

# The magma budget of Volcán Arenal, Costa Rica from 1980 to 2004

G. Wadge<sup>a,\*</sup>, D. Oramas Dorta<sup>b</sup>, P.D. Cole<sup>b</sup>

<sup>a</sup> Environmental Systems Science Centre, Harry Pitt Bldg., 3 Earley Gate, University of Reading, Reading, RG6 6AL, UK

<sup>b</sup> Department of Geography, Environment and Disaster Management, University of Coventry, Coventry CV1 5FB, UK

Received 15 June 2005; accepted 28 March 2006

Available online 12 June 2006

## Abstract

Using topographic data collected by radar interferometry, stereo-photogrammetry, and field survey we have measured the changing surface of Volcán Arenal in Costa Rica over the period from 1980 to 2004. During this time this young volcano has mainly effused basaltic andesite lava, continuing the activity that began in 1968. Explosive products form only a few percent of the volumetric output. We have calculated digital elevation models for the years 1961, 1988 and 1997 and modified existing models for 2000 and 2004. From these we have estimated the volume of lava effused and coupled this with the data presented by an earlier study for 1968–1980. We find that a dense rock equivalent volume of 551 M m<sup>3</sup> was effused from 1968 to 2004. The dense rock equivalent effusion rate fell from about 2 m<sup>3</sup> s<sup>-1</sup> to about 0.1–0.2 m<sup>3</sup> s<sup>-1</sup> over the same period, with an average rate of about 0.5 m<sup>3</sup> s<sup>-1</sup>. Between 1980 and 2004, the average effusion rate was 0.36 m<sup>3</sup> s<sup>-1</sup>, a similar rate to that measured between 1974 and 1980. There have been two significant deviations from this long-term rate. The effusion rate increased from 1984 to 1991, at the same time as explosivity increased. After a period of moderate effusion rates in the 1990s, the rate fell to lower levels around 1999. © 2006 Elsevier B.V. All rights reserved.

*Keywords:* magma budget; effusion rate; lava flow; digital elevation models; InSAR

## 1. Introduction

Volcán Arenal in Costa Rica has effused lava almost continuously for over 36 years, since it began erupting in 1968 after several hundred years of dormancy. The rate at which lava erupted during the first 12 years was estimated by Wadge (1983). This paper adds another 24 years to that history by estimating the lava output for the period 1980–2004. The techniques we use to do this are photogrammetry and spaceborne and airborne Synthetic Aperture Radar Interferometry (InSAR). There have been a number of

distinct phases to the behaviour of the volcano during this time, some of which are related to the rate of magma flux through the volcano:

- 1968–1973 relatively high effusion rate of lava from Crater A (Fig. 1)
- 1973–1974 7-month hiatus (August 1973 to March 1974) in lava effusion
- 1975 pyroclastic flows to the northwest
- 1974–1984 lower effusion rate of lava, generally non-explosive effusion from Crater C, 400 m higher than Crater A and 400 m to the east
- 1984–1998 mixed explosive and effusive eruptions from Crater C
- 1998–2004 infrequent explosions and short lava flows from Crater C.

\* Corresponding author. Tel.: +44 118 378 6412; fax: +44 118 378 6413.

E-mail address: [gw@mail.nerc-essc.ac.uk](mailto:gw@mail.nerc-essc.ac.uk) (G. Wadge).

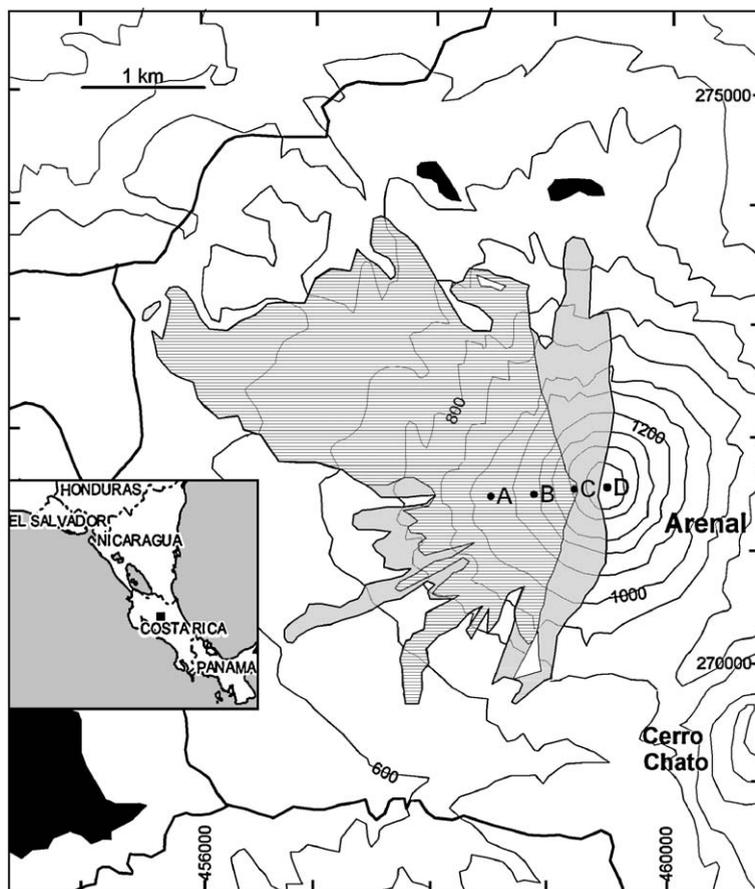


Fig. 1. Map of the lava flow-field of Arenal. The extent of the flow-field in 1980 is shown by the horizontal ruled area. The subsequent extension is shown in stipple. A, B and C are the craters of the 1968–present eruption whilst D is the original summit crater. Contour intervals are 100m, the roads are shown by bold lines and lakes in black. The location of Arenal in Costa Rica is shown by the square in the inset map.

Despite these changes, the continuity of the eruption implies an underlying magmatic system in dynamic equilibrium. We investigate the mass budgetary constraints on this system implied by the 36-year record and support this with evidence from other work on Arenal.

## 2. The eruptive activity of Arenal

The volcano grew rapidly during the Holocene at the eastern end of an E–W-trending graben that cuts the Central American volcanic front in the Cordillera Central of Costa Rica (Borgia et al., 1988). This part of the volcanic front lies above a segment boundary of the subduction zone that marks the discontinuity between crust formed at the East Pacific Rise and crust formed at the Galapagos Spreading Centre (Ranero et al., 2003). Stratigraphic and geomorphologic evidence indicates that the Cerro Chato cone, 2.5 km to the southeast of Arenal (Fig. 1), was an earlier locus of

volcanism from the same crustal source. Borgia et al. (1988) showed that both edifices are asymmetrical about a NW-trending axis with lava fields dominant to the east and a tephra apron to the west (borne by the Trade Winds towards  $280^\circ$ , Melson, 1994). Radiocarbon dates from the latest Cerro Chato tephra of  $3720 \pm 150$  B.P., and from the earliest Arenal deposits of  $7010 \pm 170$  years B.P. suggest some overlap in activity (Soto and Alvarado, 2004), contrary to earlier indications (Borgia et al., 1988). The earliest proximal deposits of Arenal are not well exposed but the more distal tephra succession of 10 early air fall deposits is (Melson, 1994). The most recent tephra deposit prior to that of 1968 is dated at around 1500 A.D. (Melson, 1994) and the average repose interval over the last 4000 years is about  $300 \pm 150$  years (Borgia et al., 1988). Borgia et al. (1988) also indicate that there have been five major lava-effusing events such as the current one. The more recent of these lava-producing cycles have erupted

volumes in the range of 0.5–1.0 km<sup>3</sup> (Soto and Alvarado, 2004).

### 2.1. The 1968–present eruption

A 1-km-long radial fissure trending westerly from the summit of the Arenal cone was formed on 29 July 1968. Eruptive activity became focused at three new craters: (A) 1050 m above sea level (asl); (B) 1170 m asl; and (C) 1460 m asl and 400 m west of the old summit vent, termed Crater D, which has an altitude of 1633 m asl (Melson and Saenz, 1973, Fig. 6). These craters were the source of a Vulcanian blast, a sub-Plinian ash cloud and pyroclastic flows that devastated a small community on the western slopes (Minakami and Utibori, 1969; Melson and Saenz, 1973; Melson, 1994). On 19 September 1968 a lava flow was emitted from Crater A, marking the end of the explosive phase. A series of lava flows were erupted from this vent over the next five years. These flows from 1968 to 1971 were the most voluminous of the eruption and the flow-field reached its furthest western limit in September 1971 (Wadge, 1983). Lava continued to flow from Crater A between 1971 and 1973. After a 7-month hiatus, from August 1973 to March 1974, effusion moved to Crater C about 400 m higher up the volcano. All subsequent lava flows were erupted from this crater. Typically, quiet effusion of lava was accompanied by rhythmic degassing from a vent between 5 and 10 m wide. The lava flows, of basaltic andesite composition, often initially formed aa surfaces, but became blocky in character downslope as the flow was disrupted (Cigolini et al., 1984). Flows were typically 7–15 m thick and 20–60 m wide on the upper slopes, forming channels that were used repeatedly by multiple units that diverged downslope.

After the 1968 explosions, Crater C was a horseshoe-shaped crater, open to the west (Malavassi, 1979). In the years prior to 1984 the interior of the crater was a shallow depression about 60 m in diameter with a rim breached where the lava flowed out. Lava typically effused from one of two vents on the north and south sides of the crater. Random collapses of this rim caused abrupt re-direction of lava flows (e.g., in April 1983, Linneman and Borgia, 1993). In June 1984 the character of the activity became much more explosive, with frequent explosions (which were often Vulcanian), together with lava flows (Van der Laet and Carr, 1989). Between 1987 and 1990 large explosions generated frequent column-collapse pyroclastic flows (Cole et al., 2005). After 1991 explosions

were less strong, diminishing markedly in frequency after 1998. The largest pyroclastic flows in the period from 1990 to 2001 were generated by collapse of the summit crater (Alvarado and Soto, 2002; Cole et al., 2005). Occasional lava flows continued throughout the 1990s, mainly to the northwest and west but increasingly to the north. As the cone has grown it has created a lengthening slope to the east where it abuts the old, pre-eruption, cone with its Crater D (Fig. 1) and some flows have therefore flowed eastwards to then be directed north or south. The morphology of Crater C changed in the late 1990s, becoming broader and effectively migrating northwards by 50–100 m (Cole et al., 2005, Fig. 3). Small cones developed at the summit in 1994, 1996 and 1999. Since 1998, explosivity has continued to decrease and lava flows have become shorter and tended to disintegrate on the very steep slopes of the upper flanks of the cone.

The areal extent of the lava flow-field has not increased much in the last 24 years relative to the first 12 years (Fig. 1). However, new flows extended over uncovered ground to the south and southwest in the 1980s and early 1990s and onto the northern slopes in the 1990s and 2000s. Many other flows have overridden the earlier flows. The general pattern, however, has been for flows to become shorter with time. As a result the centre of mass of the whole lava flow-field has migrated closer to the vent.

#### 2.1.1. Altitudes of the craters

The altitudes of the craters and their vents from which lava flows and explosions occur have increased during the eruption. Flows solidifying next to the vent, agglutinating spatter and accumulation of tephra have all played a part in this process. There are no accurate measurements of the altitude of Crater C before 1987, but since then the crater rim has been surveyed systematically (R. Van der Laet, personal communication) (Fig. 2). In 1968 Crater C intersected a steep slope with its eastern end at about 1480 m asl and its western end at about 1390 m asl (Melson and Saenz, 1968, Fig. 3; Melson and Saenz, 1973). Here we adopt the value of 1460 m asl as the altitude of the rim of the crater visible by field survey in 1974 when lava began to flow from it, though the height of the vent was probably as low as about 1400 m asl. During the next 10 years of relatively low-explosivity effusion, the altitude of the crater rim probably rose only a few tens of metres. In the period from 1984 to 1991, when activity was much more explosive, the altitude of the crater rose rapidly, perhaps by as much as 180 m. During the last 15 years, the rate of growth has slowed (Fig. 2). Crater C was at

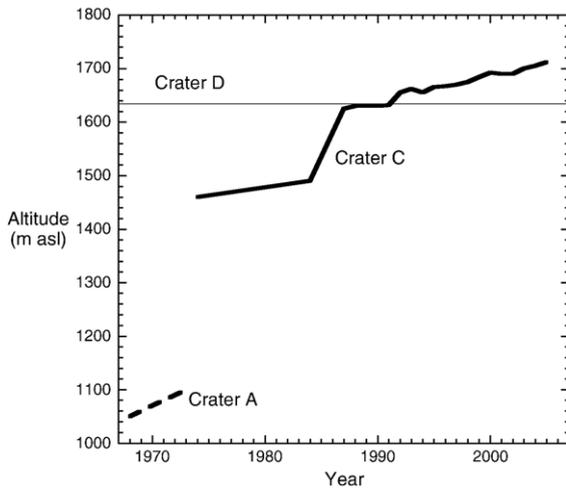


Fig. 2. Plot of the altitude of the Craters A, C and D at Arenal from 1968–2005. Data from 1987 to 2004 are courtesy of R. Van der Laet (uncertainties of a few metres, earlier data have a few tens of metres of uncertainty).

the same height as the old summit of the volcano (Crater D, 1633m asl) in about 1988. Its current altitude of about 1710m asl means that the point of effusion has risen by about 250m since 1974 and 660m since 1968.

### 3. Measurements of topography

Wadge (1983) used three sources of data to estimate the volumes of lava flows at Arenal: stereo-air photographs, field measurements of flows, and maps and reports of flow positions and pre-eruption topography. From the air photographs he derived two topographic surfaces of the lava flow field, for May 1977 and March 1980, and from these estimated the individual volumes of 30 lava flows from the 1968–1980 period. This work extends the earlier results by estimating the pre-eruption topographic surface, the surface in 1988 from photogrammetry, and the surfaces in 1997, 2000 and 2004 from InSAR. The DEMs (Digital Elevation Models) of these surfaces, created by different means, had to be co-registered horizontally and vertically in order to derive quantitative estimates of differences in lava volume. In Figs. 3–9, we present lava volume maps produced by differencing the relevant DEMs.

#### 3.1. Pre-eruption topography

A DEM of the pre-eruption surface around Arenal was created from the 1:50,000 scale topographic map of the Costa Rican Instituto Geografico Nacional,

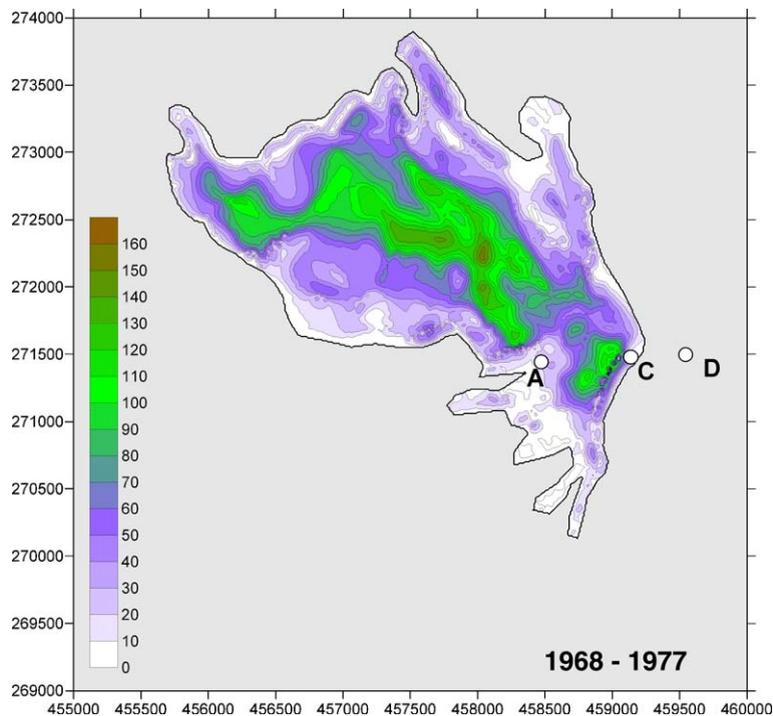


Fig. 3. Isopach map of lava flow thicknesses from September 1968 to May 1971 re-calculated from Wadge (1983, Fig. 3). Contour interval is 10m. Craters A, C and D are marked.

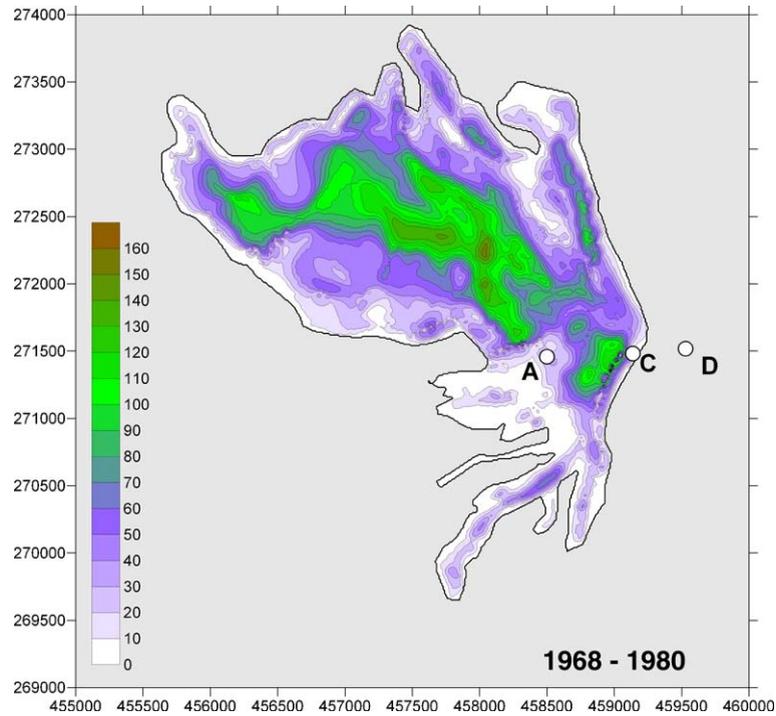


Fig. 4. Isopach map of lava flow thicknesses from September 1968 to March 1980 re-calculated from Wadge (1983, Figs. 3, 4). Contour interval is 10m. Craters A, C and D are marked.

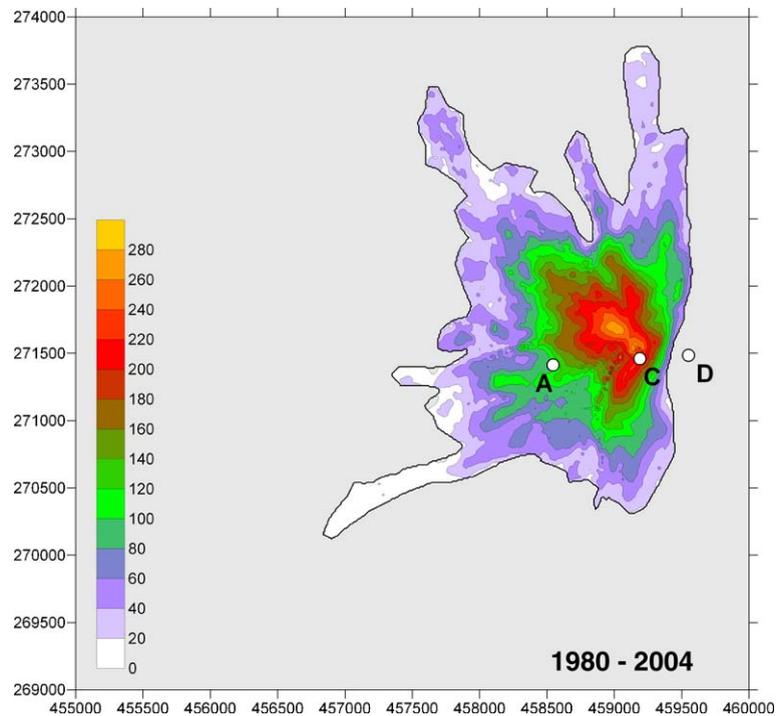


Fig. 5. Isopach map of lava flow thicknesses from March 1980 to March 2004. Contour interval is 20m. Craters A, C and D are marked.

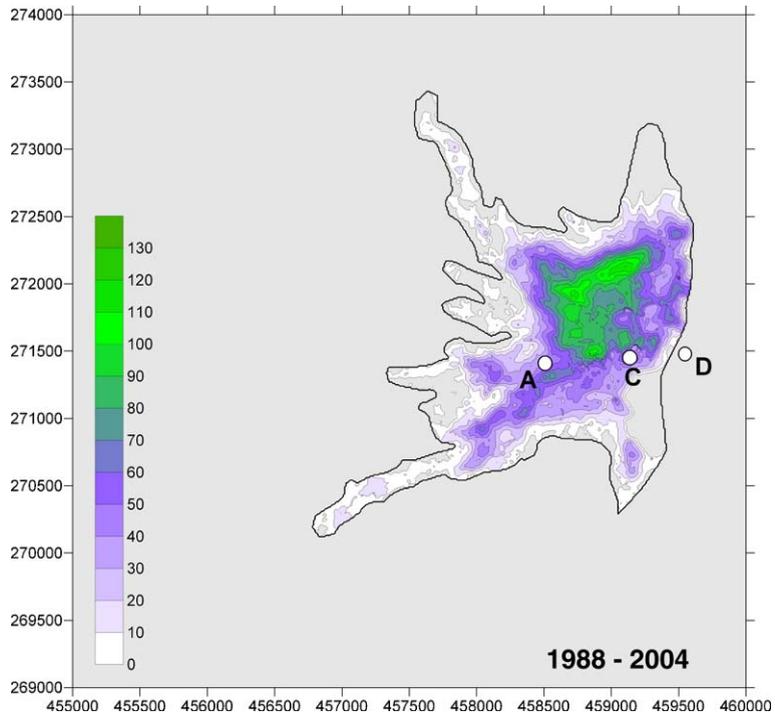


Fig. 6. Isopach map of lava flow thicknesses from January 1988 to March 2004. Contour interval is 10m. Note the area of poor to no data to the southwest of the vent. Craters A, C and D are marked.

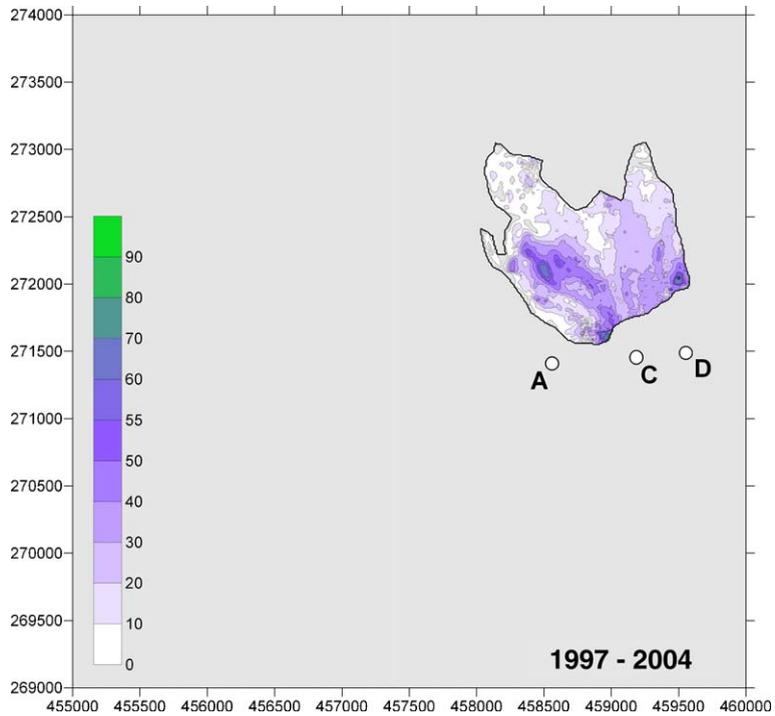


Fig. 7. Isopach map of lava flow thicknesses from October 1997 to March 2004. Contour interval is 10m. Craters A, C and D are marked.

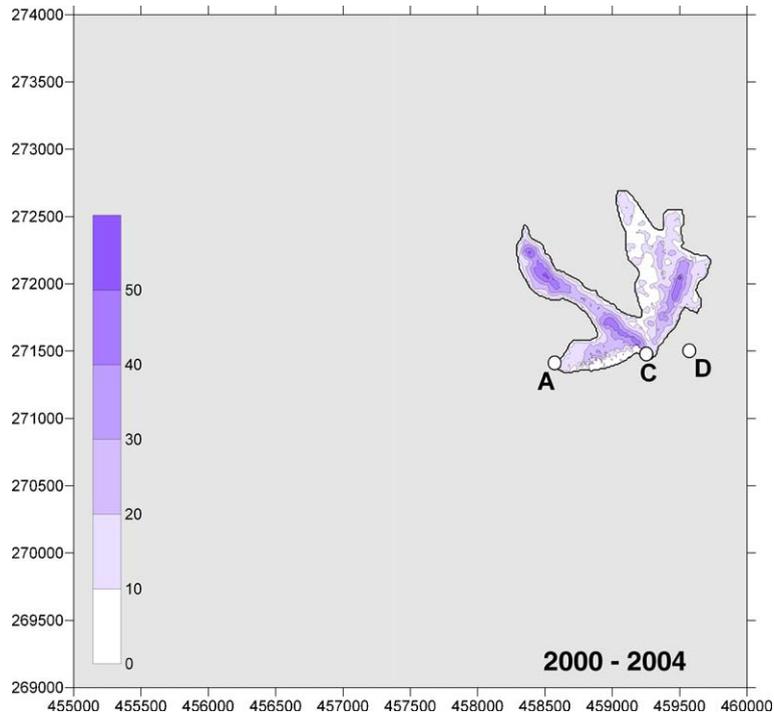


Fig. 8. Isopach map of lava flow thicknesses from February 2000 to March 2004. Contour interval is 10m. Craters A, C and D are marked.

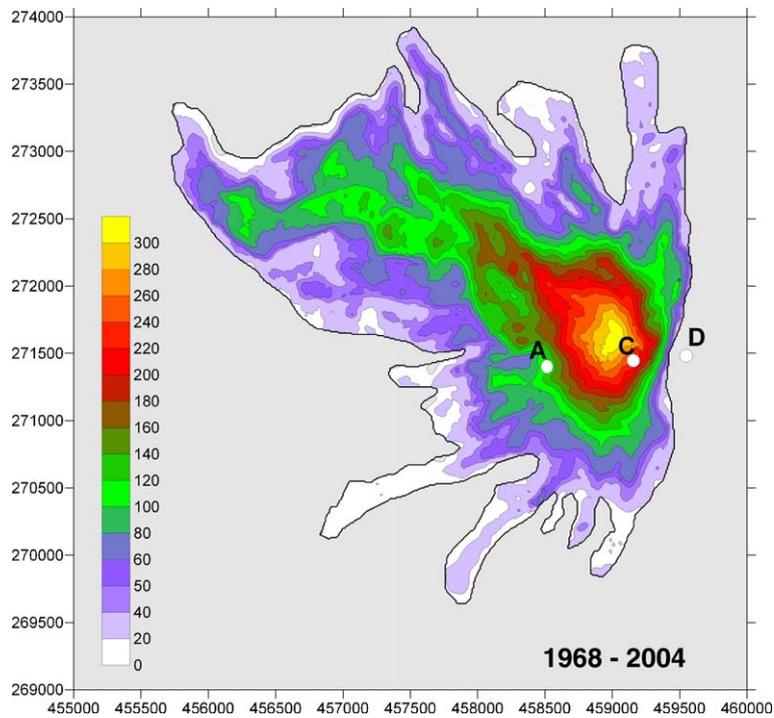


Fig. 9. Isopach map of lava flow thicknesses from September 1968 to March 2004. Contour interval is 20m. Craters A, C and D are marked.

originally derived from stereo-photogrammetry in 1961. This map has contours at 20m intervals on a Lambert projection using the local Ocotepaque datum, which is 10m below the WGS84 datum. The DEM was created by kriging interpolation with a horizontal posting every 10m and has an estimated vertical accuracy relative to GPS-derived benchmarks of about 7–10m. It is presumed that this represents the ground surface not a vegetation surface.

### 3.2. Photogrammetry

#### 3.2.1. 1977, 1980

The lava flow isopach maps derived from the analytical photogrammetry presented by Wadge (1983) were digitised and re-gridded for this study at a 10 m posting. The topography of the area near Crater C in both of these pairs of photographs was poorly represented there because the gas plume obscured the surfaces. Fig. 3 is an isopach map of lava flow thickness created by differencing the pre-eruption (1961) DEM and the 1977 DEM derived from analytical photogrammetry. It is clear from Figs. 3 and 4 that the lava from Crater A (active until 1973) mainly flowed to the northwest, but that lava from Crater C mainly flowed to the north and south during the later 1970s (Fig. 4). This can be explained partly by the existence of the north and south vents of Crater C.

#### 3.2.2. 1988

Stereo-aerial photographs taken in January 1988 were scanned and a photogrammetric model constructed using Leica Photogrammetric Suite software. Ground control points were measured in 2005 using differential GPS to decimetric precision, though there were no GPS points above about 900m asl on the upper volcano because of safety concerns. The quality of the DEM near the summit is poor and there is a gap in data to the south of Crater C (Fig. 6), due to poor contrast of the stereo pair in that area.

### 3.3. InSAR

Airborne and spaceborne radars can provide InSAR measurements of topography that are not susceptible to cloud obscuration. Single-pass and repeat-pass InSAR techniques have been used on volcanoes (e.g., Rowland, 1996; Lu et al., 2003) to measure topography and topographic change. InSAR has also been used to measure surface deformation to centimetric accuracy, but not in this study. Here we use the single-pass Shuttle Radar Topographic Mission (SRTM) data collected in

February 2000, AIRSAR data collected in March 2004, and repeat-pass ERS data from the late 1990s.

#### 3.3.1. SRTM InSAR

From the single-pass C-band/X-band radar interferometric mapping performed in orbit from the Space Shuttle during 11 to 22 February 2000, two global data sets of digital topography have been produced: the 3-arc-second DEM (one height posting about every 90m) and the 1-arc-second DEM (values every 30m). Here we use the X-band-derived 1-arc-second data over Arenal. Muller and Backes (2004) indicate root mean squared (rms) absolute height accuracies of about 4–5m from European test sites. The local scene error map for the Arenal area data indicates accuracies varying from about 3m on gradual slopes to about 10m on steeper slopes. This SRTM DEM shows a “rougher” surface than the pre-eruption DEM and there are some obvious local gross errors, mainly in the steep terrain around Cerro Chato (Fig. 1). The X-band radar, like the C-band, measures returns from near the top of any vegetation canopy. The natural forest cover on Arenal has a height of about 15m and this is the expected and observed difference between the forested surfaces of the SRTM DEM and the pre-eruption DEM. By 2000, the surfaces of the earliest, most distal lava flows had a variable cover of new vegetation including shrubs up to 3m in height. Thus, the SRTM DEM surface in this part of the flow-field will be higher than the lava surface.

#### 3.3.2. AIRSAR InSAR

An airborne, single-pass interferometric radar (AIRSAR) was flown over Arenal by a NASA plane in March 2004. The resulting DEM has height postings every 5m, making it the InSAR DEM with the highest spatial resolution and the most accurate (1–3m vertical rms error; Madsen et al., 1995). In some areas no height data were recorded because of radar shadowing or layover, and the largest of these is to the southwest of the volcano's summit. These areas have been filled in with data from the SRTM DEM as well as local interpolation from neighbouring AIRSAR height values. As with the SRTM DEM, the surface represented by the AIRSAR DEM will be higher than the lava flow surface on the re-vegetated, oldest parts of the flow-field.

#### 3.3.3. ERS InSAR

Repeat-pass C-band ERS InSAR, unlike the single-pass technique used by SRTM and AIRSAR, does not work over the forested surfaces typical of the undisturbed terrain in Costa Rica (see Massonnet and Feigl (1998) for an explanation of this and other technical

InSAR issues). However, the vegetation-free surfaces of the Arenal lava flow-field and the tephra-covered surfaces to the west of the volcano do preserve coherent radar signals. There is a limited archive of ERS SAR scenes of Arenal from 1992 to 2000. The choice is limited even more by the following factors. Only descending pass orbits (the satellite travels from north to south looking to the west) of ERS-1/-2 view the west-sloping lava flow-field at sufficiently low incidence angles to supply good spatial information. The perpendicular baselines of the interferograms must be in the range of 100–500 m to provide height resolutions of about 10–2 m. Interferograms formed by image pairs with 1-day separation are the only ones able to provide good data. This is because 35-day separation interferograms (the normal ERS repeat cycle) are susceptible to surface creep effects on recent lava flows that cannot be readily separated from the topographic information (Stevens et al., 2001; Wadge, 2004).

The ERS interferograms with 1-day separation from two orbital tracks are listed in Table 1. Residual errors in the corrections for orbital geometry can sometimes be removed by identifying long-wavelength fringes in the interferogram. But in the case of Arenal, it was not possible to correct empirically for orbital errors in this way because of the low coherence in the wider scene. Similarly, atmospheric delay anomalies remain uncorrected explicitly. It is also not possible to stack multiple interferograms to lessen noise (cf. Lu et al., 2003) because the topography changes between interferograms. The phase values of the interferogram are modulo two pi and these are converted to a continuous scale (unwrapping) to represent change in altitude of the ground surface. The best results from phase unwrapping were achieved with the Flynn algorithm (Ghiglia and Pritt, 1998). Coherent areas in these ERS 1-day interferograms include tephra-covered surfaces on the WSW flanks of Arenal. Because the relatively smooth

Table 1  
ERS-1, -2 tandem data used for measurement of topography at Arenal

Dates	Satellite	Track/frame	Orbit	Bp (m)	Quality
2/10/95	1	011/3393	22043	576	Poor
3/10/95	2		02370		
6/10/97	1	011/3393	32564	376	Good
7/10/97	2		12891		
25/10/97	1	283/3392	32836	347	Good
26/10/97	2		13163		
19/12/98	1	283/3393	38848	338	Good
20/12/98	2		19175		
23/01/99	1	283/3393	39349	463	Moderate
24/01/99	2		19676		

Table 2

Estimates of lava flow volumes erupted from 1968 to 2004

Period	DEM difference volume (M m <sup>3</sup> )	Corrected volume (M m <sup>3</sup> )	Uncertainties (M m <sup>3</sup> )	DRE volume (M m <sup>3</sup> )
1968–1977	279	294	±60	253
1968–1980	300	320	±60	275
1980–2004	331	321	±55	276
1988–2004	100	145	±20	125
1997–2004	29	34	±20	29
2000–2004	13	13	±3	11
1968–2004	641	641	±75	551

topography here had changed little during the 1990s and the data were of good quality, this tephra area could be used as a calibration surface to help correct for any planar phase gradients, such as those produced by imperfect orbital positional knowledge across the 5 × 4 km area of interest covered by the lava flow field on Arenal (Fig. 1). The best quality interferogram, from 6 to 7 October 1997, is used here. The DEM derived from this has a data gap to the north of Crater C (Fig. 7).

### 3.3.4. Estimates of uncertainty

Each of the topographic data sets for Arenal has its own associated errors. In Table 2 we have estimated an average uncertainty for each post-1977 DEM of the lava flow-field. These uncertainties are relative to the most accurate, AIRSAR DEM, based on measurements in the most distal part of the flow-field (Fig. 1). A more complete analysis of error characteristics of the DEMs is in preparation (Oramas-Dorta et al., in preparation).

## 4. Volume estimates

### 4.1. Lava flows

#### 4.1.1. DEM estimates

We have calculated the volume of lava flows added to the surface by differencing the DEMs for the different periods. These volumetric differences are calculated for those areas known to have had active flows during the periods concerned (Figs. 3–9). There are some known errors in the DEMs whose effects on the volumetric estimates we have tried to correct (Table 2). These are

- (i) Missing data around Crater C in 1977 and 1980,
- (ii) Missing data to the south of Crater C in 1988 (Fig. 6), and
- (iii) Missing data in the area of Crater C and to the north in 1997 (Fig. 7).

We follow Wadge (1983) in converting topographic volume to Dense Rock Equivalent (DRE) volumes using a multiplicative factor of 0.86.

From the DEM differences relative to 1968 and 2004 (Table 2), the DRE volume estimates for consecutive periods are calculated (Table 4). The volumes for the 1968–1977 and 1977–1980 periods agree well with those of Wadge (1983). It is clear from Figs. 3–9 how the location of lava flow accumulation switched from west and south in the late 1970s to 1994, to the northwest and north after 1994. The total DRE volume erupted over the 36 years is estimated to be  $551 \text{ M m}^3$  (Table 2, Fig. 10), which yields a mean DRE effusion rate of about  $0.5 \text{ m}^3 \text{ s}^{-1}$ .

#### 4.1.2. Other estimates

During the 1980–1982 period when explosivity was weak, several workers measured the motion of individual lava flows both in channels and at the flow fronts on the western and southwestern slopes. Although net lava volumes were not calculated, instantaneous flux rates of these flows were estimated from plug/shear zone velocity flow profiles measured by field survey techniques. Cigolini et al. (1984, Fig. 8, Table 3) measured a flow on 11 May 1981 that gave a flow rate of about  $0.5 \text{ m}^3 \text{ s}^{-1}$ . Measurements by G. Wadge (unpublished data) on 18/19 January 1982 gave a flow rate of  $0.25 \text{ m}^3 \text{ s}^{-1}$  for one of two active flows. Measurements by Borgia et al. (1983) during March 1982 gave a flow rate of about  $0.36 \text{ m}^3 \text{ s}^{-1}$ . These are compatible with the long-term effusion rates calculated from the DEM differences.

From October 1991 to the end of 1996, Soto et al. estimated the erupted volume of lava using binoculars and topographic maps for flows above 800 m asl and direct

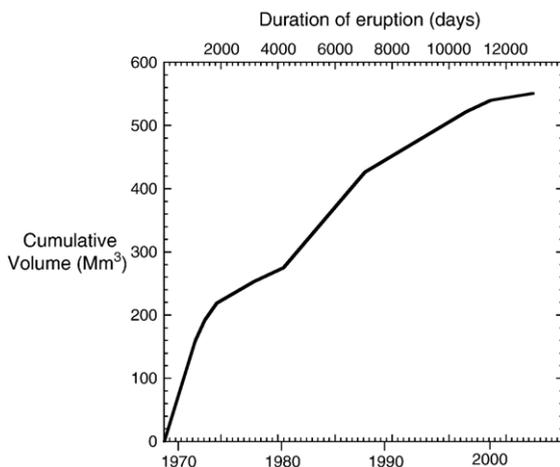


Fig. 10. Plot of cumulative DRE volume versus time.

Table 3

Volume estimates of the larger pyroclastic flow deposits at Arenal

Date	Volume (M m <sup>3</sup> )	DREV <sup>a</sup> (M m <sup>3</sup> )	References
29–31/7/68	1.8	1.3	Melson and Saenz (1973)
17–21/6/75	1.4	1 ± 0.3	Matumoto and Umana (1976)
24/2/92	0.01	0.007	Cole et al. (2005)
28/8/93	2	1.4	Cole et al. (2005)
5/5/98	0.5	0.35	Cole et al. (2005)
23/8/00	2	1.4	Cole et al. (2005)
24–6/3/01	0.2	0.14	Cole et al. (2005)

<sup>a</sup> 30% porosity is assumed to convert to dense rock equivalent volume (DREV).

measurements with tape measure and altimeter for flows below that altitude (Soto et al., 1991, 1992, 1993; Soto and Arias, 1996). These estimates (with uncertainties of about 20%) are combined in Fig. 11. The data show that there was a higher rate of effusion in late 1991–early 1992 ( $0.43 \text{ m}^3 \text{ s}^{-1}$ ) than in the period from early 1992 to mid-1993 ( $0.16 \text{ m}^3 \text{ s}^{-1}$ ). This produced the longest lava flow from Crater C (Soto et al., 1992) that reached 3.2 km from its vent later in the year. After the pyroclastic flow event of 28 August 1993 (see below; Alvarado and Soto, 2002), the 1993–1996 average effusion rate increased to  $0.36 \text{ m}^3 \text{ s}^{-1}$  (Fig. 11) as the effusion shifted from the south to the north vent of Crater C. This independent set of effusion rate derivations, with a mean value of  $0.31 \text{ m}^3 \text{ s}^{-1}$  during 1991–1996, agrees well with the overall 1988–1997 figure of  $0.31 \text{ m}^3 \text{ s}^{-1}$  (Table 4).

In April 2005 radar ranging measurements of the topography of a lava flow advancing down the upper southern slopes of Arenal were made by Macfarlane et

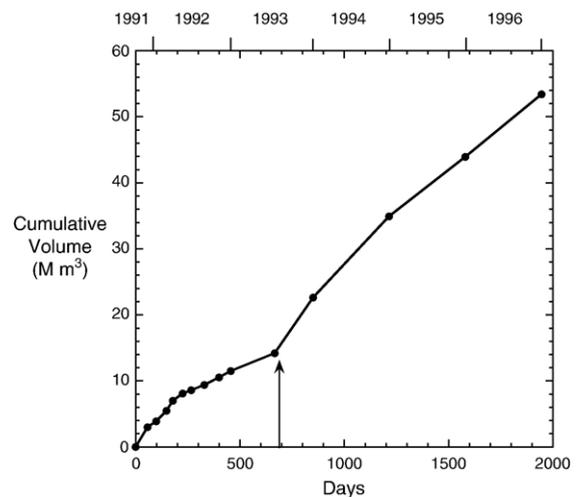


Fig. 11. Plot of cumulative volume emitted from October 1991 to December 1996. Vertical arrow marks the date of the pyroclastic flow eruption of 28 August 1993.

Table 4  
Estimates of effusion rates from 1968 to 2004

Period	Duration (days)	DRE volume (M m <sup>3</sup> )	Cumulative DRE volume (M m <sup>3</sup> )	DRE effusion rate (m <sup>3</sup> s <sup>-1</sup> )
1968–1977	3159	253	253	0.93
1977–1980	1032	22	275	0.25
1980–1988	2858	151	426	0.61
1988–1997	3554	96	522	0.31
1997–2000	861	18	540	0.24
2000–2004	1487	11	551	0.086

al. (2006) over a period of 10-days. These measurements gave a minimum effusion rate of  $0.2 \pm 0.08 \text{ m}^3 \text{ s}^{-1}$ . This lava flow and others showed a tendency to disintegrate on the steep slopes producing a talus of greater areal extent but lower thickness than the intact lava flows. This may explain why this short-term effusion rate is higher than the 2000–2004 rate ( $0.1 \text{ m}^3 \text{ s}^{-1}$ ) reported above. The differences between the 2000 and 2004 DEMs probably underestimate the effect of the talus accumulation.

#### 4.2. Pyroclastic flow deposits

The initial eruption of July 1968 produced column collapse pyroclastic flows to the west. Eruptive activity has involved all gradations from rockfalls to true pyroclastic flows, particularly since the mid-1980s, and most of the small events have not been measured. Table 3 lists the major pyroclastic flow deposits for which there are volumetric estimates. With the exceptions of the 1968 pyroclastic flows and the distal parts of the 1975 (Matumoto and Umana, 1976), 1993 and 2000 pyroclastic flows, the rest of them were deposited on existing lava flows or were subsequently covered by them and hence form part of the current lava flow-field volume estimated above.

#### 4.3. Pyroclastic fall deposits

The Trade Winds usually carry the airborne ash to the west of the volcano. The larger fragments fall out onto the lava flow-field and effectively get incorporated within it, but a substantial fraction is carried farther. Melson and Saenz (1973) estimated the volume of the airfall deposits within 20 km of the summit from the July 1968 explosions to be  $43 \times 10^6 \text{ m}^3$ . Including the unmeasured distal ash may increase the total volume to a figure on the order of  $100 \times 10^6 \text{ m}^3$ . All subsequent ash fall deposits are very much smaller. Soto (1997) estimated about 80,000 t/year for 1992–1997, about

$0.03 \times 10^6 \text{ m}^3/\text{year}$  DRE. Duarte et al. (2004) estimated that from 1987–97 there were 20–40 explosions per day, each with a volume of  $1\text{--}10 \text{ m}^3$  for the fraction less than 2 mm in size. Individual total explosion volumes are probably in the range of  $10\text{--}50 \text{ m}^3$  (Cole et al., 2005). Taking the upper limits for the non-ballistic ash component gives a rate of  $400 \text{ m}^3/\text{day}$  for material not incorporated into the lava flow-field volumes, a total of about  $1.5 \times 10^6 \text{ m}^3$  over 10 years.

## 5. Magma budget

### 5.1. Volume of the volcano

The sections through the volcano constructed by Borgia et al. (1988, Fig. 4) were used to create a crude DEM of the basal surface of the Arenal edifice to distinguish it from the Cerro Chato edifice. The difference between this surface and the pre-eruption topography gives a volume of  $7.2 \text{ km}^3$ . Although this has uncertainties of perhaps 20%, it is more accurate than the previous, cruder estimates of Carr et al. (2003),  $13 \text{ km}^3$ , and Wadge (1983),  $6 \text{ km}^3$ . If the current eruptive cycle is typical of Arenal's growth ( $\sim 600 \times 10^6 \text{ m}^3$  erupted and 300 years of quiescence since the previous eruption) then it would take about 3000–4000 years to produce  $7.2 \text{ km}^3$ .

### 5.2. Lava effusion rates

Table 4 shows the lava DRE volumes for consecutive periods and the equivalent effusion rates. In general, the effusive vigour of the eruption has decreased over 10-fold since the start of the eruption. Wadge (1983) calculated an effusion rate of  $2\text{--}3 \text{ m}^3 \text{ s}^{-1}$  for the period 1968–1971 that fell to about  $0.9 \text{ m}^3 \text{ s}^{-1}$  by the end of effusion at Crater A in 1973. This had apparently fallen to about  $0.1\text{--}0.2 \text{ m}^3 \text{ s}^{-1}$  by 2000–2004. The average effusion rate for 1980–2004 was  $0.36 \text{ m}^3 \text{ s}^{-1}$  and  $0.49 \text{ m}^3 \text{ s}^{-1}$  for 1968–2004. The effusion rate for 1980–1991 was higher than for the periods immediately before and after. We suggest that this is largely due to a high rate during the 1984–1988 period which began with a major increase in explosivity (Cole et al., 2005). Unfortunately, we do not have any direct observation of this increase in effusion rate around 1984.

### 5.3. Pyroclastic eruption rates

With the exception of the ash fall deposits of the 1968 explosions, the proportion of the magma converted to pyroclastic deposits compared to lava during the

eruption was very low. Table 3 indicates total pyroclastic flow deposits of  $<10\text{M m}^3$  with perhaps  $10\text{--}20\text{M m}^3$  for the pyroclastic fall deposits. In total, the pyroclastic deposits comprise at most 4–6% of the total output.

#### 5.4. Volatile emission rates

Williams-Jones et al. (2001) measured an average sulphur dioxide emission rate from Arenal in 1995–1996 of  $130\pm 60$  t/day. The annual rate was about  $0.047\text{M t/year}$  of sulphur dioxide with an inferred carbon dioxide rate of  $0.3\text{M t/year}$ . Earlier measurements from 1982 (Casadevall et al., 1984) were in a similar range. There are no measurements from the 1984–1988 early period of high explosivity, when higher gas emission rates might have occurred. Williams-Jones et al. (2001) also estimated the proportion of sulphur lost from the Arenal magma melt fraction during eruption as 332 ppm, a rate about three times less than that measured from the atmosphere. This implies degassing of magma that is not being extruded as lava.

## 6. Discussion

The growing lava flow-field of Arenal has now covered much of the western half of the volcano. The main WNW axis of the flow-field produced from 1968 to 1977 had a thickness of more than 100m for much of its 3 km length (Fig. 3). Subsequently most of the early flows from Crater C were narrower, but had an aggregate thickness of over 100m just downslope from Crater C. The centre of mass of the lavas erupted since 1980 (Fig. 5) is much closer to the source (Crater C) than for the pre-1980 flows. Lower effusion rates, higher slopes with divergent orientations help to explain this. Over 270m of lava has been added along an axis northwest of Crater C, with a secondary axis to the southwest.

From 1980 onwards, most of the lavas flowed northwards, with the exception of the 1992 southwest flow (Fig. 6). This pattern is repeated in the 1997–2004 and the 2000–2004 intervals (Figs. 7, 8). However, there is known to be missing data from around and to the south of Crater C. Also increasingly, the lava flows from Crater C have developed a tendency to disintegrate on steep slopes to form a talus deposit downslope. It is suspected that some of the thinner parts of this talus are not recorded by differencing these DEMs. Overall, the 1968–2004 flow-field (Fig. 9) has a deltaic shape. Over 300m of new lava has accumulated to the northwest of Crater C.

The history of lava extrusion at Arenal during the current eruption records an overall waning rate of effusion. Within this, other patterns are evident. From

1968 to 1973 the initial high effusion rate from Crater A decayed quite rapidly. Effusion from Crater C between 1974 and 2004 was at a more constant and lower overall rate ( $\sim 0.36\text{m}^3\text{ s}^{-1}$ ). In the late 1980s the effusion rate increased, the magma became more explosive, and the edifice containing the effusive vent rose rapidly. The onset of explosivity may reflect a more abundant gas content of the magma, or more probably, higher degrees of shallow degassing-induced pressurisation in the magma caused by higher rates of magma ascent in the conduit. The inferred period of higher effusion rate from the mid-1980s to the early 1990s may also be captured by the long-term surface deformation signal measured by the dry-tilt method and thought to be due to loading by the growing lava flow-field (Mora et al., in preparation). Most of the dry-tilt stations show an inflection in deformation gradient around 1990–1991. This coincides with the sharp reduction of measured tephra output (Cole et al., 2005, Fig. 4d) and suggests that the extrusion rate of lava (equivalent to the loading rate) decreased at that time.

At 37 years (as of 2005), the eruption of Arenal is now very long-lived, implying a system in near equilibrium. Additional evidence for the dynamic equilibrium of the Arenal volcanic system comes from petrology. The most important observation is that the 1968–2004 rocks of Arenal are “compositionally monotonous, petrographically complex” (Streck et al., 2002). From this, Streck et al. (2005) inferred that the system is nearly continuously supplied by basaltic magma rising from the mantle. The interaction of this volumetrically minor basalt with a larger basaltic andesite body is locally heterogeneous and episodic. The resulting crystal fractionation, magma mixing and heat exchange events produce mineralogical changes that are preserved in the phenocrysts, mainly the clinopyroxenes (Streck et al., 2002). Where in the crust these events take place is not well constrained, but a significant vertical range (few kilometers) is indicated.

In addition to this general picture, there is also evidence of temporal petrological variability. Reagan et al. (1987) showed how the early years of the eruption could be interpreted in terms of three stages: I (1968–1970), II (1970–1974), III (1974–1984). The lavas of I were phenocryst-poor ( $\sim 20\%$ ) and became increasingly mafic (Malavassi, 1979). The compatible trace elements of the lavas rose in stage II as did the phenocryst content. Gill et al. (2004) argued that the  $\sim 250 \times 10^6\text{-m}^3$  of lavas erupted during phases I and II represent closed system differentiation of magma within the crustal reservoir, largely prior to the start of the eruption, and that all the subsequent effusion was dominated by magma mixing,

together with fractionation, in an open system. 1973–1974 marked the one major hiatus during the eruption and the change in location of the effusion from Crater A to C. There does not seem to have been any major change in bulk magma composition during 1984 when the surface activity changed to a more explosive style. However, the amounts of  $^{210}\text{Pb}$  and  $^{226}\text{Ra}$  in the lavas, which had been rising since 1973 stabilised in about 1986 (Reagan et al., 2006-this issue, Fig. 3), though their ratio did not change (Reagan et al., 2006-this issue, Fig. 4). This may reflect a change in reservoir flow regime at this time. On the basis of the temporal variation of trace elements and isotopic ratios in the lavas, Ryder et al. (2006-this issue) identified another change in petrology (in addition to those in 1970, 1974 and 1984) in 1992/3, defining another phase of common petrological character from 1984 to 1992 which we term phase IV.

In Fig. 12 we plot the variation in effusion rate with time and we suggest how these rates might relate to the recognised major phases of petrological and explosivity variation in Fig. 13. The correspondence between the effusion rate history of 1968–1973 and the evacuation of the pre-eruption batch of magma from the reservoir has been discussed by Reagan et al. (1987) and Gill et al. (2004). Our DEM measurements were too infrequent to capture it, but we suggest that there was an increase in effusion rate around 1984 that was responsible for the development of explosivity at that time (Fig. 13). Also the subsequent acceleration in increase of the altitude of Crater C (Fig. 2) during 1984 to 1988 was probably caused by the increased accumulation of near-vent explosive deposits. This period of elevated effusion rates probably ended in 1991 and corresponds roughly

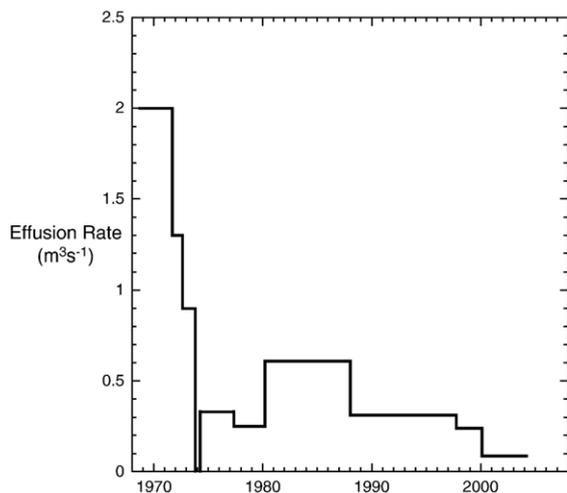


Fig. 12. Plot of lava effusion rate with time. Data for 1968–1977 are from Wadge (1983).

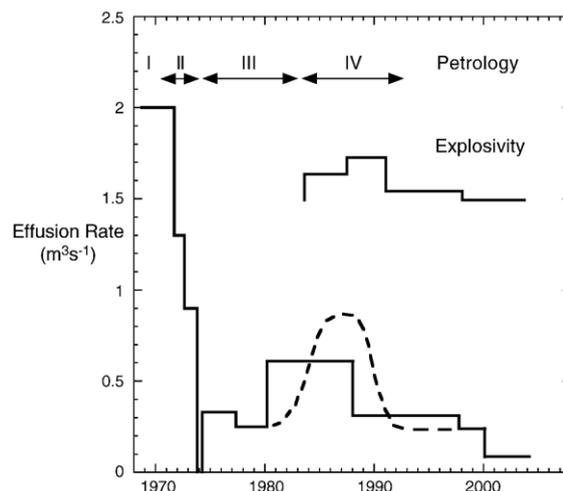


Fig. 13. Effusion rate plot from Fig. 12. The dashed curve is the inferred effusion rate for the period between 1984 and 1991. This period corresponds to petrological phase IV and was one of increased explosivity. The petrological phases are taken from Reagan et al. (1987) and Ryder et al. (2006-this issue). The explosivity curve is partly taken from Cole et al. (2005).

to petrological phase IV. The reduction in effusion rate at the end of the 1990s indicated by our data agrees with the further reduction in explosivity in about 1998 (Cole et al., 2005, Fig. 4b and d).

The effusion rates of recent years ( $\sim 0.1\text{--}0.2\text{ m}^3\text{ s}^{-1}$ ) may be close to the lowest sustainable average rates for a basaltic andesite magma. Thermal cooling effects and lack of magmatic head may eventually halt such an eruption. Reduced magma driving pressures are implied. Pinel and Jaupart (2003) showed theoretically how the accumulation of mass (lavas) near the vent overlying a magma reservoir will tend to increase reservoir pressures and generate a stress field that will serve to keep open the vent.

The sparsity of the time series of effusion rate measurements at Arenal is obvious and as a result we are undoubtedly aliasing shorter period variations in the effusion rate (e.g., 1984–1991) that may well hide valuable clues to the working of the volcanic system. Arenal does not display clear evidence of decadal-scale cyclicality, such as that invoked by the non-linear systematics of Melnik and Sparks (2005), but the data in this study (together with the petrological and other geophysical evidence) could be used to constrain dynamic models of the behaviour of this volcanic system.

## Acknowledgements

We thank our Costa Rican colleagues: E. Duarte, E. Fernandez, R. Van der Laat, E. Malavassi, M. Berrocal, G.

Alvarado and G. Soto for their generous help and ideas. The altitude of Crater C was surveyed by Rodolfo Van der Laet. Thanks to Bruce Chapman for supplying the NASA/JPL-Caltech AIRSAR data. Referees comments from Eduardo Malavassi, Jon Dehn and Scott Rowland greatly improved our paper. GW and PC acknowledge ESA for the Cat-1 grant for ERS data. GW's work was supported under NERC Contract F60/G6/12/02.

## References

- Alvarado, G.E., Soto, G.J., 2002. Pyroclastic flow generated by crater-wall collapse and outpouring of the lava pool of Arenal Volcano, Costa Rica. *Bull. Volcanol.* 63, 557–568.
- Borgia, A., Linneman, S., Spencer, D., Morales, L.D., Brenes, J.A., 1983. Dynamics of lava flow fronts, Arenal Volcano, Costa Rica. *J. Volcanol. Geotherm. Res.* 19, 303–329.
- Borgia, A., Poore, C., Carr, M.J., Melson, W.G., Alvarado, G.E., 1988. Structural, stratigraphic, and petrologic aspects of the Arenal-Chato volcanic system, Costa Rica: evolution of a young stratovolcano complex. *Bull. Volcanol.* 50, 86–105.
- Carr, M.J., Feigenson, M.D., Patino, L.C., Walker, J.A., 2003. Volcanism and geochemistry in Central America: progress and problems. Inside the subduction factory. AGU Geophys. Monogr. 138, 153–174.
- Casadevall, T.J., Rose Jr., W.I., Fuller, W.M., Hunt, W.H., Hart, M.A., Moyers, J.L., Woods, D.C., Chuan, R.L., Friend, J.P., 1984. Sulfur dioxide and particles in quiescent volcanic plumes from Poás, Arenal, and Colima volcanoes, Costa Rica and Mexico. *J. Geophys. Res.* 89, 9633–9641.
- Cigolini, C., Borgia, A., Casertano, C., 1984. Inter-crater activity, a-block lava viscosity and flow dynamics. *J. Volcanol. Geotherm. Res.* 20, 155–176.
- Cole, P.D., Fernandez, E., Duarte, E., Duncan, A.M., 2005. Explosive activity and generation mechanisms of pyroclastic flows at Arenal volcano, Costa Rica between 1987 and 2001. *Bull. Volcanol.* 67, 695–716.
- Duarte, E., Cole, P., Fernandez, E.A., Saenz, W., Malvassi, E., 2004. Grain size, mass per day and morphological characteristics of tephra from Arenal Volcano, Costa Rica. *Eos Trans. AGU* 85 (47), 1987–2000 (Fall Meet. Suppl., Abstract).
- Ghiglia, D.C., Pritt, M.D., 1998. Two-dimensional Phase Unwrapping. John Wiley and Sons Inc, New York. 493 pp.
- Ryder, J.B., Tepley, C., Ramos, F., 2004. Closed to Open-system crustal-level differentiation during eruption of andesite: Arenal, Costa Rica. *AGU 85 (47)*, 1968–2003 (Fall Meet. Suppl., Abstract V23D-02).
- Linneman, S.R., Borgia, A., 1993. The blocky andesitic lava flows of Arenal Volcano, Costa Rica. In: Kilburn, C. (Ed.), *Handbook for Monitoring Active Volcanoes*. UCL Press.
- Lu, Z., Fielding, E., Patrick, M.R., Trautwein, M., 2003. Estimating lava volume by precision combination of multiple baseline spaceborne and airborne interferometric synthetic aperture radar: the 1997 eruption of Okmok volcano, Alaska. *IEEE Trans. Geosci. Remote Sens.* 41, 1428–1436.
- Macfarlane, D.G., Wadge, G., Robertson, D.A., James, M.R., Pinkerton, H., 2006. Use of a portable topographic mapping millimetre wave radar at an active lava flow. *Geophys. Res. Lett.* 33, L03301. doi:10.1029/2005GL025005.
- Madsen, S.N., Martin, J.M., Zebker, H.A., 1995. Analysis and evaluation of the NASA/JPL TOPSAR across-track interferometric SAR system. *IEEE Trans. Geosci. Remote Sens.* 33, 383–391.
- Malavassi, E., 1979. Geology and petrology of Arenal Volcano, Costa Rica, Ms thesis, Univ. Hawaii at Manoa. 111 pp.
- Massonnet, D., Feigl, K.L., 1998. Radar interferometry and its application to changes in the earth's surface. *Rev. Geophys.* 36, 441–500.
- Matumoto, T., Umana, J.E., 1976. Informe sobre la erupcion del Volcan Arenal ocurrida el 17 de Junio de 1975. *Rev. Geofis. Inst. Panam. Geogr. Historia* 5, 299–315.
- Melnik, O., Sparks, R.S.J., 2005. Controls on conduit magma flow during lava dome building eruptions. *J. Geophys. Res.* 110, B02209. doi:10.1029/2004/JB003183.
- Melson, W.G., 1994. The eruption of 1968 and tephra stratigraphy of Arenal Volcano. In: Sheets, P.D., McKee, B.R. (Eds.), *Archaeology, Volcanism and Remote Sensing in the Arenal Region, Costa Rica*. University of Texas Press, Austin, pp. 24–48.
- Melson, W.G., Saenz, R., 1968. The 1968 eruption of Volcan Arenal, Costa Rica: preliminary summary of field and laboratory studies. Smithsonian Center for Short-Lived Phenomena, Report 7/1968. 35 pp.
- Melson, W.G., Saenz, R., 1973. Volume, energy and cyclicity of eruptions of Arenal Volcano Costa Rica. *Bull. Volcanol.* 37, 416–437.
- Minakami, T., Utibori, S., 1969. The 1968 eruption of Volcano Arenal, Costa Rica. *Earthq. Res. Inst. Bull.* 47, 783–802.
- Mora, M., Soto, G.J., Alvarado, G.E., Lesage, P., in preparation. Deformation produced by the 1968–2005 lava field of Arenal volcano, Costa Rica measured during the 1986–2000 period. *J. Volcanol. Geotherm. Res.*
- Muller, J.-P., Backes, D., 2004. Quality assessment of X- and C-SRTM with ERS-Tandem DEMs over four European CEOS WGCW test sites. *Proc. FRINGE03*.
- Oramas-Dorta, D., Wadge, G., Cole, P.D., in preparation. Error analysis of digital elevation models of Arenal Volcano.
- Pinel, V., Jaupart, C., 2003. Magma chamber behavior beneath a volcanic edifice. *J. Geophys. Res.* 108 (B2), 2072. doi:10.1029/2002JB001751.
- Ranero, C.R., Morgan, J.R., McIntosh, K., Reichert, C., 2003. Bending-related faulting and mantle serpentinization at the Middle America trench. *Nature* 425, 367–373.
- Reagan, M.K., Gill, J.B., Malavassi, E., Garcia, M.O., 1987. Changes in the magma composition at Arenal volcano, Costa Rica, 1968–1985: real-time monitoring of open-system differentiation. *Bull. Volcanol.* 49, 415–434.
- Reagan, M.K., Tepley III, F.J., Gill, J.B., Wortel, M., Garrison, J., 2006-this issue. Timescales of degassing and crystallization implied by  $^{210}\text{Po}$ – $^{210}\text{Pb}$ – $^{226}\text{Ra}$  disequilibria for andesitic lavas erupted from Arenal volcano. *J. Volcanol. Geotherm. Res.* 157, 135–146. doi:10.1016/j.jvolgeores.2006.03.044.
- Rowland, S.K., 1996. Slopes, lava flow volumes and vent distributions on Volcan Fernandina, Galapagos Islands. *J. Geophys. Res.* 101, 27657–27672.
- Ryder, C.H., Gill, J.B., Tepley III, F.J., Ramos, F., Reagan, M., 2006-this issue. Closed to open system differentiation at Arenal Volcano (1968–2003). *J. Volcanol. Geotherm. Res.* 157, 75–93. doi:10.1016/j.jvolgeores.2006.03.046.
- Soto, G.J., 1997. Ceniza eruptada por el Volcán Arenal, 1992–1997. *Bol. OSIVAM* 10 (19–20), 14–24.
- Soto, G.J., Alvarado, G.E., 2004. Eruptive history of Arenal volcano, Costa Rica. *Eos Trans. AGU* 85 (47), V33B-1464 (Fall Meet. Suppl., Abstract).

- Soto, G.J., Arias, J.F., 1996. Síntesis de la actividad del Volcán Arenal, año 1996. *Bol. OSIVAM* 9 (17–18), 11–18.
- Soto, G.J., Barquero, R., Fernández, M., Van de Laat, R., 1991. Arenal. *Global Volcanism Netw. Bull.* 16/12, 10–11.
- Soto, G.J., Arias, F., Barquero, R., 1992. Resumen de la actividad del Volcán Arenal durante 1992. *Bol. Obs. Vulcanol. Arenal* 5 (9–10), 7–23.
- Soto, G.J., Arias, F., Alvarado, G.E., Madrigal, L.A., Barquero, R., 1993. Resumen de la actividad del Volcán Arenal durante 1993. *Bol. Obs. Vulcanol. Arenal* 6 (11–12), 5–22.
- Stevens, N.F., Wadge, G., Williams, C.A., Morley, J.G., Muller, J.-P., Murray, J.B., Upton, M., 2001. Surface movements of emplaced lava flows measured by synthetic aperture radar interferometry. *J. Geophys. Res.* 106, 11293–11313.
- Streck, M.J., Dungan, M.A., Malavassi, E., Reagan, M.K., Bussy, F., 2002. The role of basalt replenishment in the generation of basaltic andesites of the ongoing activity at Arenal volcano, Costa Rica: evidence from clinopyroxene and spinel. *Bull. Volcanol.* 64, 316–327.
- Streck, M.J., Dungan, M.A., Bussy, F., Malavassi, E., 2005. Mineral inventory of continuously erupting basaltic andesites at Arenal volcano, Costa Rica: implications for interpreting monotonous, crystal-rich, mafic arc stratigraphies. *J. Volcanol. Geotherm. Res.* 140, 133–155.
- Van der Laat, R., Carr, M.J., 1989. In: McClelland, L., Simkin, T., Nielsen, M., Summers, E., Stein, T.C. (Eds.), *Global Volcanism 1975–1985: The First Decade of Reports from the Smithsonian Institution's Scientific Event Alert Network (SEAN)*. Prentice Hall, Englewood Cliffs, NJ, pp. 510–511.
- Wadge, G., 1983. The magma budget of Volcán Arenal, Costa Rica from 1968 to 1980. *J. Volcanol. Geotherm. Res.* 19, 281–302.
- Wadge, G., 2004. Measuring the rate of lava effusion by InSAR. *Proc. of FRINGE 2003 Workshop, Frascati, Italy, 1–5 Dec. 2003 (ESA SP-550, June 2004)* 112\_wadge.
- Williams-Jones, G., Stix, J., Heiligmann, M., Barquero, J., Fernández, E., González, E.D., 2001. A model of degassing and seismicity at Arenal volcano, Costa Rica. *J. Volcanol. Geotherm. Res.* 2001, 121–139.