Magmatic Processes: Physicochemical Principles
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Editor B. O. Mysen

The significance of observations at active volcanoes: A review and annotated bibliography of studies at Kilauea and Mount St. Helens

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Abstract—Study of active volcanoes yields information of much broader significance than to only the discipline of volcanology. Some applications are 1) interpretation of lava-flow structures, stratigraphic complexities, and petrologic relations in older volcanic units; 2) interpretation of bulk properties of the mantle and constraints on partial melting and deep magma transport; 3) interpretation of geophysical characteristics of potentially active volcanic systems; 4) direct determination of physical properties of molten and solidified basalt, and of intensive variables (*e.g.,* oxygen fugacity and temperature) accompanying cooling and crystallization; 5) quantitative assessment of crystal fractionation and magma mixing, 6) tests of theoretical and experimental geochemical, geophysical, and rheologic models of volcanic behavior; and 7) confirmation in nature of laboratory experiments related to crystallization in igneous systems.

The critical factors that make real-time study of volcanic activity valuable are that the location and timing of events are known, and that molten rock and gases are available for direct observation and sampling for subsequent study. Observations made over a period of time make it possible to calculate rates of magma transport, storage, and crystallization, as well as to quantitatively determine elastic and inelastic deformation and the build up and decay of stress within the active volcanic system.

Discussion of these topics is keyed to an annotated bibliography from which quantitative information on properties and processes may be obtained. Emphasis is on Hawaii's active basaltic volcanoes for which the most information is available. Additional references are made to research at Mount St. Helens, one of the first real-time studies of an active volcano of dacitic composition.

INTRODUCTION

SCIENTISTS have long been attracted by active volcanoes and have made observations and measurements that have increased our understanding of how volcanic systems behave. Much of this information has been published in the volcanologic literature and disseminated within the small community of volcanologists. The thesis of this paper is that study of active volcanoes provides important constraints on geological processes to disciplines as diverse as geology, seismology, geochemistry, experimental petrology, and rock mechanics.

Continuous monitoring of volcanoes enables quantitative measurement of the rates at which certain volcanic processes take place (*5a, b*). Such processes range from accumulation and release of strain in rocks to rates of magma transport and their effect on igneous differentiation. We discuss these applications below, beginning with surface observations and progressing to inferences regarding deeper processes. The text is supported by an annotated bibliography for Kilauea with additional references to recent work at Mount St. Helens. We have not attempted to cover studies of other active volcanoes. For Kilauea the reference list includes 1) review articles which themselves contain useful bibliographic coverage, 2) papers that contain quantitative determinations of physical parameters or quantitative demonstrations of specific volcanic processes, and 3) the most recent articles. A primary reference for recent research at Kilauea is *U.S. Geological Survey Professional Paper 1350,* published on the occasion of the 75th anniversary of the founding of the Hawaiian Volcano Observatory in January of 1987 (*4a01*). A primary reference for the catastrophic events at Mount St. Helens in 1980 is *U.S. Geological Survey Professional Paper 1250* (*4a02*).

OBSERVATION OF ERUPTIONS

Observation of volcanic eruptions is a key to understanding the origin of volcanic units preserved in the geologic record. A useful distinction here is between catastrophic and milder volcanic events. For catastrophic eruptions (*e.g.,* Crater Lake, the

Bishop tuff, or flood basalts of the Columbia Plateau) a nearly complete record of eruption may be preserved in the deposits themselves. Observations of explosive eruptions such as that of Mount St. Helens in 1980 are difficult to make but serve to limit the time frame in which various kinds of deposits—such as surges, pyroclastic flows, and airfall ejecta—are formed (*4a02*). Eruptions at Kilauea, in contrast, leave a very confused stratigraphic record that is virtually impossible to decipher after the fact (*3a01–04; 3b05, 06*). Continuous monitoring of eruptions as they take place is the best means of specifying what constitutes a single eruption, or of determining the sequence of events that accompany construction of a large volcanic edifice or lava field that may be preserved in the geologic record. One application of real-time observation of volcanic activity to older rocks involves the origin of thin, dense, streaky layers of basalt exposed locally on the Columbia Plateau. They were identified as collapsed pahoehoe from their similarity to layers that were observed to form during the Mauna Ulu eruption of Kilauea (see Figure 4 in *3b05*). The occurrence of collapsed pahoehoe on the Columbia Plateau was then used as evidence for the proximity of source vents. Another example is how observed formation of the debris avalanche at Mount St. Helens on May 18, 1980, elucidated the process and enabled proper reconstruction of similar past events at many volcanoes in the world (*6a01*).

Volcanic eruptions are also a laboratory for studying the complex behavior of natural silicate melts, consisting of liquid, one or more crystalline phases, and a volatile phase. Laboratory simulations and theoretical study of fountain dynamics and flowing lava can be tested by direct observation. Field observation of the transition from pahoehoe to a'a (*3b04*) can likewise be used to constrain theoretical or experimental derivation of the rheologic properties of basalt. Finally, deuteric alteration and weathering may be quantified by study of lavas of known age (*3a06;* last paragraph of following section.)

KILAUEA LAVA LAKES

In contrast to study of eruption dynamics and flowing lava, the filling of circular pit craters at Kilauea by basaltic lava created natural crucibles for study, by core drilling, of the cooling and crystallization of basaltic magma at low pressure and under static conditions (*1a–1d*). The rates of cooling and crystallization of basaltic magma have been measured, and direct measurements have been made of properties such as density, viscosity, and oxygen fugacity at different stages in the cooling history (*1c01b, 1d02, 1d03*). These observations combined with estimates of primary volatile contents (*2d*) can be used in the laboratory to simulate real conditions in basaltic systems under study by experimental petrologists. It is encouraging that the pioneering experimental work of N. L. Bowen, H. S. Yoder, C. E. Tilley, and others at the Geophysical Laboratory on crystallization and differentiation of basaltic magma has found solid confirmation in the observations made on the natural lava lakes (see, for example the temperatures of crystallization of different phases in Kilauea Iki lava lake presented in *1b09*).

Several processes of crystal-liquid fractionation have been observed in the lava lakes, and the chemistry of a liquid line of descent has been directly specified. The question of whether high-SiO_2 rhyolite can be derived from a crystallizing basalt is answered affirmatively (*1b01*). Residual glass of rhyolitic composition is present in Alae and Makaopuhi, comprising 6 per cent by weight of the starting basalt. In the larger Kilauea Iki lava lake, liquids of rhyolitic composition were segregated and entered fractures; deep in the lake, however, slower cooling resulted in complete crystallization with no residual glass remaining. Thus we have placed quantitative limits on the possibility of deriving rhyolite from a basaltic liquid that should lead to better understanding of the rhyolite-basalt association in large volcanic fields.

Study of Alae and Makaopuhi revealed differentiation processes that could be directly applied to the origin of differentiated liquids erupted from Kilauea's rift zones. The deeper and more olivine-rich lake, Kilauea Iki, underwent different differentiation processes, including diapiric transfer of one melt through another without appreciable mixing (*1b01, 02*), that can be applied to the origin of chemical and mineralogical layering in shallow mafic intrusions.

Another significant benefit from lava lake studies is the geophysical determination of the relative proportions of liquid and solid. Geoelectrical measurements made in Kilauea Iki (*1b06*) generally agreed with the petrologists' definition of "melt" and "crust" (see *1a01; 1b01*). Seismic measurements generally underestimated the amount of "melt," presumably due to differences between the seismic attenuation of shear waves expected for passage through a single phase liquid and those observed for a liquid which contained a large population of suspended olivine crystals (*1b07*). These results have important implications with regard to geophysical prospecting for magma, either deep (*e.g.*, hot dry rock) or shallow (*e.g.*, beneath active geothermal systems).

The lava lakes give data on the initial oxidation state of basaltic magma and on the effects of deuteric oxidation during cooling. Minimum weight-percent ratios of ferric to ferrous iron are about 0.12, in equilibrium with directly measured oxygen fugacities slightly above the QFM buffer (*1d01, 03*). High oxygen fugacities that developed in Makaopuhi lava lake (*1d01, 03*) resulted only in a streaky hematitic alteration of mafic silicates. No hydrous mineraloids, such as iddingsite, have been observed. The occurrence of iddingsite in older Hawaiian flows can thus be ascribed to low temperature alteration long after initial cooling and solidification. Kilauea Iki lava lake, whose upper crust has a well developed hydrothermal system at temperatures lower than 100°C, shows increasing deuteric alteration at a given depth in successive drillings of the lake. Eventually we should be able to specify the alteration history, mineralogically and chemically, as a reference for the interpretation of alteration in older ponded basaltic lava flows.

INTERPRETATION OF SUB-VOLCANIC PROCESSES

Kilauea is an ideal laboratory for study of subsurface volcanic processes because of its accessibility and frequent activity. Major events—eruptions and earthquakes—occur with a frequency that permits repeated testing of hypotheses of volcanic and seismic behavior. Kilauea's shallow plumbing system has been intensely studied (*2a–e*) with the result that we can specify depth and size of a primary magma-storage reservoir (*2a01–05; 2b01, 02*), measure rates of magma transport from storage to eruption (*2a07, 08; 2b17, 18*), identify locations of secondary storage (*2a05; 2b08, 09; 2c05; 2e04, 05*), and evaluate seismicity and ground deformation as they relate to accumulation and release of strain in brittle rocks surrounding the magma reservoir and active rift systems (*2a06; 2b14–16; 2e01, 02*). The record of the chemistry and petrography of all eruptions since 1952 has resulted in quantitative interpretation of crystal-liquid fractionation and high-temperature magma mixing in the rift zones (*2c05–08*). These processes are not restricted to Kilauea. Numerous papers on the mid-ocean ridge basalt system and, more recently, on the Krafla system in Iceland, have described processes similar to those first documented for Kilauea.

The concept that volcanic rocks provide a window into the earth's mantle is not new. Nevertheless most geophysical and geochemical models of mantle processes do not use the constraints and insights gained from study of active volcanic areas. The process of magma generation in the mantle often leads to eruption of lava on the earth's surface. At Kilauea a key observation connecting shallow and deep processes is the magma supply rate, the rate at which basaltic magma is supplied to shallow storage (*2f01, 02; 2b04*). Kilauea's magma supply rate has been estimated at 0.1 km^3 per year. From storage the magma may either be intruded or extruded; the net result of endogenous and exogenous growth (*2f02*) and the isostatically controlled subsidence of the volcanic pile into the crust (*3a05*) is what determines the rate of growth of an Hawaiian volcano above the sea floor.

Several other critical observations constrain melt generation in the Hawaiian hot spot:

1. More than one volcano can be active at a given time.
2. Simultaneously active volcanoes are chemically identifiable (*2c01,02*).
3. Deeper storage areas in the mantle have not been identified (*2a03*).
4. Magma is rapidly resupplied from depth following partial draining of the summit reservoir during summit (*2b04*) or rift (*2b08, 09*) activity.

Observations 3 and 4, combined with knowledge of the size of the shallow reservoir and the estimated constant magma-supply rate, require a geologically short time between melting in the mantle and eruption at the surface; current estimates are in the range of a few decades to at most 100 years. Thus each of us is a witness, well within one's lifetime, to the entire process of melting, magma transfer to shallow storage, and eruption or intrusion of a particular batch of magma. The short times involved make it likely that melting occurs at a relatively shallow depth, but the question of the ultimate depth of the source material brought up to be melted remains unresolved. The fundamental parameters for melting in the mantle, for example, degree and depth of partial melting and the chemistry and mineralogy of the bulk mantle, all may be better addressed in the context of the magma supply rate and the chemistry of erupted lavas associated with an active volcanic system. Again we emphasize the importance of knowing the magma supply rate. To the extent that the supply rate reflects the melting rate within the Hawaiian hot spot, the degree of partial melting is constrained by consideration of the total volume of mantle available to be melted per unit time, the physical dimensions of magma transport systems in both the asthenosphere and lithosphere, and the rates at which melts can be homogenized to produce a broadly uniform composition. New methodologies in seismology (*e.g.*, tomographic mapping), following on earlier work (*2a02, 03*), may be important to apply to the roots of volcanic areas (*e.g.*, the Hawaiian hot spot) to elucidate further the distribution of melt in the uppermost mantle. Likewise, theoretical and experimental modeling of magma transport mechanisms (*e.g.*, rates of collection of magma in the asthenosphere from an originally solid crystal framework; fracture mechanisms in a rigid lithosphere) may be constrained by knowledge of magma-supply rates for specific volcanic systems.

A final application of real-time volcanic studies to deeper processes is the determination of volatile contents and rates of outgassing of the earth's mantle. These are critically dependent on determinations of the concentrations and saturation pressures of volatiles in magmas, as well as quantitative determination of the rates of outgassing of volatiles from an active volcano. Kilauea has provided both kinds of data. Determination of volatile concentrations in rapidly quenched volcanic glasses, both subaerial (glass inclusions in phenocrysts—*2d09*) and submarine (pillow rinds—*2d07, 08*), has given estimates of saturation concentrations for CO_2, S, and H_2O). Study of Kilauea gases emitted from fumaroles and active vents (*2d04–06*) as well as measurement of volcanic plumes both between and during eruptions (*2d01–04*) yield limiting values for volatile content (*2d05*) and outgassing rate (*2d06, 10*) of the mantle.

COMPARISON OF MOUNT ST. HELENS WITH KILAUEA

Volcanic monitoring by the U.S. Geological Survey is currently conducted at two very different active volcanic centers (*5a, b*). Kilauea is a basaltic volcano in an oceanic intraplate tectonic setting; Mount St. Helens is a dacitic volcano in a continental margin setting. Similar instrumentation for study of seismicity and ground deformation is used on both volcanoes. The contrasts in eruptive style, magma supply rate, shape of volcanic edifice, types of volcanic deposits, and chemistry and petrology of erupted magmas are obvious. What are perhaps more interesting are the similarities in magma storage and the constancy of magma supply rate as inferred from instrumental monitoring.

Seismic evidence obtained prior to and during the eruption of May 18, 1980 suggests the presence of a magma reservoir 7–8 km below the surface (*4a05*). This depth correlates exactly with the depth of storage and crystallization inferred on the basis of experimental work on pumice erupted on May 18 (*4a04*). Seismic studies since 1980, however, have failed to detect a magma body beneath Mount St. Helens, although the volcano has been in episodic eruption during this time. This failure might relate to the resolution scale of existing techniques, but by analogy with the Kilauea Iki experiment (*1b07*) the absence of a clear seismic definition of magma might also reflect a high crystal content in the reservoir that feeds the 50-percent-crystalline dacite into the dome.

The magma supply rate at Mount St. Helens is estimated from study of post-1980 dome growth to be about one order of magnitude less than that estimated for Kilauea. It is, like Kilauea, remarkably constant over the short period of time in which measurements have been made (*4a06*).

Acknowledgements—This paper grew out of an afternoon workshop moderated by one of us (TLW) entitled "Study of Active Volcanism: Constraints on Petrologic and Geophysical Models of Dynamic Earth Processes" held at the symposium honoring Hat Yoder. We are grateful to the following persons who also participated in the workshop: Fred Anderson, Rosalind Helz, Peter Lipman, Christina Neal, Michael Ryan, and George Ulrich. The present paper covers the overview and not the substance of the workshop. We appreciate the cooperation of Bjorn Mysen in offering a forum in Hawaii and in this volume to present some of our thoughts on the importance of studies at active volcanoes.

Finally, it is appropriate to recognize the contribution that the Geophysical Laboratory and Hatten S. Yoder himself have made to understanding Hawaiian volcanic processes. From the earliest visits of Day, Allen, and Shepherd to collect gas at Halemaumau to the weighty synthesis of basalt genesis by Yoder and Tilley, based in part on experiments using Kilauea tholeiite, there has been an important scientific interchange between the Carnegie Institution's Geophysical Laboratory and the U.S. Geological Survey's Hawaiian Volcano Observatory. We dedicate this paper to that continued association and hope that a similar association can be established between the Geophysical Laboratory and the fledgling Cascades Volcano Observatory.

The manuscript was reviewed and improved by Paul Greenland, Charlie Bacon, Peter Lipman, and Bjorn Mysen. Fred Anderson provided additional insight into the significance of volatile studies at Kilauea.

ANNOTATED REFERENCES

1. KILAUEA LAVA LAKES

a. Overviews of lava lake studies **1a**

WRIGHT T. L., PECK D. L. and SHAW H. R. (1976) Kilauea lava lakes, natural laboratories for the study of the cool-

ing, crystallization, and differentiation of basaltic magma. In *The Geophysics of the Pacific Ocean Basin and Its Margin.* Amer. Geophys. Union Monograph 19, p. 375–392. **1a01**

A summary of data and interpretations from earlier studies of Kilauea lava lakes.

Wright T. L. and Helz R. T. (1987) Recent advances in Hawaiian petrology and geochemistry: *U.S. Geol. Survey Prof. Paper 1350,* Chap. 23. **1a02**

Gives an updated summary of differentiation processes observed in the Kilauea lava lakes.

b. Kilauea Iki. **1b**

Eruption of November–December 1959. Drilled in 1960–61, 1967, 1975, 1976, 1979, and 1981. Depth = 365 feet.

Helz R. T. (1987) Studies of Kilauea Iki lava lake: an overview. In *Magmatic Processes: Physicochemical Principles,* (ed. B. O. Mysen), The Geochemical Society Spec. Publ. 1, pp. 241–258. **1b01**

A valuable reference to geophysical and petrological studies of the largest, and only extant, Kilauea lava lake.

Helz R. T. Diapiric transfer of melt in Kilauea Iki lava lake: a rapid and efficient process of igneous differentiation. *Bull. Geol. Soc. Amer.* (In press) **1b02**

This paper contains a wealth of information on igneous processes of potential importance to the crystallization of olivine-rich basaltic intrusions.

Helz R. T. (1987) Character of olivine in lavas of the 1959 eruption of Kilauea Volcano, Hawaii, and its bearing on eruption dynamics. *U.S. Geol. Survey Prof. Paper 1350,* Chap. 25. **1b03**

Eaton J. P., Richter D. H. and Krivoy H. L. (1987) Cycling of magma between the summit reservoir and Kilauea Iki lava lake during the 1959 eruptions of Kilauea Volcano, Hawaii. *U.S. Geol. Survey Prof. Paper 1350,* Chap. 48. **1b04**

These papers provide insight into the unusual character of the 1959 eruption (see also *2c04*). They document the appearance of new magma during the early part of the eruption, and Helz presents evidence that this magma came directly from the mantle.

The 1959–60 eruption of Kilauea Volcano, Hawaii.

Murata K. J. and Richter D. H. (1966) Chemistry of the lavas. In *U.S. Geol. Survey Prof. Paper 537,* Chap. A. **1b05a**

Richter D. H. and Moore J. G. (1966) Petrology of the Kilauea Iki lava lake. In *U.S. Geol. Survey Prof. Paper 537,* Chap. B. **1b05b**

Murata K. J. (1966) An acid fumarolic gas from Kilauea Iki. In *U.S. Geol. Survey Prof. Paper 537,* Chap. C. **1b05c**

Richter D. H. and Murata K. J. (1966) Petrography of the lavas. In *U.S. Geol. Survey Prof. Paper 537,* Chap. D. **1b05d**

Richter D. H., Eaton J. P., Murata K. J., Ault W. U. and Krivoy H. L. (1966) Chronologic narrative. In *U.S. Geol. Survey Prof. Paper 537,* Chap. E. **1b05e**

This classic reference is the first detailed study of a Kilauea eruption using modern seismic and geodetic techniques, and documents the formation of the first modern lava lake in a pit crater.

Anderson L. A. (1987) The geoelectric character of the Kilauea Iki lava lake crust, Hawaii. *U.S. Geol. Survey Prof. Paper 1350,* Chap. 50. **1b06**

Chouet B. and Aki K. (1981) Seismic structure and seismicity of the cooling lava lake of Kilauea Iki, Hawaii. *J. Volcan. Geotherm. Res.* **9,** 41–56. **1b07**

These papers summarize the structure of the lava lake as studied by geophysical methods. The electrical structure agrees with that obtained by drilling and with petrologic definitions of "melt" and "crust." The seismic structure is biased toward lower amounts of "melt", presumably because the olivine-rich crystal mush transmits shear waves, an important observation relative to seismic prospecting for buried bodies of melt.

Zablocki C. J. and Tilling R. I. (1976) Field measurements of apparent Curie temperatures in a cooling basaltic lava lake, Kilauea Iki, Hawaii. *Geophys. Res. Lett.* **3,** 487–490. **1b08**

Shows agreement of curie temperatures measured in the field with laboratory measurements on drill core from other lava lakes.

Helz R. T. and Thornber C. T. Geothermometry of Kilauea Iki lava lake. *Bull. Volcanol.* (submitted) **1b09**

This paper shows a linear relationship between lava temperature and the CaO and MgO contents of natural glass. The geothermometer as constructed is applicable to most Kilauea lavas.

c. Alae. **1c**

Eruption of August 1963. Depth = 50 feet. Drilled until lake reached ambient temperature in 1967. Covered by new lava in February 1969. The data for Alae lava lake are basic to studies of Hawaiian olivine-poor tholeiite.

Solidification of Alae lava lake, Hawaii. **1c01**

Peck D. L. and Kinoshita W. T. (1976) The eruption of August 1963 and the formation of Alae lava lake. In *U.S. Geol. Survey Prof. Paper 935,* Chap. A. **1c01a**

Peck D. L. (1978) Cooling and vesiculation of Alae lava lake, Hawaii. In *U.S. Geol. Survey Prof. Paper 935,* Chap. B. **1c01b**

Chapter B gives (1) important measured and derived physical data for Hawaiian basalt, including density of solidified and molten basalt, vesicularity and conductivity, and (2) cooling history, with an evaluation of additional physical properties by fitting theoretical cooling models to the observed data.

Wright T. L. and Peck D. L. (1978) Crystallization and differentiation of the Alae magma, Alae lava lake, Hawaii. In *U.S. Geol. Survey Prof. Paper 935,* Chap. C. **1c01c**

Chapter C contains a direct determination of the liquid line of descent for tholeiitic basalt, the order and temperature of crystallization of different phases, and the process in which low-temperature basaltic liquids are segregated.

Skinner B. J. and Peck D. L. (1969) An immiscible sulfide melt from Hawaii. *Econ. Geol., Monograph No. 4,* 310–322. **1c02**

Identification of the temperature of formation, composition, and mineralogy of primary sulfide segregations. These may become altered and disseminated with further cooling or lava movement, thus obscuring their origin in older lava.

d. Makaopuhi. **1d**

Eruption of March 1965. Depth = 270 feet. Drilled until covered by new lava in February 1969.

Wright T. L. and Okamura R. T. (1977) Cooling and crystallization of tholeiitic basalt, 1965 Makaopuhi lava lake, Hawaii. *U.S. Geol. Survey Prof. Paper 1004,* 78 p. **1d01**

Reports all results of the four-year study of cooling, crystallization, and differentiation. Processes of convection-driven high temperature fractionation and differentiation by filter-pressing at low temperatures also apply to olivine-poor magma bodies stored in the Kilauea rift zones.

Shaw H. R., Wright T. L., Peck D. L. and Okamura R. T. (1968) The viscosity of basaltic magma: an analysis of field measurements in Makaopuhi lava lake, Hawaii. *Amer. J. Sci.* **266,** 225–264. **1d02**

First direct measurement of viscosity in a cooling lava pond. Demonstrated the non-newtonian behavior of the melt.

Sato M. and Wright T. L. (1966) Oxygen fugacities directly measured in magmatic gases. *Science* **153,** 113–1105. **1d03**

First direct measurement of oxygen fugacity-temperature profiles through the upper crust of a cooling basalt flow. Updated in *1d01.*

2. REAL-TIME STUDY OF MAGMA TRANSPORT AND STORAGE

a. Seismic **2a**

Koyanagi R. Y., Unger J. D., Endo E. T. and Okamura A. T. (1976) Shallow earthquakes associated with inflation episodes at the summit of Kilauea Volcano, Hawaii. *Bull. Volcanol.* **39,** 621–631. **2a01**

First detailed seismic portrayal of summit reservoir, using distribution pattern of shallow earthquakes.

Thurber C. H. (1984) Seismic Detection of the Summit Magma Complex of Kilauea Volcano, Hawaii. *Science* **223,** 165–167. **2a02**

A different seismic definition of summit reservoir using inversion of local earthquake P-wave arrival times.

Ellsworth W. L. and Koyanagi R. Y. (1977) Three-dimensional crust and mantle structure of Kilauea Volcano, Hawaii. *J. Geophys. Res.* **82,** 5379–5394. **2a03**

Thurber C. H. (1987) Seismic structure and tectonics of Kilauea Volcano, Hawaii. *U.S. Geol. Survey Prof. Paper 1350,* Chap. 38. **2a04**

These papers apply 3-dimensional seismic methods to the subvolcanic structure. Paper *2a03* gives evidence for the absence of deep areas of magma storage.

Ryan M. P., Koyanagi R. Y. and Fiske R. S. (1981) Modeling the three-dimensional structure of macroscopic magma transport systems: application to Kilauea Volcano, Hawaii. *J. Geophys. Res.* **86,** 7111–7129. **2a05**

Presents seismic data in three dimensions to illustrate the plumbing system of Kilauea.

Ryan M. P. The Mechanics and Three-dimensional internal structure of active magmatic systems: Kilauea volcano, Hawaii. *J. Geophys. Res.* (In press) **2a06**

Continuation of the work above, adding finite-element modeling of summit and rift-zone responses to intrusion of magma.

Klein F. W., Koyanagi R. Y., Nakata J. S. and Tanigawa W. R. (1987) The seismicity of Kilauea's magma system, Hawaii. *U.S. Geol. Survey Prof. Paper 1350,* Chap. 43. **2a07**

A comprehensive study of the relationship between seismic activity and magmatic intrusion. Data are given on both lateral and vertical rates of intrusion.

Karpin T. L. and Thurber C. H. The relationship between earthquake swarms and magma transport. Kilauea Volcano. *Pure Appl. Geophys.* (In press) **2a08**

Additional definition of dike propagation using analysis of earthquake focal mechanisms.

Koyanagi R. Y., Chouet B. and Aki K. (1987) The origin of volcanic tremor in Hawaii. *U.S. Geol. Survey Prof. Paper 1350,* Chap. 45. **2a09**

A comprehensive summary of the occurrence of volcanic tremor and its relationship to magma transport. Assessment of the relative importance of aseismic magma transport and the identification of common source regions for different active Hawaiian volcanoes.

Koyanagi R. Y., Tanigawa W. R. and Nakata J. S. Seismicity associated with the eruption of Kilauea from January 1983 to July 1984. In The Pu'u O'o eruption of Kilauea volcano, Hawaii: the first 1½ years, (ed. E. W. Wolfe), *U.S. Geol. Survey Prof. Paper 1463,* (In press) **2a10**

A fundamental study of seismicity associated with a long-lived eruption of Kilauea. *2a07, 2a09,* and this paper form a basic reference for study of volcanic seismicity.

b. Ground deformation **2b**

Eaton J. P. and Murata K. J. (1960) How volcanoes grow. *Science* **132,** 925–938. **2b01**

Eaton J. P. (1962) Crustal structure and volcanism in Hawaii. *Amer. Geophys. Union Monograph 6,* 13–29. **2b02**

Classic papers defining the Kilauea summit reservoir from the modeling of ground deformation during inflation-deflation cycles.

Fiske R. S. and Kinoshita W. T. (1969) Inflation of Kilauea Volcano prior to its 1967–1968 eruption. *Science* **165,** 341–349. **2b03**

Kinoshita W. T., Koyanagi R. Y., Wright T. L. and Fiske R. S. (1969) Kilauea Volcano: the 1967–1968 summit eruption. *Science* **166,** 459–468. **2b04**

These companion papers illustrate the complex structure of the Kilauea summit reservoir during a long inflation cycle and the response of the volcano to a major summit eruption.

Decker R. W., Koyanagi R. Y., Dvorak J. J., Lockwood J. P., Okamura A. T., Yamashita K. M. and Tanigawa W. R. (1983) Seismicity and surface deformation of Mauna Loa volcano, Hawaii. *EOS* **64,** 545–547. **2b05**

Lockwood J. P., Banks N. G., English T. T., Greenland L. P., Jackson D. B., Johnson D. J., Koyanagi R. Y., McGee K. A., Okamura A. T. and Rhodes J. M. (1985) The 1984 eruption of Mauna Loa volcano, Hawaii. *EOS* **66,** 169–171. **2b06**

Lockwood J. P., Dvorak J. J., English T. T., Koyanagi R. Y., Okamura A. T., Summers M. L. and Tanigawa W. R. (1987) Mauna Loa volcano, Hawaii. A decade of intrusive and extrusive activity. *U.S. Geol. Survey Prof. Paper 1350,* Chap. 19. **2b07**

These papers establish the similarity of Mauna Loa's magma reservoir and feeding system to that of Kilauea, in the first fully documented account of a Mauna Loa eruption cycle.

Jackson D. B., Swanson D. A., Koyanagi R. Y. and Wright T. L. (1975) The August and October 1968 east rift eruptions of Kilauea Volcano, Hawaii. *U.S. Geol. Survey Prof. Paper 890,* 33 p. **2b08**

Swanson D. A., Jackson D. B., Koyanagi R. Y. and Wright T. L. (1976) The February 1969 east rift eruption of Kilauea Volcano, Hawaii. *U.S. Geol. Survey Prof. Paper 891,* 30 p. **2b09**

These two papers are the most complete summaries of typical short rift eruptions that combine extrusive and intrusive processes, the latter revealed largely by measurement of ground deformation.

Duffield W. A., Christiansen R. L., Koyanagi R. Y. and Peterson D. W. (1982) Storage, migration, and eruption of magma at Kilauea Volcano, Hawaii, 1971–1972. *J. Volcanol. Geotherm. Res.* **13,** 273–307. **2b10**

The first documentation of intrusion above the Kilauea summit reservoir. This activity resulted in the eruption at a later time (1974—see *2c07*) of slightly fractionated lava at Kilauea summit, the first documented occurrence in historic time.

Dieterich J. H. and Decker R. W. (1975) Finite element modeling of surface deformation associated with volcanism. *J. Geophys. Res.* **80,** 4094–4102. **2b11**

First modeling of surface deformation using a dike rather than a point source geometry.

Ryan M. P., Blevins J. Y. K., Okamura A. T. and Koyanagi R. Y. (1983) Magma reservoir subsidence mechanics, theoretical summary and application to Kilauea Volcano, Hawaii. *J. Geophys. Res.* **88,** 4147–4181. **2b12**

Presents a novel approach to modeling the ground deformation over the reservoir using emplacement of sill-like bodies instead of a point source (*2b01, 02*) or vertical dikes (*2b11*).

Dvorak J., Okamura A. and Dieterich J. H. (1983) Analysis of surface deformation data, Kilauea Volcano, Hawaii October 1966 to September 1970. *J. Geophys. Res.* **88,** 9295–9304. **2b13**

Models deformation data for a variety of source geometries, concluding that a point-source is adequate. Documents inelastic deformation at Kilauea summit (See also *2e03*).

Swanson D. A., Duffield W. A. and Fiske R. S. (1976) Displacement of the south flank of Kilauea Volcano: the result of forceful intrusion of magma into the rift zones. *U.S. Geol. Survey Prof. Paper 963,* 39 p. **2b14**

Shows geometry of deformation related to diking, as determined by geodetic surveys throughout the century. Documents that deformation follows and is probably caused by intrusion.

Lipman P. W., Lockwood J. P., Okamura R. T., Swanson D. A. and Yamashita K. M. (1985) Ground deformation associated with the 1975 magnitude 7.2 earthquake and resulting changes in activity of Kilauea Volcano, Hawaii. *U.S. Geol. Survey Prof. Paper 1276,* 45 p. **2b15**

Details nature of deformation event resulting from diking in east rift zone and documents how this deformation increased the storage capacity of the rift zone for several years.

Dvorak J. J., Okamura A. T., English T. T., Koyanagi R. Y., Nakata J. S., Sako M. K., Tanigawa W. T. and Yamashita K. M. (1986) Mechanical response of the south flank of Kilauea Volcano, Hawaii, to intrusive events along the rift systems: *Tectonophysics* **124,** 193–209. **2b16**

Further investigation of the relationship between intrusive activity and seismicity and ground movement on Kilauea's south flank.

Okamura A. T., Dvorak J. J., Koyanagi R. Y. and Tanigawa W. R. Surface deformation during dike propagation: the 1983 east rift eruption of Kilauea Volcano, Hawaii. In The Pu'u O'o eruption of Kilauea Volcano, Hawaii: the first 1½ years, (ed. E. W. Wolfe), *U.S. Geol. Survey Prof. Paper 1463,*(In press) **2b17**

The first quantitative modeling of dike emplacement at Kilauea using data from continuously recording electronic tiltmeters.

Dvorak J. J. and Okamura A. T. (1984) Variations in tilt rate and harmonic tremor amplitude during the January–August 1983 east rift eruptions of Kilauea Volcano, Hawaii. *J. Volcanol. Geotherm. Res.* **25,** 249–258. **2b18**

A novel approach to estimating magma-transport rates from ground deformation and seismic measurements. Comparison with observed extrusion rates permits an estimate of the ratio of material erupted to that left underground as intrusions.

c. Petrology **2c**

Wright T. L. (1971) Chemistry of Kilauea and Mauna Loa in space and time. *U.S. Geol. Survey Prof. Paper 735,* 40 p. **2c01**

Summarizes high-quality major-oxide analyses for all olivine-controlled historical eruptions of Kilauea through 1968, all historical eruptions of Mauna Loa through 1950, and selected prehistorical eruptions from both volcanoes. Interpretations made in this paper are largely superseded by later work (*e.g., 2c02, 09, 10*).

Tilling R. I., Wright T. L. and Millard H. T. Jr. (1987) Trace-element chemistry of Kilauea and Mauna Loa lava in space and time: A reconnaisance. *U.S. Geol. Survey Prof. Paper 1350,* Chap. 24. **2c02**

A sequel to *2c01*, presenting trace-element data for the same samples, and showing that both Kilauea and Mauna Loa show long-term chemical trends.

Rhodes J. M. (1983) Homogeneity of lava flows: Chemical data for historic Mauna Loan eruptions. *J. Geophys. Res.* **88,** A869–879. **2c03**

Demonstrates the homogeneity of different Mauna Loa eruptions after correcting for olivine-controlled chemical variation.

Wright T. L. (1973) Magma mixing as illustrated by the 1959 eruption, Kilauea Volcano, Hawaii. *Bull. Geol. Soc. Amer.* **84,** 849–858. **2c04**

A well-documented example of an eruption fed from two sources.

Wright T. L. and Fiske R. S. (1971) Origin of the differentiated and hybrid lavas of Kilauea Volcano. *Hawaii. J. Petrol.* **12,** 1–65. **2c05**

Wright T. L., Swanson D. A. and Duffield W. A. (1975) Chemical composition of Kilauea east-rift lava, 1968–1971. *J. Petrol.* **16,** 110–133. **2c06**

Wright T. L. and Tilling R. I. (1980) Chemical variation in Kilauea eruptions, 1971–1974. In *The Jackson Volume,* (ed. A. Irving), *Amer. J. Sci.* **280-A,** pt. 2, 777–793. **2c07**

These three papers constitute a comprehensive treatment of crystal-liquid fractionation and high-temperature mixing of Kilauean magmas, derived by analysis of the complex record of eruption chemistry from 1952–1974.

Garcia M. O. and Wolfe E. W. Petrology of the lava from the Pu'u O'o eruption of Kilauea Volcano, Hawaii: episodes 1–20. In The Pu'u O'o eruption of Kilauea Volcano, Hawaii: the first 1½ years, (ed. E. W. Wolfe), *U.S. Geol. Survey Prof. Paper 1463,* (In press) **2c08**

Provides alternative interpretations to those in *2c05–07* to explain the chemical variation in Kilauea's most recent eruption.

Wright T. L. (1984) Origin of Hawaiian tholeiite: a metasomatic model. *J. Geophys. Res.* **89,** 3233–3252. **2c09**

Provides critical data obtained from real time study of recent Kilauea activity that constrain geochemical and geophysical models of magma generation.

Hofmann A. W., Feigenson M. D. and Raczec I. (1984) Case studies on the origin of basalt: III. Petrogenesis of the Mauna Ulu eruption, Kilauea, 1969–1971. *Contrib. Mineral. Petrol.* **88,** 24–35. **2c10**

Precise determinations of incompatible trace elements and Sr isotopes for part of the data set for which major-oxide chemistry is presented in *2c06*. Model for origin of Kilauea magma differs substantially from that presented in *2c09*. The importance of working with samples documented as to time and place of eruption is acknowledged in both papers.

d. Geochemistry of magmatic volatiles **2d**

Greenland L. P., Rose W. I. and Stokes J. B. (1985) An estimate of gas emissions and magmatic gas content from Kilauea Volcano. *Geochim. Cosmochim. Acta* **49,** 125–129. **2d01**

Gerlach T. M. and Graeber E. J. (1985) The volatile budget of Kilauea Volcano. *Nature* **313,** 273–277. **2d02**

Gerlach T. M. (1980) Evaluation of volcanic gas analyses from Kilauea Volcano. *J. Volcanol. Geotherm. Res.* **7,** 295–317. **2d03**

Greenland L. P. (1987) Composition of Hawaiian eruptive gases. *U.S. Geol. Survey Prof. Paper 1350,* Chap. 28. **2d04**

Together these papers address the chemical composition of volcanic gas in equilibrium with Kilauea magma 1) as it arrives from the mantle, 2) after degassing in shallow storage at pressures of 1–2 kbar, and 3) in solidified lava after degassing during eruption. Oxygen fugacities derived from gas collections are similar to those directly measured in the Kilauea lava lakes.

Greenland L. P. Estimated mantle content of volatiles from basaltic compositions: *Bull. Volcanol.* (In press) **2d05**

Uses data from real-time gas collections to estimate volatile contents of the magma source.

Greenland L. P., Okamura A. D. and Stokes J. B. (1987) Constraints on the mechanics of eruption of PU'u O'o, In The Pu'u O'o eruption of Kilauea Volcano, Hawaii: the first 1½ years, (ed. W. E. Wolfe). *U.S. Geol. Survey Prof. Paper.* **2d06**

This paper extends studies of gas chemistry to address subjects such as lava fountain dynamics, dimensions of eruptive conduits, size of immediate source areas, and magma supply rates.

Moore J. G. (1965) Petrology of deep-sea basalt near Hawaii. *Amer. J. Sci.* **263,** 40–52. **2d07**

First determination of water saturation values in naturally quenched basaltic glass.

Moore J. G. and Fabbi B. P. (1971) An estimate of the juvenile sulfur content of basalt. *Contrib. Mineral. Petrol.* **33,** 118–127. **2d08**

First determination of sulfur saturation values in naturally quenched basaltic glass, and an estimate of sulfur loss during eruption.

Harris D. M. and Anderson A. T. (1983) Concentrations, sources, and losses of H_2O, CO_2, and S in Kilauea basalt. *Geochim. Cosmochim. Acta* **47,** 1139–1150. **2d09**

Analyses of volatiles in glass inclusions in olivines from the 1959 eruption of Kilauea agree with saturation values determined from pillow glasses (*2d07, 08*) and the estimates of restored equilibrium compositions of Kilauea gases (*2d03*).

Gerlach T. M. Exsolution of H_2O, CO_2, and S during eruptive episodes at Kilauea Volcano, Hawaii: *J. Geophys. Res.* (In press) **2d10**

Quantitative modeling of the equilibrium pressures at which different volatile species are exsolved.

e. Other geophysical studies **2e**

Ryan M. P. (1987) The elasticity and contractancy of Hawaiian olivine tholeiite. *U.S. Geol. Survey Prof. Paper 1350,* Chap. 52. **2e01**

This study combines laboratory measurements and theory related to rock mechanics, and real-time deformation and seismic data, to derive a model showing that magma reservoirs bear a fixed relationship to the surface altitude and size of the summit caldera on Hawaiian shield volcanoes.,

Ryan M. (1987) Neutral bouyancy and the mechanical evolution of magmatic systems. In *Magmatic Processes: Physicochemical Principles,* (ed. B. O. Mysen), The Geochemical Society Spec. Publ. 1, pp. 259–288. **2e02**

A comprehensive treatment of the relationship between the location of magma storage reservoirs and the mechanical properties of the surrounding basaltic shield.

Johnson D. J. (1987) Elastic and inelastic magma storage at Kilauea Volcano, Hawaii. *U.S. Geol. Survey Prof. Paper 1350,* Chap. 47. **2e03**

Applies gravity data obtained during the period of episodic east rift eruption to refine interpretations of the summit reservoir to reconcile vertical and horizontal displacement data. The analysis complements those obtained by modeling deformation data with conventional source geometries.

Jackson D. B. and Kauahikaua J. (1987) Regional self—potential anomalies at Kilauea Volcano, Hawaii. *U.S. Geol. Survey Prof. Paper 1350,* Chap. 40. **2e04**

Jackson D. B. Geoelectric observations: September 1982 summit eruption and the first year of the 3 January 1983 middle east rift eruption. In The Pu'u O'o eruption of Kilauea Volcano, Hawaii. The first 1½ years, (ed. E. W. Wolfe), *U.S. Geol. Survey Prof. Paper 1463,* (In press) **2e05**

Jackson D. B., Kauahikaua J. and Zablocki C. J. (1985) Resistivity monitoring of an active volcano using the controlled-source electro-magnetic technique Kilauea, Hawaii. *J. Geophys. Res.* **90,** 12545–12555. **2e06**

Kauahikaua J., Jackson D. B. and Zablocki C. J. (1986) The subsurface resistivity structure of Kilauea Volcano, Hawaii. *J. Geophys. Res.* **91,** 8267–8284. **2e07**

Zablocki C. J. (1976) Mapping thermal anomalies on an active volcano by the self-potential method, Kilauea, Hawaii. In *2nd U.N. Symposium on the Development and Use of Geothermal Resources, San Francisco, California, May 1975, Proc. 2,* 1299–1309. **2e08**

Zablocki C. J. (1978) Applications of the VLF induction method for studying some volcanic processes of Kilauea Volcano, Hawaii. *J. Volcanol. Geotherm. Res.* **3,** 155–195. **2e09**

These papers document the electrical structure of Kilauea and discuss dike impoundment of high-standing water tables and aseismic magmatic intrusion without accompanying ground deformation.

Hardee H. C. (1987) Heat and mass transport in the east rift magma conduit of Kilauea Volcano, Hawaii. *U.S. Geol. Survey Prof. Paper 1350,* Chap. 54. **2e10**

Derives the physical state of basaltic magma from modeling flow in active volcanic conduits using real-time monitoring data.

Ryan M. and Sammis C. G. (1981) The glass transition in basalt. *J. Geophys. Res.* **86,** 9519–9535. **2e11**

A generalized rheologic model for the subsolidus portions of basaltic lava lakes, and a general model for the origin and development of columnar jointing in basalt, based on the combination of in-situ field measurements and laboratory measurements at high temperature.

f. Estimates of magma supply rate **2f**

Swanson D. A. (1972) Magma supply rate at Kilaueas Volcano, 1952–1971. *Science* **175,** 169–170. **2f01**

First documentation of constant magma supply rate (about 9×10^6 m^3/mo) during long-lived eruptions of Kilauea.

Dzurisin D., Koyanagi R. Y. and English T. T. (1984) Magma supply and storage at Kilauea Volcano, Hawaii, 1956–1983. *J. Volcanol. Geotherm. Res.* **21,** 177–206. **2f02**

Attempts to calculate minimum supply rates on the basis of tilt changes, and to partition the magma into that erupted and that stored in the two rift zones.

3. REAL-TIME STUDY OF VOLCANIC ERUPTIONS: APPLICATION TO OLDER VOLCANIC ROCKS

a. Construction of volcanic edifices and lava fields **3a**

Swanson D. A., Duffield W. A., Jackson D. B. and Peterson D. W. (1979) Chronological narrative of the 1969–1971 Mauna Ulu eruption of Kilauea Volcano, Hawaii. *U.S. Geol. Survey Prof. Paper 1056,* 55 p. **3a01**

A detailed account of the growth of a satellitic lava shield formed of dominantly pahoehoe lava.

Tilling R. I., Christiansen R. L., Duffield W. A., Endo E. T., Holcomb R. T., Koyanagi R. Y., Peterson D. W. and Unger J. D. (1987) The 1972–1974 Mauna Ulu eruption, Kilauea Volcano, Hawaii: an example of "quasi-steady state" magma transfer. *U.S. Geol. Survey Prof. Paper 1350,* Chap. 16. **3a02**

Completes the study of the growth of the Mauna Ulu shield.

Wolfe E. W., Neal C. A., Banks N. G. and Duggan T. J. Geologic observations and chronology of eruptive events during the first 20 episodes of the Pu'u O'o eruption, January 3, 1983, through June 8, 1984. In The Pu'u O'o eruption of Kilauea Volcano, Hawaii: the first 1½ years, (editor E. W. Wolfe), *U.S. Geol. Survey Prof. Paper.* (In press) **3a03**

A detailed narrative account of the growth of the Pu'u O'o cone and associated a'a lava flows.

Wolfe E. W., Garcia M. O., Jackson D. B., Koyanagi R. Y., Neal C. A. and Okamura A. T. (1987) The Pu'u O'o eruption of Kilauea Volcano, episodes 1–20, January 1983 to June 1984. *U.S. Geol. Survey Prof. Paper 1350,* Chap. 17. **3a04**

A synthesis of geological observations made during the first 1½ years of the current Kilauea east rift eruption.

Moore J. G. (1987) Subsidence of the Hawaiian Ridge. *U.S. Geol. Survey Prof. Paper 1350,* Chap. 2. **3a05**

Emphasizes the high rates of subsidence of Hawaiian volcanoes and the implications of this for volumes and growth rates of Hawaiian shields.

Moore J. G., Fornari D. J. and Clague D. A. (1985) Basalts from the 1877 submarine eruption of Mauna Loa, Hawaii: New data on the variation of palagonitization rate with temperature. *U.S. Geol. Survey Bull. 1663,* 11 p. **3a06**

Shows that vesicularity of flows can provide information on depth of cooling of ancient lava.

b. Lava flow dynamics **3b**

Neal C. A., Duggan J. J., Wolfe E. W. and Brandt E. L. Lava samples, temperatures, and compositions, Pu'u O'o eruption of Kilauea Volcano, Hawaii, episodes 1–20, January 3, 1983–June 8, 1984. In The Pu'u O'o eruption of Kilauea Volcano, Hawaii: the first 1½ years, (ed. E. W. Wolfe), *U.S. Geol. Survey Prof. Paper 1463,* (In press) **3b01**

An excellent summary of field methods used to obtain quantiative data on erupted lava.

Lipman P. W. and Banks N. G. (1987) Aa flow dynamics, 1984 eruption of Mauna Loa Volcano, Hawaii. *U.S. Geol. Survey Prof. Paper 1350,* Chap. 57. **3b02**

Lipman P. W., Banks N. G. and Rhodes J. M. (1985) Degassing-induced crystallization of basaltic magmas and effects of lava rheology. *Nature* **317,** 604–607. **3b03**

These two papers analyze behavior of lava flows during a typical Mauna Loa eruption. Data on "aging" of the feeding channel, undercooling, and volatile loss.

Peterson D. W. and Tilling R. I. (1980) Transition of basaltic lava from pahoehoe to aa, Kilauea Volcano, Hawaii: field observations and key factors. *J. Volcanol. Geotherm. Res.* **7,** 271–293. **3b04**

A comprehensive treatment of the pahoehoe to a'a transition in terms of the combined effects of viscosity and rate of shear strain. Chemical composition, temperature, and volatile content, considered independently, are found to be unimportant in determining whether lava is a'a or pahoehoe.

Swanson D. A. (1973) Pahoehoe flows from the 1969–1971 Mauna Ulu eruption, Kilauea Volcano, Hawaii. *Bull. Geol. Soc. Amer.* **84,** 615–626. **3b05**

Describes different kinds of pahoehoe flows and their preservation in sections of the lava pile exposed by collapse. First explanation of the origin of dense pahoehoe far from the vent as being supplied in lava degassed during flow in tubes.

Swanson D. A., Duffield W. A., Jackson D. B. and Peterson D. W. (1972) The complex filling of Alae Crater, Kilauea Volcano, Hawaii. *Bull. Volcanol.* **36,** pt. 1, 105–126. **3b06**

Discusses the difficulties in deriving eruptive history from stratigraphic sections of older volcanic rocks.

Swanson D. A. and Fabbi B. P. (1973) Loss of volatiles during fountaining and flowage of basaltic lava at Kilauea Volcano, Hawaii. *J. Res. U.S. Geol. Survey* **1,** 649–658. **3b07**

Points out the use of analyses of volatiles in cooled lava to indicate distance from and direction to vent.

Moore J. G., Phillips R. L., Grigg R. W., Peterson D. W. and Swanson D. A. (1973) Flow of lava into the sea, 1969–1971, Kilauea Volcano, Hawaii. *Bull. Geol. Soc. Amer.* **84,** 537–546. **3b08**

Moore J. G. (1975) Mechanism of formation of pillow lava. *Amer. Sci.* **63,** 269–277. **3b09**

These two papers given an account of the formation of basaltic pillows from direct observation of lava flowing into the ocean, the first such observations ever made.

Peck D. L. and Minakami T. (1968) The formation of columnar joints in the upper part of Kilauean lava lakes, Hawaii. *Bull. Geol. Soc. Amer.* **79,** 1151–1166. **3b10**

The first real-time study of joint formation, including determination of maximum temperature at which joints propagate (1,000°C), the direction of propagation, and the effects of rainfall.

Duffield W. A. (1972) A naturally occurring model of global plate tectonics. *J. Geophys. Res.* **77,** 1543–2555. **3b11**

A fascinating paper which treats an active lava lake surface as a scaled analogue of mantle-crust processes occurring at much higher viscosities and much slower rates.

4. SELECTED BIBLIOGRAPHY TO ENABLE COMPARISON OF MECHANICAL BEHAVIOR OF MOUNT ST. HELENS WITH THAT OF KILAUEA **4a**

U.S. Geol. Survey (1987) Hawaiian Volcanism, (eds. R. W. Decker, T. L. Wright, and P. H. Stauffer), *U.S. Geol. Survey Prof. Paper 1350,* Chap. 1–63. **4a01**

A modern reference to studies of active Hawaiian volcanoes. Individual chapters are annotated throughout this reference list.

U. S. Geol. Survey (1981) The 1980 eruptions of Mount St. Helens, Washington, (eds. P. W. Lipman and D. R. Mullineaux), *U.S. Geol. Survey Prof. Paper 1250,* 844 p. **4a02**

A comprehensive summary of the May, 1980 catastrophic eruption of Mount St. Helens. Articles include eyewitness accounts, geophysical monitoring before, during, and after, detailed accounts of the volcanic deposits formed, and environmental effects of the 1980 eruption.

Carey S. and Sigurdsson H. (1985) The May 18, 1980, eruption of Mount St. Helens. 2. Modeling of dynamics of the Plinian phase. *J. Geophys. Res.* **90,** 2948–2958. **4a03**

Challenging model relating eruption dynamics to decompression and vesiculation at a depth of about 4.5 km.

Rutherford MJ., Sigurdsson H., Carey S. and Davis A. (1985) The May 18, 1980, eruption of Mount St. Helens. 1. Melt composition and experimental phase equilibria. *J. Geophys. Res.* **90,** 2929–2947. **4a04**

Provides experimental evidence consistent with seismic evidence (*4a05*) for a magma reservoir at 7–8 km depth.

Scandone Roberto and Malone S. D. (1985) Magma supply, magma discharge and readjustment of the feeding system of Mount St. Helens during 1980. *J. Volcanol. Geotherm. Res.* **23,** 239–262. **4a05**

Provocative discussion of effects of varying supply and discharge rates on nature of eruptions. Presents seismic evidence for existence of magma reservoir whose top is about 7–8 km deep.

Swanson D. A., Dzurisin D., Holcomb R. T., Iwatsubo E. Y., Chadwick W. W. Jr., Casadevall T. J., Evert J. W. and Heliker C. C. Growth of the lava dome at Mount St. Helens, Washington (USA), 1981–83. In The emplacement of silicic domes and lava flows, (ed. J. H. Fink). *Geol. Soc. Amer. Spec. Paper 212.* (In press) **4a06**

Provides volume data documenting relatively constant rate of magma supply during eruption.

VOIGHT B., JANDA R. J., GLICKEN H. and DOUGLASS P. M. (1983) Nature and mechanics of the Mount St. Helens rockslide-avalanche of 18 May 1980. *Geotechnique* **33,** 243–273. **4a07**

Includes good discussion of development of bulge resulting from intrusion of magma into the cone.

EICHELBERGER J. C. and HAYES D. B. (1982) Magmatic model for the Mount St. Helens blast of May 18, 1980. *J. Geophys. Res.* **87,** 7727–7738. **4a08**

KIEFFER S. W. (1981a) Blast dynamics at Mount St. Helens on 18 May, 1980. *Nature* **291,** 568–570. **4a09**

KIEFFER S. W. (1981b) Fluid dynamics of the May 18 blast at Mount St. Helens. *U.S. Geol. Survey Prof. Paper 1250,* 379–400. **4a10**

These three papers discuss the relative roles of magmatic volatiles and vaporized groundwater in driving the lethal blast. Eichelberger and Hayes favor magmatic gas as the driving agent, whereas Kieffer stresses the role of flashing water in the hydrothermal system. These papers demonstrate how even with close observaton, transient events can have controversial origins.

5. GENERAL REFERENCES ON THE MONITORING OF ACTIVE VOLCANOES

BRANTLEY S. and TOPINKA L. (eds.) (1984) Volcanic studies at the U.S. Geological Survey's David A. Johnston Cascades Volcano Observatory, Vancouver, Washington. *Earthquake Information Bull. 16,* 44–122. **5a**

HELIKER C. C., GRIGGS J. D., TAKAHASHI T. J. and WRIGHT T. L. (1986) Volcano monitoring at the U.S. Geological Survey's Hawaiian Volcano Observatory. *Earthquakes and Volcanoes* **1,** 1–70. **5b**

Comprehensive summaries of visual and instrumental monitoring of two currently active volcanic areas.

6. OTHER REFERENCES

SIEBERT L. (1984) Large volcanic debris avalanches: Characteristics of source areas, deposits, and associated eruption. *J. Volcanol. Geotherm. Res.* **22,** 163–197. **6a01**