outbreak about December 16, but as there was no major paroxysm at all in that year, and the main initial happening was an inner collapse of the 1903 dome followed by inner growth, it seems likely that it was chiefly magmatic like the fluctuations of Kilauea lava (Jaggar 1947).

Perret's "Plinian" and Lacroix's "paroxysmal" show that these authors recognized distinct steam-blast eruption, but it is curious that neither of them recognized ground water as a heavy body of liquid under the land merging downward into salt water. Lacroix mentions the suggestions made by one author concerning the increase of water vapor during the progress of a blast to the effect that such water might have been furnished in part by wet ground in contact with hot material. Lacroix replies that such a source of steam would be insignificant, as the heating of the "soil" would require a certain time incompatible with the rapidity of the progress of a down-blast; the quantity of steam in a down jet exhibited no variation, whether it went down a wet gulch or traveled over the still-hot dry surface of the next preceding blast. Ground water as a voluminous deep body is not mentioned.

Lacroix considered that explosions probably occur inside the new lava dome under the shell:

> "Explosion is occasioned by the sudden expansion (détente) of water vapor contained in the magma. As the production of 'ardent clouds' was accompanied by increase of magma from the depths, manifested by a re-elevation of the spine which had previously lost height from its summit breakage, it appears that deep upthrust of new material played an important part in the phenomenon."

It is on this possibility of internal steam in the dome that Lacroix relies for his entire theory of the "ardent clouds," because superheated steam has potential energy comparable to a high explosive. This explanation was accepted by Perret, postulating excessive high temperatures, lava underground in the form of compressed vapor, discharged to the surface and condensed into crystalline ash. The reply to this is that vaporized magma would be close to the temperatures of an electric arc, white hot; that such gas would leave its orifices with a vitreous lip of black glass, like fulgurite; that the condensation would be vitreous globules, identifiable; and finally that white heat at night would appear at erupting vents. Such phenomena were not observed. Perret cited this possibility as merely a dream, but his error lay in considering the nuées ardentes as all emerging from the new summit andesite dome.

This dome cannot be conceived as housing such gigantic compressed energy in units of erupted magma that they roll down as avalanches 3 miles on a flat slope, carrying with them 50-ton boulders, if they have no eruptive cracks or water along the route to assist. Such avalanche would not stop at definite places halfway down, or at the sea, where the sea water does not particularly renew explosions; they would not renew explosions in contact with obstacles, and retain explosive energy so as to make fresh vertical or inclined cauliflower jets, either forward springing or backwards, at several places in the valley. Opening vents would localize all these definite places. Another defect in the avalanche globule was to make these identical in series in "extremely wide range of intensity," yet the downblasts were full of muddy water at those major paroxysms when there was no andesite dome, and the second of these, May 5, was confessedly a phreatic flood.

At other volcanoes with similar domes there are no nuées ardentes. At still other volcanoes there are downblasts with or without mud flows, and without any domes. At Pelée there are carefully investigated and acknowledged rift structure and rift solfataras right under the track of the blasts, which solfataras the globule explanation does not use. There are minutely detailed synchronous floods and photographed mud flows coming directly up the track of the blasts, all explained away as secondary.

The subterranean water of Daubrée is important and so are the studies of salt water admixture in Holland and Germany of Ghyben 1889, Herzberg 1901, Lindgren in Hawaii 1903 in the very porous basalts of Molokai, Imbeaux and Pennink 1905, (see Tolman, 1938) and the many studies of geyser waters

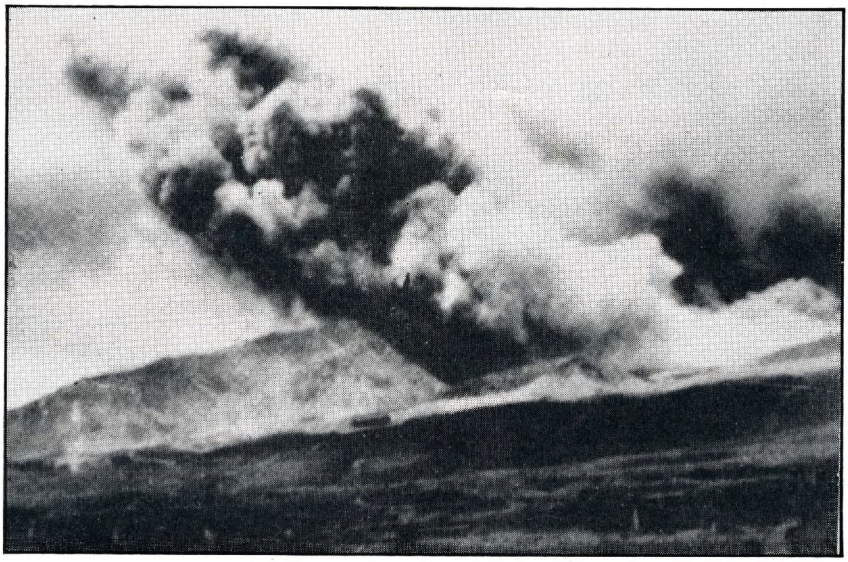


FIGURE 34. *Photograph by Jaggar from Fonds Coré region on shore, of blast rising behind Morne Lénard July 6, 1902.* Compare Figure 29.

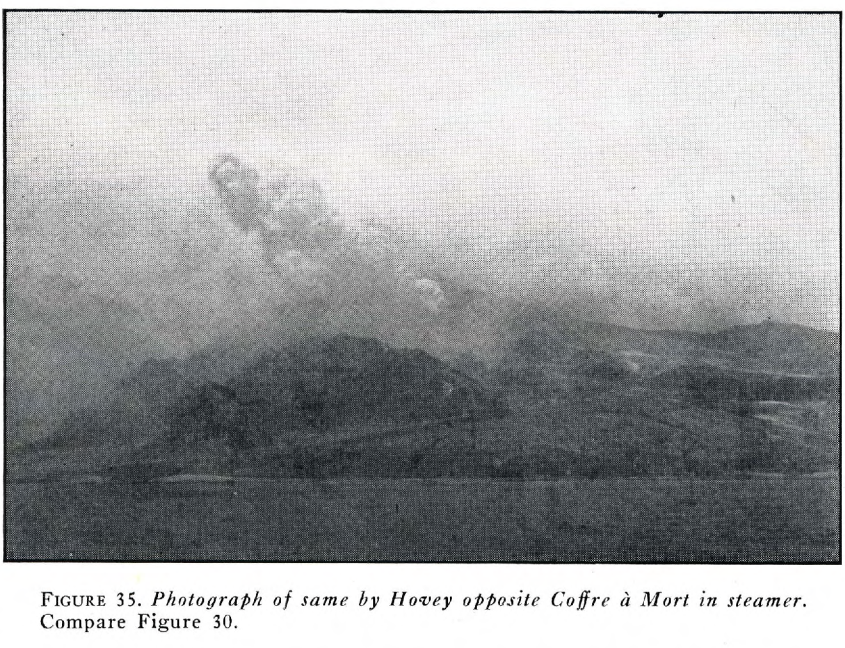


FIGURE 35. *Photograph of same by Hovey opposite Coffre à Mort in steamer.* Compare Figure 30.

FIGURE 36. *Photograph by Perret February 9, 1930, of similar blast in same place.* Compare Figure 31.

in Iceland, New Zealand, and Yellowstone Park. Excessive aqueous potency of magma in contrast to obvious structure and water the present writer does not find necessary, as his experience of magma gases makes water vapor a secondary product (Jaggar 1940).

To him in 1902 and now, surface volcanism in eruption on the earth today is contaminate and degenerate, and subterranean structure of rock, containing water and air, may be given first consideration in studying volcanic process.

Suggested Explanation of Major Blasts

The author's explanation of the paroxysmal downblast at St. Pierre is that a nozzle jetting south, of about 40° dip north, was opened on the River Blanche rift for a geyser spout of water, steam, and mud. This was similar to the west and southwest jets of Figures 29-32 and 34-36, but southward, more violent, and cushioned by the downfall of material from above. It was more aqueous, less magmatic and of different inclination than the magma-mixed "nuées" later, but both came up the cracks in the bottoms of the valleys. These violent geyser jets from ground-water invasion of a dike chamber came at increasing intervals (Figures 16, 21 and 38). The culminations were dated by aqueous boiling effervescences reached by increasing volumes of water in chamber fillings. The geyser furnace was from released magma heat of exothermic gas reaction, the liquid magma rising and frothing. The source of disaster was ground water. The mud and boulder ejecta were robbing the walls and enlarging the chamber. Boulder fills were especially characteristic of the deep solfataras of River Blanche, the rift opening itself from crater seaward. The water chamber is under a plexus of radial spring fissures in gulches, the River Blanche rift being dominant. The magma column is more central and crateral. Paroxysmal dates were those when release by minor overflow permitted sudden lift of boiling-point isobars, major expansion down the boiler tubes, and breaking open of the same north-dipping rifle barrel each time that St. Pierre was invaded (May 8, May 20, June 6, etc.).

We know from photographs (Figs. 5, 34, 19) that the rifle barrels of the dome wall crack dip vertical, the Lenard crater dips northeast and the lower Blanche nearly vertical; presumably the north-dipping vent (south-directed mortar) is a crook not identified in the Blanche rift somewhere below the crateral notch that develops the southward jet only over exceptional stress, like the weak rivets of a yielding steam boiler. But this is a valve which gravity closes.

Such valves, even when hidden, are not obscure or hypothetical. The rift in Pelée is clearly expressed in Lacroix's Figure 70 here reproduced as Figure 28. This is a photograph of the track of a downblast in November 1902, exaggerating the ash ridgelet by retouching, but useful as a diagram to show the two main bends in the rift which nuées followed. The upper crook bends west to the Claire and avoids the inconspicuous low escarpment Morne Lénard (Fig. 4, location 42): the lower crook eastward is probably the bend around Hovey's deep solfataras, location 51, back into the old lower valley. It is clear from Figures 34 to 36 that a blast shot up westward from an east-dipping vent in the upper bend. Figures 13 and 14 show nuées emerging from the whole rift. Lacroix's deep solfataras of locations 52 and 58 were at the same elevation as Hovey's, but do not seem to have been used in the ordinary nuées as they form an extensive series in the east branch of River Blanche. It may well be that the dip here of the underground shafts is north, they are deep and superficially long, NE-SW, progressively hotter up the valley, and if they opened they would be in line with the upper Blanche below its sharp bend, at location 58. This may be the paroxysm vent. It would rightly have been identified as "Morne Lénard crater."

Comparing this rift with the southwest rift of Mauna Loa, Figure 15 (photographed from an airplane), when erupting basaltic lava at 7:20 a.m. April 18, 1926, we see a different expression of a similar rift belt. Here the active crack of the moment is piling up basaltic pumice conelets, each over a separate "rifle barrel" of its own selection along the small open zigzag gashes of the rift, the choice determined by the wider openings which are naturally at the bends. In the lower left-hand part of the photograph, lava torrents are pouring along the rift itself and masking it. In the upper right part of the picture may be seen the extreme width of the rift belt, with the 1919 line of big cones behind the fumes, and the belt about 2 miles wide, marked by old gashes and cones with old lava flows masking portions of it. The inscribed white dashed lines show how the cracks made an echelon pattern. As lava builds up conelets in a line, even if first gas emission were inclined, construction by lava makes surface wells vertical. The assemblage of lines makes a ridge, a small model of world ignisepta, so that the Mauna Loa rift belt stands up in relief in contrast to that of Pelée shown by erosion valleys and depression.

Nevertheless, as indicated by Figure 28 and many of the magnificent later pictures of Lacroix and Perret, the whole series of nuées ardentes definitely made a ridge and ridgelets, but from ash and mud-geyser rifle barrels. Beautiful conelets of ash and mud were built up in many places and photographed. It is true that some such conelets, as figured by Curtis, were formed through secondary invasion of red-hot beds by surface waters. Those that I saw in St. Vincent however, tended rather to build elongate dams across streams, and multiple craterlet pits and erosion cliffs, as illustrated by Flett and Anderson, Curtis and Hovey. This does not exclude many others that are formed by deep vents. None of the deep ejections of mud during violent outbreaks was ever seen building because no one was there. Many of the shallow ejections formed by secondary contact of water and hot ash could be approached, hence the overaccent on secondary action.

The recovered head of ground water supplies the thermal spring basin during each interval. The recovery seepage is supplied by that same paroxysmal rainfall stimulated by volcanic convection which has been made so much of as "secondary." Torrential rain produces abundant secondary erosion and valley sediment with surface explosions, but its only effect on the paroxysmal power of the deep waters exploding up radial fractures is to mask with sediment the surface openings of the fractures.

There is no question of the value of rainfall in supplying the fresh underground water system, any more than in the geyser basins of the Yellowstone or Iceland. The only subject of controversy is whether the heavy ocean plus ground water, holding up the high and hotly fluid Herzberg lens of fresh water, and doing so as a reservoir, for lava to set throbbing, when magma ruptures subterraneous waterways, has not vastly more functional value in eruptive paroxysm, than has been credited to it. The rhythmic curves of Figures 21 and 38 indicate that it has. Incidentally this philosophy extends to the ground water pressure under the deep oceans, when volcanism from within opens ruptures.

The sympathy between Pelée and Soufrière 102 miles apart in this accordant rhythm, means that paroxysmal reaction involves an extensive deep volume of both water and magma in comparison with which the vents are small. The huge Caribbee ridge is piled and tumefied above a restrained intrusive system, released by tensional wedging open of the igniseptal fissure under shock of effervescence from one crater to another. Release of two big geysers and then a very small andesitic melt up a solfataric bore hole may be disastrous for congested mankind, but it is trivial when compared with the size of the magmatic engine.

Interpreting Soufrière on May 7 we get the same machine, itself an eccentric crater bowl (Fig. 18), and know principally the crateral vertical wall-crack rifle barrels, some of which inclined their jets southward to make the Wallibu-Rabaka "avalanche." If there were rift openings, they have no such certain positions or directive powers as the angles of the zigzag fracture of River Blanche. The outblast at Soufrière pit was a more intense edition of Halemaumau pit of Kilauea 1924, and similar to Taal 1911, with vertical ejection of mud and steam, magma foaming below, and backfall cushioning upjets to become radial outblasts. The rhythm of major sequence kept pace with Pelée, but the minutiae were not so observable, as the crater was a concealed bowl, the magma column did not rise above the flanks, and flank eruption through cracks was not so much its habit as at Pelée.

The verticality and radiality of the August 30 blast at Pelée, still using also the St. Pierre rifle barrel, appears to imply a final extra stress for the geyser component owing probably to the increased size of the boiler, and some extension of steam ways to the wall crack around the crateral lava column. Soufrière followed on September 3 and irregularly for two months.

The December 16 crisis matched the flattening curve (Fig. 38) for Pelée, but with inmixed magma gas fountaining, rather than geyser intensity. It utilized the whole Blanche rift to the ocean, and like the later glow clouds represented geyser steam, mud gush and lava, the magma having penetrated the water chambers after the maximum of August and so taken control of subsequent events.

The geyser steam gave place to lava gas, a watery edition of the 500-foot lava fountains of Mauna Loa, the settling of the rift blocks over magma partly shut off the ground water, and the system slowly settled into recurrent semi-geyser sheets of water, magmatic ash, and gas up the line of rifle barrels to make "nuées ardentes," without any more destructive paroxysms heaving open the mortar formerly directed to the siege of St. Pierre.

The Shore Rift Embayments

There is a peculiar rectangular inset to shore lines of volcano islands represented by the Waipio and Mohokea embayments of the island Hawaii (Fig. 8). These are occasioned by sector downfaulting, with cross step faults, distinctive of radial volcano rifts. They generate by erosion "verwerfungs thaler," fault valleys, exhaustively discussed by Friendlaender, and well known in the Canary Islands studied by Von Buch. As every scrap of surface evidence is valuable in dealing with so masked a feature as the Pelée rift, it is worth while to examine the physiography. A straight stretch of shore is notched inward between Precheur and St. Pierre, just as the vertical profile is notched downward between the Precheur and St. Pierre escarpments. A sector fault block is indicated. There were old hot springs bounding it.

The same thing is true of the west face of Soufrière, and here the case is even stronger, with the crater offset on the side of the indented shore. Between Wallibu and Larikai there is a smooth line of shore, indented. The Crater-Wallibu line was suspected as a rift in the 1902 eruption. The Crater-Larikai line has all the characters of a fault from the somma to the sea. There were old warm springs along the beach.

Inspection of the map of Hawaii, Figure 8, shows three lines of boundary in a somewhat equilateral triangle, of which the northeastern is about parallel to the Hawaiian chain. Lowthian Green called attention to the equidistant triangular spacing of the volcano centers. Other authors in Friedlaender's "Zeitschrift fur Vulkanologie" have suggested that the triangle mosaic in earth crust with volcanoes at the angles, gives a clue to depth of crust by distance of spacing.

These questions of structure by shore embayment and spacing the reader may verify by inspecting other maps, (Friedlaender 1916). Series of amphitheatres, sectors, embayments, and radial rifts may be found. Suffice it for this paper that sector blocks and fault valleys are accepted facts.

Note on Pelee 1851

In an old magazine of 1854 the drawing of Figure 37 was discovered by the writer, a very accurate pen-and-ink sketch of Mount Pelée made evidently on the spot from St. Pierre during the eruption of 1851. The striking features of

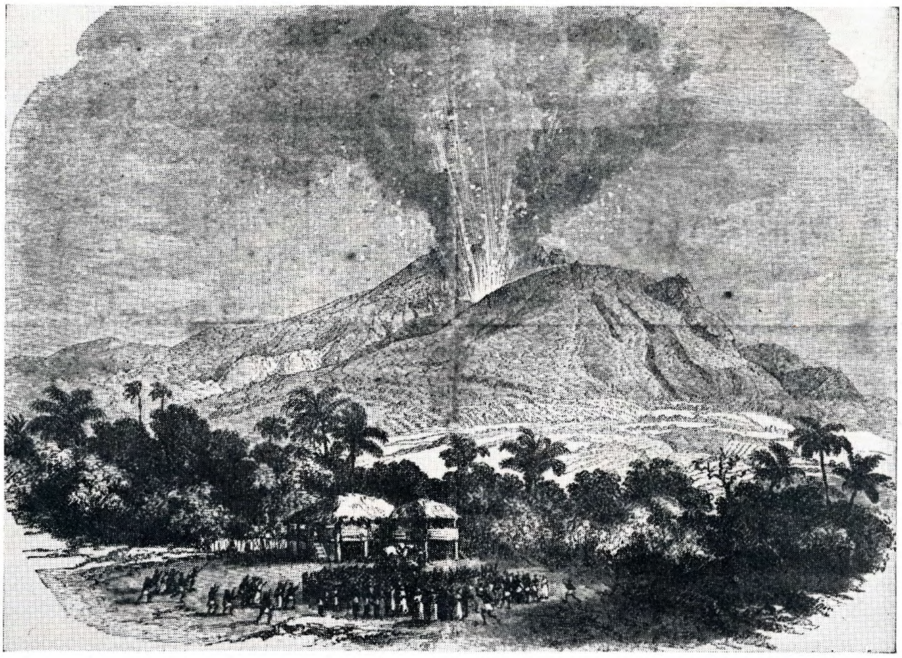


FIGURE 37. *Wood-cut of Pelée from St. Pierre in 1851 eruption of August 5.* Copied from "Ballou's Pictorial Drawing-room Companion" of 1854. Accuracy of the drawing compared with modern photographs is remarkable, and makes the 1851 eruption and the River Blanche rift below it appear to be in the same places as 1902.

The text reads: "August 5, 1851, the long extinguished crater of this volcano Pelée or Pelion began to vomit wreaths of smoke, with a noise resembling the deep mutterings of distant thunder. In the morning, within a vast circuit, houses, roads, plantations and vessels were covered with a light layer of cinders and calcined earth thrown out by the volcano during the night. This eruption occasioned no damage, and it was only from the ash and by seeing three enormous columns of smoke rising in the morning from the summit of the mountain, that many of the inhabitants of St. Peters knew anything of the phenomenon which had occurred. No shock of earthquake accompanied the eruption. At the first noises of the volcano, the terrified population of the town of Prêcheur abandoned their dwellings and removed to St. Pierre. The eruption has been followed by no indications of further outbreaks."

this drawing are its identity of feature with modern photographs, and the seeming identity of location of the 1851 crater with Etang Sec, the crater of 1902. As shown by the writer's translation of the old official account of the 1851 eruption (Jaggar 1903) the crater of that year was supposed to be at the head of River Claire (Fig. 5) and distinct from Etang Sec. There is no such distinction in evidence in the drawing of 1851, and if anyone in that year endowed with prophecy had drawn a picture of what Pelée would look like in 1902, he could not have done a better job than appears in this woodcut. Moreover he has well expressed the River Blanche rift, the old hard rock plugs, the transition from cone to the Plaine de la Consolation, and the Precheur escarpment. The accompanying magazine account of the 1851 eruption is in caption of Figure 37, wherein it appears that the inhabitants of Precheur bore the brunt of the alarm just as in 1902, and the "three enormous columns of smoke" suggest three openings on the rift.

"New Crater" of Soufriere

In this connection attention is called to the "Crater of 1812" or "New Crater" on the map of Soufrière (Fig. 7, location 64). Hovey and others assumed this the source of the 1812 eruption, for which there is no evidence. It is incredible that that big eruption was outside the main crater bowl. There is a tradition that the 1812 eruption was so big that it extended the main crater rift to the northeast, creating a little subsidiary crater, which was named the new crater. Its interest is in its alignment with Wallibu, and the main crater, and the highest summit, suggesting a true rift NE-SW. The main crater being eccentric (Fig. 18) in about the Lénard position compared with Pelée (Fig. 16), the 1812 enlargement amounted to a splitting back toward the central plug which should be found under the old somma somewhere northeast of the "New Crater."

THEORETICAL CONCLUSIONS

General Statement

The synthesis of facts introducing ground water steam makes use of the author's field work at Pelée and Soufrière in 1902 and 1936, of the bibliography of the Caribbees and its photographic record, and of comparative study of headings 1 to 27 in the appended synopsis applied to these volcanoes and to Hawaii. This sequence applies equally to any single volcanic system in time, and to different volcanic systems at the same time, as representative each of a world habit for the phase of volcanism that an igniseptum is in. The fundamental questions concern magmatic gases, boiler explosion of ground water steam, rift systems, intrusive magma before eruption, and cycles of engulfment.

All five subjects are vital to understanding of Kilauea and Mauna Loa, their rare steam explosions, their regular gas action, their lava-flow rift openings, their underground movements revealing intrusion continuously, and their controlled cycles varying diurnally, seasonally, and tidally, and aberrantly in relation to sudden lava drainage.

The paroxysmal steam blasts of 1924 showed how engulfment determined a series of geyser explosions of pure water vapor when submarine outflow drained a pit and carried the lava furnace below the artesian level, the pit clogged itself by collapse, and a surging rhythm of ejections was set up. This was ground water steam and chemically distinct from the gases of lava fountaining.

These Hawaiian questions, rift, ground water, intrusion furnace, and engulfment-lowering of magma, are applied to the volcano Pelée. Soufrière and five other volcanoes famous for steam blasts have been examined.

The writer has assembled witnesses and their statements. Essentials have been reviewed for Pelée, for the Hawaii comparison, for Soufrière, Tarawera, Sakurajima, Katmai, Taal, and Tomboro, and the conclusions combine structure, ground water and magma.

Rifts

Circular craters begin as linear rifts. Cones have radial or concentric fractures. Radial fractures in Pelée along the bottoms of the southwestern gorges are old features, revivified as deep solfataras, clogged with large boulders, developing temperatures over 400° C. in volcanic gases with excess of argon along with ammonium chloride as investigated years after the St. Pierre disaster by Hovey, Lacroix and Moissan.

The principal rift gorge is River Blanche, connecting sea and crater as the path of the downblasts; the crater accumulated a pile of dacite, eccentric to the mountain summit, and the "glow clouds" rose from the wall crack of the crater, from the notch below it, from next to an old plug halfway down the valley called Morne Lénard, and from two points in the great fan-cone delta of debris near the sea. The glow clouds migrated, they rose from a bubbling liquid, travelled a mile a minute, and evolved their product from mud to an incandescent dry pulp of ash. They stopped at the sea and did not boil the sea water.

They jetted up from the valley, but left only a ridgelet and solfataric heaps of boulders. The jets were at an angle or straight up in a belt, with accumulating cauliflower energy from crater to a maxima near the sea and showed a linear overhang of cumulus the whole length of the valley rift belts. MacDonald described the same extension of crater blast to rift belt westward at Soufrière in St. Vincent.

The valley rift belts appeared to be *en échelon* respectively at River Sèche, east branch River Blanche, main River Blanche, river Claire, river Canonville and possibly rivers Lamare and Precheur. Apart from the discovery by Hovey and Lacroix of the big deep solfataras in the Rivers Blanche and Claire on each side of the Lénard ridges, the remainder of the rift openings tended to be repeatedly masked by wet and dry valley-fill ejections.

After each paroxysmal ejection a boiling flood of mud was sweeping down the River Blanche without corresponding rainfall, and with no possibility of summit crater origin at the incandescent magma. On the downblast ridgelet scars, mud-flow linear sources were found in a V-point upstream, giving place up-valley to incandescent pulp. Similar mud flows mis-named "lava" flows were described by Calder and MacDonald in the western and southern valleys of Soufrière.

The paroxysmal valley eruptions of Pelée carried mountain blocks, partly from the notch and partly from the cumulo dome, weighing up to maxima of 50 tons or more, measuring scores of cubic yards, from crater to sea, a distance exceeding 3 miles. Nothing there but mud flood could do that work, and no mud-flow could travel a mile a minute on that grade, except over an opening crack that opened up at that rate and vomited up the flood from crater to Lénard, or from crater to sea. Lénard and shore were the two points observed as stopping places, or source places of upblast.

Underground Water Body

Volcanic islands have a water table, surface of a fresh water lens floating on sea water. The height of fresh water may be any distance above sea level, dependent on rainwater seepage supply, but its depth as a lens below sea level is forty times as much, dependent on sea water being one-fortieth heavier than fresh water. Lavas are porous rocks, seismically fractured and water permeable. Confined water between impermeable dikes may stand high above the water table, especially near craters, for craters are generated by dikes. Hot springs occur near craters in all the volcanic districts of the world.

Springs are heated by intrusive magma and magmatic gases. If all the fresh water were ejected or evaporated, the ocean source is illimitable and its pressure is invasive of a heaving mosaic of joints in a shore volcano, the topography of which is much more submarine than supramarine. Unless magma thermally insulates itself from ground water with a vitreous shell—which it does in solfataric simmering—magmatic inbreak (irruption) or outbreak (eruption) necessarily ruptures new waterways to contact with frothing slags, exothermically self heating when pressure is released.

In his paper on magmatic gases the writer (1940) is committed to statement from experiment that fundamental gases are principally carbon dioxide, hydrogen, nitrogen and the argon group, and that surficial contamination yields excess of air and water vapor, while chlorine and sulphur are from crateral concentrates. The sal ammoniac crystals and hydrochloric traces of River Blanche are evidence of subterranean chlorine from below sea level, but not necessarily magmatic chlorine. Moissan (Lacroix 1908, Jaggar, 1940, 344) found here, in the deep solfatara gases saturated with water vapor, about 8 percent hydrogen, 15 percent carbonic acid, 1.6 percent carbon monoxide, argon 8 percent in excess of its requirement for the 70 per cent of air present, 5.5 percent methane, and traces of sulphur and hydrochloric acid.

Shepherd (Jaggar 1940, 344) heating Pelée rocks in vacuo found water vapor, carbon dioxide, fluorine, nitrogen, carbon monoxide, sulphur, chlorine and argon in that order of decreasing volume after eliminating air. The remarkable gas specimens were two from the hypersthene andesite dome containing 12 and 2: per cent carbon gases with abundant sulphur and fluorine; a pumice from nuées ardentes of July 1902 containing nearly 3 percent of sulphur, 10 percent of chlorine, and 4 percent fluorine; and a breadcrust shell of 1902-1903, containing 96 percent water vapor, 26 cubic centimeters gas to the gram, fluorine second to water among all the constituents and chlorine almost as much; these two, fluorine and chlorine, made up 2 percent of airfree gases. The chlorine contents from the River Blanche pumice is many times greater than in any of the plutonic rocks or basalts from other volcanic districts, and ten times greater than any other Pelée specimen. This agrees with the sal ammoniac evidence of the River Blanche solfatara, to the effect that sea water did its work.

In May 1902 at Fort de France the writer published a warning that the eruptions of May 3, 5, 8, and 20 had increasing intervals, suggested a geyser with enlarging water chamber, and compared Krakatau that began May 20 and culminated August 26; there seemed in Martinique to be accumulation of steam in the depths that demanded periodic explosion. After the eruption of July 9 this took the form of a specific warning published in Martinique, as after May 20 the intervals to June 6 and July 9 confirmed the expectancy.

After the destruction of Morne Rouge August 30 justified the warning, and 2000 more people were killed, I printed in Science (1902) the data for the

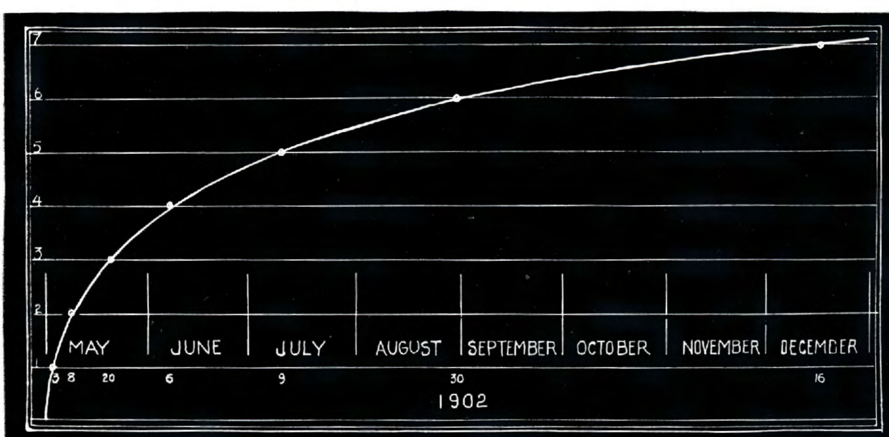


FIGURE 38. *Original geyser curve of Pelée made by Jaggar and Marks.* Data published in November 1902 (in Science, Jaggar). Obtained by matching a French curve graphically to a plat with constant on the ordinate and six dates of major Pelée paroxysms on the abscissa. The dates are May 3, 8, 20, June 6, July 9, August 30, 1902. This at that time was projected to a seventh point that on this graph comes out exactly December 16. No simple analytical solution was found.

The writer at that time obtained the kind assistance of Professor L. S. Marks of Harvard University, skilled in steam dynamics. On the data given he wrote "this is the most probable curve. Why don't you predict the next explosion to take place within one week of December 20?"

This was done, with the remark (based on "L'Opinion" of Fort de France, Martinique, October 21, 1902) that "a French astronomer has predicted an eruption December 16, because at that time the moon will be full and nearest the earth, with maximum pull on any local instability in the earth." December 16 turned out to be the remarkable crisis in our Figures 12 and 19 (after Lacroix). See Perret's curve for 1902 (in Science August 28, 1908) where the luni-solar maximum of December 16 is the greatest of the year.

curve of Figure 38 inclusive of six points, assuming a constant on the ordinate and I projected it graphically to December 16 as the next probable paroxysm of Mount Pelée. As the dates of paroxysms fall on a parabola, it appears that boiler enlarges or heat decreases systematically.

The history of this curve is in caption of Figure 38. The large nuée of December 16 (Figs. 19 and 12) fell on this line as shown so that by purely graphical methods it was possible with the help of Krakatau analogy and the St. Vincent accoıds (Figure 21) of May 7, May 18, and September 3, to use geyser theory in published forecasts of May, July, August, and November which were confirmed by volcanic events.

Figure 21, curves C and D, exhibits the lighter blasts of Pelée and Soufrière respectively after September, while the compound parabolic curve of the system as a whole flattens out beyond the graph to infinity intervals. Curve A, guided by rapid decline of Soufrière paroxysms has the shortest radius: in curves (B, Pelée) (D, Soufrière) and (C, Pelée) the curves open, and Pelée closed the eruptive period after 1904.

This appears to justify the geyser conception of ground water heated and evacuated, the chamber enlarged and refilled with cool water, and new intervals thereby lengthened, with a relatively constant source of heat.

The Supply of Energy

It remains to consider magma. The existence of magma makes the islands or domes volcanoes. It flowed freely as a more basic substance at one time. It is profound and voluminous as the aligned building material and it came from below. In coming it was impelled by its self-heating gases in solution. Its presence in aligned fissures of its own hardened substance implies growing restraint by shells, lithospheric, atmospheric, and hydrospheric, in origin volcanic: slags, gases, liquids. All three encase a globe containing their ancestral solar fluid. The intrusive fluid charged with gaseous energy fills the igniseptum as a remnant of what extrusively was free-flowing in hotter times.

In o.her words, volcano chains have intrusions active under them. This deep magma has confining walls, it ruptures its container, the ruptures are elongate and vertical. Old sections show dikes, some longitudinal (Fig. 23), some transverse. The dike is the principal feeder of craters. The pit is a dike below, a concentric heap above.

We have seen how a cold dike complex confines water at high levels and pressures. A hot dike rupture is an intrusive act of vitreous hypomagma (Jaggar, 1920), its gases released to vesiculation of pyromagma, which with loss of gas and temperature semi-crystallizes to epimagma. The epimagma is the bulky paste of every lava column. The rock enclosing the lava column is the perilith.

The little known energy supply of deep magma, the "ascensive force" as it was called by Dana, becomes reality to every field volcanologist. It is the rising force that makes pressure, that by distribution in a dike swarm makes massive tumescence, and that takes part in epeirogenic uplift, for magma is always underneath. Uplift of a volcanic system is the oceanic equivalent of continental plateau uplift. Neither vesiculation swelling nor isostatic adjustment nor weight of sea bottom on a substratum is a satisfactory explanation of magmatic pressure, revealed as suddenly relieved by gas vesiculation. The cyclical responses in large and small edifices, the spatial distribution in very long volcanic ridges, and the geologic recurrences of volcanic revolutions in identical fields, all mean that deep-seated ignisepta are persistent inheritances today from the primitive earth. If so, the pressure that made them ridges is magmatic, the underlying rupture was tensional and not compressional, and magmatic vertical stress from the core outward was essential. This is the energy of hypomagma, the force that can impel plutonic intrusives between the folia of slates, an endogenous residual condition of glass and its solutes. The intramural deep magma of ignisepta is increasingly energetic within fissures widening downward, to the inface of the 2900-kilometer shell. The age-long adjustment of the energy to the confinement of congealed primitive fault blocks and fault steps makes the volcanic globe as we find it, most of its surface under the sea and river deltas.

The lakes and lava flows of Hawaii differentiate the magma into three substances; volumes of burning gas at highest temperature, spouting floods of vesicular glass at next lower temperature, and shells of incandescent crystalline paste at still lower temperature. Lava emission creates a blow-pipe system from the deep region upward wherein the gases are impelling, heating, and liquefying the foam; the border selvage is creating a mantle of differentiated mobile crystalline paste from the sides and top of the lava column inward, and the bursting of the bubbles at the surface creates in relatively minor volume the fountains, lakes and liquid streams confined within marginal shells or spreadout fields of the crystalline paste. Aa and pahoehoe are merely crystal-sprouted or glass-wrinkled surfaces.

In Halemaumau pit and far down the shaft this marginal paste is the most voluminous moving unit of the lava column; in any lava flow, either aa or pahoehoe, the marginal paste is the large low-temperature field flowing slowly, crusted over on top but pasty within, that lies on all sides of the distributary streams that make channels and tunnels within a wide-spread sheet of slag. At Pelée and Soufrière it is the andesite paste column: there the glassy pahoehoe is sputtered pumice.

Remelting by gas in the tunnels adds glass to the liquid melt, for glazes are remelted on the ceilings of such tunnels. The gas differentiate of the magma is the only ingredient at the surface capable of melting solidified lava: its temperature is 1300°-1400° C., the pyromagma measures about 1100° C., and the epimagma about 900° C. Epimagma in the depths brings to light a new consideration. Measurement of the detail of semi-consolidation of the bottom and sides of shallow Halemaumau lava pools, and the rising and lowering of upright pencils of this substance in much greater volume than that of the shallow lake liquid in the wells, proves that this semi-crystalline substance extends downward.

Differentiation and semi-congealing goes on in the depths. The pyromagma is escaping from the hypomagma in a gas-charged foam consisting of vitreous bubbles at the top of the hypomagma chamber. The crustal edifice above yields to tumescent force or tectonic tensional stress, and a crack permits the foam to penetrate the crust towards the surface of the earth. This foam can actuate assimilation. It is the pumice of the Antilles.

Contact cooling takes place, expansion cooling is permitted, conduction into the wall occurs, and a glassy or semi-crystalline paste forms a shell around glass-blowing mechanism upward.

Gases play an important role in connecting volcanism with the primary magmatic chambers, and the contact refuse of vesiculate glass rising up crustal fissures makes crystalline intrusions. Basaltic dikes of Hawaii show nothing particularly glassy in their middle zones, and aa flows do not consolidate glassy in their frozen streams. Basaltic dikes go geologically deepest in the earthcrust known to geology. Trap dikes cutting ancient formations may have had pyromagma gushing up their middle zones to feed volcanoes at the surface of the earth. What about andesites, rhyolites, monzonites, diorites and all prophyries? The profundity, uniformity, and world distribution of trap dikes have been used as arguments for a basaltic substratum, but lava in action rises from igniseptal depths and has space and time for assimilation. The wedging action of such magma makes earthquakes determined by the seismologists to be 30 miles or more deep under volcanoes, and 300 miles deep down the ignisepta around the Pacific.

The eruptive phenomena from the beginning in Hawaii are:

(1) Hypomagmatic pressure
(2) Opening of the crack
(3) Effervescence, vesicle-accumulation and reactions of gas, in the crack
(4) Surface opening and escape of gas, devesiculation
(5) Burning of gas on contact with air
(6) Deep effervescence and overflow or rift outflow
(7) Sudden stiffening on loss of gas
(8) Differentiation crystalline and vitreous
(9) Crystallization within the vent.

The end of an eruption is a reassertion of the mountain pressure against crystalline epimagma, a shrinkage by loss of gas of the internal hypomagma still vitreous to abyssal depths, and an added weight of slag to the outside of the mountain.

Tempest Anderson's (1908) comment in his second report to the Royal Society after revisiting Soufrière in 1907 is a published statement (along with Fenner's concerning Novarupta at Katmai, 1923) showing active assimilation along linear upright dikes within ignisepta.

He writes:

"I venture in conclusion to submit the following speculation as to the depth of the volcanic foci beneath St. Vincent and Martinique. The chimneys of the two volcanoes appear to have some connection underground . . . the eruptions have been repeatedly either simultaneous or so nearly so that the difference in time might be accounted for by the magma being delayed in travelling through a devious and perhaps branching passage or system of pasages blocked in different degree by various obstructions . . . The chemical composition of the ejecta is not more different than could be explained by the interaction between the magma at a high temperature and the walls of the passage, supposing them to intersect various strata. It seems, therefore, natural to conclude that the two volcanoes are at the ends of two branches of one common passage, and it is not unreasonable to suppose that these branches divide at an angle not very obtuse and consequently at a great depth."

Anderson explicitly expressed objection to the conception of a shallow reservoir as an extended intrusive sheet. His wide experience showed him that upright dikes from profound source on all scales are the feeders of a volcanic ridge.

A mechanism of invasion of magma by ground water under hydrostatic pressure, and of mud or debris seals held fast by vent engulfments and ridge pressure above, adds a powerful agent, water vapor under pressure, in contact with deep magma. On the one hand it reduces viscosity (Morey 1938) on the other it increases vapor pressure (Goranson 1931) and stimulates sudden stiffening when the vapors are discharged (Shepherd 1938). The addition of water to silicate systems has been discussed by Day and Allen (1922, 1925) in connection with Lassen and the Yellowstone, and has formed the subject of many papers by the Geophysical Laboratory (Sosman 1947).

To the relatively simple principles of inflowing cold water at a heated geyser chamber (Jaggar 1898), there is added in the region of Anderson's "branches dividing at great depth" a plexus of high-temperature hydrous physical chemistry added to oxidizing gases of hydrogen, carbon, sulphur, and chlorine, and also such gases as silicon hydrides (Shepherd 1938), sulphides and halides. This is the energy field that supplies an intrusion furnace for operating steam-blast eruption.

Engulfment Lowering

"The geologist will never be wholly certain as regards the precipitating cause of the catastrophe." So wrote Heilprin about Mount Pelée as a challenge to twentieth century science. The precipitating stress was due to magma lowering.

Both Pelée and Soufrière began with engulfment. Santa Maria in October 1902 engulfed its flank. Vesuvius had its cyclical paroxysms of a third of a century with engulfments in 1872, 1906 and 1944. Bogoslof built a lava heap and then engulfed it in 1907, and has repeated the process. Taal lowered its entire crater island in Bombon Lake, and its crater lake below sea level, in 1911. Rotomahana chasm lowered its lake 500 feet in 1886. Sakurajima in 1914 executed a two-flank collapse immediately compensated by upwelling magma. Katmai engulfed its summit in 1912. Kilauea engulfed its inner pit in 1924. Both Lassen in 1915 and Pelée in 1929 began steam blast eruptions with engulfment rupture of summit domes of dacite. Howel Williams (1941) announces engulfment for most of the world's calderas.

Kilauea and Vesuvius have set the standard from a century and a half to three centuries, in demonstrating periodic crateral engulfment, alternating with crateral and flank upbuilding. The crateral engulfments are small or large, occasioned by magma withdrawal, and send up wall-crack steam from the periphery of the lowered epimagma column.

The twentieth century cases of engulfment were accompanied by steam blast, with various forms of internal and external avalanching, some with mud floods, and at least seven out of ten with tornado outblasts; and the other three, Bogoslof, Vesuvius and Kilauea, certainly vomited lateral trajectories. Taal and Bogoslof, both at sea level, had obscure rift elongations, but Bogoslof has three domes in a line, and Taal opened NE-SW earthquake cracks; all the other volcanoes had obvious rifts.

Recent studies of Krakatau by Stehn, and Crater Lake by Williams, make certain that magma lowers and craters collapse. Becker's denial of this (Maso, 1904) in the old Bombon Lake at Taal, in opposition to four distinguished German and Spanish students of geology of the Philippines, was simply error.

Magma rises with various viscosities and high gas content up rifts, capable of straining the rock apart, and capable of withdrawing from high levels as a mobile liquid when it lengthens dike fissures subterraneously. If it lengthens them under the sea it makes submarine outflow and crateral collapse.

This mechanism of lava lowering visibly and rapidly within a few hours, with seismic and outflow accompaniments, is now common observed fact. Crateral collapse is merely an extension of this common happening, and what can happen to crateral magma can also happen to mobile intrusive magma at any depth in a faulted rigid crust. The crust blocks are everywhere under-shot with magma, and magma strongly influences tectonics, achieving cyclical compensation and migration along ignisepta, whereby igneous bodies now alive, in the geologic age of tomorrow may be dead.

The island Hawaii today is pressing upward and alive, but Midway Island at the other end of the chain has lowered and become an atoll. In 1919 over stress upward Kilauea summit had risen. Wilson (1935) proved by precise levelling that the mountain went down in 1924 when the crater collapsed and the tumescent lava of the preceding decade lowered and flowed out under the sea. The nearby sea bottom was 22,000 feet lower. There was room for lava to siphon out. The precipitating cause of the act was measured in time pulsations by an observatory; a seasonal cycle, a cycle of decades, a cycle of centuries. It was confirmed by correlated acts of adjacent volcanoes, and by correlated seismical acts timed and located. The precipitating cause was revealed as an age of pressure, an age of withdrawal, half a decade of pressure, a few years of withdrawal, then a half-year of pressure and a crisis of withdrawal.

The leading event, followed by explosion at Vesuvius, Sakurajima, Kilauea, Krakatau, Soufrière, Santa Maria and Katmai, was in each case lowering of magma, with definite prolonged tumescence preceding in the cases of Vesuvius, Kilauea, and Sakurajima. These three were under observation, the lowering fulfilled expectancy, they were liquid lava producers. Kilauea and Vesuvius exhibited crateral lava before the crisis; Vesuvius and Sakurajima emitted it above sea level during the crisis, Sakurajima continued to eject it as the country lowered and Kilauea restored it craterally immediately after the crisis. All these crises were accompanied by paroxysmal steam blasts. The steam blasts were magmatically exogenous—they were ground water.

Mercalli and Matteuci at Vesuvius, Omori at Sakurajima and Jaggar at Kilauea built up expectancy published before the event and were professional volcano observers, at laboratories that made topographic measurement before and after the crisis. Volcano observatory determinations of topographic tumescence and magmatic lowering prove plus and minus volcanicity as cyclical. (Jaggar 1925). Perret has repeatedly published successful expectancy on the basis of measurement and experience (1914, 1924, 1935).

Measurement of lowering and recovery of visible crater lava within pits has been occasionally possible in prolonged spells at some few such volcanoes as Kilauea, Vesuvius, and Nyamlagira. The conception of the cycle originated at such lava-flow volcanoes. It is essentially a twentieth century conception, predicted however by William Lowthian Green (1887). It has been elaborated for a century in connection with time and space distribution of earthquakes, and the sciences of seismology and tectonics are gradually tying to magma. Tidal rhy:hm in the earth crust is suggested to anyone studying statistics in time, of volcanic eruptions and earthquakes (Sapper 1927, Jaggar 1947).

The excess of local frictional earthquakes at Kilauea concomitant with lava-lowering, and the migration of the centers to progressively greater distances and depths, leads to the conclusion that magma underground is extensive along the ignisept, when it is trivial and localized within a crater. So in time the eternal crunching motions of intrusion are innumerable along any single volcanic ridge like the Antilles when the vast extent of the subterranean rifts is appreciated.

The Pelée type of catastrophe is a measurable and expectable event in time and space, when the distribution of unseen elevations, tilts and engulfment lowerings, and their proximity to the ground water level is seismically evaluated and recorded with geophysical instruments.

Conclusions of this study, for the paroxysmal steam and mud blasts at Pelée that repeatedly lashed St. Pierre, are that lateral rift, groundwater floods of boiling mud, magmatic furnace, and engulfment pulsations of mixed-pressure releases for both steam and magma controlled the initiation and sequence of events.

Support for this explanation of such mechanism is found by comparisons with St. Vincent, Hawaii, Tarawera, Sakurajima, Katmai, Taal, and Tomboro. It is thought that ground water steam blast in its paroxysmal phase is not identical with lava gas or nuées ardentes, and that at Pelée the nuées developed gradually, beginning the night after the major paroxysm, while later the explosive blasts rhythmically declined.

The old solfataric radial rift in the cone was the ejection center at Pelée for both paroxysms and nuées, for both steam and magma gas, for boiling mud and pumice froth, for migratory splitting and mud transport of glowing ejecta. The crater basin was not the unique center. Central eruption is more linear and eccentric than has usually been believed.

The Ghyben-Herzberg ground water body is definite and permanent and indestructible below sea level in shore and island volcanic belts, and magma steam is too small in volume to serve for paroxysms. Ground water cannot avoid magmatic contact when rupture of the structure begins, and near sea or lakes the supply is unlimited.

The magma bodies are dike shaped, as shown by all the dike swarms of Hawaii (Stearns) and the world (Daly 1933). Sills and laccoliths with tubular conduits to a central shaft do not occur in old volcano structure sections; these exhibit no such "reservoirs." The dike rifts of volcanic chain and cone are verities. Volcanic magma is primarily gas-charged and basic, and when acidified with digested silica is subject to expansion, gas heating, and viscosity change, in contact with water under pressure dropped from the groundwater body. This can furnish energy. An acid magma body cannot by itself furnish paroxysmal energy of volatiles, and even hot basalt at much higher temperature has not nearly enough volatiles to supply an explosive eruption. Obsidian is a continental low temperature product contaminate by assimilation. It is not an eruption maker, but an irruption product.

Engulfment as the great post-Miocene process of surface terrestrial volcanism (calderas) is now at last being given its due credit (Williams 1941). From Vesuvius in the year 79 A.D. to Krakatau in 1883, volcanoes collapsed, they did not blow their heads off. The estimates of "explosion" output in cubic miles were excessive.

The time intervals terminated abruptly by steam blast are not accidental chance, but are controlled by a science of cycles long and short within structures big and little. A downward withdrawal of magma locally is correlated to upward secular pressure in a larger structure of earth crust that fails. The larger failure prepares the local lowering of dike fluid, under surface crust full of water.

There need be no observed regularity, except for short term geyser pulsation. Long-term volcano-chain regularity is too large for human time, but even this may be diagnosed if multiple volcanoes are measured within a bigger system.

The conclusions of this paper revert to sub-oceanic and subterranean water, to elongate rift belts of volcanic action, to magmatic energy relative to those belts rather than to density stratified shells, and to engulfment collapse as occasioning contact of water and magma for the maximum paroxysms of volcanism.

Implicit in this is a return to some nineteenth century conceptions, wherein volcano proximity to seas and lakes was supposed to be connected with sedimentary water. The new approach, however, is not concerned with sediments, and has no illusions about shallow magma reservoirs. Isostasy, petrology, seismology and modern facts and theories about sea bottoms and continents the writer has reviewed in relation to volcanoes (Jaggar 1940, 1945, 1947). In the "synopsis" that follows an hypothesis of volcano origins is suggested, based on the doctrine of deep ignisepta and the facts of deep oceanic trenches.

SYNOPSIS OF VOLCANISM

After respectively a half century and ninety years of quiet, Pelée and Soufrière erupting suddenly in 1902 led to the inquiry whether this was different from the mechanism of Vesuvius and Kilauea, with very few years of such quiet. The facts call for reconciliation of lava eruption with steam eruption.

Vesuvius and Kilauea have sudden steam happenings after quiet periods of lava gushing. Kilauea, Vesuvius, Pelée and Soufrière may be graded in their approaches to sudden steam blasts; Kilauea lava very liquid froth, Vesuvius more refractory, Pelée very refractory, Soufrière keeping its stiff lava underground. The Kilauea system reached crisis in a decade, Vesuvius in a third of a century, Pelée in a half century, Soufrière in a century. In this we refer to cycles of magmatic effervescence emitting steam, not necessarily major paroxysms.

This is only an illustration of possibilities. The possibility of ground water stimulating even minor magmatic crises like lava flows leads the writer to re-examine all the facts about Pelée and Soufrière in comparison with the highly hydrous event of 1924 at Kilauea.

The admirable geological surveys of ground water in Hawaii have drawn attention to the Ghyben-Herzberg law (Stearns 1935, 65, Tolman 1938). Hawaiian Volcano Observatory work has suggested ignisepta (Jaggar 1947, 410) rather than shallow substrata. The invasion of a downward pressing water layer, whenever magma reaches the superficies of the globe, seems unavoidable. Possibly order may be found, where Java, New Zealand and Japan in the nineteenth century made explosions that were considered disorderly.

The argument of this synopsis is exhibited under the headings that follow:

(1) Ground water in world volcanism
(2) Volcano lines
(3) Deep crust
(4) Ignisepta
(5) Caribbee water floods volcanic
(6) Pelée geyser through radial rift
(7) Kilauea geyser replaces efflux
(8) Pelée comparable with Kilauea
(9) Kilauea reconciles discordant eruptions
(10) Kilauea sequence from magmatic to hydrous
(11) Pelée sequence from hydrous to magmatic
(12) Rupture of igniseptum with deep seisms
(13) Rupture of local edifice with shallow seisms
(14) Engulfment of ground water
(15) Exothermic heat of magmatic furnace
(16) Loss of magma and lowering
(17) Effervescence makes floods
(18) Repetition sequences
(19) Magma mantle seals off ground water
(20) Intrusive or effusive magma episode
(21) Graben collapse ending cycle
(22) Ground water always available
(23) Aleutian trench profiles
(24) Gravity defect along ocean trenches
(25) New data from the Albatross expedition
(26) Suggestions concerning an earth model
(27) Summary of Earth-core volcanism

Number (26) modifies the earth models of Daly (1933) and those of his predecessors, but accepts his splendid scholarship as first authority on crust blocks isostatic within stable areas of 400km diameter, and on abyssal dikes, overthrusting and underthrusting orogenesis, and tensions dependent on distortion. So eclectic is Daly that he mentions the possibility that "early convective stirring would have tended to produce chemical uniformity of the earth shells," and also "without much delay a solid crust would form" (1933, 232, 233, 235 footnote, 1940, 362). Earth shells and substratum appear to the writer less important for volcanology, than tension cracking as the 2900km crust thickened and block-faulted inward.

This is illustrated by Sandberg's (1924, 49) diagram and its caption, Fig. 40 (his Figures 13, 1 and 2). Transition by global concentric zones within ignisepta is still possible as a form of density stratification if the ignisepta are numerous enough. The addition of great pressures of condensed water as a surface feature of volcanism, of a gas tight shell, of varied size of original and evolved ignisepta, and of graded density and nucleonic energy of the 79 elements heavier than iron inward to a solar core, complete the writer's picture of a thick fractured earth box. Geikie's generalizations (1897) are fundamental: (1) subsidence has always exceeded upheaval (see his Textbook 1903, p. 1366); (2) subsidence dominates in volcanism of all ages; (3) volcanism in all ages recurs in the same areas. This means permanent ignisepts and down-faulting on igniseptal planes.

(1) Ground water in World Volcanism

Ground water above worldwide upright dike system partitions in the crust of the earth makes explosive steam eruptions at cyclical intervals in some volcanoes, and is quite distinct from magmatic frothing that has shorter intervals. Kilauea revealed this in 1924, but as a world process it was revealed at Pelée in 1902.

(2) Volcano Lines

Volcanoes in lines on the map as world features, along unquestionable deep rifts, are primitive non-tectonic features. Their curvilinear quality is to be expected of deep rupture on a sphere (Spurr 1948, Pl. I). Their eviscerations are terrestrially deeper than foreland folding. Olivine basalt is predominant. Igneous lines as ancient as the Appalachians and the Himalayan curve, the Cordillera and the Asiatic ranges, the Pacific arcs and the African rift, antedate Miocene volcanism. Intrusion is terrestrially older than intracontinental sedimentation.

(3) Deep Crust

The assured earth crust of seismology 2900 kilometers deep is a thick wall over fluid or subatomic sun matter. It has contracted and ruptured in rigidifying. At the surface the rifts are covered by extrusions. Up these rifts thermal gassy sun-matter originated volcanicity. Most volcanic outpourings are under oceans, and more surface volcanism is intrusive than appears as lava.

(4) Ignisepta

Below pre-Archean rocks there are a rifted crust and intrusive dike systems which are filled ruptures much deeper than batholiths, widening out downward. The rifts are deeper than any folded geosynclinals, are prolonged into echelons of dike systems, making vertical partitions down to the core called ignisepta, and lines of volcanoes lie over them.

They fed the first volcanism and by ocean basin infaulting outlined the first continents. Earth and moon show what they outlined. Volcanism is the most ancient process of the earth, the creator of air, crust and ocean. Volcanism as intrusion built the thick shell downward, and built it outward from the ignisepta. The globe is igneous, shells of sediment are trivial. The Cordillera from the Aleutian Islands to Cape Horn is a succession of fissure fillings in the deep crust, shown by active linear volcanicity. The Caribbee, Aleutian and Hawaiian chains are active curved ignisepta.

(5) Caribbee water floods Volcanic

At the St. Pierre disaster in 1902 the initial magma movement under Martinique was an internal withdrawal from unperceived earlier intrusion. Collapse sucked down ground water, a geyser ensued, and the flank rift was the explosion path. Eruptive water made repeated floods from the boiler pressure.

(6) Pelee Geyser through Radial Rift

Crateral mushroom plugging forced a horizontal steam blast from radial rift in the bottom of the crateral gorge. Later eruptions developed returning magma, made repetition of geyser jets at increasing intervals, and repeated the emissions up through flank rift by heaving action.

(7) Kilauea Geyser replaces Efflux

Kilauea in 1924 showed that a liquid-lava volcano could suddenly reverse habit from magma gases to pure steam, and this led to comparison with steam blast eruptions such at Pelée. The sequence from intrusive tumefaction to internal or submarine disruption is normal volcano mechanism for cone structures weighing down on restrained magma. The internal disruption lets in crustal water, the crateral collapse plugs the vent. Geyser action replaces magmatic efflux. Magmatic recovery shuts off water. Steam blast eruptions are non-magmatic crises, but water contact stimulates magma to reduced viscosity, to increased vapor pressure and pumicification and to sudden stiffening after effervescence.

(8) Pelee comparable with Kilauea

Volcanism with its submarine heavy accumulations and worldwide deep intrusions is the bulkiest geological process. The experiments of volcano stations have dealt with gases, temperatures, quakes, tilts, elevations, viscosities, water wells, photography, surveys, sequences, soundings, physiology, gravity, magnetism and engineering. The subterranean processes are the basis of geological uniformity of surface deforming and rupturing, of contacts between magma and water, and of emission of new nitrogen, oxygen, carbon and hydrogen, elements of air and ocean. Pelée from 1901 to 1930 is comparable with Kilauea in the same period.

(9) Kilauea Reconciles discordant Eruptions

In existing books the steam blasts of St. Pierre, of Lassen, of Katmai, of Vesuvius and of Sakurajima, with their contiguous lava domes or flows, have not hitherto been reconciled with those of the Hawaiian Islands as belonging to a single family. The Kilauea steam blasts of 1924 suggest a mode of reconciliation, by reaction with ground water, which need not be called "phreatic" as something exceptional.

(10) Kilauea Sequence from Magmatic to Hydrous

The steam blasts of pure water vapor at Kilauea were not different from the pure water vapor which Perret (1924) had smelled at the steam blasts of Vesuvius in 1906. In both volcanoes the sequence from prolonged magmatic accumulations emitting noxious gases, to sudden collapse emitting pure steam, was evidence of a subterranean rupture that lowered ground water into magma.

(11) Pelee Sequence from Hydrous to Magmatic

The steam blasts of pure water vapor at Pelée were in sequence on prolonged magmatic intrusion emitting noxious gas at solfataras. This intrusion gave place through two weeks to sudden internal engulfment of ground water into andesitic magma which vesiculated to voluminous pumice. Rapid magmatic swelling forced ground water steam out along a deep radial crack in the bottom of a valley, deflected to horizontality by the mushrooming of crateral magma, though beginning by vertical migratory jets of boiling water.

(12) Rupture of Igniseptum with Deep Seisms

The Pelean igniseptum had ruptured and made earthquakes throughout a year from Guadéloupe to St. Vincent. This was occasioned by limit of intrusion pressure in the long echelon of dikes. At quiet times intrusion under accumulated weight adjusts itself to processes of assimilation, to tumescence of the Caribbee ridge, and to gravity factors (possibly salic rock of (Day and Allen 1925, 81) light weight differentiation or pumice, lies for some reason under the negative anomaly (Hess 1938) deep trench on the Atlantic side). Intrusion normally induces a simmering solfataric gas escape in critical equilibrium with underground water. The rain makes a deep lens of fresh water convex downward under the land, with gradation to salt water there and under the sea bottom, and beyond that is probably volcanic hydrogen seepage upward under the deep ocean floor. The igniseptum is a filled chasm of inverted V shape 2900 km deep, and at least as long as the Caribbee arc (1500 km), presumably a composite dike complex. It is close to positive anomaly axes (excessive gravity) in Martinique and St. Vincent.

Periodic rupture and graben faulting are expectable in cycles, and eruptive times are when water makes contact with magma, and releases vesiculate pumification. A minor negative anomaly axis lies 140 km west of the Martinique-St. Vincent line, a direction down the trade wind stream, which presumably has buried pumice in that direction throughout geologic time if the igniseptum is an old feature.

(13) Rupture of local edifice with Shallow Seisms

The volcano is a heavy dome of radially diked lava strata, with more or less central well or caldera, the inbreak of which gives rise to concentric faults with dikes. Over the tensional rupture of the igniseptal shell the volcano edifice breaks, magma spurts its way upward with wedge splitting, calderas fault inward, rifts gape open centrifugally, and the ground water starts central surging that adds to collapse.

Paths of least resistance determine the order of events, and resistances are weight of dome sectors, and weight of avalanche plugs. Shallow earthquakes and tremors accompany rupturing, faulting and surging.

(14) Engulfment of Ground Water

Igniseptum and edifice are now loosened by mass cracking, ground water is free to pour down upon hot magma, to boil up in enlarged springs, and to react with the magma. The ground water is a large body, the spring orifices are small, steam pressure and vesiculation pressure are added to secular intrusion pressure, and under subaerial conditions the stage is set for cataclysm. Under deep submarine conditions with many atmospheres pressure of seawater, there is "absorption of water by a magma, with non-explosive formation of pumice" (Sosman 1947).

(15) Exothermic Heat of Magmatic Furnace

Added tumefaction and rupture in the high ridge uncorks localized confined magma under the volcano edifice. Escape of gas from solution adds to reactional vesiculation, and exothermic heat raises temperature through the water-and-pumice system. This supplies a self heating furnace dependent on release of pressure, new access of water, access of inflammable gases to air, and magma liquefied to a foam. The geyser process is now started.

Elements of the geyser process are a ground water table, a crack system, a head of water under subaerial pressure, a vent, and a furnace under the vent. If the vent or crater is above the head of ground water, the impulses of upjetting will be rhythmically timed, for cool water of replacement takes time intervals to boil. If other vents or springs are below the head of ground water, (such as all river sources), they will continually increase in volume and temperature, but they will not erupt at rhythmic intervals.

(16) Loss of Magma and Lowering

From the beginning of eruption, vesiculating magma is thrown away as gas or pumice or vitreous ash, stimulated by steam blast. On Hawaii the process exhibits little steam ordinarily, and basaltic pumice is flung up violently when magma surface is low. If not, vesiculate pahoehoe overflows crater, or flows out through rifts. If a deep igniseptal dikeway is followed as a subterranean channel like that from Soufrière to Pelée, the vesiculate loss may be vented internally, while weight of ridge roof holds crest to small emissions. There is a loss and a general magmatic lowering. Magmatic lowering competes with hydromagmatic effervescence until the slag stiffens and gravity of ridge once more dominates.

(17) Effervescence makes Floods

The boiling of water under the edifice, where crateral vent is, is a part of eruption pressure under the ridge, where the larger ground water body is. Contact of magma and ground water makes a graduated vapor pressure from the rift eruption center above the water table, which has geyser qualities, outward to spring sources of all the rivers. The steam pressure made floods in the valleys of Martinique and St. Vincent, all below the water table. The floods are not apportionate to rainfall as runoff. The springs of Kilauea mountain have not been measured because there are no rivers or valleys, and the springs open at the beach level. Special wells might profitably be equipped with chronographic gauges, to learn whether ground water level fluctuates with volcanic activity.

(18) Repetition Sequences

Kilauea in its steam blasts of 1924, and Pelée in those of 1902, exhibited a lengthening of intervals, and a cyclical sequence of phenomena, accordant with geyser expectancy for participation of ground water in the eruptive events.

Kilauea had visible live lava, split its flank, emitted progressively lower and lower flows of lava, caved in at the caldera, and finally entered on geyser discharges of steam from that central pit. Lava followed in succeeding years.

Pelée's magma was intrusive and solfataric, entered on a seismic year in sympathy with Soufrière, then started geyser discharges through cracks under a gorge, followed by a series of systematic lengthening intervals of crater explosion and river floods, with pumice eruption and finally a lava dome, extended into added constructive extrusion twenty-six years later.

The Kilauea crisis started with magma through flank, ended with steam. The Pelée crisis started with intrusive seismic magma movements, continued with steam through flank, ended with magma superficially. Pelée's final magma was a stiff dome, Kilauea's was liquid lava in a pit. Both volcanoes finished with intrusive repose.

(19) Magma Mantle seals off Ground Water

The terminal magma phase creates a glassy contact layer against the walls of the shaft or rift dike, broken matter there is percolated by lava and cemented, magmatic pressure has reasserted itself along the igniseptum, and ground water is in some measure shut off from any reaction with incandescent lava. Remnant moving lava is within a chilled shell, motion is slight, and equilibrium is restored between intrusion and load, between magmatic expansion and solfataric simmering. Weight is dominant, and upflow of magma awaits an igniseptal accumulation, leading to small edifice tensions, for the next water and magma reaction crisis. A tectonic faulting at any such critical depth would be competent to start eruption. The collapse with rupture of the volcano edifice, followed by inrush of ground water, will physically and chemically create a limit to repose and make a new effervescence (Perret 1935, 88).

(20) Intrusive or Effusive Magma Episode

There ensues after repose a magmatic episode of a third of a decade (Mauna Loa), a decade (Kilauea and Vesuvius), a third of a century (the secondary cycle), or a century and a third (the supercycle of explosion). The seeming uncertainty of volcanoes resides in unperceived intrusion and unrecorded intervals for systems as a whole. The advantage for science in Nyamlagira, Mauna Loa, Etna, and Kilauea as "liquid lava" volcanoes is their perceptible external routine of flowing basalt.

Perceptibility for other volcanoes may be crater floor upbuilding as at Vesuvius, pulsation in springs and rivers (not measured), gravity changes (not measured), tilting of the ground (usually not distributively measured), and tremor (insufficiently located), elevation changes (insufficiently located secularly) and finally the physical chemistry changes of hot springs and solfataras.

Intrusion requires on the ground a chronographic instrumental approach not yet invented. Seeming but unreal equilibrium is the characteristic, and agents of change are tumescing magma and ground water as a challenge to detective geophysics.

(21) Graben Collapse ending Cycle

The sequence returns to a new elastic limit. Land has lifted, magma has percolated, shoreline has extended, water head has changed, chemistry and seismic index have altered statistically, thermal properties have shifted, run-off is moving up or down. Probability error from rainfall, temperature or pressure has been evaluated.

A magma plug is about to sink somewhere at a solfataric volcano. Internal magma on a larger scale is about to shrink from intrusion walls. Solidified mantle of glassy contacts will crack with the bedrock. Ground water will drop down the cracks. Critical water lowering in a crater lake is the first sign. Minute quantities of percolating water and a localized seismic jarring signalize effervescence.

In the Carib volcanoes of 1902 along 500 miles of ridge foundation the withdrawal might have affected crater lakes of St. Kitts, Montserrat, Guadéloupe, Dominica, Martinique, St. Lucia or St. Vincent. Martinique was in the middle of the arcuate gash, St. Vincent 100 miles farther south. Rumblings, quakings and milky coloration of crater lakes for more than a year at both Pelée and Soufrière prior to eruption showed 200 miles of igniseptum shrinking. Lake water at Soufrière lowered 14 months before outbreak, signalizing subsidence of ground water. These two volcanic plugs were elected, and St. Lucia in between was spared. That the whole belt shared in the withdrawal as a unit was proved by dates of eruption, St. Vincent May 7, 1902 and Martinique May 8.

Graben downfaulting at the plugs succeeds repose, initiates effervescence of magma internally by water inrush, when viscosity lowers, temperature rises and vapor tension increases. On an oceanic scale, graben downfaulting at the deeps produces the same results, complicated by great water pressure. A crisis of interrupted equilibrium becomes explosive by confinement, with excessive temperatures, pressures and ruptures, and available vapors, fluids, orifices and fractured solids. Water and magma follow paths of least resistance, bubbling up of pumice adds a semi-solid, rapid cooling conflicts with exothermic gaseous heating, and the plexus of effects is a vast expansion and a vast resistance. The heavy ridge dominates. The localized crater plug margins and rift extensions shape rifle barrels of discharge, but collapse of land is dictated from the outset. If the expansion is wholly in the intrusion region, the effect superficially might be only disturbance of a hot spring or a warm lake. If higher, any kind of volcanic eruption might ensue, from a Kilauea spurting to a Krakatau exploding. If the intrusion region were very low, the result might be a major earthquake or an unexplained tidal wave or river flood.

(22) Ground Water is always Available

Whether a volcanic eruption is the beginning or the end of a magmatic cycle will bear analysis. Intrusive magma and ground water are always present. Magma erupting always forecasts repose to follow. Among alignments of active volcanoes, a sudden eruption on any scale, followed by a sealed conduit, is an end of accumulation. The defined repose that follows is the beginning of the next cycle.

Hot springs are expectable but unexplored on ocean floors. Oceans, seas, lakes, river basins, hot spring areas, swamps and glaciers cover the greater part of the globe, and the very small dry and high areas are mostly places where volcanism at the surface has departed. Active volcanic ignisepta are notably in places of deep ground or ocean water. The height of the water table in such places may be volcanometric datum of change in underground magmatic pressure, a kind of datum index which has never yet been discovered through tides, temperatures or meteorology. Old volcanic ignisepta may be suspected as intrusion belts all over the globe.

To say that ground water is always available is an understatement when we consider the oceans as 72 per cent of earth surface, and the relative depth of ocean to land height as 4000 meters versus 800 meters, and the depth of water in the rock under the oceans totally unknown. The island arcs are margined by

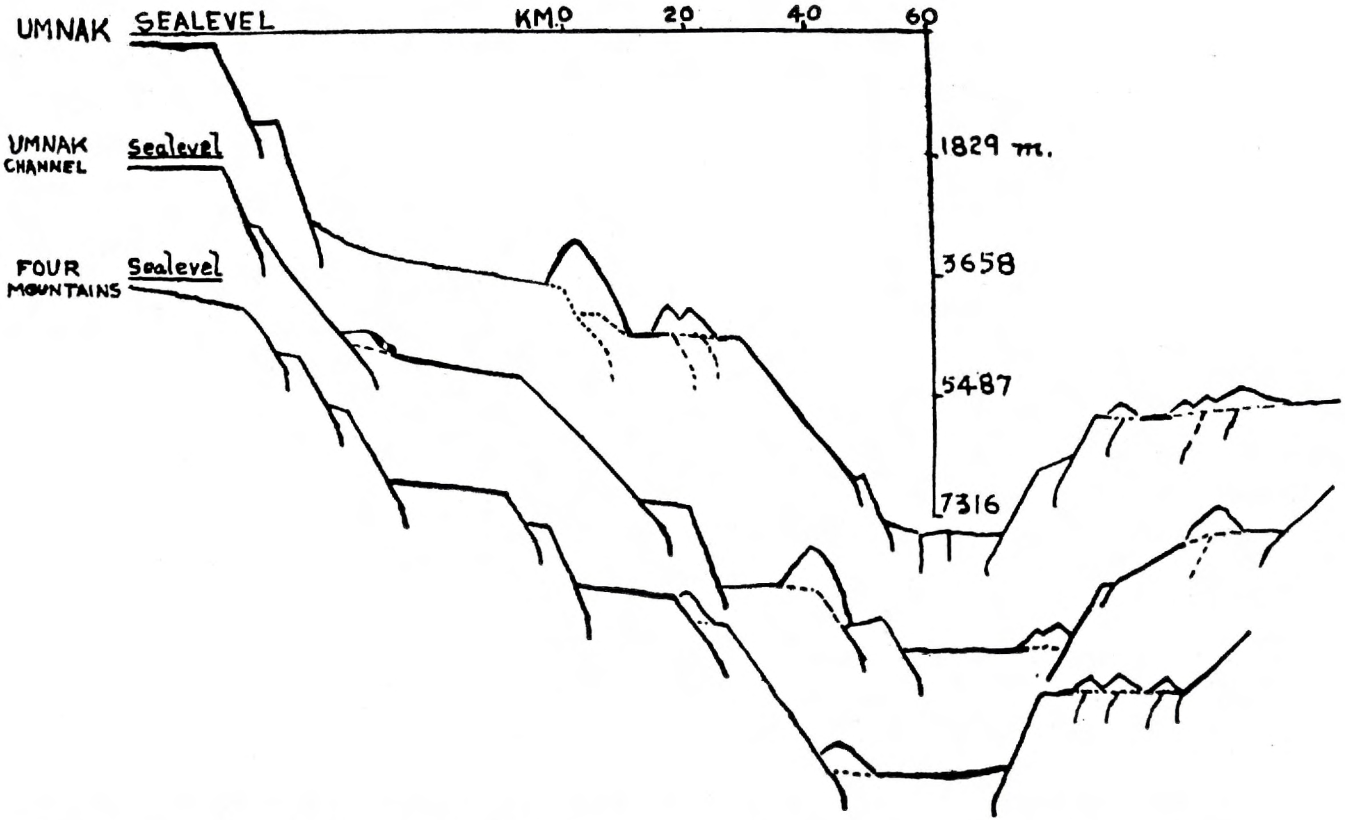


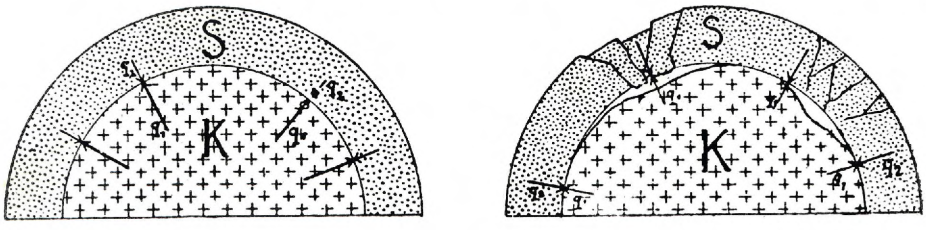
FIGURE 39. Murray's Pacific seabottom profiles of his Figure 9, Nos. 42, 43, 44, Group VIII, off Umnak Island (Murray 1945), redrawn as sections of downfaulted Aleutian Trench. From echo soundings by U.S. Coast and Geodetic Survey 1925-1939. Vertical exaggeration ten times. Slopes, projected down as inclined faults, might better be drawn as talus over vertical faults. Approximately 350 soundings in these three profiles.

trenches. The trenches are grabens and the ridges are horsts. Fault cracks emit magma along both graben and horst fissures, and terrestrial tensions open the fissures. At the trenches water presses downward at more than 600 atmospheres. At the fissures magma presses upward at from 800 to 1200 degrees temperature C. The head of water wherever volcanoes are, varies from subaerial Ghyben-Herzberg pressure of a few hundred kilograms to submarine hundreds of atmospheres.

(23) Aleutian Trench Profiles

These facts are illustrated by Murray's (1945) profiles of the Aleutian trench, part of his Figure 9 here redrawn as a section Fig. 39. The profiles reveal the trench as stepfaulted on the flank of the Aleutian ridge, and blockfaulted to a graben on its bottom 4000 fathoms deep. Going east (Murray's Figure 3) to the 2500-fathom continental front, with the flat slab of the bottom of the Gulf of Alaska faulted against it, the seabottom appears to be a monocline slipping down against the steeper fault steps of the land front. From Yakutat Bay to opposite the Aleutian volcano ridge the profile changes from a seabottom angle to a fault chasm of downsunken blocks. A collapse on this chasm made the large tidal wave of April 1, 1946. The Pacific flat may be conceived as sinking and pulling away from the fracture at the edge of the tumescent horst of the Aleutian ridge. The wider the fault chasm profile, the deeper the trench. The profile suggests stepfaults and volcanic heapings over cracks, it does not suggest folded strata, compare Fig. 41.

What chemical and mechanical conflict between released magma and water at excessive pressure and temperature would happen under oceanic depths is unknown. At 4000 fathoms with 1200° C., water is at 826° above its critical temperature (374°), and under pressure of 750 atmospheres, which is 532 atmospheres above its critical pressure (218 atmospheres). The profiles of Fig. 39 show graben depressions, and hills 2000 feet high built over the cracks between the stepfaults. The presumption is that crust blocks continue to sink as in 1926, and



A B

Figure 40. Sandberg's figures to illustrate an igneous bulb in contact with a hemispherical shell, serving to represent ignisepta. As a stage of the thickening crust in A the force q_1 is in balance with force q_2. In B shrinkage of core K and contraction of shell S induces the graben faulting of the primitive ocean basins, and distribution of the process through the ages makes the igniseptal fissures of geologic time. In the case of the earth the voids shown between core and shell never exist, and q_1 is always in balance with q_2 at some depth down the fissures, this being the equilibrium between the gravity of the shell and magmatic pressure from the core.

that magma foams up the fissures. Perhaps dike expansion by water-activated pumicification adds to the compressive stress against the Aleutian ridge.

Sosman (1947) shows that basic slag of an iron smelter will absorb water quietly at 1400-1500°, remains mobile at 1000°, and at 700-800° the water is released and the slag swells into a porous sponge, while part of it is converted into a mass of minute glassy hollow spheres ranging down to miscroscopic size. Sosman comments "A reaction such as this suggests the possibility that an igneous magma, intruding rocks which are saturated with water, may absorb the water rapidly enough to produce a pressure gradient *toward* the intrusive, instead of surrounding itself with a blanket of outward driven steam."

We reproduce in Fig. 41 a section of the Puys district in France (Suess 1918 Figure 370) showing down-faulting with lava cones built over faults, which is remarkably like the Aleutian Trench profile of Figure 39, and justifies interpreting submarine mounds as volcanoes over faults.

(24) Gravity Defect along Ocean Trenches

The Meinesz belts of negative gravity anomalies, suggesting lighter rocks than normal weight underground, coincide with belts of earthquake epicenters, lie about 100 miles oceanward from the island arcs of volcanoes, are themselves arcuate, and the trenches follow their oceanward borders: this applies to Japan,

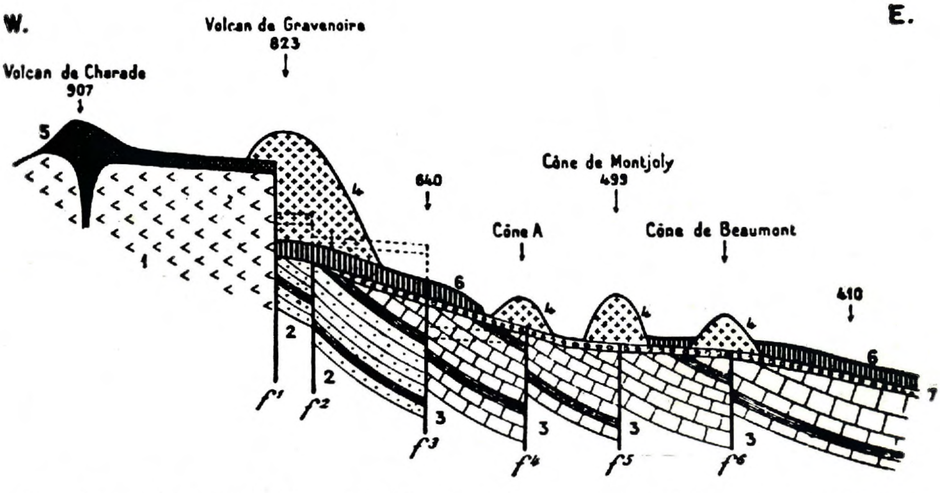


Fig. 370. — Coupe synthétique des volcans de Charade, Gravenoire et Beaumont (Chaîne des Puys), d'après Ph. Glangeaud (*Bull. Service Carte géol. de la France*, XII, 1900-1901, n° 82, p. 181, fig. 13).

1. Granite; 2. Arkoses et argiles (Sannoisien supérieur); 3. Marnes, calcaires marneux et arkoses (Stampien); 4. Cônes de scories; 5. Coulées du volcan de Charade (les parties de cette coulée découpées par les failles sont figurées en pointillé); 6. Coulées de Gravenoire et des cônes de Beaumont; 7. Alluvions sous-basaltiques (Quaternaire inférieur); f-f. Failles volcaniques et hydro-thermales (Sources de Royat et de Clermont). — Échelle approximative des longueurs 1 : 30 000.

FIGURE 41. Section of Puys of France from Glangeaud (Suess 1918, Fig. 370), to compare with Fig. 39.

East Indies and West Indies by measurement, and to the Aleutian arc as an identical structure.

Assimilation of concentrated light weight matter along with water in contact with volcanic engulfments may account for negative anomalies as a primitive volcanic process. It is possible that fissure engulfment and caldera engulfment accompanied primitive surface volcanism. There is a large body of primitive siliceous shell missing from the ocean basins as compared with the continents. Volcanism was more primitive than isoclinal folding (Hess 1938, Ewing 1938) and was an ancient process on a scale as large as the settling of entire ocean bottom blocks, and as the condensation of water finding its level in the first oceanic low places of the globe. The violation of isostasy whereby the heavy ridge remains in relief, and the light trench matter faults itself downward in graben step blocks is more satisfactorily accounted for magmatically than tectonically. Crustal stress under the cooling oceans was tensional as the shell congealed. The water must have pumicified the upwelling acid magma, and developed pressure on the ruptured contact belt between ocean and igniseptum. This pressure assisted graben faulting as a much more extensive surface process, the remnant of which remains along the trenches, which are critical lines of the earth's surface today. They are relics of engulfed salic matter created by water-magma contact, critically placed where excessive water pressure and excessive volcanic engulfment lie adjacent to excessive relief under air pressure only. The trench process was probably similar to what Sosman (1947), Morey (1938), and Goranson (1931), have outlined for water effects. The ocean bottom process was density settling (Day and Allen 1925, 81).

The greater the mass deficiency the larger is a graben fault chasm and the deeper the trench, between an extensive ocean flat and a heaped up continental ridge, capped with volcanic igniseptal vents and ejecta. P. S. Smith's (1938) geological map of Alaska shows the Aleutian igniseptum extending through Mount Spurr to Mount McKinley, with undifferentiated intrusive and extrusive igneous bodies of several ages. The ignisept carries active volcanoes of Wrangell and Mount Natazhat around the orogenic bend southeast to the line of other volcanoes from Sitka Sound to the Cascade Mountains.

The geology of Alaska shows the post-Miocene igniseptal belt on the flank of a pre-Cambrian core of the continent. Continental pre-Cambrian the world over is granitic, the primitive siliceous shell. This convectionally rose through ignisepta, by a succession of migrating complications with orogenesis and sediment, until the basic gravity differentiate became the implement of volcanism as it is today. The complication of hot siliceous magmas in contact with water, itself stimulated density settling of basalt over the water areas. Salic pumices float, femic pumices sink.

(25) New Data from the Albatross Expedition

Pettersson (1947) has found basaltic lavas widely distributed on the bottom of the Pacific and Indian Oceans. He found agglomerate in the Java-Sumatra

Deep. In one test he found indication of a steep sub-Pacific thermal gradient. The Meinesz gravity expectation and the Joly (1926) hypothesis are, within these limits, confirmed by direct contact. Pettersson by echo sounding of sediment found the Pacific muds shallow. The Aleutian trench data and the Pettersson findings encourage speculation about a pre-Archean geology of ignisepta.

(26) Suggestions concerning an Earth Model

If we accept deep trenches of graben faulting as correlatives of volcanic ignisepta (Valparaiso deep opposite Chilean volcano line), and ocean basins as faulted correlatives of continents or continental shallow seas (the Pacific opposite the Aleutian ridge and Bering Sea), and both groups as pre-Archean igneous geology comparable to the surface of the moon: then it appears probable there was engulfment of water and water-turbulent siliceous magma in deep linear fault block chasms under the oceans, parallel to tumescent dike injection of magma along the step faulted horst rim of those blocks of earth surface that remained in relative relief.

The Aleutian ridge is a step faulted continental rim built high with pre-Archean magmatic effusions backed in the hinterland by the granitic shell. The Aleutian trough is a step faulted engulfment zone at the edge of a large area of fundamentally heavier crust blocks which delineated the early Pacific Basin. This area received the earliest condensed water. It was surfaced by granitic magma reacting to intense pumiceous effervescence with the water, a reaction that was denied the continents. Engulfment volcanism assimilated water and salic matter in largest quantity where the trench fissuring became deepest. Femic matter by hydrous reduction of viscosity settled as basalt over the oceans. The engulfed sial on the ocean margin of ignisepta may account for negative anomalies where they are found today.

Evolution of ignisepta becomes evolution of magmatic differentiation. Basicity of later volcanism was the outcome of thickening crust of accretion inward, down to the 2900km discontinuity of today. All the turbulence of primal subaerial volcanism of the continents, in contrast to the density stratification of the ocean blocks and deep isostatic underflow towards the highlands, may well have concentrated sial in the continents by a relatively short lived sialic volcanism mixed with erosion and sedimentation. So came about rhythms of geologic revolutions and climates, dominantly continental, in contrast to the stability of ocean water pressures and temperatures, where the greater water volumes and areas created the world map of basaltic volcanism.

Basicity of later volcanism was the outcome of thickening crust and deeper source. The real differentiation to solar matter down the ignisepts on the way to the core is unknown. Both sial and sima are light weight matter as compared with the 79 uncommon elements heavier than iron which are only one twentieth part of all surface rocks (Jaggar 1947, 345). Pattern of intracontinental and intraoceanic minor ignisepta is more or less revealed in orogenic belts and island chains. Engulfment volcanism along the trenches today under water pressure would make Sosman sponge and Morey enrichment in salic minerals. The dynamic elements of the problem in heaving up ridges with basaltic tumescence in violation of isostasy are unexplained: they are kinetic units and as such uphold themselves by action as positive anomalies.

The evolution to basic volcanism led also to assimilation phenomena as known in batholiths. Primitive engulfment was the ancestor of stoping. Possibly subaerial sialic volcanism of the primitive continents was faintly echoed in Krakatau and Katmai, where Novarupta is siliceous. The distribution and proportions of the 79 heavy elements down the ignisepts depend on the difference between mean density of surface rock at 2.76, and mean density of the globe 5.52—just double the figure. If mass has its appropriate energy inside the globe, energy should increase from the surface to the core down the dikeways, with the density similarly distributed. If so there may be concentration of heavy matter and nucleonic energy towards the earth's center of gravity.

(27) Summary of Earth-core Volcanism

The new approach may be called "Earth-core Volcanism." It attempts to accommodate primitive moonlike earth volcanism to modern intrusive siliceous volcanism in contact with surface water. This is by way of probable nucleonic reactions still existing at the 2900-kilometer discontinuity, between massive white hot fluid core, and differentiated thick rifted shell. The differentiation proceeded rapidly in the primitive earth by thickening the shell inward, faulting downward the ocean basins, generating the lighter elements outward, and retaining the heavier ones in greater proportions inward. Oxygen, nitrogen, argon, carbon dioxide and hydrogen dominated the surface field, and their mixtures remain in atmosphere and hydrosphere; and their light compounds with silicon and metals in lithosphere.

The three principal novelties in accent are: (1) Proportionate importance of the step-faulted surface of the earth called oceans, 90 percent of the whole earth's surface a water charged basin. (2) Quantity of water accumulation over this 90 percent including oceans and river basins, much deeper than continents are high, and with contacts of water and magma at fissures never seen by man. (3) Persistence of intrusion actuated by nucleonic energy up deep faultplanes from the core itself, with energy at the core derived from its mother the sun. This implies atomic fission in progress at the surface of the core, while surface volcanism is the direct degradation of that energy, and not from remnant pockets in shallow substrata.

This experiment in thinking, based on volcano experience and the world map, rather than on assumptions of spheroidal stratification, is influenced chiefly by:

(1) Visible ignisepta as long volcanic fissures through earth crust, volcano chains.

(2) Their lengths apportionate to a deep crust, 1500 to 2000 miles.

(3) Their either curvilinear or straight quality characteristic of the breakage of a primitive sphere of very thick shell.

(4) Their parallelism with areally small continental elevations, and oceanic border trenches of areally large basins that received the primitive water accumulations of condensing vapors voluminously.

(5) The trenches graben-faulted to depths where water pressure is in hundreds of atmospheres.

(6) World dominance of normal faulting.

(7) World dominance of intrusion, compared to which sedimentary tectonics is trivial.

(8) Complete absence in the deepest erosion sections of field evidence of deep igneous stratification.

(9) World dominance of basic lava as dike product and volcano product.

(10) Presence of inconstant thermal gradient wherever tested, and mostly unknown because of unknown ocean bottoms.

(11) Steepness of thermal gradient in volcanic places, and the reverse in oldest continental places.

(12) Association of hot springs with volcanic magma, presumably equally true of submarine volcanic places.

(13) Estimates of what suboceanic topography, petrology and geophysics may reveal in the future.

Finally this experiment in thinking is influenced by the desire to stimulate experiment in earth exploration, by physical testing and rock sampling under ocean basins, with great originality expended in floating laboratories using all the resources of modern nucleonic physics, and the mechanical engineering of oil drillers. With this, volcanology can become a quantitative science extended to the whole earth, and through volcanology, geology, both theoretical and economic, can expand its usefulness.

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