Lava-Effusion Rates for the Pu‘u ‘Ō‘ō-Kūpaianaha Eruption Derived from SO_2 Emissions and Very Low Frequency (VLF) Measurements

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Abstract

Lava-effusion rates have been estimated on a regular basis throughout the Pu‘u ‘Ō‘ō-Kūpaianaha eruption by several techniques, including mapping of lava-flow surface area and thickness, very low frequency (VLF) electromagnetic-profiling measurements over active lava tubes, and measurements of SO_2 discharge. Together, these three techniques indicate that Kīlauea erupted roughly 0.13 km^3/yr or about 2.4 to 2.6 km^3 of dense-rock-equivalent (DRE) lava between January 1983 and May 2002. VLF and SO_2 measurements produce total-volume estimates for the eruption within 10 percent of each other. SO_2- and VLF-derived lava-effusion rates are statistically correlated at the 99-percent-confidence level for the extent of both datasets but show the best agreement for the period 1997–2002, when sampling density for both datasets was highest and activity varied; they produced instantaneous lava-effusion rates episodically exceeding 1 million m^3d^{-1} per day. The data, which are consistent with magma at a CO_2-equilibration depth of 1.0 to 1.5 km, may indicate the minimum depth of the duct feeding magma in the east rift zone. The reliability of east rift SO_2 data, in combination with a rapidly evolving technology for inexpensively and remotely measuring plume SO_2, points toward the practical application of this technique to continuously monitor lava-effusion rates during this and similar eruptions.

Introduction

Knowledge of lava-effusion rates is a key to understanding magma supply and transport and for improving real-time lava-flow-hazard assessments. From January 1983 to July 1986, lava-effusion rates for the Pu‘u ‘Ō‘ō-Kūpaianaha eruption were derived by using the duration of discrete eruptive intervals and the lava volume calculated from the mapped area and thickness of the flows produced (Ulrich and others, 1984, 1985, 1987; Wolfe, 1988; Ulrich and others, written commun., 2002; see Heliker and others, this volume). This approach was effective during the period of episodic fountaining that characterized the first 3.5 years of the eruption, because the lava flows during each episode could be completely mapped and because the episodes had specific start and end times. This technique could no longer be easily applied, however, when the style of the eruption changed to continuous, lower-rate effusion that built the shield around the Kūpaianaha vent. A substantial amount of the volume increase of the shield was endogenous and difficult to measure, particularly during 1987. During the same year, lava carried by newly developed tubes reached the sea and so could not be quantified by surface mapping. New techniques to estimate lava-effusion rates were needed.

In this chapter, we describe the methods used to derive lava-effusion rates from eruptive-gas emissions and measurements of the volume rate of flow through lava tubes. We also present a comprehensive record of annual lava-effusion rates obtained by these techniques throughout the current east-rift-zone eruption and compare them with the rates obtained by traditional mapping methods.

Background and Methods

Jackson and others (1988) showed that very low frequency (VLF) electromagnetic profiling could be used at Kīlauea to quantify the instantaneous volume rate of flow through a lava tube. Kauahikaua and others (1996) improved the technique and, by intensive monitoring throughout 1991, used it to accurately predict the February 1992 demise of the Kūpaianaha vent. Since that time, VLF profiling has been used routinely to estimate lava-effusion rates for the eruption and to map active tubes as deep as 20 m beneath the ground surface (Kauahikaua and others, 1998).

The volume rate of lava flow through a tube can be estimated by using the VLF electromagnetic technique (Zablocki, 1978). The measurements consist of sets of data obtained on a profile over the tube. These data are reduced by using an empirical relation (Kauahikaua and others, 1996) to a single estimate of cross-sectional area of fluid of an assumed electrical conductivity in the tube. A flow velocity can be measured either by timing the transit of objects or by using a Doppler radar gun, if there is a skylight nearby where the lava stream is actually visible. The product of the average flow velocity and cross-sectional area results in an estimate of the volume rate of lava flow through the tube at that site, typically reported as the dense-rock-equivalent (DRE) lava-effusion rate (Kauahikaua and others, 1996; Heliker and others, 1998, and this volume).

VLF data not previously published are included here from monthly summaries and, in some cases, more frequent field measurements (J.P. Kauahikaua, unpub. data, 1997, 2001–2).

Lava-effusion rates may also be estimated by using geochemical data related to measured eruptive-gas release (Greenland and others, 1988; Andres and others, 1989; Sutton and others, 2001). Mass-balance calculations give a CO_2 content of 0.0195 weight percent for early production of lava from the eruption, corresponding to the shallowest equilibration depth of 1.0 to 1.5 km reached within the summit reservoir or during transport down the rift zone (Gerlach and Graeber, 1985; Gerlach, 1986). Bottinga and Javoy (1991) estimated the CO_2 content at 0.021 weight percent, and Greenland at 0.02 weight percent (Greenland and others, 1985, 1988). Essentially all of this CO_2 is lost on eruption after migration down the rift zone. This observation, in combination with the CO_2/SO_2 molar ratio measured in eruptive-gas samples along the rift zone and the east-rift-zone SO_2-emission rate, can be used to estimate the lava-effusion rate, using the equation

$$W_{CO_2}/W_{SO_2} = [CO_2/SO_2]\,(f_{CO_2}/f_{SO_2}), \qquad (1)$$

where W_{CO_2}/W_{SO_2} is the eruptive CO_2/SO_2 weight-fraction ratio, $[CO_2/SO_2]$ is the average molar eruptive-gas ratio, and f_{CO_2}/f_{SO_2} is the ratio of their formula weights. Solving equation 1 for W_{SO_2} yields

$$\begin{aligned} W_{SO_2} &= ([SO_2/CO_2]\,(f_{SO_2}/f_{CO_2}))\,W_{CO_2} \qquad (2)\\ &= 1.49 \text{ kg } SO_2 \text{ released per tonne of lava erupted.} \end{aligned}$$

We calculated W_{SO_2} by using $[CO_2]/[SO_2]=0.19\pm0.01$, the average of 204 analyses of eruptive gas collected from the east-rift-zone eruption site. These analyses, which were carried out by several investigators from 1983 to 1997, were summarized by Gerlach and others (1998).

Knowing the value of W_{SO_2}, the volume of DRE lava discharged and degassed on eruption, V_m, is related to the mass of SO_2 emitted, E_{SO_2}, by the equation

$$E_{SO_2} = V_m\, W_{SO_2}\, \rho_m \qquad (3)$$

Kīlauea’s SO_2 emissions during the Pu‘u ‘Ō‘ō-Kūpaianaha eruption have been measured on a nearly weekly basis by using correlation spectrometry (COSPEC) (Casadevall and others, 1987; Elias and others, 1998; Sutton and others, 2001; Elias and Sutton, 2002). The void-free lava density, ρ_m, is taken as 2.8 ± 0.1 t/m^3, on the basis of the DRE densities of the glassy rinds of 24 lavas from Kīlauea’s submarine east rift zone (Clague and others, 1995). Rearranging equation 3 to solve for V_m, we obtain

$$V_m = E_{SO_2}/\,(W_{SO_2}\,\rho_m), \qquad (4)$$

where $(W_{SO_2}\,\rho_m)^{-1}$ is a degassing constant, for the current eruption equal to 233±80 m^3 of lava per tonne of SO_2. If we call this value K_d, then from COSPEC-based measurements of E_{SO_2} and the equation

$$V_m = E_{SO_2}\, K_d, \qquad (5)$$

we can estimate east-rift-zone lava-effusion rates for this eruption. In an earlier report, Sutton and others (2001) calculated SO_2-derived lava-effusion rates by using a preliminary K_d value of 207.

Estimates of the lava-effusion rate based on intermittent SO_2 emission-rate measurements using equations 1 through 5 are necessarily inexact. In equation 5, we estimate the uncertainty in E_{SO_2} as typical for COSPEC measurements, at about 20 percent, and that of K_d at about 35 percent, largely owing to the uncertainty in W_{CO_2} and ρ_m. The absolute value of the constant W_{CO_2}, in particular, strongly affects K_d. Thus, we estimate the absolute uncertainty in V_m at about ±40 percent. Because both W_{CO_2} and ρ_m are constants, we expect the precision of our reported lava-effusion rates to be substantially better, likely closer to ±30 percent.

The earliest lava-effusion rates calculated by using equation 5 use COSPEC data collected in September 1986 for this study. From 1986 to 1991, we used emission data recorded at the Pu‘u ‘Ō‘ō cone, even though the main eruptive vent was Kūpaianaha, 3 km downrift, because the cone continued to act as a degassing chimney for magma that passed beneath it on the way to the Kūpaianaha vent. The lava-effusion rates through 2001 are derived from SO_2-emission measurements included in previously published reports (Elias and others, 1998; Elias and Sutton, 2002), and those for 2002 are based on USGS-HVO data.

An instrumental data set spanning more than 15 years inevitably incorporates changes, generally from improvements in method and processing techniques. Changes also occur as investigators respond to variations in the system under study, and conclusions based on long-time-series data sets must take these changes into account. For example, we have learned that east-rift-zone lava-emission rates calculated from near-vent, tripod-based COSPEC data are generally lower than those based on vehicle measurements along Chain of Craters Road (Andres and others, 1989; Elias and others, 1998; Sutton and others, 2001; Elias and Sutton, 2002). Because routine Chain of Craters Road measurements did not begin until 1992, emission-rate data from early in the eruption are all near-vent and tripod-based. In their raw form, these data likely represent a minimum estimate of east-rift zone SO_2 emissions.

We therefore applied a correction factor to SO_2-emission data from 1986 to 1991 based on comparisons showing that the Chain of Craters Road vehicle-based emission rates were

2.1 times higher than the tripod-based emission rates on contemporaneous days (*r*=0.95). This relation, which was established by using the small available number of paired data points (*n*=7), brackets the 1986–91 range of data values. We believe that the corrected tripod data, though not as reliable as data obtained along Chain of Craters Road, more reasonably represent the total east-rift-zone SO_2 emissions than do the raw, east-rift-zone tripod-based rates themselves.

Results and Discussion

The Big Picture: Annual Pu‘u ‘Ō‘ō-Kūpaianaha Lava-Effusion Rates, 1983–2002

Table 1, which summarizes void-free lava (DRE) lava-effusion rates based on COSPEC, mapping, and VLF measurements for January 1983 through mid-May 2002, is organized in two sections: SO_2 plus mapping-derived effusion rates and VLF plus mapping-derived effusion rates. It includes descriptive statistics for SO_2- and VLF-derived lava-rates on a cubic-meters-per-day basis.

We estimated the integrated annual discharges listed in table 1 by applying the nonparametric digital filter (NPDF) contained in the Peakfit software (version 4, Jandel Scientific, San Rafael, California) to generate a refined data set with an evenly spaced (daily) time base from the intermittent measurements. Using the NPDF, generating one data point per day simplified exact annual integrations for the years when data were not obtained precisely on the first and last days of the year. Integration of each year of daily values yielded the annual estimates. Annual integrations for the data filtered with the NPDF agreed with nonfiltered data within 1 percent. Lava-effusion rates for the first 19.5 years of the eruption peaked in 1998, at about 0.19 km^3/yr, and were lowest during the first three years, at about 0.11 km^3/yr.

The data listed in table 1 show that Kīlauea has discharged a total of about 2.4 to 2.6 km^3 of lava in the 19.5 years of the current eruption. Our estimates, based on mapping plus VLF profiling and mapping plus SO_2 profiling, yield integrated lava-effusion rates for the eruption that agree within 10 percent.

The data plotted in figure 1 and listed in table 1 show how the respective estimates of lava-effusion rates and sampling frequencies compare for each year. No VLF or surface-mapping measurements were available for the period 1989–90, when much of the lava produced by the eruption

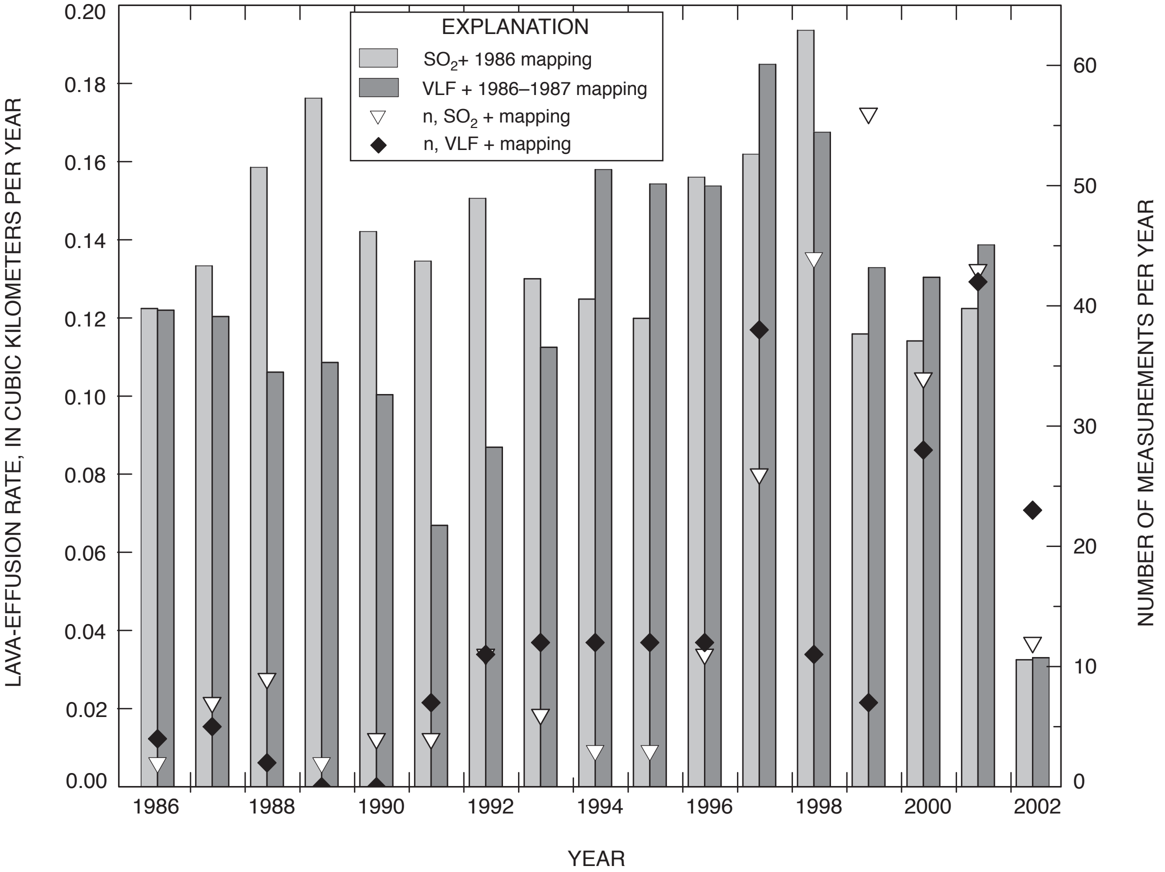

Figure 1. Integrated annual lava-effusion rates derived from SO_2-emission rates plus 1986 mapping data, and very low frequency (VLF) electromagnetic profiling plus 1986–87 mapping data, and number of samples (n) for each year.

Table 1. Annual effusion rates for the Puʻu ʻŌʻō-Kūpaianaha eruption, 1983 through mid-2002.

[From 1983 to mid-1986, effusion rates were calculated solely on mapped flow area and thickness. SO_2-emission measurements began in September 1986. Very low frequency (VLF) electromagnetic profiling began in 1991, except for two data points in 1988, and continued through mid-May 2002. All lava-effusion rates listed in dense-rock equivalent (DRE). Shaded area of table (1983 through mid-1986 and 1987 includes flow-mapping data adapted from Ulrich and others (1985, 1987, 2002), Wolfe and others (1987, 1988, written commun., 2002), and Heliker and Mattox (this volume). Minimum, maximum, mean, and SD (standard deviation) values derived from N field data points processed with a non-parametric digital filter to obtain a daily rate.]

	SO_2-emission-rate and mapping-derived lava-effusion rates						VLF electromagnetic profiling-derived lava-effusion rates					
	Total volume	Daily lava effusion rate (10^5)					Total volume	Daily lava effusion rate (10^5)				
Year	(km^3)	Minimum	Maximum	Mean	SD	n	(km^3)	Minimum	Maximum	Mean	SD	n
1983	0.11	--	--	--	--	--	0.11	--	--	--	--	--
1984	.10	--	--	--	--	--	.10	--	--	--	--	--
1985	.11	--	--	--	--	--	.11	--	--	--	--	--
1986	.12	--	--	--	--	--	.12	--	--	--	--	--
1987	.13	2.80	4.63	3.67	.56	7	.12	--	--	--	--	--
1988	.16	3.36	5.76	4.34	.33	9	.10	2.53	2.77	2.63	.56	2
1989	.18	4.41	5.12	4.84	.18	2	.10	2.69	2.73	2.71	.12	0
1990	.14	3.27	4.70	3.90	.44	4	.10	2.73	2.77	2.76	.11	0
1991	.13	3.44	4.06	3.69	.36	4	.07	0.70	2.76	1.84	.76	7
1992	.15	2.14	6.42	4.12	.95	11	.09	1.33	2.75	2.38	.48	11
1993	.13	1.24	4.63	3.57	.85	6	.11	2.65	3.89	3.09	.30	12
1994	.12	3.16	3.60	3.43	1.12	3	.16	3.00	5.00	4.33	.74	12
1995	.12	2.83	4.35	3.30	.37	3	.15	3.02	5.58	2.56	.55	12
1996	.16	1.98	5.48	4.27	.68	11	.15	4.06	4.64	4.22	.16	12
1997	.16	0.33	15.86	4.45	3.37	26	.18	0.95	7.48	5.08	1.83	38
1998	.19	3.44	9.00	5.32	1.16	44	.17	3.03	8.08	4.60	1.28	11
1999	.12	1.72	5.39	3.18	1.10	56	.13	2.99	4.23	3.65	.41	7
2000	.11	2.26	4.07	3.13	.48	34	13	1.12	5.06	3.57	.48	28
2001	.12	1.98	9.10	3.36	.92	43	.14	2.88	4.73	3.81	.51	42
2002	.03	0.42	3.34	2.41	0.37	12	.03	1.37	3.74	2.43	.64	23
Totals	2.62						2.38					

flowed directly into the sea. Thus, SO_2-derived lava-effusion rates were the only measure of lava effusion during these 2 years; the VLF-mapping values in figure 1 and table 1 are interpolated. The sampling frequency for both techniques has increased since 1996, as has overall agreement between the SO_2- and VLF-derived data sets.

The average SO_2- and VLF-derived annual lava-effusion rates for the 19.5-year duration of this study, of 0.13 and 0.12 km^3/yr, are similar to the rate of 0.12 km^3/yr reported by Swanson (1972) for the Halemaumau eruption of 1967–68 and the first 7 months of the Mauna Ulu eruption of 1969. They also compare well with the overall lava-effusion rate of 0.11 km^3/yr reported by Swanson for sustained eruptions during the 19-year period beginning in 1952. Dvorak and Dzurisin (1993), who studied both eruption rate and magma-supply rate at Kīlauea over the past 160 years, reported that an average and fairly constant magma-supply rate of 0.09 km^3/yr$^-$ has been characteristic for sustained eruptive periods at Kīlauea since 1950. More recently, Cayol and others (2000) calculated an average magma-supply rate to Kīlauea between 1961 and 1991 of 0.18 km^3/yr. This value, 50 percent more than the previous estimate (Swanson, 1972), would—given our measured lava-effusion rate—require that much of the magma supplied to Kīlauea has been stored in the rift zones. Gerlach and others (2002) showed that a magma supply rate of 0.18 km^3/yr is supported by an attendantly high CO_2-emission rate from Kīlauea's summit.

Shorter-Term Variation: Daily Lava-Effusion Rates, 1986–2002

Raw, intermittent-time series of daily estimates for SO_2- and VLF-derived lava-effusion rates show a short-term variation (fig. 2*A*). Both figure 2*A* and the FFT-smoothed traces in figure 2*B* show the good overall agreement of the two data sets, with visibly improved tracking during years when sampling density is higher. A notable discrepancy between the VLF- and SO_2-derived lava-effusion rates occurs from 1988 through 1991, when SO_2-derived lava-effusion rates exceed those based on VLF and mapping. Just previously, substantial endogenous shield building occurred at Kūpaianaha, culminating in lava extrusion from the base of the shield (Heliker and Wright, 1991). The volume of endogenous shield growth was difficult to quantify. During this period, SO_2 emissions at Kīlauea's summit, 23 km uprift, were the highest recorded since the eruption began, possibly indicating increasing magma throughput in the summit reservoir (Sutton and others, 2001). Unfortunately, few mapping-derived lava-volume estimates, no VLF lava-effusion data, and only a few measurements of SO_2-emission rate were available for this period.

Notably, a decrease in the SO_2-derived lava-effusion rate did not accompany the decline in lava extrusion at Kūpaianaha in 1991 as tracked by VLF profiling (Kauahikaua and others, 1996). Kūpaianaha may have been shutting down as new magma was aseismically intruding and degassing in and near the Pu‘u ‘Ō‘ō edifice, priming the middle east rift zone for episode 49 in November 1991 (Mangan and others, 1995).

The period of more frequent measurements, including 1996 through 2002, is shown in figure 3. Both techniques captured the eruptive pause and slow restart after episode 54 in early 1997 (Thornber and others, 1997). In late 1997, SO_2 and VLF data recorded some of the highest extrusion rates since the continuously effusive stage of the eruption began in 1986. These high lava-effusion rates, more than 1 million m^3/d, were mirrored by the eruptive activity as Pu‘u ‘Ō‘ō's crater filled and overflowed for the first time since 1986 (Heliker and others, 1997). Flank vent activity and shield building on the cone also increased.

Correlation of SO_2-and VLF-Derived Lava-Effusion Rates: Statistical Considerations

We examined the SO_2 and VLF time series statistically for two periods: (1) 1991–2002, the entire duration of simultaneous VLF and SO_2 data collection; and (2) 1996–2002, a subset of more frequent data collection and the period of greatest variation for both the VLF and SO_2 time series. SO_2 data were seldom collected on the same day as VLF data, and so we interpolated each data set by using Peakfit's NPDF to produce two identically spaced time series, at the smaller data-point sample size of the VLF data set.

Linear regression shows that both data subsets correlate significantly at both the 95- and 99-percent-confidence levels. The subset of more frequently obtained data in 1996–2002 produced the most significant linear correlation, with *r*=0.53, between SO_2-and VLF-derived lava-effusion rates at the 99-percent-confidence level. The regression and residual plots and statistics for these two periods are plotted in figure 4 and listed in table 2. The slope of the regression plot, 0.75, is not

Table 2. Parameters for linear regression *y=a+bx*, where y is the SO_2-emission-rate-derived lava-effusion rate, *x* is the very low frequency (VLF) electromagnetic-profiling-derived lava-effusion rate, and *b* is the slope *d*(SO_2)/*d*(VLF).

[The two time periods were chosen based on sampling frequency and eruptive activity.]

Parameter	Time Period 3/1991–5/2002	 1/1996–5/2002
Intercept, a	238,211	78,334
Slope, b	0.36	0.75
Correlation coefficient, r	.34	.53
Coefficient of determination, r$_2$	.12	.28
Degrees of freedom	213	121
Critical r at 99 percent confidence	.181	.228
Critical r at 95 percent confidence	.138	.174

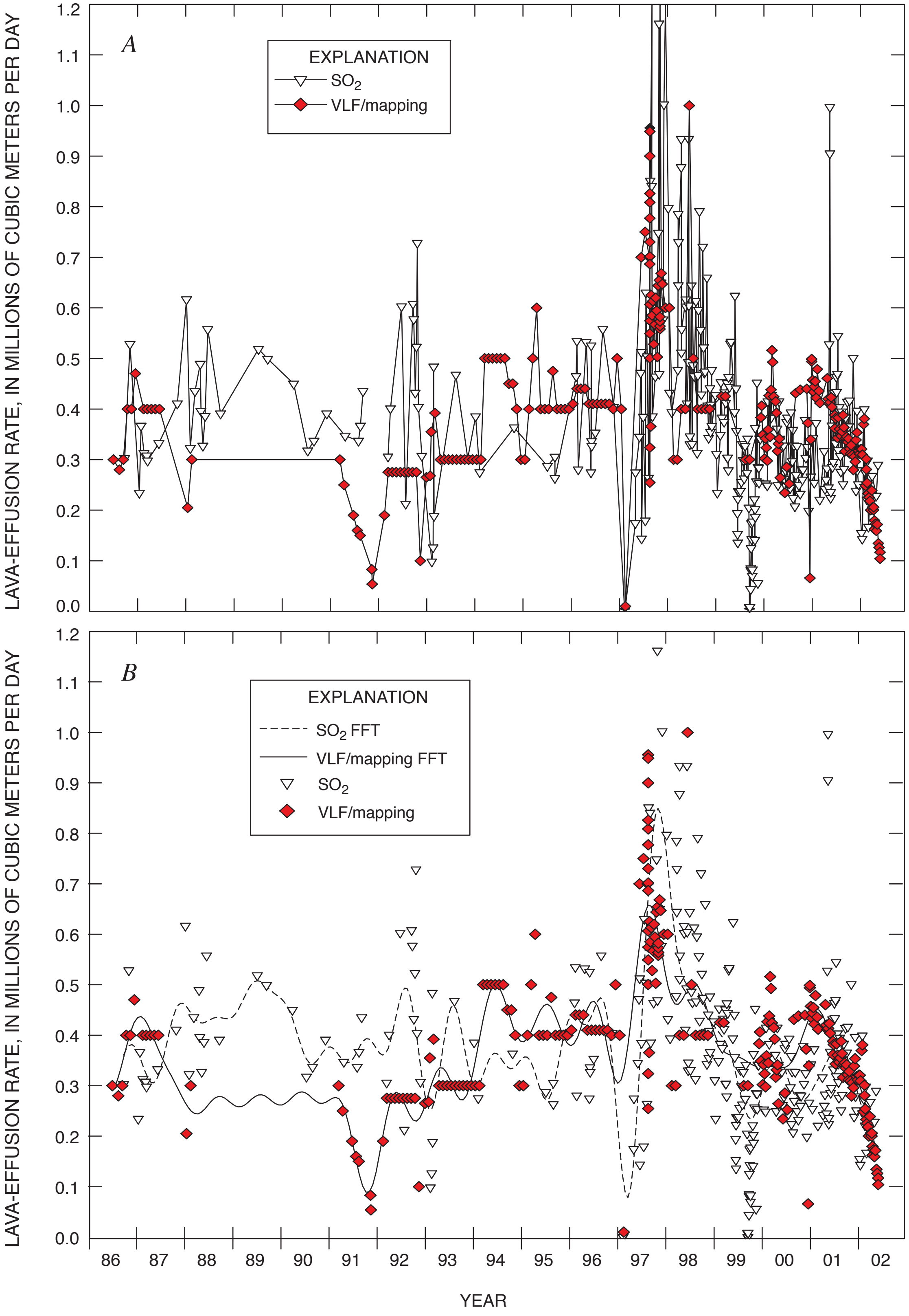

Figure 2. Long-term change in lava-effusion rate over time. *A*, SO$_2$-emission-rate-based and very low frequency (VLF) electromagnetic-profiling-based estimates of lava-effusion rate. Except for two measurements in 1988, VLF profiling plus mapping measurements reported before 1991 are based on mapping data only. Monthly lava-flux estimates from these data are used through 1996 and individual measurements for 1997–2002. SO$_2$-emission rates use east-rift-zone vehicle-based data (1992–2002) and corrected, tripod-mounted correlation-spectrometric (COSPEC) data (1986–91). *B*, Raw data (triangles and diamonds) were fast Fourier transform (FFT)- smoothed to produce dashed and solid lines that show data trends.

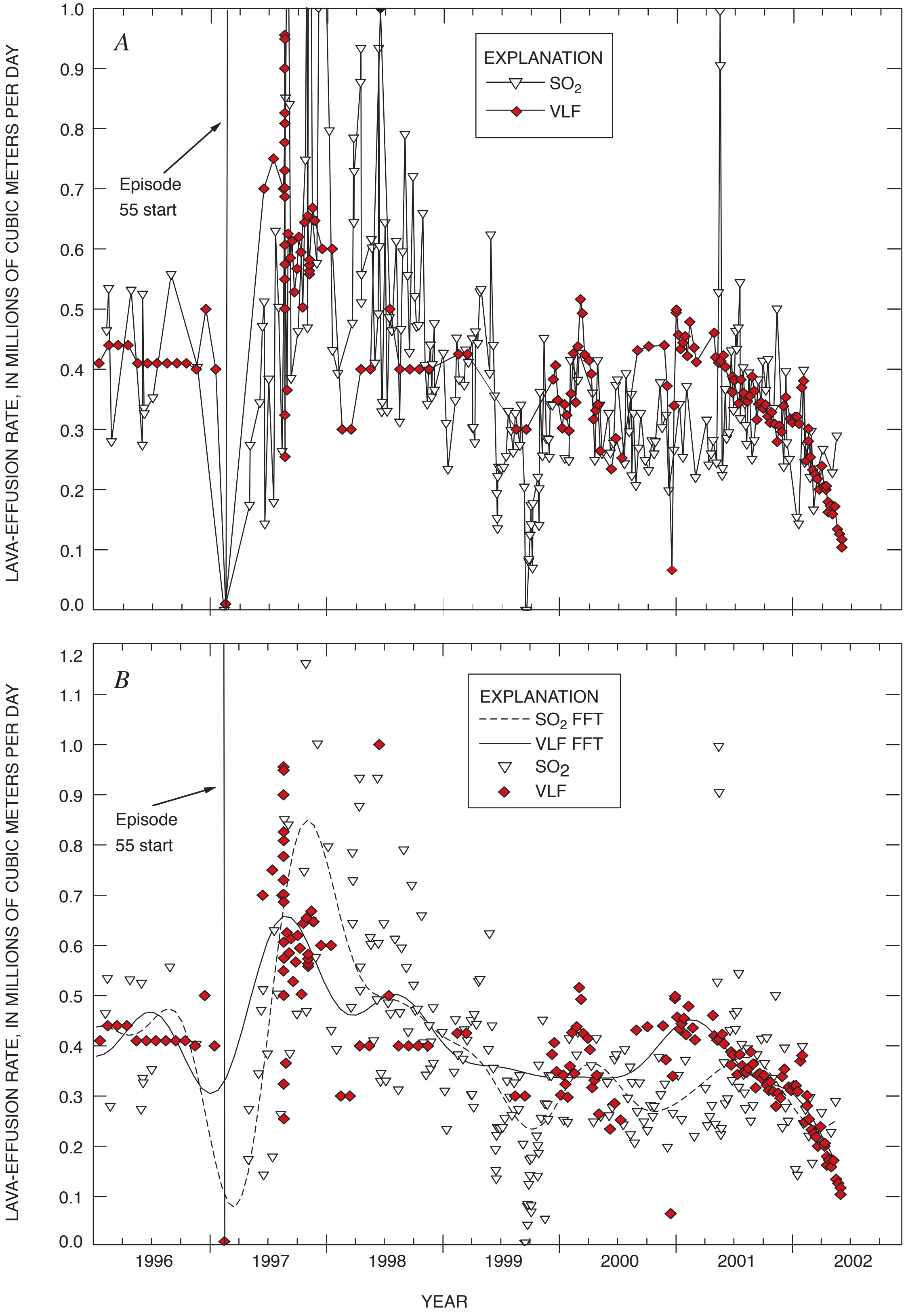

Figure 3. Short-term change in effusion rate over time. *A*, Comparison of SO_2-emission-rate-derived and very low frequency (VLF) electromagnetic-profiling-derived lava-effusion rates shows that effusion rates climbed markedly through third quarter of 1997. During this period, Puʻu ʻŌʻō's crater and flank-vent activity increased, and lava eventually overflowed crater. Tracking for these two data sets improved markedly as sampling frequency increased. *B,* Raw data (triangles and diamonds) were fast Fourier transform (FFT)-smoothed to produce dashed and solid lines that more clearly show data trends.

unity as for a perfect correlation, but the intercept of 0.07 million m^3/d is fairly close to 0 for data sets ranging as high as 0.9 million m^3/d for the interpolated data.

The regression residuals for both periods show a maximum deviation at high lava-effusion rates. These results are expected because high variation in both the SO_2 and VLF data accompanied the large (up to 1.0 million m^3/d) lava-effusion rates observed. The absence of precisely coincident VLF and SO_2 data degrades the overall correlation and magnifies the problem of deviating residuals. The large variation during a high-effusion-rate event recorded in August 1997, using the VLF technique, is plotted in figure 5. This large variation, 0.7 million m^3/d, constitutes 75 percent of the total signal. No accompanying SO_2 data are available for this period.

The variation in lava-effusion rates derived from SO_2 emissions also increases in the higher ranges. The variation in SO_2-emission rates is reported as the standard deviation of measurements during an observation day (Elias and others, 1998). Higher SO_2-derived lava-effusion rates have higher standard deviations (fig. 6).

Although the foregoing discussion demonstrates the overall agreement between SO_2- and VLF-derived lava-effusion

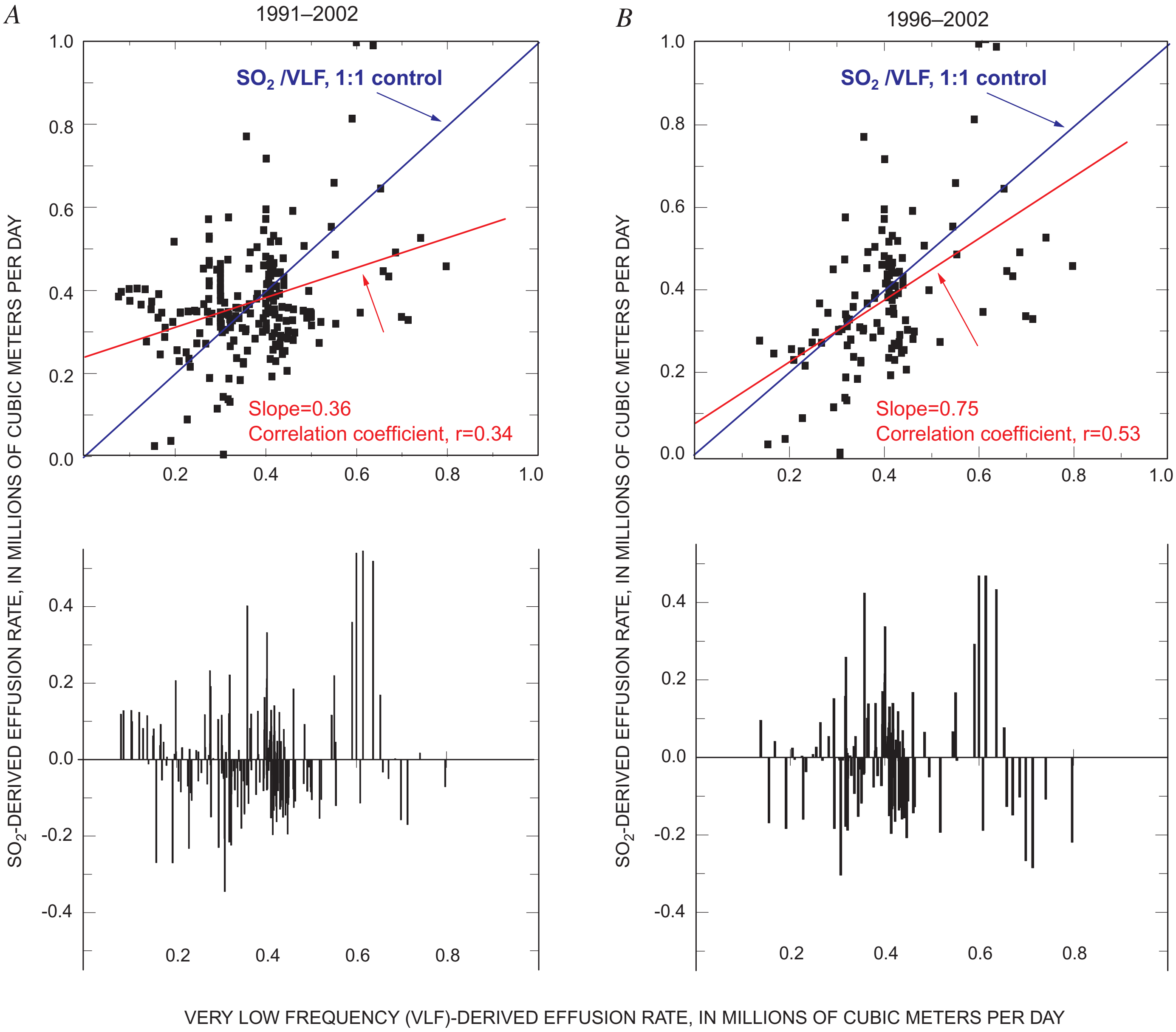

Figure 4. Lava-effusion rates derived from very low frequency (VLF) electromagnetic profiles and SO_2-emission rates statistically correlated at 95- and 99-percent-confidence levels for periods 1991–2002 (*A*), and 1996–2002 (*B*). Correlation during 1996–2002, when sampling frequency was higher, is stronger (see table 2). Residuals (lower plots) show notable deviation toward region of higher lava-effusion rate, when effusion rate shows large temporal variation.

rates, a precisely contemporaneous data set including SO_2 and VLF data is needed to rigorously test the agreement between the two techniques.

Other Remote Techniques for Measuring Lava-Effusion Rates

Several space-based techniques have been used to infer lava-effusion rates on Kīlauea. Topographic synthetic-aperture radar (TOPSAR) was used to estimate lava-effusion rates for episodes 50 through 53 of the eruption. These estimates agree with direct VLF measurements within 6 to 30 percent (Rowland and others, 1999). Harris and others (1998) showed that lava-effusion rates could be derived by leveraging the high spatial resolution of Landsat Thematic Mapper (TM) data with coarser but more frequent data obtained by an advanced very high resolution radiometer (AVHRR). These two data streams were used to sequentially image the flow field and detect changes in heat from one satellite pass to another, deriving lava-effusion rates from these data (Wright and others, 2001). Although remote space-based techniques show promise, they are significantly challenged by cloud cover and the absence of remotely visible surface flows.

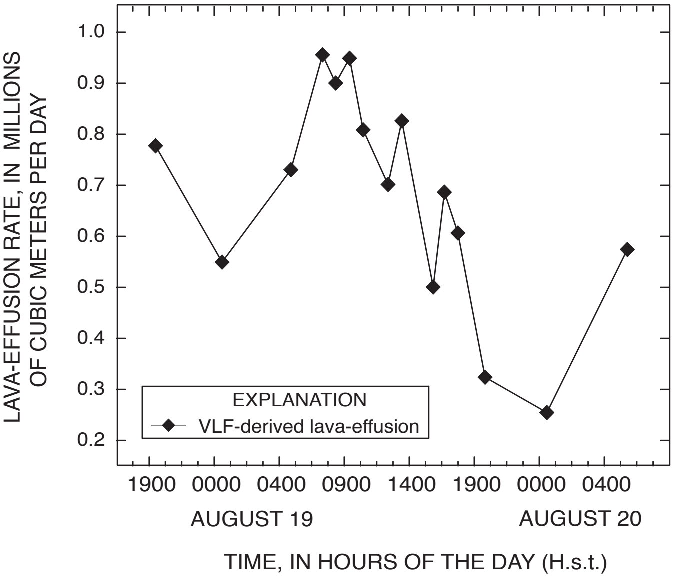

Figure 5. Very low frequency (VLF) electromagnetic-profiling-derived lava-effusion rates near Pu‘u ‘Ō‘ō record the large variation in volume rate of flow through primary tube that carries lava away from vent during period of increasing eruptive activity. SO_2 emissions, though not quantified precisely during this interval, show similar variation during other periods of increased activity.

Conclusions

VLF data and SO_2 profiling, in combination with surface-thickness measurements and area mapping, show that the Pu‘u ‘Ō‘ō-Kūpaianaha eruption produced from 2.4 to 2.6 km^3 of DRE lava between January 1983 and May 2002. The total volumes of magma calculated by SO_2 and VLF techniques for the 19.5 years of the current eruption agree within 10 percent. Heliker and others (this volume) report 2.3 km^3 of lava erupted through the end of 2001, based onVLF and mapping data. With the notable deviation during the period from about 1996 through 1998, the overall eruption rate has been fairly steady at about 0.13 km^3/yr.

We believe that the CO_2/SO_2-ratio approach used in this study accurately approximates the east-rift-zone lava-effusion rate. The simplicity of equations 2 and 5 applies a system-specific empirical measure, $[CO_2]/[SO_2]$, the value of which has been exhaustively refined at the vent and within the plume (Gerlach and others, 1998), where COSPEC SO_2-emission rates are measured. Furthermore, lava-effusion rates calculated in this way are supported by those calculated independently from VLF measurements. The agreement of lava-effusion rates calculated by using two fundamentally different techniques, VLF and COSPEC, demonstrates that monitoring SO_2 emissions, at least at Kīlauea, can serve as a useful proxy for tracking lava-effusion rates.

The results from the CO_2/SO_2-ratio approach imply that the magma supplying the current eruption is equilibrated at 1.0- to 1.5-km depth before being erupted on the east rift zone. This equilibration could be occurring within a shallow part of the summit reservoir or, alternatively, on the way to the east rift zone. Dawson and others (1999) found a high-V_p/V_s zone 1 to 2 km beneath the summit, consistent with possible summit-reservoir equilibration. This equilibration point might, in turn, indicate the depth of the duct leading outward to the east rift zone.

The excellent agreement between the VLF- and SO_2-derived lava-effusion rates for the Pu‘u ‘Ō‘ō-Kūpaianaha eruption since 1991 and especially since 1992, when regular east-rift-zone SO_2 measurements began, has resulted in these two techniques becoming the mainstay of eruption-rate monitoring at Kīlauea. Under certain conditions, however, it is difficult or impossible to make measurements with one technique or the other. East-rift-zone COSPEC measurements along Chain of Craters Road require brisk winds within a fairly narrow range of wind direction (Sutton and others, 2001). Thus, seasonal interruption of northeasterly trade winds disturbs measurement frequency and overall data quality. Similarly, VLF measurements on the eruptive flow field requires the existence of lava tubes and a skylight high on the tube with an unobscured view to the lava stream to measure flow velocity. Both types of measurements are compromised and can be hazardous in poor weather conditions.

The degree of VLF-COSPEC temporal correlation is encouraging, considering that both techniques function as effusion-rate monitors by scaling up measurements, gathered over a few hours or less, to report a daily rate. Both COSPEC measurements of east-rift-zone SO_2 and VLF

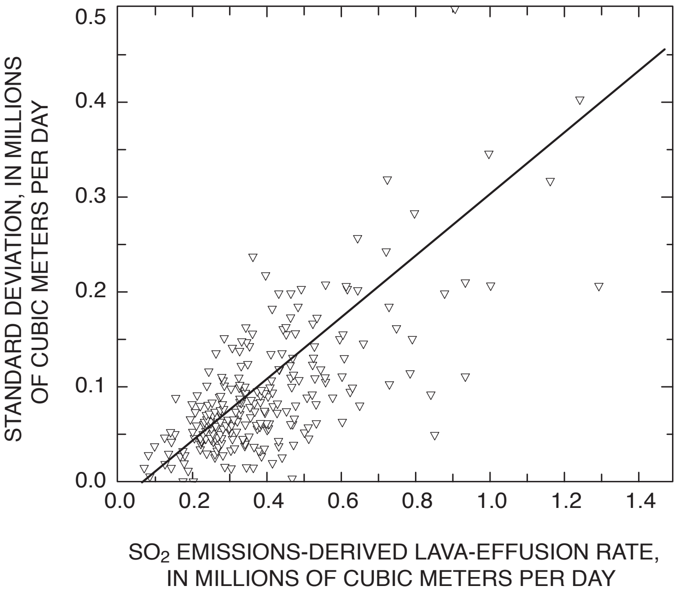

Figure 6. Standard deviation of lava-effusion rates based on daily average SO_2-emission-rate measurements, shows a positive linear trend with increasing effusion, corroborating large variation in lava-effusion-rate data shown by very low frequency (VLF) electromagnetic-profiling data in figure 5 and supporting finding of deviating residuals at high lava-effusion rates.

measurements are typically conducted only once each week at Kīlauea. A more thorough evaluation of the agreement between the two methods for effusion-rate monitoring is warranted but requires contemporaneous measurements.

Weekly VLF- and SO_2-emission-rate measurements have significantly improved our ability to track changes in the status of the Pu‘u ‘Ō‘ō eruption over periods of weeks to months. Short periods of more frequent data collection with these techniques have illuminated eruptive processes, such as gas pistoning and hornito formation, at and near the vent.

Recent availability of miniaturized, high-resolution ultraviolet spectrometers, coupled with practical, real-time data processing, has led researchers to pursue development of lower-cost alternatives to the electromechanical COSPEC developed in the 1960s (Horton and others, 2002; Galle and others, 2002). The potential of automating such low-power devices shows promise toward deployment of a continuous SO_2-emission and effusion-rate monitor at Kīlauea.

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