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Emplacement conditions of the 1256 AD Al-Madinah lava flow field in Harrat Rahat, Kingdom of Saudi Arabia — Insights from surface morphology and lava flow simulations

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A B S T R A C T

Lava flow hazard modelling requires detailed geological mapping, and a good understanding of emplacement settings and the processes involved in the formation of lava flows. Harrat Rahat, Kingdom of Saudi Arabia, is a large volcanic field, comprising about 1000 predominantly small-volume volcanoes most of which have emitted lava flows of various lengths. A few eruptions took place in this area during the Holocene, and they were located in the northern extreme of the Harrat Rahat, a close proximity to critical infrastructure and population living in Al-Madinah City. In the present study, we combined field work, high resolution digital topography and morphometric analysis to infer the emplacement history of the last historical event in the region represented by the 1256 AD Al-Madinah lava flow field. These data were also used to simulate 1256 AD-type lava flows in the Harrat Rahat by the MAGFLOW lava flow emplacement model, which is able to relate the flow evolution to eruption conditions. The 1256 AD lava flow field extent was mapped at a scale of 1:1000 from a high resolution (0.5 m) Light Detection And Ranging (LiDAR) Digital Terrain Model (DTM), aerial photos with field support. The bulk volume of the lava flow field was estimated at 0.4 km^3, while the source volume represented by seven scoria cone was estimated at 0.023 km^3. The lava flow covered an area of 60 km^2 and reached a maximum length of 23.4 km. The lava flow field comprises about 20.9% of pāhoehoe, 73.8% of 'a'ā, and 5.3% of late-stage outbreaks. Our field observation, also suggests that the lava flows of the Harrat Rahat region are mainly core-dominated and that they formed large lava flow fields by amalgamation of many single channels. These channels mitigated downslope by topography-lava flow and channel–channel interactions, highlighting this typical process that needs to be considered in the volcanic hazard assessment in the region. A series of numerical lava flow simulations was carried out using a range of water content (0.1–1 wt.%), solidification temperature (800–600 °C) and effusion curves (simple and complex curves). These simulations revealed that the MAGFLOW code is sensitive to the changes of water content of the erupting lava magma, while it is less sensitive to solidification temperature and the changes of the shape of effusion curve. The advance rate of the simulated lava flows changed from 0.01 to 0.22 km/h. Using data and observations from the youngest volcanic event of the Harrat Rahat as input parameters to MAGFLOW code, it is possible to provide quantitative limits on this type of hazard.

1. Introduction

A compelling reason for studying the evolution of lava flows is to construct predictive models of their behaviour, motivated by the necessity of assessing the immediate hazards posed to people and property by advancing lava flows. Crucial for hazard assessment are estimation of flow paths, flow advance velocities, and final flow lengths that might be expected in future eruptions (Rowland et al., 2005; Wright et al., 2008; Del Negro et al., 2013; Cappello et al., 2015a; Harris and Rowland, 2015). These parameters are easily determined for observed eruptions; however, they are more difficult to infer from solidified flows that represent most of the eruptive history of volcanoes worldwide. For this reason, new approaches have been developed for

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inferring emplacement conditions from older, solidified lava flows, focusing particularly on flow geomorphology, morphometric measurements of flow units and numerical simulations of lava flows paths (Rowland and Walker, 1987; Rossi, 1997; Soule et al., 2004; Tarquini et al., 2012; Kereszturi et al., 2014; Murcia et al., 2014; Cappello et al., 2015b; Dietterich et al., 2015).

The dynamics and emplacement of lava flows are controlled by different parameters, such as viscosity (determined by temperature, chemical composition, gas content, and crystallinity), effusion rate at the vent(s), eruption duration, and the ground topography over which the lava flows (Rowland and Walker, 1990; Griffiths and Fink, 1993; Pinkerton and Wilson, 1994; Cashman et al., 1999; Kerr et al., 2006; Harris and Rowland, 2009). The interplay between such parameters imprints signatures on the lava flows that may vary on multiple spatial scales, and are defined by existent lava surface morphologies, structures and textures. Lava structures include lava rises, lava tubes, tumuli, breakout flows, among many others (Rowland and Walker, 1987; Rossi, 1997; Soule et al., 2004; Guilbaud et al., 2005; Murcia et al., 2014), occurring at a kilometre to metre scale. Lava textures refer to smooth, spiny, blistered, clinker, agglutinated surfaces as well as vesicle distribution (Rossi, 1997; Guilbaud et al., 2005; Murcia et al., 2014), occurring at a much finer scale of metres to millimetres. As a whole, these lava structure and texture characterize the surface morphology that is related to the classical definition of a lava flow after solidification, such as pāhoehoe, 'a'ā and blocky (Macdonald, 1953; Swanson, 1973; Rowland and Walker, 1990; Rossi, 1997; Self et al., 1998). The distribution of flow surface morphologies varies in both space and time, is directly linked to changing flow-emplacement conditions, and results from changes of many internal and external influences down-flow. Despite this, however, quantifiable surface characteristics, defining lava types, are limited by the difficulties inherent in collecting accurate field data on flows with rough topography and large spatial extents. The increasing availability of Light Detection And Ranging (LiDAR) systems allows high-resolution (<1 m horizontal) topographic data to be obtained, thereby offering opportunities to better understand geomorphic processes from topographic signatures and their hazards (Favalli et al., 2010; Deardorff and Cashman, 2012; Kereszturi et al., 2012b; Cashman et al., 2013). Consequently, the combination of high-resolution topography and morphometric analysis can hold important clues to emplacement conditions of already solidified lava flows, when direct measurements of active flows are not possible (e.g. Griffiths, 2000; Soule et al., 2004; Cashman et al., 2013).

Significant aspects of lava flow emplacement can also be explored using numerical models that simulate flowing lava. Great advances have been made in understanding the physical processes that control lava flow dynamics and emplacement, as well as the complex feedbacks between cooling, crystallization and rheology that govern those dynamics (e.g. Griffiths, 2000). As a result, over the past years various numerical codes have been developed to predict lava flows footprint and emplacement dynamics (Felpeto et al., 2001; Harris and Rowland, 2001; Crisci et al., 2004; Favalli et al., 2005; Hidaka et al., 2005; Vicari et al., 2007; Connor et al., 2012). However, existing physics-based models cannot yet consider the entire complexity of lava properties, since they have all necessarily involved simplifications of the thermo-

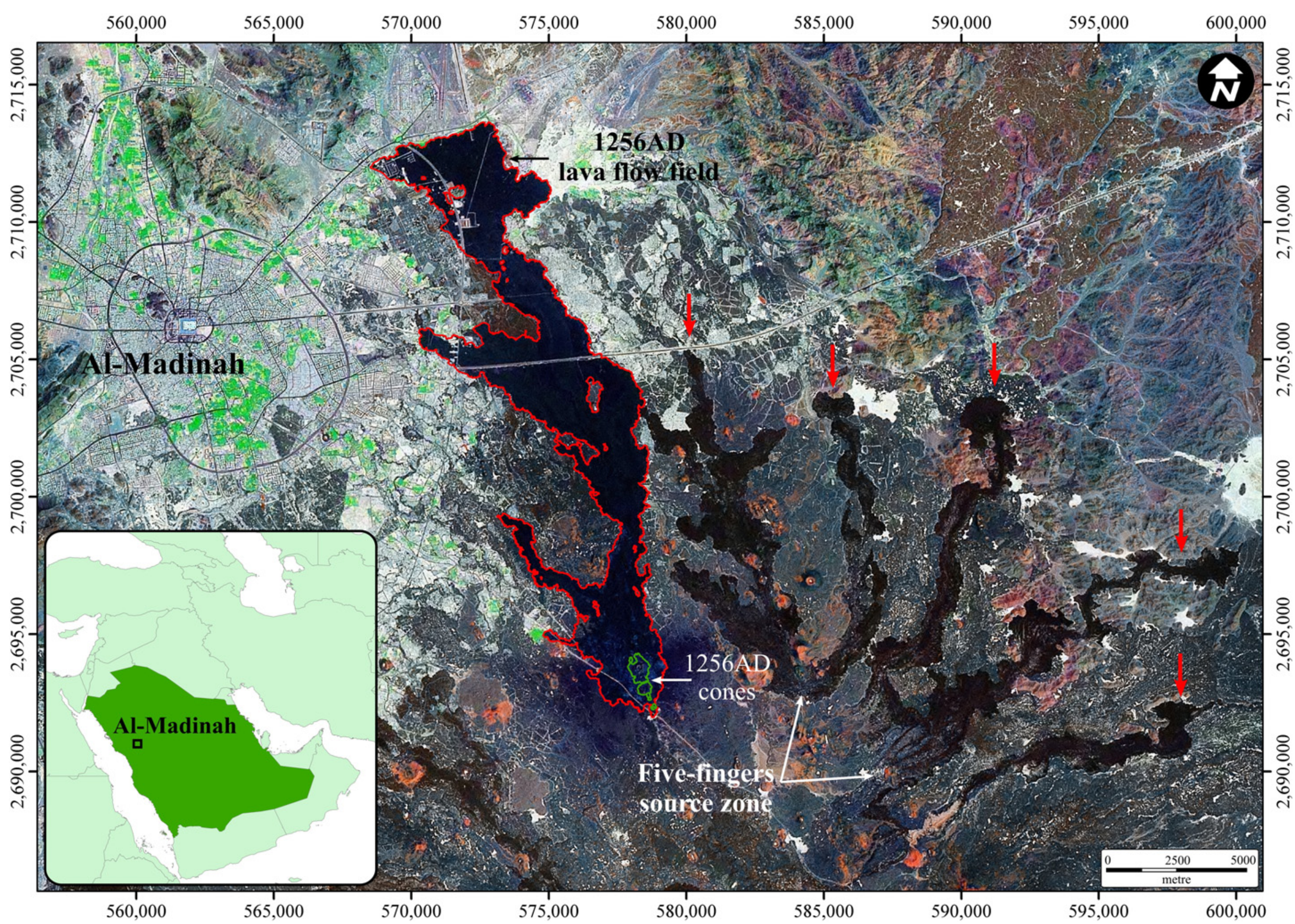

Fig. 1. Overview satellite image (LANDSAT ETM + 7; R = band 3, G = band 2, B = band 1) of the northern Harrat Rahat, showing the outline of the 1256 AD lava flow field. The red arrows show the lava flows of the Five-fingers eruption.