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Insights into lahar deposition processes in the Curah Lengkong (Semeru Volcano, Indonesia) using photogrammetry-based geospatial analysis, near-surface geophysics and CFD modelling

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ABSTRACT

Semeru Volcano is an active stratovolcano located in East Java (Indonesia), where historic lava flows, occasional pyroclastic flows and vulcanian explosions (on average every 5 min to 15 min) generate a stock of material that is remobilized by lahars, mostly occurring during the rainy season between October and March. Every year, several lahars flow down the Curah Lengkong Valley on the South-east flank of the volcano, where numerous lahar studies have been conducted. In the present contribution, the objective was to study the spatial distribution of boulder-size clasts and try to understand how this distribution relates to the valley morphology and to the dynamic and deposition dynamic of lahars. To achieve this objective, the method relies on a combination of (1) aerial photogrammetry-derived geospatial data on boulders' distribution, (2) ground penetrating radar data collected along a 2 km series of transects and (3) a CFD model of flow to analyse the results from the deposits. Results show that <1 m diameter boulders are evenly distributed along the channel, but that lava flow deposits visible at the surface of the river bed and SABO dams increase the concentration of clasts upstream of their position. Lateral input of boulders from collapsing lava-flow deposits can bring outsized clasts in the system that tend to become trapped at one location. Finally, the comparison between the CFD simulation and previous research using video imagery of lahars put the emphasis the fact that there is no direct link between the sedimentary units observed in the field and the flow that deposited them. Both grain size, flow orientation, matrix characteristics can be very different in a deposit for one single flow, even in confined channels like the Curah Lengkong.

1. Introduction

This contribution uses two components of lahar deposits that have been mostly left unused in lahar studies so far: (1) the distribution of boulders, which are often too large to enter typical grain-size analysis; and (2) the imaging of the subsurface structure of the valley floor; with the aim to (i) better understand the deposition processes of lahars in a complex environment, (ii) relate how one type of landform, deposit or anthropogenic structure influences lahar deposition, and (iii) improve the geomorphic knowledge of the Lengkong Valley at Semeru Volcano, Indonesia.

Beyond volcanological interests, such research is important because lahars have been single-handedly responsible for several tens of thousands of casualties globally during the 20th Century alone (Witham, 2005; Auker et al., 2013), with the worst case recorded at Armero City in 1985, where 23,000 perished (Pierson et al., 1990; Voight, 1990). Single events are usually of smaller scale however with for instance 350 casualties at Mt. Pinatubo in 1991 (Pierson et al., 1992), and 151 casualties at Mt. Ruapehu in 1953 (Stilwell et al., 1954): but it is the repetition of events and the return of population that claim large number of lives (e.g. over the last 95 years period, lahars at Kelud Volcano (Indonesia) have killed at least 5400 lives - Thouret et al., 1998). Hazards and disaster risk are particularly acute on the middle-to lower slopes of the volcanic aprons, where the slope gradient is low enough to start deposition and also where local communities can still "easily" settle, but often in conflict with the pathways of volcanic material (Jenkins et al., 2015). This phenomenon is particularly important on the Island of Java where space is at a premium and where the economic appeal brings people to put themselves in harm's way (Belizal et al., 2011; Lavigne et al., 2008). Even away from the volcanic structure, lahars remain an important hazard, and are a more treacherous threat to work against, because lahars would only reach those areas occasionally. On

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the Coatan River Fan in Mexico for instance, mostly built from lahar deposits from Tacana Volcano, >200,000 people live at risk (Murcia and Macias, 2014). Indeed, lahar hazards can expand hundreds of kilometers away from the volcanic structure itself, with runout distances reaching >300 km at Cotopaxi Volcano (Mothes et al., 1998) or 150 km at Mount Rainier (Vallance and Scott, 1997).

Rheologically, lahars are mixtures of debris and water that transition between debris-flow phases (>60% of volume sediment concentration) and hyperconcentrated flows (20–60% of volume sediment concentration) as well as more dilute flows (Pierson and Scott, 1985; Smith and Lowe, 1991; Coussot and Meunier, 1996; Lavigne and Suwa, 2004), and can be considered to be rheological continuum of Newtonian flows to viscous plastic fluids (Pierson and Costa, 1987). Lahar material can be rich in lithic clasts, like at Merapi Volcano in the Boyong and the Bedog Rivers, (Lavigne and Thouret, 2002), or they can show higher proportion of scorias, like at Semeru Volcano because of the regular vulcanian activity observed since the 20th Century (Gomez, 2001 – unpublished). While these volcanoes produce typical uncohesive flows, lahars can also be cohesive, like at Papandayan volcano where the clay content was >35% (Lavigne et al., 2004). Thus, the rheology of lahar is still not completely understood, and furthermore is the role of material types and density (scoriaceous material should not behave the same way as lithic material, for its density is different, for the scoriaceous material will eventually capture water changing its volumic mass and for its resistance to impact in purely granular phases will be different than lithic material). Finally, if models attempt to account for the role of grain, the place of large boulders and the links between deposits and the flow also need further investigation (Gomez and Lavigne, 2010; Starheim et al., 2013).

A large amount of lahar research has been accomplished from the survey of deposits however. Contemporary lahar deposits are typically observed from outcrops cut by the tail of the lahars in their own deposits, creating vertical walls that make the morphology of the deposit looks like fluvial terraces (although their formation process and geomorphologic significance is different). At Indonesian volcanoes such as Merapi, or Semeru volcanoes, the vertical walls often display an alternation of units rich in boulders supported by a sandy-gravel and gravel matrix intercalated with thinner units composed of laminated sand to gravel deposits.

In East Java (Indonesia), the Semeru Volcano (Fig. 1) is the highest point of the island reaching 3676 m a.s.l. Situated on the southern outer-rim of the Tengger Caldera (8°o6′05″S, 112°55′E) its age is estimated to be late Pleistocene to early Holocene, during which it grew to a calculated 60 km^3 (Thouret et al., 2007). Erupting every 5 min to

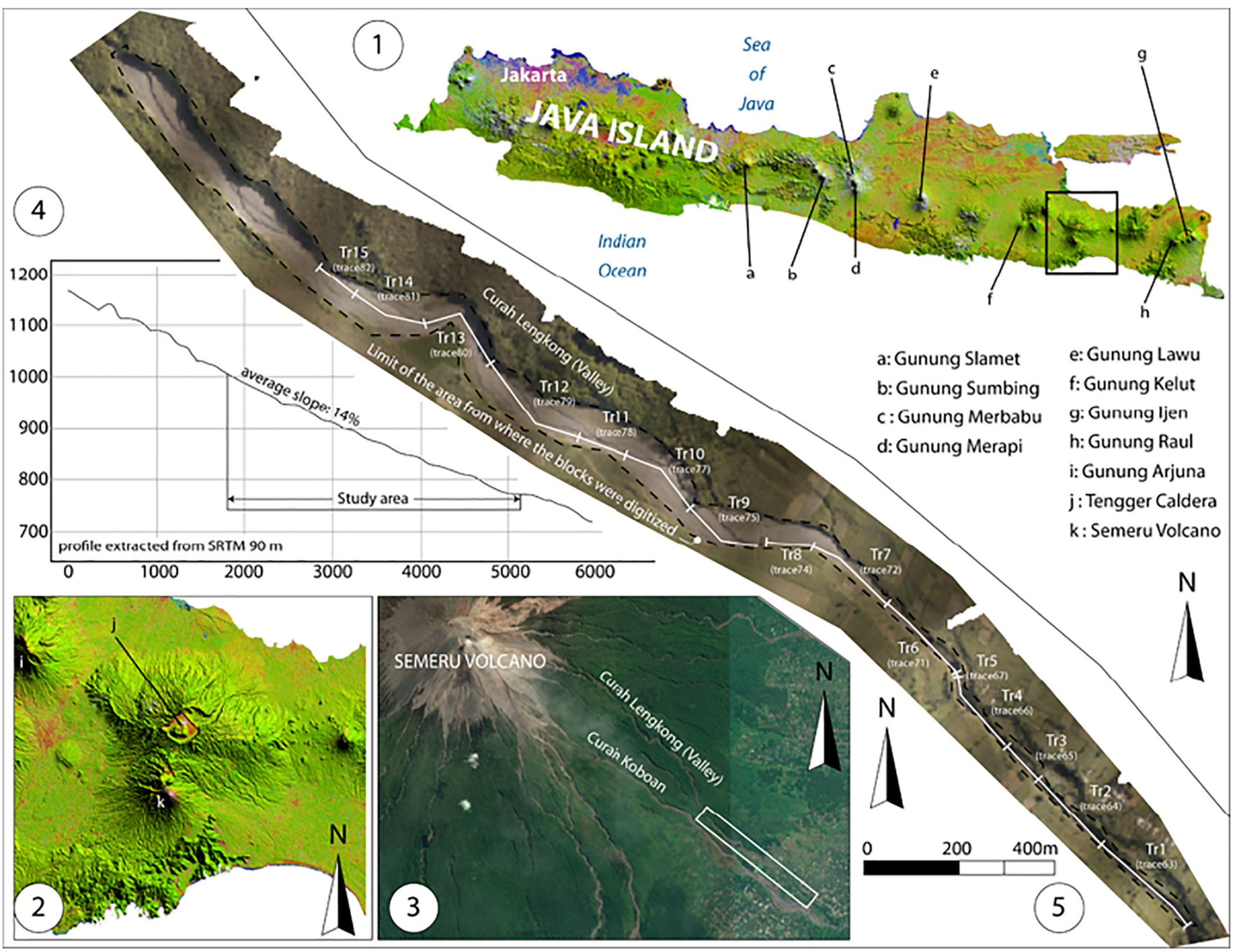

Fig. 1. Field survey location. (1) Java Island with some of the Quaternary active volcanoes of East and Central Java. The black box is the location of (2); (2) zoom on Semeru Volcano as part of the Tengger caldera complex; (3) zoom on the South-East flank of Semeru Volcano and location (white box) of the field area, which is approximatively 3.2 km long; (4) topographic profile of part of the Curah Lengkong with the field study area; (5) stitched aerial photographs of the survey area with delineation of the zones from which boulders and blocks have been digitized (delineated by the black dash-lines) and location of the GPR transects. The 15 transects are also presented with the names of the original files. The GPR files are accessible upon request. If the reader wishes to access the original ground penetrating radar data, please provide the file name in your correspondence.