Journal of Volcanology and Geothermal Research 275 (2014) 103–113

Contents lists available at ScienceDirect

Journal of Volcanology and Geothermal Research

journal homepage: www.elsevier.com/locate/jvolgeores

Discussion

# Reply to comment on: "Cobeñas, G., Thouret, J.-C., Bonadonna, C., Boivin, P., 2012. The c.2030 yr BP Plinian eruption of El Misti volcano, Peru: Eruption dynamics and hazard implications. Journal of Volcanology and Geothermal Research 241–242, 105–120." by Harpel et al., JVGR 2013

Gisela Cobeñas [a,1], Jean-Claude Thouret [a,*], Costanza Bonadonna [b,2], Pierre Boivin [a,3]

[a] *Clermont Université, Université Blaise Pascal, Laboratoire Magmas et Volcans, UMR6524 CNRS & IRD UR163, 5 rue Kessler, 63038 Clermont-Ferrand cedex, France*
[b] *Earth and Environmental Sciences Section, University of Geneva, 13 Rue des Maraîchers, Geneva CH 1205, Switzerland*

ARTICLE INFO

*Article history:*
Received 7 December 2013
Accepted 16 February 2014
Available online 25 February 2014

*Keywords:*
Misti volcano
Plinian eruption
Pyroclastic flows
Lahars
Deposits

ABSTRACT

The comment provided by Harpel et al. challenges our interpretation of the most recent Plinian eruption of El Misti c.2070 yr BP* situated near the city of Arequipa, Peru (*revised age from our previously stated date of c.2030 BP). In our view, the sequence of deposits points to another example of a Plinian (pumice-rich) tephra fall followed by lithic-rich pyroclastic density currents (PDCs). Locally, late rockslide avalanches have emplaced mass-flow deposits on top of PDCs, while elsewhere post-eruption lahars have led to their remobilization. One of the main criticisms from Harpel et al. was in our interpretation of the deposits as being of PDC origin, rather than post-eruption lahars. We revise each of the diagnostic features that Harpel et al. have used for attributing the deposits to lahars. We present two tables of the revised age of the eruption and criteria based on lithofacies, lithological components, grain-size distribution and statistical indices for each of the c.2070 yr BP-old PDC, lahar and mass-flow deposits. Our maps and simulations of PDCs and lahars, based on two numerical codes with volume inputs from identified deposits around El Misti, do not "*fall short*" of the hazard assessment goal.



## 1. Introduction

We thank Harpel et al. for their comment on our paper published in 2012, and we take the opportunity to clarify the description of the most recent El Misti's Plinian deposits and interpretation of the eruption. Harpel et al. claim a "*dramatically different*" interpretation of the c.2030 yr BP deposits of El Misti based on three premises: 1) pyroclastic-flow deposits being "*lahar deposits*" instead; (2) their interpretation of "*six beds*" compared to our three that together form the tephra-fall deposit, and (3) their belief that "*no rockslide-avalanche deposit was associated with the eruption*".

Firstly, we emphasize that the c.2030 deposits of El Misti were described long before Harpel et al. (2011). In fact, several publications on El Misti volcano from our team preceded their report: Suni Chambi (1999), Navarro Colque (1999), Thouret et al. (1995, 1999, 2001), Legros (1998, 2001), Delaite et al. (2005), Mariño et al. (2007), Rivera (2010), and Vargas Franco et al. (2010). We are surprised that previous works from our research team and other Peruvian literature are not cited. Only one from Legros (2001), is quoted in Harpel et al.'s comment list (see our reference list including our Peruvian colleagues and student works).

Secondly, Harpel et al. (2011 and comment) do not acknowledge the c.2030 yr BP dating evidence for the deposits of the Plinian eruption by Thouret et al. (2001). The "2 ka" age mentioned in their report title is not correct for two reasons. We published the mean age 2030 ± 50 yr BP or 160 cal BC–340 cal AD at 1σ interval (Thouret et al., 2001; Cobeñas et al., 2012). We take this opportunity to bring the age of the Plinian eruption up to date. A personal communication by M. Nathenson drew our attention to the weighted mean age from our data set, which "should be calculated on the basis of the disparate uncertainties of the measurements and overlap of the ages including their uncertainties". From Cobeñas et al. (2012; Table 1 p. 111), the mean age is 2036 $^{14}$C yr BP (using the most recent radiocarbon calibration of Reimer et al., 2009), whereas the weighted mean age is 2074 $^{14}$C yr BP (Nathenson, *pers. com.*). The weighted mean age, rounded and accounting for the calculated standard error of the mean (80 years in the calibration), is 2070 ± 20 $^{14}$C yr BP or 1990–2060 cal yr BP (Fig. 1).

DOI of original article: http://dx.doi.org/10.1016/j.jvolgeores.2012.06.006.
* Corresponding author. Tel.: +33 473346773; fax: +33 473346744.
*E-mail addresses:* gcobenas@utas.edu.au (G. Cobeñas), J.C.Thouret@opgc.univ-bpclermont.fr (J.-C. Thouret), Costanza.Bonadonna@unige.ch (C. Bonadonna), P.Boivin@opgc.univ-bpclermont.fr (P. Boivin).
[1] Now at CODES, University of Tasmania, Australia. Tel.: +61 362262478; fax +61 362262547.
[2] Tel.: +41 223793055; fax +41 223793601.
[3] Tel.: +33 473346750; fax: +33 473346744.

http://dx.doi.org/10.1016/j.jvolgeores.2014.02.014
0377-0273/

We revise each diagnostic feature that Harpel et al. have used for attributing the deposits to lahars. We present sedimentological criteria for all the c. 2070 yr BP-old deposits (see Table 1, Figs. 2 & 3).

## 2. Pyroclastic-flow and surge (PDC) deposits versus lahar (LH) deposits

Cobeñas et al. (2012) termed all pyroclastic deposits (other than tephra fall) pyroclastic density currents (PDCs, which include pyroclastic-flow and surge deposits). For the sake of comparison here we use the term 'tephra' for deposits from tephra fall, PF from pyroclastic flows, PS from pyroclastic surges, LH from lahars, and RA from rockslide-avalanches (Table 1).

We strongly disagree with Harpel et al.'s interpretation for the majority of the c.2070 BP deposits around El Misti being formed by '*lahars*'. Most of these are lithic-rich PF deposits based on a number of criteria (Table 1). First, we note that the authors concur with us that at least four PF units can be observed and the lowermost unit is a pumice-rich deposit (Figs. 2 and 3A–B). Second, Harpel et al. recognize that this pumice-rich unit dominates the deposits in the Quebrada (ravine) Agua Salada, which cuts the south flank of El Misti. Here the PF deposits are 5–10 m thick at a distance of 11 km from the vent, and up to 25–35 m thick 6.5 km away at the break-in-slope c.3250 m (Fig. 3C). The original valley, which was the largest and deepest on the south flank at the time of the eruption, is one of the eight (not *six*), principal valleys filled by confined PF deposits.

### 2.1. Grain size and lithological components

Grain-size distribution alone is not sufficient for distinguishing LH deposits from PF deposits. A combination of lithofacies, together with lithological components, grain-size distribution and statistical indices, and the presence of charcoal at the base of the lowermost pumice-rich unit led us to interpret the deposits as 'PFs' (pp. 111–113). The lithic-rich PF deposits have a polymodal distribution and plot in the field of PF deposits not in the tephra field, as shown in Walker's (1971) diagram, which we do not take at face value. Statistical grain-size indices, including skewness, kurtosis, and Mz or Md ratios (Cobeñas et al., 2012, Fig. 7), do not speak in favor of LH deposits (for the purpose of comparison see the characteristics of the 1990 LH and PF deposits from the Kelud volcano: Thouret et al., 1998). At El Misti, four to five 2–8 m-thick, massive PF units contain pumice (20–30%, commonly sub-rounded), and variable proportions of accidental and accessory lithics (40–50%) in a coarse ash matrix comprising free crystals and glass shards (10–25%; Figs. 2 & 3A–E). The lithic-rich PF deposits are not clast-supported lithofacies, nor contain dense, closework large blocks, and are instead composed of abundant matrix of lapilli with a large amount of ash. Internal layering is outlined by clots or discontinuous, thin layers of sub-rounded pumice lapilli that were produced by shear within flows that moved down irregular and steep slopes (Fig. 4A, B). In contrast to what is expected from LH deposits, (1) the clast size ranges are relatively homogeneous, (2) abundant, sub-angular lapilli are dispersed in the matrix, and (3) normal (or sometimes inverse) grading is common towards the top of the PF units. Furthermore, the amount of fine ash (>3%) contrasts with what has been found in non-cohesive lahar deposits (<3%, Scott, 1988; Scott et al., 1992; Pierson, 2005). However, some fine-grained LH deposits that can be recognized on El Misti have likely been emplaced by hyperconcentrated flows (Fig. 4C).

### 2.2. Induration, air bubble vesicles, hardpan, and sieve beds

We disagree with Harpel et al.'s statement that "*The deposits are compact and locally indurated*" because induration alone is not a discriminating criterion, while "*locally indurated*" is a vague statement as PF deposits are often massive and compact, hence "indurated" (Figs. 3A, E

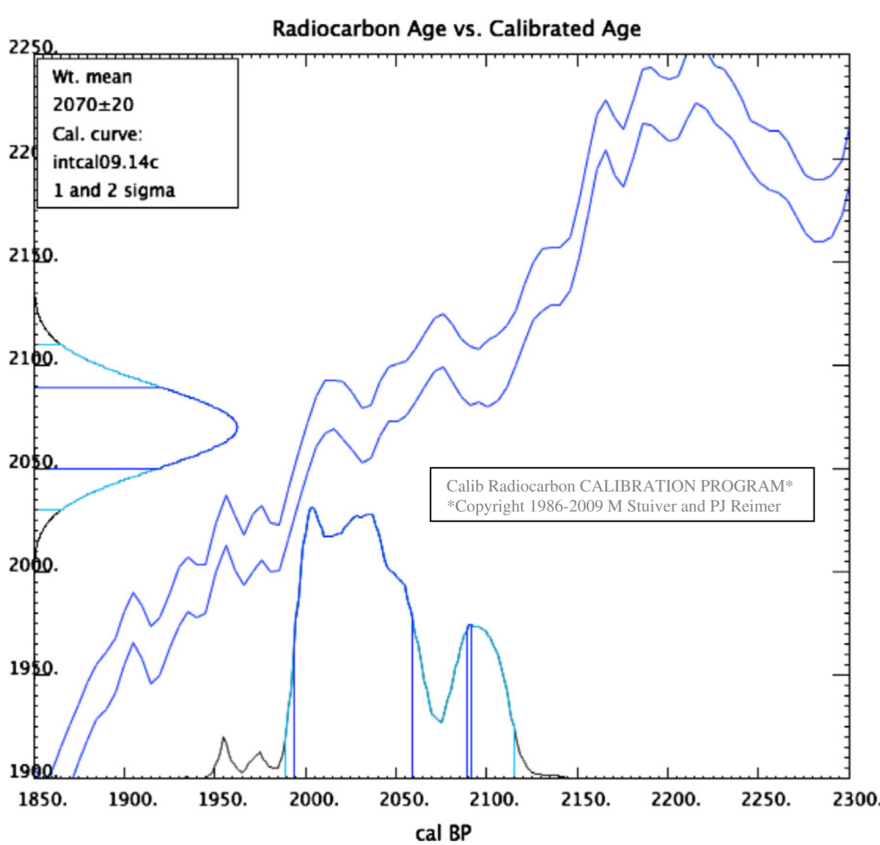


**Fig. 1.** $^{14}$C Age calibration plot of El Misti's c.2070 yr BP eruption (courtesy of M. Nathenson).