



SULFUR AND CARBON ABUNDANCES IN HAWAIIAN THOLEIITE LAVAS: 1972-1975 ERUPTIONS OF KILAUEA AND 1975 ERUPTION OF MAUNA LOA

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ABSTRACT

Analysis of sulfur and carbon abundances in 135 samples of fresh Hawaiian basalts erupted subaerially during 1972-1975 indicates that the different degassing behavior of sulfur and carbon volatiles and the ease of contamination by atmospheric carbon explain the different relationships observed between the sulfur and carbon contents in the samples and their density, flowage distance, and type of eruptive material. Sulfur abundances range from 37 to over 15,000 $\mu\text{g/g}$ (median value 153 $\mu\text{g/g}$); these values are lower by a factor of 4 to 6 than those for submarine tholeiitic basalts. Decreases in sulfur abundance away from the vent further document previous findings that sulfur is progressively lost by degassing during lava fountaining and flowage; the greatest loss occurs within about 2 km of the active vent. Sulfur abundance is best preserved in spatter (mean value 177 $\mu\text{g/g}$) and more depleted in pahoehoe (mean value 152 $\mu\text{g/g}$) and aa (mean value 96 $\mu\text{g/g}$) flows, a distribution controlled largely by increasing distance from the vent. A weaker inverse relation was found between sulfur content and relative sample density.

The carbon content measured in this study reflects the combined contribution from the magmatic carbon (CO_2 dissolved in the basaltic glass) and a nonmagmatic surficial component adsorbed after eruption and even after sample collection. Total carbon abundances range from 11 to 1,099 $\mu\text{g/g}$; the median value (69 $\mu\text{g/g}$) falls within the range of total carbon abundances reported for submarine basalts, but the value range is considerably greater. This distribution is opposite from that expected from a comparison between submarine (nondegassed) and subaerial (degassed) samples; posteruption contamination by atmospheric carbon is inferred to account for the wide dispersion in our data. In contrast to the sulfur data, the carbon data show no systematic relation of measured abundance to sample type, relative density, or distance from the vent. Such an observation is compatible with recent experimental and volcanic-gas studies that demonstrate extensive and rapid loss of CO_2 from the magma during storage in Kilauea's shallow summit reservoir and at the onset of an eruption. Alternatively, this absence of any recognizable degassing pattern for carbon volatiles during lava fountaining and flowage could mean simply that any variations in magmatic carbon content are obscured by contamination-caused variations in nonmagmatic carbon. Subsequent studies involving stepwise combustion in the analytical procedure are required to determine the carbon budget for subaerial basalts.

INTRODUCTION

The sudden escape of volatiles from magma provides the driving force for volcanic eruptions. Many investigations have been conducted, therefore, of the distribution of volatiles, principally water, sulfur, and carbon, in the gaseous and solid eruptive products of volcanoes. Because of their high eruption frequency and good accessibility, Kilauea and Mauna Loa Volcanoes on the Island of

Hawaii (fig. 31.1) have provided abundant materials for such studies.

The staff of the Hawaiian Volcano Observatory (HVO) systematically sampled, in time and space, the eruptive products of the long-lived 1972-74 Mauna Ulu activity (Tilling and others, chapter 16), as well as eruptive products of the following short-lived activity: the July, September, and December 1974 Kilauea eruptions (Lockwood and others, chapter 19); the July 1975 eruption at Mauna Loa summit (Lockwood and others, 1976); and the small eruption at Kilauea summit triggered by the magnitude -7.2 Kalapana earthquake on November 29, 1975 (Tilling and others, 1976).

We have determined the total sulfur and carbon abundances in 135 selected samples from these events (tables 31.1-31.2) in an attempt to describe their variation and to document any patterns of volatile behavior during subaerial eruption. To the best of our knowledge, the data set presented herein is the most comprehensive obtained to date for subaerially erupted tholeiitic basalts. Problems involving initial degassing, collection state of the samples, and ease of sample contamination by atmospheric carbon (Des Marais and Moore, 1984) combine to introduce a large degree of uncertainty in interpretation of the data. Nonetheless, in this paper we note several general systematic relations. The validity of these relations remains to be tested by additional studies specifically designed to eliminate or minimize posteruption carbon contamination by utilizing better controlled field sampling, sample storage and preparation, and modified analytical procedures.

ACKNOWLEDGMENTS

Our thanks go to the staff members of the Hawaiian Volcano Observatory for their diligent and timely efforts in making the systematic collection of eruptive products of Kilauea and Mauna Loa during 1972-1975. Some of the materials, had they not been sampled at, or shortly after, the time of their eruption, would have been unavailable for study because of burial by later flows. Robert L. Engram assisted with sample preparation and some of the analyses. Careful and incisive reviews of earlier versions of this paper by our USGS colleagues L. Paul Greenland (Hawaiian Volcano Observatory) and James G. Moore (Menlo Park) were most helpful and greatly appreciated.

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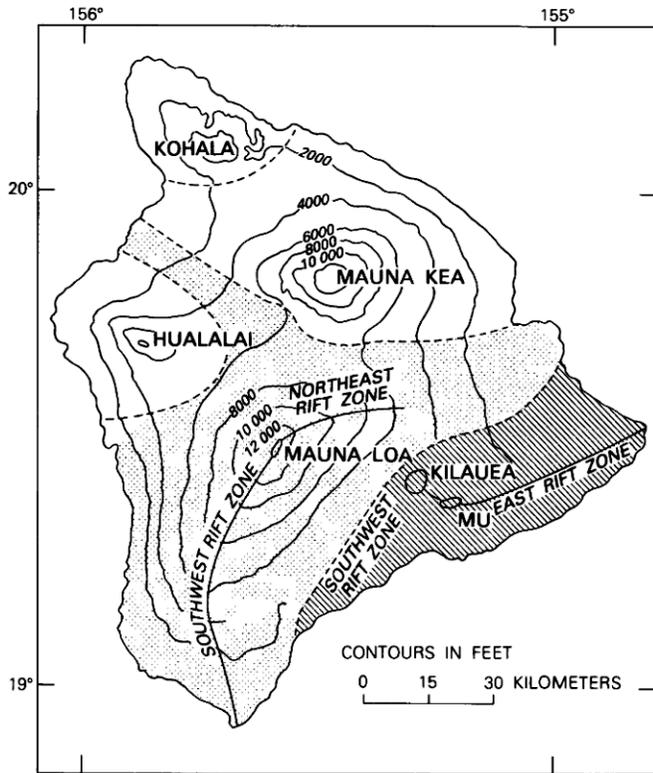


FIGURE 31.1.—Index map of Hawaii from Tilling and others (chapter 24) showing the five volcanoes that make up the island. Elevation contours are in feet. The site of the 1969–74 Mauna Ulu eruptions on Kilauea's upper east rift zone is also shown. (For more details on the Mauna Ulu eruptions, see Tilling and others, chapter 16).

ANALYTICAL METHODS

Sulfur and carbon abundances were determined in 127 samples from the 1972–75 eruptions of Kilauea Volcano and 8 samples from the 1975 Mauna Loa eruption. The analytical data, together with pertinent information on the samples (location, type, relative density, distance from the vent, and collection state), are given in tables 31.1–31.2.

Measurements of total sulfur and carbon were made using a LECO IR-32 sulfur analyzer and a LECO IR-12 carbon analyzer following the procedures of Gibson and Moore (1973). Powdered samples of approximately 300 mg were combusted in oxygen at 1,800 °C, and the resulting SO₂ and CO₂ measured with an infrared Luft-cell detector. Detection limits were 1 µg sulfur or carbon. Each sample was ground and divided into three parts that were individually analyzed and the results averaged to provide the reported sulfur and carbon abundances given in tables 31.1–31.2. The accuracy of the sulfur and carbon analyzers were checked against the National Bureau of Standards reference steel 55e (S: 110 ± 10 µg/g; C: 112 ± 10 µg/g). The analytical uncertainty of the determinations is estimated to be less than 10 percent of the amount of S or C in the samples.

The relative density of each sample was qualitatively assigned after visual examination. Samples with very few or no vesicles were designated as having a high relative density, and those with extremely abundant or large vesicles were designated as having very low relative density. Samples falling between these two extremes were ranked as moderately high, moderate, moderately low, and low.

PREVIOUS WORK

During the past two decades, significant advances have been made in the understanding of the distribution and the isotopic compositions of volatiles in ocean-floor and Hawaiian basalts (Moore and Fabbri, 1971; Moore and Schilling, 1973; Swanson and Fabbri, 1973; Mathez, 1976; Javoy and others, 1978, 1982; Muenow and others, 1979; Harris, 1981; Harris and Anderson, 1983; Des Marais and Moore, 1984; Kyser and O'Neil, 1984; Matthey and others, 1984; Sakai and others, 1984). More recently, complementary studies of the volcanic gases emitted at Hawaiian volcanoes have made possible improved models of the magmatic budgets of carbon and sulfur for the Kilauea and Mauna Loa volcanic systems (Greenland, chapter 28, 1984, in press; Gerlach, 1980, 1982; Gerlach and Graeber 1985; Greenland and others, 1985, in press). Many of these studies have focused on estimations of the juvenile contents of sulfur and carbon and their implications for the abundance and occurrence of these elements in the magma source regions. It is now well known that submarine basalts erupted under conditions of great hydrostatic pressure are the least degassed, and hence the measurements of their sulfur and carbon abundances most closely approximate juvenile concentrations. Subaerially erupted basalts are typically lower in total sulfur abundance than submarine basalts because of the substantial degassing loss to the atmosphere during fountaining at the vent and lava flowage (Moore and Fabbri, 1971; Gibson and Moore, 1974, fig. 5).

Des Marais and Moore (1984) have demonstrated that carbon abundance in submarine basalt decreases with decreasing ocean depth of eruption site. This relation reflects the increased solubility of CO₂ in the melt at high pressure and the attendant greater tendency for volatiles to escape from magma at shallow water depths (that is, at lower confining pressure). Several recent studies (Des Marais and Moore, 1984; Matthey and others, 1984; Sakai and others, 1984) have shown that carbon typically occurs in three forms: (1) posteruption carbon on sample surfaces (adsorbed gases, organic matter, weathering coatings, and other nonmagmatic carbon species acquired by the basaltic glasses); (2) magmatic carbon dioxide trapped in vesicles; and (3) magmatic carbon dissolved in basaltic glasses. For the 12 midocean basalts they analyzed, Des Marais and Moore (1984) found that forms (1) and (3) provide the bulk of the measured total carbon content. Furthermore, they demonstrated that posteruption carbon can be easily acquired by the sample, as evidenced by the 19 µg/g of surficial carbon yielded by reanalysis of a sample exposed to the atmosphere for four days following a previous analysis (maximum combustion temperatures 504 °C).

We designed our study as a broad survey of the carbon and sulfur abundances in Hawaiian tholeiitic basalts in order to build on the earlier studies of Moore and Fabbi (1971), Swanson and Fabbi (1973), and Swanson (1973) with the following general objectives: (1) To obtain a larger data base for fresh subaerially erupted Hawaiian basalts that have not been subjected to weathering; (2) to examine the relation between volatile content and the different materials produced during the course of an eruption; (3) to document better the degassing behavior of sulfur and carbon during lava fountaining and flowage; and (4) to detect changes, if any, in volatile content of magma through time. We did not anticipate the magnitude of the problem of sample contamination by atmospheric carbon recently brought to light and the additional uncertainty in data interpretation created by posteruption contamination effects. Despite the difficulty in data interpretation presented by these factors, we believe that it is useful to report our carbon data because they constitute the best available data set for subaerial basalts obtained to date.

DISTRIBUTION OF SULFUR AND CARBON CONTENT IN DIFFERENT ERUPTIVE PRODUCTS

The gas content and degassing patterns of magma are some of the primary controls on the morphology of lava flows (Swanson, 1973). In our study, spatter (near-vent) and pahoehoe and aa flows were extensively sampled, but we did not differentiate between the varieties of pahoehoe (see, for example, Swanson, 1973) nor the varieties transitional between pahoehoe and aa (see, for example, Peterson and Tilling, 1980). Because these products have undergone different degassing histories and the lavas may have varied in original volatile content, the eruptive products might be expected to differ in measured sulfur and carbon contents.

To facilitate comparison of the data, which show great scatter, we computed mean sulfur and carbon values according to sample type for each of the eruptive episodes of Kilauea, for Kilauea samples as a whole, and for the 1975 Mauna Loa eruption (tables 31.3–31.5). The small sample populations for many of the eruptive episodes allow only a general comparison between the products of the same episode. However, the mean values for aggregated Kilauea data provide a better statistical basis for comparison.

On the basis of the aggregated Kilauea data, the mean sulfur content of 177 $\mu\text{g/g}$ for spatter is the highest, followed by 152 $\mu\text{g/g}$ for pahoehoe, and 96 $\mu\text{g/g}$ for aa. There are deviations from this general pattern when the products of a single eruptive event are compared, but these probably result from the small sample populations for most of the single events, as well as from the lumping of pahoehoe varieties and the disregard of the transitional flow types between pahoehoe and aa. Comparison of the products of the 1975 Mauna Loa eruption is hampered by a small sample population; the one pahoehoe sample exceeds in sulfur content the mean for spatter, but some individual spatter samples contain more sulfur than the pahoehoe sample.

The time of formation and location of deposition of these three

eruptive products explain the general decrease in sulfur content from spatter to pahoehoe to aa. Spatter, deposited by lava fountaining in the vicinity of the active vent, commonly represents material ejected early in the eruption or during more vigorous vent activity. Because spatter is an air-quenched product, it undergoes minimal degassing and thus retains a relatively high sulfur content. In contrast, the pahoehoe and aa form lava streams that are continually degassing as they advance from the vent.

Swanson (1973) documented numerous types of pahoehoe and concluded that gas content and mode of flowage of the lava determine the resultant morphology and gross texture. Different types of pahoehoe were not differentiated in our study, but some of the variations we found in sulfur content in the pahoehoe samples no doubt reflect different morphologic types, distances from the vent, and multiple phases of pahoehoe formation. The role of gas loss in the transition from pahoehoe to aa has been debated. Pahoehoe is generally regarded to be richer in gas than aa (see, for example, Williams and McBirney, 1979). Swanson (1973), however, believed that a higher rate of cooling, and not the loss of gases, causes the transition from pahoehoe to aa. Others (Sparks and Pinkerton, 1978) have attributed aa formation to the high yield strength of lava that has lost a significant amount of gas. Peterson and Tilling (1980), though not directly addressing the issue of gas loss, proposed that lava changes from pahoehoe to aa once a certain critical relation (the so-called transition threshold) between viscosity and rate of shear is attained. In general, magma viscosity increases with decreasing gas content, and we interpret the lower mean sulfur values for aa to indicate that it had degassed to a greater extent than the pahoehoe or spatter. This interpretation is consistent with the observation that aa lava is predominantly found at the toe of an advancing flow, hence farther from the vent, and so has had more opportunity to degas than its associated pahoehoe lava.

The carbon values for spatter, pahoehoe, and aa show more variation and, unlike the sulfur values do not exhibit any systematic trend. Swanson and Fabbi (1973) similarly did not observe any demonstrable trends in the behavior of carbon volatiles and suggested that their analytical techniques were not precise enough to detect small but possibly significant changes. However, the low solubility of CO_2 in the melt and its tendency to degas rapidly before or during eruption (see Greenland, chapter 28; Basaltic Volcanism Study Project, 1981; Gerlach and Graeber, 1985; Greenland, in press) may better explain the incoherent variation pattern for carbon abundances. If indeed most of the CO_2 is lost by degassing during storage in the shallow summit reservoir or immediately with the onset of eruption, then products that formed later in the eruption and flowage sequence would not on average contain noticeably less carbon than those formed early in the eruption. Moreover, the great range in carbon content within each category of material analyzed and the slightly higher mean carbon value for pahoehoe than for spatter, contrary to expected degassing behavior, probably also reflect scatter in the data resulting from posteruption contamination by atmospheric carbon. Given these great uncertainties, the difference between the mean carbon values for Kilauea aa (85 $\mu\text{g/g}$)

TABLE 31.1.—Sulfur and carbon contents and other characteristics of selected lava samples from Kilauea Volcano

[For most samples, the date given is both the date of eruption and the date of sample collection; where they differ, the collection date is given in parentheses. Relative density estimated by visual inspection of sample vesicularity before crushing: H, high; MH, moderately high; M, moderate; ML, moderately low; L, low; VL, very low; *, density not estimated. Physical state of sample at time of collection: S, solid; H, hot; W, warm; C, cool; L, liquid. Most spatter samples collected in the immediate vicinity of the vent; approximate distances from vent are given for other samples]

Sample	Date erupted (Date collected)	Material	Relative density	Collection state	S ($\mu\text{g/g}$)	C ($\mu\text{g/g}$)	Distance from vent	Remarks
Mauna Ulu eruption (upper east rift zone), February 1972 - May 1973								
MU272-2	2/8/72	Spatter	M	S,H	164	46	0	Still glowing when collected
MU272-3	2/9/72	Pahoehoe	MH	L	153	223	1 km	Toe of active flow
MU272-16	2/27/72	Spatter	M	S,H	182	270	0	
MU372-23	3/18/72 (3/19/72)	Spatter	L	S,W	232	181	0	
MU372-27	3/21/72	Pahoehoe	ML	L	170	245	20 m	
MU472-30	4/11/72	Pahoehoe	L	L	258	350	40 m	Dipped from Alae lava lake
MU472-32	4/14/72	Aa	MH	L	120	68	200 m	Pasty, glowing core of moving flow
MU472-33	3/18/72 (4/14/72)	Spatter	ML	S,C	216	226	0	
MU572-34	5/8/72	Pahoehoe	VL	L	299	561	0	Dipped from Alae lava lake (air-quenched)
MU572-35	5/8/72	Pahoehoe	VL	L	163	114	0	Dipped from Alae lava lake (water-quenched)
MU572-39	5/23/72	Spatter	MH	S,H	189	94	0	Alae lava lake
MU672-41	6/1/72	Pahoehoe	M	S,H	301	112	0	N. rim overflow, Alae lake
MU672-43	6/9/72	Spatter	M	S,W	162	119	0	
MU772-47	7/11/72	Spatter	MH	S,C	201	60	0	
MU772-48	7/11/72	Pahoehoe	M	L	197	123	2 km	Flowing from Alae
MU872-51	8/4/72	Pahoehoe	H	L	105	54	2 km	Makaopuhi Crater floor
MU872-55	8/12/72	Pahoehoe, spinose	M	L	132	68	2 km	Liquid cooled on thermocouple tip
MU972-57	9/3-5/72 (9/5/72)	Spatter	M	S,C	201	56	0	
MU972-61	9/28/72	Pahoehoe	H	L	123	77	10 km	Very viscous flow, lava lake
MU1072-64	9/28/72	Stalactite and wall glaze	M	S,H	15,025	68	1.5 km	Edge of skylight, active tube
MU1072-65	10/16/72 (10/17/72)	Spatter	MH	S,W	227	115	0	
MU1072-66a	10/25/72	Lava	MH	L	133	66	2 km	Quenched; outside of steel bucket; glassy
MU1072-66b	10/25/72	Lava	M	L	157	221	2 km	Inside of bucket; more slowly cooled
MU1172-68	11/7/72	Pahoehoe	H	L	153	36	3 km	
MU1172-69	11/28/72	Pahoehoe	M	L	182	92	250 m	
MU1272-70	11/29-12/1/72 (12/1/72)	Spatter	M	S,C	197	74	0	
MU1272-74	12/14/72	Pahoehoe	ML	L	190	47	1 km	
MU173-76	1/9/73	Pahoehoe	M	L	102	107	2.5 km	Temperature measured
MU173-77	1/9/73	Pahoehoe	M	L	100	84	3 km	
MU173-78a	1/9/73	Aa	H	L	64	36	7.2 km	Pasty, glowing core; air-quenched
MU173-78b	1/9/73	Aa	H	L	57	68	7.2 km	Water-quenched
MU173-79a	1/9/73	Pahoehoe	M	L	105	94	7 km	Air-quenched
MU173-79b	1/9/73	Pahoehoe	M	L	92	83	7 km	Water-quenched
MU173-80	1/9-1/10/73 (1/10/73)	Spatter	L	S,W	166	157	0	
MU173-89	1/31/73	Pahoehoe	MH	L	85	21	8 km	
MU273-95	2/28/73	Pahoehoe	H	L	111	31	1 km	Leaking from tumulus
MU273-97	2/28/73	Pahoehoe	H	S,H	94	23	10 km	5-m depth sea
MU373-98	3/3/73	Pahoehoe	H	S,H	223	66	10 km	Average S and C values for entire sample
MU373-98a					389	67		Glassy rim, 1 cm thick
MU373-98b					157	92		21-cm thick fine-grained interior
MU373-98c					123	39		Glassy lower rim
MU373-99	3/4/73	Pahoehoe	MH	S,H	120	24	10 km	Collected in tide pool
MU373-101	3/6/73	Black sand	*	S,C	121	53	10 km	Newly formed
MU373-103	3/14/73	Spatter	MH	S,C	190	51	0	
MU373-107	3/23/73	Pahoehoe	H	L	107	20	10 km	Temperature measured
MU473-108	4/10/73	Spatter	MH	S,H	133	26	0	
MU473-109	4/10/73	Pahoehoe	M	L	112	11	10 km	Temperature measured
MU573-111	5/1/73	Spatter	M	S,W	217	25	0	
MU573-112	5/1/73	Pahoehoe	M	L	150	48	1.5 km	

TABLE 31.1.—Sulfur and carbon contents and other characteristics of selected lava samples from Kilauea Volcano—Continued

[For most samples, the date given is both the date of eruption and the date of sample collection; where they differ, the collection date is given in parentheses. Relative density estimated by visual inspection of sample vesicularity before crushing: H, high; MH, moderately high; M, moderate; ML, moderately low; L, low; VL, very low; *, density not estimated. Physical state of sample at time of collection: S, solid; H, hot; W, warm; C, cool; L, liquid. Most spatter samples collected in the immediate vicinity of the vent; approximate distances from vent are given for other samples]

Sample	Date erupted (Date collected)	Material	Relative density	Collection state	S ($\mu\text{g/g}$)	C ($\mu\text{g/g}$)	Distance from vent	Remarks
Pauahi-Hiiaka eruption (upper east rift zone), May 5, 1973								
PH573-1	5/5/73	Pumice	VL	S,C	213	437	0	Highest fountaining
PH573-2	5/5/73	Pahoehoe	M	L	135	99	1 km	
PH573-3	5/5/73	Spatter	M	S,H	161	110	0	
PH573-4	5/5/73	Spatter	M	S,W	165	85	0	
PH573-5	5/5/73 (5/23/73)	Pahoehoe	MH	S,C	324	123	0	High lava lake, Hiiaka stand
PH573-6	5/5/73 (5/23/73)	Pumice	VL	S,C	210	181	0	Hiiaka Crater
PH973-8	5/5/73 (9/10/73)	Spatter	M	S,C	177	109	0	Pauahi Crater
PH973-10	5/5/73 (9/10/73)	Pahoehoe	ML	S,C	121	119	0	Pauahi, high lava lake stand
PH973-11	prehistoric 9/10/73	Lava	H	S,C	37	106		Prehistoric lava; wall of Pauahi
Mauna Ulu eruption (upper east rift zone), June 1973 - November 1973								
MU673-115	6/5/73? (6/7/73)	Pahoehoe	L	S,W	413	77	100 m	Glassy rind of shelly pahoehoe, Alae
MU673-116	6/7/73	Pahoehoe	M	L	175	13	0	Dipped from Mauna Ulu lava lake
(Mauna Ulu not sampled again until October)								
MU1073-117	10/30/73	Spatter	L	S,H	234	114	0	
MU1173-120	11/4/73	Spatter	ML	S,W	229	15	0	
MU1173-122	11/4/73	Pahoehoe	ML	L	253	32	200 m	Lava lake overflow
MU1173-125	11/8/73	Pahoehoe	M	L	140	29	150 m	Dipped lava lake
Pauhi eruption (upper east rift zone), November - December, 1973								
PH1173-12	11/10/73	Spatter	L	S,C	187	146	50 m	Watch it fall
PH1173-15	11/11/73	Pahoehoe, glassy rind	ML	S,H	197	118	0	Glowing toe
PH1173-16	11/11/73	Spatter	*	S,W	318	135	300 m	Fissure 300 m from Puu Huluhulu
PH1173-21	11/29/73	Spatter	M	S,C	102	135	0	
PH574-25	12/9/73 (5/1/74)	Pahoehoe, glassy skin	M	S,C	86	119	0	Last erupted material in west pit
Mauna Ulu eruption (upper east rift zone), December 1973 - June 1974								
MU1273-127	12/14/73 (12/27/73)	Pahoehoe	M	S,C	286	62	<100 m	Lava-lake high stand
MU174-131	1/25/74	Pahoehoe	M	L	78	66	<25 m	
MU174-132	1/25/74	Spatter	L	S,W	243	69	0	Collected as it fell
MU174-133	1/25/74	Pahoehoe	M	L	81	46	140 m	
MU174-134	1/25/74	Pahoehoe	M	L	80	69	400 m	Slabby pahoehoe
MU274-142	1/25-26/74 (2/2/74)	Aa	*	S,C	208	91	2 km	Terminus of 1/25/74 flow
MU274-143	1/25-26/74 (2/2/74)	Pahoehoe, spinose	M	S,C	70	81	0.6 km	Edge of 1/25-26/74 flow
MU274-147	2/14/74	Pahoehoe	ML	L	144	58	10 m	
MU274-148	2/14/74	Pahoehoe	ML	L	168	31	50 m	
MU374-154	3/5/74	Spatter	ML	S,C	149	67	0	Vent F
MU374-155	3/17/74 (3/18/74)	Spatter	L	S,W	202	36	0	Vent E
MU374-156	3/23/74	Spatter	L	S,H	229	41	0	Collected as it fell
MU374-157	3/23/74	Pahoehoe	M	L	168	45	24 m	
MU374-158	3/23/74	Pahoehoe	M	L	118	48	0.6 km	
MU474-161	4/3/74	Pahoehoe, interior	MH	S,H	93	67	5 km	Collected 3 minutes after solidification
MU474-161a	4/3/74	Pahoehoe, crust	MH	S,H	119	77	5 km	Collected 3 minutes after solidification
MU474-162	4/5/74	Spatter	ML	S,C-W	141	57	0	
MU474-163	4/8/74	Spatter	MH	S,H	146	53	0	
MU474-168	4/22/74	Pahoehoe	*		162	115	5 m	Vent F
MU574-169a	5/3/74	Pahoehoe	H	S,H	159	62	5 km	Collected a few hours after solidification
MU574-169b	5/3/74	Pahoehoe	MH	S,H	151	143	5 km	Collected a few hours after solidification
MU574-170	5/6/74	Spatter	H	S,W	162	83	0	
MU574-171	5/30/74	Spatter	L	S,H	155	98	0	Watched it fall
MU574-172	5/31/74	Pahoehoe	ML	L	149	127	25 m	
MU674-173	6/3-5/74 (6/8/74)	Spatter	M	S,W	147	82	0	

TABLE 31.1.—Sulfur and carbon contents and other characteristics of selected lava samples from Kilauea Volcano—Continued

[For most samples, the date given is both the date of eruption and the date of sample collection; where they differ, the collection date is given in parentheses. Relative density estimated by visual inspection of sample vesicularity before crushing: H, high; MH, moderately high; M, moderate; ML, moderately low; L, low; VL, very low; *, density not estimated. Physical state of sample at time of collection: S, solid; H, hot; W, warm; C, cool; L, liquid. Most spatter samples collected in the immediate vicinity of the vent; approximate distances from vent are given for other samples]

Sample	Date erupted (Date collected)	Material	Relative density	Collection state	S ($\mu\text{g/g}$)	C ($\mu\text{g/g}$)	Distance from vent	Remarks
Summit eruption, July 19-22, 1974								
KIL774-1	7/19/74	Pahoehoe	L	L	149	84	0	
KIL774-2	7/19/74	Spatter	L	S,H	177	81	0	Watched it fall
KIL774-6a	7/20/74	Pahoehoe	M	L	107	67	0	Fissure F
KIL275-10	7/19/74 (2/16/75)	Spatter	ML	S,C	166	70	0	Fissure A
KIL275-11	7/19/74 (2/16/75)	Spatter	M	S,C	154	159	0	
KIL275-12	7/19/74 (2/16/75)	Pahoehoe	M	S,C	110	135	0.5 km	Terminus of flow fed by fissure F
KIL275-13	7/19/74 (2/16/75)	Aa	H	S,C	111	97	2 km	Terminus of flow fed by fissure A
Summit eruption, September 19, 1974								
KIL974-8	9/19/74	Spatter	MH	S,H	141	64	0	
KIL375-14a	9/19/74 (3/24/75)	Pahoehoe	M	S,C	123	139	0	
KIL375-14b	9/19/74 (3/24/75)	Spatter	ML	S,C	152	114	0	Same location as KIL375-14a
KIL375-15	9/19/74 (3/24/75)	Pahoehoe	M		123	149	1 km	Glassy skin of toe
Southwest flank eruption, December 31, 1974								
SWR1274-1	12/31/74	Spatter	L	S,H	135	127	0	First material, fissure E
SWR1274-2	12/31/74	Spatter	ML	S,H	122	89	0	Last material, fissure E
SWR1274-3	12/31/74	Spatter	L	S,W-C	192	191	0	Fissure B
SWR1274-4	12/31/74	Spatter	M	S,C	122	35	0	Fissure B
SWR1274-5	12/31/74	Spatter	MH	S,C	125	137	0	Fissure I
SWR1274-6	12/31/74	Spatter	L	S,C	156	147	0	Last material, last fountain, fissure D
SWR175-7	12/31/74 (1/18/75)	Pahoehoe	MH	S,C	65	118	1.5 km	Average S and C content for entire sample
SWR175-7a					79	117		Glassy top rim
SWR175-7b					61	92		Fine-grained interior
SWR175-7c					56	144		Fine-grained bottom rim
SWR175-8	12/31/74 (1/18/75)	Pahoehoe	M	S,C	80	110	2.5 km	
SWR175-9	12/31/74 (1/18/75)	Pahoehoe	M	S,C	78	142	5.5 km	
SWR175-10	12/31/74 (1/18/75)	Aa	H	S,C	48	38	5.5 km	
SWR175-11	12/31/74 (1/18/75)	Pahoehoe	MH	S,C	58	159	9 km	Transitional pahoehoe
SWR175-12	12/31/74 (1/18/75)	Aa	H	S,C	66	200	10.5 km	Weathered - terminus of 12/31/74 flow
Summit eruption, November 29, 1975								
KIL75-1	11/29/75	Pahoehoe	L	S,H	334	99	400 m	From vent A
KIL75-2	11/29/75 (12/3/75)	Spatter	M	S,C	132	38	10 m	From vent B-1
KIL75-3	11/29/75 (12/3/75)	Spatter	MH	S,C	160	48	0	Irregular, clinkery
KIL75-4	11/29/75 (12/3/75)	Cinder	*	S,C	695	49	0	Irregular
KIL75-5	11/29/75 (12/4/75)	Spatter	L		200	69	0	
KIL75-6	11/29/75 (12/4/75)	Pahoehoe	M		174	443	1 km	Average S and C content for entire sample
KIL75-6a					172	163		Glassy rim
KIL75-6b					179	68		Fine-grain interior; vesicles 1-2 mm
KIL75-6c					173	1099		Fine-grained basal, rim; vesicles <1 mm

TABLE 31.2.—Sulfur and carbon contents and other characteristics of selected lava samples from the July 5–6, 1975, summit eruption of Mauna Loa Volcano

[For most samples, the date given is both the date of eruption and the date of sample collection; where they differ, the collection date is given in parentheses. Relative density estimated by visual inspection of sample vesicularity before crushing: H, high; MH, moderately high; M, moderate; ML, moderately low; L, low; VL, very low; *, density not estimated. Physical state of sample at time of collection: S, solid; H, hot; W, warm; C, cool; L, liquid. Most spatter samples collected in the immediate vicinity of the vent; approximate distances from vent are given for other samples.]

Sample	Date erupted (Date collected)	Material	Relative density	Collection state	S ($\mu\text{g/g}$)	C ($\mu\text{g/g}$)	Distance from vent	Remarks
ML775-1	7/6/75	Aa	MH	S, H	48	28	5 km	Red hot when collected at active flow front
ML775-17	7/6/75) (7/15/75)	Spatter	ML	S, C	227	199	0	
ML775-21	7/6/75 (7/15/75)	Spatter	H	S, C	108	58	40 m	
ML775-22	7/6/75 (7/15/75)	Spatter	ML	S, C	134	52	0	
ML775-23	7/5/75 (7/21/75)	Spatter	L	S, C	238	205	8 m	
ML775-24	7/5/75 (7/21/75)	Pahoehoe	L	S, C	196	115	0.5 km	
ML775-26	7/6/75) (7/29/75)	Spatter	ML	S, C	184	73	0	
ML775-27	7/5/75 (7/31/75)	Aa	H	S, C	28	41	2.5 km	

TABLE 31.3.—Distribution of mean sulfur and carbon contents in spatter from Kilauea and Mauna Loa Volcanoes

Location and month of eruption	Number of samples	Mean S ($\mu\text{g/g}$)	Mean C ($\mu\text{g/g}$)
Kilauea Volcano, all samples	45	117	96
Mauna Ulu 2/72-5/73	14	191	99
Pauahi-Hiiaka 5/73	3	168	101
Mauna Ulu 6/73-11/73	2	231	64
Pauahi-Hiiaka 11/73-12/73	3	202	139
Mauna Ulu 12/73-6/74	9	175	65
Summit 7/74	3	166	103
Summit 9/74	2	147	89
Southwest flank 12/74	6	142	121
Summit 11/75	3	164	52
Mauna Loa Volcano 7/75	5	178	117

TABLE 31.4.—Distribution of mean sulfur and carbon contents in pahoehoe from Kilauea and Mauna Loa Volcanoes

Location and month of eruption	Number of samples	Mean S ($\mu\text{g/g}$)	Mean C ($\mu\text{g/g}$)
Kilauea Volcano, all samples	60	152	103
Mauna Ulu 2/72-5/73	25	153	108
Pauahi-Hiiaka 5/73	3	193	114
Mauna Ulu 6/73-11/73	4	245	38
Pauahi-Hiiaka 11/73-12/73	2	141	119
Mauna Ulu 12/73-6/74	15	130	68
Summit 7/74	3	122	95
Summit 9/74	2	123	144
Southwest flank 12/74	4	70	132
Summit 11/75	2	254	271
Mauna Loa Volcano 7/75	1	196	115

and for spatter (96 $\mu\text{g/g}$) is probably not significant, even though the difference is compatible with the presumed greater degassing of the aa samples.

Several eruptive products other than the three general types discussed above were sampled and analyzed. The only cinder sample collected (KIL75-4) has the highest sulfur content (695 $\mu\text{g/g}$) of any of the material (excluding the stalactite) we analyzed but a low carbon content (49 $\mu\text{g/g}$). The relatively low carbon content is suggestive of little posteruption contamination; therefore, if sulfur has not been adsorbed, then the sulfur content, which is similar to the mean (680 $\mu\text{g/g}$) for submarine basalts (Moore and Fabbi, 1971), perhaps approaches the original sulfur content of the basaltic magma erupted in November 1975 at Kilauea. Two pumice samples

(PH573-1 and PH573-6), collected during the May 1973 Kilauea eruption at Pauahi and Hiiaka craters, also contain high sulfur contents (213 and 210 $\mu\text{g/g}$, respectively) and high carbon contents (437 and 181 $\mu\text{g/g}$, respectively). Sample PH573-1 formed during the highest fountaining observed for the Pauahi-Hiiaka eruption. If this sample was not contaminated, then the comparison of this carbon value to a spatter sample (MU1173-120) that contains only 14 $\mu\text{g/g}$ carbon indicates that almost complete degassing of CO_2 is possible during eruption. Alternatively, the wide ranges in sulfur and carbon contents observed for the cinder and pumice samples could simply reflect adsorption trapping of plume gases during high fountaining, as suggested by unpublished data of L. Paul Greenland of the

TABLE 31.5.—Distribution of mean sulfur and carbon contents in aa from Kilauea and Mauna Loa Volcanoes

Location and month of eruption	Number of samples	Mean S ($\mu\text{g/g}$)	Mean C ($\mu\text{g/g}$)
Kilauea Volcano, all samples	7	96	85
Mauna Ulu 2/72-5/73	3	80	57
Mauna Ulu 12/73-6/74	1	208	91
Summit 7/74	1	111	97
Southwest flank 12/74	2	57	119
Kilauea Volcano totals	7	96	85
Mauna Loa Volcano 7/75	2	38	35

Hawaiian Volcano Observatory (written commun., 1985) from the Puu Oo eruption on Kilauea's east rift zone that began in 1983 (Wolfe and others, chapter 17).

A sample of red, oxidized, hollow-cored stalactite (MU1072-64) taken from the roof of an active lava tube through a skylight has an extremely high sulfur content of 15,025 $\mu\text{g/g}$ but a low carbon content of 68 $\mu\text{g/g}$. The high sulfur content possibly results from degassed sulfur volatiles that condensed and formed a sulfide-mineral phase near the skylight because of changes in temperature and Eh conditions. The very low carbon content suggests that most of the CO_2 degassed before the lava entered the lava tube or that carbon escaped through the skylight without reacting with the wall material.

A sample of prehistoric lava (PH973-11) from the wall of Pauahi crater has a very low sulfur content of 37 $\mu\text{g/g}$, which would place it in the range of modern aa samples analyzed in this study. The moderate carbon content of 106 $\mu\text{g/g}$ provides no clues to its origin or its distance from the vent, because carbon abundances vary greatly in all categories of eruptive products. In addition, such a prehistoric (older than A.D. 1750) lava must have a higher probability of being affected by atmospheric carbon contamination than the fresh materials erupted during 1972-75 at Kilauea.

Three samples of pahoehoe were selected for analysis of sulfur and carbon contents in each of several distinct textural zones (glassy upper rind; fine grained, moderately vesicular interior; and glassy or fine-grained, slightly vesicular basal rim) for comparison with results of zoned pillow basalts analyzed by Moore and Fabbi (1971). Two samples (MU373-98 and SWR175-7) have sulfur content highest in the upper glassy rim and lowest in the lower rim. Sample KIL75-6 showed no significant variation in sulfur content among the zones. Thus, the sulfur distribution in our zoned subaerial pahoehoe samples generally follows the trend observed by Moore and Fabbi (1971) for zoned submarine pillow basalts, but the sulfur contents in the pahoehoe are much lower. The carbon distribution for the three zoned pahoehoe samples is irregular, most probably because of posteruption contamination; carbon was not analyzed in the Moore and Fabbi pillow-basalt study.

VARIATIONS IN SULFUR AND CARBON CONTENT WITH DISTANCE FROM VENT

Degassing of lava during fountaining and flow from the vent has been previously observed and documented (Swanson, 1973; Swanson and Fabbi, 1973; Gibson and others, 1975). If the degassing process is efficient and systematic, eruptive products that have travelled greater distances from the vent should show progressively lower sulfur and carbon contents.

In general, sulfur abundance does tend to decrease with increasing distance from the vent, the greatest loss occurring within 2 km of the vent (fig. 31.2). Sulfur abundances in samples collected 2-10 km from the vent do not show a well-defined decreasing trend, indicating that variations caused by differences in sample type,

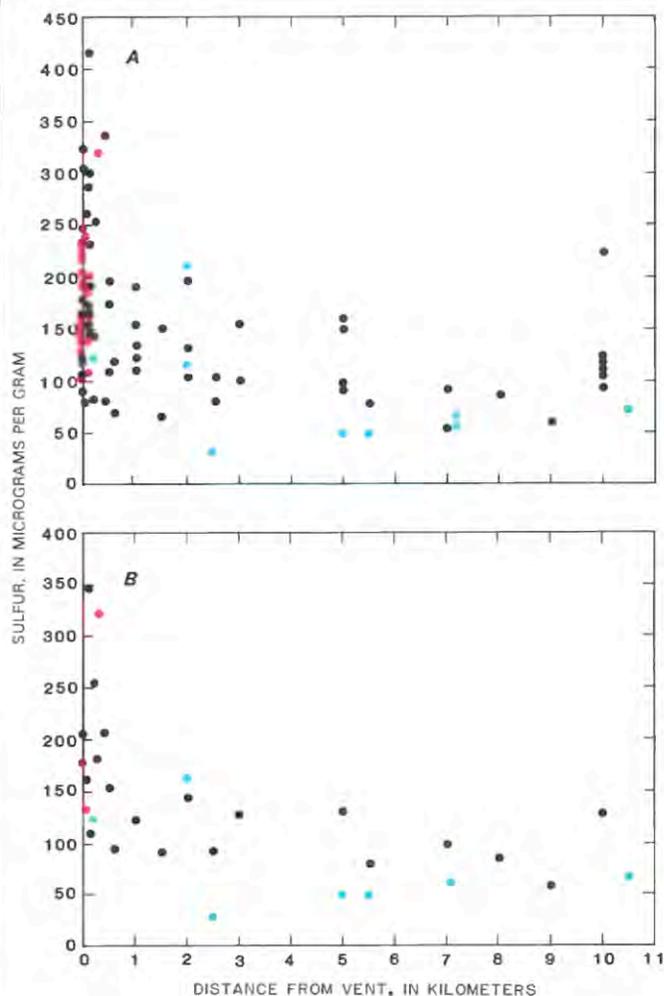


FIGURE 31.2.—Sulfur contents of Kilauea and Mauna Loa lavas plotted against distance from eruptive vent. Red, spatter; black, pahoehoe; blue, aa. **A**, Sulfur content of individual samples. **B**, Mean sulfur content of samples grouped by distance from eruptive vent. Samples collected 5-50 m from vent are grouped together and the mean value is plotted at 0.05 km.

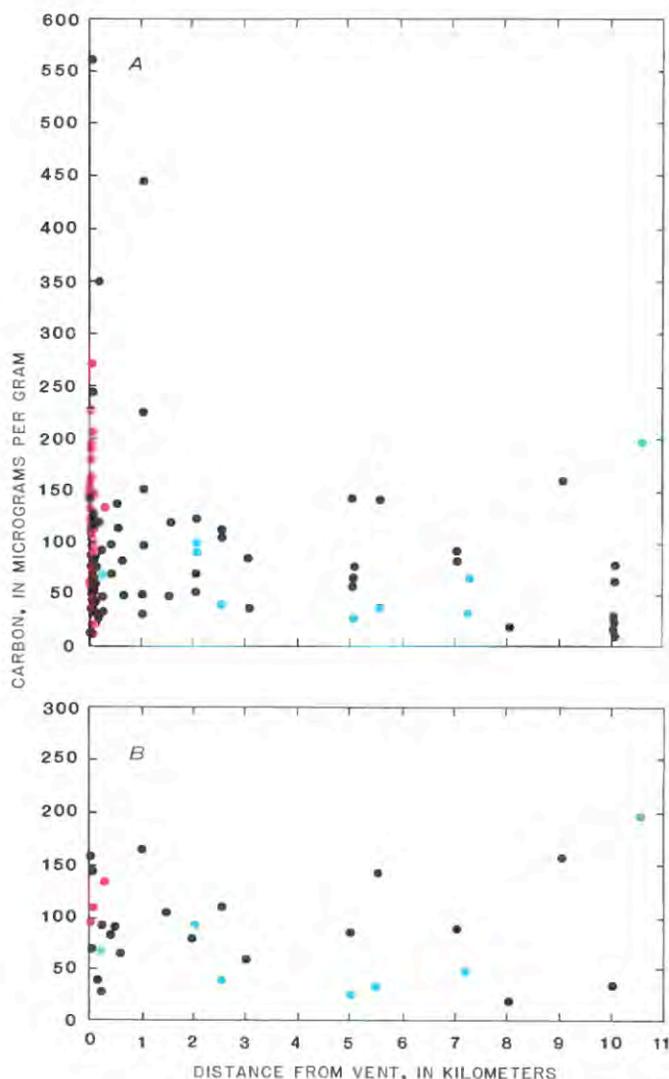


FIGURE 31.3.—Carbon contents of Kilauea and Mauna Loa lavas plotted against distance from eruptive vent. Red, spatter; black, pahoehoe; blue, aa. *A*, Carbon content of individual samples. *B*, Mean carbon content of samples grouped by distance from eruptive vent. Samples collected 5–50 m from vent are grouped together and the mean value is plotted at 0.05 km.

especially for pahoehoe, are greater in that interval than those related to degassing alone. Although the distance the lava flows from the vent is an important determinant of the type of pahoehoe formed, it is not the sole control. Swanson (1973) has shown that the original volatile content, the rate of flow of the lava, the gradient of the surface over which the lava flows, and the mode of lava extrusion all help control the type of pahoehoe formed. Presumably pahoehoe with different morphologies and volatile contents can occur at the same distance from the vent; the sampling in our study was inadequate to permit such distinctions.

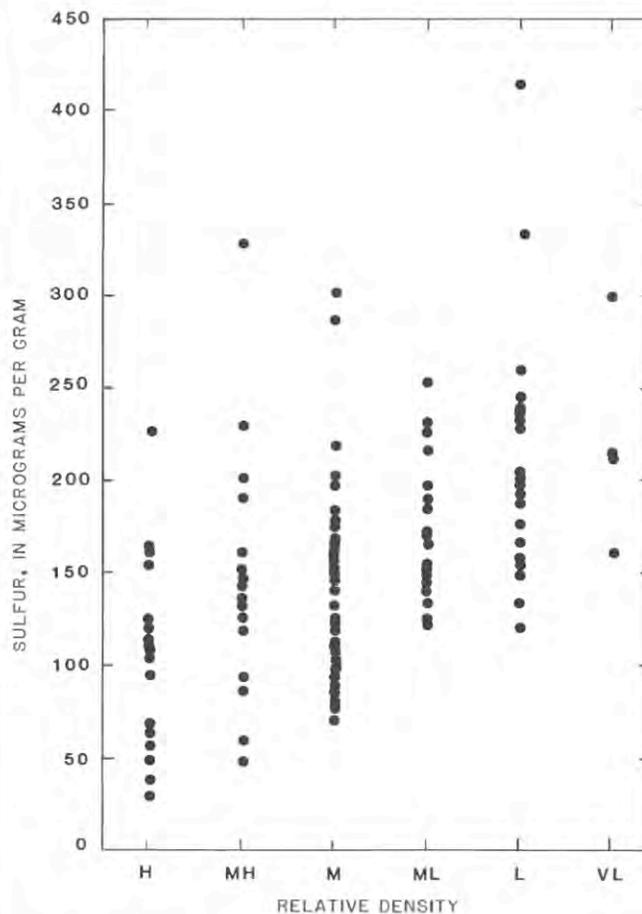


FIGURE 31.4.—Sulfur contents of Kilauea and Mauna Loa lava samples plotted by relative density estimated qualitatively from visible vesicularity: H, high; MH, moderately high; M, moderate; ML, moderately low; L, low; VL, very low.

Carbon abundance shows little apparent correlation with distance from the vent (fig. 31.3). Although the highest carbon values do occur closest to the vent, whatever progressive degassing trend may exist is obscured by contamination-caused variations in total carbon content. If immediate, sudden release of most carbon volatiles occurs during the initial phases of the eruption, then the high carbon contents in some samples collected far from the vent are difficult to explain and are almost certainly related to posteruption contamination.

VARIATION IN SULFUR AND CARBON WITH SAMPLE DENSITY

Sulfur and carbon abundances show different general patterns when plotted against relative density (figs. 31.4 and 31.5). Although high sulfur contents may be encountered in most of the arbitrarily defined density classes, sulfur values generally become lower as the density increases. This general trend corresponds to a decrease in lava vesicularity as degassing of volatiles progresses. For

example, Swanson (1973) noted a 10-percent decrease in lava vesicularity that he attributed to gas loss during 4 km of flowage. Without actual measurements of the density, we cannot estimate the average decrease in vesicularity with lava flowage, but our qualitative data affirm the occurrence of generally lower concentrations of sulfur volatiles in denser, more degassed lavas.

A similar plot of carbon content against relative density (fig. 31.5) yields an almost random pattern. The highest carbon contents are not restricted to the samples with lowest density, and the lowest carbon values are distributed almost equally among all density classes. This lack of correlation is compatible with the notion that carbon volatiles may degas rapidly before or during the earliest vent activity rather than systematically during flowage. The wide range and scatter in carbon contents may again reflect the ease of posteruption contamination of the samples.

POSSIBLE VARIATION IN SULFUR AND CARBON CONTENT WITH TIME

Temporal and spatial variations in the chemical composition of Hawaiian basalts, even those formed during a single eruption, have been well documented in many previous studies (see, for example, Tilling and others, chapter 24; Wright, 1971; Wright and others, 1975; Wright and Tilling, 1980; Hoffman and others, 1984). Theoretically, variations in the volatile content of the eruptive products might be expected to correlate with differences in the composition of the magma in equilibrium with the volatiles. Swanson and Fabbi (1973) suggested that the differences in the energy level of vent fountaining might be linked to changes in volatile content of the magma; the most vigorous fountaining indicated the highest volatile content. They did not believe that the original volatile content of a magma could be estimated by analyzing subaerial eruptive products, because more than 80 percent of that content would have been lost. Swanson and Fabbi (1973) concluded, however, that spatter samples would retain the original volatiles better than any other eruptive product.

Although we cannot estimate the original volatile content of the magma associated with each eruptive event, we have plotted the sulfur and carbon content of spatter as a function of time (figs. 31.6, 31.7) in an attempt to ascertain any systematic secular changes in volatile content. Sulfur values (fig. 31.6) for most spatter samples fall in the range 125–250 $\mu\text{g/g}$, but the distribution appears random and no systematic temporal trend is apparent. Spatter samples collected during the same eruptive sequence may vary by as much as 130 $\mu\text{g/g}$. The plot of carbon content versus time (fig. 31.7) shows even more variation than that for sulfur. Spatter samples formed during the same eruption may differ in carbon content by as much as 156 $\mu\text{g/g}$. Such variations indicate that many more analyses of spatter samples, together with modifications in analytical procedure (such as stepwise combustion for carbon analysis), are needed before the possible existence of systematic temporal variations in volatile content of magma can be tested with any confidence. Furthermore, recent studies of volcanic gases from Kilauea rift eruptions indicate remarkable uniformity in the contents and propor-

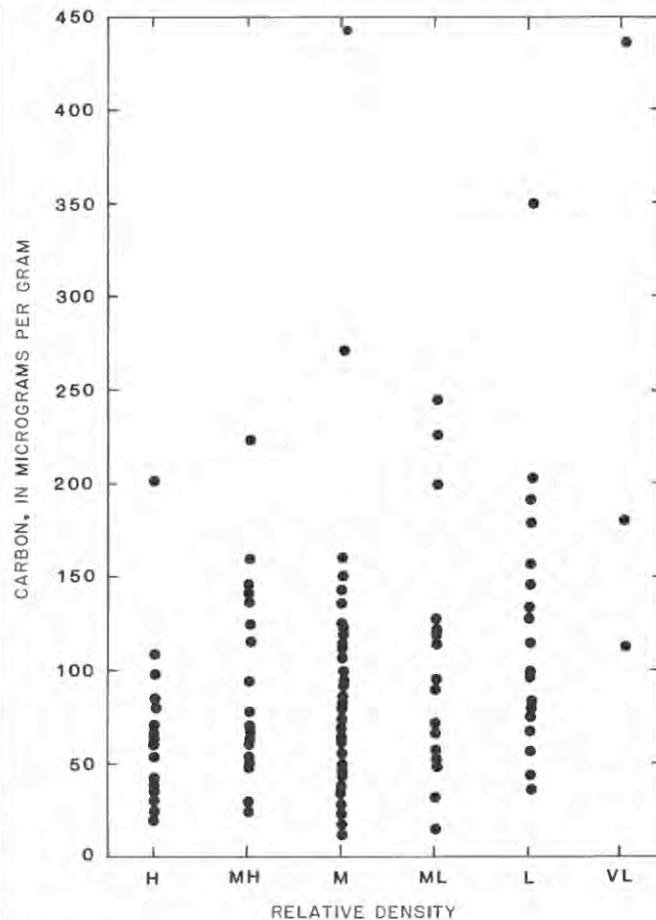


FIGURE 31.5.—Carbon contents of Kilauea and Mauna Loa lava samples plotted by relative density estimated qualitatively from visible vesicularity. H, high; MH, moderately high; M, moderate; ML, moderately low; L, low; VL, very low.

tions of the carbon and sulfur gases (Greenland, 1984; Gerlach and Graeber, 1985; Greenland and others, 1985). Such uniformity implies that the magma source region in the mantle beneath Hawaii is very homogeneous in volatile contents and, correspondingly, that variation in the volatile content of Hawaiian eruptive magmas may be so slight as to be extremely difficult to demonstrate with presently available sampling and analytical techniques.

DISCUSSION

In our broad survey of recently erupted subaerial Hawaiian basalts, the total sulfur abundances ranged from 37 to 15,025 $\mu\text{g/g}$ (median value 153 $\mu\text{g/g}$). The greatest sulfur abundances were found in a stalactite sample and wall glaze from an active lava tube. Presumably the stalactite sample served as a cold surface on which sulfur had condensed and accumulated; evidence of elemental sulfur deposits could be observed on the sample. The sulfur abundances for the subaerial basalts we analyzed are lower by a factor of 4 to 6

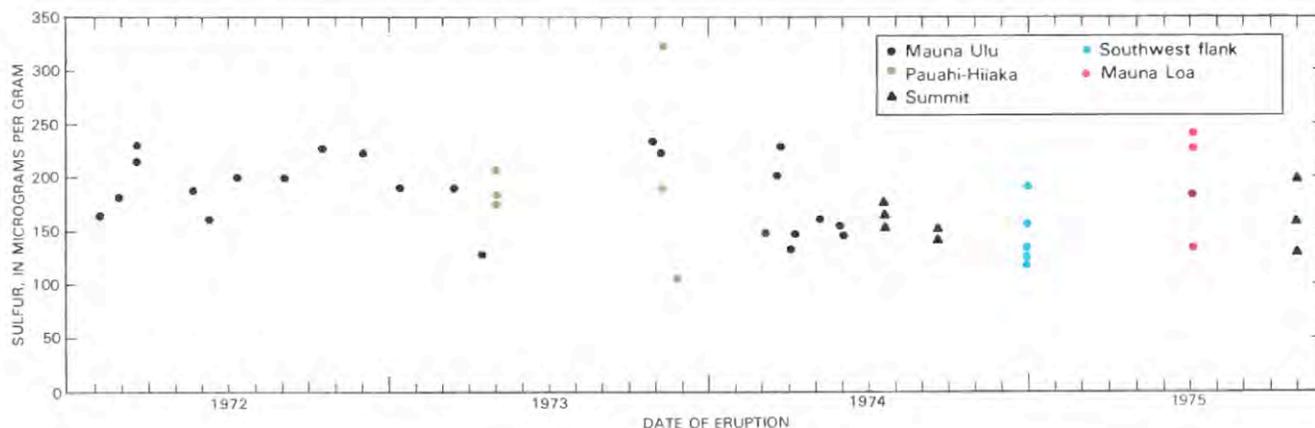


FIGURE 31.6.—Sulfur content of Kilauea and Mauna Loa lava spatter samples plotted by date of eruption.

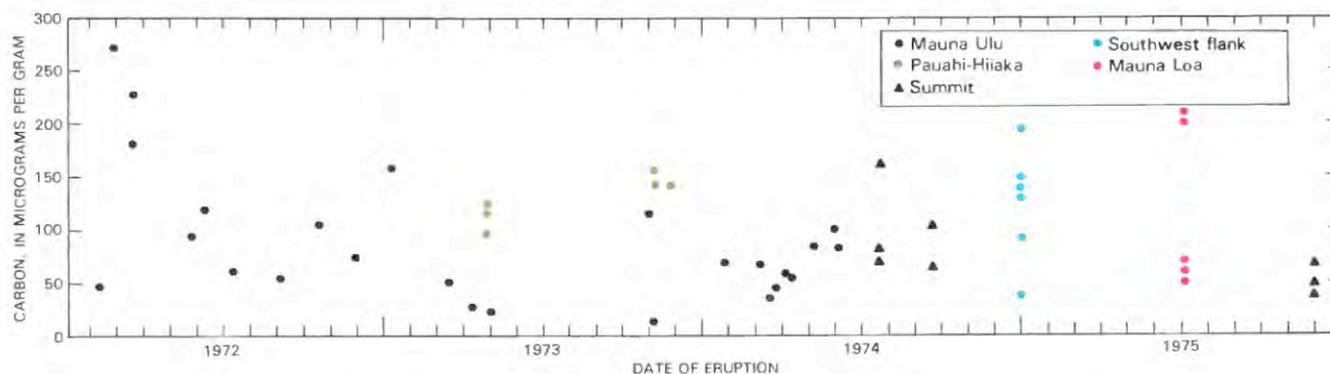


FIGURE 31.7.—Carbon content of Kilauea and Mauna Loa lava spatter samples plotted by date of eruption.

than those reported for submarine basaltic glasses (Des Marais and Moore, 1984; Sakai and others, 1984).

Sulfur abundances for ocean-floor basalts range from 60 to 990 $\mu\text{g/g}$ (Moore and Fabbi, 1971; Moore and Schilling, 1973; Killingley and Muenow, 1975; Delaney and others, 1978; Naldrett and others 1978; Garcia and others, 1979; Des Marais and Moore, 1984; Sakai and others, 1984). The upper value approaches the inferred limit of saturation for lavas dredged at water depths exceeding 200 meters (Moore and Calk, 1971; Mathez, 1976). Swanson and Fabbi (1973) noted that recent subaerially erupted basalts contain 50 to 2,000 $\mu\text{g/g}$ S, with the lower value typical of degassed samples and the upper value characteristic only of glass inclusions in phenocrysts (Anderson, 1974). Naldrett and Goodwin (1977) and Naldrett and others (1978) found that the sulfur contents of Archean basalts range between zero and 8,000 $\mu\text{g/g}$, with a maximum frequency near 1,000 $\mu\text{g/g}$. Their interpretation of these S concentrations, which are extraordinarily high compared to those of recent basalts, is that the retention of sulfur, despite extensive redistribution by metamorphism, resulted from the

rapid accumulation of the Archean volcanic pile, allowing little interaction with seawater.

Carbon abundances of the basalts we analyzed range from 11 to 1,099 $\mu\text{g/g}$ (median value 69 $\mu\text{g/g}$). The median value falls within the range of total carbon values reported for submarine basalts (see Des Marais and Moore, 1984; Sakai and others, 1984). However, our range of carbon contents in the subaerial basalts of Kilauea and Mauna Loa is considerably greater (by a factor of 4–5) than that for submarine basalts, contrary to what would be expected from subaerial (degassed) samples. Although additional factors may help account for this anomaly, we suspect that posteruption contamination by atmospheric carbon is most likely the principal cause of the wide dispersion observed in our data.

In terrestrial basalts, carbon is present usually as CO_2 , the second most abundant volatile associated with volcanic systems. Most other volcanic gases are far more soluble in basaltic melts than CO_2 (Anderson, 1975), and this carbon gas species should dominate the vapor phase at fairly high pressures (about 400 MPa), in accordance with the experimental data of Kadik and others (1972).

Because the samples analyzed in this study were powders, most or all of the carbon dioxide that might have been present within vesicles in the rock has been lost during sample preparation. The total carbon abundances we measured represent the combined contributions of magmatic carbon (dissolved CO₂ in the glass) and nonmagmatic carbon acquired by the sample after eruption. Some of the samples contained olivine phenocrysts, generally making up less than 2 percent of the sample, and these phenocrysts were not removed from the sample. Any CO₂ inclusions in the phenocrysts therefore also contributed, though probably only a minor amount, to the total carbon abundance. For several submarine basalts from Kilauea's east rift zone, the carbon dissolved in the glass (released at combustion temperatures 1,200 to 1,270 °C) constituted 49 to 85 percent of the total carbon abundance (Des Marais and Moore, 1984, table 1). However, for a subaerial Kilauea basalt they analyzed, the carbon released in the high-temperature combustion represented only 5 percent of the total carbon.

For subaerial basaltic volcanism, Swanson and Fabbi (1973), on the basis of limited data, suggested that carbon dioxide volatilization does not vary appreciably with fountaining activity or with distance of lava flowage. If this is so, it implies that because of its low solubility in basaltic melt, CO₂ escapes very rapidly during the onset of eruptive activity and during the effervescent stage immediately preceding. In addition, recent studies of volcanic gases at Kilauea (Gerlach and Graeber, 1985; Greenland and others, 1985; Greenland, in press) indicate that substantial loss of CO₂ from the magma may occur during storage in the volcano's summit reservoir (at a depth of 2–6 km). In order to obtain a direct estimate of the magmatic carbon in subaerially erupted basalts and of the variations in its abundance induced by degassing, it would require determination of individual abundances for the various forms of carbon that contribute to the total carbon abundance. Such studies would need to use analytical procedures involving stepwise combustion and sample preparation methods similar to those used in the recent detailed studies of submarine basalts (for example, Des Marais and Moore, 1984). We hope that our broad data base of total carbon and sulfur abundances in fresh subaerial basalts from Kilauea and Mauna Loa will provide a starting point for the subsequent, more systematic studies required to evaluate the carbon budget in the subaerial eruption and attendant degassing of basaltic lavas.

REFERENCES CITED

- Anderson, A.T., 1974, Chlorine, sulfur, and water in magmas and oceans: *Geological Society of America Bulletin*, v. 85, no. 9, p. 1485–1492.
- 1975, Some basaltic and andesitic gases: Review of Geophysics and Space Physics, v. 13, no. 1, p. 37–55.
- Basaltic Volcanism Study Project, 1981, Volatiles in planetary basalts: hydrogen, carbon, and sulfur gas species, in *Basaltic Volcanism on the Terrestrial Planets*: New York, Pergamon Press, Inc., p. 385–398.
- Delaney, J.R., Muenow, D.W., and Graham, D.G., 1978, Abundance and distribution of water, carbon and sulfur in the glassy rims of submarine pillow basalts: *Geochimica et Cosmochimica Acta*, v. 42, no. 6B, p. 581–594.
- Des Marais, D.J., and Moore, J.G., 1984, Carbon and its isotopes in mid-oceanic basaltic glasses: *Earth and Planetary Science Letters*, v. 69, p. 43–57.
- Garcia, M.O., Liu, N.W., and Muenow, D.W., 1979, Volatiles in submarine volcanic rocks from the Mariana Island arc and trough: *Geochimica et Cosmochimica Acta*, v. 43, no. 3, p. 305–312.
- Gerlach, T.M., 1980, Evaluation of volcanic gas analyses from Kilauea Volcano: *Journal of Volcanology and Geothermal Research*, v. 7, no. 3–4, p. 295–317.
- 1982, Interpretation of volcanic gas data from tholeiitic and alkaline mafic lavas: *Bulletin Volcanologique*, v. 45–3, p. 235–244.
- Gerlach, T.M., and Graeber, E.J., in press, The volatile budget of Kilauea Volcano: *Nature*.
- Gibson, E.K., Jr., Chang, S., Lennon, K., Moore, G.W., and Pearce, G.W., 1975, Sulfur abundances and distributions in mare basalts and their source magmas: *Proceedings 6th Lunar Science Conference*, p. 1287–1301.
- Gibson, E.K., Jr., and Moore, G.W., 1973, Carbon and sulfur abundances in lunar fines: *Proceedings 4th Lunar Science Conference*, p. 1577–1586.
- 1974, Sulfur abundances and distributions in the valley of Taurus-Littrow, in *Lunar Science Conference, 5th, Houston, Tex., 1974, Proceedings: Geochimica et Cosmochimica Acta*, supp. 5, v. 2, p. 1823–1837.
- Greenland, L.P., 1984, Gas composition of the January 1983 eruption of Kilauea Volcano, Hawaii: *Geochimica et Cosmochimica Acta*, v. 48, p. 193–195.
- in press, Estimated mantle content of volatiles from basaltic gas composition: *Journal of Geology*.
- Greenland, L.P., Casadevall, T.J., and Stokes, J.B., in press, Emission rate of CO₂ and SO₂ from Kilauea Volcano, Hawaii: *Nature*.
- Greenland, L.P., Rose, W.I., and Stokes, J.B., 1985, An estimate of gas emissions and magmatic gas content from Kilauea Volcano: *Geochimica et Cosmochimica Acta*, v. 49, no. 1, p. 125–130.
- Harris, D.M., 1981, The concentration of CO₂ in submarine basalts: *Journal of Geology*, v. 89, p. 689–701.
- Harris, D.M., and Anderson, A.T., 1983, Concentrations, sources and losses of H₂O, CO₂, and S in Kilauean basalt: *Geochimica et Cosmochimica Acta*, v. 47, p. 1139–1150.
- Hoffman, A.W., Feigenson, M.D., and Raczek, Ingrid, 1984, Case studies on the origin of basalt: III. Petrogenesis of the Mauna Ulu eruption, Kilauea, 1969–71: *Contributions to Mineralogy and Petrology*, v. 88, p. 24–35.
- Javoy, M., Pineau, F., and Allegre, C., 1982, Carbon geodynamic cycle: *Nature*, v. 300, p. 171–173.
- Javoy, M., Pineau, F., and Iiyama, I., 1978, Experimental determination of the isotopic fractionation between gaseous CO₂ and carbon dissolved in tholeiitic magma: *Contributions to Mineralogy and Petrology*, v. 67, p. 35–39.
- Kadik, A.A., Lukanin, O.A., Lebedev, Y.B., and Korovushkina, E.Y., 1972, Solubility of H₂O and CO₂ in granite and basalt melts at high pressures: *Geochemistry International*, v. 6, p. 1041–1050.
- Killingley, L.S., and Muenow, D.W., 1975, Volatiles from Hawaiian submarine basalts determined by dynamic high temperature mass spectrometry: *Geochimica et Cosmochimica Acta*, v. 39, p. 1467–1473.
- Kyser, T.K., and O'Neil, J.R., 1984, Hydrogen isotope systematics of submarine basalts: *Geochimica et Cosmochimica Acta*, v. 48, p. 2123–2133.
- Lockwood, J.P., Koyanagi, R.Y., Tilling, R.I., Holcomb, R.T., and Peterson, D.W., 1976, Mauna Loa threatening: *Geotimes*, v. 21, no. 6, p. 12–15.
- Mathez, E.A., 1976, Sulfur solubility and magmatic sulfides in submarine basalt glass: *Journal of Geophysical Research*, v. 81, p. 4269–4276.
- Mattey, D.P., Carr, R.H., Wright, I.P., and Pillinger, C.T., 1984, Carbon isotopes in submarine basalts: *Earth and Planetary Science Letters*, v. 70, p. 196–206.
- Moore, J.G., and Calk, L., 1971, Sulfide spherules in vesicles of dredged pillow basalt: *American Mineralogist*, v. 56, p. 476–488.
- Moore, J.G., and Fabbi, B.P., 1971, An estimate of the juvenile sulfur content of basalt: *Contributions to Mineralogy and Petrology*, v. 33, p. 118–127.
- Moore, J.G., and Schilling, J.G., 1973, Vesicles, water, and sulfur in Reykjanes Ridge basalts: *Contributions to Mineralogy and Petrology*, v. 41, p. 105–118.
- Muenow, D.W., Graham, D.G., and Liu, N.W.K., 1979, The abundance of volatiles in Hawaiian tholeiitic submarine basalts: *Earth and Planetary Science Letters*, v. 42, p. 71–76.
- Naldrett, A.J., and Goodwin, A.M., 1977, Volcanic rocks of the Blake River Group, Abitibi Greenstone Belt, Ontario, and their sulfur content: *Canadian Journal of Earth Sciences*, v. 14, p. 539–550.
- Naldrett, A.J., Goodwin, A.M., Fisher, T.L., and Ridler, R.H., 1978, The

- sulfur content of Archean volcanic rocks and a comparison with ocean-floor basalts: *Canadian Journal of Earth Sciences*, v. 15, p. 715-728.
- Peterson, D.W., and Tilling, R.I., 1980, Transition of basaltic lava from pahoehoe to aa, Kilauea Volcano, Hawaii: Field observations and key factors: *Journal of Volcanology and Geothermal Research*, v. 7, p. 271-293.
- Sakai, H., Des Marais, D.J., Ueda, A., and Moore, J.G., 1984, Concentrations and isotope ratios of carbon, nitrogen, and sulfur in ocean-floor basalts: *Geochimica et Cosmochimica Acta*, v. 48, no. 12, p. 2433-2442.
- Sparks, R.S.J., and Pinkerton, H., 1978, The effect of degassing on the rheology of basaltic lava: *Nature*, v. 276, p. 385-386.
- Swanson, D.A., 1973, Pahoehoe flows from the 1969-71 Mauna Ulu eruption, Kilauea Volcano: *Geological Society of America Bulletin*, v. 84, p. 615-626.
- Swanson, D.A., and Fabbri, B.P., 1973, Loss of volatiles during fountaining and flowage of basaltic lava at Kilauea Volcano, Hawaii: U.S. Geological Survey *Journal of Research*, v. 1, p. 649-658.
- Tilling, R.I., Koyanagi, R.Y., Lipman, P.W., Lockwood, J.P., Moore, J.G., and Swanson, D. A., 1976, Earthquake and related catastrophic events, Island of Hawaii, November 29, 1975: A preliminary report: U.S. Geological Survey Circular 740, 33 p.
- Williams, Howel, and McBirney, A.R., 1979, *Volcanology*: San Francisco, Freeman, Cooper & Co, 397 p.
- Wright, T.L., 1971, Chemistry of Kilauea and Mauna Loa lava in space and time: U.S. Geological Survey Professional Paper 735, 40 p.
- Wright, T.L., Swanson, D.A., and Duffield, W.A., 1975, Chemical compositions of Kilauea east-rift lava, 1968-1971: *Journal of Petrology*, v. 16, p. 110-133.
- Wright, T.L., and Tilling, R.I., 1980, Chemical variations in Kilauea eruption 1971-74: *American Journal of Science*, v. 280-A, p. 777-793.