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Evidence for Recent Large Magnitude Explosive Eruptions at Damavand Volcano, Iran with Implications for Volcanic Hazards

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Abstract

Damavand is a large dormant stratovolcano in the Alborz Mountains of northern Iran located in one of the most populous provinces, which could be adversely affected by tephra fall from Damavand. The youngest known eruption is a lava flow on the western flanks with an age of 7.3 ka. The volcanic products are predominantly porphyritic trachyandesite. Three major young pumice deposits, named here as Mallar, Karam Poshteh and Reyneh pumices, are identified, with provisional ages in the interval >7.3 ka and < 25 ka. The deposits cover much of the southern and western flanks of the volcano. The Mallar and Reyneh deposits consist of extensive basal pumice fall deposits with dispersal axes to the east, overlying pumiceous pyroclastic flow deposits extending up to 20 km from the summit and late-stage lahar deposits. The middle unit (Karam Poshteh) consists of a coarse-grained pumice fall deposit with proximal welded facies dispersed to the west, but lacks pyroclastic flow deposits. Based on reconnaissance field data they were formed by explosive eruptions of VEI4. Some of the villages on the flanks of the volcano are built on pyroclastic flow and lahar fans, and thus would be at high risk in the event of future explosive eruptions. We present an analysis of wind data and the applications of a computer tephra dispersal model to assess tephra fall hazards. Explosive eruptions of Damavand in the future would adversely affect large cities in the neighbouring provinces to the east, reflecting the dominant regional stratospheric wind directions.

Keywords: Damavand Volcano; Explosive eruptions; Volcanic hazards; Pyroclastic units

Introduction

Damavand is a large dormant stratovolcano in the Alborz Mountains of northern Iran in Mazandaran Province (Fig. 1). It is located 60 km to the ENE of Tehran, a megacity with more than 12 million populations and is the highest mountain (5670 m) in the Middle East and west Asia. Mazandaran Province is one

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of the most populous provinces (over 2 million people) by population density and one of the most wealthy in Iran with diverse natural resources. The province's four largest cities are Sari, Babol, Amol and Qaemshahr with populations of 490830, 464535, 343747, and 293721 respectively. There are also large populations in Golestan and Semnan Provinces further east. Many people live in hundreds of small towns and villages. The regional economy relies heavily on agriculture (Rice, grain, fruits, cotton, tea, tobacco, sugarcane), with the highest farm fish production and famous caviar throughout Iran. Millions of tourists visit the region every year. The region is vulnerable to tephra fall. As many as 50,000 people live on the flanks of the volcano in numerous villages and small towns and could be at high direct risk from the volcano. The main highway connecting Tehran with the Caspian Sea passes down the Haraz valley on its southern flanks.

There are no known historic eruptions. A seismic swarm was experienced by local people in 1979, but this has not been documented in any scientific literature. In 2007 mountain guides noticed that the summit fumaroles had become more active and, together with a magnitude 2.9 earthquake in January 2007 close to the volcano, there is increasing interest and concern among Iranian geoscientists.

Geology of Damavand

Geology of Damavand has been studied by many researchers. Most studies concentrated on general geology, petrography, petrology and geochemistry of lavas and volcanic rocks. [1&2] did a systematic study on geology of Damavand and [12] did an important petrological and Geochemical study on volcanic and some pyroclastic rocks of Damavand. The results of study appear as internal report of Geological survey of Iran. Geology of Damavand also studied in Few MSc and PhD theses. Knowledge on pyroclastic and volcano-sedimentary rock units of Damavand is quite limited and confined to reconnaissance study [10] and [13]. [10] described young pyroclastic deposits that they concluded were formed by sub-Plinian explosive eruptions.

Knowledge about the stratigraphy, age and geochemistry was significantly enhanced by the study of [11]. This study showed that the volcanism goes back to at least 1 ma with on older sequence (Old Damavand) and younger sequence (Young Damavand). There is, however, no detailed or reliable geological map. The youngest known eruption is a lava flow on the western flanks with an age of 7.3 ka. [11] also confirmed that the largely volcanic products are remarkably uniform in composition and petrology, being predominantly porphyritic trachyandesite. Alkaline basalts of Damavand known as early stage of volcanism. They also showed that the trace element geochemistry has affinities with intraplate volcanism rather than subduction-related volcanism.

The tectonic setting of Damavand is puzzling. It is located in a young and very active zone of compression and strike-slip faulting. Deep thrust faults border the mountain range with large strike-slip faults towards the centre and south [17,22]. Volcanoes located in regions of compressional thrust faulting are uncommon, although there are some rare examples [14].

To our knowledge there has been no published research on the volcanic hazards at Damavand and the volcano as not been monitored until recently. The purpose of this article is to report the results of a reconnaissance study of young pyroclastic deposits and an initial assessment of related hazards. Our new data indicate that the volcano has had high intensity explosive eruptions, producing widespread pyroclastic fall and flow deposits. Hithertoo Young Damavand has been regarded as a dominantly extrusive volcano erupting lavas that are unlikely to cause major hazards. Although recent pumice deposits were recognised by [11], there are no descriptions of their stratigraphy or characteristics. Our new evidence points to three major explosive eruptions in the recent geological past.

In this article we describe the distribution and characteristics of three pyroclastic units and interpret the, in terms of eruption style, likely magnitude, and hazardous effects. We then discuss the current state of

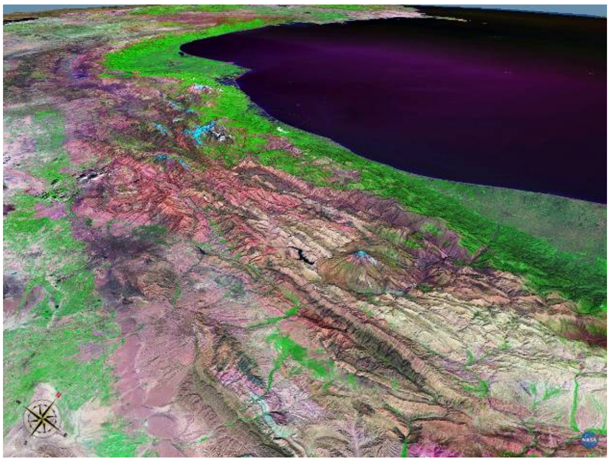

Figure 1. Satellite image of Alborz Mountains showing location of Damavand volcano located on the crest of the mountain range with Tehran to the west-south-west and the Caspian Sea to the north.

the volcano and the likelihood of the next eruption being explosive. We discuss possible scenarios and impacts of future eruptions locally and regionally. We present an analysis of wind data and the applications of a computer tephra dispersal model to assess the hazards that would result from tephra fall in the cities and provinces neighbouring Damavand.

The discussion draws on analogous volcanoes where the eruptive history is better documented and better understood than Damavand. Given this limited state of knowledge there are more questions than answers. We briefly make recommendations for the further research to allow a robust hazard assessment of Damavand.

Pyroclastic Units

Our reconnaissance study was confined to the southern and western flanks of the volcano from the Gazaneh valley (~100°) to the major scarp north-west of the summit (~310°). In this sector we identified three major pyroclastic deposits. Figure 2 shows the distribution of localities described in this paper. Figure 3 shows a lithostratigraphic section through the three major deposits at the type locality of Varkaly Springs (locality 1 in Fig. 2). Varkaly Spring is the most important locality from a stratigraphic point of view as all three deposits are exposed, allowing their stratigraphic order to be established. The deposits were named after the most prominent localities and are, in stratigraphic order from oldest to youngest: Reyneh pumice deposits, Karam Poshteh pumice deposits, and Mallar pumice deposits. Figure 4 shows additional representative sections through the Reyneh and Mallar pumice deposits to illustrate their internal stratigraphy. The deposits are now described from oldest to youngest.

Reyneh Pumice Deposits

These deposits are found in local valley fills from Mallar adjacent to the Gezaneh valley to valleys due west of the Damavand summit. Exposures have been found up to 20 km from the volcano’s summit. The best exposure is in a working quarry 3 km west of Reyneh, which was also sampled by [11] as grey pumice sample 19G for geochronological analysis. We found only one exposure of basal pumice fall at Mallar (locality 2 in Fig 2), where it is 95 cm thick (Fig. 4a and 5a). There is no basal pumice fall to the west, indicating a tephra dispersal axis to the east.

Most exposures consist of an amalgamated sequence of numerous thin pumice flows deposits, with flow tops and edges marked by pumice concentration zones and lenses (Fig. 5b and 5c). Individual flow units are typically 0.5 to 2 metres thick and are commonly

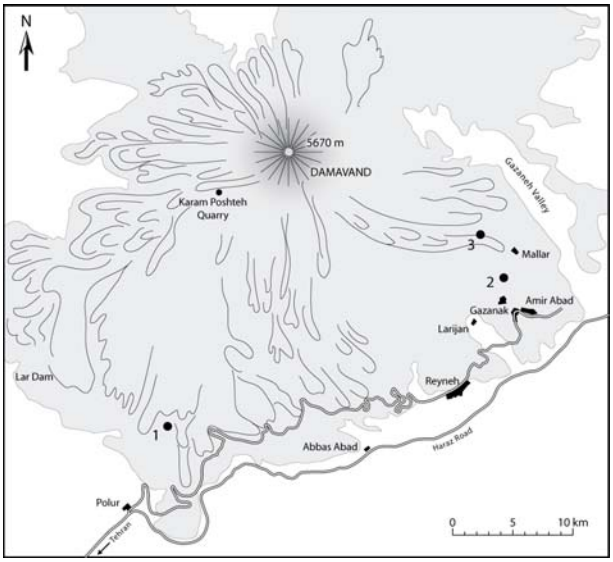

Figure 2. Locations of key sites studied in this paper with outline of Damavand volcano, major villages and geographic features.

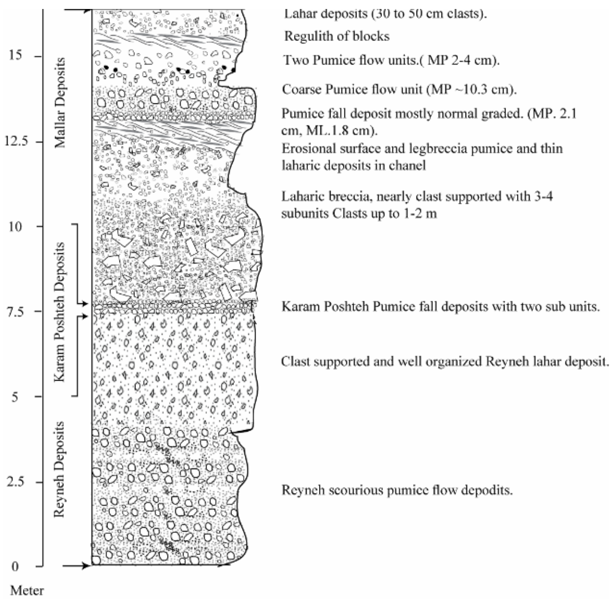

Figure 3. Lithostratigraphic section at Varkaly Springs (locality 1 in Figure 2), showing the stratigraphic relationships of three main pumice deposits of this study. MP = maximum pumice clast and ML = maximum lithic clast. Maximum values are average five largest clasts from measurements of the major and minor widths of each clast. Sections are to scale except that some thin units have been exaggerated for display purposes.

reversely graded with the basal layer 2a of [20] prominent in most flow units (Figure 5b). Low amplitude channels, pumice-rich flow margins, and pumice lenses give the deposits a wavy layered appearance (Fig. 5c). Pumice clasts over 5 cm in diameter typically make up > 20% of the deposits, while visible lithic content (clasts > 1 cm) vary from 5 to 25%. The larger clasts are set in a poorly sorted ash-rich matrix. A characteristic of the Reyneh deposits is that clasts below 10 cm are mostly light grey and vesicular when broken open, while most larger clasts are dark grey to black (Fig. 5b), can be described as scoriaceous pumice and are denser than the smaller clasts. The dark clasts stick out against the light grey ash and pumice matrix; an appearance that is sufficiently distinctive that that isolated exposures of the deposit can be readily recognised around the volcano. Bread-crust bombs and pumice with alternating pale grey and dark bands are also distinctive features. Lithic clasts include fresh dense trachyandesite lava, weathered trachyandesite lava clasts and reddening clasts of highly oxidised lava.

At locality 2 (Fig. 2) three thin horizons of pumice fall deposits are intercalated with the pumice flow deposits (Fig. 5c), showing that there were significant pauses in the generation of pyroclastic flows. The pumice flow deposits are overlain in most localities by coarse-grained lithic-rich lahar deposits with some scoriaceous pumice clasts. The transition from pumice flow deposits to laharic deposits is continuous and no channels were observed at the boundaries, consistent with the lahars being emplaced shortly after the eruption.

Karam Poshteh Pumice Fall Deposit

A young pumice fall deposit is found distributed over much of the south-western and western flanks, although the in areas with rough lava topography the deposit is commonly not preserved. The deposit can be usefully divided into thin more distal unconsolidated pumice fall deposits and think proximal welded pumice fall deposits. The distal deposit is mostly ungraded and well-sorted pumice with low (<5%) lithics (Fig. 6a). Slight normal grading near the top is indicated. Several localities are complicated by avalanching from surrounding steep slopes into local depocentres, generating reversely graded lensoid bedding (Fig. 6b). The pumice clasts are low density (500 < < 1000 kg/m^3) and white. Pale grey, slightly vesicular lithic clasts are distinctive.

Near the Karam Poshteh quarry 6.5 km to the WSW of the summit (Fig. 2) the deposit thickens and incipiently welded beds of pale pink pumice become apparent (Fig. 6c). Some minor cross-layered ash beds are probably surge deposits. The quarry is located at the foot of the steep Damavand cone at the mouth of a ravine where the proximal welded facies is well exposed on the ravine walls (Fig. 6c and 6d). The welded pumice deposit is up to 10 m thick. It is strongly layered, which is partly due to grain size bedding and partly due to variations in colour and degree of welding (Fig. 6c).

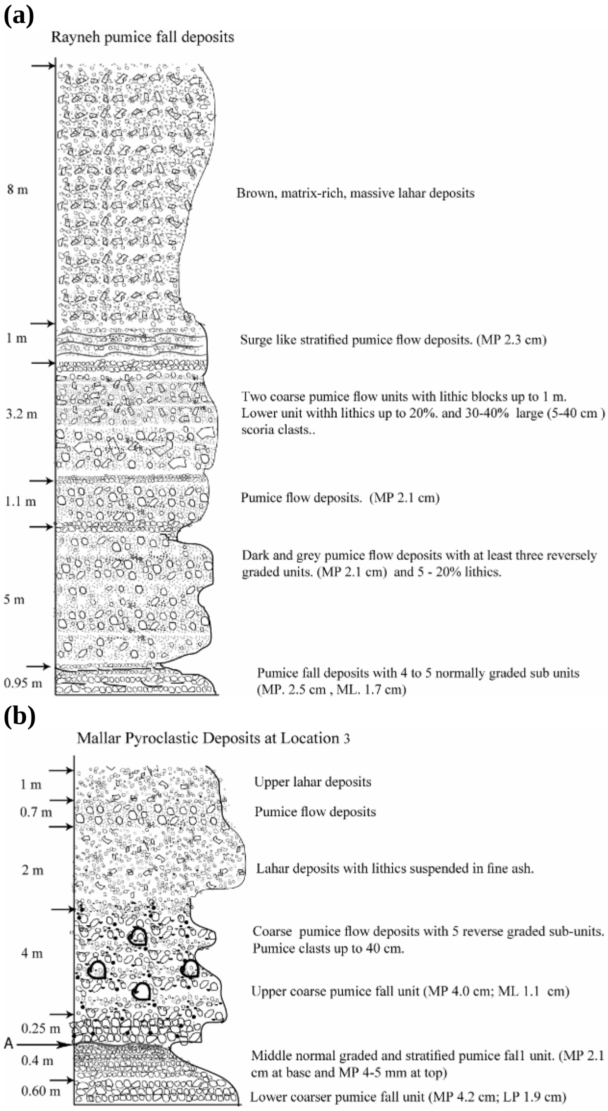

Figure 4. Lithostratigraphic sections at key localities to illustrate internal stratigraphy and major lithologies of pumice deposits. (a) Reyneh pumice deposits at Mallar road in Gazaneh valley (locality 2 on Figure 2). P1-P3 are thin pumice fall deposits intercalated with the pumice flow deposits with thickness given in parenthesis. (b) Mallar Pumice deposits at Siyah Var Valley close to Mallar village (locality 3 on Figure 2). Horizon A in the section is a thin (3 to 5 cm thick) stratified and vesiculated ash layer composed of fine to medium sand ash.

Incipiently welded pumice deposits can be bright orange or dark grey, which reflects both high temperature and oxidation. Where most intensely welded smaller pumices have collapsed into fiamme in zones of dense welding, while large pumice clasts have not collapsed, giving an unusual lensoid structure in the field (Fig. 6e). No pumice flow deposits have been found so far in the Karam Poshteh deposits.

Mallar Pumice Deposits

The Mallar pumice deposits are found in local valley fills and fans over most of the sector from Mallar above the Gezaneh valley to the western flanks of the volcano. A basal pumice fall deposit reaches 95 cm thickness at Mallar (Fig. 4b at locality 3 in Figure 2), thinning and fining to the west. The pumice fall deposit is not present on the western flanks, so the observations suggest an easterly dispersal. At Mallar the pumice fall deposits has three distinct sub-units (Figs 4b, 7a and. 7b). The lower and upper sub-units are coarse-grained and ungraded, while the middle sub-unit is normally graded with well-developed planar stratification (Fig. 7b). The middle unit is capped by thin layers of fine and vesiculated ash, suggesting a temporary pause in major explosive activity in which there was ash fall. The pumice is white and low density (~500 kg/m^3) and the lithic content is very low (~<2%).

The basal pumice fall deposit is overlain by a series of pumice flow deposits. There are commonly several flow units identified from reverse grading of pumice and pumice lenses (Fig. 7a). Lithic contents are moderate to low (15-5%). Pumice clasts are highly vesicular (density about 500-700 kg/m^3) and white top pale grey. Occasional larger pumices (> 10 cm) are grey to dark grey (Fig. 7a). Biotite is prominent in the ash matrix.

Other Pumice Deposits on Damavand

Other pumice deposits have been recognised on Damavand [11]. The most important pumice deposit is the Axe ignimbrite, which is a widespread and thick (up to 100 m) welded pumiceous pyroclastic flow deposit. [11] assigned an age of 260 ka to the Axe ignimbrite. On the flanks of the volcano the ignimbrite forms a multiple package of numerous pumice flow deposits, which have similar appearance to the Reyne deposit. In the Haraz valley the ignimbrite is much thicker and massive in appearance.

[11] reported pyroclastic deposits on the eastern rim of the Gazaneh valley. We examined these deposits briefly and observed 6 pumice fall deposits alternating with paleosoils, two pumice flows deposits and reworked pumice and ash. None of the deposits could be correlated with the recent pumice deposits, and the deep

(a)

(b) **(c)**

Figure 5. Images of the Reyneh pumice flow deposits. (a) The image shows the Reyneh basal Plinian pumice fall deposit overlain by coarse pumice flow deposits at locality 2 in Fig. 2. The pumice fall displays three sub-unit that drape an inclined paleosoils surface developed in older lithic-rich lahar deposits. See Figure 3a for graphic log of this section. (b) Working quarry 3 km to the west of the village of Reyneh displays several thin lenticular pumice flow units marked by pumice-rich tops and margins. Many of the pumice clasts have dark interiors. (c) Exposure of lenticular pumice flow deposits at locality 2 in Fig. 2 showing one of three the intraformational thin pumice fall deposits (marked by arrow), indicating pause in column collapse activity (see Figure 3a for graphic log.

(200 m) Ganazeh valley stands between the summit of Young Damavand and these deposits. The pumice flows deposits could not have reached here if the present Gazaneh valley existed and we conclude that these are an older sequence of explosive eruptions that formed prior to valley formation and deposited on a thick sequence of volcaniclastics and lavas that form the eastern wall of the valley. We also observed other older

(a)

(b)

(c)

(d)

(e)

Figure 6. Images of the Karam Poshteh pumice deposit. (a) Close-up of well-sorted pumice fall deposit at locality 15 km to the west of the summit of Damavand volcano. Hammer 30 cm long. (b) Avalanche bedding in pumice fall deposit 10 km to the west of the summit of Damavand volcano with typical reversely graded and well-sorted sub-units. Hammer 30 cm long. (c) Welded Pumice fall deposit near Karam Poshteh quarry, 6 km WSW of summit, showing internal grain-size layering. The intensity of welding increase up through the section from basal white unwelded pumice to incipient welded dark pumice to more densely welded, paler grey layers at the top of the section, in which pumices are slightly flattened. (d) View of the orange-coloured welded pumice fall deposit mantling the slopes of Damavand 0.5 km to the east of the Karam Poshteh quarry; two people on path indicate scale. (e) close-up opf strongly welded fall deposit 5.5 km west of summit. The smaller pumices have completely collapsed to form fiamme with eutaxitic foliation, which forms anastomising regions between larger and paler uncollapsed, commonly angular pumice clasts. Hammer is 30 cm long.

pumice deposits in this volcaniclastic succession. The importance of the older deposits is that they demonstrate that the volcano has repeatedly been in phases where explosive eruptions were dominant.

Debris Avalanches

There have been debris avalanches in Damavand's evolution, which is unsurprising for a steep stratocone volcano. [11] documented the Varna debris avalanche and we observed, for example a younger debris avalanche deposit underlying the Reyneh pumice deposits near Millar. In the steep-sided summit cone there is a marked unconformity between older lavas dipping to the east and the youngest lavas covering the western slopes. This unconformity could be a sector collapse scar.

Ages

Here we discuss about three major pyroclastic deposits mentioned in pyroclastic deposit section. We were not able to locate any carbon in the pyroclastic deposits and so the ages will remain uncertain until alternative radiometric dating techniques can be carried out. The Karam Poshteh and Mallar pumice fall deposits drape a region of relatively young lavas to the west of Reyneh, while the Reyneh pumice flow deposits occur as local valley fills cut in the lavas in a topography that was similar to the present. A lava on the upper Poloor-Reyneh road as 66.5 ka and a thick lava at the base of the lava succession in the Axe gorge has an age of 25 ka [11]. However, [11] also present a date for a biotite separate of Reyneh grey pumice. This very old age is difficult to reconcile with the distribution of the Reyneh deposits in an essentially contemporary landscape developed on lavas, which yield much younger ages. [11] drew attention to the difficulty of dating Damavand rocks by $^{39}Ar/^{40}Ar$ methods and in particular problems with excess Ar in biotite. This age is thus suspect. One of the youngest lavas on Damavand is located on the western flanks and has an age determined from apatite separates of 7.3 ka (Fig. 8). We searched for pumice on its surface but found none even though an exposure of the Mallar pumice flow was located about 1 km away. We note here the unpublished observation in Iceland that blocky and aa lava flows are very good places to trap pumice from younger eruptions. We suggest that the available evidence is consistent with eruption of the three pumice deposits younger than certainly 66 ka and probably 25 ka, but older than 7 ka. However, direct dating of the deposits is required.

(a)

(b)

Figure 7. Images of the Mallar pumice deposits at locality 3 (Figs. 2 and 4b). (a) A basal pumice fall deposits with three main sub-units is shown draping an inclined paleosoils surface with coarse pumice flow deposits above. (b) Close-up of well-sorted pumice fall deposits showing a basal coarse pumice subunit, a middle finer grained and stratified sub-unit and a coarse upper sub-unit. Note the fine vesiculated ash layer that separates the upper and middle sub-units at about the level of the hammer head. Hammer is 30 cm long.

Figure 8. The youngest lava from Damavand occurs on the western flanks with an age of 7.3 ka (Davidson et al., 2004). There are no remnants of young pumice deposits on its surface.

Eruption Magnitudes, Intensities and some Comparisons

The reconnaissance nature of this study means that there is insufficient data on the three pumice deposits to make quantitative estimates of magnitude and intensity. However, some more qualitative assessments can be made by comparison with products of well-documented eruptions of other volcanoes. The pumices fall deposits are widely dispersed placing them in the sub-Plinian to Plinian categories of [23]. At a distance of about 18 km downwind of the vent the Mallar pumice fall deposit is thicker (95 cm versus 40 cm) and coarser than Mount St Helens pumice from the sustained phase of the 18 May 1980 eruption [9], which is approximately at the boundary of the sub-Plinian to Plinian category. However, pumice fall deposits from the AD 79 of Vesuvius are much thicker at comparable distances [18]. Pumice flows from Mount St Helens extended about 8 km from vent [15] & [9] and about 10 km for the pumice flows produced in the 1993 eruption of Lascar volcano, Chile [7], while the pumice flows in the Mallar and Reyneh eruptions have run-outs of at least 20 km. The larger run-outs at Damavand can partly be explained by steep slopes, but also reflect more energetic eruptions. These comparisons thus place the Mallar and Reyneh eruptions as having comparable to somewhat larger magnitudes and intensities than Mount St Helens in 1980 (VEI4), but well below the scale of AD 79 Vesuvius (VEI5). They appear to be in the VEI 4 category of explosive eruptions [19].

Eruptive Style

The Reyneh deposits and to a lesser extent the Mallar deposits show evidence for pulsatory activity with intraformational pumice fall in the Reyneh and minor reworked horizons in the Mallar. The pyroclastic flow deposits are an amalgamation of numerous individual flows. The 1993 pumice flows of Lascar from an analogy in which seven major pulses of column collapse over a 2 day period formed a similar pumice flow fan of multiple flow units [7]. Repetitive explosive eruptions at Mount St Helens in 1980 over a period of several months formed the pumice flow fan with periods of several weeks between each burst of activity. However, no major erosive channels or intra-formational volcaniclastic sediments (such as lahars) formed in the pause, with the major laharic deposits being above the primary pyroclastic deposits. The lack of intra-formational reworked deposits thus suggests periods of hours or days rather than months for the pauses.

Hazards Assessment

The recent past has involved lava flows, lava domes and VEI4 explosive eruptions. The geological history of the volcano also indicates that there have been debris avalanches in the past, and any steep-sided cone raises the possibility for sector collapse events and associated volcanic blasts too. The upper steep-sided cone of the young Damavand is the source of many young lava flows, so another lava eruption with limited or no hazardous consequences would not be a surprise. However, there are reasons to suggest that the next eruption could be explosive. Patterns of activity at comparable stratovolcanoes, such as Vesuvius (Italy), Karkatoa (Indonesia), Santiaguito (Guatemala), Santorini (Greece) and Mount St Helens (USA), suggest that it is common for such volcanoes to have long periods of dormancy (hundreds to thousands of years) prior to major explosive eruptions. Large explosive eruptions are commonly followed immediately by periods of enhanced lava flow of dome extrusion building up lava shields, lava cones or dome complexes. Such constructive activity then stops and a long period of dormancy then ensues before the next explosive eruption. Given that Damavand has alternated between periods of lava extrusion and explosive eruptions and has had no eruptions for perhaps as long as a few thousand years, its behaviour could well conform to this common pattern.

If Damavand moved into a state of unrest with episodes of earthquake swarms, increased fumarolic activity, and signs of ground deformation then a major explosive eruption is a plausible scenario that should be planned for. Here we consider the Mallar and Reyneh as the kind of likely eruptions then the hazards are easy to identify. The possibility of sector collapse and debris avalanche would need to be evaluated. However, many explosive eruptions occur without sector collapse. Early activity could involve phenomena such as phreatic explosions, high gas emissions, lava extrusion. The early extrusion of lava should not be used as evidence that an explosive eruption will not develop since some major eruptions such as Pinatubo in 1991 and Mount St Helens in1980 have been preceded by lava dome extrusion or cryptodome intrusion.

The most significant hazard is pyroclastic flows with associated surge clouds. Survival rates are very low in areas inundated by flows and surges (typically >90% fatalities). The areas under threat will be considerably wider than the valleys in which the young pumice flow deposits are now preserved since surges deposits have low preservation potential and can sweep hundreds of metres up the sides of valleys. The pyroclastic flow hazards will certainly extend into the Haraz valley and the authorities might need to close the main highway for a period of weeks or even months. After the eruption has finished lahar hazards will remain for months and possibly years in periods of heavy rain.

Modelling of Tephra Dispersal, Fallout and Associated Hazards

Here we apply models of tephra fall using the TEPHRA2 to understand regional hazards from tephra fall. TEPHRA2 is an advection-diffusion numerical model that solves a mass conservation equation which forecasts mass accumulation on the ground relative to a particle-release source [5]. The model uses analytical solutions of equations describing tephra diffusion in the atmosphere, transport and sedimentation, where all particles are released instantaneously and are assumed to be spherical. Particle fallout is controlled by wind advection horizontally, settling velocity vertically, which varies according to the particle's Reynolds number [4], and by turbulent diffusion. The atmosphere is divided into horizontal layers characterized by uniform wind velocity and direction. Particles are transported by the wind specific to each layer; when they fall into a lower layer they are affected by different wind. This process continues until the particles reach the ground. The model has been extensively calibrated against tephra fall data [5].

Based on the field observations at Damavand and estimates of eruption magnitudes, we choose a volume of ejected tephra equivalent to 0.5 km^3 of dense erupted magma as representative. Tephra dispersal was simulated according three eruptive scenarios with column heights of 15, 20 and 25 km above the summit of the volcano at approximately 5 km. Grain size distribution was assumed to be dominated by fine particles (Md =4.5; =3), similar to that reported for the Mount St. Helens eruption of 1980 [8]. A topographic grid, taken from a global digital elevation model (GTOPO30) was input into the model, with a horizontal grid spacing of 3 km. In order to account for seasonal atmospheric variability, simulations were performed using quarter-day regional wind profiles, during three years.

Using TEPHRA2 outcomes, probabilistic maps were constructed based on the *One Eruption Scenario* methodology described by [6]. These maps show the probability distribution of reaching a particular mass accumulation on the surface based only on wind profile variations, whilst all eruption parameters are specified deterministically. Consequently, contours P[M(x,y) > *threshold* | eruption] were calculated, where M(x,y) is the mass per unit area at a given point, and *threshold* is a given accumulation of tephra on the surface. Thresholds were chosen according to potential environmental damage at different scales. The initial pumice fallout can cause roof collapse hazards in the populated areas on the volcano's flanks, which is potentially lethal to occupants. Accumulations of more than 50 cm of pumice can start to result in collapse [3] the Mallar and Reyneh pumice fall deposits exceed this threshold in many places on the south-east flanks of the volcano. For roof collapse we use 200 kg/m^2 threshold. Further away thicknesses of only a few cm can be very disruptive to urban environments and to transport [3] & [21]. Here we use 10 kg/m^2 as the threshold for serious environmental impact. Fine ash is principally a nuisance and might, for example, cause airports to close, as well as disrupt transportation. Aircraft should avoid flying through ash clouds. There may also a public health issue, because fine ash can exacerbate people with breathing difficulties (e.g. asthmatics). Ash can also pollute water supplies with heavy metals and acid components (e.g. HCl and H_2SO_4) depending on gas compositions. A few millimetres of ash can destroy agriculture in the growing season and poison of livestock due to fluorinosis. Here we use a threshold of 1 kg/m^2. A fuller description of the environmental effects of tephra fall can be found in Chapter 17 of [21].

Wind Data

Atmospheric information, in particular wind data, is crucial in order to perform tephra dispersal simulations. Meteorological stations that supply wind profiles at different altitudes are scarce throughout the study region. Due to this lack of information available, wind data from global datasets was used. The so-called *Reanalysis Project* provides complete global coverage that has proven to be a useful tool to capture atmospheric circulation patterns in a particular region, even where sparse conventional observations are available. All variables are representative at 2.5°x2.5° latitude-longitude grid nodes. 17 pressure levels (at 1000, 925, 850, 700, 600, 500, 400, 300, 250, 200, 150, 100, 70, 50, 30, 20 and 10 hPa), cover as high as 30-31 km above sea level. Temporal resolution varies from monthly averages to sub-daily data, typically at the synoptic hours of 00, 06, 12 and 18 UTC. A linear interpolation was applied in order to obtain 1 km of vertical resolution from the original 17 pressure levels. Both wind direction (provenance) and velocity for four atmospheric levels are shown in Figures 9 and 10 considering three consecutive years. The former shows upper tropospheric levels and the latter stratospheric ones.

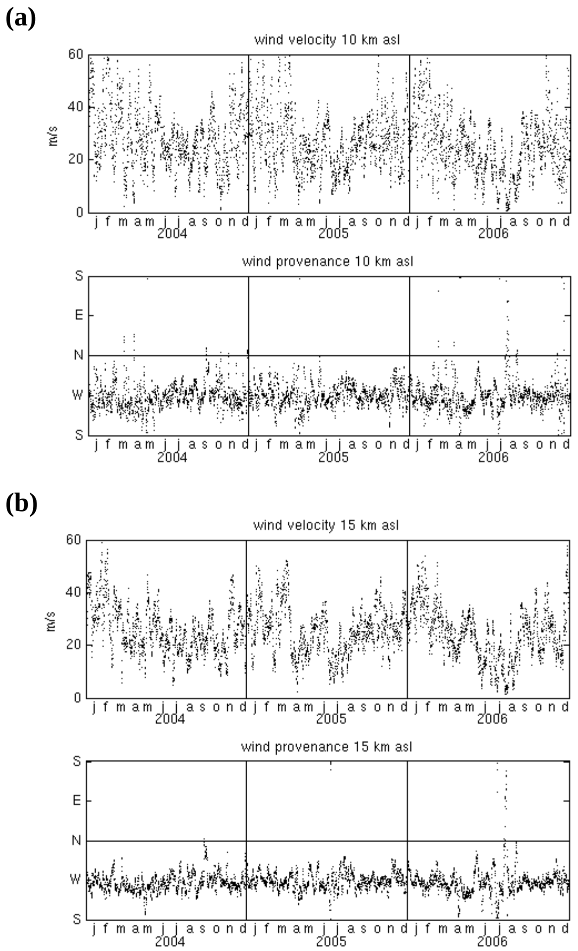

Figure 9. Wind velocity and provenance for tropospheric levels (a) 10 km asl and (b) 15 km asl, at Damavand volcano. Four data points per day between 2004 and 2006 are shown. Westerly winds are persistent throughout the year, especially at 15 km asl. Wind velocities are higher during winter months reaching on average around 40 and 30 m/s for 10 and 15 km asl respectively. In contrast during summer months the velocity drops to around 20 m/s in both cases.

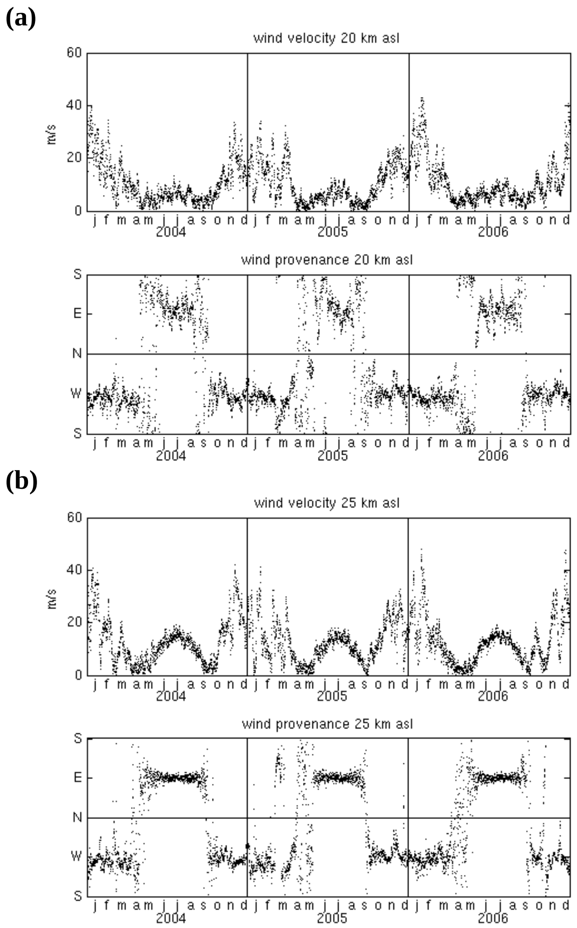

Figure 10. Wind velocity and provenance for stratospheric levels (a) 20 km asl and (b) 25 km asl, at Damavand volcano. Four data points per day between 2004 and 2006 are shown. At 25 km asl, where summer easterlies wind reach a maximum during July, with 15 m/s on average. Wind velocity during the winter is higher than summer mainly due to the winter polar vortex, that is originated by the hemispheric temperature gradient, where velocities during January are around 20-25 m/s on average. The most prominent features in the stratospheric circulation are a westerly jet in the winter hemisphere and low velocity easterly jet in the summer hemisphere.

Results and Discussion

Figure 11 shows probability maps for thresholds of 100, 10 and 1 kg/m^2 for a model with a 20 km high column and Figure 12 shows the effects of season on dispersal for a 25 km high column. Tephra dispersal is dominantly towards the east in all seasons (Fig. 12). For roof collapse (Fig. 11a) the results confirm the high hazard to communities around the southern and eastern flanks of the volcano. For significant environmental disruption (Fig.11b) areas of up to 15000 km^2 to the east of the volcano have high hazard with the major cities of Mazandaran Province having between 0.1 and 0.2 probability of experiencing more than 10 kg/m^2 fallout. The risk of the cities of Sari, Amol, Babol and Qaemshahr increases in the spring and early summer (Fig. 12). Agricultural and pollution problems may have much larger footprint (Fig. 11c); areas of up to 100,000 km^2 could be affected at distances of up to a few hundred kilometres. The hazard in Tehran is low, because of the dominance of westerly tropospheric winds. However, Tehran could experience tephra fall for

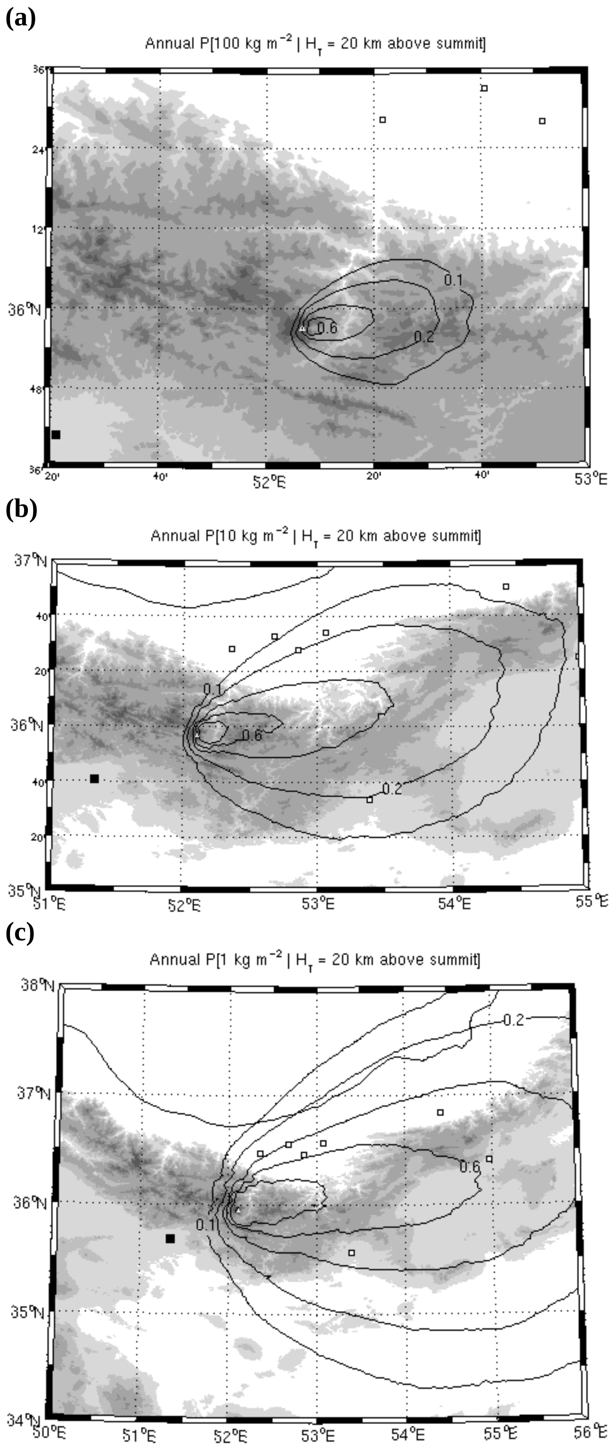

Figure 11. Probabilistic maps of mass accumulation on the surface for 20 km height scenario. Contour lines at 0.1, 0.2, 0.6 (labelled), 0.4 and 0.8 probability to reach the respective thresholds: (a) 100 kg/m^2 (thickness ca. 10 cm), (b) 10 kg/m^2 (thickness ca. 1 cm) and (c) 1 kg/m^2 (thickness ca. 1 mm). Damavand volcano is indicated by a triangle. Main cities are shown as white squares and Tehran as a solid square.

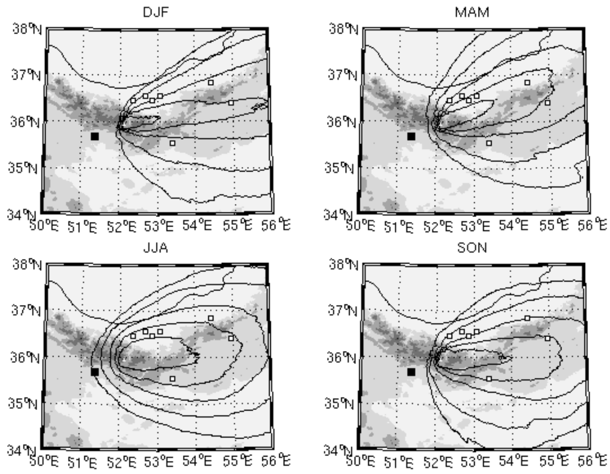

Figure 12. Probabilistic maps of mass accumulation on the surface for 25 km height scenario, highlighting seasonal variability. Simulations were grouped each three consecutive months. Contour lines at 0.1 (outermost), 0.2, 0.4, 0.6 and 0.8 (innermost) of probability to reach 1 kg/m^2 threshold (thickness ca.1 mm). Westward transport of tephra is enhanced during summer months (JJA).

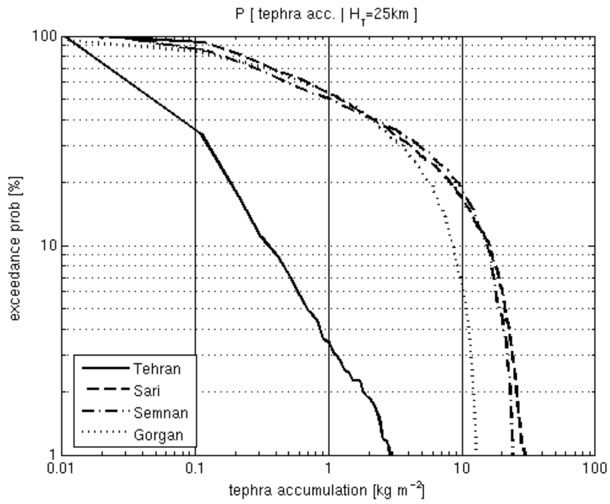

Figure 13. Exceedance probability plot for four cities in the study area. Note the contrast amongst a city located west of the volcano (Tehran, ca. 70 km from the source) and the cities towards the east (Sari, ca. 110 km; Semnan, ca. 120 km; and Gorgan, ca. 230 km).

high columns and during the summer. The relative hazards to Tehran and the eastern cities are shown in Figure 13, which compares exceedance probability curves for Tehran, Sari and Semnan.

Damavand has at least three young pumice deposits formed in the last 25,000 years as a consequence of major VEI4 explosive eruptions with magnitudes inferred to be larger than Mount St Helens in 1980 but smaller than Vesuvius in AD79. These inferences need to be confirmed by detailed mapping of the deposits and more precise dating. Pumice fall deposits up to a metre thick drape much of southern flanks. The distribution of the pumice fall deposits indicates easterly tephra dispersal for two of the eruptions, observations consistent with the dominant tropospheric and stratospheric wind directions.

Probabilistic modelling of tephra dispersal indicates that the provinces to the east of Damavand are vulnerable to environmental damage when the pyroclastic flow and debris avalanche hazard will be a scenario that should be planned for it. Finally we strongly suggest that to study the stratigraphic and physical volcanology aspects and also on the volcanic hazards of Damavand.

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