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Journal of Volcanology and Geothermal Research 108 (2001) 121–139

Journal of volcanology and geothermal research

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A model of degassing and seismicity at Arenal Volcano, Costa Rica

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Abstract

Arenal volcano is the most active volcano in Costa Rica and has emitted at least 1.3 Mt of SO_2 since its reactivation in July 1968. Gas emissions from the volcano have been both by passive degassing and explosive eruptions, with passive degassing being dominant. Based on correlation spectrometry (COSPEC) measurements made during 1982, 1995 and 1996, the minimum average daily output is 130 ± 60 t d^{-1} SO_2 emitted from Arenal. Arenal is extremely active, with tremor fluctuations showing a distinct correlation with Earth tides; decreased explosive activity and increased tremor appear to coincide with the maximum rate of change in Earth tides. This suggests that a system such as Arenal may be extremely sensitive to small changes in the confining pressure or stress regime of the conduit. The cyclic nature of explosive activity also may be caused by corresponding fluctuations in the extrusion rate of lava. At high extrusion rates, lava from the non-explosive conduit may overflow into the explosive conduit, temporarily blocking it with a resulting pressurisation of the system. Arenal is likely tapping a deep to mid crustal magma chamber and, unlike many volcanoes, there is a comparatively small difference between petrological and COSPEC SO_2 estimates (0.41 vs. 1.3 Mt, respectively, since 1968), suggesting that Arenal is being continuously supplied by fresh magma. © 2001 Elsevier Science B.V. All rights reserved.

Keywords: Arenal volcano; SO_2 degassing; correlation spectrometry (COSPEC); seismicity; earth tides

1. Introduction

Arenal is a 1657-m-high conical stratovolcano situated in northern Costa Rica (10.463°N, 84.703°W), 90 km northwest of the capital San José (Fig. 1). It has been in continuous activity since 29 July 1968, when it reactivated with a plinian explosive phase. Aa lava flows of basaltic andesite have been extruded nearly continuously since 19 September 1968 (Cigolini et al., 1984). Arenal progressed into a second major eruptive phase in June 1975, which included numerous Merapi- and Soufrière-type nuées ardentes. The volcano entered an intense strombolian phase in 1984, with increased eruptions of ash, lapilli, and blocks which continue to the present day. The frequency of eruptions was observed to be approximately 30 min in 1984 (Van der Laat and Carr, 1989), while a similar eruptive frequency was noted by us in 1995 and 1996. Activity at Arenal has been accompanied by gas emissions since 1968, and currently includes continued lava extrusion and numerous ash emissions, some ascending to over 1 km above the active crater C (Fig. 1), with small infrequent pyroclastic flows travelling down the northwest flanks

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PII: S0377-0273(00)00281-X

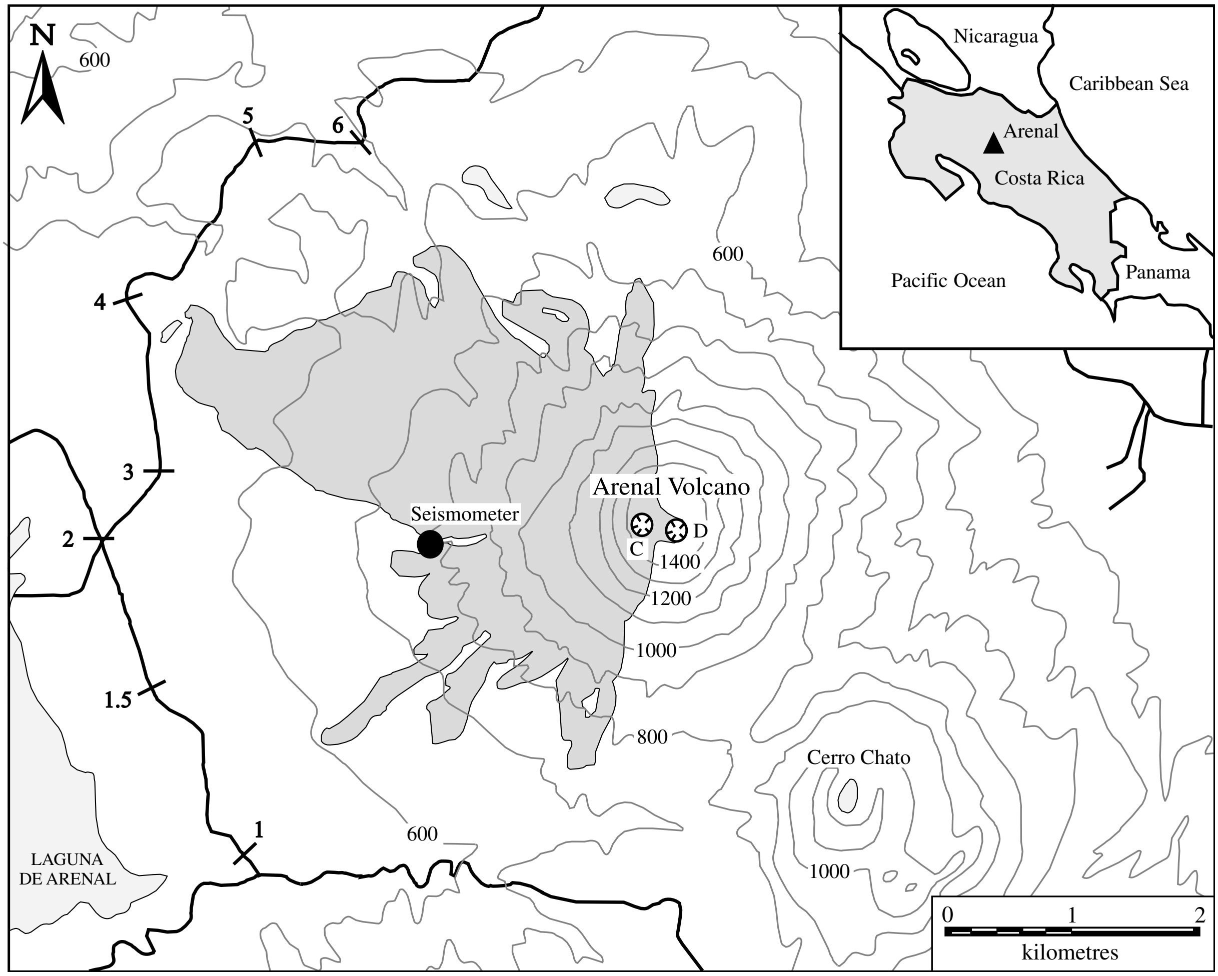

Fig. 1. Topographic map of Arenal volcano showing the location of the seismometer station (black circle) and road segments for COSPEC measurements (ticks and numbers). Recent lava flows (September 1968–June 1996) are shaded in grey. Crater C is the currently active of the two summit craters. Contours are 100 m.

(Fernández et al., 1996a). Bombs and blocks have been ejected ballistically to 1100 m elevation (Fernández et al., 1996b). Field observations indicate that crater C is likely divided into at least 2–3 vents from which lava, gas and ash are emitted separately. The summit (crater C) continues to grow at a rate of ~5 m year^{-1} (Fernández et al., 1996a).

Arenal is probably tapping a lower to mid-crustal magma chamber possibly located at a discontinuity ~20 km below the surface (Matumoto et al., 1977; Wadge, 1983; Reagan et al., 1987). Three stages of differing magma compositions at Arenal are believed to coincide with variations in eruptive activity (Reagan et al., 1987). Stage-1 zoned magmas likely resided in the magma chamber prior to the 1968 eruption. A new magma intruded into the chamber in July 1968, resulting in the plinian eruption and ejection of the stage-1 magma. It subsequently mixed with the more mafic parts of stage-1 to produce stage-2 magmas. Stage-3 magmas (mid-1974 to present) are the product of continued mixing and fractional crystallisation along the walls of the conduit and chamber. Each change in stage appears to correlate with a variation in the cumulative volume of extruded material (Reagan et al., 1987).

The extended duration and high level of activity of

Arenal are enigmatic. The periodic explosions and fluctuations in volcanic tremor and gas flux can provide information on the eruptive mechanisms which control the volcano. Arenal's near-continuous extrusion of lava, in conjunction with explosive activity, also raises the question of how magma travels to the surface through the plumbing system of the volcano.

Due to the high level of activity at the volcano and the inaccessibility of the crater area, we used remote sensing techniques to study volcanic gases at Arenal. Ultraviolet correlation spectrometry (COSPEC) has been used to study volcanoes since the early 1970s and is ideal for the measurement of SO_2 at active volcanoes such as Arenal. In this article, we present results from two field seasons on Arenal, in which 151 SO_2 flux measurements were made, currently the largest data set for this volcano. These data are compared with seismological measurements which we made in 1996 in order to develop a degassing model that may explain the variations in seismicity and SO_2 flux seen at Arenal. The problems of SO_2 flux measurements also are discussed. COSPEC and petrological estimates of the total SO_2 emitted since 1968, as well as annual rates of CO_2 and SO_2 flux, are made and used to show the impact that continuously erupting volcanoes such as Arenal have on the troposphere.

2. Methodology

2.1. SO_2 flux

The concentration of SO_2 in the volcanic plume was measured using a Plume Tracker (an instrument similar to the COSPEC) and a COSPEC IV in 1995 and 1996, respectively. These ultraviolet spectrometers were connected to a portable computer and/or chart recorder and transported beneath the volcanic plume, during which time the SO_2 signal was recorded. The instruments were driven below the column at an approximately constant speed (e.g. $20\ \mathrm{km\ h^{-1}}$) and approximately perpendicular to the column. Gas-cell calibrations were made before and after each traverse. Comparatively elevated SO_2 concentrations in the plume necessitated the use of high-concentration calibration cells (300 and 339.2 ppm-m for Plume Tracker and COSPEC, respectively). The digital data were then processed and graphed using commercial spreadsheet software. From the graph, the beginning and end of the plume transect were deduced, and consequently the flux calculated. Windspeed measurements were typically made in the morning prior to the start of SO_2 flux measurements (~0900 h local time), at midday, and in the afternoon at the end of flux measurements (~1600 h). There is a steady easterly trade wind that blows over Arenal and westward out across Laguna Arenal. Because of the inaccessibility of the summit area, windspeeds were measured on the western flank of the volcano at an elevation of ~550 m using a handheld anemometer. An individual traverse below the gas plume was divided into segments in order to correct for the deviation from perpendicularity of the traverse with respect to the plume. The SO_2 flux for each segment was calculated and summed to determine the total SO_2 flux for a given traverse. The SO_2 flux in metric tonnes per day (F) was calculated using the following equation:

$$F = (\cos\theta)(d)(\nu)(0.00023)([\mathrm{SO2}]) \tag{1}$$

where θ (°) is the deviation from perpendicularity of the segment of road with respect to the gas plume, d the width (m) of a particular segment determined from a topographic map, ν the average windspeed ($\mathrm{m\ s^{-1}}$) measured at ground level 2–3 times per day; 0.00023 is a factor to convert $\mathrm{ppm\text{-}m^3\ s^{-1}}$ into metric tonnes per day and $[SO_2]$ is the path-length concentration of SO_2 (ppm-m) in the column. The concentration of SO_2 in the plume was calculated from

$$[\mathrm{SO_2}] = \frac{P_{\mathrm{avg}}}{P_{\mathrm{cal}}}(C_{\mathrm{cal}}) \tag{2}$$

where P_{cal} is the peak height of the calibration gas cell in arbitrary units, P_{avg} the average peak height for the segment and C_{cal} the concentration of the calibration gas cell in ppm-m.

2.2. SO_2 flux errors

Variations in measured SO_2 fluxes may be due, in part, to fluctuations in windspeed and direction, changes in cloud cover, and change in sun angle, resulting in variable amounts of solar ultraviolet radiation. The opacity of an eruptive plume also varies

Table 1
Error calculation for SO_2 measurements

Calibration cell concentrations	
Plume tracker: 300 ppm-m	2%
COSPEC: 339.2 ppm-m	2%
Digital record reading error	2%
Variation in car speed	5%
Plume opacity due to ash in eruptions	10%
Windspeed determination	
1995: 0–60%	30%
1996: 6–26%	16%
Total Error (square root of the sum of the squares)	
1995 Minimum	6%
Maximum	60%
Generally	32%
1996 Minimum	9%
Maximum	27%
Generally	20%

due to changes in ash content which will increase the absorption of ultraviolet radiation. However, recent laboratory experiments by Andres and Schmid (1997) indicate that the COSPEC reliably measures SO_2 burdens within 10% accuracy for ash-laden plumes that are up to 50% opaque. Instrumental uncertainties include instrument calibration (±2%), digital chart reading error (±2%), varying car speed (±5%), and windspeed measurement (±0–60%) (Table 1; Casadevall et al., 1981; Stoiber et al., 1983).

Windspeed measurements were affected in part by instrumentation errors. Wind measurements made in 1995 have an average standard deviation of ~30%, as the digital anemometer that was used gave readings that varied continually with local wind gusts (Table 2). The operator was thus forced to estimate the average range of speeds at the time of measurement. The 1996 wind measurements used a fully mechanical anemometer that allowed for the integration of windspeed over an interval of one minute, thus eliminating the need for estimates on the part of the operator. Consequently, the standard deviation was ~16%, or about half that of the previous year (Table 2). Thus, instrumental errors for the SO_2 flux were generally of the order of 30% and ~15% for 1995 and 1996, respectively (Table 1), similar to those calculated by Stoiber et al. (1983).

The error in windspeed measurement is also due to the fact that measurements were made at the base of Arenal (elev. ~550 m) and thus do not necessarily represent windspeeds at the summit of the volcano where degassing is taking place. As there is approximately 1–1.5 km difference in altitude between the ground and the base of the plume, the plume velocity may be up to 1.5–3 times greater than that measured on the ground (Willett and Sanders, 1959). Our flux measurements are thus minimum values. When investigating variations in SO_2 flux over time, uncertainties due to windspeed measurements may be eliminated by normalising the windspeed (in the flux calculations) to $1\ \mathrm{m\,s^{-1}}$ (Zapata et al., 1997). This leaves only instrumental uncertainty (~12%, Table 1), facilitating comparison with other data sets (see below).

Generally, 10–15 traverses were made per day, with individual traverses lasting approximately 20 min. Plume Tracker/COSPEC measurements were typically made to the west and southwest of the volcano, at a distance of between 4 and 4.5 km from the crater (Fig. 1). Plume widths varied between 2 and 6 km but were typically 2–3 km. In order to minimise the errors arising from variable amounts of ultraviolet radiation, measurements were made only when the sun was at a relatively high angle, from ~0900 h until ~1600 h local time.

2.3. Seismicity

Seismic data were collected using a single Personal Seismograph PS-1 having a frequency range of 0.2–30 Hz. In the low-gain mode used in this study, the instrument was able to detect a vertical acceleration of 0.93 μgal and ground displacement of 231 nm at 1 Hz. At 40 Hz, a vertical acceleration of 2.92 μgal and ground displacement of 0.45 nm was detectable. The PS-1 was placed at ~750 m elevation on the western flank of the volcano near an inclinometer maintained by the Departemento de Geologia of the Instituto Costaricense de Electricidad (ICE) (Fig. 1). The seismometer was buried approximately 50 cm below the surface to reduce the effect of wind, and was connected to a portable computer for the collection of digital data. The seismic data later were analysed using commercial software.

Table 2
Windspeed measurements taken 4 km west (elev. ~550 m) of the summit of Arenal volcano

1995								1996						
Date	Speed (m s^{-1})				Avg. (m s^{-1})	Std.Dev.	% Dev.	Date	Speed (m s^{-1})			Avg. (m s^{-1})	Std.Dev.	% Dev.
28/02/95	2.5	2.5	2.5		2.50			28/02/96	2.23	2.13	2.39	2.25	0.13	5.83
04/03/95	4.1				4.10			01/03/96	3.29	3.84	2.25	3.13	0.81	25.83
05/03/95	3.9	3.6			3.75	0.21	5.66	03/03/96	2.63			2.63		
08/03/95	2	1			1.50	0.71	47.14	05/03/96	2.77	4.09	4.09	3.65	0.76	20.88
22/03/95	2.6				2.60			06/03/96	2.73	3.83	3.6	3.39	0.58	17.13
23/03/95	2	1.75			1.88	0.18	9.43	08/03/96	2.82	3.33		3.08	0.36	11.73
24/03/95	1.2	1.15	1	3	1.59	0.95	59.56						Average 16.28	
27/03/95	2.2	1.25	3.5		2.32	1.13	48.76							
30/03/95	4	3.5			3.75	0.35	9.43							
31/03/95	2.25				2.25									
01/04/95	4	1.75			2.88	1.59	55.34							
						Average 33.62								

3. Results

3.1. SO_2 flux

Sulphur dioxide flux measurements were collected during the months of February–April 1995 and February–March 1996 (Table 3). The 1995 data consisted of 11 days of Plume Tracker measurements, with average SO_2 flux of 110 ± 52 t d^{-1} (Table 4). The overall SO_2 flux varied between 50 ± 20 and 200 ± 110 t d^{-1}, and between 20 (a single measurement) and 190 ± 120 t d^{-1} when eruption-related SO_2 was excluded. Eruption-related SO_2, which is the additional sulphur dioxide from an explosive eruption, was distinguished from passive degassing of the volcano in order to study trends that were not influenced by eruptions. A maximum explosive value for the 1995 field season of 370 t d^{-1} was measured on 30 March 1995, while a minimum of 20 t d^{-1} also was seen on the same day.

The 1996 field season consisted of six days of COSPEC measurements, with an average SO_2 flux of 160 ± 60 t d^{-1} (Table 4). The overall SO_2 flux varied between 110 ± 50 and 260 ± 80 t d^{-1}, and between 90 ± 20 and 190 ± 40 t d^{-1} when eruption-related SO_2 was excluded. Standard deviations varied between 10 and 90 t d^{-1}. A maximum value for the 1996 field season of 360 t d^{-1} was measured on 8 March, while a minimum of 40 t d^{-1} was seen on 5 March (Table 3). Maximum values for both years are quite similar, with the average daily flux for 1996 (160 t d^{-1}) only slightly higher than the 1995 flux (110 t d^{-1}). Similarly, the non-eruptive passive SO_2 flux is only marginally higher in 1996 (130 t d^{-1}) than in 1995 (100 t d^{-1}), although any differences are well within the error of the measurements. However, if one takes into account the fact that windspeed at the plume height may be as much as three times greater than at ground level, a maximum average value of 330 and 480 t d^{-1} is obtained for 1995 and 1996, respectively. Maximum non-eruptive passive SO_2 flux was therefore 300 t d^{-1} (1995) and 390 t d^{-1} (1996). The 1995–1996 data are similar to the eight measurements made by Casadevall et al. (1984) in 1982 which had an average SO_2 flux of 200 ± 40 t d^{-1} and are 2–3 times greater than the flux of ~50 t d^{-1} measured in 1982 by Stoiber et al. (1982) (Tables 3 and 4).

Due to the high level and frequency of eruptive activity at Arenal, it was difficult to obtain statistically adequate data necessary to demonstrate systematic changes in SO_2 levels prior to an eruption. There are, however, some instances where SO_2 levels appear to decrease progressively prior to an explosive eruption. In the afternoon of 5 March 1996, for example, SO_2 flux, normalised to a 1 m s^{-1} windspeed, decreased from 30 ± 4 t d^{-1} (120 ± 20 with measured windspeed) to 10 ± 1 t d^{-1} (40 ± 10)

Table 3
Daily SO_2 flux for Arenal volcano from 1982 to 1996 (values in italics represent eruption measurements)

Date	Time (local time)	Windspeed ($m\ s^{-1}$)	SO_2 flux ($t\ d^{-1}$)	SO_2 flux[a] (at 1 $m\ s^{-1}$)
1982 Data				
16/02/82[b]			225	
16/02/82[b]			200	
16/02/82[b]			250	
16/02/82[b]			190	
16/02/82[b]			240	
19/02/82[b]			200	
19/02/82[b]			140	
19/02/82[b]			140	
11/82[c]			50	
1995 data				
28/02/95	09:24:39	2.5	85	34
28/02/95	09:46:22	2.5	96	39
28/02/95	10:20:23	2.5	60	24
28/02/95	10:30:24	2.5	*203*	*81*
28/02/95	10:51:54	2.5	24	10
28/02/95	11:39:43	2.5	24	10
28/02/95	11:55:44	2.5	60	24
28/02/95	13:16:07	2.5	33	13
28/02/95	13:35:15	2.5	64	26
28/02/95	13:54:48	2.5	53	21
28/02/95	14:03:46	2.5	*92*	*37*
28/02/95	14:24:32	2.5	21	8
28/02/95	14:46:44	2.5	*104*	*42*
04/03/95	10:01:31	4.1	77	19
04/03/95	10:32:38	4.1	59	15
04/03/95	10:49:00	4.1	63	15
04/03/95	11:19:52	4.1	*99*	*24*
04/03/95	11:37:19	4.1	71	17
04/03/95	12:00:47	4.1	96	23
04/03/95	12:10:25	4.1	34	8
04/03/95	12:21:42	4.1	45	11
04/03/95	12:34:43	4.1	147	36
04/03/95	12:45:54	4.1	*83*	*20*
04/03/95	13:00:56	4.1	34	8
04/03/95	14:49:48	4.1	*124*	*30*
04/03/95	15:06:53	4.1	59	14
04/03/95	15:18:42	4.1	83	20
05/03/95	09:32:57	3	58	19
05/03/95	09:59:21	3	42	14
05/03/95	10:18:30	3	42	14
05/03/95	10:32:57	3	88	29
05/03/95	10:44:28	3	23	8
05/03/95	10:57:44	3	42	14
05/03/95	11:36:36	3	62	21
05/03/95	11:56:33	3	55	18
05/03/95	12:08:34	3.88	*114*	*29*
05/03/95	12:22:15	3.88	36	9
05/03/95	13:25:37	3.88	67	17
05/03/95	13:42:10	3.88	53	14
05/03/95	13:58:34	3.88	62	16
05/03/95	14:13:51	3.63	40	11
05/03/95	14:24:16	3.63	*152*	*42*
05/03/95	14:37:13	3.63	61	17
05/03/95	14:53:08	3.63	43	12
05/03/95	15:06:16	3.63	47	13
08/03/95	09:35:44	2	*79*	*39*
08/03/95	09:57:01	2	59	29
08/03/95	10:21:24	2	95	48
08/03/95	10:35:20	2	*64*	*32*
08/03/95	11:09:49	2	146	73
08/03/95	11:26:20	2	40	20
08/03/95	11:44:30	2	70	35
08/03/95	14:18:57	2	130	65
08/03/95	14:41:18	1	93	93
08/03/95	14:58:52	1	118	118
22/03/95	09:59:34	2.6	103	39
22/03/95	10:18:27	2.6	88	34
22/03/95	10:31:14	2.6	112	43
22/03/95	10:44:32	2.6	*74*	*28*
22/03/95	10:50:15	2.6	98	38
22/03/95	10:59:41	2.6	189	73
22/03/95	11:24:36	2.6	65	25
23/03/95	09:36:38	2.3	132	57
23/03/95	09:59:03	2.3	181	79
23/03/95	10:15:25	2.3	*164*	*71*
23/03/95	10:35:45	2.3	194	84
23/03/95	10:48:03	2.3	99	43
23/03/95	12:02:56	1.75	218	125
24/03/95	11:48:11	1.2	*50*	*42*
24/03/95	12:04:56	1.2	22	18
24/03/95	14:36:04	1.2	*67*	*56*
27/03/95	09:51:31	2.6	56	22
27/03/95	10:09:10	2.6	*94*	*36*
27/03/95	10:27:02	2.6	*93*	*36*
27/03/95	10:38:55	2.6	73	28
27/03/95	10:54:14	2.6	75	29
27/03/95	11:04:53	2.6	79	30
27/03/95	11:17:53	2.6	50	19
27/03/95	11:30:21	2.6	98	38
27/03/95	11:45:25	1.25	70	56
27/03/95	13:03:25	1.25	66	53
27/03/95	14:17:16	3.5	*129*	*36*
30/03/95	09:38:51	4	*367*	*92*
30/03/95	09:57:37	4	*232*	*58*
30/03/95	10:21:17	4	239	60
30/03/95	10:39:04	4	106	26

Table 3 (*continued*)

Date	Time (local time)	Windspeed (m s^{-1})	SO_2 flux (t d^{-1})	SO_2 flux[a] (at 1 m s^{-1})
30/03/95	10:58:27	4	286	72
30/03/95	11:11:44	4	246	61
30/03/95	12:06:00	4	285	71
30/03/95	13:22:40	4	94	23
30/03/95	13:40:02	4	146	36
30/03/95	14:18:12	4	18	5
31/03/95	10:11:25	2.25	225	100
31/03/95	10:43:14	2.25	121	54
31/03/95	11:01:51	2.25	220	98
31/03/95	11:19:45	2.25	155	69
31/03/95	12:14:29	2.25	*242*	*108*
31/03/95	12:34:25	2.25	114	51
31/03/95	13:47:26	2.25	*170*	*75*
01/04/95	09:59:39	4	111	28
01/04/95	10:35:32	4	*203*	*51*
01/04/95	11:02:06	4	174	44
01/04/95	11:13:28	4	234	58
01/04/95	11:27:29	4	42	11
01/04/95	11:37:53	4	122	31
01/04/95	13:10:25	4	71	18
01/04/95	13:42:06	4	79	20
01/04/95	13:51:42	4	56	14
1996 data				
29/02/96	11:06:38	2.25	*115*	*51*
29/02/96	11:38:23	2.25	*220*	*98*
29/02/96	12:12:02	2.25	*111*	*50*
29/02/96	12:37:24	2.25	*131*	*58*
29/02/96	14:25:24	2.25	*93*	*41*
29/02/96	14:57:59	2.25	*64*	*28*
29/02/96	15:12:09	2.25	90	40
29/02/96	15:34:00	2.25	76	34
29/02/96	15:55:58	2.25	87	39
01/03/96	10:47:02	3.13	150	48
01/03/96	11:15:44	3.13	*155*	*50*
01/03/96	11:33:37	3.13	182	58
01/03/96	11:48:36	3.13	171	55
01/03/96	13:50:21	3.13	239	76
01/03/96	14:11:38	3.13	242	77
01/03/96	14:29:10	3.13	253	81
01/03/96	14:55:45	3.13	164	52
03/03/96	10:15:08	2.63	113	43
03/03/96	10:37:05	2.63	116	44
03/03/96	10:51:54	2.63	91	35
03/03/96	11:08:24	2.63	*124*	*47*
05/03/96	09:58:00	3.65	155	42
05/03/96	10:33:26	3.65	*263*	*72*
05/03/96	13:42:59	3.65	117	32
05/03/96	13:59:25	3.65	80	22
05/03/96	14:18:22	3.65	41	11
05/03/96	14:47:47	3.65	103	28
05/03/96	15:16:40	3.65	*181*	*50*
05/03/96	15:36:22	3.65	102	28
06/03/96	10:38:43	3.39	218	64
06/03/96	10:54:51	3.39	*162*	*48*
06/03/96	11:29:24	3.39	*339*	*100*
06/03/96	14:33:30	3.39	316	93
08/03/96	12:01:20	3.08	*360*	*117*
08/03/96	12:19:42	3.08	114	37
08/03/96	12:35:32	3.08	*242*	*79*
08/03/96	13:07:30	3.08	113	37
08/03/96	13:24:24	3.08	*130*	*42*
08/03/96	13:42:49	3.08	*215*	*70*
08/03/96	14:05:20	3.08	201	65
08/03/96	14:16:37	3.08	139	45
08/03/96	14:39:46	3.08	65	21
08/03/96	14:50:06	3.08	128	42

[a] SO_2 flux in tonnes per day normalised to a windspeed of 1 m s^{-1}.

[b] Casadevall et al. (1984).

[c] Stoiber et al. (1982).

prior to an eruption at 1417 h. The flux subsequently increased to 30 ± 3 t d^{-1} (100 ± 20) after the eruption (Fig. 2E and F). Although this post-eruption flux measurement may contain an eruptive component, the marked contrast before and after the eruption may nevertheless be significant as it suggests that sealing of the conduit may be taking place. Although more data is necessary to fully characterise the eruptive nature of the volcano, these repetitive fluctuations raise the possibility that Arenal undergoes cyclical opening and closing of the conduit.

3.2. SO_2 budgets at Arenal

3.2.1. COSPEC/Plume Tracker estimates

An estimate for the total SO_2 emission from Arenal may be made by taking the average of measured SO_2 flux and extrapolating back to 1968. There is very little published SO_2 flux data for Arenal, with only eight airborne COSPEC measurements made in February 1982 (Table 3; Casadevall et al., 1984) and some ground-based measurements in November, 1982 (Table 3; Stoiber et al., 1982). At the time of these measurements, the gas originated mainly from

Table 4
Average daily SO_2 flux for Arenal volcano with and without eruptions

	All SO_2 data			SO_2 data excluding eruptions		
Date	Average	Std. Dev.	Number	Average	Std. Dev.	Number
16/02/82[a]	221	26	5			
19/02/82[a]	160	35	3			
11/82[b]	50	N.A.	N.A.			
28/02/95	71	49	13	59	30	10
04/03/95	77	32	14	65	25	9
05/03/95	60	31	18	51	15	16
08/03/95	89	34	10	70	21	6
22/03/95	104	41	7	90	18	6
23/03/95	165	43	6	144	36	4
24/03/95	47	23	3	22		1
27/03/95	80	22	11	80	22	11
30/03/95	202	107	10	193	120	8
31/03/95	178	51	7	167	53	5
01/04/95	121	68	9	107	57	8
29/02/96	110	46	9	87	17	5
01/03/96	194	43	8	186	39	7
03/03/96	111	14	4	107	14	3
05/03/96	130	69	8	99	42	5
06/03/96	259	83	4	162		1
08/03/96	171	86	10	127	44	6
Avg. '82–'96	130	61	8			
Avg. 1995	109	52	10	95	53	8
Avg. 1996	162	58	7	128	39	5

[a] Casadevall et al. (1984).

[b] Stoiber et al. (1982).

fumaroles near crater C (Cheminée et al., 1981; Casadevall et al., 1984). Hundred and fifty-one measurements were made by us at Arenal between 1995 and 1996, resulting in an average of $130 \pm 60\ \mathrm{t\ d^{-1}}$ of SO_2 gas, likely originating from crater C (Table 4). If one takes a weighted average of the three data sets, a mean daily SO_2 flux of $130 \pm 60\ \mathrm{t\ d^{-1}}$ is calculated. We estimate that, since 1968, at least ~1.3 Mt of SO_2 (using ground level windspeeds), and even as much as 3.9 Mt SO_2 (assuming a windspeed three times ground level speeds), has been emitted. These are nevertheless lower limits for the following reasons: (1) significant quantities of SO_2 likely were emitted explosively during the initial 1968 eruptive episode and the June 1975 eruption phase; and (2) these data neglect sulphur released in the form of H_2S.

3.2.2. Petrological estimates

Estimates of total sulphur released also were made using melt inclusion data from samples of the 1968 surge deposit and a 1992 lava flow (Table 5). We assumed that the non-degassed pre-eruption melt was the only source of sulphur, and that melt inclusions trapped in plagioclase and pyroxene crystals represent the non-degassed sulphur content of the magma. The coexisting matrix glass was assumed to represent sulphur contents of the degassed melt after eruption. The difference, which is the quantity of SO_2 released, can be determined from the difference in the sulphur contents of the melt inclusions and matrix glass. This petrological SO_2 emission (E_{SO2} in Mt) can be calculated for Arenal basaltic andesites using the following equation (Gerlach and McGee, 1994):

$$E_{SO2} = (2 \times 10^{-15}) \Delta S_m \rho_m \phi_m V \tag{3}$$

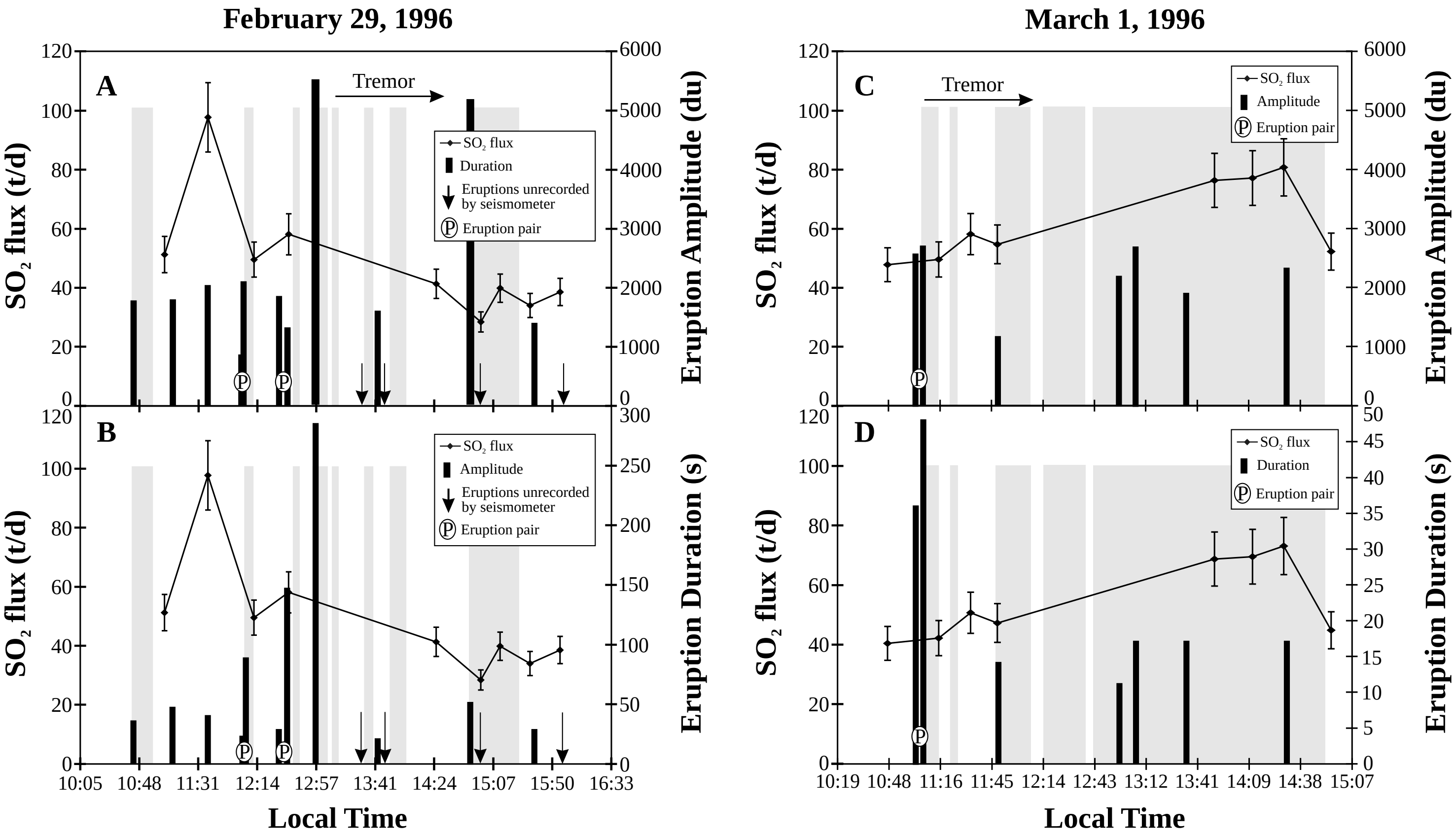

Fig. 2. SO_2 flux and eruption amplitude and SO_2 flux and eruption duration versus time for (A), (B) 29 February; (C), (D) 1 March (E), (F) 5 March; and (G), (H) 6 March. SO_2 fluxes have been normalised to a windspeed of 1 m s^{-1}; error bars are thus 12%. Seismic eruption amplitude is in digital units, eruption duration in seconds, and SO_2 flux in metric tonnes per day. Shaded area represents periods of tremor. Eruption pairs are noted by an encircled P. Inverted arrows represent eruptions that were seismically unrecorded but noted visually.

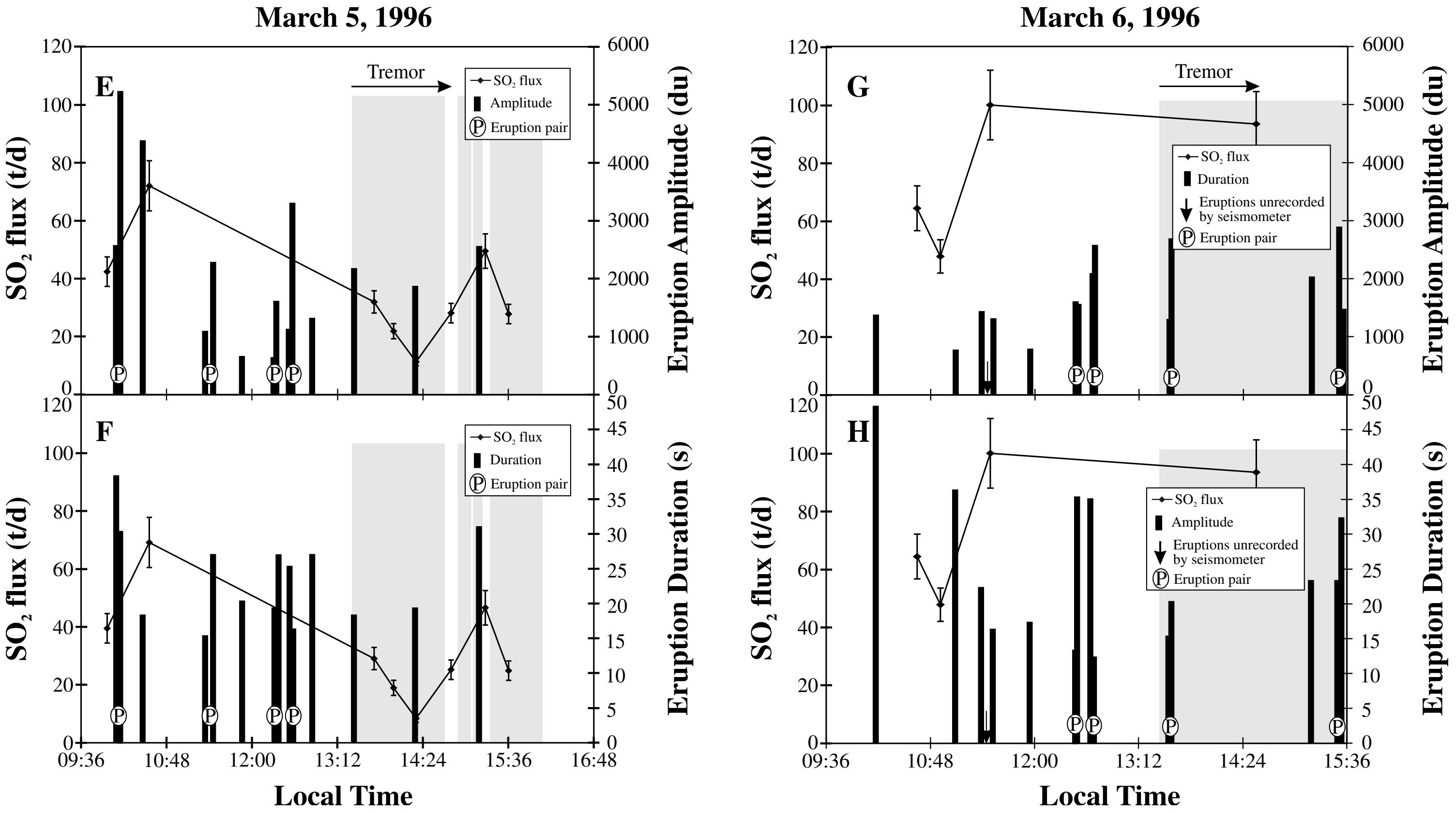

Fig. 2. (*continued*)

Table 5
Chemical analyses for melt inclusions and matrix glasses from 1968 surge deposit and 1984 and 1992 lava at Arenal volcano

	Melt Inclusions							Matrix Glasses							
	1968 surge	1992 lava						1968 surge		1984 lava				1992 lava	
Sample	px687a	px9215a	px9215b	px9215c	px9215d	px9215e	px9216a	gl68mtxd	gl68mtxc	pg84mtxb	pg84mtxc	pg84mtxd	gl84mtxa	gl92mtxc	gl92mtxd
Analysis wt%															
SiO_2	61.67	65.30	65.58	64.61	63.70	63.11	63.15	66.56	64.35	64.89	65.29	65.96	67.09	70.64	67.12
TiO_2	0.60	0.54	0.57	0.60	0.32	0.29	0.77	0.56	0.47	1.54	1.33	1.46	1.24	1.00	0.85
Al_2O_3	18.59	18.41	18.01	18.42	17.53	17.18	18.38	15.08	17.11	11.42	11.95	11.49	12.97	11.98	15.05
FeO[a]	5.09	3.09	3.24	3.31	4.56	4.70	4.04	3.86	3.64	9.51	8.73	8.67	6.28	4.41	3.66
MnO	0.08	0.03	0.04	0.04	0.03	0.05	0.03	0.03	0.04	0.07	0.06	0.08	0.04	0.03	0.04
MgO	1.26	0.34	0.45	0.47	2.43	2.83	0.48	1.02	0.91	0.98	0.83	0.80	0.56	0.52	0.36
CaO	4.48	5.19	4.52	5.12	5.07	5.23	5.24	4.03	4.94	3.81	3.76	3.41	2.94	2.10	3.52
Na_2O	4.66	4.24	4.13	4.17	4.04	4.01	4.19	3.96	4.03	4.14	4.19	3.93	4.80	3.76	4.23
K_2O	2.24	1.31	1.36	1.26	0.95	0.87	1.40	1.59	1.44	1.55	1.41	1.72	1.66	2.58	2.34
P_2O5	0.26	0.31	0.31	0.29	0.24	0.24	0.35	0.28	0.13	0.49	0.44	0.49	0.47	0.33	0.52
F (ppm)	250	140	70	200	180			250	0	0	0	0	0	0	110
Cl (ppm)	2730	2200	2320	2150	2450	2330	2300	1840	1470	2660	2790	2780	2490	1640	1210
S (ppm)	176	208	264	312	661	681	192	20	>20	24	20	>20	>20	>20	24
Total	99.19	98.99	98.46	98.54	99.23	98.86	98.24	97.14	97.17	98.61	98.19	98.20	98.26	97.48	97.78

[a] Total Fe expressed as FeO.

where the constant 2×10^{-15} is a conversion factor for sulphur (ppm kg^{-1}) into sulphur (Mt), ΔS_m is the S lost from the melt during eruption in ppm, determined by the difference (332 ppm) in mean S contents of seven melt inclusions (356 ppm) and eight matrix glasses (<24 ppm, Table 5), ρ_m the basaltic andesite melt density, assumed to be 2700 kg m^{-3}, ϕ_m the melt volume fraction of 0.5, estimated from thin sections of 1968, 1984 and 1992 surge deposit/lava and V the volume of magma extruded between 1968 and 1996. The value for ΔS_m, which was determined from samples of the 1968 and 1992 eruptive activity, is assumed to be representative of the 30-year course of the eruption. An estimate of the total volume of lava extruded to date may be obtained by using rates of lava extrusion. Extrusion rates from 1973 to 1985 (9.3×10^6 m^3 $year^{-1}$; Wadge, 1983; Reagan et al., 1987) and 1992 to 1996 (1.0×10^7 m^3 $year^{-1}$; Soto, 1997; Soto and Arias, 1998) are quite similar; thus, we assume an extrusion rate of 1.0×10^7 m^3 $year^{-1}$ between 1985 and 1996. Therefore, by adding the volume of lava extruded from 1968 to 1985 (3.5×10^8 m^3; Reagan et al., 1987) to the volume of lava extruded from 1985 to 1996 (1.0×10^7 m^3 $year^{-1}$ times 11 years $= 1.1 \times 10^8$ m^3), we estimate that a total lava volume of 4.6×10^8 m^3 has been extruded between 1968 and 1996. The resulting E_{SO_2} is ~0.41 Mt of SO_2, approximately 3.2 times less that the 1.3 Mt estimated using COSPEC data. If one assumes that the maximum sulphur in melt inclusions (avg.: 671 ppm S; px92-15d, px92-15e, Table 5) represents samples from the least degassed magma, the petrologically estimated mass of SO_2 emitted since 1968 is ~0.83 Mt. This is 1.6 times less than the mass estimated from COSPEC data. If maximum windspeeds are used yielding 3.9 Mt SO_2 for the COSPEC estimates, the petrologic estimates are 4.7–9.5 times less than the COSPEC. Although this difference seems large, it is in fact quite small compared to other volcanoes (e.g. Williams et al., 1990; Andres et al., 1991).

Using SO_2 fluxes measured by COSPEC and appropriate CO_2/SO_2 ratios (Arenal SO_2 130 t d^{-1}, CO_2/SO_2 6.4; Williams et al., 1992), we calculate crater CO_2 fluxes of 830 t d^{-1} for Arenal. This flux is 2–3 orders of magnitude smaller than at Mount Etna (Allard et al., 1991).

3.3. Seismic data

Seismic measurements were made in conjunction with COSPEC measurements during six days in 1996. A total of 63 eruptions were measured over the six day period between ~1000 and ~1600 h local time. The durations of these events varied between ~5 and ~90 s, while amplitudes ranged from 120 to 4400 digital units. Numerous periods of tremor also were recorded between eruptions, with durations ranging from 14 s up to a period of continuous tremor lasting >6600 s on 2 March 1996. Fast Fourier Transform (FFT) analyses of the tremor signal revealed that frequencies typically varied between 2 and 5 Hz. These tremors fall in the class of intermediate frequency tremor which is believed to be associated with strong degassing. Low frequency tremor at <2 Hz also has been noted and may represent conduit resonance, gas fluctuation, or degassing (Barquero et al., 1992; Hagerty et al., 1997, 2000).

The relationship between tremor and eruptive events varies somewhat over the period of measurement; nevertheless, some interesting correlations are apparent. A relative decrease in tremor was seen before eruptions on 29 February (1450, 1537 h local time, Fig. 2A and B) and 1 March 1996 (1520, 1529 h, Fig. 2C and D). For eruptions on 29 February and 6 March, tremor amplitudes decreased before eruptions on a timescale of minutes (Roberge, 1997). Many eruptions also were followed by tremor events on 29 February (1043, 1257, 1342, 1450 h, Fig. 2A and B). The post-eruptive tremor at Arenal was noted by Benoit and McNutt (1997) and Garcés et al. (1998), and also at Karymsky volcano by Johnson et al. (1998). The development of tremor immediately after an eruption implies that the conduit was opened by the eruption, allowing increased degassing and/or magma movement to occur.

Locomotive-like sounds, called “chugs”, have been recognised at Arenal and are believed to be caused by repetitive gas emissions (Melson, 1989). Such chugs frequently were accompanied by harmonic tremor, which, although they are not well understood, likely indicate the presence of an open conduit (Barboza and Melson, 1990; Benoit and McNutt, 1997). We also have noted this correlation, typically in the early part of the day. For example, on 2 March 1996, a general decrease or dissipation of both chugs and tremor was observed prior to eruptions at 1129, 1159 and 1214 h. This was also the case on 29 February (1450, 1537 h) and 1 March (1520 and 1529 h). 1 March was also notable for the comparatively low level of explosions and the relatively high number of chugs and tremor events (Fig. 2C and D).

During the period of observation, there were a greater number of eruptions in the mornings compared to the afternoons. This also was remarked upon briefly by Barboza and Melson (1990). For example, on 5 March 1996, there were 11 eruptions between 1000 and 1300 h, yet only three eruptions between 1300 and 1650 h. Additionally, the morning eruptions were characterised by pairs of eruptions; eight eruptions out of the total were paired with less than 10 min separating them (Fig. 2E and F). Of the 11 paired eruptions during the four days shown in Fig. 2, the initial event has a smaller amplitude in 8 of the 11 eruption pairs. By contrast, only two of the eruption pairs have a second event with an amplitude smaller than the first. In terms of duration, the first event of the pair is shorter than the second in 7 of the 11 eruption pairs. The first eruption of the pair may partially open the conduit with comparatively little release of gas pressure. The second, larger-amplitude event will then destructively open the conduit. The amplitudes of the morning eruptions (except for 6 March) also tend to be greater and more variable than those of the afternoon. The subsequent decrease in afternoon eruption occurrences and amplitudes generally coincided with increasing Earth tide (Fig. 3). This variation coincides with changes in the occurrence and nature of the tremor (Barboza and Melson, 1990). Prior to ~1326 h on 5 March, for example, there was very little chugging or tremor activity; however, after this point significant tremor commenced and lasted throughout the afternoon until the cessation of measurements at ~1600 h. Similarly, on 6 and 8 March, tremor started after ~1328 and ~1357 h, respectively, and was accompanied by a decreased frequency of eruptions. For 1, 5, 6, and 8 March, the afternoon tremor invariably began very soon after the onset of the maximum rate of change in Earth tide (Fig. 3).

The presence of small-amplitude, high-frequency (15–17 Hz) events prior to eruptions was observed on 6 March. This coincided with the highest daily SO_2 average ($260 \pm 80\,t\,d^{-1}$) of the field season (Table 4). Excluding the eruption-related SO_2 flux, 6 March still has the second highest daily value of $162\,t\,d^{-1}$ (single value). Such high-frequency events may be related to rock fracturing (Anderson, 1978), which together with high SO_2 fluxes, suggests that there may have been increased intrusion of comparatively gas-rich magma into the conduit.

In summary, there appears to be an inverse correlation between frequency and magnitude of explosive eruptions on the one hand, and occurrence of tremor on the other during our period of observation. The mornings were characterised by more frequent eruptions with larger amplitudes, accompanied by little tremor. By contrast, the afternoons showed periods of continuous tremor that began soon after minimum Earth tide. The tremor was accompanied by correspondingly fewer eruptions of smaller amplitude.

4. Discussion

4.1. Conduit opening and closing

The seismic data presented above appear to point to the repetitive opening and closing of at least part of the shallow conduit system. The frequent periods of chugs and tremor, as well as Arenal's continuous activity since 1968, indicate that the volcano is generally behaving as an open system. However, on a daily or hourly scale, Arenal appears to go through cyclic changes between a closed and an open system.

The higher number of explosive eruptions in the morning (e.g. 29 February, 5, 6, and 8 March 1996) and the observed sequence of paired eruptions in the morning (e.g. 5 and 6 March 1996) suggest that Arenal behaves as a comparatively closed system at these times. The relative quiescence of seismic activity before eruptions on the mornings of 29 February, 5, and 6 March may indicate closure of the conduit prior to the eruptions (Fig. 2). The paired eruptions of 5 March also suggest that the system is relatively closed. These paired eruptions (29 February, 1, 5, and 6 March; Fig. 2) disappear with decreased eruptive activity in the afternoon, which coincides with the onset of tremor. In contrast to these days, 1 March shows a distinct lack of eruptive activity and greater tremor and chugging (Fig. 2), suggesting that the

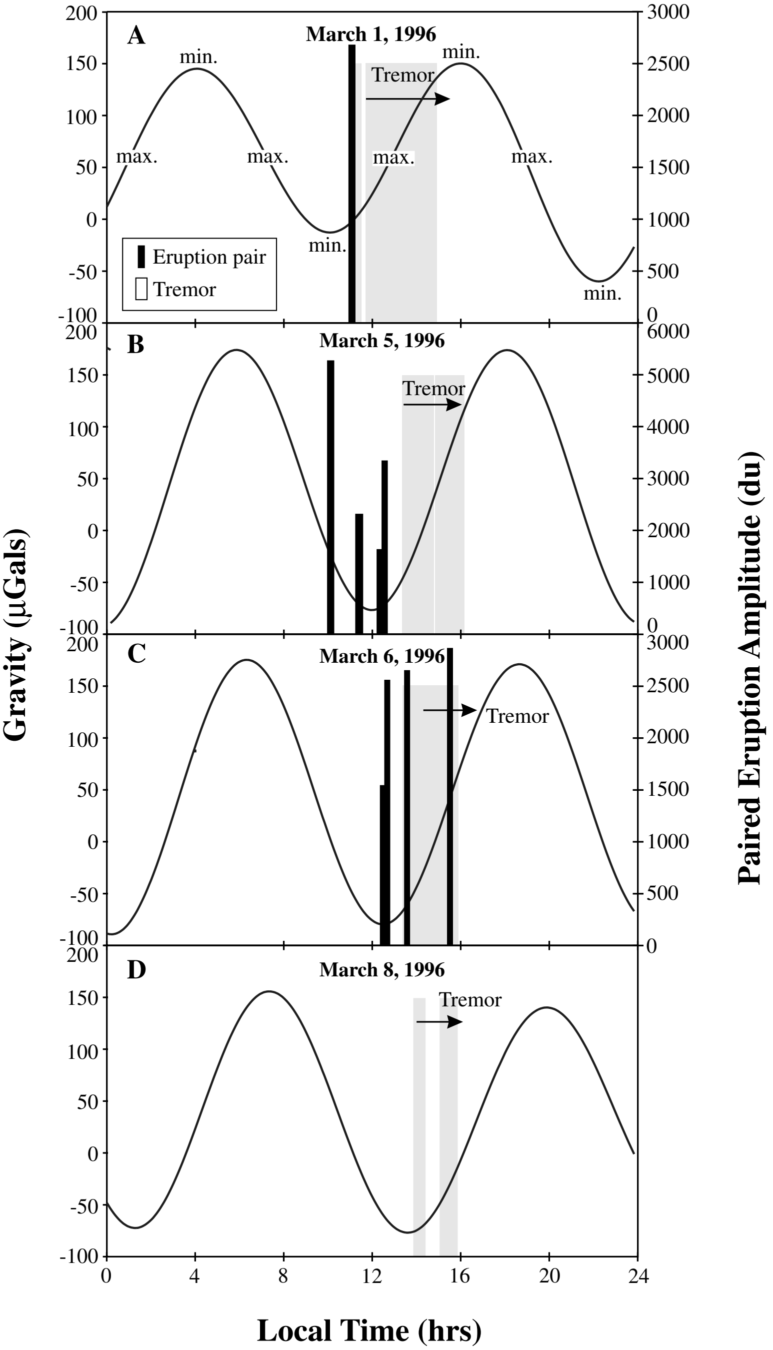

Fig. 3. Fluctuation of gravity due to Earth tides on: (A) 1 March; (B) 5 March; (C) 6 March; and (D) 8 March 1996. Eruption pairs (each bar represents an eruption pair) typically occur before the onset of tremor. Periods of near-continuous tremor (shaded area) generally begin just prior the maximum rate of change in Earth tide; these continue up to and likely after the end of data collection. Note that there were no eruption pairs on 8 March. Gravity data are in microgals, eruption amplitudes are in digital units. Points of minimum and maximum rate of change in Earth tides are shown.

volcano was behaving as an open system throughout the day.

The decrease in eruptive activity and increase in tremor activity also coincide with increasing Earth tide (Fig. 3). The correlation between volcanic activity and Earth tides has been recognised for some time (Eggers and Decker, 1969; Johnston and Mauk, 1972; Hamilton, 1973; Mauk and Johnston, 1973; Golombek and Carr, 1978; Mauk, 1979), as has a correlation between Earth tides and volcanic SO_2 emissions (Stoiber et al., 1986; Connor et al., 1988). The increased lunar attraction causes the flow of water towards the locus of maximum attraction, resulting in high tide. This mechanism also may affect volcanic activity. Barboza and Melson (1990) suggest that the inverse correlation between tremor activity and eruptions may be due to the rise of magma in the conduit. We suggest that as the rate of change in tidal stress increases to a maximum, comparatively hot fresh magma may rise towards the surface, with resulting changes in the rate of vesiculation (Shimozuru, 1987). Thus, there is a change in the stress regime of the conduit with increase exsolution of gas and degassing and a resulting decrease in the number of explosive eruptions. Stoiber et al. (1986) noted that at Masaya caldera, bursts of gas from the lava lake were twice as likely to occur during the maximum or minimum rates of change of the Earth tides (Fig. 3). The close relationship between the reduced amplitude and frequency of eruptions, tremor and maximum rates of change in Earth tide, for four days at least, suggests that Arenal's eruptive activity may be sensitive to relatively small changes in the confining pressure or stress conditions in the upper crust. In a comparatively active system, these small changes may be sufficient to shift the activity from a relatively closed system to a more open one or vice versa.

There also may be a relationship between magma supply/extrusion rates and periods between explosive eruptions. Changes in the extrusive activity from the northern vent of crater C could affect the explosive activity of the southern vent (M. Davies, personal communication). If extrusion rates are high, lava may be forced into the southern conduit, causing a temporary blockage. This would allow for overpressurisation and explosive eruption.

Our COSPEC measurements (e.g. 5 March 1996) show fluctuations in SO_2 flux which also suggest that the conduit may undergo cycles of gradual sealing leading to overpressurisation and eventual eruption. Progressive decreases in SO_2 flux suggest a decrease in the conduit opening and resulting increase in conduit pressure. In some instances, this increase in pressure continues until a critical limit is reached, at which point the closure is destroyed by an explosive event. However, field observations suggest that much of the gas released may come from another vent not directly connected to the repeatedly opening/closing explosive vent. This would explain the lack of direct correlation between SO_2 flux and open/closing of the explosive vent.

Another possibility is that gas bubbles rising in the column become trapped below a roof in the conduit leading to bubble accumulation and the development of foam. At a certain point, this foam would collapse, releasing a gas slug which would rise in the conduit and explode at the surface, producing a strombolian eruption (Jaupart and Vergniolle, 1989; Vergniolle and Brandeis, 1996). It is therefore possible that the timescale at which gas bubbles accumulate and then collapse is too small to be measured by COSPEC.

4.2. *The sulphur budget of Arenal*

The SO_2 (0.047 Mt year^{-1}) and CO_2 estimates (0.30 Mt year^{-1}) from Arenal are only a small fraction (SO_2: 0.02%, CO_2: 0.04%) of the annual global output of continuously erupting volcanoes (Williams et al., 1992). By contrast Galeras, with at least 1.9 Mt SO_2 emitted over a seven year period, represents approximately 1.4% of annual volcanic output, while CO_2 estimates of 2.6 Mt at Galeras represent 0.57% of total annual volcanic CO_2 flux (Zapata et al., 1997; Williams et al., 1992). At Mount St. Helens over 1000 COSPEC measurements between 1980 and 1988 gave a total SO_2 emission of 2 Mt (Gerlach and McGee, 1994). The 1963 eruption of Gunung Agung (Bali, Indonesia) released 2.5 Mt of SO_2 into the atmosphere (Self and King, 1996). Although Arenal's annual SO_2 output is small compared to these volcanoes, its total output is nevertheless of the same magnitude as Mount St. Helens, Galeras, and Gunung Agung. We estimate that Arenal has degassed between 1.3 and 3.9 Mt SO_2 between 1968 and 1996. On a short timescale, small volcanoes such as Arenal may not have a significant impact on global volcanic output.

However, over long periods of time, continuously active volcanoes such as Arenal may emit significant quantities of SO_2 into the troposphere which are comparable to volcanoes which exhibit vigorous degassing over more restricted periods of time.

The difference in SO_2 estimates between Plume Tracker/COSPEC and petrological methods necessitates a source for this excess sulphur. Various mechanisms have been proposed to explain these discrepancies. At El Chichón, for example, excess sulphur may have been derived from magmatic anhydrite and/or an S-rich vapour phase (Luhr et al., 1984). At Nevado del Ruiz, anhydrite (Fournelle, 1990) and sulphur-rich vapour phases (Sigurdsson et al., 1990) also were shown to be important. Excess sulphur also may derive from the syn-eruptive degassing of sulphur from a non-erupted convecting magma (Williams et al., 1990). Convection cells would allow for the continued upward cycling of fresh undegassed magma and consequent downward movement of degassed magma (Casadevall et al., 1983; Andres et al., 1991; Kazahaya et al., 1994; Allard, 1997). Excess sulphur also may arise from the degassing of mixed or commingled intrusions of basaltic magma. It has been suggested that redox reactions following the injection of reduced sulphide-saturated basaltic magma into oxidised sulphate-saturated dacitic melt may have been responsible for the excess SO_2 and eruption at Mount Pinatubo (Kress, 1997). The exsolution and upward migration of less soluble species such as CO_2 also may transport more soluble species such as SO_2 to the surface (Andres et al., 1991). SO_2 also might be directly absorbed by the hydrothermal system (Williams et al., 1990). Extensive hydrothermal systems may act to seal a volcano and allow for the accumulation of an independent vapour phase. This could then lead to the release of a large sulphur-rich gas bubble (Westrich and Gerlach, 1992; Gerlach et al., 1996). However, this scenario is unlikely at Arenal, since it does not have an extensively developed hydrothermal system.

Unlike Láscar and Lonquimay volcanoes in Chile where petrological estimates are 50–100 times less than COSPEC estimates (Andres et al., 1991), petrological estimates for Arenal are only 2–10 times less than COSPEC values. The melt inclusions analysed in our study may be samples of melt that had already undergone some degassing and thus may not represent a pristine undegassed melt. If so, then the difference between petrologic and COSPEC estimates will be even smaller. Whatever the cause of excess sulphur, it is of much less importance at Arenal. This small difference, the near continuous activity over 30 years, and the relative constant SO_2 flux indicates that Arenal is not being supplied by an isolated, slowly degassing body of magma. Rather, Arenal appears to behave as an open system which is being continuously replenished by fresh sulphur-rich magma.

Convection may play an important role in transporting magma to the surface. Fresh, low-density, gas-rich magma injected at depth will tend to rise quickly to the surface due to buoyancy effects. This magma is then efficiently degassed and removed from the magmatic system by explosive or effusive eruption. By contrast, a magmatic system such as Mount Etna needs both ascending and descending convection (Allard, 1997). Ascending magma is required to bring magma to shallow levels where it can degas efficiently. Descending convection of degassed magma is also necessary, since the amount of magma that is erupted is very small compared to the amount of SO_2 that is released. Basically, a system such as Mount Etna requires significantly larger amounts of unerupted, endogenous magma compared to Arenal because the ratio of erupted magma to SO_2 released is an order of magnitude smaller at Mount Etna than at Arenal (53 at Etna vs. 625 at Arenal). By contrast, volcanoes such as Láscar, Lonquimay, and Pinatubo have undergone extensive sulphur degassing from the melt within an isolated, slowly cooling magma chamber, resulting in huge discrepancies between COSPEC and petrological emission estimates.

4.3. The open nature of Arenal

According to Stoiber et al. (1986), an overall steady decrease in volcanic SO_2 flux with time suggests that a single batch of magma is progressively degassing, without the influx of new gas-rich magma. This appears to be the case for Galeras, Nevado del Ruiz, and Mount St. Helens, which show rate decay constants of 0.27, 0.38 and 1.41 year^{-1}, respectively (Zapata et al., 1997; Williams et al., 1990). In contrast to these volcanoes which clearly have acted as relatively closed systems, SO_2 fluxes at Arenal have actually increased slightly over time (Table 4). Unlike

Galeras or Masaya, which receive episodic (decades) supply of small shallow magma batches, Arenal appears to have a continuous input of magma from depth. Rather than being supplied from a stagnant shallow chamber or small body of magma that progressively degasses, magma beneath Arenal resides in a chamber which is itself open to replenishment. Based on observed geochemical changes in extruded lavas, Reagan et al. (1987) concluded that the Arenal magma has undergone three compositional stages prior to and after the 1968 reactivation. Changes in composition of stage-3 magmas (1974-present) also indicate continued influx of magma along with crystal removal. The chamber is probably located in the middle to lower crust (Reagan et al., 1987), from which a series of conduits or fractures, opened by magmatic pressure, rise to a kilometre beneath the volcano. The final kilometre to few hundred metres likely consist of a conduit or conduits which open and close on short timescales, resulting in frequent strombolian eruptions and extrusion of lava (Wadge, 1983).

Extrusion of lava at Arenal also appears to be independent of these strombolian eruptive cycles, which further suggests that there may be a complex system of conduits or fractures just below the surface. Low frequency volcanic tremor (2–4 Hz) seen before and after eruptions may represent the oscillation of magma or an organ-pipe effect in these conduits (Matumoto and Umana, 1976; Wadge, 1983; Alvarado et al., 1988; Barquero et al., 1992; Benoit and McNutt, 1997; Hagerty et al., 1997).

5. Conclusions

Correlations between seismic activity and Earth tides suggest that an open system such as Arenal may be sensitive to minor variations in confining pressures or stresses, changing from a relatively closed system to a comparatively open system over the space of minutes to hours. The cycle of explosive eruptions may be explained in part by repeated closure of the conduit(s) due to solidification of a surface crust or overflow of lava from a non-explosive vent, leading to overpressurisation and destruction of the blockage. The lack of direct correlation between changing SO_2 flux and eruptive activity may either be due to the fact that a non-explosive vent is responsible for the majority of gas release or because formation, collapse and explosion of gas bubbles in the conduit may be occurring at timescales smaller than can be measured by COSPEC. The small difference between petrological and COSPEC estimates of the sulphur budget suggests that Arenal is being continuously supplied by fresh magma. While Arenal may have only a small influence in terms of the annual global volcanic input of SO_2 and CO_2 to the atmosphere, the continuous activity of the volcano has nevertheless contributed between 1.3 and 4.0 Mt of SO_2 to the troposphere since 1968, comparable to or higher than volcanoes such as Mount St. Helens, Nevado del Ruiz, and Galeras. Arenal's high level of activity allows for the study of multiple cycles of conduit opening and closing and thus is an excellent natural laboratory for better understanding the manner by which an open-system volcano degasses and erupts.

Acknowledgements

We are grateful to Eduardo Malavassi, Vilma Barboza and all the staff of OVSICORI for their enthusiastic support, as well as the personnel of the Arenal National Park for allowing us access to the volcano. We thank Mark Davies and Nicki Stevens for support in the field, Hazel Rymer for Earth tide data and Bill Melson for seismic data and encouragement. We acknowledge the support of Dr Ray Hoff of Environment Canada, who loaned us a COSPEC IV in 1996. The research was supported by grants to J.S. from the Natural Sciences and Engineering Research Council of Canada, the Fonds pour la Formation de Chercheurs et l'Aide à la Recherche (Québec), and the Université de Montréal. Careful reviews by M. Kusakabe and an anonymous reviewer greatly improved the manuscript.

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