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RESEARCH ARTICLE

Estimating the eruptive volume of a large pyroclastic body: the Otowi Member of the Bandelier Tuff, Valles caldera, New Mexico

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Abstract The 1.60 Ma caldera-forming eruption of the Otowi Member of the Bandelier Tuff produced Plinian and coignimbrite fall deposits, outflow and intracaldera ignimbrite, all of it deposited on land. We present a detailed approach to estimating and reconstructing the original volume of the eroded, partly buried large ignimbrite and distal ash-fall deposits. Dense rock equivalent (DRE) volume estimates for the eruption are 89 + 33/−10 km^3 of outflow ignimbrite and 144 ± 72 km^3 of intracaldera ignimbrite. Also, there was at least 65 km^3 (DRE) of Plinian fall when extrapolated distally, and 107 + 40/−12 km^3 of coignimbrite ash was "lost" from the outflow sheet to form an unknown proportion of the distal ash fall. The minimum total volume is 216 km^3 and the maximum is 550 km^3; hence, the eruption overlaps the low end of the super-eruption spectrum (VEI ~8.0). Despite an abundance of geological data for the Otowi Member, the errors attached to these estimates do not allow us to constrain the proportions of intracaldera (IC), outflow (O), and distal ash (A) to better than a factor of three. We advocate caution in applying the IC/O/A = 1:1:1 relation of Mason et al. (2004) to scaling up mapped volumes of imperfectly preserved caldera-forming ignimbrites.

Keywords Bandelier Tuff · Otowi member · Valles caldera · Ignimbrite volume · Super-eruption

Introduction

Volcanic eruptions are major agents of mass transfer between the interior and surface of the Earth, and it is therefore important to determine the sizes of individual eruptive events. In particular, knowing the volumes of major rhyolitic caldera-forming eruptions is an essential component in assessing the potential for past environmental impacts, models of caldera formation, magma chamber evolution and pluton emplacement, and the volcanic mass flux in persistently active regions. Estimates of the volumes of emplacement units within a large compositionally complex eruption sequence may additionally place constraints on petrogenetic models.

It is difficult to estimate accurate volumes for pyroclastic units (Wilson 1991), even in cases of observed eruptions that leave near-perfectly preserved deposits (Bonadonna and Houghton 2005); for example, the volume of the 1991 Pinatubo eruption deposits is known to have an accuracy of no better than ~50 % (Scott et al. 1996). The difficulty is compounded for prehistoric and ancient deposits that may have experienced significant erosion or burial. This study presents a reconstruction of the minimum total dense rock equivalent (DRE) volume of the Otowi Member of the Bandelier Tuff, Valles caldera, New Mexico, USA, and may serve as an example of how volumes of large ignimbrites and fall deposits that are partially or extensively eroded can be calculated.

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The Jemez Mountain volcanic field (JMVF) of north central New Mexico, which hosts the Valles caldera, is one of the most intensely studied large volcanoes in North America (e.g., volumes edited by Heiken 1986; Goff and Gardner 1988; Goff et al. 1996; Kues et al. 2007). Despite this knowledge, there is a lack of detailed studies regarding the volumes of the two main ignimbrites which have been erupted over the past two million years. The Bandelier Tuff is subdivided into the Otowi (lower) Member erupted at 1.60 ± 0.01 Ma and the Tshirege (upper) Member erupted at approximately 1.24 ± 0.01 Ma (Izett and Obradovich 1994; Spell et al. 1996; Phillips et al. 2006; Wolff and Ramos 2014). Both members of the Bandelier Tuff are compositionally zoned, high silica rhyolitic pyroclastic units exhibiting systematic internal stratigraphic variations in incompatible trace element concentrations (Smith and Bailey 1966; Self et al. 1996).

The Otowi Member (OM) is associated with the first major collapse event at Valles caldera (Bailey et al. 1969; Goff et al. 1989; Self et al. 1986; Smith and Bailey 1966, 1968). The eruption produced both the Guaje Pumice Bed (incorporating the initial Plinian fall unit and later coignimbrite fall deposits), and outflow and intracaldera ignimbrites (which are not separately named; Gardner et al. 2010). Most of the fall units were coeval with ignimbrite deposition (Wolff et al. 2006; Cook 2009; Self et al. 2010).

Prior estimates of OM volume have been based on the distribution of existing outcrops and also on the distribution of the similar, better preserved, and exposed Tshirege Member. Smith and Bailey (1966) initially proposed a total volume of 200 km^3 DRE based on an assumption of similarity between the Tshirege and Otowi Members. Self et al. (1996) inferred a total erupted volume of 400 km^3 DRE, which included 20 km^3 DRE for the Guaje Pumice Bed, based on extrapolation of thicknesses from isopach maps constructed from the proximal deposit.

In this paper, we improve on prior estimates by considering distal ash fallout and ignimbrite exposures, precaldera and postcaldera collapse phases of the eruption, and the buried intracaldera volume, with an estimate of errors. Mason et al. (2004) reviewed the literature on large, caldera-forming ignimbrite eruptions and proposed that volumes of intracaldera ignimbrite, outflow ignimbrite, and ash fall deposits are roughly equivalent (the IC/O/A = 1:1:1 relationship), hence an estimated volume for any one of the three components has predictive value for the size of the whole eruption. We use our results from the Otowi Member to test the outflow = intracaldera = distal ash relationship of Mason et al. (2004).

Data sources

A combination of geological maps, commercial geothermal drilling results, and scientific core hole study data provide information on the thickness and distribution of the proximal to medial OM deposits. The geological map of Smith et al. (1970) defined the mapped extent of the deposit and provided coarse-scale thickness data for the entire area around the caldera. Hulen et al. (1991) provided a summary of drill hole data and isopach maps of the OM and other units within the western part of the Valles Caldera. Geophysical models of the caldera fill have been provided by Segar (1974) and Nowell (1996). On the Pajarito Plateau, east of the caldera (Fig. 1), numerous holes have been drilled for water, environmental remediation, and seismic hazard studies by Los Alamos National Laboratory; these data were compiled by Broxton and Reneau (1996), who provided an isopach map of the OM in this area that we use here.

Two significant issues make volume calculations difficult. First, the OM has been extensively eroded and subsequently covered by younger units making it difficult to determine the true extent of the original deposit. Second, the paleotopographic surface onto which the OM was erupted is covered by the deposit itself and younger units, and is thus not well constrained in most areas. Otowi Member thicknesses are best constrained on the Pajarito Plateau, due to extensive deep dissection and the many drill holes that penetrate it. Consequently, the paleosurface has been mapped on the Pajarito Plateau (Dransfield and Gardner 1985; Potter and Oberthal 1987; Reneau and Dethier 1996).

Methods

To estimate the volume of ignimbrite, we adopt and extend the approach of Wilson (1991), which begins with characterization of overall unit geometry as low (<1:1000; thin and widespread) or high aspect ratio (>1:1000; thick and localized). Aspect ratio is defined as average thickness divided by the diameter of a circle of equivalent area to the unit. Wilson (1991) found that for low aspect ratio ignimbrites, the original extent of the deposit (prior to erosion) can be estimated by drawing a single envelope around all known exposures and calculating its area. For high aspect ratio ignimbrites, a closer approximation of original outcrop area is obtained by drawing multiple envelopes around present day outcrops. Using thickness data derived in this study, an average OM thickness of 110 m was calculated, and, on the basis of the Smith et al. (1970) geological map, a maximum enclosing diameter of 90 km was determined for the ignimbrite, excluding extreme outliers such as those near Santa Domingo Pueblo and Truchas (Fig. 1); including these add

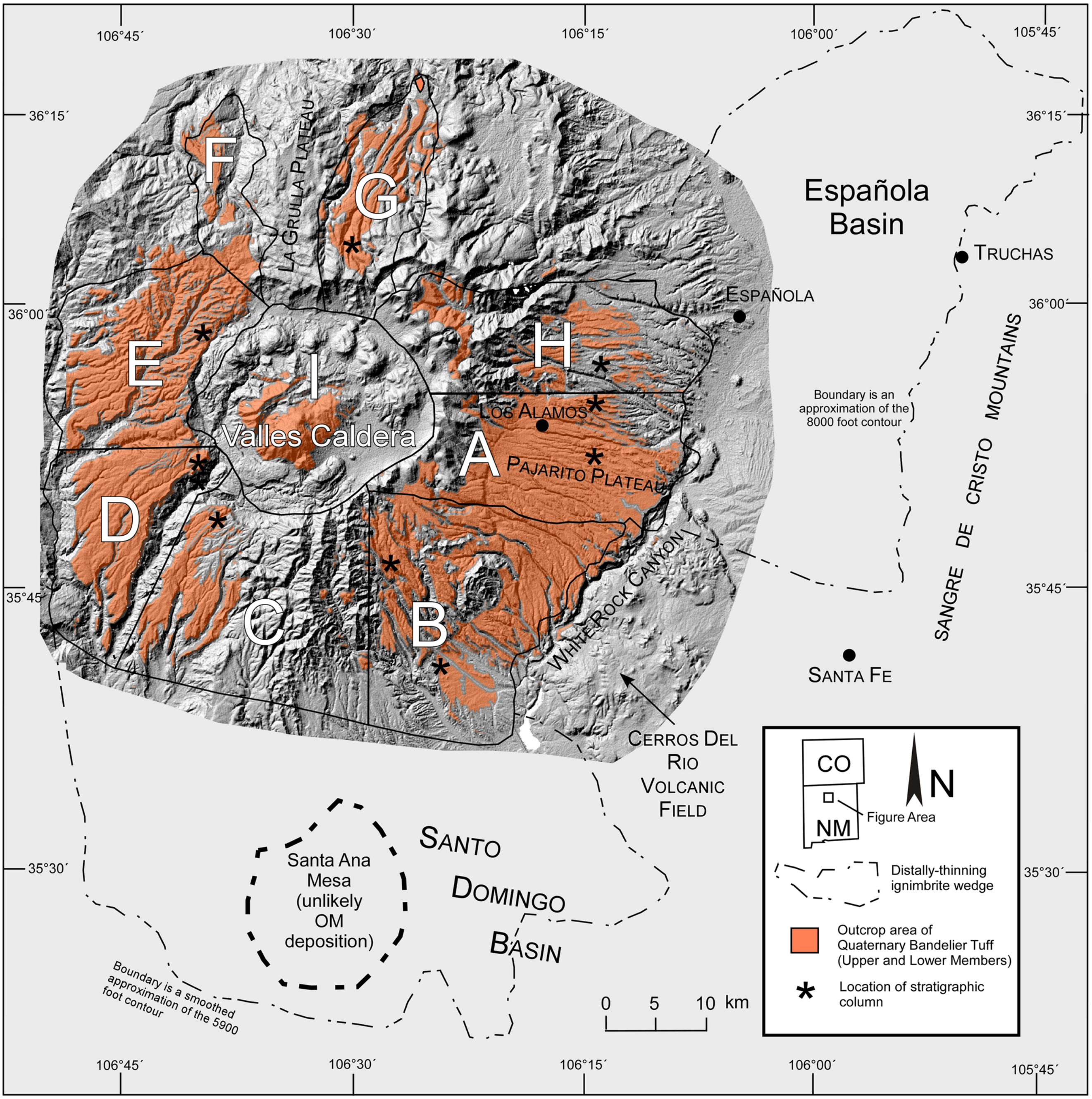

Fig. 1 Map showing individual zones used in the calculation of the volume of the Otowi Member. Note that Zone I is intracaldera tuff. Also shown are possible distal ignimbrite limits in rift basins (*dot-dash* outlines), explained in the text

little to the total volume (see below). These figures yield an average aspect ratio of 1:820, thus the OM is a high aspect ratio ignimbrite.

Note that the average OM thickness (110 m) was not used uniformly for the volume calculations in this study. Rather, in our procedure, the outline of the ignimbrite is defined using its current outcrop area. Then, the deposit is broken down into zones, based on geological characteristics. For outflow ignimbrite, average thicknesses were determined for each separate zone and these thicknesses were used to calculate individual zone volumes. These volumes were summed to derive a total volume (Fig. 1, Table 1). The intracaldera ignimbrite was treated separately using available thickness data and geophysical data. Fall deposits (including Plinian and probable coignimbrite distal ash) are calculated separately using preexisting and new isopach maps.

In localities where both the Tshirege and Otowi Members are present, the Tshirege Member was used as a guide to help identify the OM extent, as the more-welded top of the younger ignimbrite acts as a caprock for parts of the OM; structural

Table 1 Estimated volumes of outflow tuff

Zone	Area (km^2)	Ave. thickness (km)	Volume (km^3)	Volume (km^3 DRE)
A	187.3	0.071	13.3	7.7
B				
B1	122.0	0.146	17.8	
B2	122.0	0.067	8.2	
B3	17.1	0.046	0.8	
B4	8.5	0.046	0.4	
B5	64.7	0.094	6.1	
B6	75.6	0.057	4.3	
B7	21.5	0.107	2.3	
			39.9	23.1
C				
C1	87.3	0.094	8.2	
C2	113.7	0.137	15.6	
C3	110.6	0.072	8.0	
C4	78.6	0.073	5.7	
			37.5	21.8
D				
D1	99.0	0.046	4.6	
D2	50.5	0.065	3.3	
D3	68.3	0.027	1.8	
			9.7	5.6
E				
E1	116.8	0.095	11.1	
E2	94.2	0.095	8.9	
			20.0	20.0
F	73.7	0.067	4.9	2.8
G	94.9	0.079	7.5	4.4
H	67.1	0.037	2.5	1.5
White Rock Cyn.	23.1	0.130	3.0	1.7
Distal outflow (thinning wedge)			38.9	22.6
Uncertainty			17.7	10.3
Outflow Totals:			*138.3 (+56.6/−17.7 km^3)*	*88.6 (+32.9/−10.3 km^3) (DRE)*

Letters in italics represent zones used in calculating volumes; subheadings (E1, E2 etc.) represent subsections of the italicized zones that have been broken out on the basis of thickness to allow for a more accurate volume calculation per zone. Note that ignimbrite of Zone E is assumed to be densely welded; ignimbrite of all other zones is assumed to have a bulk density of 1430 kg m^{-3}. Uncertainty is derived from estimates of possible buried paleotopographic irregularities. See text for details

contours therefore form the basis of volume estimates where the Tshirege Member is present. Knowledge of pre-OM paleotopographic features was used to augment estimates of the preerosion extent of outflow ignimbrite.

Nine separate zones labeled A–I were created based on geological criteria (Fig. 1). Distal OM ignimbrite has been added onto the periphery of the existing ignimbrite distribution in the Santo Domingo Basin south of the caldera and in the Española Basin east of the caldera; there are isolated ignimbrite exposures at two localities near Truchas and Santo Domingo Pueblo, respectively. Large gaps in OM ignimbrite outcrop distribution occur north and northeast of the caldera. There is no evidence that OM ignimbrite was ever deposited in these areas; we attribute this to blocking of pyroclastic flows by large precaldera domes of Tschicoma dacite situated on the north-northeast rim of the caldera (Smith et al. 1970; Goff et al. 2011). Similar reasoning applies to the lack of OM ignimbrite on the La Grulla Plateau located between zones F and G, and to the San Miguel Mountains within Zone B (Fig. 1). In contrast, scattered remnants of OM resting on precaldera rocks south of the caldera (zone C) indicate that the ignimbrite formerly covered most or all of this area.

On the periphery of the volcanic field, OM exposures are very scarce due to extensive erosion. It is possible that ignimbrite was deposited over much of the Santo Domingo and Española Basins, hence hypothetical volumes are calculated by assuming coverage below elevations where the most distant outcrops occur (see below).

Density considerations

Over most of its exposed extent, the Otowi Member is non-welded. More specifically, it conforms to welding intensity ranks I–II of Quane and Russell (2005): "unconsolidated, non-coherent, loosely packed, little to no adhesion between shards" and "coherent, some adhesion between shards, no coalescence of glassy material." Quane and Russell (2005) base their welding intensity scheme on porosity and density measurements of the Tshirege member of the Bandelier Tuff, which is physically very similar to the Otowi Member at equivalent welding intensity except for its lower lithic content (Self et al. 1996); the average density for non-welded Tshirege Member is 1310 ± 50 kg m^{-3}. Typical Otowi Member contains 10–20 % by weight of dominantly andesite lithic fragments, which indicates bulk densities in the range 1370–1450 kg m^{-3}. This is confirmed by the average of five density measurements of non-welded Otowi, which is 1430 kg m^{-3}. We use the latter figure as an estimate for the bulk density for all Otowi ignimbrite except where densely welded. Intracaldera tuff and the northwest sector (zone E, Fig. 1) are dominated by densely welded tuff and are assumed to be dense rock. For dense rock, we assume the value of 2450 kg m^{-3} used by Mason et al. (2004). Otowi ignimbrite in all other zones is converted to equivalent dense rock using a factor of 1430/2450 = 0.58.

Estimation of volumes

Proximal to medial outflow ignimbrite

For each zone (A–H), areas of OM ignimbrite were estimated from the Smith et al. (1970) map (Fig. 1, Table 1). For each lettered zone, an average thickness was calculated using available drill core data and stratigraphic thicknesses and multiplied by the area of the zone to determine volume. The separate results were summed to determine a total volume for each lettered zone.

The pre-OM topography is only well constrained for Zone A (Broxton and Reneau 1996). Elsewhere, the pre-OM surface exhibits deep canyons and broad valleys that extend radially away from the current caldera. It is likely that many former canyons were completely filled and remain buried beneath the tuff, leading to underestimation of volumes; alternatively, exposures in modern canyons that follow paleocanyons could lead to overestimation of thicknesses and hence volumes. We attempt to quantify uncertainties arising from paleotopography by estimating possible paleocanyon volumes for areas B, C, D, E, and G (Table 1).

A total ignimbrite volume of 138 km^3 was calculated for zones A–H (Table 1). This includes a volume of ignimbrite that ponded in White Rock Canyon southeast of zone B. Using the density conversion factor of 0.58 in the non-welded portions of the ignimbrite, and assuming 0 % porosity in the welded portions (zone E), the calculations yield a DRE volume of 89 km^3. The uncertainty arising from paleotopography is 17.7 km^3 bulk volume or 10.3 km^3 DRE.

Distal ignimbrite in the Rio Grande rift basins

Two exposures suggest that the original extent of OM ignimbrite may have been much greater than that now preserved: a thin (30 cm) flow deposit interbedded with fallout units at the eastern boundary of the Española Basin approximately 55 km from the vent near Truchas, NM (Fig. 2a), and a 15-m thick ignimbrite outcrop found in the eastern Santo Domingo Basin (Fig. 1). Extrapolation of OM coverage to elevations where these remnants are found suggests that originally much of the Española and Santo Domingo Basins were filled with ignimbrite. Distal boundaries were therefore defined using topographic contour lines, smoothed to remove the effects of post-1.6 Ma stream erosion (Fig. 1). This procedure adds 38.9 km^3 bulk volume or 22.6 km^3 DRE to the total. The geometry of the basin-filling ignimbrite is unknown; for example, the surviving distal deposits could have been emplaced by directed flow lobes, rather than representing basin fill. Hence, we quote this as an uncertain addition to the total volume of ignimbrite outflow. The total volume of outflow, with uncertainties, is therefore estimated at 138 + 57/−18 km^3 bulk or 89 + 33/-10 km^3 DRE.

Intracaldera tuff

Intracaldera subsurface geology is well constrained for a small area in the west central part, covering about 10 % of the total caldera area, which has been extensively drilled for geothermal exploration, plus two Continental Scientific Drilling Project core holes, VC-2A and VC-2B (Hulen et al. 1991). There is no direct information about subsurface stratigraphy for the remaining 90 %. However, gravity modeling by Segar (1974), refined by Nowell (1996), provides estimates of total caldera fill (Otowi Member + Tshirege Member + other volcanic units across the entire topographic caldera) and demonstrates that intracaldera fill is much thicker in the eastern than in the western part of the caldera and provides some constraints on extrapolation of the drill hole data across the caldera. The gravity modeling cannot distinguish between the two main ignimbrites, which are presumed to be densely welded tuffs with a density of 2350 kg m^{-3} (Nowell 1996). Here, we employ the results of the geophysical modeling and

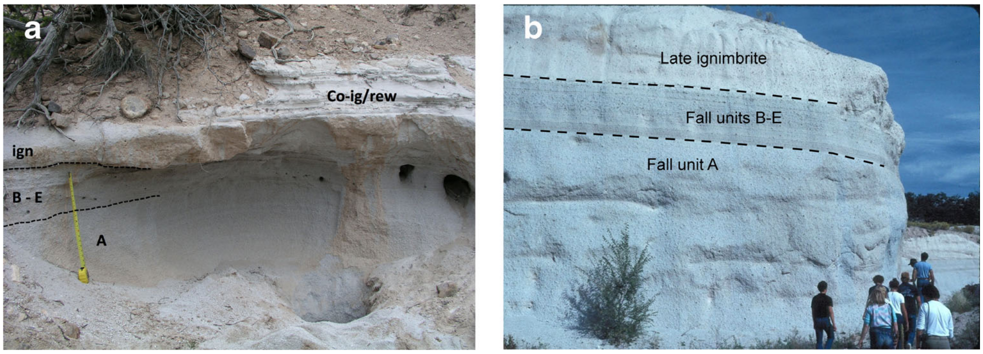

Fig. 2 **a** Otowi Member exposure at Truchas (~55 km east-northeast of vent, Fig. 1). *A*: Fall unit A, 1.4 m thick; *B–E*: fall units B, C, D, and E, aggregate thickness 21 cm; *ign*: massive, poorly sorted ignimbrite flow unit, 20 cm thick; *co-ig/rew*: bedded, partly reworked coignimbrite ash overlying the flow unit. Tape is extended to 50 cm. **b** Guaje Pumice Bed fall deposits at the Copar pumice mine, on the north rim of Guaje Canyon, 20–25 km E of the vent area and on the dispersal axis for fall unit A, which is approximately 10 m thick at this locality. Fallout pumice is overlain by late ignimbrite flow units of the Otowi Member

the well data summarized by Nielson and Hulen (1984) and Hulen et al. (1991) to arrive at a range of estimates for the volume of intracaldera Otowi Member. We also discount a contribution from lithic megablocks (sensu Lipman 1997) that might be present in the collar zone of the caldera.

We additionally adopt two limiting values for the area of the caldera produced during the Otowi collapse episode. The maximum, 335 km^2, is simply the area enclosed by the contact between the caldera wall and caldera fill (note that the Toledo Embayment is excluded from the caldera). The minimum, 250 km^2, is the area enclosed by a curve extending the “Valles Caldera structural margin” (Hulen et al. 1991) through the post-Otowi Cerro Toledo Rhyolite domes in the north and east of the caldera. This treatment adopts the assumption that the second major collapse feature, formed in association with the Tshirege eruption, is partly nested within the first (as proposed by Heiken et al. 1986; Self et al. 1986). Thickness data (Hulen et al. 1991) support the assumption that the margins of the two features are coincident in the western caldera.

The Valles has been referred to as a trapdoor caldera due to the much greater thickness of fill in the eastern half (Heiken et al. 1986). Most of the eastward thickening of intracaldera tuff is accounted for by the Tshirege Member (Hulen et al. 1991). Within the part of the caldera sampled by drilling, the Otowi Member was apparently emplaced onto a highly irregular topography, either preexisting or produced by syneruptive faulting of the caldera floor. It is thickest in the northwest (585 m) and southwest (~875 m) caldera and may even thin from the caldera center toward the east, although the latter observation is partly dependent on a single well (177 m, Hulen et al. 1991). More significantly, where drilled, the Otowi is consistently thinner than the Tshirege (max. 1296 m), regardless of total thickness, except close to the northwest structural margin of the caldera (Hulen et al. 1991). In the area most densely sampled by drilling, average Otowi thicknesses at ~500 m are ~50 % those of the Tshirege, rising to 80 % elsewhere.

Nielson and Hulen (1984) and Hulen et al. (1991) identify a sequence of “lower tuffs” of varying thickness beneath the Otowi Member in the drill holes. These can be confidently correlated with the La Cueva Member of the Bandelier Tuff (the San Diego Canyon ignimbrites of Turbeville and Self 1988) in cores, but the correlation is less certain in the majority of wells and it is possible that part of the Lower Tuffs was produced during the Otowi eruption (Hulen et al. 1991). We therefore include the lower tuffs in the Otowi to estimate an upper limit to thickness and volume based on the drill hole data. We ignore the relatively insignificant post-Otowi “S$_3$ Beds” of Hulen et al. (1991).

We have estimated intracaldera volumes of the Otowi Member using three approaches. In all cases, the tuff is assumed to be densely welded as seen in CSDP core hole VC-2B, which provides the most complete continuously cored section through the caldera fill (Hulen and Gardner 1989).

1. Extrapolation of the arithmetic mean of Otowi thicknesses (436 m) over the whole topographic caldera yields 109 km^3 (minimum area) to 146 km^3 (maximum area), or 145–194 km^3 if the Otowi and Lower Tuffs are combined. The problem with this approach is that most of the thickness measurements on which it is based are concentrated in a very small area (Fig. 4 in Hulen et al. 1991).
2. The area-weighted average thickness of the Otowi based on the subsurface contour maps of Hulen et al. (1991) is ~300 m, which extrapolated over the whole caldera yields 75–100 km^3, or 95–127 km^3 if the Otowi and Lower Tuffs are combined. This approach does not take into account the eastward thickening of the total (lower tuffs + Otowi Member + Tshirege Member) caldera fill.
3. Nowell (1996) estimates 750 km^3 for the total volume of caldera fill. If the relationships found in the western caldera are typical of the whole, then less than half this volume can be Otowi. Extrapolation of the eastward thickening rate of the

Tshirege from Hulen et al. (1991) and comparison with the dip of the caldera floor as modeled by Nowell (1996) indicates that sub-Tshirege units also thicken eastward, but at a much smaller rate than the Tshirege; on average, the sub-Tshirege units account for 30 % of the thickness of the total, leading to a volume estimate for Otowi + lower tuffs of 225 km^3, or 178 km^3 for the Otowi alone.

In summary, the intracaldera volume of the Otowi Member can be estimated at a minimum of 75 km^3 (approach 2 above) and a maximum of 225 km^3 (approach 3 above), i.e., 150 ± 75 km^3, or 144 ± 72 km^3 corrected to a density of 2450 from 2350 kg m^{-3} used by previous workers. We suggest that the third approach used above is likely to be the most accurate. Accepting the stratigraphy of Nielson and Hulen (1984) and Hulen et al. (1991), which identifies the lower tuffs with the San Diego Canyon ignimbrites (now the La Cueva Member, Gardner et al. 2010), and rounding, our preferred value within the limits above is 178 km^3, or 167 km^3 at a density of 2450 kg m^{-3}.

Fall deposits and volumes

The Guaje Plinian deposit consists of five fall units, A–E (Self et al. 1986). Fall deposits are dispersed E–SE from the caldera (Self et al. 1986, 1996). To the east of the caldera rim, despite fall and ignimbrite deposition being synchronous in the proximal to medial regions out to 25 km from vent, several locations in zones A and H (Fig. 1) afford near-complete sections through the fall deposits (Fig. 2b). This allows a reasonable estimate of the dispersal of the fall deposits between 15 and 25 km from the vent area.

The OM as a whole is compositionally zoned (Wolff et al. 2015), as reflected by chemical gradients preserved in the Guaje fall deposits east of the caldera. Representative abundances of Rb, Y, and Nb, three highly incompatible trace elements in Bandelier magma system, are given in Table 2. First-erupted compositions of fall unit A are strongly enriched in Rb, Y, and Nb, declining upward to fall unit E (Table 2).

Self et al. (1996) estimated that the bulk volume of unit A could be as little as 7 km^3 or as much as 30 km^3 and that units B–E could represent as much as 65 km^3 (bulk volumes). The variability is due to unconstrained thinning rates of distal deposits downwind from the exposures in the JMVF, which are likely to be different from the more proximal thinning rate (Bonadonna et al. 1998).

Total thickness for the Guaje fall units is relatively well constrained proximally to medially (Self et al. 1986, 1996). Few distal exposures of Guaje fallout are known; only one near Mount Blanco, Texas, 550 km from the vent (Izett et al. 1972, and this work) has been documented in any detail. The distal Mount Blanco ash is partially reworked based on a firsthand inspection, and a conservative estimate of the original thickness of the primary ash fall is approximately 30 cm. Fall units B–E formed coevally with ignimbrite deposition, and ash falling distally could be derived from both a high vent-derived eruption column and from coignimbrite clouds derived from the pyroclastic flows. Significant fines loss from the flows is indicated by an average crystal enrichment factor (CEF) of 2.2 for the Otowi ignimbrite (Self et al. 1996), the mean of 6 samples from the Pajarito Plateau, east of the caldera.

Table 2 Rb, Y and Nb concentrations in the Guaje pumice

Fall Unit	Sample	Rb	Y	Nb
FU A	84-11-16	363	109	187
FU A	00-01Ac	362	106	191
FU B	00-02Ac	364	106	193
FU B	00-176	367	109	189
FU C	00-03Ac	361	108	188
FU C	00-177	365	109	186
FU D	84-11-H	311	98	156
FU D	00-178	277	86	134
FU E	00-180	221	67	97
FU E	00-05R	208	62	96
Distal ash	WRC-8-01A	303	97	162
Distal ash	WRC-8-02A	288	92	152
Distal ash	WRC-8-03A	288	91	149
Distal ash	WRC-8-04A	297	94	156
Distal ash	WRC-8-05A	286	91	151

"Distal ash" is from Mt. Blanco, Texas (Fig. 3b). Analyses (Wolff unpublished data) by XRF using the methods of Johnson et al. (1999) and Steiner et al. (2015)

FU fall unit

Fall unit A calculation

For this study, we have redrawn the isopach map of fall unit A (Fig. 3a) using Self et al. (1996). Isopachs for proximal Plinian units were constructed using fall thicknesses measured by Self et al. (1986, 1996) corrected for an error in the map base in Self et al. (1996). Fall unit A is thick (>10 m at 20–25 km from source) and was dispersed along a narrow axis heading slightly north of east from the caldera (Fig. 3a). It thins quite rapidly and is 1.4 m thick at Truchas (Fig. 2a). Isopachs for fall unit A are fairly well constrained and can be extrapolated to reasonable closures.

Fall volumes were calculated using the exponential thinning method of Pyle (1989) and the Weibull function (Bonadonna and Costa 2012). A density of 900 kg/m^3 was assumed for the Guaje fall deposits, corresponding to 65 % porosity. A minimum volume of 9.0 km^3 (bulk) or 3.3 km^3 (DRE) is calculated for fall unit A by the Pyle (1989) method

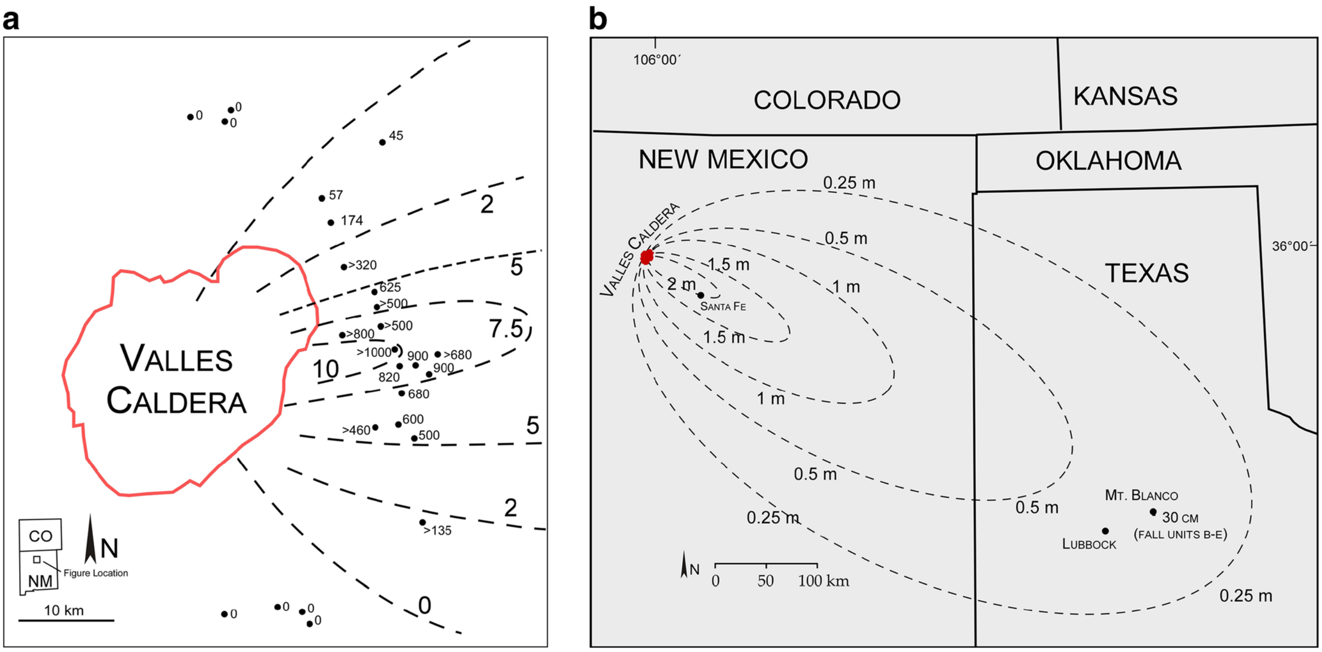

Fig. 3 **a** Reconstructed isopach map for proximal Guaje unit A. Thickness data from Self et al. (1986), Self et al. (1996) and new observations. Fall unit thicknesses are measured in centimeters; isopachs are represented in meters. **b** Extrapolated isopach map for Plinian units B–E. Data from Self et al. (1996), Holliday (1988), and Izett et al. (1972). Proximal thicknesses are constrained using the isopachs of Self et al. (1996)

or 4.4 km^3 (DRE) using the Weibull function (Bonadonna and Costa 2012).

Fall units B–E calculation

For units B–E, we use the isopach maps of Self et al. (1996), thickness data from Holliday (1988) and Izett et al. (1972), and new observations from this study as the basis for volume calculations. We follow Self et al. (1996) in grouping thicknesses of units B–E together (Fig. 3b). Fall units B–E are thinner in the Jemez Mountains but are more widely dispersed, with axes running SE from the caldera (Self et al. 1996). The total thickness of B–E is 21 cm at Truchas (Fig. 2a), which appears to be an off-dispersal-axis exposure.

Of note, we sampled and bulk-analyzed the Mt. Blanco, Texas ash; it has a significantly less evolved composition than units A, B, and C (Table 2), and must therefore contain some ash contribution from later erupted units. Unit A is not expected to have made much contribution, if any, to this location. The Mount Blanco ash is thus taken to have accumulated through the rest of the eruption. It could, of course, be solely derived from a midpoint in the eruption when pumice with a 155-ppm Nb content was being erupted (~fall unit D, Table 2), but we consider this less likely. It is likely to be the distal equivalent of Guaje units B through E with a possible additional, perhaps major (but very poorly constrained), component of coignimbrite ash.

Assuming a density of 900 kg/m^3 (65 % porosity), a minimum volume of 178 km^3 (bulk) or 65 km^3 (DRE) is calculated for fall units B–E by the Pyle method and a DRE volume of 61 km^3 using the Weibull method. This result is strongly influenced by the Mount Blanco data point, assumed to be 550 km from source and on the dispersal axis.

Combining A with B–E results in a total fall volume of 187 km^3 (bulk) or 68 km^3 (DRE), or 65 km^3 using the Weibull-based estimate (Bonadonna and Costa 2012).

Other possibly related deposits

Fluvially reworked ash and pumice deposits thought to be associated with the OM are found along the Rio Grande valley up to 400 km downstream from Valles Caldera (Cather and McIntosh 2009). We assume that these deposits represent eroded distal basin filling ignimbrite, since eroded away, and do not include them in our volume estimate.

Similarly, we have not included in our volume estimates possible primary OM ash fall deposits and fluvially reworked equivalents reported near Socorro, NM (Dunbar et al. 1996). Their age range does not permit distinction of the OM or Tshirege Member as a source.

Uncertainties

The uncertainty associated with the intracaldera volume (above) can be estimated with some confidence at ±50 % (see above). The greatest uncertainty in estimating the volume of OM ignimbrite lies in not knowing how much of the outflow has been removed by erosion. A preferential erosion scenario, in which non-welded deposits are eroded more than welded tuff, is applicable (Wilson 1991). In those regions where the ignimbrite is densely welded (zone E, and intracaldera fill in zone I), the volume estimates are more likely to be accurate than where the tuff is partly or non-welded. This is particularly true in the rift basins, where erosion has removed nearly all traces of OM ignimbrite.

Dethier and Aldrich (1988) estimated erosion rates for outflow tuff in the White Rock area from 1.1 Ma to the present at 4 cm/1000 year. Extrapolation of this rate to pre-Tshirege time is highly problematic but suggests that 10–20 m of OM may have been removed prior to emplacement of the capping Tshirege tuff; this equates, very crudely, to 30–60 km^3. At any rate, our estimated outflow volume is likely a minimum value.

The volume of "missing coignimbrite" ash calculated from the outflow ignimbrite sheet only, using the volume of outflow estimated and a CEF of 2.2 (above) is ~107 + 40/−12 km^3 (DRE). Even the minimum of 95 km^3 exceeds the volume of fallout calculated above. Thus, the 65–62 km^3 DRE fallout volume estimated above must be a minimum, and the total could be any value up to ~65 + 107 + 40 km^3, or 212 km^3. As volume estimates of ancient ash beds with sparse information are often underestimated, we feel that this uncertainty is valid.

Errors are not traditionally given for volumes of fall deposits calculated from isopach maps but they must be considerable, as the errors compound from initial thickness measurements to isopach construction and to deposit density estimates used in DRE calculations. For these reasons, we cite results from two methods of calculation of the OM fall deposits from isopachs, which are within 10 % of each other. This must be the minimum error, and we also know that the distal isopachs are very poorly constrained, depending on one point. We only include this to show that the volume of distal ash exists and should be accounted for. Moreover, in attempting to estimate coignimbrite ash from the OM ignimbrite, we introduce even bigger errors due to the multiple assumptions made—again we only include this to account for distal coignimbrite ash because crystal enrichment of the OM ignimbrite suggests it was produced. In summary, the stated volume estimates are probably within ±30 % for the vent-derived fallout and 50 % for the ignimbrite-derived fall component.

Discussion

Using a variety of data sources and application of volcanological theory, this study finds the following DRE volume estimates for the eruption (with associated uncertainties): 89 + 33/−10 km^3 of outflow ignimbrite; 144 ± 72 km^3 of intracaldera ignimbrite; at least 65 km^3 of Plinian fall (not including coignimbrite ash). We estimate that approximately 107 + 40/−12 km^3 of coignimbrite ash was "lost" from the outflow sheet alone. This yields a maximum of 550 km^3 DRE and a minimum value of 216 km^3 DRE, with a midpoint value of 383 km^3 DRE (Table 3).

Estimates of the erupted volumes of pyroclastic rocks from caldera systems rarely take into account all deposits. In some cases, estimates have been made from field data with a procedure in mind (Wilson 1991), and in others, the estimates are model-based. We have provided data on the first major eruption (OM) from a mid-sized caldera system, one in which the eruptive products may be voluminous enough to constitute a super eruption (~>450 km^3 DRE; Self 2006) and include fall and flow deposits emplaced on land in a mid-continental setting. A recent attempt at better defining ignimbrite volumes and components from a large, but older, caldera system, Cerro Galan (Folkes et al. 2011), used correction factors to arrive at volume reestimates. These include components for which we try to derive volumes from available field and geophysical data.

Components of the Otowi deposit

Sparks and Walker (1977) noted that some outflow ignimbrite deposit volumes (O) are equal to Plinian/coignimbrite ash volumes based on crystal concentration measurements (A). Later, Lipman (1984) observed that intracaldera deposit volumes (IC) are approximately equal to outflow deposit volumes (O). Mason et al. (2004) summarized volume relationships between caldera fill, outflow, and distal ash in large

Table 3 Summary of dense rock equivalent (DRE) volume calculations for intracaldera, outflow, and ash including all sources of error

	Intracaldera (IC)	Outflow (O)	Ash fall (A)	TOTAL
Calculated value (km^3)	144	89	65	298
Min. estimate (km^3)	72	79	65[a]	216
Median estimate (km^3)	144	101	139	383
Max. estimate (km^3)	216	122	212	550
Uncertainty (km^3)	±72	+33/−10	(+147, −0)	+252/−82

All values are in dense rock equivalent (DRE)

[a] The minimum fall estimate does not include coignimbrite ash

caldera-forming eruptions, comparing two eruptions for which it is possible to calculate all three components: the ~74 ka Younger Toba Tuff eruption and the 26.5 ka Oruanui eruption. At Toba, IC/O/A ≈ 1000:1000:800 km^3 (Rose and Chesner 1987), and for the Oruanui = 420:320:430 km^3 (Wilson 1991), i.e., IC, O, and A are subequal for any one caldera-forming ignimbrite eruption. However, Mason et al. (2004) do not present uncertainties for individual O, IC. and A measurements in either case.

Taking all sources of uncertainty into account, this study places constraints on the Otowi IC/O/A proportions as 144 ± 72:89 + 33/−10:65 + 147/−0 km^3 DRE (see Table 3). Permutations of these values are within a factor of 3.3 of each other. This result permits, but provides little encouragement for, a close 1:1:1 relationship (Mason et al. 2004) for caldera-forming eruptions, but nonetheless supports the assumption that it holds to better than an order-of-magnitude basis. While the lower limit of the total OM volume estimate is within previous estimates, we note that the upper limit (summing the maximum values for IC, O, and A, i.e. ~550 km), approaches 600 km^3 (Table 3). Such a volume is not unprecedented for a 24-km diameter caldera. Other calderas of similar dimensions have had up to 500–600 km^3 of eruptive units ascribed for the caldera-forming event, e.g., Bishop Tuff-Long Valley Caldera (Bailey et al. 1976).

Conclusions

Our detailed approach to calculating the total DRE erupted volume of the Otowi Member of the Bandelier Tuff from different data sources, lines of evidence, and application of volcanological theory yields an estimate of 298 + 252/−82 km^3. The minimum of 216 km^3 is very likely to be an underestimate. The errors are large despite the fact that the geology and distribution of the OM are well characterized for an ignimbrite/caldera-forming eruption of its age. Our results indicate that the subequal intracaldera/outflow/ash fall volume relation proposed by Mason et al. (2004) holds, in this case, to no better than a factor of three.

More broadly, we note that errors are infrequently quoted in volume estimates for prehistoric eruptions, including those referenced by Mason et al. (2004). We suggest that application of the precise IC/O/A = 1:1:1 volume relationship to estimation of total volumes erupted during caldera-forming events, where one of the three components (usually the distal ash) is otherwise unconstrained, is unwarranted.

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