THOMAS A. JAGGAR, JR., AND THE HAWAIIAN VOLCANO OBSERVATORY

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ABSTRACT

The digging of a cellar excavation on the north rim of Kilauea caldera in February 1912 marked the beginning of permanent facilities for what was to become the Hawaiian Volcano Observatory (HVO). The Observatory was largely the creation of Thomas A. Jaggar (1871–1953), then a Massachusetts Institute of Technology (M.I.T.) professor, who recognized the advantages, for the study of volcanism, of onsite facilities at an active volcano. Jaggar's efforts to establish an observatory at Kilauea were enthusiastically supported by Lorrin A. Thurston (1858–1931), a prominent Honolulu lawyer and businessman, who organized private support for Jaggar and HVO that continued into the 1940's. Initial support also came from M.I.T. and the University of Hawaii, and HVO was later successively sponsored by the U.S. Weather Bureau (1919–24), the U.S. Geological Survey (1924–35), the National Park Service (1935–47), and (since 1947) again the USGS.

The original HVO building, with a seismograph vault in its cellar, was in use until the early 1940's, when the Observatory was able to occupy a new building 200 m back from the caldera rim. In 1948 HVO moved to a building at the top of Uwekahuna Bluff on the northwest rim of Kilauea caldera; a new and larger building there was completed in 1986.

Under Jaggar's directorship (1912–40), HVO pioneered in seismological and other studies of volcanic processes. Seismographs were important instruments from the beginning of the Observatory, and HVO staff made numerous modifications to adapt them to the study of local volcanic seismicity. Jaggar even developed a rugged portable seismograph for use in outlying areas by amateur assistants. Early experiments in measuring the temperature of liquid lava were more educational than successful; the same can be said of the 1922 drilling program of four holes in and around Kilauea caldera. To support the drilling, HVO staff developed a modified touring car fitted with double wheels. For exploration around the coasts, an amphibious vehicle was designed and constructed.

Jaggar's campaign to obtain facilities at the top of Mauna Loa Volcano and a road leading to them was never entirely successful, but it has been made unnecessary by the advent of helicopters. Observation of the destruction of property by a lava flow in the 1926 eruption of Mauna Loa led to HVO-guided efforts to divert or stop flows threatening Hilo in 1935 and 1942 and to plans (never realized) for a set of permanent barriers. Concern for protection of lives and property also led to studies of tsunamis; in 1933 HVO used seismograms to predict (accurately) the arrival of a tsunami from a distant earthquake, and people in low-lying areas of Hawaii were for the first time successfully warned in advance. Such efforts reflected Jaggar's concern for not only the advance of science but also its application to the benefit of society.

Over its first 75 years, HVO has contributed much to the growing science of volcanology; for this a large debt is owed to the character and qualities of Thomas A. Jaggar.

INTRODUCTION

A hole was to be dug—by hand. Wooden stakes marked the corners of a rectangle about 7.3 m (24 ft) long by 6.7 m (22 ft) wide only about 6 m (20 ft) from the clifflike rim of Kilauea caldera on the Island of Hawaii. It was February 16, 1912, and the foundation to be dug was for Thomas A. Jaggar's volcano observation post, precursor of the Hawaiian Volcano Observatory (HVO).

The diggers were prisoners of the Territory of Hawaii, sentenced to a term of hard labor (HVO record book for 1912; Duncan, 1961). Jaggar was not above using free labor, prison or otherwise, to help stretch his limited funds. Their prison camp was nearby at what is now Kilauea Military Camp in Hawaii Volcanoes National Park.

The prisoners dug through almost six feet of volcanic ash and pumice to a layer of thick pahoehoe lava—a firm base for the concrete piers on which seismometers would be anchored. Plans and elevations for the piers had been hand drawn by Professor F. Omori at the Seismological Institute, Imperial University, Tokyo, Japan, and mailed two years before to Jaggar at the Massachusetts Institute of Technology. Omori also shipped to Jaggar, care of the Territorial Division of Forestry in Honolulu, "An Omori-type Horizontal Tromometer (a seismometer) (magnification = 120–200), and a seismograph for the observation of ordinary earthquakes" (Omori, 1910). These instruments were paid for and on hand in their crates as the prisoners dug.

Soon on hand at the crater rim were carpenters and workmen of the Hilo branch of H. Hackfeld and Company, Ltd., one of Hawaii's "Big Five" companies that controlled virtually all economy in the Islands—Hackfeld later became AMFAC, a multi-billion-dollar conglomerate (Weiner, 1982). Jaggar had contracted with Hackfeld for the forms and concrete work for the seismometer vault, and for the wooden structures that were to stand over and adjacent to the vault—the rimside facilities of the Hawaiian Volcano Observatory. The prime contract was for $1,785 and included a redwood tank for water storage. An additional $300 also went to Hackfeld for extra water-storage tanks (Jaggar, 1917a). Hackfeld executives

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and the directors of the other "Big Five" corporations were personally helping to sponsor the volcano observatory.

When British explorer Captain James Cook "discovered" Hawaii in 1778, Hawaiians had been living on some of the islands for as long as 1,300 years and had developed a complex, affluent Polynesian civilization. By 1795, when the various chiefdoms and islands were united to form the Kingdom of Hawaii, regular contact with Westerners had changed forever Hawaiians' environment and their way of life. However, with volcanism such an obvious presence in these growing islands, one part of the ancient Hawaiian religion that was kept—and still survives today—is the belief in the Hawaiian goddess of volcanoes, Pele.

Hawaiians believed that the goddess and her supernatural associates often entered into the political and social affairs of men. Pele could take human form, sometimes as a beautiful girl, sometimes as an old hag. Any female stranger could be the goddess. Pele was a major deity who had to be properly propitiated—she took offense easily—because in her anger she caused earthquakes and volcanic eruptions, and she personally directed the course of her lava flows.

Hawaiians believed that the summit caldera of Kilauea Volcano was the home of Pele, her family, and associates, but those deities also had "houses" elsewhere on the Islands of Hawaii and Maui that they could visit at will; these houses include the tops of mountains and all craters, cones, and hills. Pele required special behavior from humans in the vicinity of any of her houses, especially within a radius of 10 km (6 mi) or less from Kilauea caldera, and she expected tribute.

When high chiefs or other people failed to submit proper tribute, insulted Pele, her family, or her priests, or behaved improperly in Pele's domain, then the volcanic deities expressed their anger. They either flooded Kilauea caldera with lava and violently ejected it through the air over the countryside, or they took a subterranean passage to one of their "houses" near the land and homes of those who had offended and, using that house as a base of operations, proceeded to punish the offenders by, at a minimum, covering some of their land with fresh lava (Ellis, 1827; Menzies, 1920). Pele stamped her foot enough times before and between episodes of visible volcanism to remind people of her power and presence; each stamp caused an earthquake. Pele could also call down lightning and cause thunder to roll across the sky.

In 1893, the Kingdom of Hawaii was overthrown by non-Hawaiian businessmen. Five years later in 1898, during the Spanish-American War, the United States annexed Hawaii; the Islands thus became "American soil." This was one of the factors that led to the establishment of an American-sponsored volcano observatory on the rim of Kilauea Volcano (Apple, 1982; Apple and Apple, 1979a; Daws, 1968; Kuykendall, 1967).

During the nineteenth century, while the Hawaiians were being introduced to the ways of Western civilization, Hawaiian volcanoes were described in letters, reports, logs, journals, sketches, notes, and books, published in various places and some distributed worldwide. First made famous because Captain Cook was killed there, the Island of Hawaii now added another world-renowned distinction: active volcanoes. Principal fame focused on Kilauea, which appeared to be comparatively benign. Kilauea had an apparent constancy of activity within its vast summit caldera and, in contrast to some European volcanoes, was not known to wipe out villages or cast glowing fragments of lava down upon hillsides devoted to viniculture. At Kilauea, according to reports, volcanism stayed put inside a crater. While the general public was getting armchair thrills from travel writers, some scientists were also becoming aware of, and visiting, the Big Island (table 61.1).

The scientists listed in table 61.1 did not always agree. First there was the continuing, friendly controversy in the *American Journal of Science and Arts* ("Silliman's Journal") between Rev. Titus Coan, a Hilo man who hiked to and described almost every flank eruption of Mauna Loa between 1843 and 1880, and J.D. Dana, one of the journal's editors and a famous geologist, who didn't always believe the testimony of the eyewitness. For instance, after Dana published Reverend Coan's graphic and detailed description of the source and flows of Mauna Loa's 1843 eruption, Dana followed with "Mr. Coan speaks of the lavas as flowing from an orifice in a broad stream down the mountain. It is probable that fissures opening to the fires below were continued at intervals along the course of the eruption, and that these afforded accession to the fiery flood. Any internal force sufficient to break through the sides of a mountain like Mauna Loa, must necessarily produce a linear fissure or a series of fissures, and not a single tunnel-like opening." (Dana, 1852, p. 256; see also Dana, 1850; T. Coan, 1871, 1882; L. Coan, 1884.)

Arguments such as this could only be resolved by volcanologists doing the observing, but they served to publicize the need for further study. The Coan-Dana controversy helped raise questions that needed to be answered about volcanoes, thus helping pave the way for such institutions as the Hawaiian Volcano Observatory.

When a hotel on the rim of Kilauea caldera became a permanent facility in 1866, its series of guest registers became a repository of reports and observations by the guests, an almost daily record (by observers who varied from the scientist to the joker) of earthquakes felt and unfelt and of volcanism seen and unseen on Kilauea and Mauna Loa. Both Brigham (1909) and Hitchcock

TABLE 61.1.—*Some sources for early descriptions of the volcanoes of Hawaii*

	Name or type of observer	Sponsor, if any	Reference
1825	Lord Byron party	England	Byron, 1826
1834	Botanist	London Horticultural Society	Douglass, 1834, 1919
1834	Captains Parker and Chase		Kelley, 1841
1837	Geologist	———	Strzelecki, 1838, 1845
1839	Scientist	———	Lowenstern, 1841
1839	Ship's captain	———	
Shepherd, 1840			
1840	U.S. Exploring Expedition	U.S. Government	Wilkes, 1845
1840	Geologist	U.S. Exploring Expedition	Dana, 1849
1846	Professor	———	Lyman, 1851
1859	Geologist	———	Green, 1887
1868	Kilauea historian	Harvard University	Brigham, 1868, 1869
1873	Travel Writer	———	Bird, 1875
1880	Kilauea historian	Bishop Museum	Brigham, 1909
1882	Geologist	U.S. Geological Survey	Dutton, 1884
1883	Geologist	Dartmouth College	Hitchcock, 1911
1887	Geologist	Yale University	Dana, 1890
1909	Geologist	Massachusetts Institute of Technology	Daly, 1911

(1911) mined the more reliable reports from the Volcano House guest registers, quoting them along with observations from their own visits and reports from many additional sources to yield histories of both volcanoes, comprehensive up to their dates of publication.

Brigham, a scientist who once taught botany at Harvard and also practiced law in Boston, was by 1898 the Director of the Bernice Pauahi Bishop Museum in Honolulu. Hitchcock was a geologist, a member of a prominent Hilo family, and by 1909 was retired as Emeritus Professor of Geology at Dartmouth College. Both Brigham and Hitchcock kept up with the comings and goings of scientists interested in the Big Island volcanoes.

Brigham (1909, p. 216) notes that in the spring of 1909 the "well-known professors in the Massachusetts Institute of Technology, T.A. Jaggar, Jr., and R.A. Daly," visited Kilauea, and that Jaggar and Daly were "interested in the establishment of a permanent observatory at Kilauea, a result so ardently hoped for many years and frequently referred to in these pages."

Hitchcock (1911, p. 306) applauds Brigham's recommendation that a "permanent scientific observatory be established at Kilauea, where notes may be taken with the best instruments, of earthquakes, the diurnal changes of the dome of Halemaumau, the temperatures of the molten lava and steam jets, the analysis of ejecta and spectroscopic investigations."

While arguments on behalf of more formal scientific investigations in Hawaii were being presented, the public had been well prepared by press reports of devastating earthquakes and volcanic eruptions around the world, especially the eruption of Mont Pelé in 1902 and the San Francisco earthquake in 1906.

In the hope that science could close the gaps in geological knowledge and learn to predict earthquakes and eruptions, some New Englanders were willing for humanitarian reasons to finance foreign trips and support work abroad for scientists. For instance, the Springfield (Massachusetts) Volcanic Research Society supported, at least in part, the travels and studies of Frank A. Perret, an electrical engineer and inventor turned volcanologist who became well known for his studies at Vesuvius, Etna, and Stromboli. The Springfield society also helped support Perret's 1911 work at Kilauea (Wentworth and Powers, 1962; Macdonald, 1972).

It was in this climate of opinion that the trustees of the estates of Edward and Caroline Whitney gave to the Massachusetts Institute of Technology the sum of $25,000 for a memorial fund; the principal and interest were to be expended at M.I.T.'s discretion for research or teaching in geophysics, especially seismology, "with a view to the protection of human life and property" (Jaggar, 1917a). Investigations in Hawaii were recommended. The Whitney fund was deeded to M.I.T. by the trustees on July 1, 1909, and three years later a group of twelve other New Englanders supplied M.I.T. with supplemental funds for geophysical research in Hawaii (Jaggar, 1917a).

Even before the Whitney gift, M.I.T. had been searching for a suitable site for full-time, resident study of volcanoes and earthquakes. Professor Thomas A. Jaggar, Jr., had investigated sites in Italy, the Caribbean, and Alaska. At private expense, both Jaggar and Professor Daly visited Kilauea in 1909. Jaggar went on to Japan; Daly stayed to study the action in Kilauea caldera (Daly, 1911). In Japan, Jaggar investigated two volcanoes in eruption and studied the Japanese seismometer network, then the world's most advanced. He became a lifelong friend of Professor F. Omori, famed Japanese seismologist.

After what he termed "mature deliberation," Jaggar chose Kilauea for M.I.T.'s volcano observatory. He gave M.I.T. eight reasons for his choice: (1) Kilauea was the safest known volcano in the world; (2) Kilauea and Mauna Loa were isolated, more than 3,000 km (2,000 mi) away from complications other volcanic centers might impose; (3) Kilauea was reasonably accessible—it could be reached by a 50-km (30-mi) road from Hilo harbor or a day's sail from Honolulu; (4) the central Pacific was good for recording distant earthquakes and was served by good transportation east or west; (5) the climate was uniform, with air clear enough for astronomy; (6) small earthquakes were frequent and easily studied; (7) hot and cold underground waters were available for both agricultural and scientific purposes; (8) "The territory is American, and these volcanoes are famous in the history of science for their remarkably liquid lavas and nearly continuous activity" (Jaggar, 1917a, p. 2).

Jaggar stopped in Honolulu twice in 1909; obviously aware of funds to be forthcoming from the Whitney Fund and sure of support from M.I.T. for an observatory at Kilauea, he sought added patronage in Honolulu. Jaggar gave lectures and met with the Chamber of Commerce, the Bishop Museum, and key businessmen. Guiding him through the interlocking directorships of the Hawaiian business community and introducing him into its parallel island society network was Honolulu businessman Lorrin A. Thurston, who headed, among other things, the Hawaiian Promotion Committee, forerunner of the Hawaii Visitors Bureau. Thurston and Jaggar became close friends.

JAGGAR AND THURSTON: BACKGROUND

Thomas Augustus Jaggar (1871–1953) was born in Philadelphia, Pennsylvania, son of an Episcopal Bishop. He obtained three geology degrees from Harvard (A.B., A.M., and Ph.D.), studied in Munich and Heidelberg, and then began teaching at Harvard. Jaggar was one of the scientists sent by the U.S. Government in 1902 to investigate the volcanic disasters at Soufrière and Mont Pelé. His experiences there led him to devote his career to active volcanoes and related geophysics. In 1906, already a much-published, respected, well-known geologist, writer, and lecturer, he became head of M.I.T.'s department of geology. Jaggar saw the need for full-time, on-site study of volcanoes. He had long deplored that to date, especially in America, it was only after news of an eruption was received that geologists rushed from academic centers to study volcanism. There was generally no trained observer there beforehand, and scientists from afar often arrived after the eruption was over. There was then only one volcano observatory in the world, that at Vesuvius established in 1847. Jaggar thought America needed one (Jaggar, 1910; Macdonald, 1972; Bullard, 1975; Day, 1984).

Lorrin Andrews Thurston (1858–1931) was born in Honolulu, grandson of one of the pioneer missionaries from New

England. He studied law at Columbia University and became a member of the Honolulu bar. In the Kingdom of Hawaii, Thurston served in both elected and appointed positions, but he was a leader in the revolution (January 17, 1893) that overthrew Queen Liliuokalani and ended the native monarchy. The very next day Thurston sailed from Honolulu for Washington, D.C., to serve the "Provisional Government," which he helped establish, as envoy extraordinary and minister plenipotentiary. He stayed for two years and paved the way for annexation of Hawaii by the United States in 1898. In his business life he developed sugar plantations and railroads, brought the first electric street cars to Honolulu, and was the major stockholder in the Volcano House on the rim of Kilauea caldera. Being a volcano buff, he often visited Kilauea and frequently brought officials and delegations from the United States to see the volcano from the porch of his Volcano House. In 1900, Thurston became publisher of the *Pacific Commercial Advertiser*, a Honolulu daily newspaper (still today under the management of a descendant). Not only did he promote a volcano observatory for Kilauea, but he also wished to make Kilauea a U.S. national park (Day, 1984). Thurston had a powerful influence because of his family connections and the many positions he held, and his support for HVO in its early years was invaluable.

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BEGINNINGS OF THE OBSERVATORY

In 1909 Jaggar proposed to prospective financial supporters in Honolulu an observatory program. Its purposes were listed as follows: (1) To establish "on the brink of the Volcano of Kilauea" buildings for instruments, laboratory, offices, and record storage; (2) to provide a room for a local museum; (3) to welcome advanced students for special work; (4) to establish a network of stations, some manned by volunteer observers, to study tides, soundings, earthquakes, and coastal movements; (5) to mount expeditions to other volcanic and earthquake belts for comparative studies; (6) to conduct research in gravity, magnetism, and latitude variations; (7) to initiate geological surveys; all of these with their "main object * * * humanitarian—earthquake prediction and methods of protecting life and property on the basis of sound scientific achievement" (Jaggar, 1917a, p. 2–3).

Thurston's Honolulu connections in 1909 pledged $3,450 a year for five years to help M.I.T. sponsor the observatory. M.I.T. officials did not think this was sufficient. In Honolulu, the plan was shelved. Jaggar and Daly returned to teaching at M.I.T., but they continued planning for a Kilauea observatory.

The Whitney Fund became available to M.I.T. in July 1909. Part was spent in 1909 and 1910 to secure (from the Werkstätte für Präzisions-Mechanik, Strassburg, Germany) a pair of Bosch-Omori seismometers (Bosch, 1910) and to order through Professor Omori in Tokyo the three Omori-designed seismometers made by Kyo-iku-hin Seizo Kaisha (Educational Appliance Company) (Omori, 1910).

Also in 1910, M.I.T. spent some Whitney Fund money to have Leeds and Northrup, Baltimore, Maryland, construct "special resistance thermometers," designed to take the temperature of liquid lava in the so-called perpetual lake at Kilauea. Part of the fund also helped send the temperature-taking Perret-Shepherd expedition to Kilauea in 1911. Personal and teaching concerns kept both Jaggar and Daly in Boston in 1910 and 1911 (Jaggar, 1917a).

The Leeds and Northrup thermometers were each about 3 m (10 ft) long, with platinum coils inside protected by tubes of iron, nickel, and quartz. The job of measuring the temperature of the lava lake was seen by scientists in Boston and Baltimore to be something like sticking an iron rod into a pot of boiling tar. Readings were to be taken "on shore" through electric wires connected to the thermometer.

A cable system was designed and manufactured on the East Coast of the United States by the Lidgerwood Company and paid for by Whitney funds. Its job was to take a thermometer out over the lake of molten lava, lower it into the bubbling lava, hold it there while readings were taken, lift it out, and return it to shore. By the time the cable system arrived, the diameter of the lava lake in Halemaumau had so enlarged that the system did not fit and had to be modified. Six men were needed to operate the trolley that rode out on the cable and lowered the thermometer. F.A. Perret and E.S. Shepherd (from the Geophysical Laboratory of the Carnegie Institution in Washington, D.C.) had no funds to hire laborers. Work could only be done when enough volunteers showed up. The project dragged out over a month's time, while Pele's hair collected on the main cable and restricted trolley movement. The wires that pulled the trolley back and forth disintegrated and had to be replaced for each experiment. Over the course of the month, cable anchors and cables were weakened from constant exposure to steam and acid vapors. When work was under way, fumes often were so thick that the men at the winch could not see the thermometer. Signals were relayed around the rim of the lava lake to tell winchmen to reel in or out. In the thick of it all was chief volunteer Lorrin Andrews Thurston, who also recruited the other volunteers.

On July 30, 1911, after two thermometers had already been lost in the lake without readings, with the last thermometer mounted on the trolley and time running out for the disintegrating cable fittings, the last chance was at hand. Only three volunteers, including Thurston, showed up. Thurston put his family to work. Thurston himself handled the reel that lowered the thermometer; his wife Harriet held the cable tight on the drum; son Lorrin shifted coils; and daughter Margaret stood on the rim in heavy sulfur fumes to relay signals (from Perret down in the pit by the lake's edge) with a flag—signals that came to her father at the reel, to Shepherd standing by the meter, and to volunteers Emery and Ferris at the winch.

Before Pele swallowed the last thermometer, Shepherd got a reading of 1,000 C (1,832 F) from two feet under the surface of the lava lake. Shepherd himself suggested that future temperature readings be done with optical pyrometers, for "No mechanical system can long withstand the strain and abuse which Pele applies to any foreign object which invades her private lake" (quoted in Jaggar, 1917a, p. 47–50).

Perret, a meticulous observer and maker of notes, wrote reports not only on the progress of taking Pele's temperature, but also on volcanic phenomena generally. His first report covered almost a month and a half of scientific work and observations; the next five covered a week each (see Jaggar, 1917a, p. 35–46). He also wrote four scientific papers (Perret, 1913a, b, c, d).

Thurston now had hands-on involvement helping scientists begin to investigate his favorite volcano, and he had published weekly a series of six authentic reports about Kilauea in his daily Honolulu *Advertiser.* In 1911 Thurston revived the 1909 subscription list, hoping to get his Honolulu friends and business associates to up the ante sufficiently high that M.I.T. would move its observatory plans off the drawing board and onto the rim of Kilauea caldera.

At a luncheon hosted by Thurston on October 5, 1911, the guests—obviously primed and ready—formed the Hawaiian Volcano Research Association—the famed HVRA. An unpaid executive committee of five were to be elected annually. This founding meeting of the HVRA adopted a motto: *Ne plus haustae aut obrutae urbes* (No more shall the cities be destroyed) (Macdonald, 1953).

Thurston chaired the executive committee, which was quickly endorsed by the Honolulu Chamber of Commerce to raise funds from among its members. Thurston served with Albert F. Judd (representing the trustees of the Bishop Museum), John W. Gilmore (president, College—later University—of Hawaii), James A. Kennedy (of Interisland Steam Navigation Co.), and Clarence H. Cooke (of Charles M. Cooke, Ltd). The pledge was for $5,000 a year for five years, starting January 1, 1912. Treasurer Cooke and his associates of C.M. Cooke, Ltd., guaranteed the full amount in the event of failure of any individual subscribers to pay.

Negotiation by the HVRA executive committee with M.I.T. resulted in the assignment of Jaggar, as M.I.T. professor, to Hawaii as of January 1, 1912. HVRA was to sponsor and operate the Hawaiian Volcano Observatory. M.I.T. became an HVRA subscriber (indeed, the largest) for five years, using the income from the Whitney Fund and payments from 12 other New Englanders to its Seismological Fund. M.I.T. ran HVO's scientific affairs through Jaggar, who obviously received a deep delegation of authority, and granted use of its name and publishing facilities for that five-year period. In December 1911, Jaggar was granted leave of absence from his deanship and teaching duties at M.I.T to continue at Kilauea the work of recording the volcanic activity along the lines started by Perret.

Jaggar arrived in Honolulu and met with the HVRA executive committee on January 9, 1912, and then proceeded to the Volcano House on the rim of Kilauea caldera to go to work as the director of the Hawaiian Volcano Observatory on January 17, 1912. On January 18, using data collected from the Volcano House guest registers and other sources, he renewed the weekly reports to Thurston's *Advertiser.* Although Jaggar had married Helen Kline in 1903 and the couple had two children, Helen did not accompany Jaggar to accept his post as director of the Hawaiian Volcano Observatory in 1911, and a divorce followed. In 1917 Jaggar married a coworker at HVO, Isabel P. Maydwell; she was his wife, assistant, and companion for the rest of his life.

On January 19, Demosthenes Lycurgus, representing Thurston's Volcano House Company, went with Jaggar to Hilo to visit the merchants and leading citizens. Their mission was to raise funds to build a laboratory on the rim of Kilauea caldera for use by representatives of M.I.T. engaged in volcanologic research (Jaggar, 1917a). The $1,785 the merchants and private citizens of Hilo subscribed resulted in the contract with the Hilo Branch of H. Hackfeld & Company, Ltd., to build the forms and pour the concrete for what was soon to be called the Whitney Laboratory of Seismology and to build above the vault a building for the Hawaiian Volcano Observatory. In essence, the merchants of Hilo provided funds for these initial rimside facilities; the HVRA, with heavy reliance on M.I.T., promised operating funds for the first five years. Until the new facilities were built, Jaggar's first home and office at Kilauea were in the Volcano House.

PIONEERING, 1912–1953

Halemaumau—the circular pit within Kilauea caldera—contained an active lava lake about 65 percent of the time from 1823 to 1924. The lake rose and fell and sometimes overflowed onto the main caldera floor. This rare volcanic feature made Kilauea a tourist destination as well as an attraction to scientists. Two hotels, the Volcano House (1866–present) and the Crater Hotel (1911–21), provided accommodations. By 1911, roads had replaced foot and horseback trails to connect Kilauea's summit area with Hilo 50 km (30 mi) away. The altitude of Kilauea's summit, 1,200 m (4,000 ft) above sea level, created a cool climate and made it an attractive place to visit. Part of Kilauea caldera and part of its rim area were owned by the estate of Bernice Pauahi Bishop, a princess and the last survivor of the royal Kamehameha line. The Volcano House leased its extensive lands on the rim of Kilauea caldera from the Bishop estate, and in 1912, with the estate's permission, it subleased to the Hawaiian Volcano Research Association a site on the rim for the Hawaiian Volcano Observatory.

Suggestions that the Kilauea summit area become a national park began appearing in the Volcano House guest register and in newspapers in Hawaii as early as 1903. When Thurston escorted Congressional parties and Federal officials to his Volcano House to show them the boiling lava in Halemaumau, he promoted both a national park and an observatory. In December 1915, Jaggar was commissioned by the HVRA and M.I.T. to appeal to Congress to take over HVO as a permanent governmental institution and establish under the Weather Bureau a division of volcano observatories and also to help with the national park bill then pending. Jaggar failed in 1916 to acquire an independent Federal sponsorship for the observatory, but he did succeed with the national park, which became the surrogate sponsor.

The hearing in Washington (February 3, 1916) covered subjects ranging from volcanology to Hawaiian folklore; the Jaggar bill for a Hawaii National Park was reported favorably out of committee, passed by both Houses of Congress, and signed into law by President Wilson on August 1, 1916. Thurston had primed those Congressmen who visited the Islands; Jaggar in Washington had convinced many of the rest. (Congress changed the name to Hawaii Volcanoes National Park in 1961, by which time much additional land had been added). As the National Park Service took up resident management and acquired the land with existing leases and subleases, it became, among other things, the landlord for the Volcano House and HVO (Apple, 1954).

In the absence of Government sponsorship, HVO's founding organization, the privately financed HVRA, continued its support of volcano research well into the 1940's. It employed seismograph observers who worked in detached cellars, such as in Hilo and Kona, and others on research fellowships. It supplied or paid for shops, machine tools, instruments, laboratories, stationery, supplies, expeditions, books, boats, specialists, vehicles, and machines, thus making possible pathbreaking investigations that could not have been so readily attacked under Government alone, owing to the restrictions that control Government funds. The HVRA also published volcano notes from many lands, the weekly reports from Kilauea, Lassen Observatory notes from California, reviews of volcanologic books, and popular statements of the technical works in progress.

In general, after the National Park was created, the Federal Government paid the salaries of the permanent staff, while the HVRA supplied all buildings, much of the equipment and facilities, and services such as publications. The buildings and equipment, for instance, were owned by HVRA and leased to the sponsoring Federal agency. As HVRA support phased out in the late 1940's, HVO came more fully under Federal appropriations and control. By the early 1950's, ownership of all HVRA buildings and chattels had been transferred to the Federal Government.

Publications over the decades listed HVO sponsoring organizations as the Massachusetts Institute of Technology, the Hawaiian Volcano Research Association, the University of Hawaii, the U.S. Weather Bureau, the National Park Service, and the U.S. Geological Survey, in various combinations. Sponsoring organizations of HVO are shown in the following table:

Organization	*Period of sponsoring*
Massachussets Institute of Technology	1911–1917
Hawaiian Volcano Research Association	1912–1940's
University of Hawaii	1912–1942
U.S. Weather Bureau	1919–1924
U.S. Geological Survey	1924–1935
National Park Service	1935–1947
U.S. Geological Survey	1947–present

The USGS has sponsored HVO twice. In 1926, Congress established within the USGS a Section of Volcanology, with Jaggar in charge. Jaggar quickly instituted new stations and staff in California and Alaska. Contraction followed within a few years because of the economic depression. Looking back almost two decades later, Jaggar reminisced as follows: "First it was a splurge of high water mark in appropriations with work in Lassen and Alaska and Hawaii and a maximum staff. There was a navy trip to Tin Can Island and all sorts of cooperation public and private. Then came the big bust in 1932 and an 83 percent cut but we kept Hawaiian volcanology alive and there were immense accumulations to study and publish, and typewriter paper is cheap. The Hawaii business men [HVRA] came to the rescue and never faltered" (T.A. Jaggar, unpublished notes, copy in personal collection of J.P. Lockwood).

Geologist Howard A. Powers, who joined the HVO staff in 1929, also recalled that period of boom and bust. Powers received his Ph.D. from Harvard in 1929 and went to Washington to try to get sworn into the USGS there, "but they said that I would have to be sworn in at the Observatory. (Cagey—that way I had to pay my own way to Hawaii.) * * * The staff at that time was T.A. Jaggar, Richmond Hodges, accounting clerk; and two local men not civil service—Yasunaka, general handyman and husband of Jaggar's maid, and Tai On Au (a local Chinese who had graduated in machine shop from the Hilo Boarding School). The next two years were affluent—we picked up Austin Jones, graduate seismologist from Berkeley, Ed Wingate, a top-notch Topographer to take on problems of starting useful tilt recording. Then the huge cut for fiscal 1933. I was transferred to the USGS Ground Water Branch, Ed Wingate was transferred to USNPS as Superintendent of Hawaii National Park, Tai On Au was released, Austin Jones was kept on as Seismologist, Yasunaka continued his job, and Richmond Hodges transferred to the office of Headquarters, Hawaii National Park" (H.A. Powers, written commun., 1985).

BUILDINGS AND FACILITIES

TECHNOLOGY STATION (1911–1918)

In July 1911, Perret selected a site on the eastern rim of Halemaumau that commanded a view of the entire lava lake; there he built a small frame building he called "Technology Station," a place name used in many early datelines of HVO weekly bulletins to the press. Perret lived in this cabin from July 24 through September 17, 1911. By mid-August, Perret noted that vapors from the vent had formed acid, which had consumed the zinc coating of the galvanized iron roof. His field assignment finished, Perret left the cabin and Hawaii.

Jaggar came on duty in January 1912 and discovered that the Technology Station had been vandalized the month before. He believed it was vulnerable because it stood close to the parking area at the end of the road. Jaggar had the cabin torn down and rebuilt, enlarged, and surrounded by a picket fence, at a different site a few yards back from the north rim. There it was used for the storage of instruments, as a seismometer station, and as an observation camp. By early February the cabin contained a rectangular concrete platform, which protruded through the board floor and soon held a seismometer.

In June 1918, laborers tore down Technology Station and rebuilt it again on the north rim of Kilauea caldera, where it joined other HVO buildings lining the rim. There the cabin was repaired and repainted to become a staff residence; it served until all the HVO facilities along the north rim were razed in 1940.

INSTRUMENT HOUSES

Jaggar reported that in 1912 an additional hut was constructed wholly without iron for possible magnetic work on the verge of Halemaumau, to allow sheltered direct instrument observation of the lava. Seismologist H.O. Wood described the hut as "at the very edge of the northern rim of Halemaumau" (Wood, 1913, p. 16). If the hut was still standing in 1924, it must have been destroyed by the enlargement of Halemaumau that accompanied a series of steam explosions that year.

In addition, over the years at least four cellars were excavated or constructed on the floor of Kilauea near Halemaumau to house instruments for the detection of earthquakes, ground tilt, or both. Hawaii Volcanoes National Park maintains a list of buildings with assigned numbers; the four known cellars are buildings number 136, 255, 308, and 309. Building 309, the "East Vault" near Halemaumau, was constructed in 1959 and razed in 1973. Three other cellars were built by the Civilian Conservation Corps (CCC) about 1932 as stone-wall pits. The "West Pit" was buried under a lava flow in September 1971; this flow also partially covered the cellar called "Outlet," about 1 km south of Halemaumau. That left only the "North Pit" on the floor of Kilauea caldera with working instruments inside.

WHITNEY LABORATORY OF SEISMOLOGY (1912–PRESENT)

The hole those prisoners dug on the north rim of Kilauea caldera (fig. 61.1) in 1912, through six feet of volcanic ash, resulted in "a basement room, eighteen feet square, with piers and floor of concrete, reposing upon the upper surface of the basalt, and high walls of concrete. This [basement beneath what became the main HVO building] is the Whitney Laboratory of Seismology. A constant emanation of hot steam from cracks in contact with the concrete walls keeps this room at a fairly uniform temperature and thus improves it for the purposes of seismology" (Wood, 1913, p. 16).

Jaggar was a true pioneer volcanologist; he made mistakes in locating and designing the Whitney vault, but he and his staff lived with their mistakes and tried to overcome them. They made their problems and progress known through their published writings, and early HVO mistakes helped others avoid similar ones when they built vaults elsewhere.

In the Whitney vault as first built, thick reinforced-concrete walls went up to ground level, about 1.7 m (5.5 ft) above the concrete floor. From ground level to the ceiling, glass panels were fixed in wooden frames to admit natural light. When the sun shone, the temperature rose sharply. Because of temperature variations, neither Jaggar nor Wood trusted the records made by the seismometers.

Not only were the temperature swings too great, but stray breezes also blew recording arms to make confusing marks on smoked drums, and dust seeped in around the windows, mixed with oil, and gummed up delicate mechanisms. Some of these problems were solved when the windows and frames were covered with boards and battens and sealed with coats of paint. This made the cellar dark day and night. Battery-operated lights served until 1921, when HVO acquired its first electric generator.

An earthquake in October 1913 opened a crack in the north wall of the Whitney vault. Water seeped from it onto the floor until the crack was repaired and sealed (the concrete floor of the Whitney vault contained no drain).

Being a basement vault with a building above also created problems. Even in calm weather, movements of the building were recorded by the seismometers in the vault below. Winter Kona storms swept high winds from the south across Kilauea caldera, hitting with full force against the north rim and causing such rocking and trembling of the building above as to mask the records on the seismograms. In the winter of 1915–16, gale-force winds stripped the sheets of corrugated iron from the roof of the building. Rain water in the offices above poured into the vault to wash away the seismograms on their drums, flood the floor, and soak the instruments. Repairs took weeks.

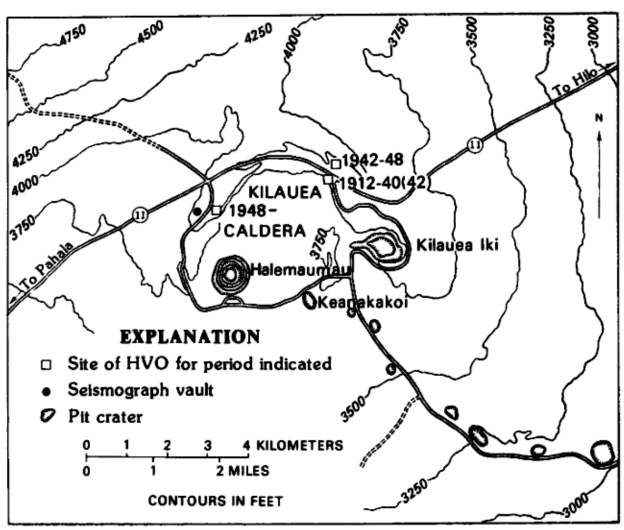

FIGURE 61.1.—Successive sites of main facilities of Hawaiian Volcano Observatory around rim of Kilauea caldera. From 1940, when original buildings were razed, until 1942, when the Observatory was able to occupy Building 41 (newly vacated by the Army), HVO staff and equipment were scattered in various buildings near the original site and elsewhere.

The Whitney vault's location 20 feet from a cliff face also imposed special problems. Cliff-face rocks expanded and contracted, from heating and cooling, sun or shadow, wetting or drying, and all such movements were recorded. Whenever high winds pressed or let up against the face, it was recorded by the seismometers, sometimes masking data about tilting of the ground caused by underground lava movements.

Then, on December 19, 1921, the nearby Volcano House began to run a Fairbanks-Morse engine to power a generator for the first electric lights at Kilauea. Variations in the engine speed as well as the exact times of starting and stopping were duly recorded by seismometers in the Whitney vault until, months later, the exhaust was directed away from a steam crack and into the air. Apparently HVO's own generating plant never caused any such problems.

Whitney vault seismometers over the years recorded much of the truck and automobile traffic that passed on the nearby road. Seismologists quickly learned to separate natural events from the local man-caused ones, but all must have wondered how much the vibrations caused by man obfuscated the records.

Except for changes in the concrete piers as instruments came and went, there was no basic change in the Whitney vault until early 1941 (fig. 61.2). In that year, the building above was dismantled, and a reinforced-concrete slab was poured by the Civilian Conservation Corps (CCC) to become the vault's new roof. The slab was covered with 45 cm (18 in.) of topsoil. The isolation (from the building above) and insulation (from the ambient air) resulted in a nearly constant temperature around 35 °C (95 °F), and the daily variation seldom exceeded 0.5 °C (1 °F).

Two other unfortunate vault characteristics persisted, however. One was that quick body movements often caused recording arms to move because of the air currents generated. Another was the oppressive warmth caused by the natural steam heat. Scientists through the active life of the vault (1912–1963) bundled up in wooly sweaters, scarfs, and raincoats to walk to the vault through the chilling rains and fog at 1,200-m (4,000-ft) altitude and then peeled down to undershirts when they entered the vault to attend the instruments.

The Whitney Laboratory of Seismology went out of active service in 1963 and is, since July 24, 1974, a property in the National Register of Historic Places, complete with some of the original instruments. Part of its nomination to the Register reads: "The Whitney Seismograph Vault, built in 1912, represents the beginnings of the continuous and resident study by American scientists of the earth's volcanic and seismic activity at Kilauea and Mauna Loa volcanoes. The Hawaiian Volcano Observatory, a U.S. Government facility since 1919, used the vault from 1912 through 1963 when more sophisticated instrumentation made the seismometers and tiltmeters it was designed to house obsolete" (U.S. Department of the Interior, 1973).

OTHER EARLY FACILITIES

Original facilities in 1912 included water-storage tanks, a stable (complete with horse), and a garage. Added over the years were at least one staff residence (1918), a shop and electric plant (1922), an archives building used for storage of records, with corrugated-iron walls and roof to reduce the fire hazard (1922); a chemistry laboratory (complete with chemist O.H. Emerson) (1922, 1923); a new machine shop (complete with instrument maker F.Y. Boyrie) (1927); and additional water tanks, garages, and various sheds, outbuildings, and shacks. After 1922, a drill tower also stood along the rim. The view from its top is shown in figure 61.3. All these were built with HVRA funds. Except for the Whitney vault, all rimside buildings and facilities were razed in 1940.

Also built in 1912, standing above the Whitney Laboratory, with the ceiling of the vault part of the floor, was the main HVO building—a "substantial, wood frame structure containing a photographic darkroom; a workshop and storage room; a large, well-lighted room for drafting, study, routine work, etc.; a room designed for the storage and exhibit of collections, photographs, seismograms, maps, etc., and the accommodation of visiting workers; and an office room for the Director" (Wood, 1913, p. 16). The "large, well-lighted room" is shown in figure 61.4.

A covered porch on two sides permitted views, weather obliging, of the volcanoes Kilauea, Mauna Loa, and Mauna Kea. On the Kilauea caldera side, set so its top could be used from the porch, was a concrete pyramid with an elevation bench mark. The flat top served as a mount for a Theodolite or a camera. A photograph of Halemaumau lava lake was taken daily, and a vertical-angle shot to a bench mark on Halemaumau's rim was also recorded if weather permitted.

The main Observatory building was razed in 1940. Now only the concrete post remains; it, like the nearby Whitney vault, is a property in the National Register of Historic Places. Also in 1940, on February 11, the main Volcano House burned to the ground, and it was this, in fact, that led to the relocating of the HVO facilities. The two-story hotel, built in 1891, had been enlarged in 1921 (see fig. 61.3). Owner-manager "Uncle George" Lycurgus left immediately after the hotel burned down for Washington, D.C., to confer with the many friends in Government whom he had entertained over the years in his hotel at Kilauea. In effect, Uncle George called in his chips.

Lycurgus' Washington conferences resulted in five proposals: (1) The site for a new Volcano House was to be near the old site on the north rim of Kilauea, where HVO facilities had stood since 1912; (2) all HVO structures (except the Whitney vault) on the north rim were to be razed to make room for the hotel; (3) the new hotel building was to be constructed with Lycurgus funds; (4) the Volcano House operating contract would be renewed, with Lycurgus continuing as National Park concessioner but with a different fee structure; and (5) a new building would be built with Federal funds, well back from the rim, to house the Hawaiian Volcano Observatory and provide a place where Park naturalists could meet the public. Such a new HVO building had been in the talking stage since at least 1938.

This proposed HVO building was assigned the number 41 by the National Park Service and labeled the "Volcano Observatory

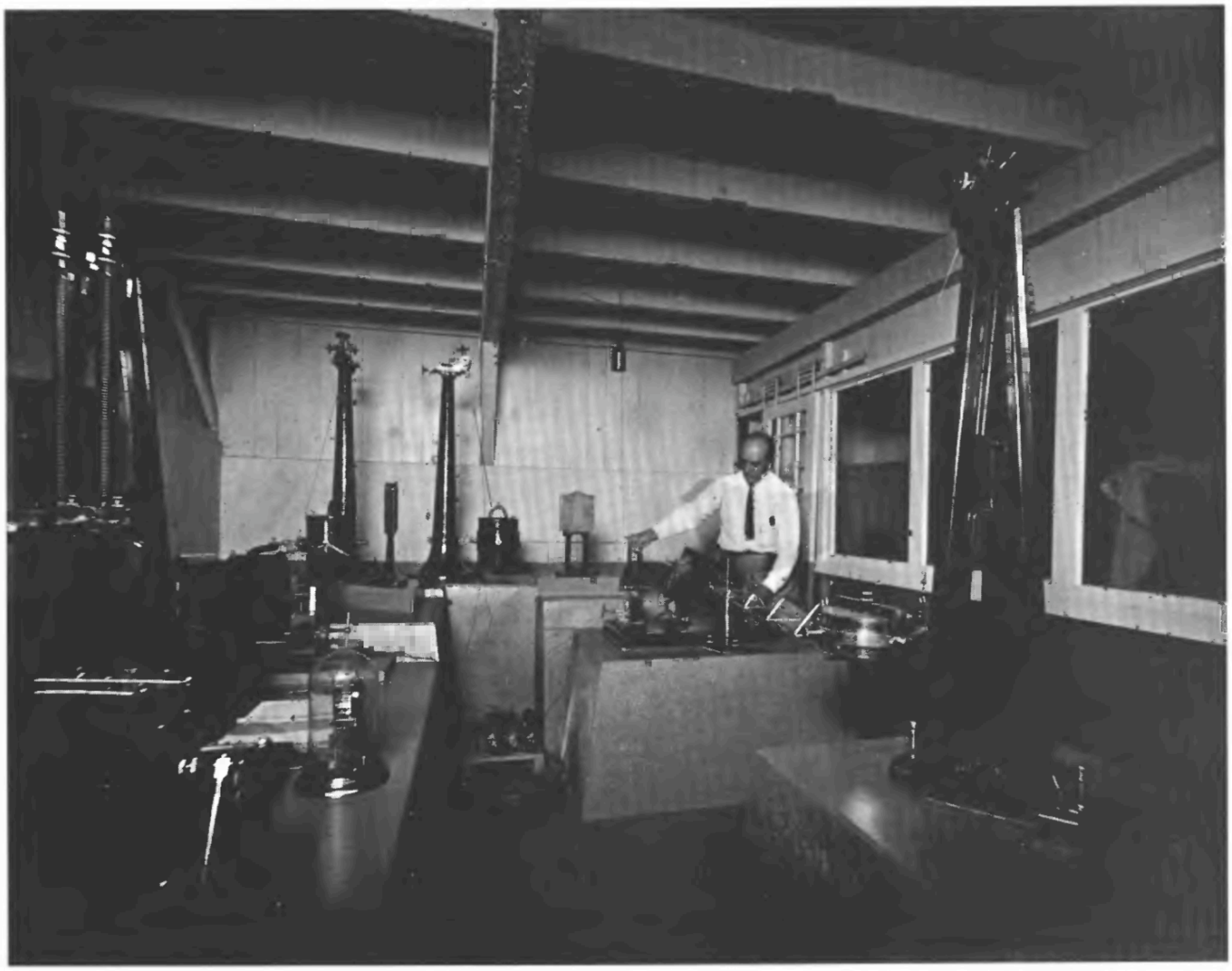

FIGURE 61.2.—T.A. Jaggar in Whitney Laboratory of Seismology, 1913. Stairs from HVO Main Building above come down to right of glass partition. Invited spectators stood behind the glass and were not admitted into instrument room. Jaggar is handling smoked drum that records east-west Earth movements detected by Omori seismometer designed for teleseisms. Two piers against far wall held two-component Bosch-Omori seismometer. Double springs in left foreground are part of self-starting Omori "Ordinary," a three-component seismometer. Photograph courtesy of the Bishop Museum (negative CPBM 58815).

and Naturalist Building." Plans were quickly initiated and whisked through the National Park bureaucracy, and the CCC began construction as soon as the plans were received.

The new Volcano House opened for business in November 1941, an elapsed time of 21 months since the fire. During that time the first four of the five points above were accomplished, and the fifth (Building 41) was almost completed. Inserted in the cornerstone of the "Kilauea Volcano House" and dated July 20, 1941, was a memorandum by Jaggar which said in part: "Under the hotel lobby is a drilled 4-inch well sixty feet deep where drilling experiments were made in 1922, one of about thirty wells for measuring temperatures. The line of observatory houses was strung out exactly where the hotel now stands. The U.S. National Park Service now is erecting a larger laboratory under R.H. Finch. The records are being duplicated at the University of Hawaii, where Jaggar is now research associate in geophysics. It is appropriate that the actual gazing upon crater fires from the old Observatory site should hereafter be the privilege of volcano hotel guests."

BUILDING 41 (1940–PRESENT)

Workers from the CCC began construction of the "Volcano Observatory and Naturalist Building" 180 m (600 ft) in from the rim of Kilauea caldera (see fig. 61.1) in 1940. Delays were experienced, but by March 1942 Building 41 was almost complete.

By that time, a vertical-component seismometer had been installed and tested in Building 41's basement seismograph vault. The building also had a fireproof room for storage of HVO records

FIGURE 61.3.—Hawaiian Volcano Observatory (foreground) at its first site on north rim of Kilauea caldera (see fig. 61.1). Main observatory building is at left, the Whitney vault in its celler. To right is the machine shop. In right background is Volcano House Hotel, which burned down in 1940. The unknown cameraman climbed a 30-ft drill tower, probably in the late 1920's, to take this picture, facing away from Kilauea Crater.

and what was considered ample office, machine shop, drafting, and library space. Its seismograph cellar was about 195 m (640 ft) from the north cliff of Kilauea caldera. Only slight diurnal and seasonal temperature variations were anticipated, because this vault and basement (unlike the earlier Whitney vault) butted against only a few steam cracks.

Like the Whitney Laboratory, Building 41's seismometer vault also had a building topside. The so-called "second vault" kept its temperature at about an even 29 °C (85 °F), but because Building 41 swayed back and forth in response to above-ground daily temperature variations, ground-tilt data collected in the vault proved to be unreliable. Building 41's vault was as close to the through road (60 m [200 ft] away) as was the Whitney vault, and its records also were marred by the frequent passing of heavy trucks. HVO seismologists maintained only the vertical-component seismometer and a tiltmeter under Building 41, and kept the Whitney vault instruments in operation.

When the HVO rimside buildings were vacated in 1940, records, gear, supplies, machines, furniture, and other chattels had been stored in various places in the national park, including the CCC camp on the rim of Kilauea Iki. As the basement of Building 41 became available—while carpenters finished the floor above—some of the stored items were moved in.

Martial law, which came to Hawaii with World War II, was in effect in 1942, and the U.S. Army commandeered Building 41 as soon as it was completed. It became the Island Military Headquarters—a convenience more to the officers and men stationed there (because of the nearby Kilauea Military Camp) than to the rest of

FIGURE 61.4.—T.A. Jaggar, at work in the "large, well-lighted room for drafting, study, routine work, etc. * * *" in main building of Hawaiian Volcano Observatory, November 1, 1916. Photographer unknown.

the military and to civilians who had business with an Island Headquarters. By October 1942, Island Headquarters was ordered to move to Hilo so as to be close to population center, port, and military and communication facilities. The U.S. Army returned Building 41 to the National Park Service with not so much as a "thank you."

Army occupation of Building 41 had not greatly inconvenienced National Park management, but it certainly continued the delay in providing HVO with its own operating facility. Park Headquarters, which until 1932 had been in a cottage on the rim along with the HVO buildings, occupied a new headquarters building 30 m (100 ft) back from the rim and handy to the road from Hilo. Because of its location, it had escaped the 1940 razing and had then played host to the HVO staff, who crowded into the headquarters building with the park staff. (This headquarters building is now a detached annex of Volcano House.)

With the Army out, HVO occupied Building 41 from October 1942 to September 1948, when HVO was evicted from Building 41 and moved to the building HVRA had built in 1927 at Uwekahuna, on the west rim of Kilauea caldera. At that time, Building 41 became Park Headquarters. Now, greatly modified and enlarged, it serves both as Park Headquarters and Kilauea Visitor Center.

In 1931, two new members were added to HVO's professional staff. Two two-story buildings were acquired by HVRA to house them and add badly needed storage space. Years before, the two buildings had housed employees of the Volcano House; one was known as the "Japanese boarding house," and the other as the "Stage Station." The Stage Station (NPS Building 39) was razed in 1956; the Japanese boarding house (Building 40) was razed in 1959. After he retired in 1940, Jaggar maintained an office in the upper story of Building 40. I interviewed him there several times and, after his death, sorted, classified, and shipped his office papers to be added to the Jaggar Collection in the Archives of the University of Hawaii, Manoa.

Sometime in the 1920's, a residence for Jaggar was built by him (or the HVRA) on the north rim of Kilauea. This residence (Building 78) was razed in 1956, along with its garage and maid's quarters (Building 77). The former maid's quarters were assigned at times to visiting USGS personnel in the late 1940's and early 1950's; they were handy to the 1941 Volcano House hotel, where meals were available.

BUILDING 131 AT UWEKAHUNA (1927–PRESENT)

From the very beginning in 1912, volcano visitors often asked questions of HVO staff members they met in the field or found in HVO buildings. When Hawaii National Park came into existence, uniformed personnel began to assume the public-contact work. In 1926, the businessmen of the HVRA raised $20,000 to build an information center on the west rim of Kilauea caldera, to be staffed by park naturalists, which would keep the increasing numbers of visitors away from HVO and its staff. Ground was broken for the new building on February 22, 1927. The site selected was the actual summit of Kilauea, on top of Uwekahuna Bluff (see fig. 61.1). The main building was built of iron and concrete, with stone cornerposts; a large terrace was enclosed by rough stone and fitted with stone benches.

In April 1927 the new building at Uwekahuna was turned over to the Secretary of the Interior and the Director of the National Park Service, which designated it as Building 131. From 1927 to 1948, park naturalists met the public, gave talks, and were headquartered in this building at Uwekahuna. Its view of Kilauea caldera is excellent, and, weather obliging, the view is equally good of Mauna Loa. Park interpreters and park visitors found the facility an ideal place for orientation to local geography and volcanology. Over time, as the numbers of its visitors grew, the "National Park Museum and Lecture Hall" was lengthened and widened, with architecture that matched the original building.

On December 28, 1947, the Hawaiian Volcano Observatory was transferred within the Department of the Interior from the National Park Service to the United States Geological Survey—the second time the USGS was host agency. In 1948 HVO was moved to Building 131 at Uwekahuna, and NPS offices and public services were then consolidated in Building 41 on the north rim.

In preparation for the move, the Uwekahuna Seismograph Vault (Building 135) was built in 1948 in a location well back from the Uwekahuna cliff face and road and far from any building that could move in sun or wind. The cellar is 3.6 × 6 m (12 × 20 ft), and a small entranceway serves as an airlock and processing room. The roof is a reinforced-concrete slab covered with about 45 cm (18 in.) of volcanic ash. This vault continues in service.

To receive HVO, the National Park Service in 1948 remodeled Building 131. The former movie hall was converted into offices and machine shop, and most of the exhibit floor became offices and laboratories. HVO moved in during the fall of 1948.

At the time of the move in 1948, it was pointed out by volcanologist R.H. Finch, then the Director of HVO, that Uwekahuna had been the first site selected by Jaggar for the Observatory in 1912 but was given up on account of the scarcity of water and its relative inaccessibility at the time.

NEW BUILDING AT UWEKAHUNA (1985–PRESENT)

In May 1985, construction of a new facility for HVO began at Uwekahuna. This new building was completed and occupied a year later. Building 131 was renovated and returned to the National Park Service as an interpretation facility named the Jaggar museum. Thus, the original vision of the HVRA of a center combining ongoing scientific studies and interpretation of those studies to the public is, after 75 years, finally realized in a fully modern facility.

PUBLICATIONS AND DOCUMENTS

Much of the most reliable data about the history of the Hawaiian Volcano Observatory is contained in its publications. Two publication series had long runs, covering the period from before the 1912 start through and beyond the pioneering period. These were the Bulletin and the Volcano Letter.

Jaggar once, in his annual address as Director of HVO (Jaggar, 1917b), characterized "the proper work of volcanic recording" with two words—permanency and extension. Permanency depended on continued financial support. Publication was the method of keeping informed the 150 members (in 1916) of the HVRA, whose membership provided the guaranteed $5,000 a year of local support. Extension was also seen to be a purpose of publication—to interest scientists and governments overseas in sponsoring permanent volcano observatories.

The vehicle that served both roles of "permanency" and "extension" was the weekly report of volcanic activity prepared by the HVO staff. Taking their cue from the 6 popular weekly reports filed with the press in 1911 by Perret, Jaggar and others wrote another 1,249 weekly press reports, many labeled as bulletins. They constitute an uninterrupted series from January 18, 1912, through December 29, 1935. The last weekly press report, numbered 1,249, was published in the Volcano Letter (no. 430) in December 1935.

The weekly Bulletin was a regular feature in the *Pacific Commercial Advertiser* (now the Honolulu *Advertiser*). By arrangement with the Bishop Museum (Jaggar, 1917a), a carbon copy of each typewritten report was sent to that Honolulu institution. Soon a second carbon went to the Hilo *Tribune-Herald*. Appearance of HVO's weekly reports in two newspapers served to inform islanders and tourists about volcanic activity at Kilauea and Mauna Loa, and it kept the observatory in the public eye.

Reprints in leaflet form of the weekly press reports in the *Advertiser* were mailed by HVRA from Honolulu from 1912 through July 1, 1914, to the 150 or so members of the HVRA and to 200 or more institutions and individuals worldwide on the HVRA's exchange list. Beginning in August 1914, the weekly reports of each month were combined into a monthly before being mailed by HVRA; this practice continued through July 1929. Over the years, while there were some issues without any special back page, the published and mailed leaflet bulletins generally carried informational back pages of ten different designs (Apple, 1985).

The other regular and long-running publication of HVO was the Volcano Letter, which was printed and mailed weekly beginning the first week of January 1925, apparently to the same subscription list as the bulletins. The Hawaiian Volcano Observatory thus had for the years 1925–1929 both a weekly and a monthly publication. In 1930 the two were combined; the weekly press bulletins became a part of the Volcano Letter. The Volcano Letter ceased being a weekly and became a monthly with the June 1932 issue. It went quarterly in 1939, and was finally discontinued in 1955.

The Bulletin and Volcano Letter usually carried the bylines of the scientists involved in their writing. Both often contained illustrations, including photographic halftone plates. The Bulletin dealt mostly with day-to-day raw data, while the Letter was the vehicle for more digested data, summaries, conclusions, reviews, news, predictions, opinions, and project status reports, not only in Hawaii but worldwide.

Over the years there were other serial publications for short times—monthly, quarterly, semiannual, and annual reports, as well as special publications.

The Volcano Letter was published first by the HVRA and then by the University of Hawaii. USGS publications continued the record of observations after the Volcano Letter was discontinued.

Additional information on the history of HVO is in the original holographs and manuscripts at the Bishop Museum, Honolulu, the first archival repository. These include Kilauea record books, by months and years (from 1912 on); folders full of notes, by years; photographic albums and photographic negatives; guest books; carbon copies of weekly reports; and copies of early bulletins.

The University Archives, University of Hawaii, Manoa, has HVRA files and records, the personal papers of Jaggar, some HVO material, and related sources. It was the second archival repository.

The third repository is the University of Hawaii, Hilo. Its Mo'okini Library has a continuing file, by years, starting before 1912, of copies of non-HVO-sponsored publications by Jaggar and others of the HVO staff, copies of the Bulletin and Volcano Letter, HVO special publications, documents sent in recent years for safekeeping, and my own collection of holographic material (Apple collection), prepared over the years and used in this history. Some material is also available in the HVO library for reference use by the staff.

Bulletin and Volcano Letter deadlines over the pioneering years did not keep the professional staff from making numerous professional contributions to scientific journals and periodicals published by others. Bibliographies of contributions by staff members of the Hawaiian Volcano Observatory contain copious entries.

VOLCANO EXPERIMENTS

The comparatively easy access at Kilauea to a variety of ongoing volcanic activities stimulated and encouraged experiments, ranging from the serious scientific to the decidedly frivolous. Visitors from America and Europe fried eggs in pans that rested on moving lava flows, learned how to thrust their cigarettes and Cuban cigars into hot cracks to light them (nonsmokers lit ends of sticks in the same cracks), embedded coins in small pieces of pasty rock, and scorched the edges of postcards on hot lava before the cards were mailed home. The Volcano House supplied eggs, pans, and postcards, as well as the guide who kept hotel guests safe while performing these feats in or near Halemaumau. The guide, Alex Lancaster, probably wound up each trip into Kilauea caldera with one pocket full of tips and another full of Cuban cigars—until Jaggar put him on the Observatory's payroll as janitor, guide, and general roustabout. Lancaster's experiences close to Kilauea's flowing and fountaining lava made him a good hand for Jaggar.

Lorrin Thurston helped Jaggar to take temperatures, sample gases, and measure depths. On January 11, 1917, Thurston and his assistants helped Jaggar thrust a length of galvanized-iron pipe through the solid crust of the lava lake to take a temperature reading 1 m (3 ft) down. At the end of the pipe was a metal cylinder that contained six cones of fusible clays which melted at temperatures in a range from 900 to 1,150 °C (fig. 61.5). After the end of the pipe had been held in place for six minutes, the crew withdrew the pipe, with difficulty. Softened by heat, the pipe had bent sharply at the point where it pierced the crust, and its end was weighted with the pasty lava that clung to it. None of the clay cones had melted, and Jaggar concluded that the temperature 1 m down was lower than 900 °C. In view of more recent data, this seems unlikely. Probably the clay samples did not reach equilibrium temperatures.

Then Thurston wanted to try an experiment. He had lugged two large pieces of ohia wood out to Halemaumau to toss into the lava lake to see what would happen. Jaggar duly recorded the results for posterity (Jaggar, 1917c): Both logs burned after sinking below the surface. There were abundant yellow flames and puffs of smoke that ballooned the surface crust a bit.

In 1925, Jaggar conceived a plan to bore holes, 3 m (10 ft) deep and 300 m (1,000 ft) apart at corners of equilateral triangles, on the floors of Kilauea caldera, Kilauea Iki Crater, and Keanakakoi Crater, as well as on the surfaces surrounding them. Temperatures at the bottoms of the holes were to be taken, so that isothermal lines could be drawn on a map of the region. The holes would then be sealed so that periodic rechecks could detect changes in the temperature of the bedrock.

In preparation, J.C. Bean, USGS topographic engineer, surveyed the borehole network from December 1925 through May 1926. An air-driven hammer drill, air compressor, truck, some "tested thermometers," a high-speed camera, and some up-to-date surveying instruments were acquired for the project. Drilling got underway in 1926 but was discontinued during the winter of 1927–28 after 30 holes had been drilled. Results were apparently inconclusive or disappointing; no results were ever published.

FIGURE 61.5.—Preparing to measure temperature of lava, January 11, 1917, floor of Halemaumau Crater. L.A. Thurston stands behind Jaggar, who holds pipe to be inserted into lava lake. Cylinder at end holds six Seegar cones of fusible clay. Others, from left to right, are Norton Twigg-Smith, Joe Monez, and Alex Lancaster. Note log of ohia at Thurston's feet, ready for his experiment. Photograph by Horace Johnson.

In retrospect, the 1925–28 project can be considered pioneering, but the real pioneering was an earlier drilling in 1922, described in the various monthly issues of the HVO Bulletin for that year. John Brooks Henderson of Washington, D.C., gave Jaggar $3,000 to begin boring experiments. Local gifts from Hawaii raised the total to $8,000. Honolulu driller A.H. Hobart was hired to use an impact or "churn" drill for three months; HVO was to supply the water needed for the drill and to transport all supplies to the drill sites. By April 1922, HVO had evolved the world's first dune buggy—a Ford touring car modified, as described by Jaggar (1922a, p. 32), by "doubling each rear wheel and fitting a pair of wide non-skid pneumatic tires to each doublet; this gave to each rear driving roller eight inches of grooved rubber traction surface, including a small air space between each pair of wheels. The double wheels were made by bolting two ordinary wheels together with a wooden disc between. A rear axle planetary gear system was added, giving three extra low gear ratios in addition to the usual two forward speeds and one reverse. All unnecessary weight of fenders, steps and doors was removed, and at rear end of car was placed a drawbar and shackle and an extra heavy spring. This converted the car into a general utility vehicle for use both as tractor and conveyance for men and supplies, devised to travel over any ordinary rough lava or on the surface of deep gravels where a common truck would dig in and be stalled."

This vehicle hauled supplies and men over sand, gravel, and billowy pahoehoe lava (fig. 61.6). A new Caterpillar tractor was also tried on lava and then modified to front-wheel steering. Rubber tires went on its rear wheels. It was used as a stationary engine to drive a generator and as a tractor to haul water barrels on sleds to drillsites.

FIGURE 61.6.—Hawaiian Volcano Observatory's modified Ford automobile hauling water for drilling operators on floor of Kilauea caldera, July 21, 1922. Vehicle was stripped of unnecessary weight and fitted with additional low gears, drawbar, and double rear wheels. Photograph by T.A. Jaggar, courtesy of the Bishop Museum (negative 94119).

Boring began May 1, 1922. Hole 1 was at the east corner of Sulphur Bank. The nearby Volcano House supplied water from its tanks, transported in barrels lashed to sleds hauled by the tractor. Casings and tools were skidded to Sulphur Bank behind the touring car.

A kerosene engine powered the rig to deliver 40–50 strokes per minute to a blunt-chisel bit of 6-in. diameter. The bit was turned by hand; water was supplied to the hole also by hand—about 10½ gallons per foot. A bucket was used occasionally to clean the hole bottom. Burlap sacking was wound around the mouth of the well to protect the drillers and machine from hot acid fumes. Eventually a wooden plug was devised for the wellhead that let the cable through but kept most of the fumes in. The cable and other steel parts were frequently painted with crude petroleum to protect them from the fumes.

The temperature was taken by a maximum thermometer lowered the 7 m (22 ft) to the bottom of Hole 1 and exposed five minutes; it read 96 °C. This reading was later checked by an Alumel-Chromel thermoelement and potentiometer and checked again with another maximum thermometer of a different make.

The churn-drill rig was moved about 45 m (140 ft) to start Hole 2, also at Sulphur Bank. Drilling started June 1, 1922, with heavy steaming from the hole. Troubles with the boring limited downward progress to five days out of ten. At 6 m (20 ft) the hole was cased, and the bit diameter reduced from 8 to 7 in. Another reduction to 6 in. and casing came at 12.8 m (42 ft), but the tools became wedged and broke a camshaft and gear wheel. The field forge failed to heat and temper the steel bits properly—they had to be sent to a sugar-plantation forge at Mountain View, 30 km (19 mi) away. At 13 m (43 ft) steam greatly increased, and at 15.2 m

(50 ft) "all sludge and water disappeared in an east-west crack across bottom of hole" (Jaggar, 1922b, p. 64). The hole was complete at a depth of 15.2 m (50 ft) on June 12, 1922. Hole 2's temperature was also about 96 °C. Pipe of 7-in. diameter was set in concrete to protrude a few inches and covered with a screw cap. "In a few weeks the inner surfaces of the iron were black with sulphide; and free sulphur crystals formed" (Jaggar, 1922b, p. 64). A shed of corrugated-iron sheets was built over Hole 2's wellhead; stacked rocks now cover it.

On August 22, 1922, Eugene T. Allen of the Geophysical Laboratory in Washington tested the gases of Hole 2 and was impressed that drill holes acted like natural fumaroles to serve as vents for escaping gases.

Hole 3 was near the center of Kilauea caldera's floor on the 1894 lava flow and in line with the 1920 Kau Desert rift. To make it possible to deliver water, rig, casings, supplies, and drillers, off-duty soldiers from Kilauea Military Camp were hired for four days to beat a rough track from the end of the road near Halemaumau to the drillsite. Meteorologist R.H. Finch, Jaggar's assistant, saw to it that the soldiers made a track over which the modified touring car and tractor could pass, albeit slowly. Hole 3 was drilled to 24 m (79 ft), and the temperature at the bottom was 69 °C.

Because churn-drill holes sometimes went crooked, tools stuck, and bits dulled rapidly, Jaggar wanted to try a rotary-drill rig. One was surplus to the needs of the Hutchinson Sugar Company, and HVO purchased it on June 22, 1922. It was a Davis Calyx "shot" Drill, model BF4, capable of boring a hole of 4-in. diameter to a depth of 300 m (1,000 ft). As it dug, the tube rotated and made a core; in practice, however, the lava rock fragmented, and satisfactory cores were rare and short.

Hole 4 was on the grounds of the Observatory, along the north rim of Kilauea (fig. 61.7). A drill tower 12 m (38 ft) high was part of the package purchased and was assembled on the rim. A shed, with an opening through the roof for the cables, was built about its base to shelter the drillers.

Water in quantity was required for this drill—241 gallons per foot of progress—and the water-storage facilities of HVO were needed to supply it. As drilling proceeded, voids and openings between layers of lava were met that caused frequent loss of water pressure. These hydraulic problems had been solved by October 1922, however, and a depth of 20 m (65 ft) was reached. Bottom temperature was 97 °C. Hole 4 was the well referred to by Jaggar in 1941 as being beneath the lobby of the new Volcano House. The capping of this hole in November 1922 ended HVO's first pioneer efforts at scientific drilling.

FIGURE 61.7.—Rotary drill and its tower on grounds of Hawaiian Volcano Observatory during earliest HVO drilling program in August 1922. Photograph by T.A. Jaggar, courtesy of the Bishop Museum (negative 94121).

MAUNA LOA

T.A. Jaggar did not confine his efforts to Kilauea; he had a sustained interest in the equally active volcano of Mauna Loa and spent much time and energy attempting to obtain improved access to it. The following account is mainly compiled from various issues of the HVO Bulletin from the years 1913–17, 1920, and 1922.

ACCESS ROUTES AND FACILITIES

In late November 1914, during a summit eruption of Mauna Loa, Jaggar attempted to view the lava fountains but failed. His mounted expedition was driven back by a severe wind and snow storm near the summit; they were even forced to abandon the camp equipment. From that time on, Jaggar advocated a shelter on the summit for men and horses and for the safe storage of instruments. To reach the summit, Jaggar wanted at least a horse trail (a road for vehicles would be better) from HVO headquarters at Kilauea. This meant the trail or road would ascend the northeast rift of Mauna Loa; overnight facilities would be needed along the trail. Early in 1915, Jaggar told the HVRA that Mauna Loa was a desert waste without water. Expeditions to the summit were exhausting, and animals employed frequently had their legs cut by the rough lava; consequently, ranchers would not rent good animals. There was no shelter on the summit, little water, no feed, violent winds, and low temperatures. It cost several hundred dollars to make a trip to the summit, and one generally had to return before any real scientific work could be done.

Through 1916, the Ainapo Trail over jagged aa and thin-crusted pahoehoe lava fields was the customary route to the summit of Mauna Loa (Apple, 1973). Until horses and mules became cheap and plentiful, an arduous hike of several days' duration up this trail was the most practical way to the summit. Most of the trail lay on the Kapapala Ranch, and Kapapala cowboys were hired as guides and packers. The Ainapo was about 54 km (34 mi) long and rose from 600 m (2,000 ft) to 4,000 m (13,000 ft) above sea level. The lower trailhead was the village of Kapapala. It was by way of the Ainapo Trail that Jaggar first visited the summit caldera in September 1913.

The surface of the Ainapo Trail was rugged, and it was not maintained for either men or mounts. Jaggar wanted a "simple route to the summit" to give scientists and the public access; with Thurston's help, he got the U.S. Army to build one in the fall of 1915.

Seismologist H.O. Wood, guide Alex Lancaster, and J.F. Haworth made a preliminary survey of a trail from Kilauea up the northeast flank of Mauna Loa to the summit in August 1915. Jaggar, Thurston, and a Lt. Philoon, 25th Infantry, U.S. Army, checked it in September. Thurston and his friends had received the approval of the departmental commander for the U.S. Army to build the trail Jaggar wanted. The HVRA put up a 5,000-gallon water tank near HVO headquarters to support the Army trail builders, and transported several smaller water tanks up the flank to a camp near timberline, soon called Camp Bates after Capt. Bates, a civil engineering officer. Thirty soldiers, under Lt. Philoon, arrived on October 15, 1915; they were followed two days later by others.

This trail up the northeast flank of Mauna Loa, called the Mauna Loa Trail, was completed in December 1915, and the soldiers were back at Schofield Barracks on Oahu for Christmas. The costs of round-trip transportation for the soldiers by ship, rental of pack animals, and purchase of materials for two buildings were all borne by the HVRA. When Jaggar prepared his proposal for a Hawaii National Park in Washington, D.C., early in 1916, he already had his trail between the summits of Kilauea and Mauna Loa Volcanoes. He hoped to upgrade it to make it suitable for trucks, and he foresaw perpetual Federal maintenance of the route. His bill, when it became law, authorized a strip of land between the summits for such a road, to be surveyed and given legal boundaries at a later date.

When the trail was built in 1915, horses and mules could go as far as Puu Ulaula (Red Hill), a cinder cone at elevation 3,000 m (10,000 ft). As part of the project, the soldiers built a 10-man overnight cabin and a 12-horse stable at Puu Ulaula, 10 hiking miles from the summit. The army cabin, still in use, is called the Red Hill rest house.

HVO hand labor filled cracks with chunks of lava and generally prepared the trail above Puu Ulaula for mounts. The first riding horses and pack mules reached the summit with Jaggar and his assistant Ruy H. Finch on June 29, 1920. Because there were no stable facilities for the animals, the guides, packer, and animals were sent back to the rest house. Jaggar and Finch stayed at the summit; "Jaggar's Cave" received its first use that night. (In the same week the first tourists reached the summit over the Mauna Loa Trail; HVRA charged each member a dollar a night at the Red Hill shelter.) In 1930, National Park crews improved the trail for horses.

Until a summit shelter was built by the National Park Service in 1934, hikers and riders were forced to camp in "Jaggar's Cave," a crack in the lava roofed over with corrugated-metal sheets. It was near another crack where water, frozen in winter, accumulated.

Since 1915, in an incremental process, lower portions of the trail have been widened and improved for vehicles. In 1936, the CCC built the last increment, the road from Bird Park to near the site of Camp Bates at elevation 2,025 m (6,650 ft), to permit scientists access by small truck to a seismograph vault near that elevation. The road has since been paved. Most hikers to the summit today start their hike at the upper end of this road.

All during his HVO directorship (1912–1940), Jaggar pressured for a vehicular road from Kilauea up the northeast flank to the summit of Mauna Loa. He wanted the 1915 Army trail improved to allow easy and quick access by HVO vehicles for studies at the summit. Although the National Park Service established boundaries and acquired the strip of land within which the road could be built, it has consistently rejected the concept of a vehicular road to the summit of Mauna Loa. This rejection has been sustained over time, in spite of pressures from Jaggar and Thurston and at times from the Territorial Legislature and the Hawaii County Board of Supervisors. As a result, the road has never been built; the advent of helicopters may now have made moot the question of such a road.

Jaggar's Cave, the 1915 cabin, and the 1915 trail have been declared eligible for listing in the National Register of Historic Places (U.S Department of the Interior, 1973). All are still in use, although the trail has had to be rebuilt in places because of damage from earthquakes and lava flows.

THE 1926 ERUPTION

Mauna Loa's recognized eruptive pattern is a summit eruption followed—within hours, days, or months—by a flank eruption. In 1926 there was a brief summit eruption, followed by 14 days of eruption on the southwest rift zone. A flow from this rift zone passed through a South Kona forest, crossed the main road on April 16, and pooled behind the coastal village of Hoopuloa. Between 0400 and 0900 H.s.t. on April 18, the flow buried the village, wharf, and harbor and entered the ocean. This was HVO's first real experience with property destruction by a lava flow. The following account was compiled from Apple and Apple (1979b), Finch (1926), Jaggar (1926a, b), MacDonald and Hubbard (1982), and unpublished sources.

Edward G. Wingate, USGS topographical engineer, was mapping the summit of Mauna Loa in 1926, changing campsites as the work progressed. On April 10 his camp was along the 3,475-m (11,400-ft) elevation, well into the desolate upland above the Kau District. An earthquake wakened the campers about 0145; as they drifted back to sleep, a further series of quakes had them sitting up, talking, and wondering. About 0330 Wingate braved the cold and wind; with a blanket wrapped around him, he went outside and stood bathed in reddish light.

From his camp Wingate had a wonderful view of smoke columns lighted by the glow from below. They reached the flows about 0630. With his crew, Wingate mapped lava fountains, moving flows, steaming vents, and spewing cones.

The packer who kept Wingate's camps supplied with water, food, and firewood had spent the night on the trail on his way down to pick up another load; he reached the Ainapo trailhead midafternoon on April 11. More than supplies awaited him—there was an HVO expedition demanding guide service to Wingate's camp. This was the first news of the eruption for the packer. The expedition consisted of Jaggar, topographer J.C. Beam, cook H. Yasunaka, and packers John Kama and Joe Kaipaloa.

After a night at Ainapo, and with three additional pack animals borrowed from Kapapala Ranch, the expedition started up toward Wingate's camp. By midafternoon they reached the camp, which Jaggar described as a primitive affair consisting of three tents and a cook shelter on the rough lava fields. The cook shelter was bolstered with stone walls to protect against wind, but all the tents had to be tacked down to the pahoehoe lava with spike nails.

For three days the HVO party surveyed the sources of the eruption; then they descended and moved into Kona District, where roads, houses, and other property were threatened by the flows. Wingate and his crew stayed behind. Much of the area already mapped was under fresh lava, and there was a lot of remapping to do.

On April 16, Tom Jaggar scratched marks about a foot apart across the rutted, gravel road (the only road) between the Kona and Kau Districts. A lava flow was approaching, and Jaggar wanted to measure the flow's speed as it crossed the road. Perhaps a hundred people were waiting around the Hoopuloa Church, on the uphill side of the road, and at the Kanaana house opposite, on the downhill side of the road. They had seen and heard the flow, 4.5–6 m (15–20 ft) high and more than 150 m (500 ft) wide, as it moved through the forest uphill. When it neared the road, people who lived on the Kona side of the flow moved off to the north, and those who lived on the Kau side moved to the south, so they could go home after the road was closed.

Jaggar recorded that it reached the uphill, inland side of the road at 1222 at an estimated speed of about 2 m/min (7 ft/min); within two minutes the road was crossed. Jaggar and his assistant, H.S. Palmer, stayed on the Kau side. Soon Robinson MacWayne, Honomalino Ranch proprieter, supplied horses, ranch hands, and guide service through coastal Milolii to Hoopuloa. Jaggar and Palmer set up camp in the Hoopuloa store. Jaggar noted that the Chinese proprietor had swept the building spotlessly clean after removing his stock of goods and furniture. Both the store and the adjacent wharf lay directly in the track of the oncoming lava front. Groups of people were huddled along the stone walls back of the village, watching the glowing, crunching, relentless wall of fire behind, but watching it at leisure, without excitement, and with great weariness because the main event had been postponed. All had come to see the lava enter the sea, but it was still several hundred feet away.

Those watching parked their cars on the Kona side of Hoopuloa. One enterprising youth used his small truck to haul water from the Hoopuloa tanks to Milolii, the end of the road. When the flow reached the sea, he and his truck were cut off; he later took his truck apart and transported it piece by piece by outrigger canoe to the road on the Kona side of Hoopuloa.

At about 0300 H.s.t. April 18, the flow rode over the stone walls behind the village and started burning outhouses. Pigs heard squealing in a pen were released. Destruction of the village was gradual and complete. As soon as lava began falling into the sea, steam shot up in jets. Hundreds of dead fish floated along the edge of the turbulent water that spread out from the contact area of hot rock and cold ocean. Hawaiians from Milolii came in their canoes and gathered the dead fish for salting and preserving. Jaggar collected some dead, floating fish and noted that they were perfectly fresh and in no sense cooked.

CONTROLLING LAVA FLOWS

Many observers have noted that barriers, both natural and manmade, can sometimes stop, divert, or delay the forward movement of a lava front. The worried people of Hilo in 1881 first considered the use of explosives to stop a flow that threatened their port and homes; this is the earliest recorded suggestion for such action in Hawaii (Lockwood and Torgerson, 1980). The concept of using explosives to modify the forward motion of a lava flow was advocated by the HVRA's Thurston in his newspaper in 1929. Tom Jaggar and Ruy Finch of HVO were actively involved in using explosives in the form of aerial bombs on moving lava flows that threatened Hilo in 1935 and 1942, respectively. Bombing the upper reaches of a lava tube feeding a Mauna Loa pahoehoe flow in 1935 is credited with slowing or stopping the advance of the distal end; the 1942 bombing breached the levee of an aa flow and was also partly successful in slowing the flow's advance (Bolt and others, 1975).

In 1937 Jaggar proposed construction of a comprehensive set of embankments, 5–6 m high, to divert Mauna Loa lava flows from Hilo town and its harbor; the embankments would have had a total length of about 20 km (including 11 km in a single wall around the south side of the town) and were projected to cost about $800,000 (Jaggar, 1937). These barriers have yet to be built, though experience elsewhere shows that they could be effective (Bolt and others, 1975). Jaggar's interest in controlling lava flows to protect property continued long after his retirement from HVO (see Jaggar, 1945).

THE *OHIKI* AND OTHER EXPERIMENTS

Ohiki is the Hawaiian word for sand crab; honukai means sea turtle. In 1928, when the National Geographic Society joined with the USGS to sponsor an expedition with Jaggar in charge to map, photograph, and survey in the Aleutians around Pavlof Volcano, the Society supplied an amphibious boat, to which Jaggar gave the name *Honukai*. It was a twin-screw steel amphibian, built in Chicago by the Powell Mobile-Boat Corp. In the 650 km along the coast of Alaska from Shumagin Islands to King Cove, the expedition did not even have to pump up the tires. The *Honukai's* numerous excessively low gears even enabled them to drive up to the snowline and bring out the heavy fur and bones of a bear that Jaggar had shot on the snowy volcano, Mount Dana. Jaggar brought the *Honukai* back to Hawaii with him and based it in Kona.

In preparation for this expedition, the HVO machine shop built a wooden amphibious boat around a "low-geared small motor car with balloon tires," that Jaggar had used over tundra and beach of the Alaskan Peninsula in 1927 (Jaggar, 1927). Inlets, rivers, and rocks were obstacles that made Jaggar mentally design modifications of the car into a "car-skiff."

The land and sea trials of this preliminary vessel, the *Ohiki* (fig. 61.8), took place in the spring of 1928 (Wilson, 1928). She first took to the sea at Ninole Cove in the Kau District, and she quickly revealed the need for additional work.

After modifications (freeboard raised, length slightly increased, paddle-wheels enlarged, a winch and cable mounted in bow, 5-horsepower outboard motor added), an extended trip was made along the west coast of the Island of Hawaii to make beach and sea tests. Thurston went along as a passenger and publicity man; Mrs. Jaggar served as stewardess. The car with the boat body excited all the roadside children of Kona with delight.

Jaggar's *Ohiki* made a speed of about 6 km/h (4 mi/h) in water with the combined power of paddle wheels and outboard motor; it weighed 1,700 kg (3,800 lb), was 7 m (22 ft) long, and had a 1.5-m (5-ft) beam and an overall width of 2.1 m (7 ft) at the paddle boxes. It made more than 30 km/h (20 mi/h) over highways. As a result of his experiences and design work with the *Ohiki* and the *Honukai*, Jaggar was later able to help the U.S. Army with the design of amphibious vehicles for World War II, and he received in 1945 the Franklin L. Burr Prize of the National Geographic Society for this work.

Many other experiments were generated by HVO, though some were mostly conducted by others (see Jaggar, 1956). They included studies of the rehabilitation of lava and lava soils by organisms such as lichens; classification of the lava soils of the Kona District on the Island of Hawaii for their suitability for coffee tree cultivation; and installation of tide gauges at Hilo. College-credit courses in volcanology were given over many summers, especially for Island teachers. The widths of selected cracks, especially near Halemaumau, were measured periodically to record any changes. Topographic mapping of the Island of Hawaii and, by 1932, of almost the whole Territory of Hawaii was supported. By 1924, several triangulation and leveling projects had proved the elevation and distention of Kilauea caldera. As early as 1912, private industry (the Dictaphone Corp.) was trying out microphones in attempts to record the true sounds of a volcano in eruption.

SEISMOLOGY

The history of seismology at HVO begins in 1912 with the completion of the Whitney vault. After two decades of pioneering, Jaggar was amply aware that seismometry on an active volcano is quite different from that at a station that studies mainly distant earthquakes.

INSTRUMENTS

Instrumentation provided a challenge from the beginning. The story of the evolution of seismic instruments at HVO is documented in Curtis (1913), Jaggar and Romberg (1918), Apple (1978), and various issues of HVO's own publications, the Monthly Bulletin and Volcano Letter. The following account is synthesized and condensed from these sources.

Seismologist H.O. Wood reported for duty June 13, 1912, and he had the crated instruments from Japan installed on their "concrete tables" by July 2—installed, but not necessarily performing properly. These instruments were: (1) a sensitive Omori tromometer, designed for the registration of earthquake motion proceeding from a distant origin; (2) a less-sensitive Omori tromometer, designed for the registration of weak or moderate shocks of local origin; and (3) an ordinary Omori seismometer that started itself upon detecting a strong shock and that registered three components of motion, east-west, north-south, and vertical. The more sensitive tromometer arrived missing the north-south component; it was therefore mounted in such a way as to measure and register the component of earth motion in the east-west direction. Both tromometers had smoked drums and timing capability with marks every one minute. The ordinary Omori was set up so that when earth motion was strong enough to activate its starting device, the smoked drum revolved rapidly and marks were made every one-half second. This instrument could also be set to ring an alarm bell when it started.

Heavy horizontal pendulums detected horizontal earth motions, and a "floating" weight suspended by two balanced helical springs detected, in theory at least, the component of earth motion in the vertical direction. Time marks were made by an electromagnet operated by the brief closing of an electric circuit. Wood had all three instruments operating by August 1912, but all had, sometimes separately and sometimes simultaneously over the years, periods of nonoperation when work was done in the Whitney vault or on the instruments.

Of these three seismometers, the first to leave the Whitney vault was the less sensitive Omori. It was moved to the Technology Station at Halemaumau in February 1913 and later was apparently dismantled for parts. The three-component self-starter never really worked properly, even after it was rebuilt in 1918, renamed "Domesticus," put on full-time duty, and its vertical detection apparatus removed.

The most sensitive Omori seismometer was rebuilt into an optical recorder and given a corner mount in 1918 in the hope that it would detect both north-south and east-west teleseismic motion with its single boom. In 1923 it was retired. After retirement, this and all seismometers were cannibalized for parts to make or repair other instruments in the HVO machine shop.

During their service, the seismometers were modified and changed by the HVO staff to try to make them more suitable for use on the rim of Kilauea caldera—to be more responsive to local short-period earthquakes, volcanic tremor, and the extraordinary ground tiltings. These were the three distinctively Hawaiian geophysical phenomena Jaggar had identified by 1918. Jaggar noted that the

FIGURE 61.8.—Amphibious vehicle *Ohiki* leaving for extensive shakedown cruise and field test around the Island of Hawaii by water and road, February 1928. While T.A. Jaggar poses, his wife Isabel (cruise stewardess) peeps around stern. Paddle wheel can be seen behind Jaggar's right shoulder. It will be installed before vehicle takes to water in Kona. Building in background is HVO machine shop, built in 1927. Photographer unknown.

mechanical imperfections of standard instruments, designed for cheapness and convenience of operating and ill-adapted to such special problems, combined to yield only mediocre results. Dr. Arnold Romberg was hired by HVRA for the summer of 1918 to rebuild and otherwise improve the two original seismometers still in the Whitney vault and to do some work on the Bosch-Omori seismometer that had been acquired in 1913. Romberg also made at least two new one-component seismometers for installation in cellars to be established by HVRA in Hilo and Kealakekua. As Romberg worked, Jaggar noted with satisfaction that small improvements had been made over experiments by Milne, Galitzin, and others and that already the difficulties of friction, magnification, damping, opening the record, and time marking had been partially overcome.

The two-component Bosch-Omori seismometer, purchased from the Whitney Fund, had finally arrived from Germany by April 1913. Wood noted that in order to permit the construction of foundations and the work of installing the Bosch-Omori, a 100-kg tromometer, the seismographs in operation had to be partially dismounted temporarily. The new instrument was mechanically and dynamically superior to those hitherto in use there, and it was expected that a larger proportion of teleseismic records would be written, as well as more precise records of local shocks.

Trial runs of the new Bosch-Omori's east-west and north-south components were made on April 30, 1913; a feeble teleseism was registered, as well as strong volcanic vibrations. Adjustments were completed on May 8, 1913, for the final trial runs. From that time on through 1953, the Bosch-Omori seismometer was the main reliable, basic geophysical instrument of HVO.

Fine tunings of the Bosch-Omori never ended and were required after almost every unhinging caused by a strong earthquake. Modifications and upgradings were intermittent: steel wire replaced silk fibers to suspend the weights; oil damping baths were added, adjusted, redesigned, and readjusted; friction reduction was tried; new hinges were designed and manufactured; magnifications were lowered and raised; different levers, recording pens, and pins were tried; timing devices were improved; better drum-smoking devices were found; Dr. Romberg modified linkages and levers in 1918 so that one smoked drum recorded what two drums did originally; and one of the piers was rotated 7.5° to permit its boom to swing closer to a true east-west line.

In 1948, the Bosch-Omori seismograph in the Whitney Laboratory had a period of 7.7 seconds and a magnification of about 115 times the earth movement. It gave satisfactory records of short-period local earthquakes and of the ground tilt. This standard was the goal always attempted and sometimes met over the decades. Credit goes to the HVO staff for the daily attention they gave to the Bosch-Omori. One or more of the staff came day or night, storm or sunshine, workday or weekend, whenever a felt earthquake or home alarm signaled a potential dismantling.

Whitney vault's Bosch-Omori was the workhorse of the first four decades of the Hawaiian Volano Observatory, 1913 to 1953. HVO staff habit, respect, and momentum kept the Bosch-Omori seismometer operating in the Whitney Laboratory of Seismology for ten years after mechanical seismometers became technologically obsolete. The Bosch-Omori's last official smoked seismogram was removed, shellacked, and read on February 1, 1963, ending a daily series begun 50 years before.

Since the standard commercial seismometers had been tried and found wanting for the detection of short-period earthquakes, volcanic tremor, and ground tiltings, HVO turned its talents to designing and building special-purpose instruments. The most successful of these was the Hawaiian-type seismograph, in service worldwide by 1928. Briefly, it consisted of two horizontal components at right angles, each having a mass as much as about 100 kg (225 lb) consisting of a 69-cm (27-in.) length of pipe of 20-cm (8-in.) diameter, filled with sand. It was hinged above and below with short links of piano wire, had a free period of about 7 seconds, and was damped with light aluminum vanes dipping in oil near the outer end of the boom, giving it a lever magnification of about 130. Time was marked by an electromagnet recording on a smoked drum with paper speed of about 3.2 cm (1.25 in.) per minute. Both components recorded on the same drum, and a drum would run 24 hours without need of a change. The pair was designed for wall mounting, one on each side of a corner, with the mounting so arranged that the assemblies at the ends of the booms could record on the single drum. The only pier needed for the Hawaiian-type seismometer was one to hold the recording drum.

Pairs of Hawaiian-type seismometers were built in the HVO machine shop and supplied to Kodiak, Alaska (1927); Hilo, Hawaii (1927); the U.S. Coast and Geodetic Survey for testing and eventual placement at Sitka, Alaska (1927); Kealakekua, Hawaii (1928); Lassen National Park, California (1928); and Dutch Harbor, Alaska (1928). One design specification met by the Hawaiian-type seismograph was convenience of operation for the semiprofessionals hired by HVRA, USGS, or the Coast and Geodetic Survey at the more remote stations.

By 1929, although so far defeated in the search for a mechanical seismometer that would record the vertical component of seismic motion, staff at HVO continued experimenting. A vertical-component instrument to match the two-component Hawaiian-type already in use was especially desired. HVO seismologists wanted to measure the angle of emergence of earthquake waves at the station and believed this vertical angle would help furnish data on the depth of origin of the quake. By 1930, the HVO machine shop had built a vertical-component seismograph, with the heavy mass hung on spiral springs and temperature compensation provided by small springs. This instrument evolved after a variety of spring arrangements were tried, and it was installed in the Whitney vault. Its performance was never up to expectation, and it was the only seismometer installed under Building 41 in 1941. When that vault was abandoned by HVO in 1948, this instrument appears to have joined those in the bin to be cannibalized.

Recognizing that seismometers took the continuing care of specialists, Jaggar searched for instruments of simple enough design to be "put in the hands of amateurs" (Jaggar, 1932, p. 3). His first "shock recorder," designed in 1928, did record separate east-west and north-south motions, but it "also recorded the motion of rats, kittens, chickens, cockroaches and spiders" (Jaggar, 1931). This was redesigned so that it consisted of two wall-mounted inverted pendulums to be set up in a corner of a room and did not require a pier. Three pairs of these were set up around Halemaumau. The first field test in the hands of "amateurs" came during the earthquake swarm in 1929 under Hualalai Volcano in Kona. A shock recorder pair was installed at Puu Waawaa Ranch on the slopes of Hualalai. Mr. Hinds the ranch owner and his family learned how to twirl the two daily recording discs over the smoking chimney of a kerosene lantern until each disc was coated an even brown. They also wound the clocks used in making the time marks.

It was this model of shock recorder that Jaggar took with him on the U.S. Navy expedition to Niuafo'ou Island (Tin Can Mail Island) in 1930 and left there with the Tongans. When earthquakes suddenly became a problem in 1930 in New Zealand, Jaggar hurriedly dispatched one such instrument in response to a plea from the New Zealand government. HVRA promised to supply eight more as soon as they could be manufactured, while in New Zealand machinists copied the one Jaggar sent.

By 1937, Jaggar had a new version of his shock recorder. What it gained in simplicity, it lost in sensitivity. It no longer separated arrival times of earthquake waves but registered only maximum intensity. Each instrument depended on a small mercury cup and was called an annunciator-type shock recorder. It showed a number from 1 to 6, depending on the intensity of the earthquake. Once a number became visible, the annunciator had to be reset.

Only two of the new design were on hand when an urgent request was made in 1938 to ship as many as possible on a Coast Guard cutter leaving almost immediately to supply colonists sponsored by the U.S. Government on tiny South Pacific Islands.

H.H. Waesche, a geologist at HVO, went aboard the cutter *Roger B. Taney* to install the two which were portable and could be set up in a few minutes with only a screwdriver and a pair of pliers. No smoked paper was needed; each instrument needed only a solid base and checking every hour or so. The colonists, all young Hawaiian men, would do the checking and report observations through the mail pouch. One recorder was set to read in an east-west direction on Canton Island, and the other to read north-south motions on Jarvis Island.

It was not necessary to wait for a natural earthquake to arrive to test seismometers and shock recorders built in the HVO machine shop; artificial earthquakes of known intensity and duration were created. HVO's earthquake machine, an oscillating table, was designed and built in 1928 in the machine shop by R.M. Wilson, HVO topographic engineer. It consisted of a massive, 365-km (800-lb) concrete slab resting on steel rollers. Instruments to be tested were mounted on the slab. Levers connected the rollers to the chuck of a nearby lathe; amplitude was governed by varying the radius of a crank in the lever train, and a range of periods could be provided by changing the speed of the lathe. Seismologists believed the oscillating table could simulate in part the ground motions of a variety of local earthquakes.

While seismometers were still being tailormade at Kilauea for local earthquakes, HVO acquired a shiny, new, compact, three-component Imamura seismometer from Japan for display to the visiting public in the building at Uwekahuna. All three components recorded on a single smoked drum. Although cars in the Uwekahuna parking lot, crowds moving about the museum floor, people clapping in the projection hall, and the range of daily temperatures in the building all confused the record, Park Naturalists believed that a working seismometer, no matter how befuddled its record, was a worthwhile exhibit and fit in with their lecture content. The Imamura instrument, with its magnification of as much as 50 times, was abandoned when HVO occupied the Uwekahuna building in 1948.

Seismographs are still the principal geophysical instruments at HVO. The electronic amplification and radio-telemetered signals of the current models would be startling to Jaggar's experiences, but not to his dreams.

TRAVELTIMES OF EARTHQUAKE WAVES

A principal goal of seismological studies at HVO from their beginning has been to determine where earthquakes occur beneath the volcanic edifices. For this purpose the inference of traveltimes for earthquake waves is critical, and much has been learned from the successive attempts to interpret those traveltimes in Hawaii. The story of this evolution has been told in Jones (1935) and in various issues of HVO's Weekly Report and Volcano Letter. The following account has been gleaned from these sources.

In May 1915, HVO seismologist H.O. Wood reported that he had determined the distances of origin for 411 of the 604 local earthquakes registered in the first two and one-half years of operation of the Whitney Laboratory of Seismology. Wood used a table by Zeissig to determine these distances; for clock time he used a chronometer lent by the Territorial Surveyor, corrected by solar observations with a transit borrowed from the College of Hawaii.

The tables of Zeissig, in use then at most seismographic observatories, were designed for large earthquakes many hundreds of miles away. In 1925 HVO Seismologist R.H. Finch reported that HVO had found other tables by Omori, published in the Bulletin of the Imperial Earthquake Investigation Committee of Japan, to be more satisfactory. Omori's values came in fractions of a mile and thus helped in determining earthquake origins only a few kilometers (2–3 mi) away. That Omori's tables were better than the Zeissig table for very local earthquakes was shown by the good agreement between computed and actual distances of felt earthquakes whose approximate locations were known.

By 1925 Finch had in the Whitney cellar a Howard pendulum clock, corrected by radio signals originating from Pearl Harbor. There was a flurry of speculation in 1927 when it was noted that this clock, after being consistently late by 0.08 second per day (s/d), went to a consistent 0.66 s/d and then to a consistent 1.71 s/d. The speculation was that its pendulum might be sensibly indicating changes in the value of gravity; elevations had changed by amounts on the order of 1 m in 1924, and magma movement below might be involved.

In 1931, HVO Seismologist A.E. Jones found that the Omori traveltimes did not completely agree with the seismic facts in Hawaii. He developed a traveltime-distance graph for Hawaii, and by using $S-P$-wave intervals he showed "how to locate Hawaiian local earthquakes without the necessity of accurate time checks on all the master clocks of the several seismograph stations on Hawaii" (Jones, 1935, p. 59).

Trying to keep the scattered stations of the seismic network on the same time was given up by 1937. Most attention had gone to the station at Kealakekua. The line between Kealakekua and Kilauea passed practically through the middle of the great mass of Mauna Loa, and the stations were about equidistant from its center. In 1926, HVO's R.M. Wilson complained that, while the time at the Whitney vault was corrected by radio, the instrument tender at Kealakekua got his time—often more than a minute in error—over the telephone from the Kona switchboard operator. A radio set was supplied to the Kealakekua station in 1926 to receive time signals from the U.S. Naval radio station NPM at Pearl Harbor. A key beside the set, wired into the station clock, was depressed the instant the time signal was received; this recorded a mark on the current seismogram along with the one-minute marks made by the station clock. A measurement between the two marks on the seismogram revealed the correction necessary. It was believed this system recorded the time to within one-half second or better.

By 1939 H.H. Waesche, HVO geologist, had tied together for time control the seismograph stations around Kilauea summit, as well as the one on Mauna Loa at the end of the truck road. The Howard clock in the Whitney vault sent minute and hour signals of sufficient strength to operate relays controlling the electromagnets that lifted the recording needles on the drums. The connecting links between the stations and the clock were the existing National Park telephone trunklines, not connected to the commercial system. Waesche worked out all the circuitry and procured or made the parts to make the system operate. After some troubleshooting, the time signals did not interfere with telephone service in the Park.

Today, seismograph time signals accurate to a few thousandths of a second arrive by satellite. Tom Jaggar would be pleased.

SCALES OF EARTHQUAKE INTENSITY

"Just as four pounds of sugar ought to be four times as big as one pound, so a number four earthquake should be four times as big as number one. Herein lies the difficulty" (Jaggar, 1929).

When Perret lived in his cabin near Halemaumau for six weeks in 1911, part of his working time was spent with his seismoscope. His views through its eyepiece showed the ground to be continually in motion. Accordingly Perret devised a scale based on the seismicity for the day; five on a scale of 10 was an average day.

H.O. Wood as charter HVO seismologist in 1912 used the Rossi-Forel scale of intensity, but also used phrases such as "this [earthquake] manifested an intensity of little more than 1/20th of that of the minimum shock perceptible to the senses."

In his report for the week ending December 19, 1912, Jaggar adopted for HVO the Cancani scale, which soon appeared on the back page of the printed weekly bulletins and stayed there through 1920. Inside, however, the text often used the Rossi-Forel scale by name, and a Cancani reference is hard to find. By the 1920's, R.H. Finch was using the Rossi-Forel to rate an earthquake recorded in the Hilea (Kau) cellar, and was rating the same quake as recorded in the Whitney vault as "slight" or "feeble."

HVO's R.M. Wilson used Volcano Letter no. 124 in May 1927 to describe the Rossi-Forel scale and explain how HVO graded its earthquakes in terms of acceleration from "feeble" through "alarming." Jaggar took most of Volcano Letter no. 223 in April 1929 to explain the Rossi-Forel, Cancani, and Mercalli scales, the last of which he abridged to show human effects. Jaggar concluded: "In the writer's tests, and Professor Mercalli among Italian peasants evidently had similar experience, ignorant persons in city or country can understand a human scale. They usually distort or exaggerate physical effects on masonry, water, trees, chimneys, etc., because they have no training in measured or judicial statement" (Jaggar, 1929).

Because he believed in the use of a human scale to grade earthquakes, Jaggar borrowed from Japan its postcard reporting system. Preaddressed and franked, with a form to be filled in and signed on the back, postcards were widely supplied to residents on all parts of the Island of Hawaii starting in 1932. People were to fill out and mail cards whenever they experienced a felt earthquake.

In keeping with the seismicity concept brought to Hawaii by Perret, charts and graphs of seismicity curves over various periods and for various purposes were prepared as early as 1920 and regularly by the 1930's. Seismologists at HVO developed for their own use in Hawaii the Hawaiian Volcano Observatory Scale, whose grades were "Tremor, Very Feeble, Feeble, Slight, Moderate, and Strong" (Jones, 1932). It was based on the double amplitude of motion on the Bosch-Omori seismograph and carried a description of the noninstrumental effects ("a human scale"). Its grades were eventually cross-referenced to the Rossi-Forel and modified Mercalli scales.

TSUNAMIS

Coastal areas in the Hawaiian Islands are vulnerable to seismic seawaves (tsunamis) generated by major earthquakes anywhere in the Pacific Ocean. The tsunami of 1933 demonstrated that seismology could be used to predict the advent of such a wave and therefore to give warning to people in threatened areas. The story of that occasion, in which HVO staff prevented possible loss of life, has been told in the Honolulu *Advertiser* for March 14, 1933, and in Jaggar (1933).

Capt. Robert V. Woods, a retired ship's master who was the HVRA employee at Kealakekua, Kona, operated the seismograph vault there in the cellar of his house. Woods was more than a technician who changed drums and did routine maintenance H.s.t. his instruments. He had learned from the HVO seismologists how to determine the distance and origin of an earthquake from the arrival times of its different waves.

Woods was in his basement vault at 0700 H.s.t. March 2, 1933, getting ready to change drums, when he noticed his seismometer begin to record the arrival of a distant earthquake. The time between arrivals of the first and second different waves was about ten minutes. Woods calculated the distance at about 6,320 km (3,950 mi) and put the origin at the west edge of the Tuscarora Deep, east of Japan.

Meanwhile, in the Whitney vault on the other side of the Island, HVO seismologist Austin E. Jones saw the earthquake arrive on the Bosch-Omori instrument. He also calculated an origin point off Japan.

Over the telephone Woods and Jones agreed that such a quake could generate a tsunami in the Pacific Ocean that would travel at about 720 km/h (450 mi/h) and arrive at the Island of Hawaii about 8.5 h after the earthquake.

Jones notified the Hilo harbormaster at about 1000 to look for a tsunami at about 1530 local time; Woods also notified American factors at the small Kona ports of Kailua and Napoopoo.

Noon radio newscasts in Hawaii featured a Japanese disaster in Iwate Province from both an earthquake and a tsunami, confirming the potential of a tsunami reaching the Island of Hawaii.

People at Napoopoo, recalling tsunamis of 1893 and 1923, removed all cargo stored on the wharf and adjacent warehouses. Other Kona coastal settlements evacuated people but not property to any great extent. Tidal surges in Kona began at about 1520 and continued for hours. They began with a recession that left the sea bottom bare at Napoopoo, Kailua, Keauhou, and even at Kaalualu near Ka Lae (South Point).

On the seventh surge at Napoopoo, water receded vertically 2.5 m (8 ft) and then rose 3 m (9.5 ft). Up and down the Kona coast, rock walls were knocked over and scattered in low-lying areas. Boats were unmoored and capsized, houses flooded, lumber displaced and scattered, and property was washed out to sea. Cars left parked were flooded and some of their motors damaged by sand.

At Hilo, the sampan fleet moved out to anchorages in the harbor. Waves began to arrive at 1536, with an up-and-down motion of as much as 1 m (3 ft). There was no property damage.

No lives were lost in Hawaii during the 1933 tsunami, thanks to the warnings issued by the Hawaiian Volcano Observatory. This appears to have been the first time that a tsunami was predicted through interpretation of seismograms—a forerunner by decades of the Pacific-wide tsunami-alert system now in place.

TILT

Tilting of the slopes of a volcanic edifice is now a well-known indicator of changes in subsurface magma volume and therefore a key to predicting eruptions. Study of such tilt was pioneered at HVO (see Jaggar and Finch, 1929), and records and discussions of tilt at Kilauea appeared in the various HVO publications from their earliest years.

Seismologist Wood first noticed pronounced ground tilt soon after he set up the Bosch-Omori instruments in 1913. Systematic recording and study of daily and seasonal tilt changes and their relation to Kilauea and Mauna Loa began in 1917 and became important in volcanic research. Over HVO's pioneer period, there were three basic methods of measuring tilt: leveling, use of clinoscopes, and computation from seismograms. Leveling was expensive and time consuming but was performed intermittently with transits and spirit levels. Some precise runs were made up from sea level, and local level lines extended 300 m (1,000 ft) or more. Clinoscopes were in full use by 1932. But the standard was the reliable Bosch-Omori seismograms, which could be used to compute the tilt of the instrument's pendulums in relation to the floor of the Whitney cellar. Such computations were done almost daily from 1913 through 1963 (see Romberg, 1919). In 1940, Waesche believed that the Bosch-Omori piers were capable of detecting a 6-mm (0.25-in.) change in the end of a straight line 16 km (10 mi) long (0.3 microradian in modern terminology).

The clinoscope was a heavy, ring-shaped weight hung by a piano wire from a tripod 2.1 m (7 ft) high. The weight dipped into a bath of automobile oil for damping, and a boom came vertically upward from the space in the middle of the weight. At the top of the boom was a sharp point; this point nearly reached a horizontal circular card that was ruled in points of the compass and in concentric circles. The center of the card was placed precisely above the point at the start of each day, and the point's migration away from the center 24 hours later would indicate both direction and angular amount of change. HVO clinoscopes magnified the amount of change about 50 times.

By 1932, clinoscopes were installed at the corners of an equilateral triangle whose center was the center of Halemaumau. Two of these were in cellars, and the third was enclosed within a glass case in a hut. The frequent earthquakes beneath Kilauea, however, played havoc with the reliability of the readings, as did temperature changes. Staff at HVO hoped to redesign the clinoscopes to make them entirely earthquake proof and to allow readings to be made through a microscope. The HVO "wish list" included a ring of clinoscopes around the summit craters of both Mauna Loa and Kilauea and others at various distances away on the highways out from Kilauea.

Today, that wish has largely come true, but not with clinoscopes. Electronic tiltmeters, sensitive to 0.1 microradian, are installed at several locations on Kilauea and Mauna Loa; they radio their signals directly to recorders at HVO.

SCIENCE AND THE PUBLIC

> "The by-products of the popularity of our volcanoes [have included] * * * science guiding the police, the ranchers to safety, and the public to sight-seeing through ten lava crises. All of these things we have seen grow up during the last twenty-five years" (Jaggar, 1936, p. 4).

Volcanoes affect human communities, and the work of a volcanologist comes almost inevitably to involve questions of public policy and public safety. Jaggar had watched the 1926 Hoopuloa lava flow block a major highway and destroy a village, and he had directed the dropping of aerial bombs on a 1942 lava flow threatening Hilo. He retired (in 1940) before any more major eruptions seriously threatened human life or destroyed property. In his work, Jaggar had dealt principally with those people who held responsible positions in the local community and in major organizations like governments, academia, and publishing. He was gracious and great with ranch managers, but he did not easily exchange banter with cowboys. Islanders respected this volcanologist but did not call him friendly.

However, as a pioneering and visionary scientist, Jaggar had few peers. In his 1941 "cornerstone message" (Jaggar, 1941), he predicted: "The laboratories will be disseminated as underground earthquake-instrument cellars, underground temperature measuring wells, electrically controlled measurement stations reporting to a central office, and extended automatic and auto-metric facilities sending wired or wireless messages of underground and overground happenings on Mauna Loa. A volcano observatory must see or measure the whole volcano inside and out with all of science to help. The lesson of a third of a century has been to learn to look underground at the inner earth."

As of the time of writing of this historical summary, the Hawaiian Volcano Observatory has achieved much that Jaggar foretold. Fifty-one seismic stations radio information to the Observatory, where earthquake epicenters are located by computer within minutes after an event takes place. Electronic tiltmeters also telemeter data to HVO to give an instant report of the ground movement at various points on the active volcanoes. Other geophysical techniques have been added to these. The geochemical program that began with the early collections of volcanic gas at Halemaumau has gone on to calculate a total volcanic-gas budget for Kilauea. The Hawaiian Volcano Observatory and other institutions worldwide have made great strides in understanding how volcanoes work. This knowledge is being translated into forecasts of volcanic behavior that will reduce loss of life and property.

The volcanological community and the Hawaiian Volcano Observatory owe Thomas A. Jaggar, Jr., a debt of thanks for his vision, his dedication, and his persistence during hard times. Through those qualities he contributed much to the present vigor of volcanology. They are the lessons that must be relearned by every generation.

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