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PHYSICAL PROPERTIES OF ERUPTING HAWAIIAN MAGMAS

Abstract: Field measurements and estimates of temperature, viscosity, gas content, and specific gravity of erupting Hawaiian lavas are assembled largely in tabular form. Hawaiian tholeiitic basalt magmas as they reach the surface have temperatures of 1050°–1200° C, viscosities of 2–4 × 10^3 poises, and gas contents ranging from 0.5 to 2 weight per cent. Below the level of vesiculation they have a specific gravity of about 2.73. Flows continue in motion to apparent temperatures less than 800°.

Introduction

Measurements and estimates of the physical properties of erupting Hawaiian lavas are scattered through much of the literature on Hawaiian volcanoes. It seems worth while to assemble them in one short paper for the use, not only of persons working on active volcanoes but also of those studying the occurrences and behavior of similar magmas of ancient age. For example, the behavior of solid grains in a magma undergoing crystallization depends largely on the properties of the enclosing liquid. Persons working on crystallization differentiation of igneous masses commonly have used values for the physical properties of the magma based partly or largely on theoretical calculations. But since considerable possibility of error in such calculated values arises from possible errors in basic assumptions, it is very desirable to compare them with field measurements and estimates on actual magmas, even though the estimates may be far from precise, to confirm that they are at least approximately of the right magnitude.

In the following pages the methods of obtaining the values are summarized only very briefly. More detailed information can be obtained in the publications cited. Information exists only for tholeiitic basalt (including tholeiitic olivine basalt and oceanite) magmas, because all recent Hawaiian eruptions have been of that character. Field evidences suggest that erupting alkalic basalt magmas are on the average, richer in gas than the tholeiitic magmas, but the last eruptions of alkalic magma in Hawaii were in 1801 and about 1750, and not even eye-witness accounts of these eruptions have been preserved.

Temperature

Temperature measurements have been made in the lava lake in Halemaumau Crater at Kilauea volcano, on lava fountains at vents on both Kilauea and Mauna Loa, and on lava flows of both volcanoes at various distances from the vents. In July 1911, E. S. Shepherd and F. A. Perret obtained a brief measurement at a depth of about 2 feet near the center of the Halemaumau lava lake (Shepherd, 1914). The movement was made in the vicinity of the Old Faithful lava fountain, which probably marked the site of the main conduit through which magma was rising from depth. The corrected reading, obtained with a platinum-rhodium thermocouple after two resistance thermometers had failed, was 1000° C (± about 25°). The temperature was roughly confirmed by readings on the surface of the lake by optical pyrometer (Shepherd, 1914, p. 51). In 1909 R. A. Daly (1911, p. 73) also obtained an approximate average temperature of 1000° for the uncrusted surface of the lava lake.

Because of difficulties with resistance thermometers and thermocouple, T. A. Jaggar, in 1917, used instead groups of Seger cones enclosed in a steel pipe. The pipe was then thrust into the liquid lava of the lake through cracks between segments of crust. The temperature was found to drop from about 1000° just below the surface of the lake to 860°, at a depth of 1 m, and then rise again at a fairly regular rate to 1170° at the lake bottom, at a depth of 13 m (Jaggar, 1917). The high surface temperature was believed to result from heating by oxidation of the volcanic gases on contact with the atmosphere. The great heat produced by combustion of the gases is demonstrated by temperatures up to at least 1350° C, measured in flaming grottoes just above the edge of the lake. The bottom lava of the lake may also have been somewhat hotter than the magma rising from depth, owing to oxidation of gas by air carried down in the abundant foundering crusts. However, it was not very different from that measured in recent years in fountains at

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lava lake was giving off heat at a rate probably in excess of 230,000,000 calories per second. The heat liberated during the 1952 eruption was calculated to have been approximately 4.3×10^{16} calories, or in work equivalent, 1.8×10^{24} ergs. Seismic and explosive activity was minor and contributed little to the total energy release (Macdonald, 1959, p. 30). As would be expected from the general aspects of the eruption, in terms of energy release the 1952 eruption falls within Yokoyama's (1957, p. 96) general group of eruptions of moderate size.

TABLE 1. TEMPERATURES OF HAWAIIAN LAVAS

Date	Volcano	Approx. average temperature (°C) (uncorrected for emissivity)	Remarks	Source of data
June 7, 1950	Mauna Loa	1070	Dome fountain at vent, flank eruption	Macdonald, 1954, p. 174
June 28–30, 1952	Kilauea	1095–1130	Fountains at vents in Halemaumau	Macdonald, 1955, p. 85
July 1–Aug. 23, 1952	Kilauea	1075–1085	Fountains at vents in Halemaumau	Macdonald, 1955, p. 85
Feb. 28, 1955	Kilauea	1035–1075	Fountains at vents, flank eruption	Macdonald, 1959, p. 55
Mar. 15, 1955	Kilauea	1080–1100	Fountains at vents, flank eruption	Macdonald and Eaton, in press
Nov. 14–Dec. 5, 1959	Kilauea	1120–1190	Fountains at vents in Kilauea Iki	Eaton and Murata, 1960, p. 934
Jan. 13–27, 1960	Kilauea	1050–1060	Fountains at vents, flank eruption	Eaton and Murata, 1960, p. 934
Jan. 28–Feb. 4, 1960	Kilauea	1130	Fountains at vents, flank eruption	Eaton and Murata, 1960, p. 934
June 7, 1950	Mauna Loa	1030–1070	Lava river near vent	Macdonald, 1954, p. 174
June 2, 1950	Mauna Loa	860–1000	Lava river 20 km from vents	Macdonald, 1954, p. 174
Sept. 20, 1952	Kilauea	1030	Lava river at vent	Macdonald, 1955, p. 85
Feb. 28, 1955	Kilauea	900–1030	Lava flow fronts at varying distances from vents	Macdonald, and Eaton, in press
Feb. 28, 1955	Kilauea	1065	Lava flow front 1 km from vent; high temperature probably due to combustion of hydrocarbon gases generated from plants buried by the flow	Macdonald, and Eaton, in press
Feb. 5, 1949	Mauna Loa	745	3 feet below surface in a crack in a barely moving aa lava flow	Macdonald and Orr, 1950, p. 24
July 25, 1960	Kilauea	1064	Liquid magma just beneath crust at depth of 19.5 feet on lava pool in Kilauea Iki crater, lava erupted in December 1959	Rawson, 1960
Oct. 4, 1961	Kilauea	1065	Same, at depth of 35 feet; measured with thermocouple	Ault and others, 1962
Oct. 4, 1961	Kilauea	1100	Lava at depth of 39 feet, 4 feet below crust in Kilauea Iki	Ault and others, 1962

Viscosity

Attempts to measure the viscosity of Hawaiian lava by the rate at which fluid lava entered a steel cylinder with a small circular orifice immersed in the lava lake were made by T. A. Jaggar, but the results were regarded as indicating only relative, not absolute, viscosity. More than twice as much entered the cylinder during the same length of time at about 1200°C as entered at 1100°, thus demonstrating the effect of temperature on viscosity (Jaggar, 1921, p. 28–29).

All other figures for viscosity of Hawaiian lavas are derived by calculation from observed rates of flow on known slopes and with approximately known channel dimensions. Early calculations (Becker, 1897, p. 29; Palmer, 1927) were based on assumption of turbulent flow. It has been shown, however, that the flows on which the calculations were based amount of gas given off in the eruption cloud in relation to the volume of lava extruded, plus the vesicularity of the lava and the amount of water retained in the rock.

The average combined water content (H_2O+) in 51 recent analyses of tholeiitic basalts of Kilauea and Mauna Loa of historic age, by several different analysts, is 0.14 per cent by weight. Older analyses give somewhat higher values, but presumably the more recent analyses, by improved techniques, are more nearly correct. The average water content of four basaltic glasses, ranging in date from 1868 to 1959, is 0.12. Older glasses have higher water contents, presumably because of increasing hydration with the passage of time. Apparent freshness of the glass is not sufficient evidence that it has not absorbed additional water.

The amount of water retained in Hawaiian tholeiitic basalts after solidification thus appears to be between 0.1 and 0.2 per cent by weight. Other gases are reported in analyses only in exceedingly small amount, as would be expected from the fact that analyses of eruption gases show water to be by far the most abundant, making up 65 per cent or more of most collections. The collections of gas made by Jaggar in 1919 at Halemaumau lava lake are probably the best yet made in Hawaii. The average composition of these collections, in volume per cent at 1200° C, is as follows (Shepherd, 1921):

H_2O	70.75	A	0.18
CO_2	14.07	SO_2	6.40
CO	0.40	SO_3	1.92
H	0.33	S	0.10
N	5.45	Cl	0.05

Assuming that the gases have the average composition given above and that they behaved as perfect gases (which they probably did only approximately), the amount of gas liberated in the eruption cloud relative to that of lava poured out has been calculated for two eruptions (Macdonald, 1954, p. 136; 1955, p. 99) from the observed dimensions and rate of rise of the fume cloud. Details of the calculations are given in the original papers. This method yields a gas content during the early hours of the 1940 eruption of Mauna Loa of approximately 0.9 per cent by weight. Gas content was unusually copious during the early stages of the eruption, and at a later stage it was only approximately 0.5 per cent. In comparison, the gas liberated during the early hours of the 1952 eruption of Kilauea was approximately 2.1 per cent of the magma reaching the surface. During a later stage, when part of the lava pouring from the vent may have been recirculated by means of convection in the lava lake and when a large proportion of the lava was being returned to depth rather than accumulating in the crater, the proportion of gas was only about 0.15 per cent.

The above figures represent only the portion of the gas carried off in the eruption cloud. In order to obtain the total gas content of the magma as it approaches the surface, the gas retained in the lava on solidification must be added to that held in vesicles and liberated gradually at various distances from the vent during flowage and solidification and therefore not forming part of the main fume cloud. The average vesicularity of the 1940 lava of Mauna Loa is about 20 per cent. If a volume of gas equal to 20 per cent of the extruded lava is added to the volume of the fume cloud, the increase in volume of gas is only 0.0016 per cent and consequently negligible. Addition of the gas retained in the rock after solidification increases the gas content of the magma by about 0.1–0.2 weight per cent.

The amount of gas in the rising magma thus appears probably to be between 1 and 2.5 per cent during the early, gas-rich phase of the eruption and between 0.2 and 0.7 per cent during later phases. The former figure is close to the maximum of 2–3 per cent estimated by Daly (1944, p. 1377), and the latter is close to that of 0.5 per cent assumed as a likely proportion of volatiles in basaltic magma by Bowen (1928, p. 301). If the initial rush of gas during an eruption represents a gravitative concentration of gas from a considerable portion of the magma body, the average gas content of the magma at depth is probably much closer to 0.5 than to 2 per cent.

Specific Gravity

The approximate specific gravity of gabbroic magma at shallow depths, but below the level of vesiculation, can be derived by reducing the specific gravity of completely dense basaltic lava by amounts proportional to the percentage of gas dissolved in the magma and the thermal expansion involved in transforming the cold solid rock into a melt at 1050°–1200° C. Unfortunately, lavas are never completely dense, so determinations of the specific gravity of completely dense rock must be indirect. One method that approaches the desired result is the determination of powder densities, as was done by H. S. Washington (1923a; 1923b)

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