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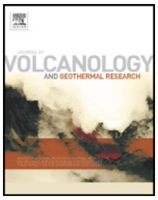

Short communication

A crystal concentration method for calculating ignimbrite volume from distal ash-fall deposits and a reappraisal of the magnitude of the Campanian Ignimbrite

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ABSTRACT

Distribution of ignimbrites is controlled chiefly by preexisting topography forming thin veneer deposits on steep-slope relief and thicker, valley-ponding deposits in valley bottoms. The calculation of volumes of ignimbrites is difficult because of the nonlinear dependence of thickness with distance. Calculation using geometrical methods is reviewed and the uncertainty with each method is discussed. Based on the genetic relationship between vitric-enriched, co-ignimbrite air-fall ashes and crystal-enriched ignimbrites, a new method is proposed to calculate ignimbrite volume. A simple equation can be used if the volume of the associate and co-genetic distal ash fall and the ignimbrite vitric loss are known. This simple relation is unaffected by deposit geometry, paleotopography irregularities and post-depositional compaction and erosion. The proposed methodology is used to reassess the controversial volume estimates of the Campanian Ignimbrite (Campi Flegrei, southern Italy). The revised volume of the ignimbrite is 54 km^3 (25 km^3 DRE). The calculated magnitude of the collapsing phase (sum of the ignimbrite mass and co-ignimbrite ash mass) is 7.2.

1. Introduction

Evaluating tephra volumes is fundamental to define the size of an eruptive event (Walker, 1980) and assess the effects of the largest eruptions on Earth (Mason et al., 2004; Self, 2006). While, many papers address the assessment of fallout tephra volumes, (e.g. Pyle, 1989; Fierstein and Nathenson, 1992; Pyle, 1995; Bonadonna and Costa, 2012) there are no widely accepted methods for estimating the volume of an ignimbrite, and even fewer proposed to calculate the volume of widespread, sheet-forming deposits outcropping on very rugged topography. Large plinian eruptions often produce both fall deposits and ignimbrites, the latter comprising a greater amount of the total eruptive product (Parfitt and Wilson, 2008) (Table 1). The volume of an ignimbrite is difficult to evaluate due to the uneven distribution and thickness of the deposit (controlled by paleomorphology), the irregularity of the ignimbrite surface, variations in deposit density, and the effects of post-emplacement erosion or burial under younger products. Furthermore, voluminous ignimbrites are often related to caldera-forming plinian eruptions (see Table 2 of Mason et al., 2004) and a significant fraction of their volume is displaced, producing an *intracaldera fill* and an *outflow sheet*. *Intracaldera fill* occurs when the caldera collapse takes place during the early phase of the eruption, trapping a large volume of the erupted material within the collapsed area. If the collapse takes place at the end of the eruption, most of the volume is transported and emplaced outside the caldera, producing the ignimbrite *outflow sheet* (Smith and Bailey, 1968). Current methods used to calculate the volume of an ignimbrite produced by a caldera-forming eruption require knowledge of the time of caldera collapse and the caldera geometry to evaluate the *intracaldera fill* (Smith and Bailey, 1968; Lipman, 1997; Salisbury et al., 2010; Folkes et al., 2011; Best et al., 2013). Lipman (1984) suggested that both volumes (outflow sheet and intracaldera fill) can be considered roughly equal; although, estimates exist in which the intracaldera fill exceeds the outflow sheet volume. Intracaldera fill is considered to be 66% of the total ignimbrite volume for the Atana Ignimbrite (Lindsay et al., 2001) and Vilama Ignimbrite (Soler et al., 2007), up to 70% for the Neapolitan Yellow Tuff (Scarpati et al., 1993) and rises to 90% for the Pastos Grandes Ignimbrite (Salisbury et al., 2010). Recently, Henry and John (2013) have postulated that the major ash-flow tuffs (>1000 km^3 per ignimbrite) of the Western Nevada field have almost no outflow counterpart; although, it is very difficult to estimate their total volume due to uncertainties in the data (thickness, erosion rate, paleotopography, caldera dimension). On the contrary, no caldera and no intracaldera deposits have been recognized for the Cottonwood Wash Tuff, probably because the associated caldera was engulfed in a younger caldera (Best et al., 1989, 2013). In the latter case, the intracaldera volume has been estimated by doubling the

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Table 1
Volume estimates from the literature associated with thirty large ignimbrites worldwide. For each ignimbrite the age, source area and the method used for the volume estimate are reported.

Eruption/Formation	Age[a]	Source area	Estimated total volume (km^3)		Method	References
			bulk	DRE		
Wah Wah Spring Tuff	30.06	Indian Peak caldera complex, Great Basin (USA)	5900		It is the average of four different values arising from four different models presented by Best et al. (2013). Each model take into account a different shape and geometric parameters for the caldera floor.	Best et al. (2013)
Fish Canyon Tuff	27.6	La Garita caldera, San Juan volcanic field, Colorado (USA)	5000		Taking into account the areal extent of the deposits, its thickness inside and outside the caldera and the areal extent of the caldera. It is just a minimum because it does not take into account the distal ash deposits.	Lipman (2000)
Youngest Toba Tuff	0.074	Toba caldera (Sumatra)		>2800	Ignimbrite volume calculated assuming an out flow sheet area of 20,000 km^2, intracaldera area of 2500 km^2 and average thickness of 80 and 400 m, respectively. Co-ignimbrite ash volume estimated using the ignimbrite crystal concentration.	Rose and Chesner (1987)
Lund Tuff	29.02	No caldera recognized	2900–3600[b]	2600–3200[b]	Taking into account the thickness of the deposits inside and outside the caldera and the crustal extension of the Great Basin after the emplacement of Lund Tuff.	Maughan et al. (2002)
Huckleberry Ridge Tuff	2.1	Yellowstone caldera, Wyoming (USA)	2450		The deposits of the HRT are divided in three Members (A, B and C; Christiansen (1979)) having different distributions. The volume of each member is calculated taking into account the areal extent and the average thickness. The intracaldera fill is not well constrained. Different source areas, almost completely concealed, are hypothesized.	Christiansen (2001)
Oldest Toba Tuff	0.85	Toba caldera (Sumatra)		2300	Distal ash volume obtained by multiplying the total area covered by ash by a minimum thickness (1800 km^3, Pattan et al. (2010)). The ignimbrite volume has been estimated assuming a 40 km wide caldera filled to a depth of 400 m (500 km^3, Knight and Walker (1986)).	Knight and Walker (1986); Pattan et al. (2010)
Cottonwood Wash Tuff	31.1	Indian Peak caldera complex, Great Basin (USA)	2000		The outflow sheet volume (1000 km^3) has been estimated taking into account the ignimbrite thickness and the areal distribution. The irregularities of the depositional surface has been considered for the thickness. The intracaldera fill volume has been estimated doubling the outflow volume. About 240 km^3 of distal ash should be added.	Best et al. (2013)
Atana Ignimbrite	4.1	La Pacana caldera, central Andes (Chile)	2500[c]	1600[c]	The intracaldera fill volume was calculated starting from the caldera volume and taking into account the rate of subsidence, the unfilled portion of the caldera and the portions filled by collapse breccias. The outflow volume was calculated assuming that two third (66%) of the ignimbrite was trapped within the caldera during the early phases of the eruption.	Lindsay et al. (2001)
Blacktail Tuff	6.5	Heise volcanic field, Eastern snake River Plain, Idaho (USA)	1500		Assuming an average ignimbrite thickness and the inferred or exposed areal distribution.	Morgan et al. (1984)
Kilgore Tuff			800			
Blue Creek Tuff			500			
Pastos Grandes	2.89	Altiplano-Puna Volcanic Complex (Argentina, Bolivia, Chile)	1575	~1500	Intracaldera and outflow volumes have been calculated multiplying the average thickness, inside and outside the caldera, of each ignimbrite sheet by its areal extent. The intracaldera thickness is considered just a minimum because the base is not visible.	Salinsbury et al. (2010)
Ignim. Guacha	5.7		1383	~1300		
Ignim. Chuhuilla	5.9		1259	~1200		
Ignim. Tara Ignim.	3.49		856	~800		
Vilama Ignimbrite	8.4–8.5	Vilama caldera, Altiplano-Puna Volcanic Complex (Argentina, Bolivia, Chile)		1000–1400	The extracaldera minimum volume has been estimated taking into account the areal extent and the mean thickness of the deposits (without considering the effect of the erosion). The intracaldera volume has been estimated with the method of Lipman (1997) that consider several geometric parameters related to the caldera. See Lipman (1997) for details. In addition, they consider that the two third of the ignimbrite sheet was emplaced within the caldera following the model of Lindsay et al. (2001) for the Atana Ignimbrite.	Soler et al. (2007)
Ora Ignimbrite	277–274	Athesian Volcanic Group, Southern Alps (Italy)	>1290		The minimum volume has been calculated from construction of average thickness contours over the intra- and extra-caldera ignimbrite successions, defined by logged field measurements and regional mapping.	Willcock et al. (2013)
Caetano Tuff	33.8	Caetano caldera, north-central Nevada (USA)	1100		Taking into account the areal extent of the deposits, its thickness inside and outside the caldera and the areal extent of the caldera. It is just a minimum because it does not take into account the distal ash deposits.	John et al. (2008)
Lava Creek Tuff	0.64	Yellowstone caldera, Wyoming (USA)	1000		The deposits of the LCT are divided in two Members (A and B, Christiansen and Blank (1972)) The volume of both members has been estimated from planimeter measurements for the areal extent and thickness measurements in field. The distribution and thickness of the Member B are better constrained than those of Member A (the base of Member A is not well exposed).	Christiansen (2001)