

INTRODUCTION

HAWAIIAN VOLCANISM AND SEISMICITY, 1779-1955 AN HISTORICAL PERSPECTIVE

The science of volcanology has benefited significantly from work done in Hawaii, particularly from direct and quantitative observation of active volcanic processes. This annotated bibliography traces the evolution of ideas regarding such questions as the source of heat for volcanic eruptions, the role of volcanic gas in triggering eruptive activity, and the association of earthquakes with volcanic eruptions. The bibliography also traces the careers of a number of scientists, some of whom became well-known within the overall discipline of Earth Science as a result of their investigations, conducted in Hawaii. As important as Hawaii's contributions were to the growing science of volcanology, we must emphasize that Hawaii remained relatively isolated from the broader geologic and geophysical community. Many advances made elsewhere came late to Hawaii, and some of the Hawaiian contributions to the general understanding of volcanoes were only gradually recognized by the rest of the world. This book is designed to make more widely known Hawaii's contribution to the development of methods for studying volcanoes and the evolution of ideas on how volcanoes work.

Earliest observations

The Hawaiian Islands were discovered by Polynesian explorers about 2,000 years ago. Captain James Cook, in 1779, probably the first European to visit the islands,* named them the Sandwich Islands, after the Earl of Sandwich. His crew landed and attempted to climb Mauna Loa, but they misjudged the distance and difficulty of the ascent and stopped well short of the summit. Cook recognized the islands as volcanic in origin, but he did not observe any eruptive activity. The next voyagers to land and explore the Island of Hawaii came in 1793 (Vancouver, 1798). Vancouver observed a large plume of smoke

*Many articles in the bibliography mention an earlier discovery of Hawaii by the Spaniards around 1555. The evidence for and against the Spanish discovery is discussed by Stokes (1939), who concludes that the Spanish did not encounter the Hawaiian Islands at that time.

onshore, possibly from eruptive activity at Kilauea. Archibald Menzies, a member of his crew, made the first ascent of Mauna Loa in 1794. He described the snow-covered floor of Mokuaweoweo Crater and measured the altitude of Mauna Loa to within 40 feet of its presently accepted height (Menzies, 1920). Many other early voyagers to the islands went into port only at Oahu or Maui, or, if they reached Hawaii, did not describe the appearance of the island, and therefore contributed nothing to our knowledge of the volcanic activity. Two voyagers did report eruptions, but not with sufficient clarity to positively identify what they had seen. James Colnett reported volcanic activity on the lee side of Hawaii between 1788 and 1791, and John Turnbull reported eruptions in the interior of the island during his voyage in 1803 (Colnett, 1940; Turnbull, 1805). It is possible that Turnbull saw the Hualalai rift zone still fuming from the eruptions of 1800-01. Colnett may have referred to activity on Kilauea's east rift zone, if one interprets the lee side of Hawaii as that part of the southeast coastline protected from the tradewinds. It is also possible, but not confirmed by later observation, that Mauna Loa was active between 1788 and 1803. Lockwood and Lipman (1987) summarize modern evidence regarding Mauna Loa's early historic eruptive activity.

Missionary chronicles

The recorded history of Hawaii's volcanoes really begins with the arrival of the first Christian missionaries. William Ellis in 1823 was the first westerner to record a visit to Kilauea (Ellis, 1825). Ellis' party included Asa Thurston, Artemis Bishop, and Joseph Goodrich, each of whose descendents became chroniclers of later volcanic activity. Ellis observed the aftermath of the 1823 eruption on Kilauea's southwest rift zone and visited Kilauea's summit, where he noted the "black ledge" left following draining of the active lava lake on the floor of Kilauea caldera. From Ellis, we learn that the native Hawaiians had a remarkably clear understanding of volcanic activity (*see also* Holcomb, 1987). They clearly connected subsidence at Kilauea with underground movement of magma toward eruption on the flank. They had observed Kilauea "burning from time immemorial" and noted that in previous times, it had overflowed its banks but had been subsequently confined within the caldera. The latter observation is confirmed by modern mapping and age-dating, which show that, prior to formation of the present Kilauea caldera, many flows had reached the ocean, originating from satellitic shields at Kilauea's summit centered near Thurston Lava Tube and Uwekahuna Bluff (Holcomb, 1987). The Hawaiians' inferences regarding Kilauea, combined with their legends describing the travels of the goddess Pele, which correctly trace the order of formation of the

Hawaiian volcanoes from Kauai to Hawaii, demonstrate the great insight the people had into their volcanic environment.

William Ellis' superb descriptions and interpretations of the volcanic phenomena he witnessed were the beginning of a tradition of "pure" scientific observation, unfettered by scientific theories, that marked the missionary's contribution to Hawaii's volcanic history. The greatest of the missionary observers was Titus Coan, who observed nearly every eruption of Mauna Loa and Kilauea between 1835 and 1882 while he served at the Hilo mission. Both Ellis and Coan had the ability to look at the cold lava before them and accurately envision the events that had taken place as the flow was emplaced and cooled. Coan saw so much volcanic activity that he could unequivocally interpret volcanic processes, such as the formation of lava tubes and tumuli in a field of flowing pahoehoe. T.A. Jaggar (1913) summed up Coan's contribution:

Coan without apparatus or endowment was an institution, a first Hawaiian Volcano Observatory, and in actual output he was a better observer and recorder than some institutions which have been elaborately equipped.

Other cogent observations by missionaries are noted in the annotations. Members of the Lyman family were among the most important contributors. C.S. Lyman (1851) was the first to correctly identify endogenous uplift on the Kilauea caldera floor, and F.S. Lyman and his family chronicled the events surrounding the great earthquake of 1868 (1912b; 1929a, b).

The history of seismic activity in Hawaii, likewise, owes a great deal to the missionaries. The Lyman family kept a journal in which its members recorded every earthquake felt at their home in Hilo, beginning in 1833 (S.J. Lyman, 1859). Prior to that, Ellis had quoted Hawaiian reports of a large earthquake responsible for the formation of a graben on Kilauea's southwest rift zone, and for the coastal subsidence associated with the 1823 eruption of Kilauea. Dibble (1843), in a heretofore uncited passage, describes a major earthquake affecting Kilauea's caldera that was associated with the 1832 eruption on Byron's Ledge. The earthquake swarm in 1868 was a dramatic and unexpected event. Prior to 1868, it was commonly thought that volcanic eruptions of Mauna Loa were not accompanied by significant seismic activity and that earthquakes associated with Kilauea collapses, as in 1840, were confined to the immediate eruption area. In 1868 an earthquake swarm, with hundreds of strong, felt events, culminated in a shock, now estimated to be of magnitude 8. This earthquake, the strongest in historic time in the

Hawaiian Islands, triggered a landslide and a tsunami, shook down virtually every building and stone wall in the Kau district, and changed forever people's perceptions of the relation between seismic activity and volcanic eruptions.

Early observations by scientists

The scientific study of Hawaiian volcanoes began with the famous U.S. Exploring Expedition's visit to Hawaii in 1840-41. Led by Charles Wilkes, the expedition included geologist James Dwight Dana, in addition to a number of others trained in the natural sciences. Others to follow were W.T. Brigham, later head of the Bishop Museum, and C.H. Hitchcock of Dartmouth College, each of whom synthesized his Hawaiian observations in book-length articles and, eventually, in books. The scientists, particularly Dana, were able to organize the broad spectrum of observations into general concepts of the workings of Hawaii's volcanoes. However, compared to Titus Coan, the scientists were hampered in two ways. First, they did not view the volcanic activity on a continuing basis; thus, their interpretations of volcanic phenomena were biased by the particular activity they had seen. Second, their observations were colored by attempts to force facts to fit then-current theories of volcanic action. Thus, the observational "edge" of the missionaries was lost upon the scientific observers. Nowhere is this more evident than in a controversy engaged in by James Dana and his friend Titus Coan. Dana felt that the source fissures for any flow must underlie the entire flow, reasoning that lava could not flow on its own for long distances. He makes the following statement (Dana, 1852, p. 256):

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 accessions to the fiery flood. Such was the case in 1840, and the three tufa hills at Nanawale, on the sea coast, mark the positions where these opened fissures reached the sea. 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.

The phrasing "Any internal force . . . must necessarily" perfectly expresses the bias of the scientists, who were encumbered with theory. Coan, having no theoretical background, simply observed and reported what he saw. Dana, to his credit, reversed his position, and, by publication time of his book in 1891, apologized to Coan, who was, by then, deceased.

By-and-large, the early scientific observations were made with a considerable degree of humility and with respect for the scientific method. William Brigham (1909a, p. 178) expresses it this way:

It is hard, often very hard, for a scientific student to admit that he does not *know*, for his conscience tells him that he has not yet exhausted all the means at his disposal to complete the analysis, but surely, if anywhere, here in this mighty laboratory where God seems to be showing us His most wonderful ways, man must confess without shame to his own ignorance and failure to comprehend. He can well give up the attempt to conceal his ignorance in obscure phrases and pompous names. Giving a thing or a force a name does not explain what it is. This does not mean that we are to quit trying to learn, in our despair at our present failure. I have believed, and the belief is greatly strengthened at each succeeding visit to this volcano, that here is the place for a scientific exploration of world-making ways. . . .

The early scientists made a significant contribution to our understanding of Hawaii's volcanoes. By the time the Hawaiian Volcano Observatory was founded, books by Dana (1891), Brigham (1909), and C.H. Hitchcock (1909a) contained all of the available information on Hawaii's eruptions, providing an historical context for HVO's future observations.

Early topics of interest

From the early descriptions of volcanic activity, one can easily list the topics that drew the most attention and interest. These were Pele's hair, lava stalactites, formation of aa and pahoehoe, action on the surface of Halemaumau lava lake, nature of the vapor component associated with the lavas, and relation of Kilauea to Mauna Loa. Everyone noticed Pele's hair, and many correctly inferred or directly observed its origin by the drawing-out of thin filaments of glass during fountaining or during surface activity on the lava lakes. The formation of lava stalactites, frequently observed in drained lava tubes, was also addressed, although, in this case, there was no consensus. Some authors felt that they were simply lava drips, formed as the tube was being drained of lava. Others thought they were chemical deposits formed by solution and re-precipitation of material on the walls and the roof of the tube. Still others thought they were precipitated directly from hot gases in the tube. The first two hypotheses are supported by more modern studies. The most common origin may be where hot gases actually remelt the lining of the tube roof and a lava drip results.

Aa and pahoehoe were recognized early to occur in the same eruption and, therefore, their origin could not be assigned to differences inherent in the magma prior to eruption. An early description by W.D.

Alexander (1859), quoted in the annotation, ascribed the formation of aa to "graining, as sugar." Although Alexander's article was overlooked by subsequent workers, the concept was repeated by both Jaggar (1947) and Macdonald (1953a), who correctly realized that formation of aa involved both loss of gas and change of viscosity, leading to "sugaring," or, in modern terms, crystallization under conditions of significant undercooling. The later workers also recognized that local conditions, such as the steepness of terrain and rapidity of eruption rate, affected the flow regime and contributed to the formation of one or the other lava type. Titus Coan, through extensive observation of the 1855-56 eruption of Mauna Loa, had an entirely correct view of how lava tubes form, and of their significance in allowing pahoehoe lava to travel long distances (Coan, 1856a). He recognized both the greater long-term hazard of slow-moving pahoehoe and the more immediate hazard posed by rapidly moving channeled aa, and also recognized the short-term mitigating effects of tube blockage in slowing the seemingly inexorable advance of pahoehoe lava toward Hilo.

There are excellent early observations of Halemaumau lava lake, which document the circulation, the stability of fountaining areas, and the process of crustal renewal through foundering. It took later workers with scientific training, such as R.A. Daly and F.A. Perret, to provide mechanistic interpretations for these descriptions. The nature of the gas phase in Hawaiian magmas was not resolved until the collections of Day and Shepherd in the early 20th century. Earlier, there was a division between those who thought the magmas had to be anhydrous, primarily inferred from the absence of visible fume on dry days, and those who thought that water was an important component of the gas. The latter all believed that water was introduced into the magmas at a shallow level. For example, Dana thought that ground water runoff from rainfall was taken up by magmas on their approach to the surface during eruption. Oddly, the process of vesiculation was rarely addressed.

The relationship of the eruptive activity of Kilauea to that of Mauna Loa was a question that engaged the early observers of Hawaii's volcanoes, lay persons and scientists, alike. The extreme views were that Kilauea was either a lateral vent of Mauna Loa, or an entirely separate volcano that happened to be built on the slope of Mauna Loa. In both of these hypotheses, Kilauea was considered to be the younger of the two, and Mauna Loa's mass was extrapolated to the sea floor, giving it a total vertical extent of 32,000 feet. T.A. Jaggar (1912b) took the idiosyncratic view that Mauna Loa was younger than Kilauea because it appeared in the center of his geometrical "cross of Hawaii." In his view, Mauna

Loa was built, not on the ocean floor, but on a base of the coalesced lava of the earlier volcanic edifices of Kilauea, Hualalai, and Mauna Kea. Of principal concern to all investigators was how Mauna Loa could erupt at an elevation of over 13,000 feet when Kilauea was continuously active at 4,000 feet. Their underlying assumption was that there had to be a hydrostatic (or "magmastatic") relation, such that Kilauea should act as a safety valve, which it clearly did not. Therefore, several elaborate theories were devised to explain the greater lifting power of Mauna Loa magma. Most theories invoked density differences, including a higher gas content in Mauna Loa's magma, compared to that of Kilauea. Dana early noted that eruption from vents on the floor of Kilauea caldera could occur simultaneously with eruption in Halemaumau, whose active surface was several hundred feet lower. This observation denied any simple magmastatic connection, even within the confines of Kilauea itself, and pointed the way toward a more modern resolution of the problem.

Today, all the evidence favors complete independence of the two volcanic systems, at least over short periods of time. For example, since the beginning of the current Kilauea eruption in 1983, Mauna Loa has completed one cycle of inflation and eruption and has begun reinflating, all without noticeable effect on Kilauea. When Kilauea and Mauna Loa were in simultaneous eruption in March 1984, an observer watching the instrumental monitors of one volcano could not have detected the activity of the other volcano, except for the far-field record of harmonic tremor from fountaining. Over the long term, Mauna Loa and Kilauea activity may wax and wane alternately. When both volcanoes are in repose, the inflation of one could have a mechanical effect, such as to make less likely the inflation of the other. In any case, the magmastatic issue is resolved by the instrumental identification of separate shallow plumbing systems that independently control the activity of each volcano.

Volcano monitoring and the history of the Hawaiian Volcano Observatory

Early visits by T.A. Jaggar, F.A. Perret, R.A. Daly, and A.L. Day and E.S. Shepherd had demonstrated the suitability of Hawaii as an appropriate place in which to study active volcanism and seismicity and, in particular, had identified Kilauea's active lava lake as an ideal site for detailed study of volcanic processes. As a direct result of these visits, the Hawaiian Volcano Observatory, under the direction of Professor Thomas A. Jaggar, was founded in January 1912. Thomas Jaggar was a remarkable individual whose ability to sell volcano monitoring to

Hawaii's business community and to his home university, the Massachusetts Institute of Technology, kept HVO alive during the formative years. Jaggar's vision extended far beyond the immediate goals of HVO. He favored, among other things, the expansion of geologic and geophysical research to include the ocean floor, and proposed a global network of terrestrial observatories similar to HVO to provide invaluable information on natural hazards. The former came to pass in the 1950s; the latter has yet to gel in the way Jaggar envisioned, although there are an increasing number of observatories located in areas with potentially dangerous active volcanoes. Jaggar's reputation today rests more on his ability to inspire other scientists than on the scientific contributions he himself made to the understanding of volcanoes. His own science was unduly affected by his belief in solar and lunar influences on volcanic behavior, inspired, in part, by the ideas of a lay scientist, W.L. Green. As a result, he forced his observations on Kilauea to fit neatly into imagined cycles of 11, 33, and 132 years. He also felt, as noted above, that Mauna Loa was Hawaii's youngest and most important volcano. Kilauea, he said, was dying, even as he was recording the activity of its seemingly permanent lava lake.

Instrumental monitoring of earthquakes in Hawaii began with the establishment of HVO. Jaggar had become a friend of the great Japanese seismologist Omori and had introduced the Omori and Imamura seismographs to Kilauea. Seismology at HVO began as little more than a serial listing of earthquakes recorded at Kilauea summit. Earthquake locations were first discriminated only as being associated with Mauna Loa or with Kilauea, with the exception of the Kona earthquake swarm in 1929, which was recognized as originating from Hualalai. Seismic studies progressed fitfully in the next several decades, mainly because of the lack of an adequate seismic network. A maximum of four seismographs were in operation at any one time; each served as a combined sensor and recorder. Austin Jones (1935a) made the first serious attempt to locate earthquakes using travel-time curves and a crustal structure model, but he was severely hampered by the lack of sufficient stations and by the limitations of the timing mechanism on the seismographs.

Geodetic studies in Hawaii began with the leveling and triangulation surveys of the 19th century (Mitchell, 1930), which were taken up by HVO in the early part of the 20th century (Wilson, 1935), and have continued to the present. Ground tilt was measured originally by deflections on the seismograph located in HVO's Whitney Laboratory of Seismology. Geologic studies conducted at HVO were largely concerned with visual observation, following in the footsteps of Titus Coan. Jaggar

emphasized, in addition, the quantitative measurement of temperature and gas content of the circulating lava in Halemaumau lava lake. Geochemistry at HVO was confined to the study of the constituents in volcanic gas. The efforts in gas geochemistry, as noted below, represent one of the most successful collaborations of the young observatory with other scientists.

Two unfortunate gaps stand out in early study of Hawaiian eruptions--gaps that remained even after the founding of HVO. First, accurate maps of the erupted lava are lacking. An exception is the Wilkes expedition's excellent depiction of the small pads of lava that erupted sequentially in 1840 between Alae Crater and the coast. Many of the erupted lavas, principally those near Mauna Loa's summit, were covered by subsequent activity, and we have only written records and crude sketch maps to aid in sorting out which flows belong to which eruption. Second, systematic collection and characterization of samples from eruptions, either megascopically, or by petrographic and chemical analysis, was not carried out. From Ellis' time on, Kilauea was visited ever more frequently, and samples were collected by all who visited; but with few exceptions, these samples did not find their way into documented collections. Thus, we have lost a valuable history of the chemical composition of lava erupted at Kilauea's summit. The arrival in the 1940s of Gordon Macdonald, with his modern training in geology and petrology, resulted in the establishment at HVO of both geologic mapping and systematic collection of samples for chemical analysis. Macdonald organized the chemical and petrographic data for Hawaiian lavas into a comprehensive body of data (Macdonald, 1949a, b).

Volcano monitoring at HVO underwent a significant advance following the arrival of J.P. Eaton in 1952. Eaton introduced the first true seismic network at Kilauea, where field seismometers were hard-wired to recorders located at the Observatory. He developed a generalized crustal model for Hawaii with which he could properly locate earthquakes from the new network. By the 1960s, HVO was able to produce an annual catalog of reliably determined earthquakes. Eaton also introduced a network of sensitive water-tube tiltmeters, which quickly replaced the seismographic method of measuring ground tilt. The modern Hawaiian Volcano Observatory can be said to date from this time.

Volcanology in Hawaii: what was learned before 1955

Our present knowledge of Hawaii's volcanic and seismic activity is based on work in the disciplines of seismology, geophysics, geodesy, geology, petrology, and geochemistry, each of which began prior to

1955. Early geophysical studies other than seismology included measurement of the gravitational and magnetic field at a few points in the Hawaiian Chain. The former were tied to interpretation of isostatic models for the volcanic load applied to the Hawaiian Chain and to large-scale problems like the density of the Earth. Magnetic measurements were largely qualitative, and paleomagnetic studies on Hawaiian lavas, anticipated by Beech and Eller (1939), were still two decades away.

Many of the advances in the science of volcanology were made by scientists collaborating with HVO. The first and foremost of these were R.A. Daly of Harvard University and A.L. Day and E.S. Shepherd, from the newly formed Geophysical Laboratory of the Carnegie Institution of Washington. Collectively, Day and Shepherd were two of the finest scientific minds ever to take on the challenges of Kilauea and its active lava lake. They devised sampling procedures and made the early collections, using the apparatus designed by Shepherd, who also did the analyses. Day and Shepherd trained Jaggar, who made some of the later collections. Due to favorable collecting conditions and adherence to good scientific procedures, the early collections of gas from Halemaumau still rank as some of the best ever taken. Day and Shepherd together established unequivocally that water is a primary component of magmatic gas, a subject previously under debate. They determined that gases were heterogeneously distributed in the melt and that gas was an important source of the energy for eruptions, although not a source of heat in the magma (Day and Shepherd, 1913a).

R.A. Daly was another important early contributor to Hawaiian volcanic studies. Following his one and only visit to Kilauea, Daly published a landmark paper on volcanic mechanism, postulating that the magma in Halemaumau was kept hot by a combination of what he called two-phase convection and by exothermic reactions in the gases themselves (Daly, 1911a). Daly discovered the laccolith in the walls of Kilauea below Uwekahuna Bluff, theorized that Kilauea was fed from an offshoot of Mauna Loa shaped like a laccolith, and concluded that the raised summit and rift zones of the volcano owed their existence to intrusive pressure from the laccolith, rather than to successive extrusions of lava. Daly also believed in a universal layer of molten basalt, located in what would now be defined as the uppermost mantle. He hypothesized that basalts everywhere in the world, which he showed to be similar chemically, were fed from the basaltic layer. In 1911 all of these ideas were far ahead of their time and provided a solid theoretical context for anyone making observations in Hawaii. Sadly, thirty years later, Daly was desperately defending each of these ideas against the insights gained by

advances in seismology, experimental petrology, and gas geochemistry, which had gradually rendered untenable all but two-phase convection.

The arrival of Harold Stearns in the mid-1920s and Gordon Macdonald in the early 1940s set the stage for the transition from the Jaggar era of visual observation of volcanic events to the modern era, when a combination of field mapping and instrumental observation assumed a greater importance. Stearns was the first to map the older rocks on the island of Hawaii, and he established the value of geologic mapping in complementing real-time observation of Hawaii's volcanoes. His work culminated in two landmark publications. The first covered the geology of the Kau district (Stearns and Clark, 1930). By careful mapping, Stearns and Clark worked out the spatial relationships between the flows of 1823 and 1868, as well as among prehistoric flows from both Kilauea and Mauna Loa that had long been confused on early maps. Later, Stearns was joined by G.A. Macdonald to map the Island of Hawaii, a collaboration which resulted in publication of the first geologic map of the island (Stearns and Macdonald, 1946). This map stood for forty years before a project to update the mapping began in 1984.

Igneous petrology in Hawaii began in the 20th century with the advent of the first reliable chemical analyses of Hawaiian lavas. The early petrologists, including C.W. Cross, G.A. Macdonald, and H.S. Washington, were hampered in petrologic interpretation by three factors: first was an emphasis on chemical classification. The interpretation of petrogenesis via elaborate normative classification schemes, rather than through study of the field relations of the samples, resulted in blurred distinctions among analyses, including incomplete discrimination of alkalic from tholeiitic rocks. Second was the tendency of all early scientists working with chemical data to "lump" rather than "split," in support of a theoretical concept of worldwide uniformity in the composition of basaltic rocks. As a consequence, they assumed that all Hawaiian lavas could be derived from a single basaltic parent magma. Third was the continued lack of consistency in the quality of chemical analyses. Even H.S. Washington, who outlined very carefully the techniques for making good analyses, produced biased ones, when compared with the best modern data.

Howard Powers was the first petrologist in Hawaii to question these concepts and thereby provide a basis for petrologic advances made decades later. Powers tended to be a "splitter" and used the chemical data to characterize the different volcanoes. He showed that the tholeiitic basalts of each shield volcano had lavas of distinctive chemistry, related

within each volcano by addition or subtraction of olivine. He also recognized the distinction between alkalic and tholeiitic rocks, noting that they could not be derived from each other by removal of phenocrysts found in the lavas themselves. Powers discarded the concept of a single parent magma for Hawaiian lavas, even discriminating separate parental magma batches for lavas that were grossly similar in petrography and chemistry.

Geochemical studies before 1955, other than the volcanic gas studies conducted at HVO, were rare. The first trace-element analyses of Hawaiian lava were published in 1953 by Wager and Mitchell; the first isotopic analyses were published a decade later. Experimental melting of Hawaiian lavas began a few years after 1955 and ultimately contributed to the understanding of permissible parent compositions for Hawaiian lava. Only in the 1980s has a full array of analytical chemistry been brought to bear on the petrogenesis of Hawaiian lava.

The goal of making an integrated study of an eruption using the full monitoring facilities of the Hawaiian Volcano Observatory, combined with traditional geologic mapping and petrological and geochemical analysis, was fulfilled with the 1955 eruption of Kilauea. The result, which was not published until nearly 10 years after the eruption (Macdonald and Eaton, 1964), was the first study of an eruption that integrated geophysical, geodetic, and visual observation into a coherent description of eruptive process. Lava flows were mapped and samples collected systematically throughout the four-month eruption in order to record variations in spatial distribution and chemical composition that would otherwise have been buried during subsequent eruptions. This study stands as a model for all eruption studies conducted by the Hawaiian Volcano Observatory.

The current work on Kilauea and Mauna Loa owes a great deal to the systematic observations of earlier workers. Many of the eruptive phenomena seen today were first described in their reports, and many modern ideas of volcanic action were anticipated, even if they could not be proven at that time. Recently, it has been possible, using the knowledge of Hawaii's active seismic zones gained by 30 years of instrumental monitoring, to go back to the Lyman's record of felt earthquakes and assign them provisional locations, intensities, and even magnitudes. This work (Wyss and Koyanagi, in press) re-emphasizes the great value of early missionary observations in Hawaii.

Future challenges

The volcanic and seismic history of Hawaii is as interesting and varied as the persons who contributed to it. From the native Hawaiians, whose geologic insights were incorporated in the fabric of their religion, and the missionaries who took time out from their parish duties to investigate the wonders of the natural world around them, to the Hawaiian businessmen who supported the fledgling Hawaiian Volcano Observatory, and the professionally-trained scientists working both inside and outside the Observatory, Hawaii's volcanoes have been well-tended. The body of observations--although covering a very short time, compared to other volcanic areas, where records extend back thousands of years--provide an historical background for understanding active volcanism in Hawaii. We intend that this annotated bibliography provide a context for modern inquiry into larger scientific questions posed by studies in Hawaii. The following are arbitrarily suggested as topics where an important contribution can be made through knowledge of the history of Hawaiian volcanism and seismicity.

1. **Origin of Kilauea caldera.** Modern study of the Keanakakoi ash at Kilauea summit (Decker and Christiansen, 1984) shows that the present caldera existed when the bulk of the ash was deposited during the explosive eruption in 1790. Recent mapping and radiocarbon dating, as well as early 19th century descriptions of relatively unvegetated lava on the trail between Olaa and Kilauea summit, show that pre-caldera flows, erupted from a center near Thurston Lava Tube, are as young as 250 years B.P., thus placing formation of the caldera in the 18th century. There are no Hawaiian accounts of a catastrophic event in that century prior to 1790, nor are there significant ash deposits close in age to that deposited in 1790. One of two conclusions seems inescapable. Either the caldera formed gradually and non-catastrophically, or it formed just prior to 1790, triggering the 1790 eruption, which then mantled the freshly-formed caldera faults with ash. There have been no events subsequent to 1790, with the possible exception of an earthquake in 1832 (Dibble, 1839), in which the caldera faults have been active. Thus, the idea of gradual collapse seems less likely. In any case, this is a problem whose resolution can benefit from study of the entire historic record.

2. **The behavior of Kilauea and Mauna Loa's south flank.** The historic record shows more large earthquakes associated with subsidence of the south coast of Hawaii than have been generally recognized. Such events took place in 1823 and 1832, and possibly in 1790 and 1840, in addition to the great earthquake of April 2, 1868.

Between 1868 and 1975, the onshore section of Kilauea's south flank was relatively quiet. However, an earthquake swarm in 1952 (Macdonald, 1955d) may have triggered subsidence of a submarine section of the south flank. Ground deformation studies in progress at HVO suggest that a deeper connection may exist between Kilauea summit and the lower part of the east rift zone. More careful study of the earlier literature, including descriptions of directed surface motion associated with large earthquakes and descriptions of collapses of Kilauea summit, may offer additional insight into the tectonics of the unbuttressed flanks of the Hawaiian volcanoes.

3. Submarine eruptions. There are a number of instances, cited in the early literature, of fish kills, offshore volcanic plumes, or floating pumice attributed to undersea eruption. In most cases, these observations are unconfirmed, and it would be easy to reject them as fantasies made up by unreliable observers. Recent GLORIA imaging of the sea floor has revealed large fields of young lava adjacent to the Hawaiian Ridge. The credibility of early reports of submarine eruptions is thus increased. It may be possible to use some of the earlier observations to better understand the eruptive history of the sea floor surrounding the Hawaiian Islands.

These and other topics can be addressed only through consideration of the full range of volcanic and seismic observations on Hawaii's active volcanoes. It is to this end that we present this annotated bibliography and subject index to Hawaiian volcanism and seismicity.

Thomas L. Wright

ANNOTATED BIBLIOGRAPHY

APPENDICES

SUBJECT INDEX

