

HAWAIIAN ERUPTIVE GASES

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ABSTRACT

Analysis of eruptive gases began at Kilauea Volcano in 1912. After the classic gas collections of 1917-19, there was a lapse of 40 years until sampling of eruptive gases recommenced in 1960. This paper summarizes results of gas analyses from Kilauea for the 1912-19 and 1968 Halemaumau eruptions, two summit eruptions in 1982, the 1960, 1965, 1977, and 1983-84 east-rift eruptions, and a shallow southwest-rift intrusion in 1981. Also included are results from the 1919 and 1984 eruptions of Mauna Loa. These data show the following: (1) Hawaiian eruptive gases predominantly have one of two compositions, defined by an atomic carbon/sulfur ratio (C/S) of ~ 0.2 for gases exsolving from magma that has had even brief storage in shallow summit reservoirs, and (much less commonly) a C/S ratio of ~ 2 for gases associated with eruptions of magma directly from the mantle. (2) The major causes of compositional variation in these gases is the introduction of varied amounts of assimilated crustal water and near-surface mixing of meteoric water. (3) The total volatile content of Hawaiian magma stored in summit reservoirs is approximately uniform and amounts to less than 0.5 weight percent.

INTRODUCTION

Studies of eruptive gas at Kilauea Volcano began in 1912 with collections from an active lava lake by Day and Shepherd (1913). Because of the sampling technique, only partial analyses of these gases could be obtained. Improvements in sampling and analytical procedures resulted in the first complete volcanic gas analyses in 1917 (Shepherd, 1919) and the culminating studies of T.A. Jaggar's classic collections of 1918-19 (Shepherd, 1921). Between 1919 and 1980, sporadic collections of volcanic gas associated with eruptive activity at Kilauea were obtained from vents during the 1960 east-rift eruption (Heald and others, 1963), from an actively filling lava lake (Finlayson and others, 1968), and from the 1977 east-rift eruption (Graeber and others, 1979).

Systematic gas studies were reinstated at the Hawaiian Volcano Observatory with the installation of modern gas-analysis facilities in 1980. Partial analyses were obtained of gases from a near-surface intrusion in 1981 and from two summit eruptions in 1982; both partial and complete analyses have been obtained from the episodic east-rift eruption of 1983-4 and from the 1984 eruption of Mauna Loa. The present paper summarizes previous work on eruptive gases and describes heretofore unpublished results of the 1981-84 partial analyses. Complete gas analyses of the 1983-84 east-rift eruption of Kilauea and of the Mauna Loa eruption are being described concurrently (Greenland, chapter 30) and will not be considered here.

To improve comparability, all analyses cited from the literature have been recalculated to an air-free basis. Furthermore, I have followed Matsuo (1962) in apportioning the S_2 reported in the 1917-19 analyses to H_2S and SO_2 , and, where reported, SO_3 to SO_2 ; for the 1981-84 partial analyses, I have assumed thermodynamic equilibrium in the gases in order to estimate apparent-equilibrium H_2O and H_2S contents. The effects of oxidation and of temperature on the composition of volcanic gas samples have been avoided by considering the analyses on an atomic basis (that is, all hydrogen-bearing species are combined to yield a value for total atomic hydrogen, and so on), and these values form the basis for most of the discussion.

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RESULTS AND DISCUSSION

GAS COLLECTIONS FROM 1912 TO 1919

Analyses of gases collected from a continuously active lava lake in Kilauea's caldera over this period are given in table 28.1, which also includes two samples from the 1919 eruption of Mauna Loa. The equilibrium compositions of the 1918-19 gas collections as estimated by Gerlach (1980) also are included in table 28.1 for reference.

The 1912 gases were collected by a pumping technique, and thus only the concentrations of gases insoluble in the acid aqueous condensate (CO_2 , H_2 , and CO) could be determined; these provide too little information for interpretation, though it is notable that temperatures (1,150-1,250 °C) inferred from the CO_2/CO ratio (from equations 1 and 5, see below) are reasonable for a protracted summit eruption.

The 1917-19 analyses have been discussed extensively (Shepherd, 1938; Jaggar, 1940; Matsuo, 1962; Nordlie, 1971; Gerlach, 1980); conclusions have ranged from Shepherd's (1921, p. 87) "We are not here dealing with a mixture of gas which is definite in composition and given off steadily by the magma. Each bubble has its own composition, ***" to Gerlach's (1980, p. 303) "****(after making allowance for meteoric water contamination)*** (1) the erupted gases initially had compositions closely approaching equilibrium, and (2) the reacting gases were quenched at some temperature near the collection temperature." These views are less far

TABLE 28.1.—Composition of Hawaiian eruptive gases, 1912–1919

[n.d., not determined; ---, not detected]

Sample	Constituents (mole percent)						Atomic ratios	
	H ₂ O	H ₂	CO ₂	CO	SO ₂	H ₂ S	H/S	C/S
1912 Kilauea Summit (Day and Shepherd, 1913)								
D-1 ----	n.d.	7.2	23.8	5.6	n.d.	n.d.	n.d.	n.d.
D-2 ----	n.d.	6.7	58.0	3.9	n.d.	n.d.	n.d.	n.d.
D-8 ----	n.d.	7.5	62.3	3.5	n.d.	n.d.	n.d.	n.d.
D-11 ----	n.d.	7.0	59.2	4.6	n.d.	n.d.	n.d.	n.d.
D-17 ---	n.d.	10.2	73.9	4.0	n.d.	n.d.	n.d.	n.d.
1917 Kilauea Summit (Shepherd, 1919)								
S-1 ----	87.8	5.45	3.42	1.34	.809	1.20	96.7	2.36
S-2 ----	61.4	2.16	28.7	.575	6.13	1.04	18.0	4.08
S-3 ----	20.5	1.78	38.1	1.62	35.3	2.72	1.31	1.04
S-4 ----	69.7	1.28	10.0	3.53	5.16	10.3	10.5	.875
S-5 ----	70.2	1.66	10.3	1.21	12.7	3.93	9.11	.692
S-6 ----	90.6	.212	1.99	.827	2.77	3.63	29.5	.440
S-7 ----	67.8	.803	18.2	.655	11.0	1.50	11.2	1.51
S-8 ----	75.5	.704	15.4	.452	7.35	.657	19.2	1.98
S-9 ----	64.7	1.96	8.98	.885	19.9	3.57	5.98	.420
S-10 ----	90.5	.372	1.55	.433	2.39	4.78	26.7	.277
1918–19 Kilauea Summit (Shepherd, 1921)								
J-2 ----	85.3	---	6.58	---	8.14	---	21.0	0.808
J-3 ----	83.6	.156	6.90	.229	9.10	---	18.4	.783
J-4 ----	87.4	.175	6.99	.144	5.05	.206	33.4	1.36
J-6 ----	98.4	.088	1.09	.200	.175	---	1130.	7.37
J-8 ----	37.1	.493	48.9	1.50	11.9	.055	6.30	4.22
J-10 ----	60.0	.118	19.4	.130	20.2	.079	5.94	.963
J-11 ----	64.2	.334	21.8	.615	12.7	.348	9.95	1.72
J-12 ----	97.8	.081	1.43	.050	.561	.094	299.0	2.26
J-13 ----	69.9	.994	17.6	.601	10.8	.124	13.0	1.67
J-14 ----	79.1	.175	15.2	.484	4.88	.137	31.7	3.13
J-15 ----	79.0	.107	12.3	.139	8.40	.043	18.7	1.47
J-16 ----	68.4	.692	18.6	.578	11.5	.206	11.8	1.64
J-17 ----	80.2	.587	11.7	.374	6.72	.324	23.0	1.71
J-18 ----	64.8	.869	18.4	.775	14.8	.307	8.73	1.27
1918–19 Kilauea Summit: estimated equilibrium composition (Gerlach, 1980)								
J-8 ----	37.1	.490	48.9	1.51	11.8	0.040	6.36	4.26
J-11 ----	40.1	.550	36.7	1.03	21.1	.200	3.84	1.77
J-13 ----	69.3	1.01	17.8	.620	10.9	.080	12.8	1.68
J-14 ----	35.1	.540	47.4	1.52	15.1	.150	4.69	3.21
J-16 ----	60.4	.870	23.2	.740	14.3	.140	8.50	1.66
J-17 ----	66.0	1.02	20.3	.620	11.4	.320	11.5	1.78
J-18 ----	58.1	1.03	21.8	.930	17.5	.170	6.71	1.29
1919 Mauna Loa (Shepherd, 1920)								
ML-1 ---	75.4	---	3.84	0.03	3.30	---	45.7	1.16
ML-2 ---	67.4	.01	6.42	.19	10.07	---	13.5	.66

apart than one might think: Gerlach (1980) recognizes the effects of oxidation and of shallow degassing of CO₂ on these compositions; furthermore, thermodynamic analyses such as Gerlach's are concerned with the relative proportions of oxidized and reduced species rather than the relative proportions of all hydrogen-bearing, carbon-bearing, and sulfur-bearing species. In addition, it may indeed be possible that each bubble has its own composition and yet approaches equilibrium when one considers the possible effects of differential degassing with pressure and of the incorporation of air and water into the vent system by a chimney effect. The highly porous edifice of Kilauea combines with the high-temperature vertical pipes of the fissure system to produce a chimney effect whereby air, water vapor, and other gases are pulled through the edifice into the depths of the fissure, heated, expanded, and expelled to the surface. A similar effect has been observed at Pagan Volcano (see Banks and others, 1984.)

The effects of oxidation and temperature, but not of water contamination, can be avoided by considering the analyses on an atomic basis. Table 28.1 includes the analytical values normalized to atoms of S for ease of comparison, and figure 28.1 is a ternary atomic H-C-S plot of these data. If all of these analyses were related simply by water contamination (with or without oxidation effects), the analyses would plot along a water-control line such as the two shown in figure 28.1; in fact, however, there is a large amount of scatter in figure 28.1, implying considerable variation in carbon/sulfur ratio independent of the obvious water variation. Gerlach (1980) attributed this variation to the preferential degassing of the very insoluble CO₂, and he suggested that the most CO₂-rich samples are most characteristic of undegassed magma. On the other hand, preferential degassing of CO₂ at least raises the possibility of the contamination of eruptive magma with deeper released CO₂. Several observations may be made from the plot in figure 28.1: (1) although the 1917 samples show considerably more scatter than the 1918–19 collections, perhaps because of the poorer sampling conditions of 1917 noted by Shepherd (1921), the compositions of the two groups overall are indistinguishable. (2) As noted by Shepherd (1920), the two Mauna Loa samples are similar in composition to the Kilauea samples. (3) The 1918–19 analyses selected as superior by Gerlach (1980) show much less scatter and much closer adherence to a water-control line than does the original complete set. (4) Nearly all samples have an atomic C/S ratio much higher than do collections made since 1979, which follow the water-control line with C/S=0.18 in figure 28.1. The third observation

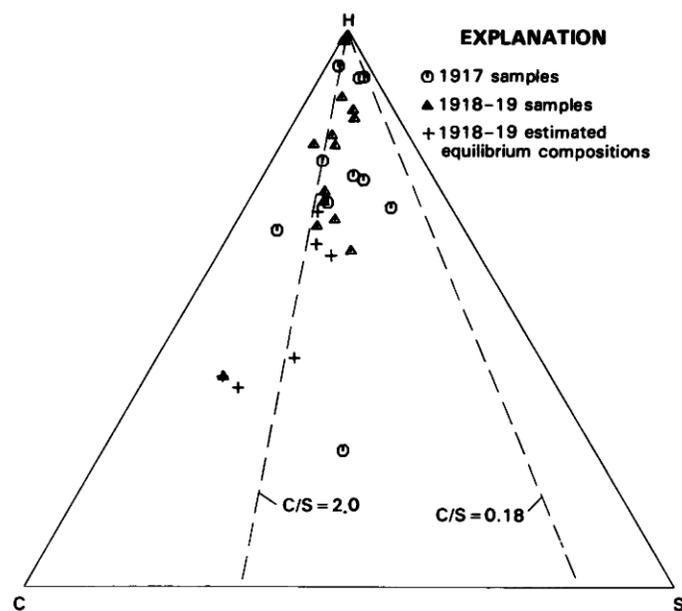


FIGURE 28.1.—Ternary H-C-S plot for 1917–19 Hawaiian eruptive gases. Data from table 28.1. Dashes indicate water-control lines for specific values of the C/S ratio. Atomic hydrogen has been reduced by a factor of 0.5 to increase clarity.

above raises the unanswerable question of how much of the observed scatter in the 1917–19 analyses might be due to analytical error; a modern analyst reading Shepherd's (1925) account of his analytical procedure can only be awed by his skill and meticulous attention to detail, while remaining aware of the inherent limitations imposed by the equipment available to him. The fourth observation above has been attributed to degassing of CO₂ during storage of magma in the summit reservoir of Kilauea, and it forms the basis of recent models (Gerlach and Graeber, 1985; Greenland and others, 1985) of magma-degassing processes at Kilauea.

The two samples from Mauna Loa have been largely neglected in the literature, perhaps because both are highly oxidized and both were collected from a low-temperature (~300 °C) ground crack near advancing lava and about 100 m from the eruptive fissure. However, oxidation does not affect the atomic composition, and it has been my experience that such sampling sites at Kilauea frequently provide excellent gas samples. The significance of these samples is that their C/S ratio is closer to that of the 1917–19 Kilauea collections than to the much lower ratio found for the 1984 Mauna Loa eruption. The distinction between high 1917–19 and low 1983–84 C/S ratios at Kilauea has been attributed to degassing during storage in the summit reservoir (Gerlach and Graeber, 1985; Greenland, and others, 1985; Greenland, in press), and the same mechanism has been invoked to account for the low C/S ratios of the 1984 Mauna Loa gases (Greenland, chapter 30). However, the 1919 Mauna Loa eruption was also a rift eruption and thus the magma would be expected to have passed through, and been degassed in, the summit reservoir; therefore, it is not obvious how the different C/S ratios of the 1919 and 1984 eruptions are to be accounted for. Perhaps the very high content of SO₃ shown in the analysis of 1919 gas (Shepherd, 1920) led to condensation of H₂SO₄ and reaction with wallrock; also, the chemistry of lava erupted on the southwest rift zone differs from that of the northeast rift zone (T.L. Wright, written commun., 1985), indicating a possibility of different storage reservoirs for the two rifts.

KILAUEA GAS COLLECTIONS FROM 1920 TO 1979

Gas collections representing the 1959 Kilauea Iki eruption were made from the degassing cinder cone of Puu Puai and from drill holes in the cooling lava lake (Heald and others, 1963). Both of these sites give information on the degassing of lava after eruption but are only indirectly related to eruptive magmatic gas compositions and will not be considered here.

Three samples were collected from the 1960 east-rift eruption at Kapoho (table 28.2). These samples, collected from a high-temperature fumarole near a lava fountain, are remarkable in showing a significant amount of CH₄ and extremely high water content and C/S ratio. Heald and others (1963) suggest, very reasonably, that these samples have been contaminated by meteoric water and by buried organic matter. In view of the probable high degree of contamination, these analyses shed little light on the nature of magmatic gases.

TABLE 28.2.—Composition of eruptive gases from Kilauea, 1920–1979

[n.d., not determined; —, not detected]

Sample	Constituents (mole percent)							Atomic ratios	
	H ₂ O	H ₂	CO ₂	CO	SO ₂	H ₂ S	CH ₄	H/S	C/S
Kapoho, 1960 East Rift (Heald and others, 1963)									
Ka-1	97.2	0.373	2.34	0.059	0.009	—	0.047	22,000.0	267.0
Ka-2	97.5	.394	1.97	.019	.152	—	.034	1,290.0	13.1
Ka-4	97.2	.432	2.21	.086	.001	.031	.023	6,100.0	71.8
Makaopuhi, 1965 East Rift Lava Lake (Finlayson and others, 1968)									
26-M	67.1	—	8.54	—	24.4	—	—	5.50	0.35
27-M	98.0	.057	1.90	—	—	—	—	n.d.	n.d.
28-M	87.5	.137	1.96	—	6.61	3.79	—	17.6	.19
29-M	97.0	1.125	1.92	—	—	—	—	n.d.	n.d.
38-M	95.8	.011	.597	—	3.60	—	—	26.6	.17
Halemaumau Fountain, 1968 (Naughton and others, 1969)									
HMM-1	95.0	n.d.	4.0	n.d.	1.0	n.d.	n.d.	190.0	4.0
1977 East Rift (Graeber and others, 1979)									
G-5	89.1	—	5.06	—	5.45	—	—	32.7	0.93
G-6	96.9	—	1.99	—	.84	—	—	235.	2.38
G-7	93.6	—	1.87	—	4.42	—	—	42.3	.42

Table 28.2 gives the analyses of five gas samples collected from the filling lava lake at Makaopuhi during the 1965 east-rift eruption. (For further analyses of gas samples from the cooling lava lake, see Finlayson and others, 1968). As shown by the low content of H₂ and the absence of CO, these samples are highly oxidized; the very high water content in four of the samples and the absence of sulfur species in two also raises doubts about the quality of the samples. Nevertheless, on an atomic basis, the three samples that contain detectable sulfur have C/S ratios very similar to the ratios observed in the 1983–84 east-rift eruption (see below) and two of these have H/S ratios in the range of the later analyses. Therefore, although these samples have been subjected to oxidation and, probably, contamination with meteoric water, they are consistent with suggestions (Gerlach and Graeber, 1985; Greenland and others, 1985) that all summit-stored magma at Kilauea has about the same composition of volatiles.

In 1968, Naughton and others (1969) made an interesting direct measurement of the major gases in a lava fountain (Halemaumau eruption of 1967–68, table 28.2) using an infrared technique. Naughton and others (1969) stress the exploratory nature of their study and the tentativeness of the results; nonetheless, fountain-gas measurements obviously are impossible to obtain by conventional sampling procedures, and it is encouraging to note the similarity of this analysis, particularly in C/S ratio, to those of the 1917–19 Halemaumau samples (table 28.1). The high water content in this analysis may be due to uncertainties inherent in the technique (a very large, and not entirely certain, correction was required for atmospheric water in the light path). However, in view of the observation that degassing of melt continues within the fountain (Swanson and Fabbi, 1973), it may be that fountain gas is enriched in water, which, because of its high solubility in the melt, is the last gas to be exsolved. It is unfortunate that this potentially rewarding technique has not been pursued.

Table 28.2 gives analyses of three gas samples from the 1977 east-rift eruption (Graeber and others, 1979). These samples were collected from one of the main vents of the fissure eruption three days after eruption of the sampled vent had ceased; the observation that the samples were almost entirely air and completely oxidized parallels my experience in sampling similar sites during the 1982 summit eruptions, the 1983–84 east-rift eruption, and the 1984 Mauna Loa eruption: sampling gases from major vents after fountaining ceases during fissure eruptions seems unrewarding. A remarkable feature of these analyses is the great variation in C/S ratio, which ranges from 0.4 to 2.4 in the three samples collected within 15 minutes of each other at the same vent. This is a greater range than shown in 14 months of the 1983–84 eruption (see below). Graeber and others (1979) observed reddish flame at this vent during the night, and it may be that the varying C/S ratio reflects pyrolyzing organic matter swept into the vent by the chimney effect, a phenomenon recognized frequently during early stages of the 1983–84 eruption.

KILAUEA GAS COLLECTIONS FROM 1980 TO 1982

During this period, gas samples were collected from a shallow intrusion into the southwest rift zone and from two summit eruptions. Gas samples during these events were collected in flowthrough bottles. The sampling technique and subsequent gas chromatographic analysis have been described previously and the results compared with conventional techniques (Greenland, 1984).

Only partial analyses (H_2 , CO_2 , CO , and SO_2) could be made of these samples, and, for comparison with other eruptions, it is necessary to make an estimate of the H_2O and H_2S content of the gases. Following the procedure described elsewhere (Greenland, chapter 30), equilibrium constants for the elementary oxidation reactions of the major gases can be expressed as

$$\log K1 = 2\log[CO_2/CO] - \log[O_2] \quad (1)$$

$$\log K2 = 2\log[H_2O/H_2] - \log[O_2] \quad (2)$$

$$\log K3 = 2\log[SO_2/H_2S] + \log[H_2] - \log[O_2] \quad (3)$$

and, over a limited temperature range, the temperature dependence of the equilibrium constant can be approximated by

$$\log K = [A/T] + B, \quad (4)$$

where A and B are thermodynamic constants. Complete gas analyses of both the 1983–84 east-rift eruption (Greenland, in press) and of the 1984 Mauna Loa eruption (Greenland, chapter 30) have shown that the partial pressure of oxygen in these gases was buffered by the magma; therefore, $\log[O_2]$ is a linear function of the reciprocal of temperature. Averaging the results from the cited complete analyses yields

$$\log[O_2] = -[18,600/T] + 4.06. \quad (5)$$

Combining equations 1, 4, and 5 makes it possible to estimate an equilibrium temperature for a gas sample from the observed CO_2/CO ratio, and equations 2 and 3 provide estimates of the equilibrium amounts of H_2O and H_2S in the sample.

Table 28.3 provides the estimated equilibrium composition of gas samples collected in the 1980–82 period. These estimates depend on the assumptions that (1) the gases were in thermodynamic equilibrium and (2) there has been no oxidation of CO or H_2 . That many eruptive gas samples approximate equilibrium assemblages has been demonstrated widely (Greenland, chapter 30; Gerlach, 1980, 1982; Greenland, in press). Examination of equations 1 and 2 show that oxidation of CO would yield a low estimate of temperature and a high estimate of water, whereas oxidation of H_2 would result in a low estimate of water. There can be no independent check on the oxidation state of these samples, and therefore the water and temperature estimates should not be taken too literally; on the other hand, as shown below, results from this calculation procedure appear to be generally reasonable and are preferable to no estimate at all. Note that this procedure does not alter the observed gas ratios, and thus the original analyses may be recovered directly from table 28.3.

A major intrusion into the southwest rift zone of Kilauea occurred on August 10, 1981, and resulted in ground cracking over a large area. A small segment of the dike reached within 250 m of the surface (estimated from deformation measurements, A. Okamura, oral commun., 1981) and magmatic gases issued from low-temperature ground cracks in this local area. The estimated equilibrium compositions of samples of these gases (table 28.3) show a rapid change with time. The initial sample has a composition similar to some of the east-rift Makaopuhi and 1983–84 east-rift gases (this paper), but subsequent samples are water-rich and show increasing C/S ratios with continued outgassing. A sample collected the following morning (August 11), after the intrusion had ended, had a C/S ratio of >100 and too little CO to attempt an equilibrium estimate. Because CO_2 is much less soluble than S , the increase of C/S ratio with time cannot reflect degassing of the near-surface melt. Perhaps CO_2 that exsolved from the deeper part of the dike percolated through the local, shallow segment as an easy route to the surface; this would account for the observation that CO_2 emissions from these cracks ceased after a few weeks when, presumably, freezing of the shallow segment of the dike blocked egress for the CO_2 .

A brief fissure eruption adjoining Halemaumau occurred in April 1982. It was impossible to obtain gas samples from the erupting vents, and samples obtained from these vents after fountaining ceased consisted only of air. Two strongly fuming ground cracks, on strike with the fissure and less than 100 m from fountains, provided the analyses given in table 28.3. The initial sample from crack no. 1 has a composition similar to east-rift samples, but the C/S ratio increases rapidly in the subsequent samples, which also become very water rich. The first sample from crack no. 2 already has a high C/S ratio and high water content, and subsequent samples show increases in both parameters. The probable explanation for the increase in C/S ratio with time at these cracks lies in their location at the edge of Halemaumau: it is likely that these cracks tap into the extensive Halemaumau fumarole system; they have continued to emit CO_2 -rich gases typical of these fumaroles through May 1985. The composition of the magmatic gas probably is best

TABLE 28.3.—Composition of eruptive gases from Kilauea, 1980–1982
[—, no data]

Collection		Temperature (°C)		Constituents (mole percent)						Atomic ratios	
Date	Hour	Collection	Equilibrium	H ₂ O	H ₂	CO ₂	CO	SO ₂	H ₂ S	H/S	C/S
AUGUST 1981 SOUTHWEST-RIFT-ZONE INTRUSION											
8/10/81	0800	84	878	83.222	0.524	3.772	0.029	11.379	1.073	13.623	0.305
	1200	84	810	93.688	.388	1.497	.006	3.906	.515	42.792	.340
	1530	82	919	90.178	.714	3.165	.034	5.421	.487	30.930	.541
	1730	82	823	91.709	.413	3.713	.017	3.692	.456	44.630	.899
APRIL 1982 SUMMIT ERUPTION											
Ground crack No. 1											
4/30/82	1540	94	1,002	79.712	0.962	3.064	0.063	15.228	0.972	10.080	0.193
	1745	85	755	94.943	.268	3.766	.008	.872	.143	187.923	3.719
	1940	80	712	94.487	.192	4.713	.006	.503	.097	315.613	7.859
	2210	79	689	94.143	.159	5.427	.006	.218	.046	713.306	20.537
	2400	--	652	93.509	.115	6.241	.004	.105	.026	1,432.087	47.747
Ground crack No. 2											
	1530	82	909	89.578	0.672	3.333	0.033	5.846	0.538	28.442	0.527
	1735	86	816	92.110	.397	4.211	.018	2.897	.367	56.906	1.296
	1940	85	743	93.566	.242	4.844	.009	1.145	.194	140.410	3.625
	2220	82	698	94.369	.172	5.343	.006	.091	.019	1,732.875	49.017
SEPTEMBER 1982 SUMMIT ERUPTION											
Ground cracks											
9/25/82	1910	22	1,128	87.644	1.813	1.732	0.080	8.297	0.434	20.591	0.208
	1920	40	1,113	88.580	1.726	1.236	.052	7.971	.435	21.589	.153
	2000	85	1,132	87.261	1.833	1.299	.062	9.076	.469	18.766	.143
Active vent											
9/25/82	2300	1,120	1,004	47.068	0.573	6.239	0.129	44.316	1.675	2.145	0.138
	2325	1,070	1,042	72.311	1.048	3.261	.088	22.129	1.164	6.399	.144
9/26/82	0125	--	995	78.632	.914	3.488	.067	15.878	1.020	9.536	.210
	0405	--	958	91.220	.887	.974	.014	6.384	.521	26.830	.143

approximated by the first sample from crack no. 1.

Another brief summit eruption of Kilauea took place in the south caldera in September 1982. Actively fountaining vents were unapproachable, but fuming ground cracks (the leading edge of the progressively opening fissure) yielded three gas samples (table 28.3). One isolated vent erupted very briefly and then continued to emit a continuous blue-green flame with spatter and occasional small lava overflows for the rest of the eruption; this provided the gas samples identified as from an active vent in table 28.3. Unlike those from the preceding eruption and intrusion, these samples maintain an approximately constant C/S ratio throughout; this ratio is the same as that of the samples considered best from the April 1982 eruption and the 1983–84 east-rift eruption. The active-vent samples show an increase in apparent water content with time. Whether this is a real effect or an anomaly caused by the procedure for estimating water is uncertain. An important observation is the similarity of the gas compositions in very low temperature samples from ground cracks and in high-temperature samples at the active vent: apparently, gases are quenched very rapidly by contact with the cold country rock, a significant result to consider when attempting to sample fissure eruptions.

KILAUEA GAS COLLECTIONS FROM 1983

A middle-east-rift eruption of Kilauea began in January 1983 and has continued episodically (through February 1986). Results of complete analyses of gas samples from this eruption are described

elsewhere (Greenland, in press) and will not be considered here. More than 400 gas samples were collected for partial analysis (CO₂, CO, H₂, and SO₂); more than half of these contained too much air or organic gases or were too greatly oxidized to be of much significance. Tables 28.4–28.8 present the results for the remainder of the samples, selected with the constraints that (1) CO₂ and SO₂ constitute more than 0.1 percent and CO and H₂ more than 0.001 percent of the original sample to ensure adequate determination and (2) the CO/H₂ ratio be less than 0.3 to exclude samples with organic contamination and some of the oxidized samples. Estimated equilibrium temperatures and H₂O and H₂S contents (see above) are included in tables 28.4–28.8; as noted above, these estimates have large uncertainties and only the general tendency of the results can be regarded as significant.

This eruption began as a fissure eruption that provided an abundance of gas sampling sites along a line of vents several kilometers long through January and part of February 1983; by June 1983, the eruption had become localized at a single vent that has provided far fewer gas-sampling opportunities. With the restriction of sampling sites, samples were increasingly collected for complete analysis rather than the rapid partial analyses described here; therefore most of the results in tables 28.4–28.8 refer to the January–March 1983 interval.

These results are summarized in the ternary atomic H-C-S diagram of figure 28.2. This diagram shows that most of the samples adhere closely to a water-control line with a C/S ratio of 0.18. A few of the samples, particularly at higher water contents,

TABLE 28.4.—Composition of gases from east rift eruption of Kilauea, 1983: actively erupting vents

[—, no data]

Sample	Date (mo/d)	Temperature (°C)		Constituents (mole percent)					Atomic ratios		
		Collection	Equilibrium	H ₂ O	H ₂	CO ₂	CO	SO ₂	H ₂ S	H/S	C/S
70	1/10	—	823	68.427	0.308	6.503	0.030	22.611	2.121	5.730	0.264
71	1/10	—	811	67.474	.282	6.508	.026	23.450	2.260	5.447	.254
259	3/31	—	827	57.568	.266	9.151	.043	30.584	2.387	3.653	.279
386	8/12	—	830	65.766	.309	6.453	.031	25.217	2.223	4.978	.236
387	8/13	—	920	74.629	.595	3.485	.038	19.772	1.482	7.218	.166
389	8/13	1,048	1,089	87.004	1.538	1.488	.054	9.386	.530	17.965	.156
390	8/13	820	954	56.578	.539	6.660	.095	34.348	1.780	3.260	.187
391	8/13	820	966	78.035	.790	3.413	.053	16.570	1.139	9.031	.196
393	8/14	820	919	64.112	.508	5.227	.056	28.265	1.831	4.416	.176
394	8/14	820	977	83.633	.895	2.629	.045	11.946	.852	13.343	.209
395	8/14	1,120	1,083	84.515	1.457	2.153	.076	11.177	.623	14.677	.189
396	8/14	1,120	1,035	92.098	1.289	2.158	.055	4.121	.279	42.575	.503
404	9/02	1,115	1,039	85.476	1.222	1.692	.045	10.887	.678	15.110	.150
405	9/02	1,115	1,051	80.879	1.216	2.359	.067	14.636	.841	10.717	.157
406	9/02	1,115	1,024	83.432	1.115	1.972	.047	12.635	.798	12.707	.150
407	9/02	1,110	982	79.500	.870	1.976	.035	16.511	1.108	9.249	.114
408	9/02	1,110	863	58.040	.335	4.311	.029	34.849	2.437	3.262	.116
409	9/03	1,113	1,074	90.476	1.502	1.319	.044	6.279	.381	27.735	.205
410	9/04	1,110	1,078	85.853	1.451	1.435	.049	10.605	.606	15.683	.132
411	9/04	1,110	1,076	85.390	1.429	1.514	.051	10.987	.628	15.058	.135
414	10/28	—	658	68.036	.088	4.118	.003	23.398	4.330	5.228	.149

TABLE 28.5.—Composition of gases from east rift eruption of Kilauea, 1983: presently inactive

[—, no data]

Sample	Date (mo/d)	Temperature (°C)		Constituents (mole percent)					Atomic ratios		
		Collection	Equilibrium	H ₂ O	H ₂	CO ₂	CO	SO ₂	H ₂ S	H/S	C/S
10	1/05	721	1,025	74.674	1.000	4.647	0.111	18.519	1.408	7.842	0.243
11	1/05	721	1,023	71.293	.948	5.543	.131	20.948	1.137	6.645	.257
20	1/05	92	1,025	88.274	1.185	5.412	.130	4.688	.311	35.915	1.109
49	1/07	—	1,116	65.527	1.295	5.373	.233	26.503	1.070	4.925	.203
50	1/07	—	1,108	67.292	1.286	4.934	.203	25.221	1.064	5.299	.195
54	1/09	285	820	48.154	.212	10.515	.046	38.491	2.581	2.481	.257
61	1/09	95	837	56.567	.278	10.208	.053	30.624	2.270	3.594	.312
69	1/09	941	1,071	71.143	1.170	3.295	.108	23.164	1.120	6.048	.140
88	1/13	498	978	50.672	.543	9.150	.156	37.831	1.648	2.678	.236
90	1/14	720	1,083	67.925	1.173	6.170	.217	23.460	1.055	5.723	.261
93	1/14	935	1,082	57.134	.984	6.672	.234	33.697	1.279	3.396	.197
98	1/15	500	963	59.777	.594	4.708	.072	33.079	1.771	3.566	.137
113	1/15	888	1,084	64.240	1.115	6.300	.224	26.976	1.145	4.730	.232
115	1/15	890	1,118	68.469	1.363	5.283	.231	23.660	.993	5.746	.224
116	1/16	888	1,076	71.707	1.202	4.874	.164	21.039	1.014	6.704	.228
118	1/16	888	1,092	71.225	1.277	4.249	.159	22.071	1.019	6.368	.191
119	1/17	887	1,064	75.852	1.209	3.346	.104	18.520	.969	8.008	.177
120	1/17	887	1,048	67.626	1.006	4.054	.114	25.940	1.260	5.139	.153
122	1/18	863	1,052	57.602	.871	5.590	.161	34.364	1.412	3.348	.161
123	1/18	863	1,054	73.850	1.124	3.952	.115	19.918	1.041	7.254	.194
143	2/12	900	990	47.358	.539	5.482	.102	44.752	1.766	2.135	.120
144	2/12	350	1,101	65.042	1.208	4.234	.167	28.181	1.168	4.594	.150
154	2/14	1,008	950	59.720	.557	2.779	.038	34.967	1.938	3.372	.076
155	2/14	1,006	677	58.464	.089	2.734	.002	33.758	4.952	3.281	.071
156	2/14	—	796	33.420	.126	9.531	.033	54.144	2.746	1.276	.168
165	2/15	985	987	67.390	.754	2.113	.039	28.116	1.589	4.695	.072
178	2/17	867	1,023	73.915	.981	3.115	.074	20.746	1.169	6.942	.146
179	2/17	867	1,003	50.070	.607	5.613	.115	41.905	1.690	2.402	.131
187	2/23	975	963	63.474	.631	3.242	.049	30.851	1.752	4.040	.101
188	2/23	975	866	77.200	.452	2.309	.016	18.345	1.678	7.924	.116
194	2/24	930	898	69.084	.487	3.968	.036	24.597	1.828	5.404	.152
195	2/24	930	896	69.048	.480	3.972	.035	24.622	1.843	5.394	.151
250	3/29	230	765	30.731	.093	8.753	.022	57.391	3.010	1.120	.145
275	4/05	900	716	41.175	.086	7.202	.010	47.427	4.099	1.761	.140
279	4/07	—	873	80.300	.492	2.025	.015	15.711	1.457	9.582	.119
281	4/08	832	842	82.835	.421	1.840	.010	13.470	1.424	11.371	.124
285	4/08	862	817	73.319	.317	3.067	.013	21.114	2.170	6.511	.132
311	5/06	810	685	48.394	.079	5.679	.006	41.046	4.797	2.324	.124
315	5/16	795	805	83.659	.334	2.477	.009	12.058	1.462	12.641	.184
317	5/20	765	839	71.198	.354	4.160	.022	22.212	2.053	6.067	.172
322	5/24	750	778	85.187	.284	2.143	.006	10.897	1.483	14.047	.174
323	5/24	750	783	85.164	.294	2.225	.007	10.860	1.450	14.120	.181

TABLE 28.6.—Composition of gases from east rift eruption of Kilauea, 1983: ground cracks near eruptive center

[—, no data]

Sample	Date (mo/d)	Temperature (°C)		Constituents (mole percent)						Atomic ratios	
		Collection	Equilibrium	H ₂ O	H ₂	CO ₂	CO	SO ₂	H ₂ S	H/S	C/S
2	1/03	140	1,143	63.183	1.388	7.571	0.385	26.498	0.974	4.772	0.290
3	1/03	141	1,296	74.433	2.771	4.913	.557	16.782	.545	8.974	.316
22	1/05	205	1,034	68.096	.952	4.723	.121	24.852	1.256	5.386	.186
23	1/05	88	1,012	71.712	.907	3.752	.082	22.295	1.252	6.274	.163
24	1/06	80	1,023	86.327	1.144	2.894	.068	8.979	.588	18.409	.310
25	1/06	77	970	91.516	.944	2.283	.037	4.838	.383	35.565	.444
26	1/06	78	1,070	80.157	1.312	3.563	.116	14.085	.766	11.075	.248
27	1/06	67	1,045	85.588	1.253	4.105	.113	8.423	.518	19.541	.472
28	1/06	82	1,075	88.020	1.472	3.915	.131	6.103	.359	27.809	.626
29	1/06	78	1,052	86.814	1.315	4.781	.138	6.551	.401	25.469	.708
30	1/06	78	1,047	87.346	1.293	4.826	.135	6.025	.375	27.817	.775
31	1/06	77	1,056	89.185	1.370	4.605	.136	4.429	.276	38.610	1.008
32	1/06	—	1,054	90.351	1.376	4.401	.128	3.521	.223	49.119	1.210
34	1/06	335	1,084	77.589	1.343	3.263	.115	16.829	.861	9.021	.191
46	1/06	48	1,107	83.573	1.589	6.113	.250	8.055	.420	20.196	.751
47	1/07	69	1,091	76.085	1.359	5.081	.188	16.475	.812	9.054	.305
72	1/11	90	919	64.839	.514	5.442	.059	27.354	1.792	4.607	.189
73	1/11	91	830	62.308	.293	6.589	.032	28.402	2.376	4.222	.215
74	1/11	—	860	72.512	.411	5.159	.033	20.122	1.762	6.826	.237
75	1/11	88	888	76.237	.508	4.909	.041	16.884	1.421	8.540	.270
162	2/14	330	941	45.600	.406	8.355	.107	43.638	1.894	2.104	.186
167	2/15	835	1,007	62.530	.771	2.588	.055	32.439	1.617	3.812	.078
168	2/15	835	1,010	60.083	.751	2.693	.058	34.762	1.654	3.432	.076
169	2/15	440	791	69.461	.252	1.661	.005	25.844	2.776	5.066	.058
198	2/27	385	1,031	62.644	.863	4.091	.102	30.850	1.449	4.022	.130
199	2/27	275	1,045	50.472	.740	4.979	.137	42.127	1.544	2.416	.117
205	3/01	270	892	44.853	.305	9.908	.085	42.741	2.108	2.108	.223
211	3/04	83	712	68.129	.139	11.184	.015	17.969	2.563	6.900	.545
212	3/04	244	766	40.682	.125	10.502	.027	45.520	3.143	1.806	.216
244	3/28	210	661	43.642	.058	7.842	.006	43.346	5.106	2.015	.162
249	3/29	125	660	61.175	.081	6.607	.005	27.576	4.556	4.096	.206
251	3/29	—	749	40.860	.111	7.646	.016	47.811	3.556	1.734	.149
329	6/13	67	965	55.816	.561	2.267	.035	39.361	1.961	2.824	.056
330	6/13	85	1,010	87.580	1.094	5.17	.011	10.105	.693	16.553	.049
331	6/13	117	999	57.747	.687	2.199	.044	37.559	1.765	3.062	.057

TABLE 28.7.—Composition of gases from east rift eruption of Kilauea, 1983: ground cracks distant from eruption center

[—, no data]

Sample	Date (mo/d)	Temperature (°C)		Constituents (mole percent)						Atomic ratios	
		Collection	Equilibrium	H ₂ O	H ₂	CO ₂	CO	SO ₂	H ₂ S	H/S	C/S
13	1/05	571	1,079	61.882	1.051	5.253	0.180	30.375	1.258	4.058	0.172
14	1/05	561	1,106	69.929	1.326	4.113	.167	23.434	1.031	5.909	.175
15	1/05	441	1,108	68.678	1.313	5.441	.224	23.339	1.004	5.833	.233
16	1/05	441	1,111	70.619	1.370	4.614	.194	22.228	.975	6.289	.207
17	1/05	420	1,079	65.772	1.117	5.367	.185	26.398	1.160	4.939	.201
18	1/05	—	1,066	64.907	1.041	4.991	.157	27.665	1.239	4.649	.178
51	1/09	72	858	85.494	.478	5.663	.036	7.551	.778	20.831	.684
52	1/09	86	816	66.681	.287	6.933	.030	23.838	2.231	5.309	.267
53	1/09	6	894	77.888	.535	9.650	.084	10.924	.919	13.399	.822
55	1/09	160	803	55.117	.218	10.728	.040	31.350	2.546	3.415	.318
62	1/09	150	923	58.210	.470	5.872	.065	33.432	1.951	3.427	.168
63	1/09	150	921	54.940	.439	6.501	.071	36.051	1.998	3.016	.173
65	1/09	70	802	69.317	.272	7.870	.029	20.426	2.085	6.368	.351
66	1/09	90	807	79.636	.322	4.267	.017	14.134	1.624	10.354	.272
67	1/09	90	768	53.077	.165	5.892	.015	37.484	3.368	2.771	.145
68	1/09	91	847	74.979	.391	9.323	.053	13.940	1.313	10.055	.615
82	1/13	90	838	58.741	.291	11.954	.063	26.896	2.056	4.220	.415
83	1/13	90	812	74.217	.310	8.945	.036	14.922	1.569	9.229	.545
85	1/13	82	835	56.364	.273	12.964	.066	28.235	2.098	3.873	.430
87	1/13	88	923	57.383	.465	10.472	.117	29.854	1.709	3.774	.335
89	1/14	145	859	54.313	.305	10.186	.065	32.950	2.182	3.234	.292
91	1/14	85	815	60.104	.257	8.989	.038	28.217	2.396	4.100	.295
114	1/15	87	843	76.489	.389	15.664	.086	6.721	.650	21.036	2.137
117	1/16	87	830	78.725	.371	12.576	.061	7.489	.778	19.324	1.529
133	1/24	732	745	75.602	.198	3.363	.007	18.292	2.539	7.521	.162
180	2/17	869	633	42.954	.044	5.198	.003	45.656	6.145	1.897	.100
226	3/08	—	830	40.895	.192	9.740	.048	46.564	2.561	1.777	.199

TABLE 28.8.—Composition of gases from east rift eruption of Kilauea, 1983: January 23 crack
[—, no data]

Sample	Date (mo/d)	Temperature (°C)		Constituents (mole percent)					Atomic ratios		
		Collection	Equilibrium	H ₂ O	H ₂	CO ₂	CO	SO ₂	H ₂ S	H/S	C/S
130	1/24	540	779	65.687	0.220	4.913	0.014	26.369	2.796	4.711	0.169
132	1/24	732	757	70.251	.201	3.780	.009	22.933	2.826	5.690	.147
135	2/04	508	688	63.512	.106	4.915	.005	27.348	4.113	4.306	.156
139	2/10	406	657	63.532	.082	4.512	.003	27.140	4.731	4.289	.142
140	2/12	385	696	44.111	.079	8.844	.010	42.657	4.298	2.065	.189
141	2/12	385	666	55.642	.077	6.624	.005	32.844	4.808	3.215	.176
176	2/17	410	744	45.538	.119	8.866	.018	41.914	3.545	2.165	.195
177	2/17	410	747	49.863	.133	7.814	.016	38.629	3.545	2.539	.186
185	2/23	407	688	33.766	.057	9.415	.010	52.559	4.194	1.340	.166
186	2/23	407	711	48.525	.098	7.338	.010	39.883	4.145	2.397	.167
192	2/24	403	738	41.876	.104	8.466	.016	45.871	3.667	1.843	.171
193	2/24	403	715	39.490	.083	8.788	.012	47.675	3.952	1.686	.170
196	2/27	403	851	37.138	.199	8.283	.049	51.917	2.413	1.463	.153
197	2/28	403	853	42.441	.230	7.798	.047	46.995	2.489	1.825	.159
202	3/01	452	764	37.414	.113	7.651	.019	51.495	3.308	1.490	.140
203	3/01	452	758	38.045	.110	7.649	.018	50.787	3.391	1.534	.142
210	3/04	435	765	45.426	.138	6.660	.017	44.318	3.441	2.052	.140
227	3/08	—	720	52.150	.113	6.601	.010	37.141	3.985	2.735	.161
228	3/08	—	733	51.516	.123	6.543	.011	37.986	3.820	2.653	.157
236	3/22	423	754	49.671	.140	5.898	.013	40.666	3.612	2.413	.133
237	3/22	423	756	47.385	.135	6.237	.014	42.638	3.592	2.211	.135
242	3/22	419	620	39.594	.036	7.780	.003	46.437	6.150	1.741	.148
243	3/28	419	663	45.064	.061	6.403	.005	43.255	5.211	2.077	.132
247	3/29	409	743	53.558	.139	5.317	.011	37.251	3.724	2.803	.130
252	3/30	394	665	54.701	.076	5.088	.004	35.051	5.081	2.983	.127
257	3/31	401	671	54.481	.079	5.058	.004	35.405	4.972	2.949	.125
262	4/01	405	676	65.667	.100	3.824	.003	26.125	4.281	4.608	.126
270	4/04	385	654	55.888	.070	5.035	.003	33.734	5.270	3.140	.129
276	4/05	392	655	54.748	.069	5.014	.003	34.843	5.323	2.995	.125
280	4/08	410	660	56.312	.074	4.820	.003	33.644	5.147	3.173	.124
286	4/08	402	666	57.777	.081	4.800	.004	32.410	4.928	3.363	.129
288	4/11	411	664	57.985	.079	4.731	.004	32.232	4.969	3.389	.127
291	4/13	398	654	59.521	.074	4.457	.003	30.820	5.124	3.601	.124

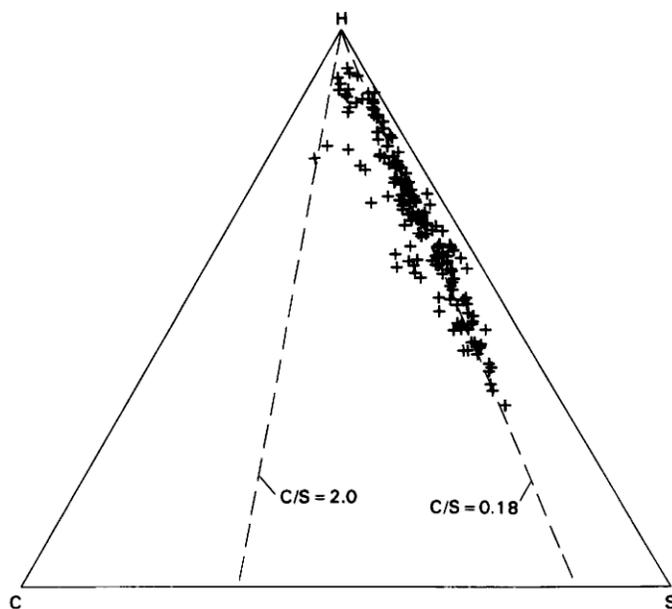


FIGURE 28.2.—Ternary H-C-S plot for gas samples from 1983 Kilauea east-rift-zone eruption. Data from tables 28.4–28.8. Dashes indicate water-control lines for specific values of the C/S ratio. Atomic hydrogen has been reduced by a factor of 0.5 to increase clarity.

deviate considerably from this line, becoming carbon-rich. Examination of the tables shows that almost all of the samples with a C/S ratio >0.3 were collected from ground cracks during January 1983; the eruption began in a heavily vegetated area, and thus contamination of the magmatic gas with organic pyrolysis products is likely. Furthermore, the eruptive area contained numerous preexisting low-temperature fumaroles emitting CO₂-rich steam, and mixing of these vapors with the magmatic gas may account for some of the samples rich in H₂O and CO₂. Samples with a C/S ratio <0.1 are associated with vents at which fountaining had ceased and with ground cracks near eruptive centers, and all were collected after the January activity; remobilization of S from the January lava is a possible explanation for the low C/S ratios of these samples.

The samples from actively erupting vents (table 28.4) were all collected within a few meters, usually a few centimeters, of actively churning, spattering or fountaining melt. All but three of these were collected in the period after July 1983, when eruptive episodes were preceded by the formation of a lava lake in the central vent that persisted for several hours to several days before full-scale eruption. This lava lake frequently became crusted over, with small vents emitting spatter, gas, and occasional overflows of lava through the crust; the August–October samples in table 28.4 were obtained from such vents. The three January–March samples in table 28.4 were collected from small holes in vigorously fountaining spatter cones. Examination of table 28.4 reveals a clear trend for apparent water (that is, the thermodynamic estimate of water content) to

increase and for the C/S ratio to decrease from the pre-April samples through the August samples to the September samples; however, this trend is not apparent in samples collected from other sites (tables 28.5–28.7) and it seems more likely to reflect vagaries in the degassing process rather than a change in the volatile composition of the magma.

The samples of gas from vents no longer active (table 28.5) collected before March 1983 were invariably from very small vents that had erupted only weakly, forming spatter ramparts less than a meter high. Samples collected from vents that had erupted vigorously either consisted solely of air or were thoroughly oxidized, often to the point where not even SO₂ was detectable. The March–April eruptive episodes ended with partial collapse of the crater wall in the central vent cone (the later Puu Oo), which completely blocked the main vent; the samples in table 28.5 from this period were obtained from degassing cracks in the debris pile. The observed variation in the C/S ratio of these samples might well be accounted for by remobilization of sulfur from the edifice and adjoining lava and by incorporation of pyrolyzed organic matter through the chimney effect.

Gas samples collected from fuming ground cracks have been distinguished as “near” (table 28.6), meaning within 200 m of an actively erupting vent, and “distant” (table 28.7), usually meaning more than 1 km from any eruptive site or collected during a noneruptive period of this episodic eruption. Comparison of tables 28.6 and 28.7, however, shows this to be a distinction without a difference; the composition of gas issuing from ground cracks appears to be unrelated to the relative proximity of eruptive centers or to whether an eruption is actually occurring. A notable feature of gas samples from these ground cracks is the high temperature of apparent gas equilibrium in spite of the very low collection temperatures, many less than 100 °C. This result, as with the 1981–82 gas collections (see above), indicates that an abundance of gas samples should be easily obtainable from Hawaiian fissure eruptions. (On the other hand, an abundance of samples is required from such sites: about half of the analyses excluded from tables 28.4–28.8 as being too oxidized or too contaminated were obtained from low-temperature ground cracks.) Comparison of these samples with samples collected in immediate contact with melt (table 28.4) shows a general tendency for the apparent water content of the crack samples to be lower; this distinction may be related to the depth at which gas became separated from the melt (see Greenland, chapter 30) but the possibility of greater oxidation of H₂, leading to low estimates of H₂O, in the low-temperature samples cannot be excluded.

On January 23, 1983, an isolated very small eruption took place at a single vent. Associated with this eruption, a ground crack formed starting at a point about 30 m from the vent and extending for about 100 m. This crack fumed strongly into April, making possible a study of the change of gas composition at a single site with time (table 28.8). These data show a general decrease in observed collection temperature with time and a corresponding, though smaller, decrease of apparent equilibrium temperature. Within this general trend, there was a notable increase in collection temperature on March 1, preceded by an equally notable increase in apparent

equilibrium temperature two days earlier; it may be significant that these temperature increases accompany the main episode 2 eruptive activity (February 25 to March 4). Paralleling the overall trend of temperature decrease is a decrease of the C/S ratio in the gas. However, the eruptive activity of episode 2 and episode 3 (March 28 to April 9) produced lava that encroached upon and even overran parts of the crack, and it is possible that significant contributions of remobilized sulfur came from these flows.

MAUNA LOA GAS COLLECTIONS FROM 1984

Complete gas analyses of collections from the recent Mauna Loa eruption are discussed in detail elsewhere in this volume (Greenland, chapter 30) and will not be considered here. Two types of gas-sampling sites were available for this eruption: “active” vents that were emitting spatter interspersed with occasional low fountains or small lava flows or both, and “feeder” vents uprift of the active vents. The feeder vents at 3,350 m elevation produced major fountains and lava flows early in the eruption but ceased activity when the lower vents at 2,930 m elevation became active. Abundant fume produced from the feeder vents after lava emission ceased there originated from magma degassing as it flowed through the conduit to the actively erupting vents. Flowthrough-bottle collections of gases for partial analysis largely overlap the collections for complete analysis, which were mostly being made at the same vent at the same time.

Results of these analyses are given in table 28.9, which includes estimates of the equilibrium temperature and content of H₂O and H₂S made as described above. These data are summarized in a ternary H-C-S plot in figure 28.3, which shows the analyses to lie along a water-control line with a C/S ratio very close to that of the 1983 Kilauea east-rift gases and very much lower than the C/S ratio of the 1919 Mauna Loa eruptive gases (see above). The low C/S ratio in these gases has been attributed, as at Kilauea, to degassing of the magma during storage in the shallow summit storage reservoir (Greenland, chapter 30).

There is no obvious difference in composition or apparent equilibrium temperature between samples collected from actively erupting vents and those from feeder vents (table 28.9). As with Kilauea (see table 28.4), apparent equilibrium temperatures of samples collected at magmatic temperatures (~1,100 °C) are uniformly lower than collection temperatures, whereas samples collected at temperatures below 900 °C almost always have apparent equilibrium temperatures that are higher than the collection temperature. This result indicates that quenching of the high-temperature flowthrough collections is not sufficiently fast to prevent gas reactions down to ~1,000 °C. The similarity of apparent equilibrium water contents of samples from the two kinds of sites contrasts with the observation from the complete analyses (Greenland, chapter 30) that the active vents have a higher total water content than do the feeder vents. However, estimating equilibrated water in the complete analyses yields the same results given here for the partial analyses (Greenland, chapter 30); the distinction between total and equilibrated water was attributed to non-equilibrium degassing of the erupting magma.

TABLE 28.9.—Composition of gases from Mauna Loa, 1984

[—, no data]

Date (mo/d)	Temperature (°C)		Constituents (mole percent)					Atomic ratios		
	Collection	Equilibrium	H ₂ O	H ₂	CO ₂	CO	SO ₂	H ₂ S	H/S	C/S
Actively erupting vents										
3/25	1,075	969	54.713	0.562	6.754	0.108	36.124	1.739	3.012	0.181
3/26	1,100	1,016	62.186	.800	5.635	.127	29.811	1.442	4.123	.184
3/26	1,100	975	47.237	.499	8.324	.139	42.079	1.723	2.258	.193
3/26	1,120	955	53.429	.510	6.534	.094	37.594	1.839	2.829	.168
3/27	1,100	978	63.592	.683	5.680	.097	28.400	1.548	4.396	.193
3/27	1,130	981	55.892	.608	7.480	.130	34.257	1.632	3.240	.212
3/30	1,100	903	52.966	.385	8.922	.084	35.641	2.003	2.941	.239
3/31	1,100	941	51.902	.461	7.672	.098	37.989	1.877	2.721	.195
4/02	1,100	1,098	57.307	1.055	8.137	.316	32.010	1.175	3.588	.255
4/02	1,100	1,073	58.389	.965	7.668	.253	31.478	1.249	3.704	.242
4/02	--	837	41.372	.204	9.987	.052	45.894	2.491	1.821	.207
4/05	835	944	44.512	.402	8.520	.112	44.582	1.873	2.014	.186
Feeder vents										
4/03	1,100	1,007	51.039	0.631	8.819	0.187	37.790	1.535	2.706	0.229
4/03	--	911	48.799	.369	10.795	.108	38.005	1.924	2.559	.273
4/05	1,010	1,078	71.865	1.214	4.309	.147	21.434	1.031	6.598	.198
4/05	1,100	1,097	58.075	1.063	6.842	.264	32.541	1.215	3.576	.211
4/05	895	983	50.474	.555	7.658	.136	39.487	1.690	2.561	.189
4/07	880	976	51.350	.544	7.412	.124	38.843	1.726	2.643	.186
4/09	875	957	49.212	.474	8.574	.124	39.830	1.785	2.474	.209
4/09	875	972	51.808	.540	8.514	.139	37.312	1.687	2.771	.222
4/11	840	946	49.270	.450	8.109	.108	40.204	1.858	2.452	.195
4/11	840	906	56.669	.417	6.900	.067	33.922	2.025	3.289	.194
4/13	820	939	48.468	.427	8.742	.111	40.381	1.871	2.403	.210

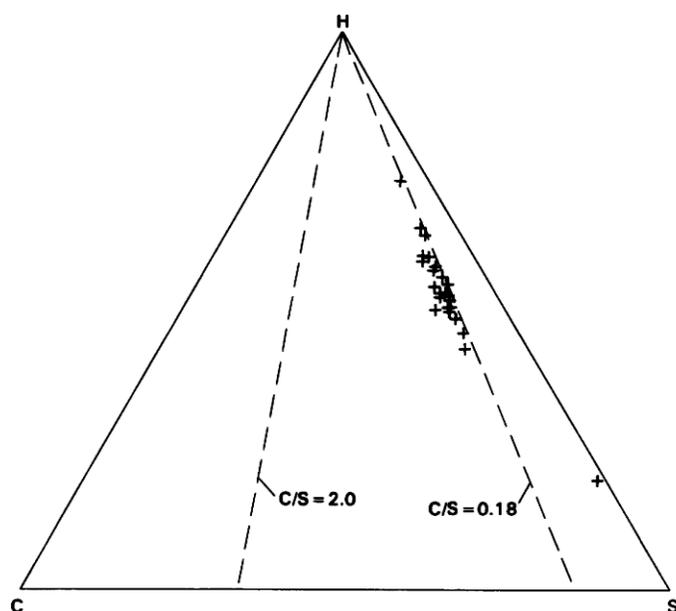


FIGURE 28.3.—Ternary H-C-S plot for gas samples from 1984 Mauna Loa eruption. Data from table 28.9. Dashes indicate water-control lines for specific values of the C/S ratio. Atomic hydrogen has been reduced by a factor of 0.5 to increase clarity.

CONCLUSIONS

Compositions of Hawaiian eruptive gas are summarized in figure 28.4. Plotted in a ternary H-C-S diagram are averages for the 1917, 1919, 1965, September 1982, and 1983 eruptions of Kilauea, and the initial (best) compositions of the April 1982 eruption and 1981 intrusion at Kilauea, and averages for the 1919 and 1984 eruptions of Mauna Loa.

It is apparent from figure 28.4 that eruptive gases in Hawaii predominantly have C/S ratios of ~ 2.0 or ~ 0.2 ; exceptions are the 1968 Halemaumau Fountain gas (C/S = 4.0) and the 1919 Mauna Loa eruption (C/S = 0.9), both of which are particularly uncertain determinations. The high (2.0) C/S ratio is associated with protracted summit eruptions of Kilauea and the low (0.2) ratio is associated with rift and brief summit eruptions. Current degassing models of Kilauea (Gerlach and Graeber, 1985; Greenland and others, 1985) and of Mauna Loa (Greenland, chapter 30) indicate that mantle-derived magma arrives in shallow (2–6 km) summit storage reservoirs bearing an immiscible CO₂-rich fluid phase and having an overall C/S ratio of about 2. Degassing of the CO₂-rich fluid phase through summit fumaroles is rapid, at least at Kilauea (days to weeks; see Greenland and others, 1985), leaving the magma with a C/S ratio of about 0.2. A consequence of this view is that eruptive gas in Hawaii will have the low C/S ratio if the magma has resided even briefly in the summit reservoir. The high ratio will be found only when magma passes directly through the reservoir to

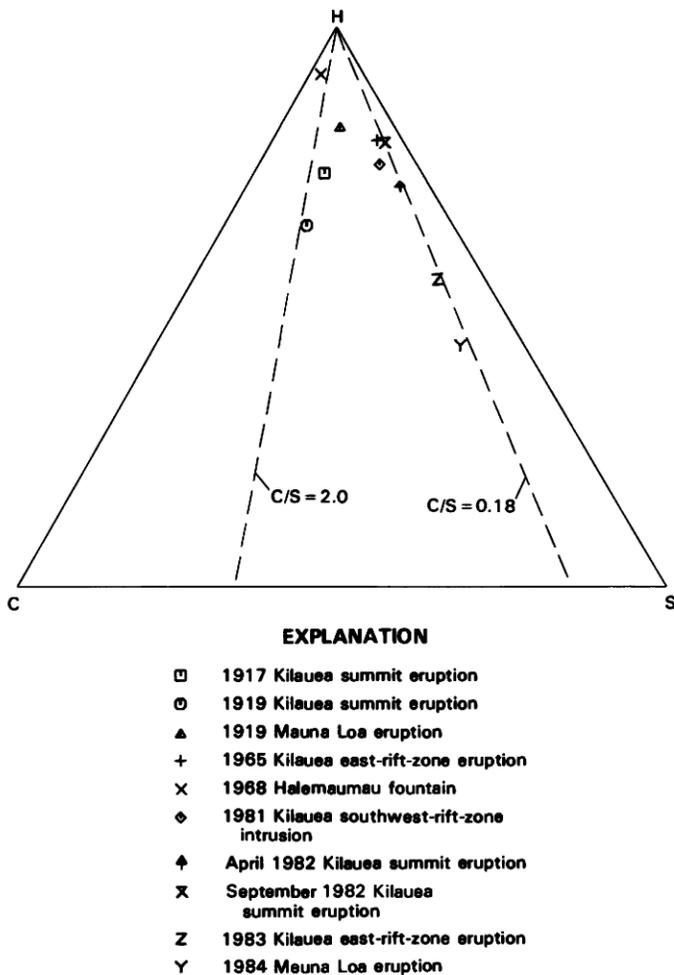


FIGURE 28.4.—Summary ternary H-C-S plot of Hawaiian eruptive gas compositions from 1917 through 1984. Dashes indicate water-control lines for specific values of the C/S ratio. Atomic hydrogen has been reduced by a factor of 0.5 to increase clarity.

the eruption center, which in practical terms means only for continuous summit eruptions that are lengthy enough to flush a passageway through the reservoir. An actual suite of gas samples collected from an eruption, however, can be expected to exhibit a considerable range of C/S ratios because of contamination by organic matter and by remobilized sulfur.

The major source of variation in these eruptive gases within a particular eruption is the water content, as is shown by figures 28.1–28.3, and water is also the primary distinguishing variable between eruptions, as indicated by figure 28.4. Hydrogen isotope studies yield convincing evidence that magma absorbs crustal water somewhere between its formation in the mantle and eruption (Kyser and O'Neil, 1984), and studies of submarine basalt (Moore, 1965) show that water is undersaturated in Hawaiian magma at the

pressure and temperature conditions of the summit reservoir. It seems probable, then, that much of the water variation in these eruptive gases is due to varying amounts of assimilation of water by magma in transit between mantle and eruption site. A further source of water variation in gas samples is contamination of the magmatic gas with meteoric water both in the vent system and from the atmosphere at the sampling site; this problem is exacerbated because meteoric water in the vent system may be equilibrated with the magmatic gas, and it is possible that the last exsolved magmatic water may be collected before equilibration with previously exsolved gas is complete (Greenland, chapter 30). It may be that variation of water among eruptions is due primarily to variable assimilation and that variation within an eruption largely reflects meteoric contamination, but only hydrogen isotope studies can resolve this problem.

Studies of gas composition as summarized here offer no direct information about the actual content of gas in the magma, which is an important question to those concerned with petrology and eruptive mechanics. If the degassing model described above is correct, however, it can be inferred that the carbon and sulfur content of Hawaiian summit-stored magma is constant and is fixed by the pressure and temperature conditions of the summit reservoir; the equilibrium amounts of carbon and sulfur dissolved in reservoir magma have been estimated (Gerlach and Graeber, 1985; Greenland and others, 1985) as about 0.03 percent CO_2 and 0.1 percent S by weight. The water content of summit-stored magma, which is not fixed by solubility limits, probably varies with the extent of assimilation of crustal water. The water content is difficult to estimate because of uncertainties about meteoric water contamination of gas samples; Greenland and others (1985) and Gerlach and Graeber (1985) independently estimate about 0.3 weight percent H_2O , which, even with the uncertainties, probably is close to correct. Therefore, excluding protracted summit eruptions, the total content of volatiles in Hawaiian eruptive magma probably is less than 0.5 percent by weight and probably varies little from eruption to eruption.

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