Indirect tephra volume estimations using theorical models for some Chilean historical volcanic eruptions with sustained columns

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Introduction

During explosive volcanic eruptions, diverse pyroclastic products are discharged from an eruptive column. Those columns are divided into three zones; 1) a basal gas thrust one, 2) medial convective and 3) a top umbrella region (Sparks, 1986) as is indicated in figure 1a. In this last one, where the column is dispersed laterally and radially forming a dispersion cloud or volcanic plume, the column reaches an H_t region due its momentum (Fig.1a). There has been defined two types of eruptive columns in relation with the time between single explosions. If the time between explosions exceeds the time of ascension of a column until its H_t height, the column is thermal, and in the opposite case, if the ascension time is smaller than the separation between explosions, this column is sustained (Sparks, 1986; Carey and Bursik, 2000). A good agreement has been found in the prediction of column heights and field observations for the case of columns which extends higher than the tropopause (Settle, 1978; Wilson et al, 1978; Sparks and Wilson, 1982; Sparks, 1986). Several recent and historical eruptions in Chile have shown those kind of eruptive columns, with VEI values greater than 3 (VEI; Newhall & Self, 1989) producing wide tephra deposits (Fig. 1b) and causing important disruptions, mainly in Argentinean, but also in Chilean communities.

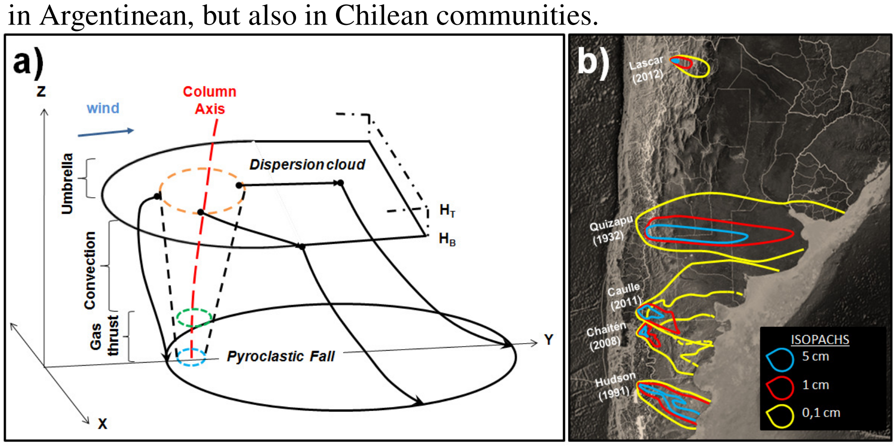

Fig. 1; a) Model of eruptive column. **b**) Isopach maps of some historical eruptions in Chile, affecting Argentina. Modified from Viramonte et al. (1994) Hildreth and Drake (1992), Romero et al. *(in prep.)*, Alfano et al. (2011) and Scasso et al., (1994).

Actually, the estimation of the volumes of fallout deposits gave us the possibility to determine a series of eruptive parameters, which are also accepted to classify the magnitude and intensity of those eruptions. If most of volumes are determined by field methods, other indirect (theorical) calculations on tephra fall deposit are based in complex physical characteristics of the eruptive column and plume dynamics and could help us to determine those characteristics. In the present investigation we obtained two new tephra volumes for recent and historical eruptions in Chile and we also compare some of them with well studied cases.

Some historical cases of moderate-to-large eruptions in Chile studied at present

The second and third largest historical eruptions recorded in the Andes where both Plinian, and took place in Chile (Tilling, 2009), from Quizapu (1932) and Hudson (1991) volcanoes, respectively, and where only surpassed by the 1600 Huaynaputina (Peru) event. Quizapu 1932 eruption lasted 18 hours and its plinian column reached 30km and emitted a 4,05km³ DRE volume (Hildreth and Drake, 1991). In the case of the Hudson 1991 eruption, after four eruptive stages, with columns varying from 13 to 25km height and a variable duration of each phases, the total DRE volume was calculated in 2,74km³ (Scasso et al., 1994; others) Also, other smaller (but moderate, VEI≥3) eruptions have occurred in Chile, as example of Caulle (1921-22; 1960), Calbuco (1961), Lascar (1993), Chaitén (2008) and Caulle (2011) which generated wide ash fallout deposits. About the 1921 eruption of Cordón Caulle volcano, there is a very poor register of the event, and is not possible to reconstruct its chronology, and also the Calbuco 1961 and Lascar 1993 events doesn´t have a calculated DRE volume of ejecta. Considering those (VEI≥3) eruptions occurred between 1921 and 2011, the cumulative bulk volume tephra is near to ~21,5km³ and represents 8,3 km³ DRE.

Sustained eruptive columns models

One way to determine the volume discharge rate and mass eruptive rate from sustained eruptive columns is to record the column height of an eruption with sustained plume from a single vent. This relation was widely studied by Wilson et al (1978) and also by Sparks et al (1997). The maximum height, Ht, depends of the thermal flux at the vent (which is the most important factor and is related to the mass discharge rate of magma and its thermal content), the stratification and moisture content of the atmosphere, and the volatile content of the magma (Carey and Bursik, 2000). Expressions are in Table 1.

Type	Sparks et al. (1997)	Mastin et al. (2009)	Solved
Volume	H_t=1,67$Q^{0,259}$ (1)	H_t =2$Q^{0,241}$(2)	Q = H_t /1,67 $^{1/0,259}$ (3) Q = H_t /2$^{1/0,241}$(4)
Mass	H = 0.220$M^{0,259}$ (5)	H = 0.304$M^{0,241}$ (6)	M= H /0,220 $^{1/0,259}$ (7) M = H/0,304$^{1/0,241}$(8)

Table 1: Expressions used to obtain the indirect volumes.

where Ht and H are the maximum plume height in km, above the vent, and Q is the DRE volume discharge rate of magma in m³/s. The constants are related to the stratification of the atmosphere. If we solve this equation for volumetric discharge rate, we can obtain the expressions 3 and 4, in the respective cases. Also, two other expressions have been used for Mass Discharge Rates (5,6) where M is the mass discharge rate in kg/s. The equations 7 and 8 are solved for mass eruption rates.

Results and Discussion

With the application of the last formulas and using the data exposed by various authors about the chronology and characteristics of eruptive events, we have simulated the Volume Discharge Rates (VDR) and Mass Eruption Rates (MER) for seven historical eruptions of VEI≥3 (Table 2). In the case of estimated VER values, we have assigned chronological durations of sustained columns of specific heights, which have been used for a DRE volume deposit prediction, also compared with real estimations reported by field methods. The accuracy of results is between 92,3 and 97,7% in comparison with field measurements, with exception of Chaitén volcano eruption (2008) which is 70% of error and has not been considered as a acceptable result. This could be reflecting a deficiency in the chronology recording of the activity and also, a high-gas poor-solid proportion in the eruptive column. Those "variable" eruption durations are related with discrete explosive pulses of plinian or subplinian type, and we considered a summation of hours of all of those pulses. In the simulation, it becomes really important to determine the real column height for accuracy of results, but also the duration of sustained columns could modify severely the final estimation, highlighting the importance of visual observation in the testing of this models, in addition to other remote sensing tools as satellite observations.

Eruptive event		**Source parameters**		**Eruption parameters (Predicted)**		**Deposit (Predicted)**	**Deposit (observed)**	**Error**	**Deposit Refer-ence**
Volcano	**Date**	**Column height [km]**	**Eruption Duration [h]**	**VDR [m³/s]**	**MER [kg/s]**	**DRE Volume [km³]**	**DRE Volume [km³]**	**|%|**	
Quizapú*	10-04-1932	29	18	6,10E+04	1,50E+08	3,96	4,05	2,273	**1**
Caulle●	24-05-1960	9	240	5,00E+02	8,00E+05	0,27	0,25	7,407	**2**
Calbuco●	10-03-1961	12	11,5	1,6-2E+03	2-5E+06	***0,07***			**7**
Hudson*	12/15-08-1991	13-25	*Variable*	0,4-4E04	0,06-1E+08	2,9	2,74	5,517	**3,6**
Láscar*	19-04-1993	20	12	0,3-1E+03	1-3E+06	***0,09***			
Chaitén●	08-05-2008	15-22	*Variable*	2,00E+04	6,00E+07	1	0,3	70	**4**
Caulle●	04-06-2011	13,5	27	2,70E+03	4,30E+06	0,27	0,28	3,704	**5**

Table 2: Results obtained from indirect calculations.*Obtained from Sparks et al. (1997) expression. ● Obtained from Mastin et al. (2009) method. **1.**- Hildreth & Drake, 1991; **2.**- Lara et al., 2006; **3.**- Scasso et al, 1994; **4.**- Major & Lara (2013); **5.**- Romero et al, *in prep*. **6.-**Kratzmann et al. (2010) 7.- Petit-Breuilh (1999).

From the tested eruptions, 3 of them show more accurate calculations using the Sparks et al., (1997) expression, showing higher eruptive columns (≥20km), and the last 4 eruptions (columns <20km) show better results with Mastin et al., (2009) method. Finally, a new expression could be obtained from the tested eruptions and the real measurements, as follows:

$$\mathbf{H_t}=1,986Q^{\,0,240}\ (9);\ \mathbf{H}=0,474M^{0,286}(10)$$

Where the column height is given by the Volume Discharge Rate (DRE) as Q, and the Mass Eruption Rate (MER) as M. If those formulas are more accurate to our data, this last one is reduced. By this reason, is probable that better results in wide samplings could be obtained from the Sparks et al. (1997) and Mastin et al. (2009) expressions.
Finally, this short investigation has contributed to determine two new DRE tephra volumes for the Calbuco (1961) and Lascar (1993) eruptions, with 0,07 and 0,09 km³ discharged respectively.

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