Pure appl. geophys. 163 (2006) 853–867
0033–4553/06/040853–15
DOI 10.1007/s00024-006-0039-9

Pure and Applied Geophysics

Fault-controlled Soil CO_2 Degassing and Shallow Magma Bodies: Summit and Lower East Rift of Kilauea Volcano (Hawaii), 1997

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Abstract—Soil CO_2 flux measurements were carried out along traverses across mapped faults and eruptive fissures on the summit and the lower East Rift Zone of Kilauea volcano. Anomalous levels of soil degassing were found for 44 of the tectonic structures and 47 of the eruptive fissures intercepted by the surveyed profiles. This result contrasts with what was recently observed on Mt. Etna, where most of the surveyed faults were associated with anomalous soil degassing. The difference is probably related to the differences in the state of activity at the time when soil gas measurements were made: Kilauea was erupting, whereas Mt. Etna was quiescent although in a pre-eruptive stage. Unlike Mt. Etna, flank degassing on Kilauea is restricted to the tectonic and volcanic structures directly connected to the magma reservoir feeding the ongoing East Rift eruption or in areas of the Lower East Rift where other shallow, likely independent reservoirs are postulated. Anomalous soil degassing was also found in areas without surface evidence of faults, thus suggesting the possibility of previously unknown structures.

Key words: Soil CO_2, Kilauea, volcanic degassing, tectonic structures, geochemical surveying.

1. Introduction

Active tectonic structures in seismogenic and volcanic areas can be pathways for the release of subsurface gases (SUGISAKI *et al.*, 1983; ROSE *et al.*, 1991; KLUSMAN, 1993). On active or quiescent volcanoes, carbon dioxide is the main species in the soil gas released through tectonic structures (BADALAMENTI *et al.*, 1988; PèREZ *et al.*, 1997; WILLIAMS-JONES *et al.*, 1997), because, after water vapor, CO_2 is the most abundant gas dissolved in magma. Moreover, according to its low solubility in basaltic melts (PAN *et al.*, 1991), CO_2 is one of the first volatile components to be released from magma during its ascent. For these reasons, the output of CO_2 could be a useful indicator of the activity of a volcanic system (GIAMMANCO *et al.*, 1995; DILIBERTO *et al.*, 2002).

Studies recently carried out on Mt. Etna (GIAMMANCO *et al.*, 1998) showed that on such an active composite volcano, old eruptive fissures can be sites of anomalous

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soil degassing as well as faults. On Mt. Etna, however, this phenomenon was solely observed in about half of the surveyed eruptive fissures, thus suggesting that only those subject to active crustal stress can have soil permeability values high enough to permit deep gas leakage towards the surface (GIAMMANCO *et al.*, 1998, 1999).

On Kilauea (Hawaii), soil CO_2 flux measurements were performed during June 1997 in order to better constrain the relationships between soil degassing and tectonic or volcano-tectonic structures at composite basaltic volcanoes other than Etna. In the case of Kilauea, tectonic structures are those with no evidence of being conduits for magma ascent. On this volcano, carbon dioxide emissions occur mainly through the active summit craters (e.g., GERLACH and GRAEBER, 1985). Few data on other soil gases at Kilauea are available in the current literature (COX, 1983; REIMER, 1987; SIEGEL and SIEGEL, 1987). Our work, therefore, also provided a first relatively large-scale survey of soil CO_2 emissions through the flanks of Kilauea.

The areas investigated on Kilauea were selected on the basis of the density of known eruptive fissures and/or of tectonic structures (Fig. 1). Our investigations were mainly aimed at determining whether a correspondence exists between the location of the soil gas anomalies and the occurrence of tectonic and/or volcano-tectonic structures. We also investigated areas with no field evidence of tectonic structures, but where faults or old eruptive fissures could be postulated based on local structural settings, such as unstable slopes, and the presence of areas covered by recent lavas or

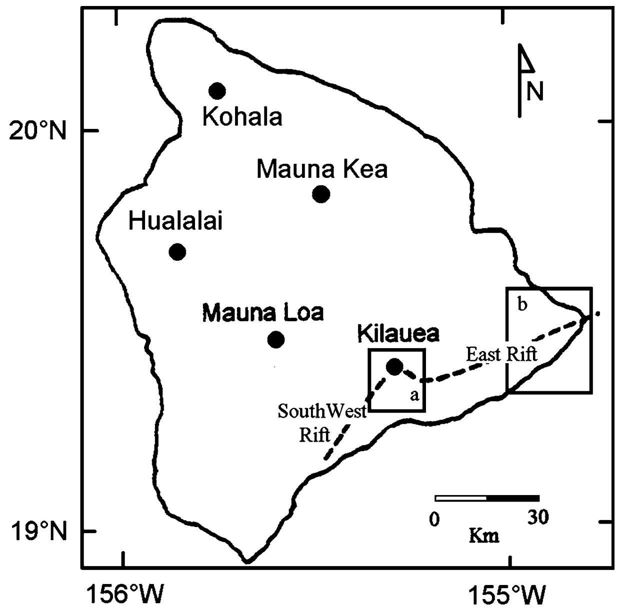

Figure 1
Location of the volcanoes on the island of Hawaii. Inset boxes a and b refer, respectively, to maps of Figures 2 and 3.

tephra. Another important scope of this work was to recognize possible connections between sites of anomalous soil degassing and shallow magmatic intrusions.

2. Geological and Structural Overview

Kilauea volcano is the youngest of five volcanoes that make up the island of Hawaii. It reaches an elevation of about 1230 m a.s.l. and has a subaerial surface area of about 1500 km^2 (Fig. 1) (HOLCOMB, 1987). Kilauea's eruptive activity is mostly characterized by the effusion of tholeiitic lava flows (WRIGHT and HELZ, 1987). These magmas originate from the mantle at inferred depths of more than 60 km (WRIGHT, 1984; TILLING and DVORAK, 1993). The characteristics of Hawaiian volcanism are typical of an intra-plate hot-spot (HOLCOMB, 1987; WRIGHT and HELZ, 1987). Magma rises from the region of partial melting through almost vertical pathways until it reaches a shallow reservoir beneath Kilauea summit (TILLING and DVORAK, 1993). Recent seismic studies indicate a magma reservoir at a depth of 5–7 km beneath Kilauea (OKUBO *et al.*, 1997) and DAWSON *et al.* (1999) used seismic data to recognize two shallower magma reservoirs at a depth of 1 to 4 km beneath the southern rim of Kilauea's caldera and the upper East Rift of the volcano. Secondary magma reservoirs may form beneath the rift zones, and are fed by the summit reservoir (TILLING and DVORAK, 1993).

Kilauea's eruptive activity mostly occurs either within its summit caldera or along two rift zones that originate from the summit and extend, respectively, toward the east (Kilauea East Rift Zone, or KERZ) and toward the southwest. Eruptions on the rift zones are fissures eruptions of highly variable duration and intensity. At the time of this writing, an ongoing eruption on the KERZ, that started in 1983, has discharged more than 1×10^9 m^3 of this lava (HELIKER *et al.*, 1998).

The whole south flank of Kilauea is subject to deformation induced by pressure of magma that is intruded into shallow reservoirs beneath the rifts (TILLING and DVORAK, 1993). Deformation due to magma intrusion causes faulting in the rocks of this flank of the volcano, with consequent gravitational slumping of whole sections toward the south, where it is not confined by other volcanic edifices (HOLCOMB, 1987; BRYAN and JOHNSON, 1991). For this reason, the southern flank of Kilauea is characterized by a high density of both normal and reverse faults.

The main tectonic structures of Kilauea's south flank are the Koa'e and the Hilina fault systems (HOLCOMB, 1987). The Koa'e system is directed roughly ENE-WSW and links the two rifts zones of the volcano just south of the summit caldera. The faults of the Koa'e system are occasionally sites of eruptions, the last of which occurred in 1973 (TILLING *et al.*, 1987). The Hilina fault system cuts the downhill portion of Kilauea's southern flank. These faults show the largest displacements in the Kilauea area, mostly towards the south. According to stratigraphic studies, the age of these faults was estimated to be at least 23 ka (HOLCOMB, 1987).

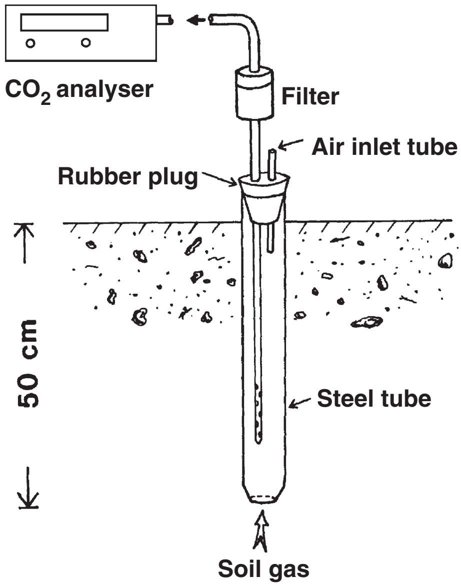

Figure 2
Sketch of the sampling and analysis system used to measure CO_2 fluxes in the soil.

3. Sampling And analytical Methods

Field work on Kilauea in May 1997 consisted of 126 soil measurements of CO_2 flux. Measurements were performed using the method of GURRIERI and VALENZA (1988), also described in GIAMMANCO *et al.* (1995) and DILIBERTO *et al.* (2002). This method (Fig. 2) uses a specially designed probe that is inserted into the soil to a depth of 50 cm. The probe is open at its bottom and with a small tube at the top, which allows air to enter it. By pumping at a constant flow rate, the CO_2 concentration in the mixture of soil gas and air inside the probe reaches a stable value, which depends on the emission rate of CO_2 through the soil. Earlier experiments determined that the values of CO_2 concentration (called *dynamic* because of the way they are determined) are directly proportional to the flux of carbon dioxide through the soil according to the relation $\Phi = k\ C_{dyn}$, where Φ is the flux of soil CO_2 (in g cm^{-2} s^{-1}), C_{dyn} is the *dynamic concentration* of CO_2 (in ppm vol.) and k is an empirical constant (in g ppm^{-1} cm^{-2} s^{-1}). The value of k depends mainly on the geometry of the sampling system and the flow of the pump, which are kept constant, and to a lesser extent on the soil permeability (GURRIERI and VALENZA, 1988; GIAMMANCO *et al.*, 1995). In order to determine the value of k, laboratory tests were carried out (GURRIERI and VALENZA, 1988) where soil degassing was simulated at different known CO_2 fluxes in samples of fine pyroclastic material characterized by permeability ranging between 10 and 60 darcy (about 1 to 6×10^{-11} m^2). It was observed that, within this range of values, soil permeability had a very small impact on the flux measurements (GURRIERI and VALENZA, 1988). Recent developments of this method indicate that the proportionality constant k assumes values that differ appreciably from that given above for soil permeability values lower than 1 darcy. The error induced by the variations of soil permeability of the investigated soils was calculated to be less than 10% (GURRIERI *et al.*, 2000).

Soil gas measurements during the present work were carried out along five sampling profiles (Table 1) in the following areas of Kilauea volcano: i) the summit and upper East Rift of the volcano, including the rim of Halema'uma'u caldera and the upper part of both the Chain of Craters Road and the Hilina Pali Road down to an elevation of about 650 m a.s.l. (Fig. 3); ii) the lower KERZ, roughly bounded by both the villages of Pahoa and Kaimu, and the area of Kapoho (Fig. 4). Measurements were performed under warm and stable weather conditions and no rain fell during the week that preceded our surveys, consequently the effect of meteoric water on soil permeability can be ruled out. This is verified by repeated measurements carried out after one or two days in some randomly selected sites.

Soil CO_2 dynamic concentration measurements were performed with a portable fixed-wavelength IR spectrophotometer (Analytical Development Company Limited, U.K.). To obtain the relevant CO_2 flux values, a k value of about 7.17×10^{-11} g $ppm^{-1}\ cm^{-2}\ s^{-1}$ was used. The instrumental accuracy was within $\pm$ 3%. Such error was obtained from repeated measurements (≥ 3) in each sampling site, and did not affect the results appreciably. In order to eliminate the possible influence of atmospheric pressure changes on soil flux measurements due to elevation effect, the instrument was frequently calibrated during the survey with standard CO_2 samples under ambient pressure and temperature conditions. A sampling interval between about 100 and 300 m was chosen as the best compromise between detail of information and number of measurements. The sampling step was deeply affected by recent lava flows, which in some cases impeded our measurements. In general, wider sampling steps increase the chances of missing faults or fissures that might have a CO_2 anomaly. However, fault zones and volcanic fissures on Kilauea have generally a width of several tens of meters or more, so the chance that we did not survey even a part of them is fairly low. Also, based on soil CO_2 data collected on Mt. Etna, which has similar soil permeability values as well as structural characteristics to Kilauea, the width of soil gas anomalies is generally comparable or larger than that of the tectonic or volcano-tectonic structures (GIAMMANCO *et al.*, 1997, 1998).

The sampling procedure used on Kilauea allowed us to complete each profile in a few hours, during which we assume atmospheric conditions remained constant. This is a necessary requirement for internal consistency of all flux measurements along any given profile. Direct measurements of atmospheric pressure were also frequently carried out to verify the constancy of atmospheric conditions. The observed variations were always less than two millibar, which produce very small effects on soil degassing (DILIBERTO *et al.*, 2002).

Table 1

Soil CO_2 flux values measured along the sampling profiles on Kilauea. All flux values are in g cm^{-2} s^{-1}. All distances are in meters from the starting point of each sampling line

Sampling line	Distance	CO_2 flux	Sampling line	Distance	CO_2 flux	Sampling line	Distance	CO_2 flux
A	0	0		2240	6.0×10^{-7}		1840	1.0×10^{-6}
	320	0		2560	1.3×10^{-7}		2400	1.0×10^{-7}
	640	0		2880	1.9×10^{-7}		3520	9.0×10^{-8}
	1120	0		3200	9.0×10^{-8}	D′	4160	7.0×10^{-8}
	1440	0		3520	7.0×10^{-8}	E	0	8.7×10^{-7}
	1920	0		4000	0		160	0
	2240	0		4560	6.0×10^{-8}		320	5.1×10^{-7}
	2560	0		5120	3.0×10^{-8}		480	1.7×10^{-7}
	4080	0		5840	0		640	6.0×10^{-8}
	4480	3.0×10^{-6}	B′	6160	0		800	2.0×10^{-6}
	4800	3.4×10^{-7}	C	0	1.7×10^{-7}		960	3.2×10^{-7}
	5120	4.7×10^{-7}		640	3.9×10^{-7}		1120	8.2×10^{-7}
	5520	3.0×10^{-8}		1120	4.7×10^{-7}		1280	1.4×10^{-7}
	5840	0		1600	2.5×10^{-7}		1440	1.7×10^{-7}
	6400	1.4×10^{-7}		2080	2.9×10^{-7}		1600	2.0×10^{-6}
	6720	0		2640	8.5×10^{-7}		1760	1.0×10^{-8}
	7120	1.0×10^{-8}		2960	0		1920	1.4×10^{-7}
	7600	4.3×10^{-7}		3360	0		2080	0
	7920	9.3×10^{-7}		3680	0		2240	2.2×10^{-7}
	8320	2.4×10^{-7}		4000	9.8×10^{-7}		2400	4.0×10^{-8}
	8720	0		4320	3.4×10^{-7}		2560	0
	9120	0		4560	0		2720	0
	9440	0		4960	1.0×10^{-6}		2880	0
	9760	0		5280	0		3040	0
	9920	1.0×10^{-6}		5560	0		3200	0
	10080	9.0×10^{-8}		6000	0		3360	7.0×10^{-8}
	10320	0		6720	0		3680	0
	10720	0		8320	0		3840	8.5×10^{-7}
	11120	0		5600	1.0×10^{-8}		4000	5.0×10^{-7}
	11440	9.0×10^{-8}		6150	0		4160	2.0×10^{-7}
	11760	0		6550	1.7×10^{-7}		4320	1.1×10^{-7}
	12160	0		6950	0		4480	2.4×10^{-7}
	12560	0		7350	0		4640	1.1×10^{-7}
	13040	0		7550	1.4×10^{-7}		4800	0
A′	13520	0		7850	1.7×10^{-7}		4960	0
B	0	1.4×10^{-7}		8150	5.4×10^{-7}		5120	1.7×10^{-7}
	320	2.0×10^{-7}	C′	8850	9.0×10^{-8}		5280	0
	640	1.0×10^{-8}	D	0	3.0×10^{-8}		5440	3.0×10^{-8}
	960	0		320	0		5600	7.0×10^{-8}
	1280	4.0×10^{-8}		800	0		5760	0
	1680	9.0×10^{-8}		1120	2.9×10^{-7}		6080	0
	1920	0		1440	6.0×10^{-8}	E′	7360	0

Soils at Kilauea are usually thin, but only rarely were we forced to move sampling locations until sufficiently deep soil was found within the above regular sampling interval.

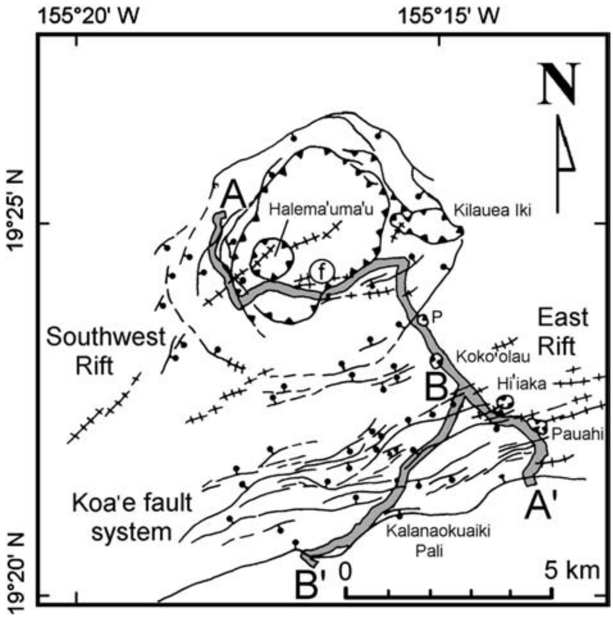

Figure 3
Location of the lines of soil gas measurements on Kilauea's summit area (box a in Fig. 1). A–A′ = Crater Rim - Chain of Craters Road; B–B′ = Hilina Pali Road. Faults (solid lines with dot on downthrown side; dashed when uncertain) and eruptive fissures (ticked solid lines) are also shown. Structural data are from WOLFE and MORRIS (1996). Letter f indicates the 1974 eruptive fissure. Letter p indicates the Puhimau crater.

4. Results and Discussion of Data

In general, the origin of the CO_2 emitted through the soil of active volcanoes, such as Kilauea, can be ascribed to the mixing of two sources: a deep magmatic one and a shallow one linked to organic activity. In contrast with the organic source, the magmatic one is able to sustain high fluxes of gas. KANEMASU *et al.* (1974) indicate a CO_2 flux value of $1.3\,l\,m^{-2}\,h^{-1}$ (corresponding to $7.36 \times 10^{-8}\,g\,cm^{-2}\,s^{-1}$) as the highest CO_2 flux that can be sustained by microbial activity in soil in general. This value will be assumed as a threshold to identify anomalous high CO_2 fluxes (presumably caused by CO_2 of volcanic origin) from the soils of Kilauea. We believe this value is certainly higher than the soil respiration CO_2 flux from the bare volcanic soil of the areas investigated on the Island of Hawaii, but anomalous degassing of magmatic origin through tectonic structures in volcanic environments is usually considerably higher than this threshold value (e.g., GIAMMANCO *et al.*, 1997, 1998; GERLACH *et al.*, 1998; HERNÁNDEZ *et al.*, 1998).

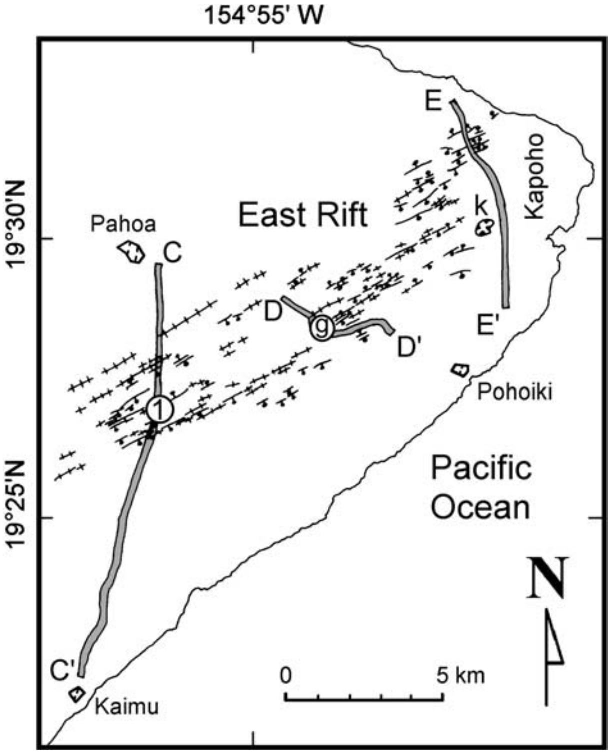

Figure 4
Location of the lines of soil gas measurements on Kilauea's lower East Rift zone (box b in Fig. 1). C–C′ = Pahoa–Kaimu Road; D–D′ = Pahoa–Pohoiki Road; E–E′ = Kapoho profile. Large circle with number inside indicates the site of soil gas sampling for chemical and isotopic analyses; k = Kapoho cone; g = geothermal well. Faults (solid lines with dot on downthrown side; dashed when uncertain) and eruptive fissures (ticked solid lines) are also shown. Structural data are from Moore and Trusdell (1991) and Wolfe and Morris (1996).

4.1 Kilauea Summit Area

Measurements in this area (Fig. 3) were carried out along the Crater Rim Road - Chain of Craters Road (line A-A′, 35 measurement points) and the Hilina Pali Road (line B-B′, 17 measurement points).

Along the Crater Rim Road the highest CO_2 flux value was found close to the western end of the 1974 eruptive fissure (sampling point at 4,480 m in Table. 1 and Fig. 5a). Slightly anomalous soil fluxes were also detected a few hundred meters east of the southeast rim of the caldera, between the eastern edge of the 1974 fissure and two faults related to the caldera-forming collapse. Other major CO_2 anomalies occurred on a fault near the Puhimau crater area (sampling points at 7,920 m in Table 1 and Fig. 5a), which is known for the presence of widespread fumarolic

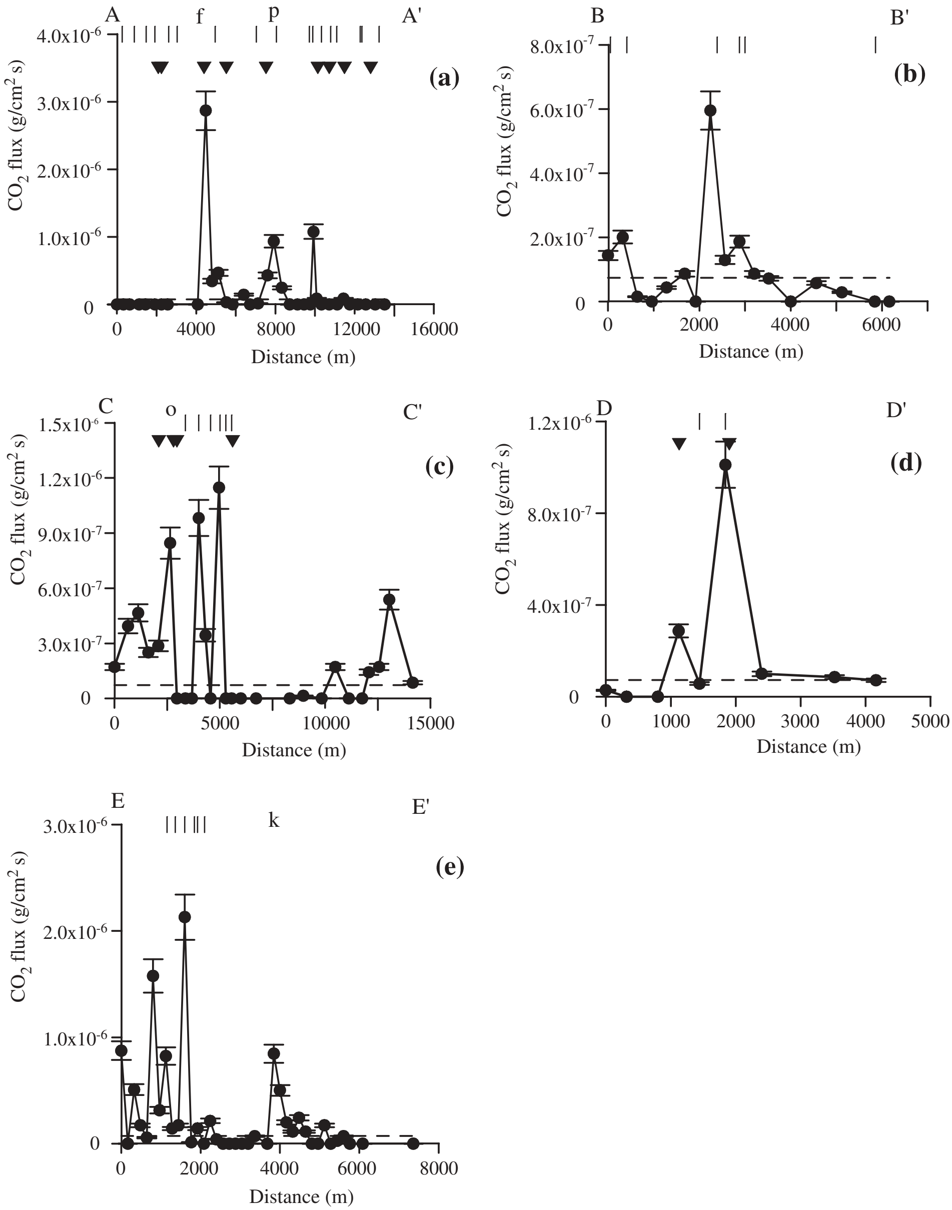

Figure 5

Soil CO_2 flux values (g cm^{-2} s^{-1}) measured along the surveyed lines on Kilauea. a) Crater Rim - Chain of Craters Road profile (A–A′ in Fig. 2); b) Hilina Pali Road profile (B–B′ in Fig. 2); c) Pahoa–Kaimu Road profile (C–C′ in Fig. 3); d) Pahoa–Pohoiki Road profile (D–D’ in Fig. 3); e) Kapoho profile (E–E′ in Fig. 3). Error bars indicate flux values ± 10%. Vertical solid lines indicate intercepted faults; solid triangles indicate intercepted eruptive fissures. The horizontal broken lines indicate the highest value due to organic activity (7.36×10^{-8} g cm^{-2} s^{-1}) in the soil (see text for explanation). f = 1974 eruptive fissure; p = Puhimau crater; o = eruptive fissure dated to 400–750 yr B.P. (see text); k = Kapoho Cone.

emissions associated with a weak thermal anomaly in the ground and where previous isotopic data on soil CO_2 ($\delta^{13}C$ values between –4.0 and –1.9 ‰) indicated a clear magmatic origin (FRIEDMAN *et al.*, 1987). The fault intercepted by our profile near Puhimau crater is part of a system that encircles the summit of Kilauea and was the site of eruptive activity as recently as 1974 (WOLFE and MORRIS, 1996). This indicates its connection at that time with the upper KERZ. Points with anomalous CO_2 degassing were also found both on a fault that marks the northernmost limit of the Koa'e fault zone, and very close to the 1973 fissure (northeast of Pauahi crater), although this latter anomaly was barely detectable.

Absence of soil degassing along the faults of the western rim of Kilauea caldera and along some of the upper KERZ may indicate that these tectonic structures are not directly connected to the present pathways used by magma. However, it must be mentioned that in the case of the western rim of Kilauea caldera some parts of the existing faults are buried by layers of hard-packed, altered pyroclastic products (ash, tephra, etc.). The low permeability of these materials may result in the absence of soil degassing in this part of the profile.

An alternative process calls for a generally low level of flank degassing of the volcano during eruptive periods except in the areas affected by faults directly linked to the pathways of magma intrusion beneath the summit caldera and into the KERZ. Such a phenomenon was observed on Mt. Etna, where during large lateral eruptions diffuse degassing is generally very low and restricted to faults connected to the eruptive dike (GIAMMANCO *et al.*, 1995). According to this hypothesis, during non-eruptive periods, including periods of persistent summit activity, diffuse degassing is higher and occurs along most, if not all, of the existing faults.

Along the Hilina Pali road profile, the anomalies of soil CO_2 flux were found on or very close to the northernmost faults belonging to the Koa'e fault system, where they intercept the East Rift zone (Figs. 3 and 5b). It is noteworthy that no anomalous soil degassing was found on the southernmost fault (Kalanaokuaiki Pali) of this system. This behavior was also observed on the same fault where it intersects the Crater Rim – Chain of Craters road profile (Fig. 5a). Also in the case of the Kalanaokuaiki Pali fault, absence of anomalous soil CO_2 emissions may be explained assuming that this fault is not directly connected to the sources of magmatic CO_2 (i.e., volcanic conduits and magma reservoirs).

4.2 Lower Kilauea East Rift Zone

Measurements (Fig. 4) were carried out along the Pahoa-Kaimu road (line C–C′, 27 measurement points), along a 4.2 km-long segment on the road connecting Pahoa to Pohoiki, just across the East Rift near the geothermal well (line D-D′, 9 measurement points), and along a 7.4 km-long segment on the road crossing the East Rift in the Kapoho area (line E-E′, 38 measurement points).

Along the Pahoa–Kaimu profile, the highest CO_2 flux anomalies were found in its northernmost part (Fig. 5c) where most of the rift fractures and faults are intercepted by the profile (Fig. 4). In particular, several contiguous anomalies in soil CO_2 degassing occur just close to Pahoa village and manifest two relative maxima, the highest one near an eruptive fissure dated to 400–750 yr B.P. (WOLFE and MORRIS, 1996). The highest values of CO_2 flux from the soil along this profile were found in two sites located four and five kilometers south of Pahoa, respectively, both at a very close distance from mapped faults. Three other zones of anomalous soil CO_2 fluxes were detected in areas where there is no evidence of faults or fissures; one in the northernmost part of the profile and two in the southernmost part. In these cases, the existence of hidden or buried faults can be postulated to explain such soil gas anomalies. The faults postulated in these zones may be concealed by recent lava flows.

Along the "Geothermal Well" profile, on the Pahoa–Pohoiki road (D–D′ in Fig. 4), CO_2 flux anomalies were found only close to the faults and fissures intercepted by the surveyed line (Fig. 5d).

Along the Kapoho line (E–E′ in Fig. 4) all of the mapped faults are exclusively located in its northern part and were associated with CO_2 flux anomalies (Fig. 5e). Several other anomalous CO_2 flux values were measured just north of the previous anomalies. A further area of anomalous soil CO_2 degassing was found about 2 km south of the southernmost fault, near a large ancient tuff cone (Kapoho Cone, labelled k in Fig. 4). In all of these areas, soil degassing is not associated with visible faults, indicating the possible presence of buried or hidden volcano-tectonic structures.

The $\delta^{13}C(CO_2)$ value from the site with the most intense degassing along this profile (site labelled 1 in Fig. 4) indicates an organic-rich source (−16.3 ‰). Probably, this is due to microbial activity in the uppermost soil horizon (e.g., KANEMASU *et al.*, 1974; HINKLE, 1990). If we assume a two component system with the magmatic end-member of $^{13}C(CO_2)$ at Kilauea having a value of about −3‰ relative to PDB standard (which corresponds to the average value measured at Sulphur Banks, a fumarole field close to the NE edge of the Kilauea caldera; FRIEDMAN *et al.*, 1987; HILTON *et al.*, 1997) and the organic end-member having a value of −28‰ (FAURE, G., 1986), then the magmatic component in the CO_2 emitted from this soil gas site would be about 50%. Such magmatic CO_2 component could originate from degassing magma bodies within the rift. The presence of magma is supported by geophysical and geochemical studies that indicate intrusions occur through the entire length of the rift and such magma bodies may remain molten for relatively long periods of time (probably on the order of several tens of years, e.g., THOMAS, 1987; TILLING and DVORAK, 1993). The magma bodies produce significant thermal anomalies in the ground water (THOMAS, 1987; CONRAD *et al.*, 1997). The heat flow is in places so intense (at least 291 MW over 25×10^6 km^2 of surface on the lower KERZ, according to THOMAS, 1987) as to produce an exploitable geothermal reservoir (tapped by the above-mentioned geothermal well). A direct magmatic source of gas can also be suggested to explain the emissions of CO_2 along the Kapoho line, consistent with the presence of a secondary magma reservoir beneath the area near Kapoho Cone, as postulated by TILLING and DVORAK (1993). However, an apparent discrepancy arises between our data that suggest an active gas-rich magmatic source, and the likely gas-depleted magma present in the secondary reservoir that results from a long residence time. A possible explanation is that envisaged by GERLACH and GRAEBER (1985) and by TILLING and DVORAK (1993): such reservoirs beneath the rift zones are periodically fed by magma that intrudes into the rifts. This mechanism allows replenishment with new magma that carries a higher amount of volatiles than the older magma body. Such volatiles would correspond to those which provide the "type II" gas described by GERLACH and Graeber (1985) as enriched in compounds that have a relatively high solubility in magma (mostly water and halogens), but still have significant amounts of SO_2 and CO_2.

5. *Conclusions*

Our investigations of diffuse soil degassing, carried out on Kilauea, indicate that degassing of magmatic CO_2 takes place not only through the summit crater of the volcano, but also through faults and old eruptive fissures on its flanks. However, our data do not allow us to quantify the amount of CO_2 released through the soils in the investigated areas. Our findings are consistent with the conclusions of geochemical investigations carried out on Etna (ANZÀ *et al.*, 1993; GIAMMANCO *et al.*, 1997, 1998) as well as other volcanic areas in the world (BADALAMENTI *et al.*, 1988; PèREZ *et al.*, 1997; WILLIAMS-JONES *et al.*, 1997). It is to be noted, however, that a few years after the end of an eruption, eruptive fissures should not show evidence of degassing. This is due either to obstruction after magma solidification or to sealing from hydrothermal alteration induced by residual magmatic fluids (GIAMMANCO *et al.*, 1999). Therefore, eruptive fissures associated with anomalous soil degassing suggest that tectonic strain is still present. Further, it is reasonable to assume that soil gas anomalies not associated with mapped faults originate from tectonic structures that are either hidden or covered by more recent lava flows. The possibility that some of the hidden structures are eruptive fissures that were covered later by newer volcanic products cannot be ruled out. In any case, these structures should be subject to active tectonic strain that keeps them open.

In contrast with observations on Mt. Etna where all of the surveyed faults and 49% of the surveyed fissures showed anomalous soil CO_2 degassing (GIAMMANCO *et al.*, 1997, 1998), anomalous soil gas emissions on Kilauea were found only over 44% of the tectonic structures and 47% of the volcano-tectonic structures intercepted by our sampling lines. The percentages were obtained by counting the number of anomalous values (i.e., greater than the "organic" threshold of 7.36×10^{-8} g cm^{-2} s^{-1}) on a "true-false" basis (i.e., any value greater than the threshold is considered an anomaly, otherwise it is not). In this computation we did not take into account the intensity of each anomaly. The measured intensity of soil gas anomalies can actually be dependent on the location of sampling points with respect to the maximum gas emission, assuming a log-normal distribution of anomalous values across a degassing fault.

The relatively low number of degassing faults at Kilauea volcano suggests that magmatic gas emissions through Kilauea's flanks occur only along tectonic structures directly connected at depth with the feeding conduits of the volcano or with the magma reservoirs beneath the summit and the rift zones. In addition to this, during periods of rift eruptions such as those when our measurements were carried out, magma is drained towards shallower parts of the volcanic system and is erupted or stored in the rift. In any case, a strong migration of magma occurs and this in turn means a drastic change in the mechanism of magmatic gas release and transport to the surface. Gases exsolved from magma would be carried with it, thus decreasing the gas pressure gradients in the shallow crust towards peripheral areas of the volcano. This causes an increase in the gas pressure gradients towards the eruptive vents and hence along the faults that are in connection with the active magma dike or reservoir. This phenomenon was already observed on Mt. Etna during the voluminous 1991–1993 eruption by GIAMMANCO *et al.* (1995), who named it "gas-drainage effect".

The "gas–drainage effect" seems to be less marked in the "Geothermal well" and Kapoho lines (respectively, lines D–D′ and E–E′ in Fig. 5), where 3/4 and 5/6 of tectonic and volcano-tectonic structures, respectively, were associated with anomalous soil degassing. This might support the hypothesis of a local magmatic source of CO_2 that is independent of that feeding soil degassing uprift and that might be identified with secondary magma reservoirs (TILLING and DVORAK, 1993).

Acknowledgements

The authors wish to thank the Hawaii Volcanoes National Park for having kindly given the permission to work in protected areas of Kilauea volcano. This work was carried out within the framework of activities coordinated and financially supported by the "Gruppo Nazionale per la Vulcanologia, C.N.R." of Italy.

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(Received: November 2003, revised: January 2005, accepted: January 2005)