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RESEARCH ARTICLE

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# Pyroclastic flow generated by crater-wall collapse and outpouring of the lava pool of Arenal Volcano, Costa Rica

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**Abstract** The pyroclastic flow that issued from the Arenal summit crater on 28 August 1993 came from the collapse of the crater wall of the cone and the drainage of a lava pool. The 3-km-long pyroclastic flow, $2.2\pm0.8\times10^6$ $m^3$ in volume, was confined to narrow valleys (30–100 m wide). The thickness of the pyroclastic deposit ranged from 1 to 10 m, and its temperature was about 400 °C, although single bombs were up to 1,000 °C. The deposit is clast-supported, has a bimodal grain size distribution, and consists of an intimate mixture of finely pulverized rock ash, lapilli, small blocks, and cauliflower bread-crusted bombs, in which are set meter-size lava fragments and juvenile and non-juvenile angular blocks, and bombs up to 7 m in diameter. Large faceted blocks make up 50% of the total volume of the deposit. The cauliflower bombs have deep and intricate bread-crust texture and post-depositional vesiculation. It is proposed that the juvenile material was produced entirely from a lava pool, whereas faceted non-juvenile blocks come from the crater-wall collapse. The concentration and maximum diameter of cauliflower bread-crusted bombs increases significantly from the base (rockslide + pyroclastic flow) to the top (the pyroclastic flow) of the deposit. An ash cloud deposited accretionary lapilli in the proximal region (outside of the pyroclastic flow deposit), and very fine ash fell in the distal region (between 5 and 30 km). The accretionary lapilli deposit is derived from the fine, elutriated products of the flow as it moved. A turbulent overriding surge blew down the surrounding shrubbery in the flow direction. The pyroclastic flow from August 1993, similar to the flows of June 1975, May 1998, August 2000, and March 2001, slid and rolled rather than being buoyed up by gas. They grooved, scratched, and polished the surfaces over which they swept, similar to a Merapi-type pyroclastic flow. However, the mechanism of the outpouring of a lava pool and the resulting flows composed of high- to moderate-vesiculated, cauliflower bread-crusted bombs and juvenile blocks have not been described before. High-frequency earthquake swarms, followed by an increase in low-frequency volcanic events, preceded the 1975, 1993, and 2000 eruptions 2–4 months before. These pyroclastic flow events, therefore, may be triggered by internal expansion of the unstable cone in the upper part because of a slight change in the pressure of the magma column (gas content and/or effusive rate). This phenomenon has important short-term, volcanic hazard implications for touristic development of some parts on the flanks of the volcano.

**Keywords** Ash-cloud surge · Arenal · Costa Rica · Lava pool · Pyroclastic flows · Volcanic hazard

## Introduction

Arenal Volcano is a small (1.1 km in height, 1,657 m above sea level, 15 $km^3$, Fig. 1) basaltic andesite stratovolcano, which began to erupt around 7000 years B.P., and has erupted a variety of products that represent a wide spectrum of phreatomagmatic to magmatic phenomena (Soto et al. 1998). In July 1968, a lateral explosion resulted in 78 deaths and damage to former Pueblo Nuevo and Tabacón villages and cattle fields (Melson and Sáenz 1973). Arenal has remained continuously active, with Strombolian eruptions, blocky lava flows, lava avalanches, pyroclastic flows, and hyper-concentrated stream-flows, which are major hazards to the rapidly growing population of tourists that visit the area surrounding the volcano. Hazard maps have been published (Alvarado et al. 1988, 1997b), and a volcano observatory

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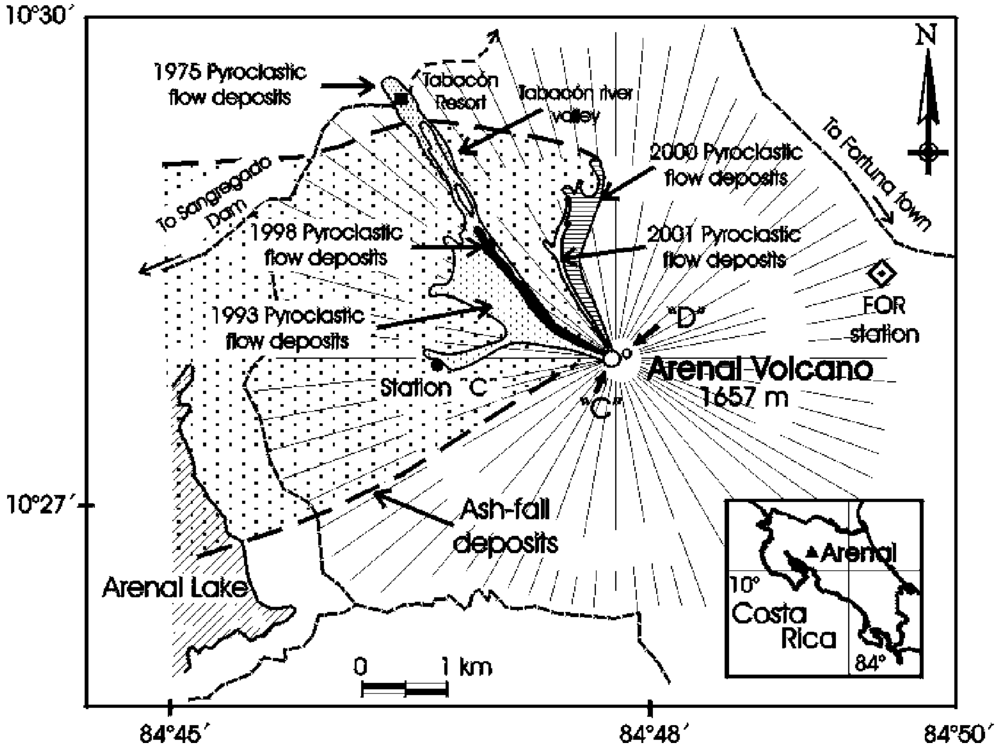


**Fig. 1** Location map of Arenal volcano and its craters "*C*" (active) and "*D*" (inactive), including station C with its tiltmeter measurement, the distribution of the pyroclastic flow and ash-fall deposits, and the location of Tabacón Resort and the seismic station, FOR. The *dotted lines* are roads

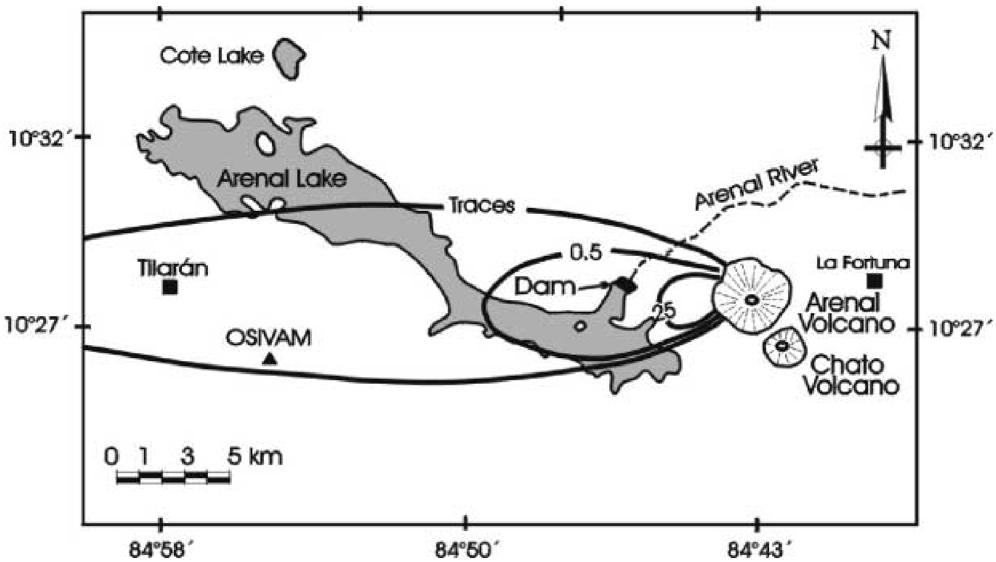


**Fig. 2** Distribution of ash (in mm) from the 1993 eruption. OSIVAM is the Observatorio Sismológico y Vulcanológico de Arenal y Miravalles

(Observatorio Sismológico y Vulcanológico de Arenal y Miravalles: OSIVAM, belonging to Instituto Costarricense de Electricidad: ICE) has been constructed to make a major effort to monitor the volcano (Fig. 2).

Since 1968, Arenal has erupted around 0.7 $km^3$ of lava flows and pyroclastics. A significant eruption occurred in June 1975 and, since then, a new composite cone on crater C, the highest of the three new craters that opened explosively in 1968 (A, B and C), has been constructed, giving the actual configuration of a twin-coned volcano. Crater D is an older cone (Fig. 1). Crater C has widened from a 60-m-diameter circular shape in early 1980 (Cigolini et al. 1984) to a slightly elongated shape of some 150–200 m in diameter, which contains a lava pool (cf. Tazieff 1994). Because of the growth of the cone and the widening of the crater, the pool must have a funnel shape. Arenal's lava pool is composed of viscous basaltic andesite, which extrudes in a pulsating pattern, forms a crust, and then overflows the crater rim and flows almost continuously down the north to southwest flanks of the volcano (Cigolini et al. 1984). Degassing occurred in rhythmic pulses along the edge of the pool. The volcano entered a Strombolian phase in 1984, but the lava pool has remained (as observed by one of the authors, G.E.A., from a fly-over in February 1987) and, since that time, a continuous pulsating glow has been observed by the authors above crater C. The pool's crust is broken by sudden degassing events and Strombolian explosions, and, periodically, small and ephemeral spatter cones are constructed in the crater.

In general, pyroclastic flows are of two main types: (1) collapse of lava domes or lava flows, and (2) collapse of the eruption column or upwelling at the vent (Cas and Wright 1987). Prehistoric and historic pyroclastic flow events have been common phenomena at Arenal (Borgia et al. 1988; Ghigliotti et al. 1992). Those that have occurred at Arenal since 1986 are generally associated with moderate column collapse from Strombolian explosions, and small block avalanches from active lava fronts (Alvarado and Arroyo 2000). The purpose of this paper is to document a previously unknown type of pyroclastic flow, generated during a partial cone collapse and outpouring of an active lava pool, which occurred during the night of 28 August 1993. A reinterpretation of similar events at Arenal in June 1975, at Cotopaxi (Ecuador) in 1877, and at Asama (Japan) in 1783, shows that the 1993 pyroclastic flow is not unique. Several recent events at Arenal (May 1998, August 2000, and March 2001) provide additional examples of the same phenomenon.

## Premonitory signals of the 1993 event

### Seismicity

A high-frequency earthquake swarm (55 A-type quakes, magnitude <2) was recorded by the Fortuna seismic station (FOR, 3.5 km east of the active vent) and by a portable seismic station, between 11 May and 3 June 1993. The shape of seismic signals was variable, suggesting a complex source. Unfortunately, no epicenter locations were possible, but the time delay between P and S waves (between 0.7 and 6.5 s) suggested a local source, whose focus (<20 km) decreased in distance (or depth) with time. Focal depths beneath the volcano were estimated empirically between 20 km for most of the first events, and less than 1 km (near or in the volcano edifice) for most of the latter events (Soto et al. 1996). The last recorded earthquake was 86 days before the crater-wall collapse.

### Ground deformation

The western flank of Arenal has been deforming for several years, following a pattern of deflation towards to the area of maximum overloading of lava flows that have erupted since 1968. The most accurate ground deformation has been recorded at station C (located 1.8 km west of the active vent, Fig. 1), which down-tilted almost constantly at a rate of 1.7–2.5 µrad/month between 1986 and 1990 (Soto 1991). A similar deformation pattern was observed up to April 1992, and then a relatively anomalous inflation occurred until January 1993. Between January and July 1993, the volcano inflated (recorded at station C as 7.2 µrad/month). Because the lava-loading deformation was still operating during the last period as background, subtracting this effect yields a total inflation of 9.7 µrad/month during this period at station C. Other reports also suggest an inflation of the west flank of the volcano of 15 µrad in the period October 1992–July 1993, but they do not precisely locate this inflation (GVN Bulletin 1993a). Unfortunately, station C was destroyed during the eruption of 28 August 1993, and we lack data after July 1993 that would have determined if deflation occurred after the eruption. Nevertheless, reports from Universidad Nacional (GVN Bulletin 1993b) suggest a post-eruptive deflation of 24 µrad of the SW quadrant of the volcano.

### Lava emission and rockslides

After March 1993, lava emission decreased to at least half of that observed during 1992, resulting in shorter and slower lava flows, and weaker and smaller explosive activity. After June 1993, the upper part of the NW flank of cone C showed many new fumaroles and cracks. It became unstable and some areas collapsed to form rockslides, the most prominent and frequent being on 26 August. Small pyroclastic flows were also generated from the collapse of blocky lava-flow fronts on the higher flank of the volcano, which reached ~800 m down slope. They were observed mainly in June 1993.

## Chronology of events and field observations

Abnormal activity at Arenal during the night of 28 August 1993 was reported by many observers. A series of rockslides containing pieces of incandescent blocks developed slowly on the NW and W flanks of the volcano after 19:50 h (all local time, LT=GMT –6 h) from cone C, and lasted at least 50 min, with high-frequency noise recorded on the seismogram. At about 21:00 h, the main incandescent event began and a heavy muddy rain shower occurred on the western flank of the volcano (including the Sangregado dam area), which led to the collapse and breakage of branches of guayabo trees (*Psidium guajaba*) and slightly affected houses in this area. Although the seismograms and reports indicated that the major pyroclastic flow lasted only a few minutes, the incandescent outpour activity continued for several hours, according to photographs taken a couple hours later, followed by the development of a new lava flow.

Vegetation was completely destroyed in the middle part of the Tabacón valley by the thermal and pressure effects of the pyroclastic flow and pyroclastic surge, which felled grasses, bamboos, and shrubs in the flow direction, although tree branches were not broken. The

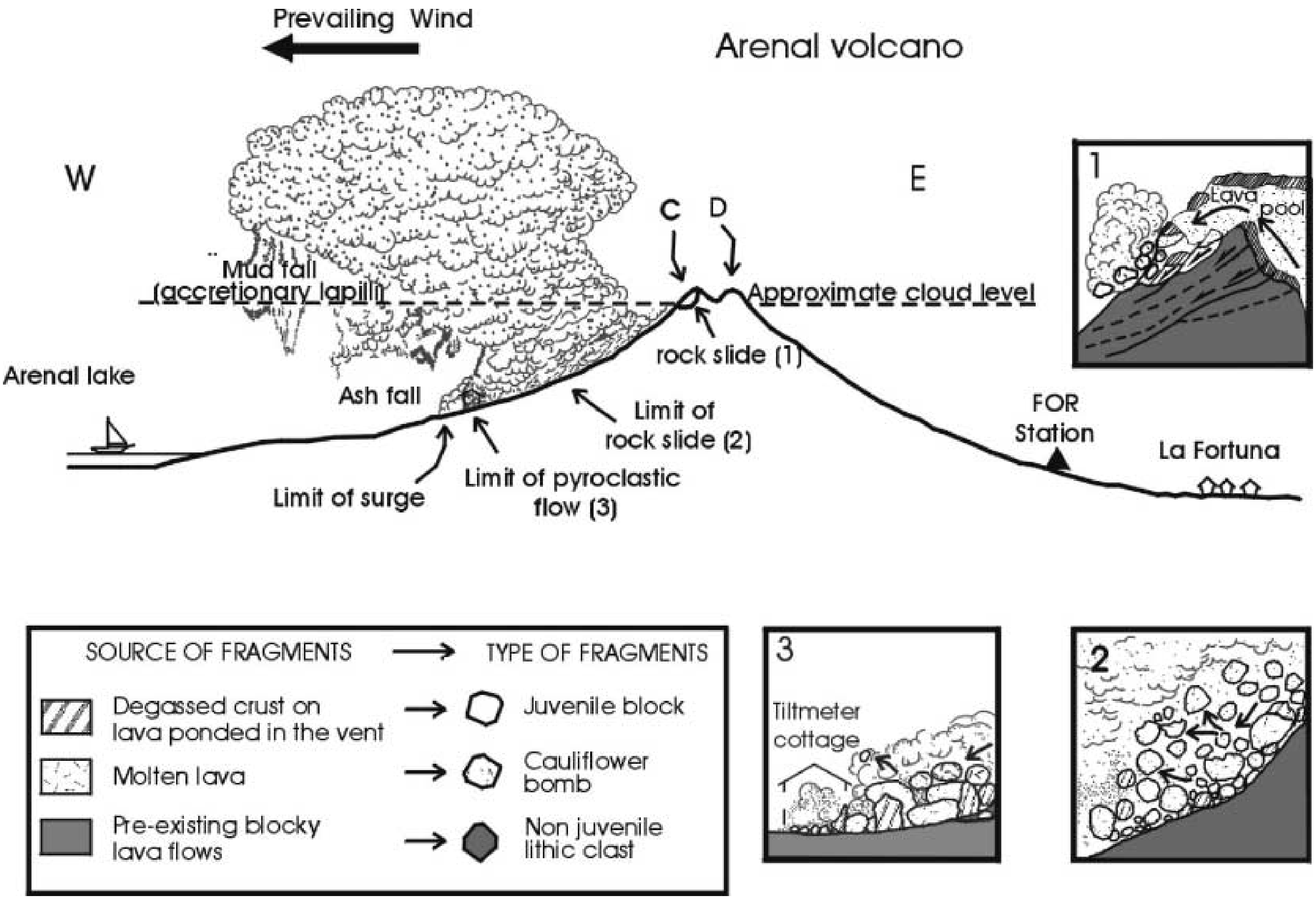


**Fig. 3** The sequence of principal events during the 28 August 1993 eruption

most significant observation of the event was that its source could be determined as the partial collapse of the summit cone and the outpouring of a lava pool, but there was no Strombolian explosion. Only a continuous noise (jet-engine-like) and lightning was reported.

No human casualties or serious material damage took place in Arenal National Park as a result of the activity. Only one dry tiltmeter, station C, and an ash sampler of the monitoring equipment installed by ICE on the volcano's western flank, were affected by the pyroclastic flow (Figs. 1, 2 and 3). One person suffered second-degree burns to his foot when he walked onto the distal part of the pyroclastic flow deposits 1 day later.

A horseshoe-like opening (about 80 m in depth) was present in the crater wall immediately after the event, in the area where intense fumarolic activity and repeated rockfalls had been observed 2 days before. The new lava flowed rapidly down the NW flank, reaching 1,000 m length during the first day, but it slowed down to <100 m/day by early September. Fieldwork was carried out a few hours after the event, and continued during the following weeks, prior to heavy rains in the area, which caused the reworking of the deposit.

## Distribution and type of deposits

Based on eyewitnesses, the deposits of the repeated rockfalls prior to the main event were restricted to the upper flanks of the volcano, less than 1 km from crater C. The pyroclastic flow at Arenal on 28 August 1993 moved down the slope from crater C and was channeled between the levees of pre-erupting lavas. The deposit formed a fan-shaped, tri-lobate apron about 500 m wide, extending up to 3 km from the vent (Fig. 1). Each lobe was between 50 and 100 m wide, and 1–~10 m thick, and consisted of blocks and bombs with a surrounding zone of directed surge. There is a definite small (<1.5 m high) flow front, and bomb-rich levees (0.5–1.5 m high) with little fine material, but concentric ridges are absent. The intra-levee channels contain fine ash mixed with large dense blocks and bombs (Figs. 4 and 5).

The deposit is massive, poorly sorted, with black to dark gray bombs and angular blocks up to 7 m in diameter, set in a fine, non-cohesive matrix. At least 75 vol% of the clasts in the deposit are large, juvenile lithic clasts, and large spherical- to elongated-shaped bombs, with cauliflower bread-crusted surfaces. Because of the fluidity of bombs, their shapes were modified during their final transport within the flow. Thus, some bombs were deformed or wrapped plastically around blocks or large trees, which were partially carbonized (Figs. 4 and 5). The poorly vesiculated juvenile blocks (density 2.5 g $cm^{-3}$) of-

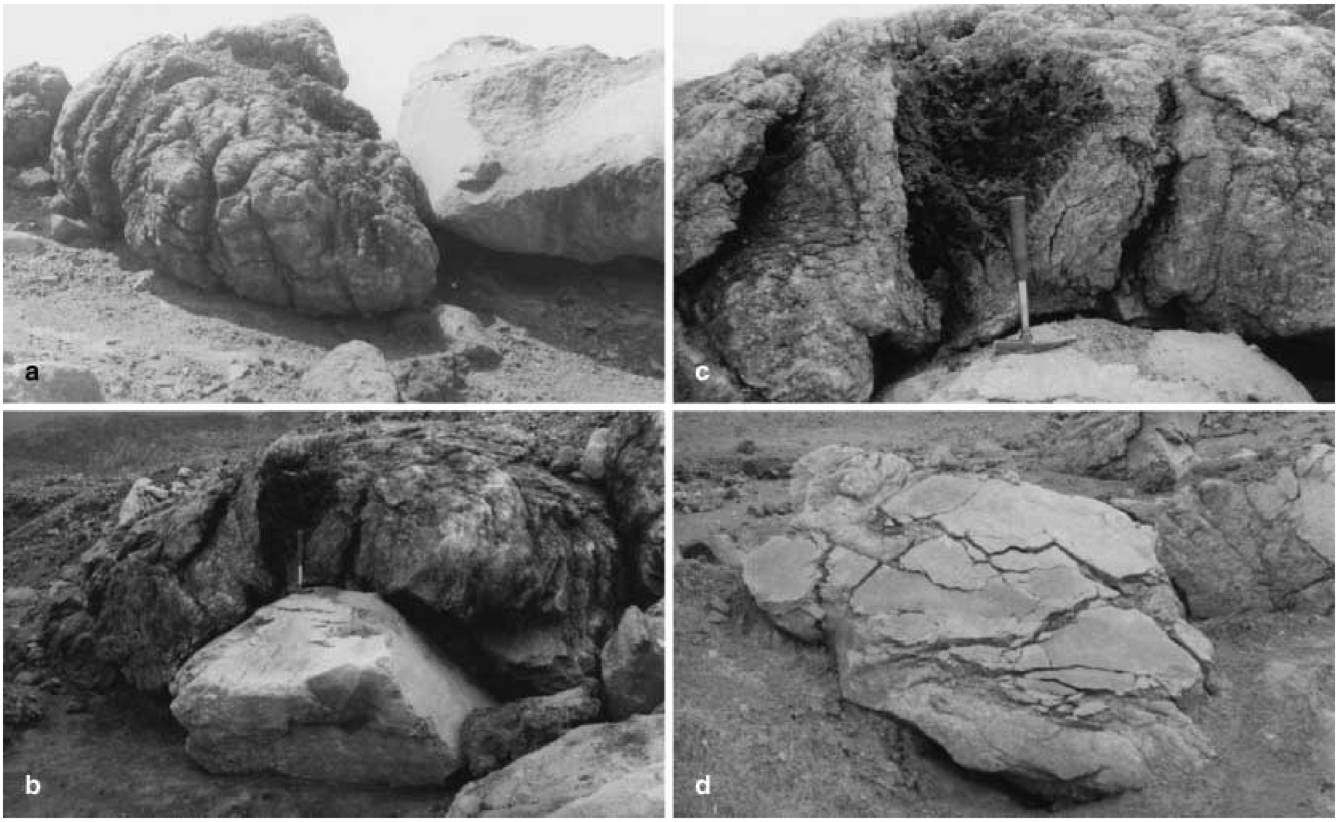


**Fig. 4** **a** Single bomb with bread-crusted texture (*left*) and non-juvenile (accidental or accessory) lithic clast (*right*), each about 1 m in diameter. **b** Bomb with post-depositional vesiculation and plastic deformation around a non-juvenile block. **c** Detail of **b** showing vesicular cracked open joints. **d** Juvenile block with bread-crusted surface

**Fig. 5** General view of the cauliflower bread-crusted flow deposit. Behind there is a historical blocky lava flow erupted during the 1970s

ten have cracked open joints with a variable percentage of vesicles (20–35% and more), with some being "spongy" or vesicular (density 1.2–1.6 g $cm^{-3}$). In many cases, some juvenile fragments have a dual character: one face is typical of angular, non-vesiculated blocks and the other of a cauliflower bread-crusted surface, with a transitional contact between both. In contrast, the non-juvenile blocks are poorly vesicular, subangular to subrounded basaltic andesites, light-gray colored, several with rusty surfaces, and without cooling fractures (Fig. 4). It is proposed that the juvenile material was produced entirely from the lava pool, whereas the faceted non-juvenile blocks originated from the crater-wall collapse.

Several stratigraphic sections were measured through the western lobe (where new gullies were quickly created by erosion of the deposits); many other localities were also examined on all lobes. The particle-size distribution is strongly bimodal, with one mode in the range of decimeters to meters and the other in the ash, lapilli, and small (<20 cm) bomb-block range (Fig. 6). The deposits occur in two main gradational facies (from bottom to top) with a crude inverse grading.

The massive, non-graded basal unit (between 25 and 100 cm in thickness) consists of juvenile and non-juvenile blocks, some clast-supported small semi-spheric bombs with a poorly sorted matrix of pulverized scoria, fragmented dense rocks, ash, lapilli, bombs, blocks, and some vegetable matter, with no internal bedding. The upper part is composed of cauliflower bread-crusted bombs and angular blocks set in a matrix, which reaches up to 1.5 m in thickness. Their average maximum diameters range from several decimeters to several meters (Fig. 6).

Tiltmeter station C at the edge of the pyroclastic flow front (Fig. 3) was partially filled by a 75-cm-thick massive debris deposit. It is characterized by angular to subangular blocks and bombs (diameter <13 cm), supported by a matrix of non-cohesive, poorly sorted ash and la-

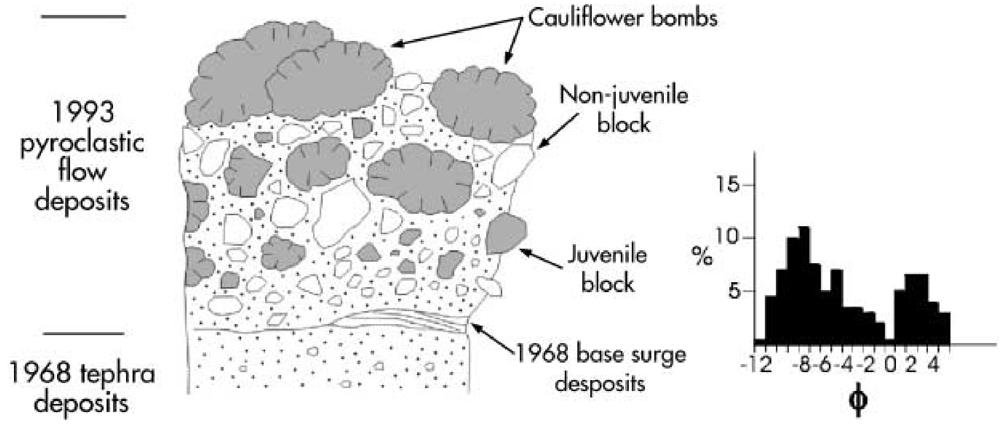


**Fig. 6** Schematic columnar section showing the 1993 pyroclastic flow deposits with the two main gradational units (see text) with a crude inverse grading. A representative grain-size histogram illustrating the bimodal grain-size distribution. For the coarse material, we used the methodology of Wolman (1954) and Kellerhals and Bray (1971)

pilli, and some plant debris. A finely laminated ash deposit with a pinch-and-swell structure was also found on horizontal wooden boards located >1.2 m above the floor. These deposits are the result of part of the flow that entered through open windows. The 2-m-high roof was not affected by impacts, and only a few lapilli were deposited. The station acted as a sedimentation trap, indicating that the deposits were now much more dense than the original moving flow, which demonstrates that the upper surface of the active flow was at least several decimeters higher than its final topography.

Very fine ash (less than 1 mm thick) fell on Tilarán, a town located 30 km westward of Arenal. Ash-sized tephra was deposited along a westward axis up to 30 km from Arenal, following the prevailing winds (Figs. 2 and 3). An elongated area of 25 km$^2$, up to 7 km away from the flow fronts, was covered with ~2-mm-thick fine ash, and up to 13.5 km away with 0.5-mm-thick, very fine ash (ca. 50 km$^2$). Our calculations, based on thickness measurements, show that at least $4\times10^3$ m$^3$ of material flowed in front of this western lobe as an ash-cloud surge. In the proximal area, the direction of cane blowdown shows that the ash-cloud surge flowed locally in many directions, and was reflected depending on topographic configuration; however, the surge deposit was very thin or was not preserved at all. In fact, a discrete deposit of fine ash, which coincided with the direction of the grasses and surrounded the main lobes by some tens of meters, is the only remains of a surge deposit. The fine ash particles that elutriated from the pyroclastic flow and to form the ash cloud, adhered to the moisture droplets of low foggy clouds around the volcano and formed accretionary lapilli. Thus, at about 4 km west of the volcano (2 km westward from the flow front), accretionary lapilli 1–3.5 mm in diameter were deposited. They show an open-framework texture, with some vesicle-like structures of irregular shape that correspond to intergranular voids. The thickness of the layer varies between 2 and 4 cm, but much of the deposit was quickly swept out by rainfall a couple of days later. The ash is moderately to well sorted, with some relative coarse ash-grained pyroxene crystals. The typical structure of the accretionary lapilli consists of a central structureless core of very fine ash, surrounded by a layer or layers of dust. Structurally, the accretionary lapilli are similar to "B-type", following Reimer (1983) or, "rim-type fall lapilli", following Schumacher and Schmincke (1991).

## Petrography

The bombs and juvenile blocks are petrographically identical to lavas erupted during recent years. They are black to dark gray porphyric basaltic andesites (18.5–30% phenocrysts) with phenocrysts of plagioclase (12–24%), clinopyroxene (2–3%), orthopyroxene (2–4%), and Fe–Ti oxides (0.5–1%). Some plagioclase xenocrysts are up to 2.5 cm in length. The vesicles are rounded (20–35% and more). The mineralogy of the interstitial groundmass is identical to that of phenocrysts, except that orthopyroxenes are rare.

## Temperature and velocity

Photographs and eyewitness accounts indicate that many clasts of the pyroclastic flow were incandescent for several hours after deposition, suggesting a temperature of about 1,000 °C, according to previous temperature measurements of lava flows at Arenal (e.g., Cigolini et al. 1984) and using the list of colors commonly used to estimated temperatures (in our case from bright cherry red to white) when glowing objects are seen at night (cf. Macdonald 1972). Others were cold and mostly consisted of angular blocks eroded from chutes and from the collapsed flank. The measured temperature of the deposit 17 h after the eruption was 100 °C at the surface, 367 °C at 10 cm depth in the matrix, and >470 °C in the meter-sized bombs. The matrix contained abundant shattered wood, which was uncharred to slightly charred, suggesting a temperature of about 400 °C. Several trees in direct contact with the bombs were charred. The lateral and frontal surge temperature was estimated to have been between 90 and 150 °C, based on deformed plastic bottles found close to monitoring station C, at the edge of the area covered by the deposit. Shrubs and canes were par-

**Table 1** Comparison between the most important Arenal-type pyroclastic flows

| Parameter | 17–21 June 1975 | 28 August 1993 | 5 May 1998 | 23 August 2000 | 24–26 March 2001 |
|---|---|---|---|---|---|
| Components | Poly-textural: cauliflower bread-crusted bombs and blocks | Poly-textural: cauliflower bread-crusted bombs and blocks | Almost mono-textural: blocks, ash and rare cauliflower bread-crusted bombs | Almost mono-textural: blocks, ash and rare cauliflower bread-crusted bombs | Poly-textural: cauliflower bread-crusted bombs and blocks |
| Length (m) | 3,600 | 3,200 | 2,000 | 2,350 | 2,000 |
| Volume ($m^3$) | $>2\times10^6$ | $2.2\pm0.8\times10^6$ | $0.5–1\times10^6$ | $2\times10^6$ | $0.24\times10^6$ |
| Number of flows | >8 | 1 | 23 | 27 | 24 |
| Velocity ($m\ s^{-1}$) | ? | >11–18 | >17 | 33 | ? |
| Structures | Unstratified? | Two gradational layers, no internal structure; levees | Two gradational layers, no internal structure; levees | Two gradational layers, no internal structure; lobes | Two gradational layers, no internal structure; lobes |
| Temperature of the juvenile fragments (°C) | ~1,000 | ~1,000 | >800 | >800 | >800 |
| Temperature of the ash cloud surge (°C) | ? | 90–150 | ? | ~100 | ~100 |
| Equivalent coefficient of friction (H/L) | 0.28 | 0.34 | 0.46 | 0.40 | 0.46 |
| Lava post-event: advance and velocity | 700 m first day, 30 m/day 8–9 days later | 1,000 m first day, 100 m/day 4 days later | 200 m first day, 100 m/day 4 days later | 500 m in 4 days, 125 m/day | 200 m in 2 days, 100 m/day |
| Seismicity | A-type swarm 4–5 months before and 2 months before increase in low-frequency events and tremor | A-type swarm 3–4 months before | Change in the frequency of the tremor before, during and after | Change in the frequency of the tremor before, during and after. A-type swarm 2.5 months before | A-type swarm 3 months before |

tially defoliated, bending towards the flow direction, some of them slightly cooked, but not burned at all.

The pyroclastic flow was highly erosive in the upper valley, particularly on steep higher flanks, as indicated by the presence of grooves and striae that produced scratches resembling glacial striae. A minimum flow velocity can be calculated using the height climbed by the flow up topographic obstacles, a situation that unfortunately was only present in three sites and, therefore, only a minimum velocity could be calculated. Using the potential energy/kinetic energy equation, $V^2=2gh$, where $h$ is the height climbed (16 m) and $g$ the gravitational acceleration, we get velocity $V$=18 m $s^{-1}$ for the main lobe at Tabacón valley, about 2 km from crater C. $V$ was also calculated as 11 m $s^{-1}$ for the lobe on the western flank of the volcano approximately at the same distance. The lower velocity is similar to that of a lava-front avalanche, which traveled about 750 m in June 1993, which was calculated at 11–14 m $s^{-1}$ (Soto et al. 1996). The velocity of the most recent events is significantly higher and is in the order of 33 m $s^{-1}$ (Table 1). This calculation is based on movie films and by the direct observations of one of the authors (G.E.A.).

## Volume

We used two methods to estimate the volume of material involved in the pyroclastic flow: (1) determination of the missing volume of the lava pool and the amount of crater-wall collapse by comparing previous aerial photographs, maps, and ground-based photos with post-event photos and observations, and (2) calculation of the area and thickness of pyroclastic flow deposit based on our field measurements. Both methods are subject to errors because (1) the exact dimensions of the lava pool (depth, diameter, and internal morphology) and the topography of the horseshoe-like crater are not exactly known, (2) there are not enough complete outcrops that show the total thickness of the proximal facies of the deposits, or they are inaccessible on the upper flanks because of high volcanic risk, and (3) a new lava flow erupted soon after the pyroclastic flow and partially covered the deposits. We calculate a volume of $2.2\pm1.0\times10^6$ $m^3$ by the first method, and $2.3\pm0.6\times10^6$ $m^3$ by the second, for an averaged volume in the range of $2.2\pm0.8\times10^6$ $m^3$ for the pyroclastic flow. In our calculations, about 75% of the deposit consists of juvenile lava and, thus, correcting for porosity and average density (2.04 g $cm^{-3}$), we obtain a DRE (dense rock equivalent of 2.5 g $cm^{-3}$) of $1.35\pm0.4\times10^6$ $m^3$ of erupted lava.

## Origin and mechanism for the emplacement of the pyroclastic flow

Rockfalls were observed 2 days before the eruption, and a rotational rockslide developed slowly from the summit cone at 19:50 h and lasted at least 50 min. The rockslide deposits were probably restricted to proximal areas (less than 1.5 km), but continuous rockslides weakened the stability of the cone walls. At about 21:00 h, the walls collapsed (without an earthquake or accompanying explosion), with the outpouring of the lava pool as an incandescent pyroclastic flow. The duration of the pyroclastic flow was only 3 min according to seismic record.

At most distal exposures, the pyroclastic flow deposit forms two gradational facies: a massive, non-graded basal unit of juvenile and non-juvenile clasts, with some bombs in a poorly sorted matrix; and an upper unit of bombs and some blocks that thickens in the levees. Therefore, the lower unit of the deposit must correspond to a starting flow with a mixture of wall rocks and juvenile fragments as confirmed in the deposit. This was immediately followed by the draining of the lava pool, starting with the partially solidified crust and side walls, and continued down to the molten material, which crowns the sequence in the deposit. The shapes of the juvenile blocks and bombs were determined mainly by the degree of crystallization of the lava pool. The sudden collapse of the wall of the lava pool allowed the drainage of a large volume of hot and relatively confined magma in a very short time, which fragmented and rolled down, instead of flowing, because of the high steep flanks (30–34°). This phenomenon produced big drops of lava that maintained their shape. During the fast flow, the bombs remained internally hot, plastic, and gas-rich, and, when they were finally deposited, they deformed by collapse into a cow-dung-like shape. Their plastic behavior is demonstrated by the fact that some juvenile pieces that encountered obstacles along their path (previous deposited blocks or standing trees), engulfed them, and then stopped.

During 1992, the average magma emission rate from Arenal was calculated to be 0.5 $m^3 s^{-1}$ (Soto et al. 1992), but from March 1993 magma emission rate decreased at least by half, to result in shorter and slower lava flows, and weaker and smaller explosive activity. This resulted in a lava pool that could develop a thicker and more viscous crust. This could explain why the calculated amount of juvenile material involved in the pyroclastic flow, which is 75%, and about 40% of these are vesiculated. The most likely explanation for the observed range in vesicularity, even in the same clast, is that it reflects varying degrees of cooling of a near-solidus lava pool prior to its fragmentation; fragments from the surface and margin of the lava pool would presumably be cooler and denser than those from the interior. Many bombs are bread-crusted, and vesicle-rich zones are concentrated in open fractures (Fig. 4c). The surfaces of these scoriaceous parts and open vesicular fractures are so fragile that the bombs could not have been transported any distance in the avalanche without the surface being destroyed. Therefore, vesiculation and expansion of the interior of the bombs must have continued during the late stages of movement of the flow and after it came to rest. One day after the eruption, during the fieldwork, small explosions were heard in the juvenile bombs. Other juvenile blocks, much less vesiculated and thus more viscous, showed striae in their surface, produced by scratching with other blocks during the flow.

The above arguments suggest that the pyroclastic flow could have been enhanced by the expansion of juvenile gas. The ratio vertical drop/horizontal distance traveled (H/L: 800 versus 2,500 m) for the pyroclastic flow is 0.32. This number is called the “equivalent coefficient of friction” (Shreve 1968). In contrast, the erosion of avalanche chutes at relatively slow speeds (at least 18 $m s^{-1}$), with short runout distances, the deposition of some debris halfway down chutes, and the presence of surface levees and channels, all indicate that the pyroclastic flow was not highly fluidized. The mobility of the pyroclastic flow was, therefore, similar to cold and hot rock avalanches, or block and ash flows (Francis et al. 1974; Rose et al. 1977; Nairn and Self 1978; Mellors et al. 1988). Thus, it is not necessary to postulate a high amount of hot gases to explain the mobility of the pyroclastic flow, although hot gases could have contributed.

High temperatures are important in producing the abundant fine-grained component of hot rockfalls and pyroclastic flows because thermal stress and residual gas within the hot rock can cause easy disruption (Mellors et al. 1988). As occurred at Mount St. Helens (Mellors et al. 1988), the basaltic andesite at Arenal has a seriate texture and phenocrystal diameters that ranges from 0.1 to 6 mm (plag + opx + cpx + mt). Each of the minerals and the groundmass have a different coefficient of thermal expansion and, therefore, each mineral or groundmass particle tends to break from its surroundings during air quenching and slide transport. During 1993, the pyroclastic flow of fine material is inferred to have been produced by repeated impacts and breakages within the hot flow, and by micro-explosions that were caused by the sudden depressurization of the most gas-rich clasts.

After the pyroclastic flow, a lava flow issued from the newly created horseshoe-crater opening. The magma involved in both events was the same. The difference between the shapes of juvenile material in the pyroclastic flow (mainly bread-crusted bombs) and the blocky lava flow (sharply faceted blocks) is a result of the cooling history. This depends strictly on the emission rate of the products. Usually, lavas in Arenal are extruded at a rate of 0.3–0.5 $m^3 s^{-1}$. The lava was effused on 23 August at a rate that was some 20 times higher, ~10 $m^3 s^{-1}$. Taking 75% to be juvenile material, with a calculated volume of $2.2 \pm 0.8 \times 10^6$ $m^3$, and a maximum eruption time of 3 min, we calculated that the magma emission rate during the pyroclastic flow was $10^4$ $m^3 s^{-1}$, which was about $10^3$ times higher than that of the lava erupted after it.

## Comparison between other historical pyroclastic flow deposits at Arenal

We found several important similarities between the eruption in June 1975 and the August 1993 eruption, and similarities between these and the May 1998, August 2000, and March 2001 eruptions (Table 1).

After a brief period of quiescence (August to December 1974), Arenal became active in January 1975. High-frequency earthquakes were recorded between the end of January and February 1975. The number of low-frequency events increased, and volcanic tremor decreased before the volcanic crisis in June, 1975 (Matumoto and Umaña 1976, 1977; Barquero et al. 1992). During the eruptions on 17 and 21 June 1975, pyroclastic flows descended into Tabacón valley from the NW flank of Arenal at about 3.6 km from crater C, and abundant ash fell at Sangregado Dam (Matumoto and Umaña 1975, 1976; Van der Bilt et al. 1976). The 1975 pyroclastic flow deposits on the lower section of the Tabacón River are 8 to 10 m thick, and consist of angular blocks of up to 8 m, but are normally less than 1.5 m in diameter, and form a heterogeneous, poorly sorted matrix of very coarse- to fine-grained angular lapilli and ash. Cauliflower bombs, many of them showing bread-crust, surface joints with scoriaceous borders, and evidence of flattening and breaking by impact, are indicative of high-temperature emplacement. However, the temperature of the ash cloud associated with the pyroclastic flow was low (about 200 °C?), estimated from the fact that most of the vegetation was not charred.

Matumoto and Umaña (1976) interpreted the eruption as a lateral explosion, Malavassi (1979) interpreted it as the avalanche of a lava flow during its effusion from crater C, Bennett and Raccichini (1977) and Matumoto and Umaña (1977) interpreted it as crater (lava pool) collapse, and Bardintzeff (1985) suggested that a lava dome, which was liquid in its interior, poured magma out through cracks to form the avalanches. Ash fell on the western flank of Arenal and on Arenal Lake. Similarly, a rapid blocky lava flow descended the flank immediately after both events. The estimated volume of the 1975 pyroclastic flow deposit was $1–2\times10^6$ m$^3$, compared with $2.2\pm0.8\times10^6$ m$^3$ for the 1993 pyroclastic deposit.

The 1975 and 1993 events were preceded, about 3 to 4 months before, by earthquake swarms that lasted for about 2 weeks, followed by low-frequency volcanic quakes (B-type) and tremors. High-frequency earthquakes (A-type seismic swarms) at Arenal Volcano show systematic patterns associated only with the main explosive phases (i.e., 1968, 1975, 1984, 1987, 1993, 1999, and 2000), but, unfortunately, no high-quality seismic locations and focal mechanisms have been determined (Barquero et al. 1992; Alvarado and Arroyo 2000). Increases in seismicity frequently precede eruptions at volcanic centers, and are thought to be related to stress changes caused by movement of magma beneath the volcano edifice. Although speculative, the earthquake swarms from 1975 and 1993 could have represented a change in the volatile content ($P_{H2O}$) and/or magma effusion rate, producing an inflation of the volcano edifice and, therefore, this could have increased the instability of the cone. The seismic behavior of the volcano changed before, during, and after the eruption because of

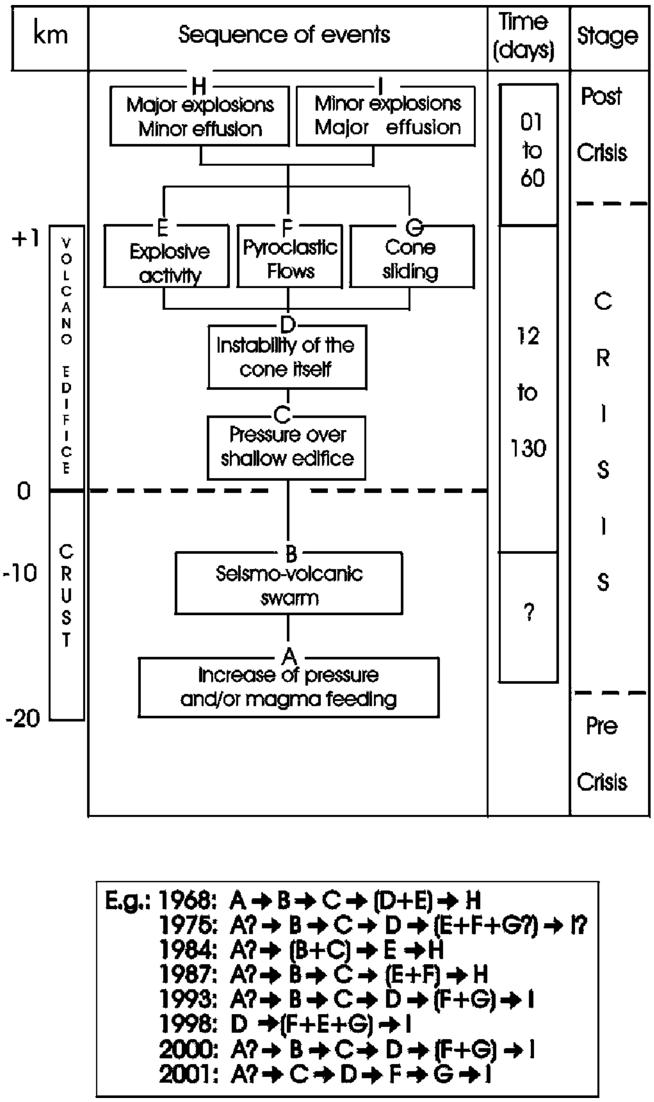


**Fig. 7** Flow-chart of correlation between volcanic events (main pyroclastic flows) and seismo-volcanic swarms in Arenal Volcano

changes from a relatively "closed" system (lava crust on the pool) to an open vent during the collapse, which allowed an almost continual lava effusion, with few explosions. This resulted in a period characterized mostly by tremor of different frequencies (see Alvarado et al. 1997a, 1998; Mora 1998). This sequence is illustrated in Fig. 7.

Recently, on 5 May 1998, 23 August 2000, and 24–26 March 2001, between 23 and 27 pyroclastic flow events (within each period) have occurred at Arenal. Photographs, videos, and direct observations by one of the authors (G.E.A.) support a flow origin for these events. Most of the coarse components of the deposits are faceted blocks, and between 5 and 50% are cauliflower bread-crusted bombs. No horseshoe-like crater was formed in 1998, but it was incipient in the 2000 and 2001 events. This suggests that most of the ejected material was produced from the crust or cap of the lava pool and a little from the NW and N parts of the cone. Premonitory high-frequency events were recorded only before the August 2000 and March 2001 events. The pyroclastic flows and the subsequent explosion, triggered by the smaller collapse of the upper part of the lava pool and crater, generated ash-cloud columns that were transported downwind. These events, which result from an increase in pressure and/or magma feeding, are not always the same. Under a state of stable crater walls, the explosive activity increases, and then Strombolian eruptions occur, which are larger than Arenal's average eruption. The lava effusion results in lower rates than average. This could be the case for other volcanic crises with premonitory seismic swarms, as in 1984 or 1987. Thus, seven ideal steps, which may overlap, repeat, or be omitted, characterize the generation of Arenal-type pyroclastic flows (Fig. 7).

## Volcanic hazard implications at Arenal

Because the timing of a crater-wall collapse or column collapse events cannot be reliably predicted, the best strategy for reducing risk to people and property is to minimize development within hazardous areas and to limit access to areas that could be swept away by a pyroclastic flow and its overriding ash-cloud surge. A large area of the most hazardous zone for pyroclastic flows is now a national park, or under a protective risk area, but, outside this area, there is a large development in tourism (hotels, cabins, swimming pools, camping areas, trails, etc.). For example, Tabacón Resort has been built on the 1968 and 1975 pyroclastic flow deposits, and the 1993 and 1998 pyroclastic flows stopped only 0.4 and 1.6 km, respectively, from this tourist center. Also, the 2000 and 2001 events stopped in a recreation area called Los Lagos camping lodge, killing two persons and severely injury one more. Pyroclastic flow events even smaller than those mentioned above (i.e., those that originate from either crater-wall collapse and outpouring of the lava pool, lava avalanches, or column collapse from a Strombolian eruption), are not rare at Arenal, with a frequency of every 3.6 events/year and a large event every 4.6 years (Alvarado and Arroyo 2000). With a velocity of about 17–33 m $s^{-1}$, a pyroclastic flow needs only 1.5–3 min to reach a tourist center.

## Other examples of this type of pyroclastic flow

The generation of pyroclastic flows from the sudden and rapid outpouring of a lava pool at Arenal is not rare. The 1993 flow is one that has been easily identified because of the resulting deposits and crater morphology. At least one pyroclastic flow associated with the 26 June 1877 Cotopaxi eruption (Ecuador) produced deposits similar to Arenal's pyroclastic flow (i.e., cauliflower bread-crusted bombs, reverse grading, a 2-m-high flow front), as was observed by one of the authors (G.E.A.). There is at least one flow recorded in the geological literature: the 1783 Agatsuma pyroclastic flow from Asama Volcano in Japan (Aramaki 1956, 1957). This flow, similar to Arenal's 1993 flow, rushed down the slope without producing explosions, and contained cauliflower bread-crusted bombs similar to those at Arenal. Other similar features are tree molds left by burned trees surrounded by deformed pyroclastic material, ridges, and levees. The Agatsuma pyroclastic flow was followed the next day by a more voluminous and disastrous pyroclastic flow, which, in turn, was followed by a rapidly emplaced blocky lava flow.

In both of these examples, the whole eruptions lasted only a few months, but Arenal has been continuously active for over 30 years. At Arenal, this type of pyroclastic flow has occurred at least five times since 1975. The juvenile material was basaltic andesite in both the Cotopaxi (Hall 1977) and Arenal eruptions, and andesite in the Asama eruption (Aramaki 1956, 1957). In addition, although there are no reports of the existence of a lava pool at the time of the Asama (Aramaki 1956, 1957) or Cotopaxi (Hall 1977) eruptions, in order to document the occurrence of this type of pyroclastic flow it is necessary to re-evaluate the original documents from eyewitnesses.

The deposits appear to have sedimentological and morphological analogies to the "pyroclastic avalanches" from the 1975 explosive eruptions at Ngauruhoe Volcano, New Zealand (Nairn and Self 1978), and "hot-rock avalanches" that have occurred during the growth of the composite dome of Mount St. Helens between 1980 and 1987 (Mellors et al. 1988), but their clast components are quite different. However, the 1998, 2000, and 2001 flow deposits at Arenal are transitional between those in highly vesiculated, cauliflower bread-crusted bombs (i.e., 1975 and 1993 events) and typical block-and-ash flow deposits (e.g., Cas and Wright 1987).

## Conclusions

The distribution and nature of fragmental components, together with eyewitness accounts of the recent pyroclastic flows from Arenal Volcano, suggest the following sequence of events: (1) initial instability and subsequent collapse of part of the summit crater wall; (2) discharge of the lava pool from the horseshoe-shaped crater, generating a pyroclastic flow; (3) ash elutriated from the pyroclastic flow, which was blown by the prevailing winds, and fell on the western side of the volcano as accretionary lapilli and in Arenal Lake as very fine ash; and (4) the rapid lava flow.

The unusual pyroclastic flows at Arenal from 1975 and 1993 were not a result of explosions, but from gravity-collapse of the crater wall and draining of the lava pool. They began as cold-rock avalanches that evolved into pyroclastic flows with a mobile, turbulent ash cloud. The resulting juvenile clast (cauliflower bread-crusted bombs) is rarely found elsewhere in other pyroclastic flow deposits. This mechanism of formation of pyroclastic flows by the draining of a lava pool must be included in the range of processes that can form this type of deposit (Arenal-type). Textural features indicate that rolling and saltation, with a strong interaction between particles, was an important mechanism during flow. High particle concentration of the pyroclastic flow is analogous to deposition from non-eruptive rock avalanches. Thus, even though vesiculation occurred during and after the movement of the pyroclastic flows, the mobility of the flow was largely caused by gravity. The 1975, 1993, 1998, 2000, and 2001 Arenal pyroclastic flow deposits have a typical bimodal grain-size distribution. The temperature distribution of clasts also showed two populations: ~100–400 °C in the matrix, and ~1,000 °C in the large juvenile pieces.

The 1993 volcanic event at Arenal is very useful in understanding the 1975 pyroclastic flow deposit. Some pyroclastic flows associated with the 1783 Asama (Japan) and 1877 Cotopaxi (Ecuador) eruptions are very similar to the 1975 and 1993 deposits at Arenal. To generate an Arenal-type pyroclastic flow, it is not only necessary to have the collapse of the crater wall and the drainage of a lava pool, but it is also necessary to have a relatively medium- to high-viscosity lava (basaltic andesite to andesite). If the viscosity of the lava is too low, the drainage of the lava lake or lava pool would generate a lava flow or lava fall, instead of a true pyroclastic flow, as happened during the 10 January 1977 eruption of the Nyiragongo Volcano (Zaire), when over $20\times10^6$ $m^3$ of low-viscosity lava drained from the lava lake in the summit crater through fractures on the flanks of the volcano, and flooded the surrounding countryside to destroy some 400 houses and kill about 300 people (Tazieff 1977, 1994). A comparison of all those events is important to understand future occurrences of this type, and must be considered in volcanic hazard assessments.

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