# Volume, Energy and Cyclicity of Eruptions of Arenal Volcano, Costa Rica

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## Abstract

The 1968-73 (and continuing) eruption of Arenal Volcano, Costa Rica, a small 1633 m strato-volcano with long periods of repose, defines an eruptive cycle which is typical of Arenal's pre-historic eruptions. An intense, short explosive phase (July 29-31, 1968) grades into an effusive phase, and is followed by a block lava flow. The eruptive rocks become increasingly less differentiated with time in a given cycle, ranging from andesite to basaltic andesite. Nuées ardentes are a characteristic of the initial explosions, and are caused by fall-back ejecta on slopes around the main crater — an explosion crater in the 1968 eruption — which coalesce into hot avalanches and descend major drainage channels. Total volume of pyroclastic flows was small, about $1.8 \pm 0.5 \times 10^6$ $m^3$, in the July 29-31 explosions, and are block and ash flows, with much accidental material. Overpressures, ranging up to perhaps 5 kilobars just prior to major explosions, were estimated from velocities of large ejected blocks, which had velocities of up to 600 m/sec.

Total kinetic energy and volume of ejecta of all explosions are an estimated $3 \times 10^{22}$ ergs and 0.03 $km^3$, respectively. The block lava flow, emitted from Sept., 1968 to 1973 (and continuing) has a volume greater than 0.06 $km^3$, and covers 2.7 $km^2$ at thicknesses ranging from 15 to over 100 m. The total volumes of the explosive and effusive phases for the 1968-73 eruption are about 0.05 $km^3$ and 0.06 $km^3$, respectively.

The last eruption of Arenal occurred about 1500 AD. based on radiocarbon dating and archaeological means, and was about twice as voluminous as the current one (0.17 $km^3$ versus 0.09 $km^3$). The total thermal energies for this pre-historic eruption and the current one are $8 \times 10^{23}$ and $18 \times 10^{23}$, respectively. The total volume of Arenal's cone is about 6 $km^3$ from 1633 m (summit) to 500 m, and, estimates of age based on the average rate of cone growth from these two eruptions, suggest an age between 20,000 to 200,000 years.

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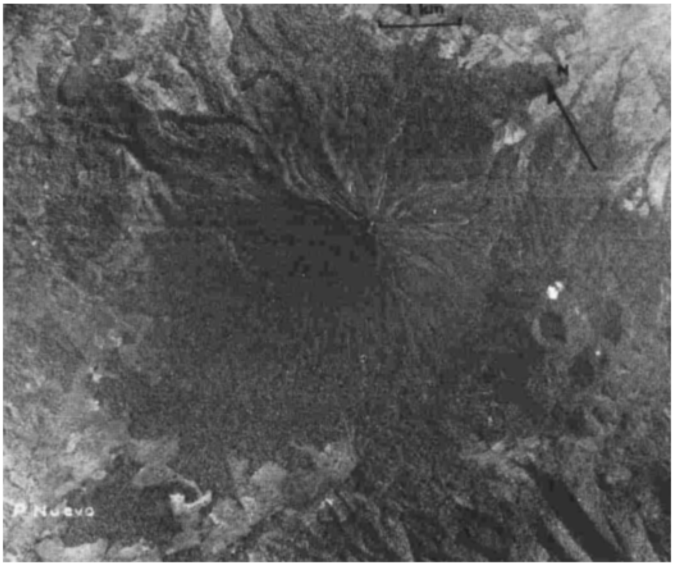

FIG. 1 - Pre-eruption vertical aerial photograph, Arenal Volcano, March 16, 1961.

FIG. 2 - Arenal Volcano, summit at about 1633 m, viewed from ruins of Tabacon, August 13, 1968. New explosion craters opened at A (largest, and source of most pyroclastic flows, impact ejecta, and air fall ash), B, and C. Summit crater (D) was in fumarolic activity only.

## Introduction

Arenal Volcano, Costa Rica, began its first historic eruption with a violent explosion on July 29, 1968. Periodic intense explosions continued until July 31, 1968. During this initial phase, approximately 80 people were killed and 12 square kilometers were devastated by hot avalanches and ejected blocks. The eruption quickly passed into quiet effusive activity with the emission of a thick andesitic flow on Sept. 19, 1968, which continues to advance at the present time (July, 1973).

Arenal Volcano had not been studied relative to the current eruption. Publications deal with its initial explosive phases (MELSON and SAENZ, 1968), the chronology of events prior to and during the explosive phases (SIMKIN, 1968), and the significance of the ejecta velocity on magma chamber pressure (FUDALI and MELSON, 1972). There is also a brief unpublished account of the early phases (WALDRON, 1968). Matumoto studied the seismology of the eruption but its results have not been published. STOIBER and ROSE (1970) have analyzed condensates from the fumaroles on the rim of the new explosion crater on March 29, 1969 and compared it with other Central American condensates (TAYLOR and STOIBER, 1973). CHAVEZ and SAENZ (1970) and MINAKAMI *et al.* (1969) have also discussed the current eruption.

## Arenal Volcano

Arenal Volcano (10° 27.8′ N, 84° 42.3′ W) is a nearly perfectly symmetrical, small, stratovolcano which rises to 1633 m in central Costa Rica (Fig. 1 - 3). The volume of Arenal above the 500 m contour is about 6 km$^3$. Cerro Chato, a truncated, probably extinct, volcano is about three kilometers south, and contains a small, lake-filled caldera, Laguna Cerro Chato (Fig. 1). The increasing age of these two volcanoes toward the west, and the opening of the current new craters and some pre-historic craters on Arenal's west side, show migration of vents to the west and northwest through time. Arenal is about midway between the active groups of Costa Rican volcanoes, and, prior to its current eruption, was not listed among the active volcanoes of the world. Like Mt. Lamington, New Guinea (TAYLOR, 1958) Arenal Volcano emphasizes the difficulty of distinguishing active volcanoes with long periods of repose from truly extinct ones.

Arenal is one of seven active and one of numerous presumably extinct Quaternary and Pliocene volcanoes of the northwest-trending continental divide of Costa Rica. It is about midway between a northwestern group — the Guanacaste Cordillera — and a south-

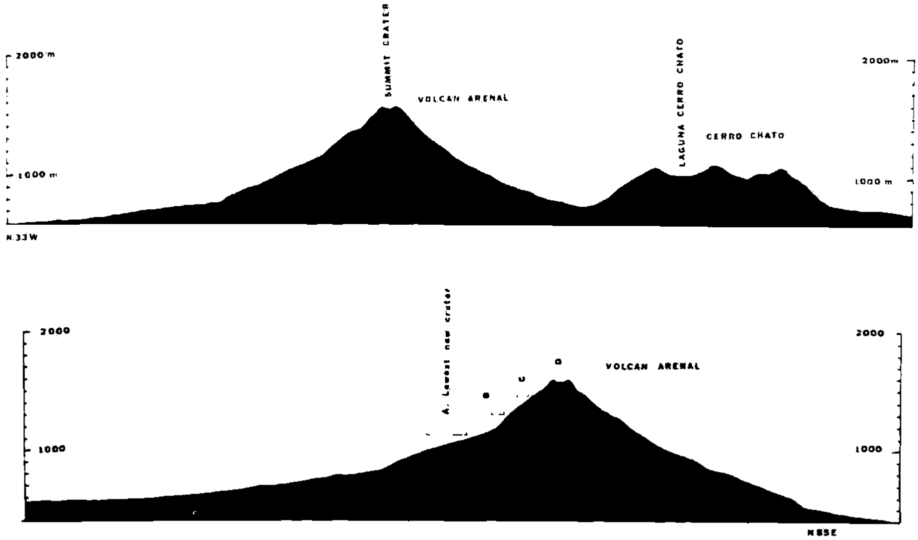

FIG. 3 - Topographic sections through Arenal and Cerro Chato (vertical equal horizontal scale). Top. N33W Section, including Cerro Chato. Bottom: location new craters; N85E section.

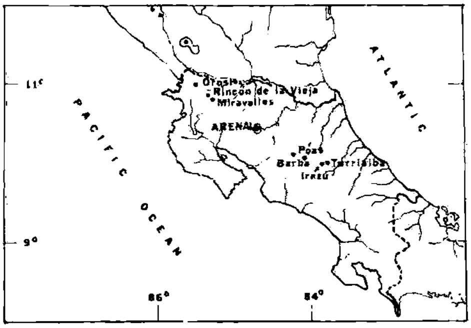

FIG. 4 - Location of Arenal Volcano.

eastern group, which is part of the Cordillera Central (Fig. 4). Arenal is one of the smaller but more perfect volcanic cones of the active volcanoes of Costa Rica. Most others are higher, larger, and have irregular forms which have been deeply incised by erosion. Their elevations range from 1487 m at Orosí to 3433 m at Irazú.

The ongoing block flow at Arenal is the first lava flow in Costa Rica's history. All other historic eruptions of Costa Rican volcanoes have yielded tephra only.

## 1968 Eruption

The eruption can be divided into six phases, with mainly gradational boundaries (Table 1). Maximum human fatalities and property damage occurred during the first explosive phase. After 10 hours of intense seismic activity, the first of a series of large explosions began at 7:30 A. M. on July 29, 1968. Most fatalities occurred in this, and the shortly following explosions. The last fatalities occurred around 1:10 P. M. on July 31, 1968, when the last major explosion

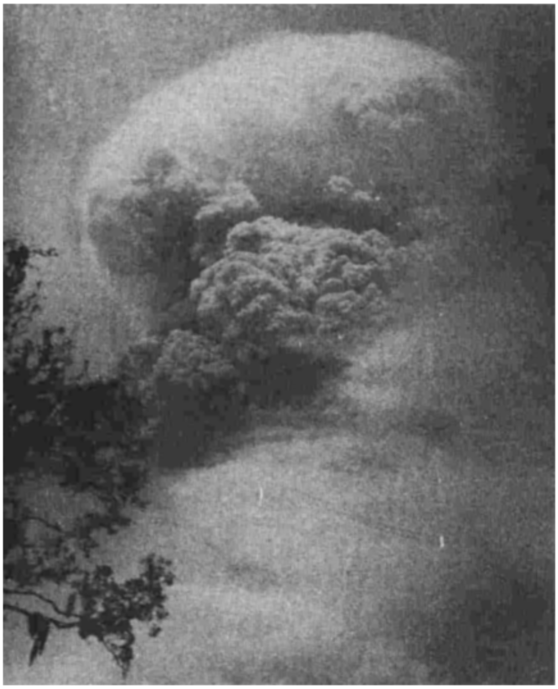

FIG. 5 - Explosion cloud, probably of around 1300 hrs., July 31, 1968, viewed from town by Arenal. Courtesy La Nacion newspaper.

occurred (Fig. 5). Figure 6 outlines the three major zones of devastation which formed, and Table 1 lists the characteristics of each. At least three new explosion craters formed during the initial three days of explosions. All are aligned along a roughly east-west zone (Fig. 6). Eyewitness accounts indicate that all three probably opened simultaneously during the first major explosion of 0730 hr., July 29, 1968.

TABLE 1 - Features of the Major Eruptive Phase of Arenal Volcano

| *Phase* | *Times* | *Features* |
|---|---|---|
| I | 0730 hr., July 29 - 1310 hr., July 31, 1968 | *Explosive phase* Three new craters were formed along an approximately east-west line on the west side of Arenal. The largest of these, and the one from which the major explosions originated, is an explosion crater located at an elevation of around 1100 meters. All fatalities occurred during this phase, and major features of devastated region formed during this phase, including formation of widespread impact craters and of blocky ash flows. |
| II | 1310 hr., July 31 - 1600 hr. (?), August 3, 1968 | *Quiet phase.* Minor ash and fumarolic activity. |
| III | 0600 (?) August 3 - to around August 10 | *Considerable ash and vapor emission.* Gradational with preceding and following phases. Strong ash emission from uppermost new crater; lower explosion crater had fumarolic activity only. |
| IV | August 10 to September 14 | *Fumarolic phase.* Fumarolic activity from lower and upper new craters. Most intensive activity from upper crater. Old summit crater appears to have had fumarolic activity throughout this and preceding phases. |
| V | September 14 to September 19 | *Renewed explosions.* Small, low energy, low volume ejection of scoriaceous to pumiceous andesite. First time that ejecta were mainly essential. |
| VI | September 19, 1968, to 1973 (continuing) | *Emission of thick dock flow.* Emitted from lower crater and slowly descending valley of Quebrada Tabacon. Approximately 1000 meters long and 25 meters thick, as of October 17. Rate of advance at that time estimated between 10 and 30 meters per day. Estimated volume as of September 11, 1971, is 0.06 $km^3$. |

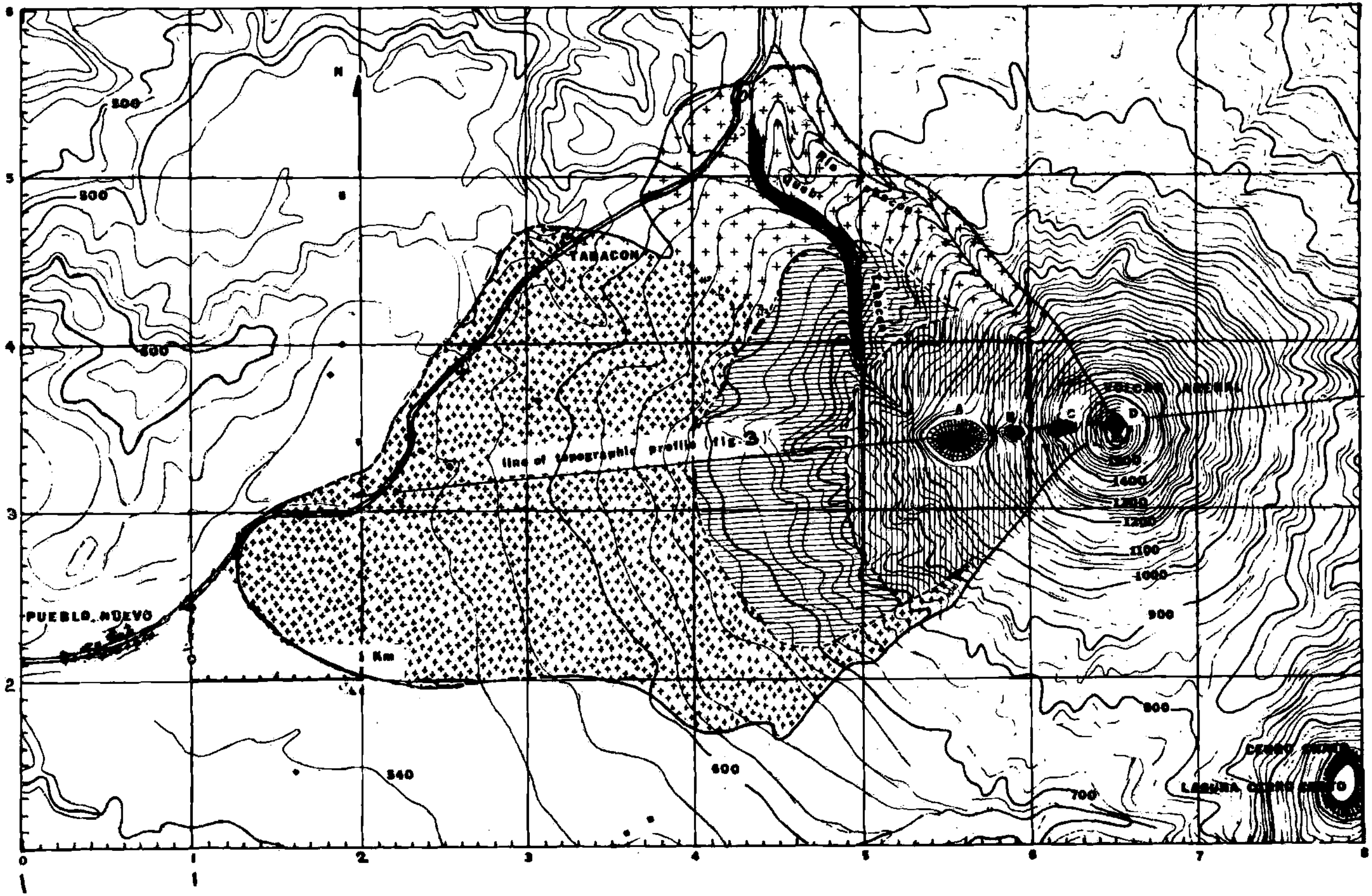

FIG. 6 - Sketch-map of the zones of devastation produced in the July 29-31, 1968 explosions.

*Zone A*: Crosses; dense crosses delimit region affected by the explosions of July 29 and 30; widely spaced crosses show zone created by final explosion, 1300 hrs., July 31.

*Zone B*: Horizontal ruling.

*Zone* C: Vertical ruling. Locations and dimensions of three new craters are approximate.

On September 14, 1968, renewed but much smaller explosions occurred in the lower crater. Ejecta this time were essential, scoriaceous bombs. These explosions produced only a small amount of ejecta, and, on September 19, 1968, the lower crater began to be filled by viscous lava, which eventually spilled over the west, or outer rim. This flow, a thick block flow (Fig. 7) first advanced down Quebrata Tabacon, but has since sent tongues far to the southwest, and other tongues now have over-ridden earlier ones. All these lava tongues originate from a vent at the end of a well-developed notch eroded through the lava which initially filled the lower crater. The lava descend a strikingly developed chute (Fig. 8) before branching into the individual lobes. The lava flow has completely filled the valley of Quebrata Tabacon, and buried all of zones A and B on the north side of the devastated zone.

FIG. 7 - Block lava flow of the 1968-71, photographed on Sept. 9, 1971, issuing from lower explosion crater. Courtesy Costa Rican Instituto Geografico.

TABLE 2 - Features of the Three Zones of Devastation (Figure 6).

*Zone A.* (Outermost zone affected by the explosions).

Numerous impact craters, ranging up to 60 m in diameter, and reaching a maximum distance of about 5 km from lower crater. Large craters are devoid of large fragments; projectiles disintegrated on impact. Projectiles largely intact in crater less than 2 m in diameter. Crater density reaches 100 % near Tabacon. Crater density decreases away from the lower crater. Zone covered by thin layer of fine to coarse tephra. Seared or withered vegetation, and uprooted trees common. Trees left standing are defoliated and bark is eroded on volcano side, and may contain embedded ejecta. The northern outer limit of Zone A changes abruptly to completely unaffected vegetation over a distance of a few meters. Air temperatures reached from 100 to 400°C moving inward in Zone A based on effects on vegetation. Most human fatalities occurred in Zone A.

*Zone B.* (Intermediate Zone).

Differs from Zone A in that it contains few craters, vegetation has been completely destroyed and removed, and contains blocky ash flows in pre-existing drainage channels. Zone littered by large isolated blocks, most of which were in excess of 300°C when deposited. One of the largest blocky ash flows filled the valley of Rio Tabacon, and has a probable volume of around $1.8 \times 10^6$ $m^3$. ' Flows ' contain considerable charred wood and whole tree trunks. Fumaroles continued for over two years in the block ash flows; flows range to over 30 m thick, but typically are around 10 m thick. No welding was observed, but internal temperatures were probably in excess of 400° C. 200° C was measured at but a few centimeters within one flow seven days after it was emplaced. Flows consist predominantly of angular, probably hot, accidental blocks with but a small component of rounded scoriaceous, probably essential ejecta. Contact between Zone A and B is gradational. Larger blocky ash flows (such as Rio Tabacon flow) extend into Zone A.

*Zone C.* (Innermost, Explosion Crater Zone).

Barren, stripped of all vegetation; mainly steep slopes on which the three new craters opened. Source region (fall back zone) of blocky ash flows of Zone B. Thick tephra deposits, and numerous fumaroles within and on rims of explosion craters. Largest, lowermost crater has volume about $7 \pm 2 \times 10^6$ $m^3$, steep inner walls, with rim about 60 m higher on volcano side than on outer lips; small crater lake formed within 7 days after last explosion; crater opened mainly through a series of prehistoric flows; crater rimmed in places by large ejected angular blocks, up to 50 m in diameter. Contacts between Zone C and B gradational.

## Nueés Ardentes

Nuées ardentes were an important part of the explosive phase of Arenal and caused many fatalities. Observations of nuées ardentes and their effects at Mayon Volcano, Philippines (1968; MOORE and MELSON, 1969), Ulawun Volcano, New Britain (1970; MELSON, 1972) and at Arenal (MELSON and SAENZ, 1968) show the dominant role of gravity in accounting for their high mobility. In all three cases, fall-back of explosively ejected materials created hot avalanches which coalesced and descended major drainage channels reaching about 3 km from the lower crater before coming to rest (Fig. 9). Composition and gas emission from the avalanching tephra, which range from basalt (Ulawun) to basaltic andesite (Mayon and Arenal), appear to play only minor roles in accounting for the high mobility of these small avalanches. The nuées ardentes — used here to designate the hot avalanche and its envelope of fine tephra and hot gases — leveled tress at their margins at the three volcanoes and produced other

FIG. 8 - Block flow issuing over rim of lower explosion crater. November, 1971.

effects which may be viewed as a result of « directed blast », where ash and gas velocities are attributed to accelerations imparted at the vent. Gravity flow alone, though, accounts for the accelerations of the avalanches of these three eruptions. The hot avalanches are analogous in some of their properties, especially their high mobility, to major landslides and snow avalanches, where entrapped air, in only partly permeable, poorly sorted debris, tends to provide « air-layer lubrication » and hence high mobility (SHREVE, 1968). MCTAGGART (1960) noted that in experiments heated sand traveled further from an incline than did sand at room temperature, indicating that thermal expansion of entrapped air may contribute to the increased mobility of hot avalanches.

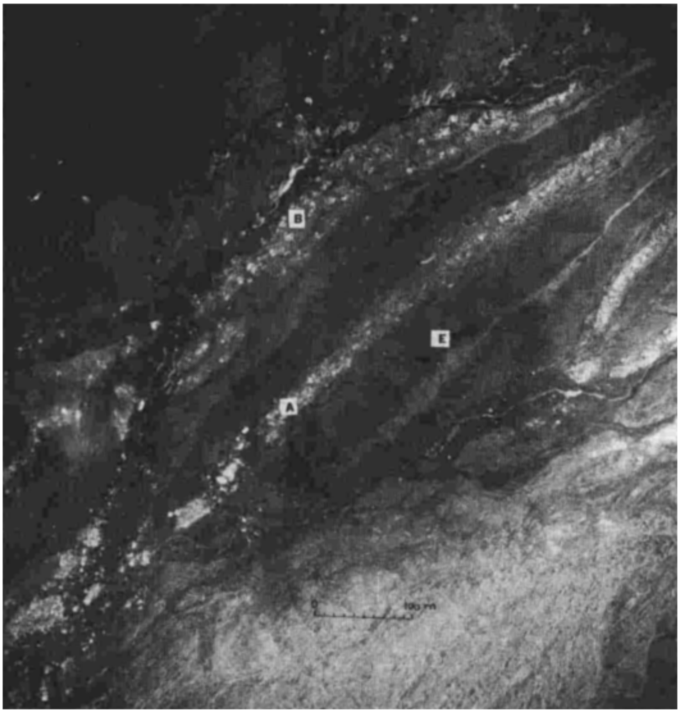

FIG. 9 - Block and ash flows filling small canyons 0.2 to about 3 km southwest of lower explosion crater. Note blown down trees of Zone A along southern portion of photograph. Blocky ash flow A is about 600 m long and from 20 to 40 m wide. Flow B is around 500 m long and up to 60 m wide. White areas are dry, still hot tephra and large blocks. E (east) is orientation marking. Photo taken in Sept. 1968. Courtesy Costa Rican Instituto Geografico.

## Magma Chamber Pressure Just Prior to Explosions

The impact crater field produced by ejected roof rocks from the lower explosion crater covered over 5 square kilometers, and is one of the most remarkable features of the explosions (Fig. 10). Large blocks reached up to 5 kilometers from the lower crater, and some areas were 100 percent cratered, as near Tabacon (MELSON and SAENZ, 1968). This maximum distance of five kilometers from the crater, considering effects of atmospheric drag on ejected blocks, was used to calculate ejection velocities of up to 600 m/sec (FEUDALI and MELSON, 1972). From this velocity, Bernoulli's equation was used to calculate an overpressure of 4700 bars in the magma chamber just prior to ejection of such blocks.

FIG. 10 - Large impact crater near Tabacon. A frew angular fragments of the ejected block are all that remain in the crater. Crater is about 3 km southwest of the lower explosion crater.

The expression of Bernoulli's equation, $P = ½ (d) V^2$, where $P$ = overpressure, $d$ = gas density, and $V$ = ejection velocity, has traditionally been used to calculate magma chamber overpressures (MINAKAMI, 1960; GORSHKOV, 1959; RICHARDS, 1965), although incorrectly, because rock density has been substituted for fluid flow in a tube under rather ideal conditions, its applicability to such cases would seem inappropriate. However, since it can be derived quite apart from any relation to fluid flow, use of rock density is appropriate, and the equation is applicable to a first approximation in calculating overpressure in magma chambers. The acceleration, $a$, required to give a velocity, $V$, over a distance equal to a column of rock or length, $L$, over a distance equal to $L$ is given by:

$$a = \frac{V^2}{2\,L}$$

The force, $F$, required to give this acceleration to mass, $m$, is

$$F = ma = \frac{m\,V^2}{2\,L}$$

where $m = (d)\ LA$, where $d$ is density, and $A$ is the cross sectional area of the column. Substituting $m = (d)\ LA$ gives

$$F = \tfrac{1}{2}\,(d)\,AV^2$$

Since pressure $P$, equals $F/A$,

$$P = \tfrac{1}{2}\,(d)\,V^2$$

To be perfectly correct, the acceleration due to gravity should be added to the calculated acceleration, increasing the calculated overpressures. However, the acceleration due to gravity is insignificantly small compared to the calculated accelerations. At Arenal, the above equation gives an overpressure of about 1200 bars for the mean ejection (300 m/sec). For the high ejection velocity, 600 m/sec, an overpressure of about 4900 bars is indicated, assuming a density of 2.7 gm/cm$^3$ in both cases. Some of the force of the expanding gas would be consumed in work required to fracture the roof rocks and in impelling them against one another. In other words, the expanding gas would do considerable work not involved in giving the ejection velocity. The above equation assumes all the force is efficiently used in ejecting the blocks, and thus the real overpressures would be larger by an unknown amount than those given by this equation.

Also, the expansion of the gases as the roof rocks fail, and move upward, will cause a decrease in pressure. The calculated overpressure is therefore somewhat of a mean value, which is exceeded at initial time of failure, and reaches a minimum as the block leaves the crater.

## Total Volume

Most material from 1968-73 has been erupted during the current quiet effusive phase (Table 3). Estimated flow volume as of September, 1971, is about $0.06 \pm .02$ km$^3$. The surface area, at that time, was about $2.74$ km$^2$. The large uncertainty in the volume results from the highly variable and poorly known flow thickness, ranging from 10 to probably in excess of 150 m where it has filled Quebrata Tabacon. The average rate of emission is about $8.3 + 2.5 \times 10^4$ m$^3$ per day from September 19, 1968 to Sept. 11, 1970. The emission rate of the block flow does not appear to be constant. The rate of advance, and flow front thickness range greatly. New additions to the flow front ranged from 4,000 to 100,000 m$^3$/day averaged weekly for the period

TABLE 3 - Volume of Eruptive Rocks, 1968-70, Arenal Volcano, Costa Rica.

| *Material* | | |
|---|---|---|
| *Explosive phase* | *Dates* | *Volume (km$^3$, including pore space)* |
| 1. Airfall apron from 4 to 20 km west. | July 29-Aug. 10, 1968 | $0.04 \pm .02$ |
| 2. Airfall apron from 0 to 4 km west. | July 29-Aug. 10, 1968 | $0.003 \pm .001$ |
| 3. Airfall apron, greater than 20 km west. | July 29-Aug. 10, 1968 | ? |
| 4. Blocky ash flows. | July 29-July 31, 1968 | $0.0018 \pm .0005$ |
| *Quiet Effusive Phase* | | |
| 5. Lava flow. | Sept. 19, 1973 (no flow movement Oct., 1973) | $0.06 \pm .02$ |
| Total volume (including pore space) | July 29, 1968-Sept. 11, 1970 | $0.11 \pm .03$ |
| Total volume (excluding estimated pore space; 3 % for lava flow; 30 % for tephra) | July 29, 1968-Sept. 11, 1970 | $0.09 \pm .03$ |

July 7 to Sept. 11, 1970. Flow thickness appears to correlate inversely with rate of flow movement. With slow emission rates. the flow cools considerably as it moves downslope, greatly increasing in viscosity and hence greatly thickening. Under such conditions, the flow front may exceed 40 meters. Such a great thickness was observed in November, 1968, during the waning of the first major pulse of lava emission. During times of rapid advance, the flow front is typically 10 to 15 m high.

About $0.03 \pm .02$ km$^3$ of tephra (corrected for pore space) was emitted in about 3 days (July 29-July 31, 1968) during the explosive phase. This gives an average rate of $1 \times 10^7$ m$^3$ per day, or nearly $10^3$ times the average rate of emission of the lava flow. The rate during an individual explosion is probably still greater by three to four orders of magnitude. The combined volume of all the new explosion craters, estimated at an upper limit of $7 \pm 2 \times 10^6$ m$^3$ is considerably less than the $3 \times 10^7$ m$^3$ ejected during this phase. Evidently about $25 \times 10^6$ m$^3$ rapidly rose up in the conduit beneath the craters during or immediately after the explosions. Any void left must have been immediately infilled by collapse of the conduit walls. Since this collapse could be no more than about 20 percent of the total volume of ejecta, a rapid rise of magma must have occurred simultaneously with, and probably caused, the explosions.

In the grossly oversimplified assumption of a 350 meter cylindrical conduit beneath the lower crater, the volume of erupted material extended approximately 300 meters below the original surface, and was replaced by the rising magma column. For the total volume of eruptives, such a column would extend to a depth of 1 km.

## Energy

The approximate equations of HEDERVARI (1963) relating volumes of essential eruptive rocks to thermal enery released on cooling can be used to calculate the approximate energies of Arenal's last two eruptions. The probable energy of the July 29-July 31 explosions was estimated as $2.4 \pm 1.2 \times 10^{21}$ ergs, based on the estimated volume of the lower explosion crater, and mean ejection velocities inferred from impact crater distributions (FUDALI and MELSON, 1972). New measurements show that the lower crater is larger ($7 \pm 2 \times 10^6$ m$^3$) than these early estimates ($2 \pm 1 \times 10^6$ m$^3$). Also, new measurements of the probable volume of explosively ejected materials give volumes of 2.4 ± 1.6 × $10^7$ $m^3$.

Assuming the same mean ejection velocities (300 m/sec), the total kinetic energy is 2.8 × $10^{22}$ ergs which is about ten times greater than the early estimate of 2.4 × $10^{21}$ ergs. This kinetic energy is about 10 % of the total thermal energy available from the volume of explosive ejecta, assuming all ejecta was essential. If all energy were supplied by heating phreatic water prior to the explosions, magma temperature drops on the order of 100° C, perhaps from 1100° C to 1000° C, assuming optimal exchange of magmatic heat to ground water prior to the explosion, would provide adequate kinetic energy for the explosions.

The total thermal energy released from the 1968-73 and Ca. 1500 A. D. eruptions is about 7.8 ± 4 × $10^{23}$ and 1.8 ± 1 × $10^{24}$ ergs, respectively, based on the volume of ejecta, and assuming most ejecta are essential.

The thermal energy involved in the formation of the rocks of the total cone of Arenal, from 1633 to 500 m, is about 6.6 ± × $10^{25}$ ergs. The total eruptives, most of which were deposited downwind from the volcano, would possibly increase this energy estimate by more than an order of magnitude, perhaps to about $10^{27}$ ergs.

These calculations show that the energy of Arenal's eruptions are small compared to a number of historic eruptions, given below (energy in ergs/$10^{23}$).

| | | |
|---|---|---|
| Santorini | ca. 1400 B.C. | 45,000 |
| Tambora | 1815 | 8,400 |
| Kilauea | 1952 | 18 |
| Arenal | 1968-70 | 8 |
| Arenal | ca. 1500 | 18 |
| Arenal | Total cone and Surrounding tephra | 700 |

The estimated energy from the formation of the total cone and surrounding tephra is less by 10 than the single 1815 eruption of Tambora, and less by nearly two orders of magnitude than Santorini's ca. 1400 B.C. eruption. On the other hand, the energy of Arenal's 1968-70 eruptions (not allowing for energy increments from the new lava of 1970-73) is larger than the number of recent explosive eruptions, including Mayon (1968, 4 × $10^{22}$ ergs) and Ulawun (1970, 6.3 × $10^{22}$ ergs).

## Eruption Cycles

The current eruption consists in simplest terms of three successive events: (1) large explosions separated by periods of quiet, (2) continuous tephra emission, and (3) a lava flow. Studies of the tephra deposits faithfully record these first two phases. Typically, a layer of coarse tephra grades sharply into a zone of fine tephra. Individual grades beds are recognizable within the coarse tephra zones. The ratio of fine to coarse tephra ranges from about 0.10 at the margin of the ash apron to 0.50 in the middle. Excavations reveal at least three pre-historic eruptions with the same cyclicity, but all of greater total thickness than the tephra from the 1968 eruption. Typically, paleosoils are poorly to well-developed in the uppermost fine tephra units, probably reflecting long periods of repose between major eruptions.

The last pre-historic major eruption followed a similar cycle, but the volumes of each phase differ from those of the current eruption. It has been possible to date this last eruption by radiocarbon and archaeological means. A mapor pre-historic lava flow is underlain by a blocky ash flow near the road crossing of Quebrata Tabacon. Two wood samples from carbonized tree trunks buried by this flow have been dated by R. Struckenrath of the Smithsonian's Radiocarbon Laboratory, giving analytically indistinguishable ages A. D. 1525 ± 20. The dated bark and wood are of *Pitnecellobium racemiflorium* (identified by B. F. Kukachka, U. S. Department of Agriculture). The low density of the wood, revealed by thin-walls of the wood fibers, suggests, fast growth and hence minimal post-sample growth errors. Indian ceramic objects were excavated from airfall ash from this eruption by Mr. George Metcalf, Smithsonian archaeologist. Mr. Metcalf and Dr.Clifford Evans infer a cultural age of between 1200 and 1400 A. D. for the excavated ceramics, an interval earlier than the radiocarbon dates.

A measured excavated section at 84° 46.00′ W, 10° 27.10′ N, about 7 km south-southwest of Arenal's summit, shows a particularly well-developed sequence of the 1968 and ca. 1500 A. D. eruptions. The 1968 eruption deposits are an upper 12 cm of fine, and lower 25 cm of coarse tephra. Beneath these, there are 100 cm of fine, and 75 cm of coarse tephra, including a 10 cm diameter pumiceous bomb (chemical analysis 6, Table 4). Assuming comparable wind directions and inten-

TABLE 4 - Chemical Composition of Eruptives of Arenal Volcano, Costa Rica. 1-4: andesite of 1968-1970 eruptions; 5-9: pre-historic eruptive rocks (see below). Analyses by E. Jarosewich, Smithsonian Institution by classical methods.

| | *1* | *2* | *3* | *4* | *5* | *6* | *7* | *8* | *9* |
|---|---|---|---|---|---|---|---|---|---|
| $SiO_2$ | 56.31 | 55.95 | 54.02 | 54.43 | 53.61 | 54.85 | 59.27 | 55.97 | 51.52 |
| $Al_2O_3$ | 20.38 | 20.24 | 20.08 | 19.36 | 19.91 | 21.07 | 18.49 | 20.80 | 20.15 |
| $Fe_2O_3$ | 2.66 | 3.81 | 4.38 | 3.00 | 3.95 | 1.87 | 3.02 | 2.36 | 2.89 |
| FeO | 3.96 | 3.06 | 3.31 | 4.72 | 4.17 | 4.73 | 3.76 | 4.25 | 5.69 |
| MgO | 2.91 | 3.10 | 4.25 | 4.82 | 4.42 | 2.93 | 2.53 | 2.85 | 4.98 |
| CaO | 9.09 | 9.09 | 9.64 | 9.28 | 9.39 | 9.37 | 7.21 | 8.87 | 10.30 |
| $Na_2O$ | 3.42 | 3.35 | 3.06 | 3.02 | 2.98 | 3.37 | 3.61 | 3.36 | 2.51 |
| $K_2O$ | 0.66 | 0.66 | 0.60 | 0.52 | 0.56 | 0.65 | 0.71 | 0.67 | 0.29 |
| $H_2$ | 0.00 | 0.00 | 0.00 | <0.10 | 0.17 | 0.00 | 0.58 | <0.10 | 0.45 |
| $H_2O$ | 0.03 | 0.05 | 0.05 | 0.06 | 0.05 | 0.06 | 0.09 | 0.00 | 0.09 |
| $TiO_2$ | 0.54 | 0.56 | 0.61 | 0.72 | 0.47 | 0.54 | 0.39 | 0.45 | 0.75 |
| $P_2O_5$ | 0.16 | 0.17 | 0.12 | 0.14 | 0.15 | 0.14 | 0.17 | 0.16 | 0.14 |
| MnO | 0.14 | 0.14 | 0.20 | 0.16 | 0.16 | 0.12 | 0.20 | 0.14 | 0.12 |
| | 100.26 | 100.18 | 100.32 | 100.23 | 99.99 | 99.70 | 100.03 | 99.88 | 99.88 |
| | | | | CIPW NORMS | | | | | |
| Q | 9.74 | 10.73 | 8.11 | 7.38 | 7.42 | 6.87 | 15.47 | 9.09 | 3.99 |
| OR | 3.90 | 3.90 | 3.55 | 3.07 | 3.31 | 3.84 | 4.20 | 3.96 | 1.71 |
| AB | 28.94 | 28.35 | 25.89 | 25.56 | 25.22 | 28.52 | 30.55 | 28.43 | 21.24 |
| AN | 38.31 | 38.24 | 39.28 | 37.74 | 39.30 | 40.45 | 32.15 | 39.70 | 47.94 |
| DI | 4.68 | 4.57 | 6.14 | 5.96 | 5.06 | 4.22 | 2.05 | 3.53 | 1.83 |
| HY | 9.41 | 7.36 | 9.51 | 54.42 | 12.49 | 11.69 | 9.44 | 10.74 | 18.56 |
| MT | 3.86 | 5.52 | 6.35 | 4.35 | 5.73 | 2.71 | 4.38 | 3.42 | 4.19 |
| IL | 1.03 | 1.06 | 1.16 | 1.37 | 0.89 | 1.03 | 0.74 | 0.85 | 1.42 |
| AP | 0.37 | 0.39 | 0.28 | 0.32 | 0.37 | 0.32 | 0.39 | 0.37 | 0.32 |

1. Pumiceous andesite bomb. Ejected during second explosive phase, September, 1968.
2. Andesite. From advancing flow front of November 11, 1968.
3. Andesite. From advancing flow front of June 17, 1970.
4. Andesite. From within active crater. Collected Ang. 1973, by Ivan Jirak.
5. Pre-historic major andesite flow which parallels Rio Tabacon. Sampled at La Fortuna - Pueblo Nuevo road.
6. Pre-historic andesite flow, southewest side of Arenal Volcano. 84°43.2′W., 10°27.6′N., USNM 111378.
7. Pre-historic pumiceous hornblende andesite bomb. USNM 11 1365. Excavated from depth of 200 cm., from coarse, airfall
8. Accidental andesite block ejected during first explosive phase. Collected from impact field near Tabacon.
9. Gabbro xenolith, pre-historic tuff-breccia, near La Palma. USNM 111250-38.

sity during these two eruptions, the ca. 1500 A. D. eruption was about 5 times more voluminous during its explosive phase. Other sections show a similar ratio between the ca. 1500 A. D. and 1968 tephra deposits. The ca. 1500 A. D. lava flow, the largest exposed pre-historic flow on the other hand, covers only about 1 km$^2$ compared to about 3 km$^2$ for the 1968-73 flow (and is thinner on the average). The probable volume of the ca. 1500 A. D. eruption is about twice that of the current one, or 0.17 km$^3$: tephra composes about 90 % of the total eruptives versus 30 % of the 1968-73 eruption.

In a given eruptive cycle of Arenal Volcano, the essential eruptive rocks become successively less differentiated through time. Since initial work (MELSON and SAENZ, 1968) 7 new analyses (Table 4) have revealed this trend. The first three analyses are of essential eruptive rocks in chronological order from oldest to most recent, spanning the 5-year period of September, 1968 to August, 1973. Small but significant decreases in $Na_2O$, and $K_2O$, and increases in total Fe, MgO, and $TiO_2$ are evident. The ejecta and lava of the previous, ca. 1500 A. D. eruption, show even stronger fractionation, with $SiO_2$ ranging from 59.27 % (pumiceous bomb, analysis 7) to 53.61 % (lava flow, anal. 5).

## Model of the Eruption

The following is put forth as one qualitative model which is consistent with the observations on the eruption. Arenal's eruption began with renewed upsurges of andesitic magma after about 470 years of repose. Three major surges occurred, all part of a single pulsating rise of magma which eventually cleared conduits, became degassed, and yielded, finally, the most voluminous emission of new lava — the present ca. 0.06 km$^3$ lava flow.

Initially, a new surge of magma moved upward along a roughly east-west trending tension fracture on Arenal's west side. This zone parallels an older fault zone just to the south of Arenal (note topographic expression of this fault in Fig. 1). The new magma rose rapidly through or pushed upward from below the cooling magma of Arenal's 1500 A. D. eruption, capped by at least 125 m of crust formed by about 450 years of cooling (calculated from equations of JAEGER, 1968). Explosions resulted from explosive degassing of the uppermost part of magma oversaturated with volatiles. The successive explosions reflect degassing of successive zones of magma, as each neared the surface, until, finally, magma undersaturated with volatiles was erupted, forming the block flow. The magma column was zoned not only in regard to volatile content, but in major and minor elements as well, with successively lower volatile contents correlating with lower $SiO_2$ and alkali contents.

Alternatively, the explosions were produced by movement of low-volatile magma in low-temperature, water-saturated rocks, mainly volcanic ash interlayered with massive flows. The rapid mingling of magma and water-saturated ash could create overpressures in excess of 4,000 bars, resulting in the explosive opening of three craters simultaneously along the east-west fracture. The lowermost crater, closest to the site of maximum pressures, became the largest, and most gas and fragmented cap rocks were blasted from it. The stratified ash and lava flows over the rising column were leaky, and may not have failed explosively in the way of a slowly-rising magma column.

The gas and ash at the base of the explosion clouds near the vent were in excess of 300° C, igniting vegetation. A mean temperature of 800° C is not unreasonable for the supercritical water-rich vapor. At such a temperature, 4,000 bars is generated in water of initial density 1.0 gm/cc if expansion is not allowed to exceed 20 % by the rock permeability and rate of heating of the water (KENNEDY, 1950). The energy of the initial explosion, supplied by the expansion of the heated supercritical vapor, was on the order of $10^{21}$ ergs. Release of vapor pressure led to a brief period of quiet, but continued explosions occurred for the next two days with upward new surges of magma. The ejecta of these phases consisted largely of heated country rocks, until, on Sept. 14, 1968, the top of the magma column broke through to the surface, with minor explosions of mainly essential, degassed, scoriaceous to pumiceous bombs of andesite. Emission of lava then became quiet and continuous but with varying rates of emission, until lava welled out into the lower crater, eventually spilling over the rim, and covering 2.7 $km^2$ in two years.

During the major two explosions — the initial and final ones — much debris fell back from the explosion cloud mainly on the steep headwaters of drainage basins adjacent to the lower crater. This fall-back stripped and ignited vegetation, and, cascading into drainage channels, generated high velocity hot avalanches, of which the blocky ash flows are the remains. Entrapped air and gases emitted from the ejecta provided air-layer lubrication and increased the mobility of the hot avalanches (SHREVE, 1968; MCTAGGART, 1960). These heated, largely trapped gases moved outward from the avalanches at high speed, leveling trees, and causing most fatalities. The high velocities of the ash-laden winds and the mobility of the blocky ash flows were impelled entirely by gravity flow. No « directed blast » from the crater was involved.

Volatile oversaturated magma could be produced by either partial crystallization of anhydrous phases (mainly plagioclase and pyroxene) since the 1500 A. D. eruption, or by displacement of deep-seated volatile saturated magma to near the surface. A volatile saturated magma initially at depths between 4 and 15 kilometers if it were to be displaced isothermally to near the surface, would, with complete retention of volatiles, be able to generate about 1 to 5 kilobars overpressure on release of volatiles.

The average total volume of ejecta from the 1968 and 1500 A. D. is about 0.13 $km^3$. If all of Arenal's eruptions average about this volume, and have the same period of repose, and if 10 % of the total volume is added to the cone, Arenal would develop in about 500 such eruptions, or about 200,000 years. However, these assumptions are probably unlikely. The relative thickness of tephra layers indicates that Arenal's early eruptions were on the average more voluminous than the current one, perhaps from 5 to 10 times more voluminous, lowering its calculated age to as low as 20,000 years.

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