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Evaluating volumes for magma chambers and magma withdrawn for caldera collapse

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ABSTRACT

We develop an analytical model to infer the total volume of a magma chamber associated with caldera collapse and the critical volume of magma that must be withdrawn to induce caldera collapse. The diameter of caldera border fault, depth to the magma chamber, and volumes of magma erupted before the onset of collapse and of entire eruption are compiled for 14 representative calderas. The volume of erupted magma at the onset of collapse aligns between the total erupted volume of the other representative caldera-forming eruptions and the volume of eruptions without collapse during the post-caldera stage, correlating with the structural diameter of the calderas.

The total volume of magma chamber is evaluated using a piston-cylinder collapse model, in which the competition between the decompression inside magma chamber and friction along the caldera fault controls the collapse. Estimated volumes of the magma chambers associated with caldera collapse are 3–10 km^3 for Vesuvius 79 A.D. to 3000–10 500 km^3 for Long Valley, correlating with the cube of caldera diameters. The estimated volumes of magma chamber are always larger than the total volume of erupted magma for caldera formation, suggesting that the magma chambers are never completely emptied by the caldera-forming eruptions. The minimum volumes of erupted magma to trigger collapse are calculated from the correlation between the caldera diameters and the evaluated volume of magma chambers. The minimum eruptive volume for the collapse correlates with the square of the caldera radius r and the square of the depth to the magma chamber h, and inversely correlates with the bulk modulus of magma, which is mainly controlled by the bubble fraction in the magma. A bubble fraction between 5 and 10% at the onset of collapse may explain the distribution of the erupted volumes at the onset of collapse of the calderas in nature.

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1. Introduction

Collapse calderas are commonly associated with catastrophic explosive eruptions, which can release up to 1000 km^3 of pyroclastic material within a few days (Druitt and Sparks, 1984; Self and Blake, 2008). These pyroclastic eruptions associated to caldera collapse are among the most serious natural disasters, releasing widespread ash and gas in the atmosphere, and can affect global climate (e.g., Rampino and Self, 2008).

A caldera is formed by the faulting and sinking of the roof of the magma chamber during the rapid withdrawal of magma from the chamber (Lipman, 1997 and references therein). Collapse mechanism has been constrained from theoretical analysis (Scandone, 1990), analogue (Roche et al., 2000) and numerical (Hardy, 2008) experiments and field observations in many eroded calderas (Lipman, 1997). These results suggest that the fundamental structure of many collapse calderas is a block surrounded by caldera-border faults, though the structure of the block may exhibits wide variation from coherent (piston) to fragmented (chaotic collapse). Geophysical observations of the recent caldera-forming eruptions also confirm the role of the caldera-border faults. Based on the observation of low-frequency earthquakes and tilt changes during the caldera formation in Miyakejima 2000 A.D., Kumagai et al. (2001) proposed a model in which the competition between the decompression of magma chamber and friction on the ring faults controls the incremental collapse of a cylindrical block. Stix and Kobayashi (2007) discuss the timing of collapse and the vesiculation in the magma chamber of the four caldera-forming eruptions using the model of Kumagai et al. (2001). This model indicates that the decompression of the magma chamber to induce caldera collapse is controlled by the eruption ratio (volume ratio of the magma withdrawn from a chamber against the total volume of

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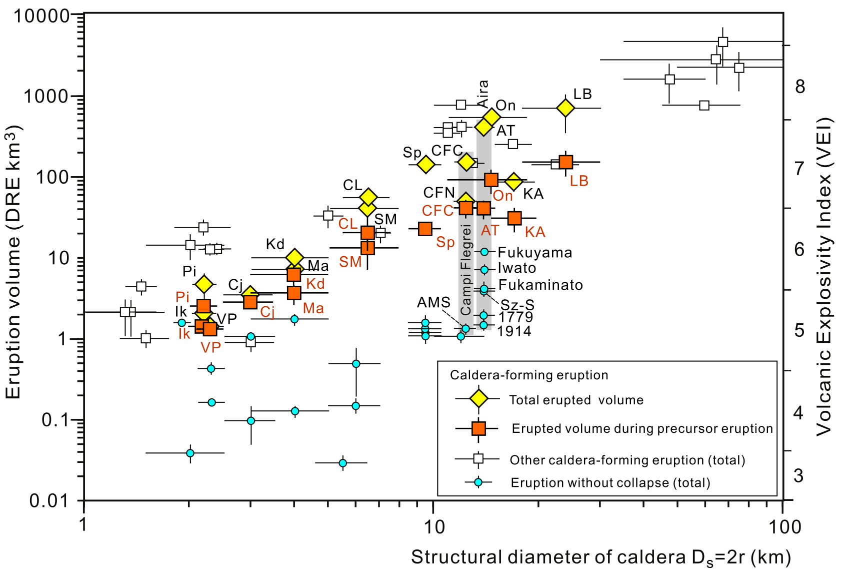

Fig. 1. Total erupted volume of caldera-forming eruptions (diamond) and erupted volume during the precursory eruption (square) of representative 14 eruptions plotted against the diameter of the calderas. Indexes show the name of caldera-forming eruptions; Ik: Ikeda 6.5 ka, VP: Vesuvius Pompei 79AD, Pi: Pinatubo 1991, Cj: Ceboruco Jala 1 ka, Ma: Mashu 7.5 ka, Ks: Kusdach 240 AD, SM: Santorini Minoa 3.5 ka, CL: Crater Lake 6.8 ka, Sp: Shikotsu 45 ka, CFC: Campi Flegrei 39.3 ka, CFN: Campi Flegrei 15 ka, AT: Ito AT 29 ka, On: Oruanui 26.5 ka, KA: Kikai Akahoya 7.3 ka, LB: Long Valley Bishop tuff 760 ka. The eruptions from Aira caldera and Campi Flegrei are highlighted. Three pre-caldera eruptions (Fukuyama, Iwato and Fukaminato eruptions) and three post-caldera eruptions (Sz-S, 1779 and 1914 A.D. eruptions) without caldera collapse of Aira are identified. Post caldera eruption of Campi Flegrei (AMS: Agnano – Monte Spina eruptions) is also identified. Total volumes of erupted magma of other representative caldera-forming eruptions (small open squares) and post-caldera eruption without caldera collapse (small circles) are also shown.

the chamber), and the bulk modulus of magma that is strongly affected by the bubble fraction in the magma. The volume of magma withdrawn from the chamber prior to the eruption can be deduced from geological evidence (Walker, 1985) or geophysical observations (Stix and Kobayashi, 2007). However, our knowledge on the size of a magma chamber is still limited, though many geophysical observations attempt to figure out the location and size of magma chamber beneath volcanoes (e.g., Sanders et al., 1995; Finlayson et al., 2003). Even though some previous works assumed the total eruptive volume as the total volume of magma chamber, this assumption seems unrealistic.

Here, we extend the model of Kumagai et al. (2001) to evaluate: 1) the total volume of a magma chamber associated with caldera collapse and 2) the threshold of the volume of magma that must be withdrawn for a caldera to collapse. First, we compile known structural diameters of caldera border faults, depth to the roof of magma chambers, volumes of erupted magma before the onset of collapse and during the entire period of the caldera-forming eruption. Then, we present an analytical model for piston collapse along a vertical ring fault to estimate the volume of the magma chamber and the erupted volume to trigger collapses in nature.

We focus on collapse calderas formed by pyroclastic eruptions mainly in silicic systems. In the case of collapse calderas formed by pyroclastic eruptions, most of magma withdrawn from the chamber is released to the Earth's surface where the erupted volumes can be estimated. In the case of historic eruptions, most magma associated with caldera collapse was erupted within several days, suggesting the rapid decompression of magma chamber and en-mass collapse (Stix and Kobayashi, 2007). Conversely, calderas formed by lateral intrusions, observed mainly in basaltic systems (Michon et al., 2011) are not considered here, because of the difficulty of a quantitative evaluation of the intruded volume of magma, and probably multiple caldera growth with repetition of collapse (Kumagai et al., 2001; Michon et al., 2011).

2. Erupted magma volumes from caldera-forming eruptions

2.1. Size and erupted volumes of calderas

To evaluate the relationship between caldera size and erupted volume of magma, we analyzed 36 calderas, with 39 eruptions with caldera collapse and 25 eruptions without caldera collapse (Appendix). They were chosen because of their well-defined caldera structure (structural diameter $D_s = 2r$; Lipman, 1997; Geshi et al., 2012) and erupted volumes (V_{etotal}).

A positive relationship between the size of calderas and erupted volumes is recognized (Fig. 1), as pointed by previous studies (Spera and Crisp, 1981; Scandone, 1990). Calderas of 3 to 5 km in diameter were formed by eruptions of 2–10 km^3 of magma, whereas calderas of 10 to 20 km in diameter were formed by eruptions >100 km^3 of magma. Calderas wider than 50 km were formed by eruptions producing more than 1000 km^3 of magma (e.g., Toba, 74 ka; Rampino and Self, 2008). For a given caldera diameter, the erupted volumes of magma without caldera collapse are smaller than those of the caldera-forming eruptions (Fig. 1). The positive correlation between caldera size and volume of the caldera-forming eruptions is weak for calderas less than 3 km in diameter. For example, some caldera-forming eruptions produced more than 10 km^3 of magma with relatively small structural diameter $\sim$2 km (e.g., Krakatau 1883; Carey et al., 1996; Deplus et al., 1995).

2.2. Precursory eruptions

Most of the collapse-episodes are accompanied by pyroclastic eruptions from central vents or ring fractures just before the onset of collapse, without significant time gap (here termed "precursory eruptions"; Scandone, 1990). In the case of historic collapses, the climatic stage of the precursory eruptions lasts within a few days (Vesuvius 79 A.D.; Sigurdsson et al., 1982, and Tambora 1815 A.D.; Self et al., 1984) though in some cases, minor eruptions and/or anomalies starts several month prior to the collapse (e.g., Krakatau 1883 A.D.; Self, 1992).

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