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A first hazard analysis of the Quaternary Harrat Al-Madinah volcanic field, Saudi Arabia

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ABSTRACT

The northern portion of the 20,000 km^2 Harrat Rahat basaltic field in NW Saudi Arabia (Harrat Al-Madinah) has hosted some of the most recent volcanic eruptions in the country. Rapid growth of the city of Al-Madinah has spread out onto the lava flows and scoria cones of the Harrat, increasing exposure to any potential renewed volcanism. We present here a first-order probabilistic hazard analysis related to new vent formation and subsequent lava flow from this volcanic field. The 501 visible eruption vent sites were integrated with aeromagnetic survey data (as representative of potential regions of buried volcanic vents) to develop a probability density function for new eruption sites using Gaussian kernel smoothing. This revealed a NNW striking zone of high spatial hazard terminating <10 km south of the city. Using the properties of the AD1256 eruption lava flows and the spatial PDF, an analysis of lava hazard was carried out. Assuming a future lava-producing eruption, around 25% of the city of Al-Madinah is exposed to a probability of 0.001 to 0.005 of lava inundation. The temporal eruption recurrence rate is estimated at approximately one vent per 3300 years, but the temporal record of the field is so poorly constrained that the lower and upper bounds for the recurrence interval are 13,300 yrs and 70 yrs, respectively. Applying a Poisson temporal model, this results in a worst-case lava inundation recurrence interval of approximately 14,300 years.

1. Introduction

When forecasting eruptive hazard from intraplate volcanic fields the primary challenge is to quantify the spatial–temporal controls on the site(s) of new eruption outbreaks (Connor et al., 2000). Identification of tectonic structures, or other features that control volcanic expression is essential, but these are often not obvious in monogenetic settings (e.g., Bebbington and Cronin, 2011). The extremely large and long-lived Harrats (lava fields) of western Saudi Arabia are located outboard of the active Red Sea Rift and volcanism is generally thought to be related to asthenospheric upwelling, although the actual mechanism is not well understood (Palister, 1987; Bohannon et al., 1989; Camp and Roobol, 1992; Hansen et al., 2006).

The youngest volcanism known from Saudi Arabia is concentrated in the northern portion of the 10 Ma to recent, 20,000 km^2 Harrat Rahat (Fig. 1) (Camp and Roobol, 1989). This vast monogenetic volcanic field encircles the south, west, and east of the culturally and economically important City of Al-Madinah (Fig. 1). The northern part of Harrat Rahat, hosting all known Holocene-aged volcanism has also been termed Harrat Al-Madinah (Moufti, 1985; Moufti et al., 2013). Triggering renewed attention of volcanic hazard in this region was a seismic swarm in 2009, associated with a surface fault rupture and modeled dyke intrusion in the neighboring Al-Shaqqah volcanic field (Harrat Lunayyir), ~200 km NW of the city of Madinah (Palister et al., 2010). A similar earthquake swarm in 1999 was located only 25 km south of Al-Madinah (Saudi Geological Survey, 2005), although in this case, definitive evidence of magma movement was not confirmed.

In this work we use the current knowledge of the surface locations and inferred subsurface regions of volcanism in the Harrat Al-Madinah as the basis of a preliminary analysis of volcanic hazard. The volcanic sequence of the overall Harrat Rahat was mapped within ten age bands. The oldest three (Tw1 from 10 to 8.5 Ma, Tw2 from 8.5 to 2.5 Ma, and Th from 2.5 to 1.7 Ma) were all primarily south of Harrat Al-Madinah. The remaining seven episodes were designated Qm1 (1.7–1.2 Ma) to Qm7 (1500 yrs BP-present) (Camp and Roobol, 1989). New Ar–Ar dating in the Harrat Al-Madinah portion, however, has identified pre-Qm1 products, extending back to at least 10 Ma (Moufti et al., 2012). A well-documented historic eruption occurred 20 km south of Madinah in AD1256 (Camp et al., 1987), producing at least 6 scoria and spatter vents, as well as >20 km-long basaltic lava flows. The city of Al-Madinah has now expanded on to these AD1256 lavas and the international airport abuts them. Another historic eruption is thought to have occurred at AD641, producing four scoria/spatter

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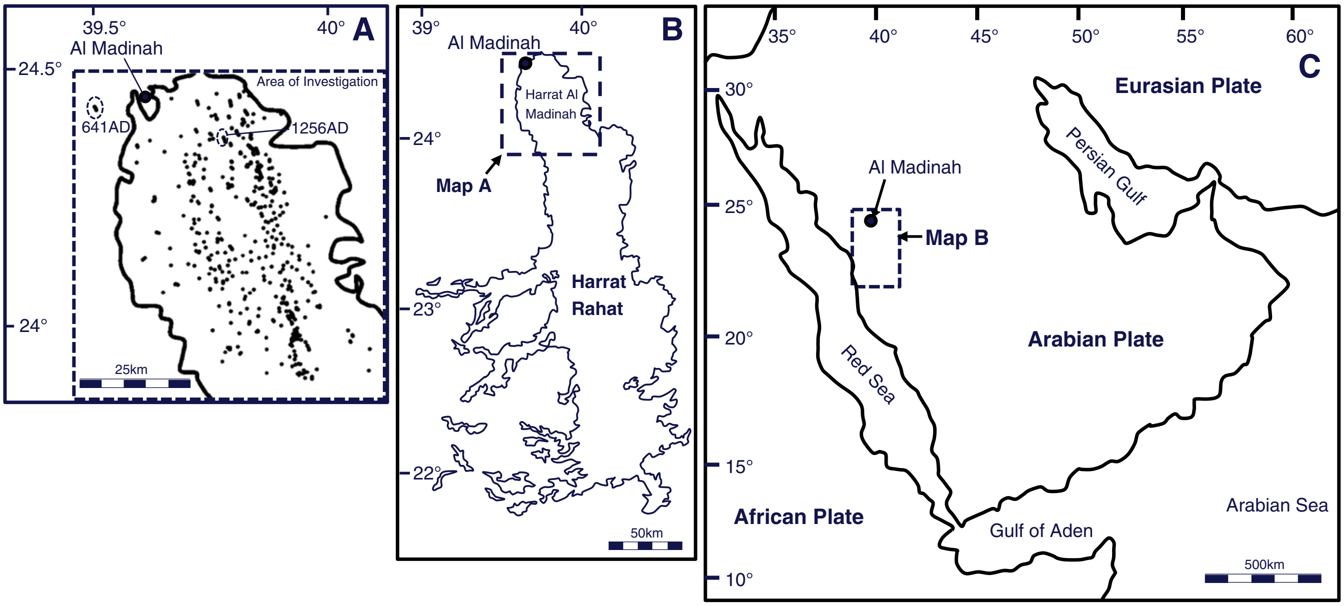

Fig. 1. Harrat Al-Madinah in NW Saudi Arabia. (A) The boundaries of the Moufti (1985) defined Harrat Al-Madinah with dots indicating >500 mapped surface vent sites, with historic eruption sites marked. (B) The Harrat Rahat (Camp and Roobol, 1989) one of the largest volcanic fields in Saudi Arabia, covering >20,000 km^2. (C) Location of the study area in W Saudi Arabia, east of the Red Sea, where active rifting has taken place since c. 30 Ma (Camp and Roobol, 1992).

cones also within the current city boundaries (Camp and Roobol, 1989). A further 11 other post-Neolithic (<4500 yrs B.P.) eruptions have also been identified, several involving more than one eruptive center (Moufti, 1985; Camp and Roobol, 1989). Further indirect indicators of volcanic-related phenomena within this area include the 1999 earthquake swarm described above and a 3.2 km-long zone of anomalous geothermal heat measured in 1991–92 within the city limits (Roobol et al., 1994). Rapidly increasing numbers of visitors to the >1 million population city of Al-Madinah and a current rapid phase in its growth and expansion make a volcanic hazard assessment overdue. Here we provide the first attempt at quantifying the spatial and spatio-temporal hazard intensity of the field.

2. Volcanic hazard assessment

The numerically and volumetrically dominant volcanic landforms of Harrat Al-Madinah include >500 alkali-basaltic scoria and spatter cones, along with very extensive lava flows (Moufti, 1985; Camp and Roobol, 1989). In addition, within the central part of the field, at least 20 evolved (benomoreitic and trachytic) eruptive centers are identified, forming domes, explosion craters and associated pyroclastic deposits (Moufti, 1985). Effusive eruptions and lava flows are, however, by far the most common and widest-distributed volcanic products of the Harrat Al-Madinah. Hence, we focus on defining the probability that a particular point in space will be inundated by lava. The main controls on this are (1) the location(s) of lava-producing vents and hence the local topography, and (2) the volume of lava flows. In the absence of any evidence to the contrary, these two factors are treated independently. As a first step, we will assess the spatial aspect of eruption occurrence, by determining the spatial probability distribution of the next vent, conditional on the occurrence of a future eruption.

For long-term infrastructure development and emergency management planning, the probable location of the next volcanic vent may be the most critical parameter in determining hazard (Martin et al., 2004; Jaquet et al., 2008; Hill et al., 2009; Marzocchi and Bebbington, 2012). To obtain a spatial density estimate, the past eruption vent data must be converted into a probability density function (PDF), or a set of these. This can be completed using a kernel function to calculate a PDF from point or line data (Connor and Hill, 1995), a method that has been frequently applied to a range of volcanic fields (e.g. Connor et al., 2000; McBirney et al., 2003; Weller, 2004; Kiyosugi et al., 2010; Bebbington and Cronin, 2011). This method assumes that the past distribution of vent locations is the main indicator for the location of future vents.

The youngest eruption centers are well preserved in the arid environment of Saudi Arabia, however, because the volcanic field is at least 10 Ma in age (Moufti et al., 2013), older vents are likely buried and thus unaccounted for. The maximum thickness of the eruptive sequence across the volcanic field commonly reaches >200 m, and in places up to 400 m as determined via drilling (Torrent, 1976) and aeromagnetic data inversion (Blank and Sadek, 1983). Many of the visible cones, spatter mounds, and lava vents in Harrat Al-Madinah are <50 m in height, and assuming previous vents were of similar dimensions, many were likely buried during the development of the Harrat. Evidence of buried volcanic vents is further provided by the results of seismic profiling (Imran, 2006).

Within Harrat Al-Madinah, $N = 501$ surface vent locations have been identified. We hypothesize that the likely location of buried vents can be inferred from magnetic data (cf. O'Leary et al., 2002), even in a highly magnetized environment dominated by basaltic lava flows. A probabilistic approach to this can be taken by converting the surface locations and the aeromagnetic data into probability density functions (PDFs) and combining the two PDFs linearly (Felpeto et al., 2007).

The visible vent locations were converted into a PDF $\lambda_V(x)$ using kernel smoothing with an anisotropic Gaussian kernel (Connor and Connor, 2009):

$$\lambda_V(x) = \frac{1}{N2\pi\sqrt{|\mathrm{H}|}} \sum_{i=1}^{N} \exp\left(-0.5(x-x_i)^{\mathrm{T}}\mathrm{H}^{-1}(x-x_i)\right) \tag{1}$$

for the spatial intensity at the point x, where the ith vent occurs at location x_i. The bandwidth matrix

$$\mathrm{H} = \begin{bmatrix} 3.88 & -5.37 \\ -5.37 & 19.20 \end{bmatrix}$$

was chosen using the SAMSE optimization method (Duong and Hazelton, 2003), and corresponds to an ellipse with major axis rotated 17.5° E of N, with major and minor axis lengths of 4.57 and 1.48 km, respectively.