Ejecta Velocities, Magma Chamber Pressure and Kinetic Energy Associated with the 1968 Eruption of Arenal Volcano

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Abstract

During the initial explosive phase of the eruption of Arenal volcano small projectiles were thrown a maximum distance of 5 km. Considering the effect of atmospheric drag these projectiles must have had initial velocities of at least 600 m/sec. For this velocity, the gas pressure in the magma chamber must have reached at least 4700 bars and the kinetic energy of the initial explosion is estimated as $2.4 \pm 1.2 \times 10^{21}$ ergs.

Had the effect of aerodynamic braking been ignored in making these calculations, as has always been done in the past, the calculated initial velocity would have been 220 m/sec; chamber pressure and kinetic energy estimates would thus be substantially lower. Clearly, velocities of ejecta, chamber pressures and kinetic energies for many explosive volcanic events have been seriously underestimated in the recent past, as has been the ability of overlying materials to contain, in certain cases, tremendous overpressures for short periods of time.

A projectile with an initial velocity of 600 m/sec would have a maximum range of more than 200 km on the moon. Thus, the presence of far-reaching secondary crater fields on the moon cannot, at this time, be considered evidence for an impact origin of the parent crater. 600 m/sec is not the upper limit for initial velocities of volcanic ejecta. There is some indication that such velocities could reach values greater than 2 km/sec, suggesting that volcanic as well as impact mechanisms may be able to impart escape velocity to lunar materials.

Introduction

Arenal volcano, situated in northwestern Costa Rica (10° 28′ N lat., 84° 42′ W long.) is a symmetrical strato volcano, 1600 meters in height, which was until recently considered extinct. Dormant for more than 500 years, Arenal came to life almost without warning on July 29, 1968, extracting a heavy toll in human life. A comprehensive account of the geology, petrology and the eruptive activity up to the summer of 1970 is given by MELSON (in press). This paper is concerned solely

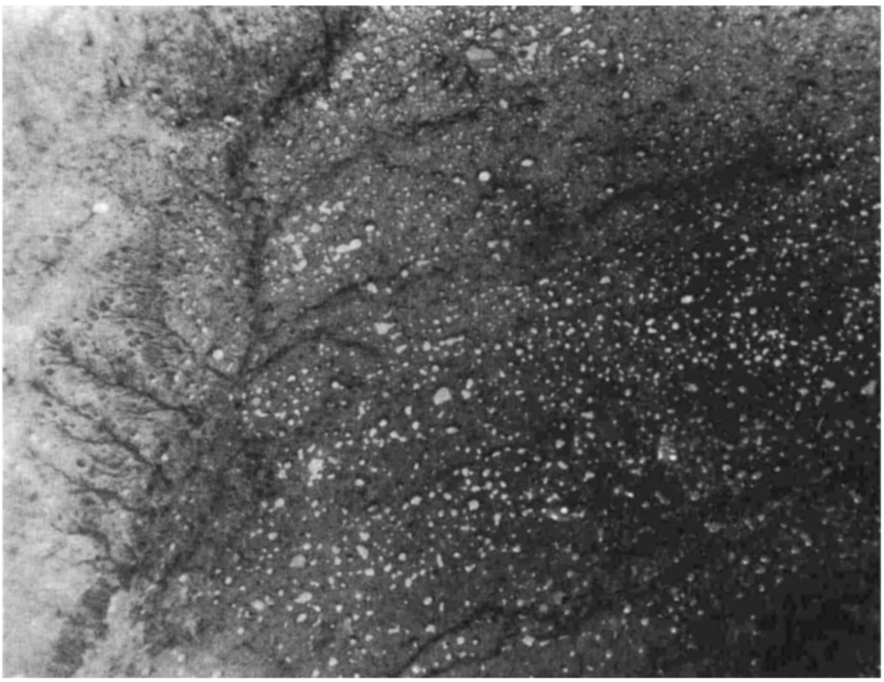

FIG. 1 - Aerial photograph of an intensely cratered area approximately 2.5 km west of the explosion crater. Craters have been modified by rainfall and most are partly filled with water.

with the energetics of the violently explosive phase which initiated the eruptive sequence.

One result of the initial explosive phase was the creation of an extensive field of secondary craters (Fig. 1), the largest of which was 30 meters in diameter. These craters were excavated by the impacts of ejected blocks derived from the material overlying an explosion crater opened on the west flank of the volcano. They were distributed asymmetrically around the explosion vent, reaching their maximum extension to the WSW. In this direction craters can be documented to a distance of approximately 5 km (Fig. 2). Isolated craters probably occur at somewhat greater distances, into a region of lush tropical vegetation which precluded any serious effort to search for them.

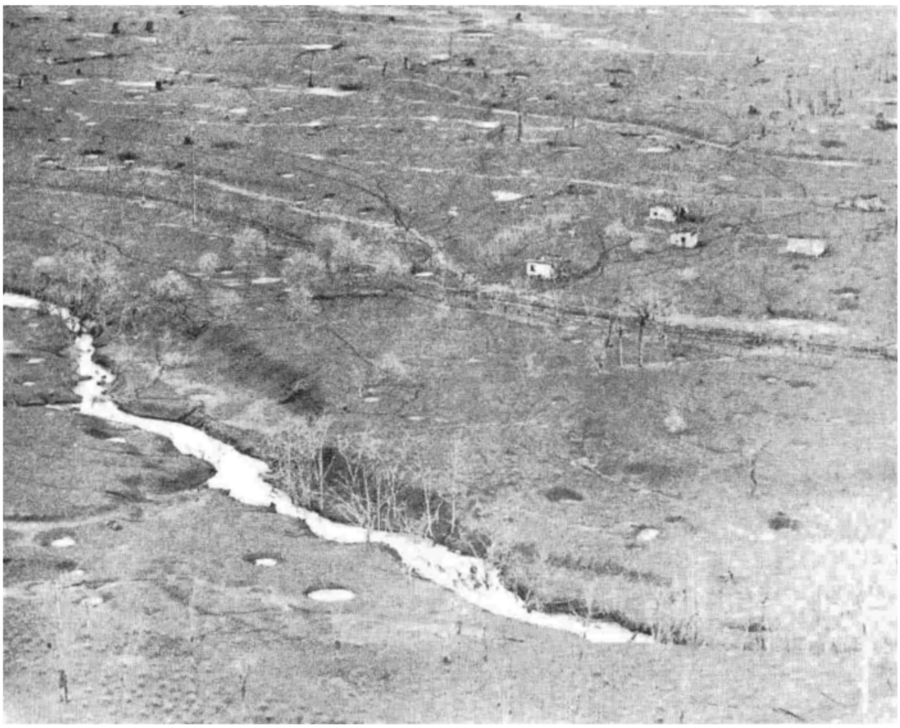

FIG. 2 - Maximum documented extent of the secondary crater field, approximately 5 km WSW of the explosion crater. Smallest craters in this photograph are approximately two meters in diameter.

From the size of these craters, and their maximum extent, it is possible to deduce minimum ejection velocities for the impacting projectiles and a minimum figure for the gas pressure in the magma chamber just prior to eruption. With somewhat less assurance, these deduced parameters may be used to estimate the kinetic energy expended in the explosive phase of the eruption. These values have significant implications for both terrestrial and lunar volcanology.

Ejection Velocity

The distance an ejected block is thrown on a ballistic trajectory, in an atmosphere, is a function of: 1) ejection velocity; 2) ejection angle; 3) mass of the projectile; 4) projected cross-sectional area of the projectile, and 5) the drag coefficient (which is in turn dependent upon the density of the atmosphere, the shape and surface roughness of the projectile and its velocity). Distances are known from the field mapping and the latter four parameters may be estimated in such a way that it is possible to calculate the *minimum* velocity a given particle must have had at the instant it was ejected from the volcanic vent to travel a given distance.

In any given explosive event particles will be ejected at velocities ranging from slightly greater than zero to some maximum value dependent upon the magnitude of the explosion. Only the *maximum* ejection velocity associated with the initial explosive event is herein calculated. More precisely a *minimum* value for the *maximum* ejection velocity is calculated. By themselves, lesser velocities do not truly reflect the chamber pressure and energetics of the explosion. Collectively, of course, it is necessary to estimate an average velocity for the entire ejected mass if the total kinetic energy of the explosion is to be estimated.

The equation of a particle moving along a ballistic trajectory, in a vacuum, is:

$$R = \frac{V_o^2 \cdot \sin 2\theta}{g} \qquad [1]$$

where R is the range, V_o is the initial velocity, θ is the ejection angle and g is the gravity constant (1). Use of this equation for flight thru an atmosphere leads to gross errors but the equation does illustrate that the most efficient ejection angle angle θ is 45°. A particle of given velocity will travel farthest if ejected at a 45° angle, or put another way, calculations based on a 45° ejection angle will yield the minimum ejection velocity for a given range. For this reason an ejection angle of 45° has been arbitrarily adopted in the following calculations.

(1) The equation ignores the curvature of the earth but the error so introduced is negligible.

The calculations become complicated upon introduction of an appropriate atmosphere but they can be handled by computer techniques. The results of a computer program ([2]) for a 45° ejection angle are plotted in Fig. 3 and 4. These plots relate range, ejection velocity, impact velocity, mass, drag coefficient and projected cross-sectional area. The computations assume that both mass and drag coefficient

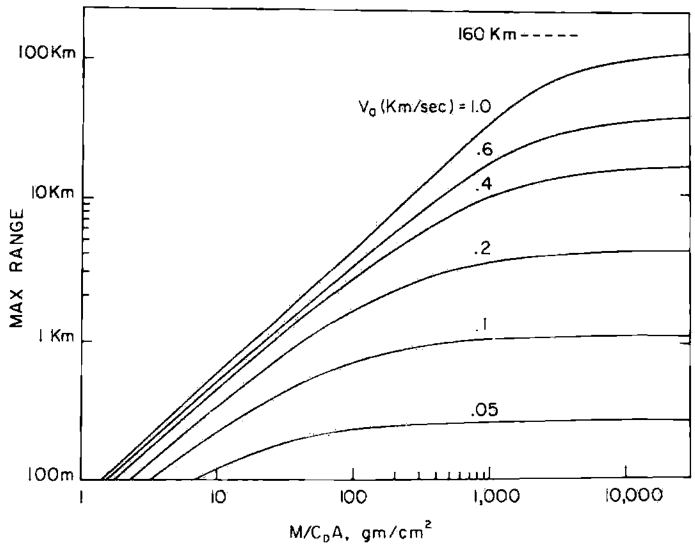

FIG. 3 - Maximum range of a projectile, in the earth's atmosphere, as a function of size, mass, and initial velocity.

(C_D) remain constant throughout the flight. In reality C_D varies as the projectile decelerates so some average value for C_D must be used. First a projectile shape must be assumed: spherical geometry is used herein. This again minimizes the ejection velocity since a sphere is the most efficient shape for a non-stabilized projectile (departures from sphericity produce increases in both projected cross-sectional area and drag coefficient). For a sphere, C_D varies from 1.0 for velocities in excess of 400 m/sec to 0.5 for velocities below 200 m/sec. These values are valid even for rough surfaced volcanic bombs provided the

([2]) Generated by Dr. Dean R. Chapman, Thermo- and Gas-Dynamics Division, NASA Ames Research Center.

Reynolds number $\rho VD/\mu$ is greater than about 10^6 (KOELLE, 1961) [3]. At these higher Reynolds numbers pressure forces on the body are large compared to viscous forces, thus minimizing drag due to surface effects. For calculations involving spheres between 0.5 and 1.0 meters in diameter an average C_D of 0.8 was used; for calculations involving spheres of 1.5 meter diameter an average C_D of 0.7 was used.

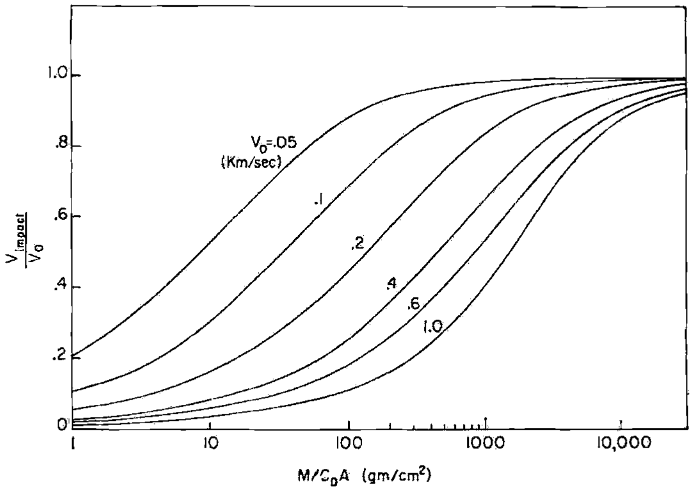

FIG. 4 - Impact velocity of a projectile, in the earth's atmosphere, as a function of size, mass, and initial velocity (45° ejection angle).

The volume and mass of a sphere increase as the cube of its radius while the cross-sectional area increases only as the square of its radius. Thus, there must obviously be a point where a given mass will no longer be affected by aerodynamic braking. This is reflected in Fig. 3 by the flattening of the constant velocity curves such that greater masses do not travel greater distances beyond a certain M/C_DA value. Prior to this point a larger projectile travels farther than a smaller projectile with the same initial velocity. Put another way, a large projectile can travel the same distance as a smaller one, given a lower initial velocity. Thus, to calculate a maximum velocity,

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(3) ρ = air density; μ = coefficient of viscosity of air; D = sphere diameter; V = flight velocity. A 10 cm sphere moving at 100 m/sec is characterized by a Reynolds number of $\sim 7 \times 10^5$.

only the smaller projectiles which reach the maximum range should be considered, bearing in mind that the very smallest particles can be helped (wind dispersion) rather than hindered by the atmosphere. The cut-off between particles which are helped and those that are hindered is probably less than 10 cm in diameter.

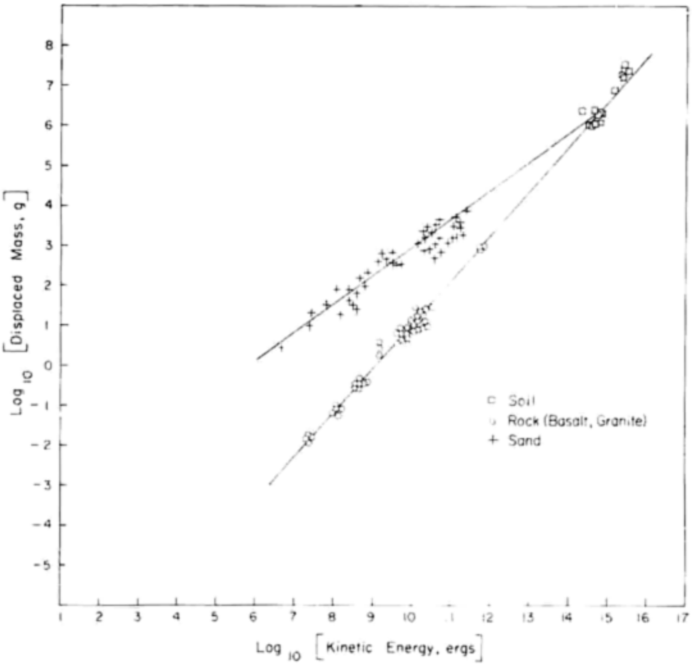

FIG. 5 - Kinetic energy required for impact cratering in a one « g » gravitational field. Rock and sand data from GAULT (unpublished); soil data from MOORE (1966).

The size of the smallest projectiles reaching the maximum range on a ballistic trajectory is the source of some uncertainty. Projectile sizes could not be directly observed since the projectiles were broken and scattered upon impact. Additionally, the crater field was subsequently modified by the deposition of a thick ash blanket and several heavy rainfalls. Using Fig. 3 and 4 it is possible to uniquely determine the size, final velocity and initial velocity of an impacting object, if the impact energy is known. The impact energy may be at least crudely estimated from the crater size since there is a direct relation between the excavated mass and the projectile energy. In

Fig. 5 some empirically observed relations between displaced (cratered) mass and projectile kinetic energy are plotted for several different target materials.

The only reliable crater parameter which could be measured at Arenal (in the area of interest) was crater diameter. Craters as small as two meters in diameter were found at the maximum range (Fig. 2). The displaced mass was calculated using an assumed soil density of

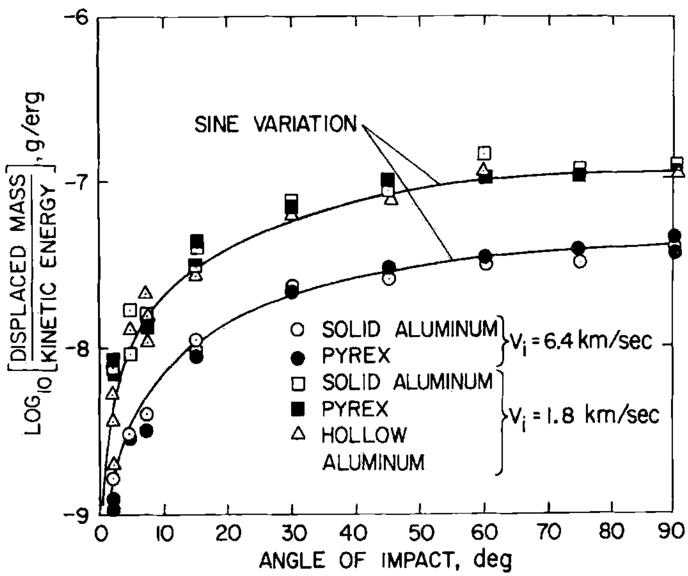

FIG. 6 - Cratering efficiency for oblique impact in non-cohesive quartz sand, 1 « g » field (GAULT, unpublished).

1.5 gm/cc and an assumed crater depth-diameter ratio of 1:4 — a commonly observed geometry for small impact craters (MOORE, 1966). The depth-diameter ratios of 15 small, approximately equant craters were directly measured in an area NE of the maximum extent of the crater field. These craters were not modified prior to the field investigation. The craters displayed depth-diameter ratios ranging from 1 : 2.1 to 1 : 6.0, with an average value of 1 : 3.8.

The calculated displaced mass of a 1:4 crater of 2 meters diameter is approximately 1.2×10^6 grams (Appendix 1). This requires a cratering energy of $\sim 10^{14}$ ergs (Fig. 5). Uncertainties in the displaced mass estimate and the substantial empirical data scatter preclude a more precise energy estimate.

It should be noted that, at this energy level, large differences in target characteristics do not have much effect on displaced mass. Further, all the data shown in Fig. 5 are for impact angles greater than 45°. This is undoubtedly true also for the Arenal impacts. Since cratering efficiency varies as the sine of the impact angle measured from the horizontal, fairly large differences in impact angle above 45° only result in minor differences in cratering efficiency (Fig. 6). For these reasons the Arenal data is directly comparable to that shown in Fig. 5 without correction for target characteristics or impact angle.

TABLE 1 - Velocities and Impact Energies of Volcanic Blocks (spheres) thrown a distance of 5 km — for an Ejection Angle of 45°.

Projectile Diameter	M/C_DA	*Initial Velocity*	*Final Velocity*	*Kinetic Energy at Impact*
0.5 m	99	1200 m/sec	84 m/sec	$10^{12.75}$ ergs
0.8 m	173	600 m/sec	144 m/sec	$10^{13.9}$ ergs
1.0 m	216	500 m/sec	160 m/sec	$10^{14.25}$ ergs
1.5 m	334	370 m/sec	178 m/sec	$10^{14.8}$ ergs

There is, however, a major uncertainty involved in using this data. This uncertainty arises because the cratering energy relations shown in Fig. 5 are strictly applicable only to relatively light projectiles moving at high velocities (2-7 km/sec). At Arenal the cratering was produced by massive projectiles impacting at much lower velocities (<0.2 km/sec). Now, even though the kinetic energies are identical, there are signicant differences between large, slow projectiles and small, fast projectiles with respect to cratering mechanics and cratering efficiency. Fortunately the trend is toward an increase in cratering efficiency with decreasing projectile velocity (Fig. 6). Assuming this trend continues to lower velocities, the use of Fig. 5 uncorrected should give an overestimate of the impact energy and a concomitant underestimate of the *initial* velocity of Arenal ejecta (Table 1).

Using Figures 3 and 4, initial and final velocities of various diameter spheres ([4]) can be determined for a range of 5 km. The kinetic energies of the projectiles are readily calculated from their mass

([4]) Mass is calculated using a measured average density of 2.6 gm/cc for the ejecta.

and final velocity. From this data, summarized in Table 1, it is clear that the most reasonable values for a projectile forming a 2 m impact crater at 5 km from its origin are a diameter of 0.8 m and an initial velocity of 600 m/sec. Bearing in mind the foregoing discussion of cratering efficiency, the Arenal projectiles responsible for the 2 m craters may have been somewhat smaller, with higher *initial* velocities, but were unlikely to have been larger. Given the other minimizing assumptions made (45° ejection angle, spherical geometry), 600 m/sec would appear to be truly a *minimum* estimate of the *maximum* ejection velocity. Use of equation 1, by contrast, would have given a value of 220 m/sec for the ejection velocity — 35 % or less of the true value.

Magma Chamber Pressures

The most reasonable explanation for volcanic explosive activity involves the sudden release and expansion of volatile constituents — principally H_2O and CO_2 — from the predominantly silicate magma. If this is so there must be a direct relation between the *maximum* initial velocity of the projectiles and the gas pressure within the chamber just prior to the explosion. The equation which is commonly used (MINAKAMI, 1950; GORSHKOV, 1959; RICHARDS, 1965) to express this relation is that form of the Bernoulli equation used to calculate gas velocities:

$$P_1 - P_2 = 1/2\ \rho\ V^2 \qquad [2]$$

For our purposes, P_1 becomes the gas pressure inside the magma chamber, P_2 becomes the gas pressure outside the chamber, ρ is the density of the material lying between the magma chamber and the surface and V becomes the initial velocity of the ejecta. When P_2 is small with respect to P_1 (as it is in this case, being only one atmosphere) the equation reduces to:

$$P_{\text{chamber}} = 1/2\ \rho\ V^2 \qquad [3]$$

Substituting 6×10^4 cm/sec for V and 2.6 gm/cc for ρ in equation 3 yields a value for P of 4.7×10^9 dynes/cm^2 or 4700 bars. Since V is a minimum estimate, a gas chamber pressure of 4700 bars is also a minimum estimate.

Kinetic Energy of the Explosive Activity

In theory, if the total mass of ejected material and the ejection velocity are known, then the total kinetic energy of the ejected projectiles can be calculated from the simple formula:

$$E = 1/2\ MV^2 \qquad [4]$$

where E is the kinetic energy, M is the ejected mass and V is the ejection velocity. One can equate this total projectile energy to the total energy of the explosion only by ignoring the amount of energy dissipated in the accompanying seismic wave and air blast and the amount of energy necessary to fracture and crush the caprock prior to its expulsion. But, since both velocity and ejected mass are extremely difficult to determine accurately, the probable error associated with the energy estimate is already much larger than any error attributable to these simplifications.

The kinetic energy estimated here is applicable only to the first, and by far the most violent, of the explosions which occurred intermittently over a three day period. This explosion resulted in the formation of the lowermost and largest of the three new flank craters which developed. The ejected mass is assumed to be equal to this crater volume. The crater was approximately equidimensional, with an estimated diameter of $\sim$ 250 meters and an estimated maximum depth of $\sim$ 40 meters. Situated on a slope, the crater was tilted toward the west, its eastern (up-slope) wall being disproportionally steep. There was no raised rim. Surveying equipment was not used in making these estimates and the crater has subsequently been partly filled by lava flows issuing from within. The crater dimensions are assumed to be accurate to within 10-15 % of the true values. No estimates are possible for the amount of material erupted from this crater subsequent to the initial explosion but field observations and eyewitness interviews indicate this amount would be small relative to the total excavated mass. Any error so introduced would also be at least partly offset by the fact that neither can estimates be made of the amount of material which, although ejected, fell back into the crater.

The calculated volume of a crater with the above geometry is $2 \pm 1 \times 10^6$ m^3 (Appendix 1).

To calculate the kinetic energy involved it is necessary to estimate the average velocity of the projectiles. The projectile ejection velocities are known to range from slightly greater than zero up to a maximum of at least 600 m/sec. If the mass-velocity distribution is normal (gaussian) then both the mean and the average velocity will be 300 m/sec. This result is valid no matter what the shape of the distribution curve as long as it is symmetrical. Actually, the distribution curve is almost certainly skewed toward higher or lower velocities but in the absence of other evidence 300 m/sec is herein assumed for purposes of the energy calculation.

The kinetic energy of the initial explosion immediately follows as:

$$E = 1/2 \times 2.6 \text{ gm/cm}^3 \times 2 \pm 1 \times 10^{12} \text{ cm}^3 \times (3 \times 10^4 \text{ cm/sec})^2$$
$$= 2.4 \pm 1.2 \times 10^{21} \text{ ergs}$$

This compares to an estimated 10^{18} ergs released by pre-eruption earthquakes (MELSON, in press). Obviously, pre-eruption earthquakes were not very effective in relieving the stress build-up, being only able to harmlessly dissipate, at best, 1/1,000 of the pre-eruption stress. This is consistant with the conclusion, discussed further in a later section, that the over-lying rock unit was able to sustain the entire energy build-up until it failed catastrophically in the explosive eruption.

It is interesting to compare the Arenal explosion with a cratering event of known magnitude. Project Sedan, a nominal 100 kiloton nuclear device detonated in desert alluvium at a depth of 635 feet, produced a crater with an estimated volume of 5.1×10^6 cubic meters (NORDYKE and WILLIAMSON, 1962). It has been shown empirically that linear crater dimensions in basalt are predictable when $E^{1/3.4}$ scaling is used (NORDYKE and WRAY, 1964). Volumes therefore scale as approximately the first power of the cratering energy, all else being equal. In Table 2 the Arenal explosion is scaled up to the energy level of the Sedan event so that crater volumes can be directly compared. The scaled crater volume at Arenal is somewhat smaller than the Sedan crater volume but still the agreement is very good. This indicates that the estimate of 300 m/sec for the average ejecta velocity is approximately correct (the scaling is insensitive to errors in estimated ejected mass since the calculated energy varies linearly with estimated mass in equation 4).

The smaller size of the scaled crater at Arenal may be attributed to: 1) The greater density of the andesite caprock at Arenal compared to desert alluvium; and 2) a smaller scaled depth of burst ([5]) and therefore a lesser cratering efficiency relative to Sedan. This is consistent with the smaller depth/diameter ratio of the Arenal crater (1:6) as compared to the Sedan crater ratio of 1:4 (BALDWIN, 1963).

TABLE 2

	Arenal Explosion Crater	*Project Sedan*	*Arenal Explosion Crater (Scaled to Sedan energy)*
Energy (ergs)	$2.4 \pm 1.2 \times 10^{21}$	4.1×10^{21}	4.1×10^{21}
Crater volume (m^3)	$2 \pm 1 \times 10^6$	5.1×10^6	3.4×10^6

It can therefore be said, with some assurance, that the Arenal explosion behaved as if it originated at a depth significantly less than 200 meters.

Discussion and Conclusions

Previous pressure-energy estimates.

Previous workers have attempted to compute chamber pressures and kinetic energies of explosive events, based on calculated ejection velocities, using equation 1 (MINAKAMI, 1950; GORSHKOV, 1959; HEDERVARI, 1968) — *i.e.* by ignoring atmospheric drag effects. Further, RICHARDS (1965) has used such estimates to construct a graph purporting to generally relate the total kinetic energy of explosive events to the chamber pressures attained just prior to the explosions (Fig. 7).

As is evident from Fig. 3, the only cases where atmospheric drag can be ignored without introducing serious errors involve very short ranges or very large values of M/C_DA. Very short ranges are useless for calculating maximum or even average velocities and large M/C_DA values for volcanic ejecta are the exception rather than the rule. Concerning the explosive eruptions of Asama (see Fig. 7) MINAKAMI's (1950) calculations were based, at least in part, on volcanic ejecta of

([5]) Scaled depth of burst has been defined as $H/W^{1/3.4}$ where H = depth and W = equivalent weight of TNT.

one meter diameter and smaller. His calculated initial velocities and gas pressures must therefore be too low — by a sustantial factor. For the Bezymianny eruption GORSHKOV (1959) does not discuss the sizes of ejecta thrown to the distance he used for his initial velocity calculation. However, he calculates an « average velocity » rather than

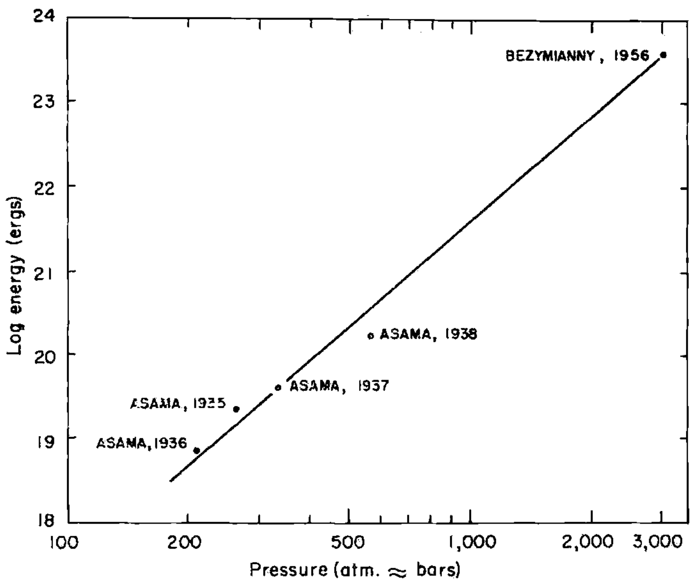

FIG. 7 - « Relation of the logarithm of kinetic energy of volcanic explosions to the logarithm of the gas pressure at the time of the explosion » (after RICHARDS, 1965).

a maximum velocity, by arbitrarily chosing a range much smaller than the maximum range to which ejecta has been thrown. As has been discussed above, the use of an « average velocity » gives a valid estimate of the collective kinetic energy of the ejected particles but gives a serious underestimate of the magma chamber pressure. Therefore, even allowing for the remote possibility that large M/C_DA values characterized the ejecta in the Bezymianny event, Gorshkov's estimated pressure must still be low. If there is a simple relationship between kinetic energy and gas chamber pressure, it is definitely not the one depicted in Fig. 7. What Fig. 7 does illustrate is the ease with which spurious straight-line relationships may be drawn using log-log coordinates. The true pressure-energy curve must lie far to the right of the straight-line drawn in Fig. 7.

Although velocity estimates of 2 km/sec or more for volcanic ejecta have been made in the past, these estimates were essentially unsubstantiated (e.g. WRIGHT, 1935) and volcanologists today commonly consider a velocity of 600-700 m/sec to be the upper limit for volcanic ejecta (*e.g.* GREEN, 1970). However, the magnitude of the Arenal eruption was not large when compared to several other explosive eruptions which have been well-documented (*e.g.* Bezymianny in 1956; Krakatoa in 1883; Tambora in 1815; Santorini in 1400 BC), yet the minimum estimate made herein for Arenal ejecta is 600 m/sec. It would appear that the ejecta velocities, pressures and perhaps energies associated with explosive volcanic activities have been consistently underestimated, by a large factor, in the recent past.

Chamber overpressures and rock strength.

The minimum estimate of gas chamber pressure at Arenal just prior to the initial explosion is a very substantial 4700 bars. If this pressure were contained, prior to the explosion, solely by the weight of the overlying rocks, the overburden thickness ($d = 2.6$ gm/cm^2) would have been about 18 kilometers. There is, however, good evidence that the explosion originated at a point not much deeper than the present crater floor (40 m $< d <$ 200 m). What this means is that the rock unit capping the magma chamber must have exhibited a substantial structural strength to contain on overpressure of this magnitude for a short period of time. This rock unit, now well-exposed in the inner walls of the explosion vent, consists of a series of tough, dense andesite flows emplaced during some previous eruptive episode.

The ability of the overlying rock to contain the gas pressure build-up for a short time was clearly necessary to promote the kind of explosive activity observed here. Indeed, *wherever* explosive volcanic activity of comparable violence is observed, the strength and coherence of the « caprock » is likely to be a primary factor.

Implications for Lunar Studies.

In the absence of direct data, many of our speculations concerning the evolution of the lunar surface have relied on what are presumed to be terrestrial analogues of lunar phenomena. Such arguments are particularly favored when discussing the nature of the craters, large and small, which populate the lunar landscape. One aspect of these arguments concerns the origin of the parent craters which are surrounded by an inner region of hummocky terrain (so-called base surge deposits) and an outer region of satellite craters which may extend for tens or hundreds of kilometers. Hypervelocity impact experiments and subsurface atomic explosions strongly suggest that meteorite and/or cometary impacts on the lunar surface can be expected to produce such a configuration. Proponents of an impact origin for these craters have further stated that volcanic processes are incapable of producing a similar configuration and that therefore such a configuration is absolutely diagnostic of an impact origin for the parent crater (*e.g.* SHOEMAKER, 1961; PHINNEY *et al.*, 1969). Concerning the extent of secondary cratering there is ample evidence to the contrary — Arenal being a case in point. Had Arenal erupted on the moon ($g = 167$ cm/sec^2, no atmosphere), ejecta with an initial velocity of 600 m/sec would have had a maximum range of more than 200 kilometers. This is quite ample to account for most of the secondary crater fields observed on the moon and suggests that the *extent* of secondary cratering is of little value for distinguishing between impact and volcanic craters, at least until we have more direct information from the lunar surface. Although the lunar rocks examined so far have undoubtedly crystallized in an environment characterized by remarkably low partial pressures of O_2 and H_2O it is premature to therefore conclude that lunar magma chamber pressures could never have reached high values in the past. Considerations of sample inadequacy aside, it is possible that the lunar rocks examined to date merely reflect a much more efficient outgassing of surface or near-surface magmas in the hard vacuum of space.

It is beyond the scope of this paper to discuss base surge deposits but there is good evidence that these too cannot be used as an absolute indicator of crater origin (MOORE, 1967; FISHER and WATERS, 1969).

Finally, as discussed above, the eruption of Arenal was not unusually energetic. It may be instructive to consider a truly catastrophic eruption. HEDERVARI (1968) mentions the presence of large volcanic blocks at Zakro, Crete, which he relates to the eruption of Santorini in 1400 BC. The distance between Santorini and Zakro is 160 kilometers and Hedervari therefore doubts that these blocks arrived on ballistic trajectories because of the excessive pressures necessary to propel them this distance. But other possible transport mechanisms seem, at this time even more implausible — and there is little doubt about the awesome nature of the explosion, which has been credited with effectively destroying the Minoan civilization on the island of Crete. Additional information is necessary to resolve the problem, but assuming for the sake of argument that the 160 kilometer range is valid it is interesting to estimate the necessary initial velocity. Although the data in Fig. 3 does not extend beyond initial velocities of 1 km/sec, it is possible to crudely estimate the positions of higher velocity curves. Bearing in mind that the projectiles would have to be small enough to be appreciably slowed by the atmosphere (*i.e.* their M/C_DA values would have to intersect the steep slope portion of the velocity curve) [6], it would appear that initial velocities well in excess of 2 km/sec would be required. This is approaching lunar escape velocity and raises the intriguing possibility that volcanic, as well as impact, processes are, or have been, capable of ejecting material from the moon. While in no sense endorsing the idea, it is interesting to note that, because of the large chemical disparity between the lunar rocks returned so far and tektites, O' KEEFE (1970) has invoked such a volcanic mechanism for the production of tektites and their transport to the earth.

Acknowledgements

This paper could not have been written without the computer-generated range-velocity curves suplied by D. R. Chapman. We are also heavily indebted to D. E. Gault for the use of his unpublished experimental data on impact cratering.

Appendix 1

The volume of a crater with a depth/diameter ratio less than 1:2 (hemisphere) is most readily computed by determining the ratio between such a geometry and a hemisphere of the same diameter.

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(6) To remain intact or almost intact upon impact.

A regular volume with a depth/diameter ratio of 1:4 is generated by revolving a plane region bounded by the parabola $y^2 = 8x$, between $x = 0$ and $x = 2$, about the x axis:

$$V_1 = \pi \int_0^2 8x \, dx = 16\,\pi$$

The volume V_2 of a hemisphere of radius 4 is:

$$V_2 = \frac{2}{3} \pi r^3 = 42.6\,\pi$$

$$V_1/V_2 = 1/2.65$$

A regular volume with a depth/diameter ratio of 1:6 is generated by revolving a plane region bounded by the parabola $y^2 = 18x$, between $x = 0$ and $x = 2$, about the x axis:

$$V_3 = \pi \int_0^2 18x \, dx = 36\,\pi$$

The volume V_4 of a hemisphere of radius 6 is:

$$V_4 = \frac{2}{3} \pi r^3 = 144\,\pi$$

$$V_3/V_4 = 1/4$$

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