Geochemical Studies of Hawaiian Rocks Related to the Study of the Upper Mantle[1]

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CERTAIN ROCKS, notably ultramafics (peridotites) and eclogite, have properties which fulfill a good many of the criteria for the material of the upper mantle. Hawaiian lavas have served as model substances in these categories (specifically nodules from Hualalai, Hawaii, and eclogite from Salt Lake Crater, Oahu). In fact, Tilton and Reed (1963), on the basis of the factors contributing to radioactive heating, believe that Hawaiian eclogites are the best guides to the composition of the upper mantle. Other investigators (Engel and Engel, 1964) are of the opinion that tholeiitic basalt, which is the predominant lava type of the Hawaiian Island chain and is unique in its abundance at this site, is the chief or only magma generated in the earth's mantle under oceanic ridges and rises.

Geochemical investigations at the Hawaii Institute of Geophysics have contributed in several ways to the understanding of Hawaiian lavas as materials recently derived from the earth's mantle.

AGE-DATING

Dating work has been directed mainly to investigations of the suitability of whole rocks for age-dating using the Waianae volcanics of Oahu, and to solving the problems of dating relatively young rock. Some preliminary results are listed in Table 1, giving an idea of the age range expected in Hawaiian lavas and the capabilities of the potassium-argon method for dating young rocks.

The results are in good agreement with the whole rock determinations of McDougall (1964). The discrepancy between whole rock and included mineral ages is under investigation and must be resolved before proceeding with further studies.

Using the convective cell theory (Wilson, 1963) and the distance from the present active source on Hawaii to the Waianae volcano, a crustal movement of about 10 cm/year has been calculated by McDougall (1964). If the age of included mica from the Waianae lower member is used (8 million years), a rate of 4 cm/year is found, which is in better agreement with the 3 cm/year calculated as the upper limit for convective currents in the upper mantle (McDougall, 1964). The alternate interpretation of these data of course is that the age relations reflect progressive development of volcanism along gradually developing fractures in the crustal mantle, rather than crustal migration from a single primary source of volcanism.

ANALYSES FOR MAJOR AND MINOR ELEMENTS

A controversy has been under way for many years as to the possible source within the upper mantle of the two main types of oceanic lavas (tholeiitic and alkalic). One school maintains that they have two completely separate magma sources (Kuno, 1959), the other that both have been derived from a single parent magma by gravitational differentiation or by separation at a different stage of lava ascent (Engel and Engel, 1964). Seismic evidence in Hawaii indicates that the primary events which culminate in eruption at active volcanoes take place within the upper mantle at a depth of about 60 km, and that build-up and storage of lava occur in a magma chamber about 3 km immediately beneath the volcano (Eaton and Murata, 1960). Thus, the active sequences in Hawaii are relatively clear, and chemical and petrological studies on Hawaiian lavas have figured most prominently in the discussions of the theories of basalt derivation.

Chemical analyses of some hundreds of samples are available for Hawaiian lavas, with many

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TABLE 1
AGES OF CERTAIN HAWAIIAN LAVAS

SAMPLES	AGES (in millions of years)
Older rocks (whole rock investigation)	
Lowest member dated, Waianae, Oahu	5.4
Low member, Waianae, Oahu (trachyte)*	3.46**
Upper member, Waianae, Oahu	2.8
Dike rock, Koolau, Oahu	2.2
Younger rocks	
Puuwaawaa trachyte, Hawaii	0.4
Laupahoehoe, Mauna Kea, Hawaii (whole rock)	0.6
Laupahoehoe, Mauna Kea, Hawaii, mica (mineral in Laupahoehoe whole rock)	2.8

* Subject of many analyses on whole rock and minerals; indications are that minerals give older date.
** Average of six determinations.

of the recent results coming from the Hawaii Institute of Geophysics. Using these analyses, the tholeiitic-alkalic dichotomy is readily recognized from the alkali content, and Macdonald and Katsura (1962) have developed the alkali-silica diagram as a quantitative means of differentiating the two types. In this diagram, when per cent alkali (K_2O plus Na_2O) is plotted against per cent silica, the tholeiites occur as a well defined group in the lower part of the diagram and the alkalic lavas occur in the upper section. Standard A-F-M (Alkali-FeO-MgO) diagrams also show a distinctive grouping of rocks of the two types. The conclusions reached by Macdonald and Katsura (1962, 1964) from studies of the chemical composition of the analyzed samples are: (1) the primitive lavas that built the Hawaiian volcanoes are tholeiitic basalt; and (2), more tentatively, alkalic rocks can be derived from a tholeiitic parent.

A study of certain minor elements in tholeiitic and alkalic suites of Hawaiian lavas is being conducted (by G. A. Macdonald, N. J. Hubbard, and I. L. Barnes) with analyses being made by emission spectroscopy. To date 39 rocks from the Waianae range on Oahu have been analyzed for cobalt, nickel, vanadium, and zirconium. Results indicate that zirconium may be a distinctive trace element between suites, and, most interestingly, that when the nickel, vanadium, and zirconium contents are plotted in a tri-varient diagram, there is a grouping of results for rocks of the two types (tholeiitic and alkalic) similar to that noted in the A-F-M diagrams. Thus, it may develop that minor elements will prove to be distinctive markers for lava types.

VOLCANIC GASES

Volcanic gases supply a probe which enables a characterization of magma to be made at depth within the earth's crust, at least to the point of separation of gas from the parent lava. Once separated, such gases have been found to be a system in homogeneous equilibrium in the gaseous phase, and quite out of equilibrium with the associated rock system. Within error of measurement, analyzed samples of gas collected at high temperatures have been shown to conform to the composition expected thermodynamically for a homogeneous system. It is possible, then, to extrapolate the composition of gases collected during eruption to discover the oxidation condition of the underground magma, provided the temperature is known; or, conversely, for a given partial pressure of oxygen to find the temperature (Heald, Naughton, and Barnes, 1963). For a more complete analysis a computer may be used to calculate the compositional changes in a homogeneous volcanic gas system with expected changes in temperature, pressure, oxygen partial pressure, and the addition or subtraction of gaseous components which might be anticipated from surrounding rock (i.e., water vapor) (Heald and Naughton, 1962).

Using reasonable estimated values of temperature and pressure, it was concluded from data obtained from the best Kilauea samples that the primary magmatic gas would have the composition shown in Table 2.

Comparison of this calculated composition with the analyzed results from good collections made from liquid lava shows that an equilib-

TABLE 2
COMPOSITION OF PRIMARY MAGMATIC GAS

COMPONENT	VOLUME % at 1500° K
H_2O	62.5
H_2	1.90
CO_2	20.2
CO	1.66
H_2S	0.38
SO_2	13.2
S_2	0.42

rium temperature of 1200°–1500°K is indicated for the actual gas. The value of the partial pressure of oxygen was found to be approximately 10^{-8} atmospheres, in agreement with the value of 10^{-6} to 10^{-8} atmospheres estimated independently from the study of basaltic rocks (Fudali et al., 1961). Measurement of the oxygen partial pressure is significant in that this quantity has been shown to influence crucially the course of magmatic differentiation (Osborn, 1962), and may be the much-sought factor causing the derivation of different types of basalt from a tholeiitic parent magma. It will be noted that the magmatic environment found from these measurements is a reducing one.

MEASUREMENT OF RADIOELEMENTS IN LAVA

Hawaiian rocks have been used extensively in work on the very low uranium content of ultrabasic rocks and minerals, with the most recent researches on ultramafics and possible mantle materials being reported by Tilton and Reed (1963), and by Lovering and Morgan (1963). Also, a great deal of interest has centered on lead isotopic anomalies observed in researches on Pb–Pb, U–Pb, and Th–Pb dating methods (Russell and Farquhar, 1960). In explaining these anomalies, discussion has involved the uncertainties regarding the cogenicity of lead and uranium, and the processes which might lead to separation of these elements during derivation from the mantle (Marshall, 1958). Larson and Gottfried (1960) made some measurements on Hawaiian rock suites, and found uranium contents varying from 0.21 to 1.8 ppm. They find an increase in uranium content in late basaltic differentiates (alkali basalts). In general, as pointed out by Heier and Rogers (1963), work on the uranium geochemistry of basaltic rocks has not been extensive.

At the Hawaii Institute of Geophysics work on the radioactivity of Hawaiian lavas is only in the preliminary stages of feasibility studies. Research with alpha-sensitive nuclear emulsions shows the uniform distribution of alpha activity in the groundmass of tholeiites, and the higher concentration of activity in alkali suite members. A study of disequilibrium in the uranium decay chain is underway with a measurement of lead − 210 through its alpha-active polonium − 210 daughter. Easily measurable activities are found, and alpha spectrometry will be applied in the study. The radon content of volcanic gas is being measured also.

Knowledge of the uranium, thorium, and potassium in Hawaiian lavas will enable estimates to be made of their contribution to the radioactive heat production, and an evaluation of a parent tholeiite magma as a reasonable direct derivative from the mantle which is in agreement with measurements of oceanic heat-flow.

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