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Relationship between crater size and ejecta volume of recent magmatic and phreato-magmatic eruptions: Implications for energy partitioning

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Abstract. Relationships between crater diameter (D in meters) and ejecta volume (V in cubic meters) of recent magmatic and phreato-magmatic eruptions are expressed as $D = 0.11\ V^{0.42}$, and $D = 0.97\ V^{0.36}$, respectively. Crater diameters of phreato-magmatic eruptions are ca. 2-5 times larger than those of magmatic eruptions of similar ejecta volume, suggesting that magma-water interaction in phreato-magmatic eruptions generated mechanical energies of crater formation 1-2 orders of magnitude larger than equivalent-volume magmatic eruptions. The conversion ratio of thermal energy to kinetic energy in phreato-magmatic eruptions is estimated to be 0.7-10 percent, which is in accord with the presently available data of laboratory experiments on melt-water interaction [*Wohletz and McQueen*, 1984].

Introduction

Explosive volcanic eruptions form craters. Phreato-magmatic eruptions typically produce maars and tuff cones, which have wide craters relative to their heights. These topographies are formed by excavation and collapse of basement rocks and volcanic edifices [*Wohletz and Heiken*, 1992]. The importance of collapse of the basement rocks around craters is well documented in explosion experiments of both TNT powder and nuclear bombs [*Ahrens and O'Keefe*, 1977]. In the case of meteorite impact crater formation, the projectiles collide on the surface at a speed of 20-30 km/sec, crashing and discharging the surface material, and the craters are further enlarged by collapse of the wall [*Melosh*, 1989]. Thus, crater sizes are mainly determined by both excavation and collapse processes. Explosion energies are generally proportional to the third power of the diameters of craters, whereas in volcanic eruptions thermal energies can be evaluated from the mass (or volume if density is known) of the ejecta. In this paper, we present available data on volcanic ejecta volumes and crater diameters of both magmatic and phreato-magmatic eruptions of recent time, and discuss the difference of the conversion ratio of thermal to mechanical energies in magmatic and phreato-magmatic eruptions

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Relationship between Crater Size and Ejecta Volume

A crater size is represented by the geometric mean diameter (D) of the area encircled by crater rim. Degradation of crater topography due to slumping, erosion and burial of sediments, may increase the apparent diameter of older craters. Most of the craters treated in this study were formed in historic time, and are little affected by degradation processes.

Estimating the ejecta volume (V) of explosive eruption is controversial because of large discrepancy of the estimated volumes of distal ash-fall deposits by different methods [*Pyle*, 1989; *Fierstein and Nathenson*, 1992; *Rose*, 1993]. Volumes of pyroclastics of an eruption can be estimated by isopach method and/or by crystal concentration method. The former is based on the available measurement of isopachs of a deposit, which afford fairly accurate volume estimate within the measured area. However, extrapolation of the thickness versus area of isopach toward distal end generally cause large differences in the volume estimates [*Fierstein and Nathenson*, 1992]. On the other hand, crystal concentration method assumes that crystal concentration of the bulk deposit is represented by that of large pumice fragments and that all crystals settled in proximal area because of high density and medium grain size. Although this method include errors as discussed by *Fierstein and Nathenson* [1993], it gives a reasonable volume estimate of distal ash of a pyroclastic deposit. Crystal concentration method has hitherto been applied for six deposits. Comparison of the estimates by crystal concentration method with those by the exponential relation between thickness and square root of isopach area shows that the former gives a factor of three larger values than the latter [$r^2 = 0.97$: *Rose*, 1993 ; *Hayakawa*, 1985]. Therefore we used volume estimates by crystal concentration method where available, and where only estimates by isopach method are available, the values are multiplied by a factor of three to get a consistent data set.

Classification criteria between magmatic and phreato-magmatic eruptions adopted here are slightly different from those generally used. Following features are recognized as characteristics for phreato-magmatic (hydromagmatic) eruptions [*Wohletz*, 1983; *Sheridan and Wohletz, 1983*]; (1) observation of finger jet, wet cloud surges, (2) occurrence of base surge deposit, (3) presence of accretionary lappili in the deposit, (4) formation of tuff rings and tuff cones. It seems these criteria are effective for relatively small scale eruptions. Because we are concerned with eruptions of variable magnitude for scaling, a following criterion is added to the above mentioned criteria. That is, accessibility of external water to the vent. Among the large phreato-magmatic eruptions treated here, Taupo and Ikeda craters are filled with abundant lake water near the sea shores. Krakatau crater is now below the sea level. *Sigurdsson et al.* [1991] suggested that the largest explosion at 1002h, 27 August of 1883 is apparently associated with collapse of the Krakatau island, and associated mud-rain in wide areas, tsunami waves [*Nomanboy and Satake*, 1995] and extraordinary long distance acoustic waves [*Yokoyama*, 1981] suggests strong magma-water interaction.

Figure 1 shows the relationship between crater diameter and the ejecta volume of both magmatic and phreato-magmatic eruptions. The crater diameters of volcanic explosions show log linear relationship to the ejecta volume for more than 5 orders of magnitude of ejecta volume. The relationships are expressed as $D_1 = 0.11\ V_1^{0.42}$, and $D_2 = 0.97\ V_2^{0.36}$ for magmatic (D_1) and phreato-magmatic eruptions (D_2), respectively. Previous works on the relationships for the crater size and ejecta volume [*Smith*, 1969; *Hildreth*, 1981; *Spera and Crisp*, 1981] show rather scattered plot in the extension of the present data of both magmatic and phreato-magmatic eruptions. These studies dealt with only large eruptions, and did not discriminated the magmatic and phreato-magmatic eruptions. Figure 1 also illustrates the relationship on meteorite impact craters, in which crater diameter is proportional to the cube root of the ejecta volume [*Mizutani*, 1980]. The meteorite impact craters are 1.5-10 times larger than those of volcanic craters of similar ejecta volumes. Among volcanic craters, those of phreato-magmatic eruptions have 2-5 times larger diameter compared with craters of magmatic eruptions of the same ejecta volume.

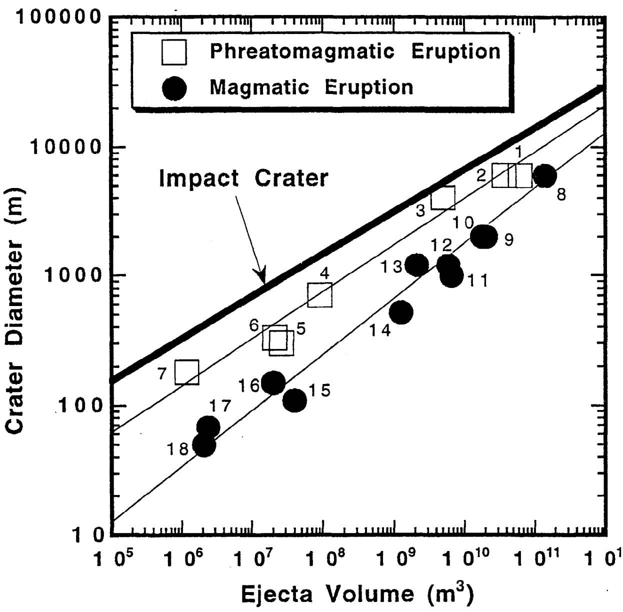

Figure 1. Relationship between crater diameter and ejecta volume of recent magmatic and phreato-magmatic eruptions. The relation for impact crater is also shown as thick solid line. Numbers attached to the symbols; phreato-magmatic eruptions; 1: Taupo 186 A.D. [Walker, 1980], 2: Krakatau 1883 [Self and Rampino, 1981], 3: 5000b.p. Ikeda Maar [Ui et al., 1992], 4: Taal 1965 [Moore et al., 1966], 5: Usu 1978 [Niida et al., 1980; Yoshida, 1995], 6: Ukinrek 1977 [Kienle et al., 1980], 7: Miyake-jima 1983 [Hayakawa et al., 1984]; magmatic eruptions, 8: Tambora 1815 [Self, 1984; Sigurdsson and Carey, 1989], 9: Santa Maria 1902 [Williams and Self, 1983], 10: Pinatubo 1991 [Ohno et al., 1996], 11: El Chichon 1982 [Sigurdsson et al., 1987], 12: Tarumae 1667 [Suzuki et al., 1973], 13: Fuji 1707 [Miyaji, 1984], 14: Asama [Hayakawa, 1995], 15: Izu Oshima 1986 B2 [Endo et al., 1988], 16: Usu 1977(4th vent) [Katsui et al., 1978], 17: Izu Oshima 1986 B3 [Endo et al., 1988], 18: Izu Oshima 1986 B1 [Endo et al., 1988].

The higher power of 0.42 for magmatic explosions compared with those of the cube root law (0.33) and impact cratering may primarily be ascribed to stronger explosive energy per unit ejecta volume of bigger magmatic eruptions, because of larger vent pressures and outlet velocities of the pyroclastics for bigger magmatic eruptions [*Wilson*, 1980; *Carey and Sigurdsson*, 1989]. Phreato-magmatic eruptions commonly show variability of the mode of eruption, i.e. water/magma mixing ratio may vary even in a eruption column, and the ratio may vary in a time sequence of an eruption. For bigger phreato-plinian eruptions, it is also envisaged that mixing ratio of water to magma varies between the center and the margin of thrusting jet column, and the central part tends to be less affected by the magma-water interaction, whereas, marginal part of eruption column incorporates and vaporizes external water, causing strong explosion and generating much finer-grained dispersive ash.

Energy Partitionings in Magmatic and Phreato-magmatic Eruptions

Quantitative analyses of the relation between explosion energy (TNT equivalent which produce the same effect including the crater size) and crater size have been carried out using artificial explosives [*Nordyke*, 1977; *Chabai*, 1965]. Explosion energy is generally proportional to the third power of the crater diameter. Figure 2 shows the relation between crater diameter and the energy for artificial [nuclear: *Nordyke*, 1977, chemical: *Mizushima*, 1970; *Piekutowski*, 1977], and volcanic [*Taniguchi*, 1993; *Taniguchi and Suzuki-Kamata*, 1992] cases. The explosion energies of volcanic eruptions have been obtained by the atmospheric over pressures observed at the time of eruptions. Slightly larger explosion energies of artificial explosions compared with those of volcanic explosions of equivalent crater-size is largely the result of larger fraction of kinetic energy of ejecta (solid and liquid) in the latter. Figure 2 illustrates that although the mode and time duration of excavation of volcanic cratering differ from those of artificial one, the energy versus crater diameter relationship holds for both cases with a common experimental equation: $E = 4.45*10^6\ D^{3.05}$ (J). Based on this equation we can make crude estimation of the explosion energies for volcanic eruptions from crater diameters.

Now, we examine the energy conversion ratio (the ratio of the explosion energy to the thermal energy) of the eruptions. In calculating thermal energy of the ejecta, we assumed average density of 1200 kg/m^3 with specific heat of $1.3*10^3$ J/(KgK). The temperature of the magma is taken from literature if available, and otherwise estimated from the composition of the magma. Many of deposits of phreato-magmatic eruptions contain abundant lithic fragments of country rocks, and proportions of essential fragment are taken into account in calculating the thermal energy of eruptions. Figure 3 shows the ratio of kienetic energy over thermal energy plotted against the ejecta volume. The efficiency of conversion of thermal energy to kinetic energy for phreato-magmatic eruption ranges from 0.7-10 %, which is consistent with the estimate of the experiments on thermite-water interaction conducted by *Wohletz and McQueen* [1984]. Plots in Figure 3 are classified by the composition of the ejecta, showing that the conversion ratio is independent of magmatic composition. Experimental and thermodynamic considerations show that maximum efficiency of kinetic energy could be attained for mass water/magma ratio of 0.3 - 1.0 [*Wohletz and McQueen*, 1984; *Koyaguchi and Woods*, 1996]. Magmatic silicate liquids initially contain 1 to 7 wt.% of water [*Johnson et al.*, 1994], degassing of which cause magmatic explosions. Another 15 - 50 wt.% of external water (water/magma ratio=0.3-1), therefore could be efficiently used to produce 1-2 orders of magnitude larger explosion energies in phreato-magmatic eruptions.

Although the obtained relationships between crater diameter versus ejecta volume include errors mainly due to errors in the estimation of ejecta volume, treatment presented here clearly demonstrated that the power law relationship holds for more than five orders of magnitude of ejecta volumes in volcanic explosions, and that interaction of magma-external water in phreato-magmatic eruptions generates 1-2 orders of magnitude larger explosion energy than exsolution of volatiles in magmatic eruptions.

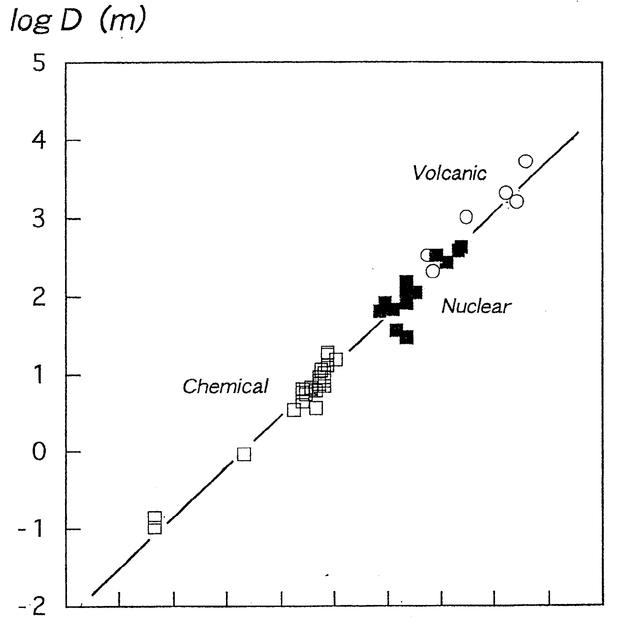

Figure 2. Relationship between explosion energy and crater diameter for volcanic, nuclear and chemical explosions [data sources are after Taniguchi, 1993].

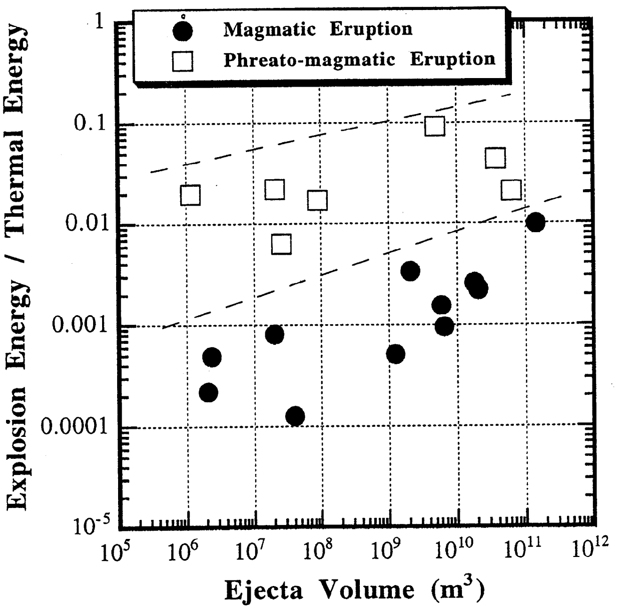

Figure 3. Ratio of explosion energy to thermal energy of of both phreato-magmatic and magmatic eruptions plotted against ejecta volume. Source of data: the same as in Figure 1. Suffix of B, A, D, R represents the composition of ejecta; i.e. B: basalt, A: andesite, D: dacite, and R: Rhyolite.

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