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A history of explosive eruptions at Young Damavand volcano, Iran

Mohsen Zadsaleh ^{a*}, Karen Fontijn ^b, Hamed Pourkhorsandi ^{b, c}, Fariborz Masoudi ^a

^a Department of Earth Sciences, University of Shahid Behesht, Tehran, Iran

^b Laboratoire G-Time, Department of Geosciences, Environment and Society, Université libre de Bruxelles, Brussels, Belgium

^c Géosciences Environnement Toulouse (GET), IRD/CNRS/UPS/CNES, Toulouse, France

Abstract

Young Damavand volcano is a steep isolated volcano in the Central Alborz Mountains, Iran, that is characterized by extensive lava flows and pyroclastic successions and is placed on the eroded remains of Old Damavand. Pyroclastic fall and density current deposits on all flanks of the volcano were sampled and studied. From a tephrostratigraphic and geochemical study of the proximal-medial sequences, 14 phases of explosive volcanic activity are identified, characterized by a combination of ash and pumice fall deposits, and/or dense and dilute pyroclastic density current deposits. Some explosive phases of Damavand are thought to have happened one after the other with only short time intervals, since almost no traces of paleosol can be identified between them. We also show that the intensity of the eruptions varied between different phases, confirmed by relative thickness and grain size of the different fall deposits and their distance from the crater. The evidence of numerous explosive eruptions, five of which with Volcanic Explosivity Index 4 in the history of the activity of Young Damavand volcano, shows the importance of assessing its potential volcanic hazards.

Keywords: Damavand volcano, Explosive eruptions, Pyroclastic density current deposits, volcanic explosivity index, Tephrostratigraphy, volcanic hazards

1. Introduction

During explosive eruptions, volcanoes produce a wide range of pyroclastic deposits with variable facies, including tephra fall and/or various types of pyroclastic density current (PDC) deposits (e.g., Cioni et al., 2003; Houghton et al., 2004; Sheth et al., 2009; Carazzo et al., 2012; Torres-Orozco et al., 2017; Tadesse et al., 2022). The characteristics of pyroclastic fall deposits depend on the nature of the eruption that generated them, including its magnitude and intensity (Carey and Sparks, 1986; Pyle, 1989; Ernst et al., 1996). PDCs are non-uniform mixtures of volcanic fragments and gases, and create deposits that are typically poorly sorted, with an ash-rich matrix that is the result of primary fragmentation in the conduit (Druitt, 1992; Wilson and Houghton, 2000; Charbonnier and Gertisser,

2008; Parfitt and Wilson, 2008; Cas et al., 2011; Roche et al., 2016; Macorps et al., 2018; Breard et al., 2018; Jones et al., 2023), but also secondary fragmentation due to collision and abrasion of larger fragments during current movement (Dufek and Manga, 2008; Hornby et al., 2020). PDC deposits may be massive, with or without grading (normal or reverse), or stratified, showing cross- and/or (sub) parallel bedding at a variety of scales (Branney and Kokelaar, 2002; Brosch and Lube, 2020).

A reconstruction of how an eruption occurred and how deposits were emplaced in cases where activity has not been reported by humans relies on studying eruptive products and (pyroclastic) deposits. Long-dormant volcanoes, especially those with little or no recorded historical activity, can be very hazardous and present “low-probability – high-risk” scenarios, especially when they are located near densely populated areas (e.g., Barberi and Carapezza, 1996; Gardner et al., 2000; Carapezza et al., 2010; Clynne et al., 2014; Loughlin et al., 2015; Kisaka et al., 2021). An example is the dormant Damavand volcano which is located in the Alborz Mountains (N Iran), only 60 km from Tehran, the capital city, with a population of more than 13 million people (Statistical center of Iran, population census report 2016). Damavand currently displays fumarolic activity at its summit (Zelenski et al., 2020). The northern and eastern flanks of Damavand are covered by glaciers in all seasons, but these are melting due to reduced rainfall and rising air temperatures (Khodaeian et al., 2010). The youngest known eruptive products of Damavand have been dated at 7.3 ka and were emplaced as lava flows on the western flank (Davidson et al. 2004). Damavand may have had more recent minor explosive activity, but its eruptive products (if preserved) have not been observed or sampled yet. The pyroclastic deposits investigated in this study are likely older than the lava flows on the western flank, though precise age determination is lacking.

Earlier studies have investigated the explosive volcanic activity of Damavand and estimated the intensity of eruptions (Darvishzadeh and Moradi 1997; Mortazavi et al 2009; Mortazavi, 2013). For example, Mortazavi (2013) suggested that some eruptions may have had a volcanic explosivity index (VEI; Newhall and Self, 1982) of 4, however individual eruptions remain poorly described. None of these studies have investigated the pyroclastic facies in detail and have not determined the general stratigraphy, both of which are critical in understating a volcano’s explosive history. In this study, we address this by performing a detailed stratigraphic study of the pyroclastic volcanic products. The diversity and ubiquity of pyroclastic facies at Damavand volcano suggest the occurrence of multiple explosive eruptions in the past. Thick deposits of pumice lapilli and ash fall and (mostly dilute) PDCs are systematically studied here and are reported as much as possible in a stratigraphic framework. We present estimates of the frequency and

magnitude of past explosive eruptions at Damavand, including an assessment of the proportion of eruptions that are associated with PDC activity.

2. Geological background

Damavand is an isolated stratovolcano and the highest peak in the Middle East, with an elevation of 5610 m a.s.l. It formed during the late Pliocene to Holocene (between 1.8 Ma and 7.3 ka) and sits on a basement of folded and faulted Mesozoic carbonate and sandstone units of the Alborz Mountains in northern Iran (Fig. 1a-b; Davidson et al., 2004; Hassanzadeh et al., 2006). Its edifice volume is about 400 km³ and it is composed of lava and pyroclastic deposits mainly with trachytic and trachyandesitic and to a lesser extent basaltic and basanitic compositions (Allenbach, 1966; Emami, 1989). In general, two hypotheses have been proposed about how Damavand volcano was formed. Damavand is either the result of the Cenozoic Neo-Tethys oceanic subduction under central Iran (Jung et al., 1976; Brousse and Moine-Vaziri, 1982; Aftabi and Atapour, 2000), or formed due to local mantle upwelling and the formation of deep fractures in the crust resulting from the changes in tectonic regime during the late Pliocene in central Alborz (e.g. Allenbach, 1966; Davidson et al., 2004; Hassanzadeh et al., 2006; Omidian, 2007; Mirnejad et al., 2010; Shabaniyan et al., 2012; Mortazavi, 2017). Based on trace element signatures, Mehdizadeh et al. (2002) and Liotard et al. (2008) suggested that Damavand was formed in a subduction zone with mantle melting. However, Mirnejad et al. (2010) suggests a process of deep mantle melting based on radiogenic ⁸⁷Sr and ¹⁴³Nd isotopic data. They thus identify that the source of Damavand alkali olivine basalts is similar to that of ocean island basalts (OIB).

Mineral textures and quantitative crystal size distribution (CSD) analysis suggest that magma mixing plays an important role at Damavand (Zadsaleh and Pourkhorsandi., 2016). Different textures in plagioclase show changes in the rate of magma ascent, small and large-scale convection cells in the magma reservoir(s), varying temperature and/or pressure and different volumes of eruptible mush/melt in Damavand's plumbing system (Zadsaleh and Pourkhorsandi., 2016; Zadsaleh et al., 2022).

Elemental geochemistry and fractional crystallization modelling show that the formation of trachyte and trachyandesites of Damavand can be explained by several stages of fractionation of a mafic magma with small effects of open system processes (Eskandari et al., 2020). According to Eskandari et al. (2016, 2018), the processes of magmatic differentiation at Damavand volcano were primarily influenced by polybaric fractional crystallization within a transcrustal magma plumbing system. Using thermobarometry and MELTS modeling for trachyandesite-trachyte lavas, they delineated three distinct levels for magma

reservoirs at depths of 22-28 km, 15-22 km, and 2-11 km. The crustal structure beneath Damavand was determined by Abbassi et al. (2010), Radjaee et al. (2010) and Afra et al. (2021). Local earthquake tomography indicates changes in P-wave velocity at different depths in the crust (3-4, 6-8, 16-17 and 24-25 km). The thickness of sedimentary rocks in the Damavand region is about 3 to 4 km (Abbassi et al., 2010), and according to the V_s velocity model of Radjaee et al. (2010), the thickness of sedimentary rocks beneath the Alborz region is about 2 to 7 km. A recent geophysical-petrological model of Damavand volcano has shown that there is a low-velocity zone in the lithospheric mantle of central Alborz that extends through continuous channels to Damavand volcano (Mousavi et al., 2023). Tomography studies have shown that a partially crystalline magma reservoir with low seismic wave velocity ($V_s \sim 2.8$ km/s) exists at depths of approximately 3 to 4.5 kilometers beneath the cone of Damavand, surrounded by rocks with higher seismic wave velocities ($V_s \geq 3$ km/s) (Mostafanejad et al., 2011; Shomali and Shirzad, 2015). The presence of a (shallow) magmatic reservoir is consistent with fumarolic activity (Eskandari et al., 2015; Zelenski et al., 2020) and the existence of a geothermal reservoir in Damavand (Ghobadian et al., 2009). Additionally, Momeni and Madariaga (2022) demonstrated that the increase in seismic activity in the region approximately 10 kilometers south of Damavand volcano is closely related to the partially crystalline magma reservoir previously identified by Mostafanejad et al. (2011) and Shomali and Shirzad (2015).

The current edifice of Damavand, also known as Young Damavand (Davidson et al., 2004), is placed on the eroded remains of Old Damavand (Fig. 1c). Remains of the old cone are revealed by an unconformity located on the northern and northeastern flanks of the present cone. The oldest products were dated by (U-Th)/He radiometric dating on apatite at ca. 1.8 Ma (Davidson et al., 2004). There is no significant difference between old and Young Damavand in terms of the geochemical composition of the rocks and minerals (Davidson et al., 2004). After the destruction and erosion of Old Damavand, the Young Damavand stratovolcano started to form about 500 to 600 kyrs ago (Davidson et al., 2004., Pandamouz, 1998). Explosive and effusive activity at Damavand is evident in the form of abundant PDC and tephra fall deposits, and lava flows. Most pyroclastic fall deposits of Damavand volcano are found on the eastern and northern flanks, at distances of up to 15 km from the summit crater (Fig. 1c). This may be consistent with the dominant wind direction (today) in the region from west to east. Preliminary studies on pumice fall deposits on the southern and eastern flanks of Damavand suggest ages between 7.3 and 25 ka, representing sub-Plinian style eruptions of VEI up to 4 (Darvishzadeh and Moradi, 1997; Mortazavi, 2013; Mortazavi et al., 2009).

3. Samples and methods

Field studies to identify different pyroclastic facies were conducted between 2018 and 2020. This led to the identification of more than 30 outcrops with pyroclastic deposits on all flanks of Damavand. Thirteen well-preserved sections were selected for detailed studies. During this process, physical characteristics such as thickness and sedimentary features (e.g., parallel or cross-stratification) of the facies, the (maximum) particle size and morphology (e.g., roundness) of pumice and lithic fragments, sorting of the deposit, pumice color, etc. were systematically recorded. We studied ash componentry to differentiate between various pyroclastic facies, considering the greater abundance and diversity of mineral components it offers compared to pumice lapilli. Thirty ash samples from fall and dilute PDC deposits were investigated for their componentry using a binocular microscope. In dilute PDC deposits the particles larger than 2 mm are mainly pumice and lithic fragments. Particles smaller than 2 mm were mounted in resin, sectioned, and polished (as a 30-micron petrography thin section), and studied by optical microscope to determine the abundance and type of particles (i.e. lithic volcanic, plutonic fragments or cumulates, lithic with argillic alteration and pumiceous) and minerals. To estimate the percentages of each component, ca. 300 particles were counted and classified in each thin section using a point counting method using JMicroVision v1.2.7 image analysis software.

To avoid loss of information, we did not sieve the ash particles. Because some minerals in the ash samples, such as amphibole and pyroxene, occur only in the smaller grain size fractions, all particles up to 2 mm, including those smaller than 0.5 mm, were included in the componentry analysis.

Twenty-six samples of pumice lapilli from both fall and PDC deposits were selected for bulk major and trace element analysis at the Laboratoire G-Time of the Université libre de Bruxelles, Belgium. Prior to the analysis, samples were manually crushed and powdered using an agate pestle and mortar. Loss of Ignition was calculated based on a two-step ignition at 500 and 1000°C, each for 60 minutes. For major and trace element analysis, a Thermo Fisher iCAP 7200 Inductively Coupled Plasma-Optical Emission Spectrometer (ICP-OES) and an Agilent 7700 Quadrupole-Inductively Coupled Plasma-Mass Spectrometer (Q-ICP-MS) operated with a He-filled collision cell were used, respectively. Y and In were used as internal standards during measurements by ICP-OES and Q-ICP-MS, respectively. BHVO-2 and RGM-2 were used as analytical secondary standards and measured a few times each during the analytical runs. The total reproducibility estimated on these standards is calculated to be better than 2% and 10% relative standard deviation (RSD) for ICP-OES and Q-ICP-MS, respectively. In addition, to ensure the reproducibility and precision of the analysis, two samples were repeated at least five times.

Our field observations, ash componentry and geochemical analyses have been used to construct our composite stratigraphy. However, due to the absence of adequate pieces of charcoal or other suitable material for chronometric dating, absolute chronological data could not be obtained. Wherever possible, we have integrated existing chronological data from Davidson et al. (2004) in our composite stratigraphy and discussions.

4. Results

4.1. Facies description

The pyroclastic facies of Damavand volcano were studied in 13 sections. Supplementary Table 1 provides an overview of the studied locations. A summary of all field observations is shown in Table 1, with their interpreted emplacement mechanisms. The studied facies include deposits interpreted to result from fully dilute PDCs (hereafter referred to as “dilute PDCs”) or granular fluid-based PDCs (hereafter “dense PDCs”), as well as deposits interpreted as the result from ash or pumice fallout. The fall deposits were observed on all flanks of volcano, except the western flank. Dilute and dense PDC deposits are observed on all flanks. In some sections, interbedded alluvial deposits and paleosols occur. In some areas, particularly near known faults (e.g. Shahan Dasht Fault), poorly sorted deposits containing small and large angular heterolithic blocks set in a sandy matrix occur, and these are interpreted as landslide deposits. Occasionally we also find massive or poorly stratified deposits with a gritty ash, but often indurated, matrix, and these are interpreted as lahar deposits. In the following sections however, we focus on the primary pyroclastic deposits. Photos and schematic logs are provided in Figures 2-4 and in Supplementary Figures 1-4. The terminology used in the paper is summarized in Supplementary Table 6.

4.2. Geochemistry

The results of whole rock (WR) analysis of ash and pumice samples are given in Supplementary Table 2. All pyroclastic samples have compositions in the range of high-potassium andesite to banakite on a K_2O-SiO_2 diagram (Fig. 5a) and plot in the trachyandesite to trachyte field on a total alkali-silica (TAS) diagram (Fig. 5b). This is consistent with previous studies on volcanic rocks from Damavand, both lava flows and pyroclastic deposits (Emami and Irannejadi, 1993; Davidson et al., 2004; Liotard et al., 2008; Mirnejad et al., 2010; Mortazavi, 2017).

The purpose of the geochemical measurements in this work is to utilize them in facies correlation. Variation diagrams were thus used mainly to fingerprint and distinguish between different units. The colored areas in Fig. 6 are initially drawn based on field observations and macroscopic relationships between the facies and

the WR geochemical data; the phase names are introduced in more detail in Section 5. As can be seen on Fig 6, the variation diagrams of major and trace elements can be used to differentiate studied units, although some units known to correspond based on field observations, show a relatively large spread in concentrations of some element oxides. The diagrams on Fig. 6 generally show a decreasing trend in MgO, CaO, and Sr and an increase in K₂O, Na₂O, Al₂O₃ and Ba with increasing SiO₂ content. However, some samples deviate from this general trend. For example, sample D67 has the lowest SiO₂ content, but its MgO concentration is not the highest in the suite (Fig. 6a).

The similarity coefficient (SC) method is used to quantify the results of geochemical data and determine the relationship between different units (Borchardt et al., 1972). This method has been widely used in tephrostratigraphic studies (e.g., Borchardt et al., 1972; Sarna-Wojcicki, 1976; Davis, 1985; Hallett et al., 2001; Carson et al., 2002; Rodbell et al., 2002; Fontijn et al., 2010). The calculations of SC, as shown in Supplementary Table 3, are based on the concentrations of 12 oxides and elements (Al₂O₃, CaO, Fe₂O_{3tot}, K₂O, MgO, Na₂O, P₂O₅, MnO, TiO₂, SiO₂, Ba, and Sr) which are systematically compared to one another for each pair of samples. Identical samples would have an SC equal to 1. It should be noted that the thresholds used to discriminate between similar and dissimilar samples are variable in the literature, varying from 0.88 (Borchardt et al., 1972; Fontijn et al., 2010), to 0.94 (Davis, 1985; Carson et al., 2002), and 0.95 (Hallett et al., 2001). Determining the appropriate threshold depends on the field observations and the extent of natural heterogeneity in the sample suite. In this study, according to the calculated values (Supplementary Table 3) and field studies, and considering the fact that we are using WR geochemical data (as opposed to glass), we considered 0.92 as an appropriate threshold for our set of samples. However, some sample pairs have a higher SC yet are clearly dissimilar, based on field observations, e.g., D76 from the DM010 outcrop and D87 from the DM013 outcrop: SC 0.96.

Different samples/units tend to show marked differences in their bulk rock composition, and this is related to the geochemical changes induced by magma differentiation (Alloway et al., 2013; Lowe, 2015; Aguiar et al., 2015; Wiwik Dyah Hastuti, 2017; Gisbert and Gimeno, 2017; Pizarro et al., 2019). The trends observed in the variation diagrams are unrelated to the age or stratigraphic position of the samples (presented in Section 5). In other words, samples with higher MgO and lower SiO₂ values are not necessarily older than those with lower MgO and higher SiO₂ (i.e., more evolved) values. For example, D74 (MgO =2.62 wt%, SiO₂=61.00 wt%) is located at the base of section DM010, D76 (MgO =2.24 wt%, SiO₂=63.09 wt.%) in the middle and D77 (MgO =3.63, SiO₂=58.25 wt.%) at the top (Fig. 3, 6; Supplementary Table 2).

The ratios of high field strength elements (HFSE) to Th are used to determine the origin of magma of different facies and to correlate units between outcrops (e.g., Monaco et al., 2021). If Nb/Th, Ta/Th and Zr/Th ratios for the samples are almost similar, it can suggest their similar magmatic origin. As shown in Supplementary Table 4, for example, pumice lapilli D39-D51-D54 from outcrops DM003-7-6, have Nb/Th ratios of 2.20-2.14-2.19 and Ta/Th ratios of 0.14-0.11-0.11, respectively. For this reason, these units are attributed to the same eruption (Polour phase, see Section 5). However, in other cases the ratios are more variable for the same correlated unit, as based on field observations. For example, ash sample D49 and pumice lapilli D48 (Fig. 8) are also assigned to the same unit (Amir Abad phase, see Section 5), although their Nb/Th ratios are 1.7 and 2, and their Ta/Th ratios are 0.43 and 0.10 respectively.

4.3. Ash fall and dilute PDC deposits componentry

In addition to the geochemical data, we used componentry on ash fall and ash from dilute PDC deposits to investigate unit correlations. Samples were taken from outcrops on different flanks except the northern and western ones, where no such fine-grained deposits were observed.

There is an obvious difference in the particle abundance and type in the different ash samples (Fig. 7). Petrographic analysis shows that most ash samples are crystal-rich, and are mainly composed of pyroxene, plagioclase, and biotite, as well as altered and fresh lithic-volcanic fragments, micro-pumice and smaller quantities (less than 4%) of amphibole, quartz, and apatite. Sometimes, for example in samples D88 (Polour phase, see Section 5) and D77 (Fireh3 phase, Section 5), the abundance of micro-lithic volcanic (lithic volcanic fragments ≤ 2 mm) particles and micro-pumice (pumiceous ash fragments ≤ 2 mm; Supplementary Table 6) is very high (D88: $>48\%$ lithic volcanic and D77: $\sim 60\%$ micro-pumice) (Fig 7). Ash samples from dilute PDC deposits are mostly coarse-grained (1-2 mm) and occasionally contain lithic volcanic fragments with dimensions between 5 and 10 mm. As explained in the method section, only particles smaller than 2 mm were studied and larger particles were discarded for the componentry analysis. The geochemical data show that most inspected ash samples are related to a different eruptive phase, (see Section 5: Tephrostratigraphy). Only samples D52, D55, and D59 from dilute PDC deposits in outcrops DM006 and DM007, and D64 from ash fall in outcrop DM003 (Fig 8) show similar componentry (Fig. 7 and Supplementary Table 5), and their geochemical compositions are also similar, suggesting their affinity to the Polour eruptive phase (Section 5). However, the dilute PDC deposit sample D88 in DM013, which also belongs to the Polour phase, shows a different abundance and type of minerals.

As mentioned above, other dilute PDC and ash fall deposit samples are related to different eruptive phases. For example, ash fall D26 and D29 were both observed in outcrop DM002, but which have contrasting abundances of micro-pumice (ca. 30% vs. 3% respectively), and lithics (ca. 4.5% vs. 38% respectively; Fig. 7 and Supplementary Table 5). Moreover, the geochemical signature of pumice lapilli (D27) immediately above the ash of D26, is completely different from that of the ash of D29 (Fig. 6), also suggesting that they belong to two different phases (Malar and Malar1; Section 5).

5. Tephrostratigraphy

Field observations on pumice and ash fall and PDC deposits (Section 4.1; Table 1), geochemical fingerprinting (Section 4.2; Fig. 6) and ash componentry (Section 4.3; Fig. 7), were used in combination and revealed fourteen different explosive phases at Damavand volcano (Fig. 8). Descriptions are detailed in Table 1, and in the following section we refer mainly to the interpreted emplacement mechanisms (e.g. fall deposit, PDC deposit). It is worth nothing that the explosive phases introduced in this work are thought to represent individual eruptions, but that in some cases may have followed each other very close in time, given the overall lack of obvious palaeosol horizons (Section 6).

In the following section, the explosive phases of Damavand are described from oldest to youngest following their relative stratigraphic position as constrained by field observations and topographic elevation. The naming of each phase is based on the nearest village where its type section is located. A terminology table is presented in Supplementary Table 6.

Near the base of the E and SE flanks of the Damavand edifice, ignimbrite deposits (Ask ignimbrite, as per Allenbach, 1966; Emami, 1989; Emami and Irannejadi, 1993; Davidson et al., 2004) (Fig. 1c) are exposed that show weak to strong welding, with fiamme and in some cases prismatic columnar jointing. These deposits were dated at ca. 280 ka (Davidson et al., 2004). All outcrops investigated in this paper are located topographically above the Ask ignimbrite deposits and are therefore younger than 280 ka.

5.1. Mon Phase

The Mon Phase is likely the oldest phase, based on the low elevation (1899 m) of outcrop DM004 where it is found. It is located near the base of the SE flank of Damavand. Below the Mon Phase (in a vertical section), thick alluvial sediments occur under which eventually the Ask ignimbrites are found (Fig. 1c and Supplementary Table 1). The Mon Phase begins with 80 cm thick pumice lapilli

fall deposit (D41) capped with a dilute PDC deposit (Supplementary Fig. 1d, e). Sample D41 of the pumice lapilli fall has a distinct geochemical composition and is particularly rich in MgO (4.77 wt%) and CaO (7.36 wt%) and poor in Na₂O (3.7 wt%) and Al₂O₃ (14.25 wt%) relative to other samples. (Fig. 6 and Supplementary Table 2). This is also reflected in the generally low similarity coefficients that it shows (0.61 to 0.89) with any of the other samples (Supplementary Table 3).

5.2. Amir Abad1 and Amir Abad Phases

At the base of section DM008 alluvial sediments are covered by a sequence of pumice lapilli (P 1, 2, 3), coarse-grained and fine-grained ash fall (Ash 1, 2, 3, 4), which is repeated 3 times (Supplementary Fig. 2c, d), interpreted as the result of pulsating intensity of the plume. We introduce these facies as the Amir Abad1 Phase. Above these fallout deposits again we find 4 meters of colluvial deposits (or probably landslide deposits), covered by coarse-grained pumice lapilli fall (D48) and coarse ash fall (D49) deposits, together named the Amir Abad Phase. Finally, all these products are covered by colluvial deposits again (Supplementary Fig. 2 and Fig. 8). The WR chemical composition of the Amir Abad 1 and Amir Abad phases are different (Fig. 6). The fine pumice lapilli of Amir Abad1 (P2, sample D84) are chemically less evolved than the pumice (D48) and coarse ash (D49) of Amir Abad. Moreover, the ash mineral components show significant differences (Fig. 7 and Supplementary Table 5). The abundance of pyroxene in the Amir Abad ash fall (D49) is about 35.5% and in the Amir Abad 1 Ash3 (D84) it is about 21.7%. The abundance of plagioclase is lower in ash fall D49 (26.2%) than in Ash 3 (34.2%). The abundance of micro pumice in Ash3 is almost three times that of ash fall D49 (19.4 vs. 6.5%) (see Fig. 7 and Supplementary Table 5).

5.3. Fireh1 Phase

No correlative unit ("unit" refers to a pyroclastic deposit with a distinct facies; Supplementary Table 6) to the Amir Abad1 Phase was found. A facies similar to Amir Abad Phase occurs in the top part of outcrop DM010 (samples D78 and D79), also located in the medial-proximal area (Supplementary Table 1) on the eastern flank (Fig. 1). However, petrographic observations suggest significant differences in componentry between D49 and D79. The abundance of pyroxene is lower in ash fall D79 (21.1%) than in ash fall D49 (35.5%). The abundance of micro pumice in ash fall D79 is almost twice that of ash fall D49 (12.2 vs. 6.5%) (see Fig. 7 and Supplementary Table 5).

The pumice samples of D48 and D78 are also geochemically distinct (Fig. 6), with a low SC value (0.88). As a result, we attribute D78-D79 samples from outcrop DM010 to a separate eruptive phase (called Fireh1). In this same section, there are at least 4 explosive eruption phases and 10 units (Fig. 8). From the base

to the top of the outcrop, it includes the Rineh1, Fireh2, Fireh3 and Fireh1 phases (Fig. 8). It should be mentioned that the base of section DM010 (unit A) is not fully exposed and the middle to upper part of the section (units D, 3 and E) could not be sampled due to lack of access (Fig. 8). The units that have been studied and sampled include A, 1, B, C, 2 and 4 (Fig. 8).

5.4. Rineh1, Rineh2 and Fireh2 Phases

There is a 2-5 cm discontinuity in the form of a clay layer (possibly pedogenic) between PDC deposit B (sample D74) and PDC deposit C (sample D76) in section DM010, and they are thus attributed to two different eruptive phases: Rineh1 and Fireh2 respectively (Fig. 8). Despite a high SC of 0.93 between samples D74 and D76, the SiO₂ content of the pumice lapilli in these two units (B and C) is indeed different (D74: 61wt% and D76: 63 wt%) (Supplementary Table 2). The higher SiO₂ content of D76 indicates its more evolved character. The pumice lapilli of unit B (sample D74, Rineh1) have a similar geochemical composition than pumice lapilli of sample D65 from a PDC deposit in outcrop DM005 on the southern flank (SC 0.95; Fig. 6; Supplementary Table 2). Unit B sits continuously above units 1 (ash fall) and A (PDC) in outcrop DM010, without any visible alteration horizon (Fig. 3f). In outcrop DM005, the PDC deposit (D66) was emplaced immediately above a pumice lapilli fall deposit (D65; Fig 8). Therefore, the sequence of units A-1-B in DM010 on the eastern flank are correlated with the fall and PDC deposits of D65-D66 in DM005 on the southern flank and are all reported as the Rineh1 Phase (Fig 8).

A fine pumice lapilli fall deposit (D67) with a thickness of about 10 cm (Supplementary Fig. 1a and Table1) occurs above the Rineh1 sequence in the DM005 outcrop and has a completely different geochemical composition (Fig. 6). It has the lowest amount of SiO₂ (57.25 wt%) and K₂O (2.69 wt%) of all the studied samples and was only identified in this outcrop (Supplementary Table 2). It is interpreted as the result of a separate explosive eruption, and here identified as the Rineh2 Phase (Fig. 8). Because of a lack of correlatives, we cannot define its relative stratigraphic position except that it sits directly above Rineh1.

Unit C (sample D76) in outcrop DM010 also sits above Rineh1 and is geochemically very similar (SC 0.93) to a fine-grained ash deposit (D61) in outcrop DM003, located on the SE flank (Fig. 1a, 6; Supplementary Table 3). We attribute them to the same phase, Fireh2 (Fig. 8), and the fine-grained ash may represent a co-ignimbrite ash fall deposit associated with the PDCs that were emplaced in section DM010. D61 is directly overlain by fine pumice lapilli and ash fall (D36-D64), but for which we do not have chemical data (Fig. 2c).

5.5. Fireh3 Phase

In outcrop DM010, a dilute PDC deposit (Unit 2, sample D77) is placed above unit C (Fireh2; Fig. 3h, 8). Unit 2 is matrix-supported but rich in very small pumice lapilli (Table 1), which can reach up to 60% in modal abundance (Fig. 7 and Supplementary Table 5). Two layers of fine-grained ash (D77a and D77b) with a thickness of 1-2 centimeters occur inside this unit (Fig. 3h). The fine-grained pumice D77 has no geochemical similarity with any other sample and is clearly much less evolved (58 wt% SiO₂) than the samples of underlying Unit C (D76: 63% wt% SiO₂; Fig. 6; Supplementary Table 2). We therefore attribute Unit 2 to a separate event called Fireh3 Phase.

5.6. Larijan Phase

On the ESE flank of Damavand, a pumice lapilli fall deposit (D50), interbedded in the middle with a thin ash fall deposit, can be seen in section DM009. Layers of ash fall formed between pumice fall deposits may represent oscillatory eruption columns and ash venting in between sustained eruptive activities (e.g., Brown and Branney, 2004; Pimentel et al., 2015). Geochemically, the pumice in this unit is different from any of the other pumice lapilli from deposits on the southern, eastern or northern flanks (Fig. 6). The composition of the D50 pumice does however correspond relatively well with that of sample D85 (SC 0.94) from a PDC deposit in section DM012 located on the western flank of Damavand. They are however different in their Al₂O₃ and Ba contents, so we remain cautious with their correlation. Nevertheless, we report both as the Larijan Phase (Fig. 6, 8).

5.7. Polour Phase

The Polour Phase is identified on the southern flank (outcrops DM003-006-007-013) and begins with a pumice lapilli and coarse ash fall (D36-D64; only observed in DM003) and continues with large-volume massive PDC deposits (D39), finally ending with dilute PDC deposits (Fig. 2, 8). The coarse-grained ash fall (D64) contains abundant modal plagioclase (~ 42%), more than other ash fall deposits (17-34%; Supplementary Table 5 and Fig. 7). A massive PDC deposit (D39) overlies the fall deposits in the DM003 outcrop and itself is overlain by a thin dilute PDC deposit (Fig. 2b). In outcrop DM013, only the upper part, i.e., the dilute PDC deposit (D88), is observed. This outcrop is topographically higher than the DM006-007 outcrop (Supplementary Table 1). Pumice lapilli D39, D51 and D54 (D54* is dark pumice) from the dense PDC deposits of the DM003-6-7 outcrops and D88 from the dilute PDC deposit in DM013 all have similar WR geochemical compositions (SiO₂ content 61.13 to 61.59 wt%; Fig. 6, and Supplementary Table 2), with SC values of 0.94 to 0.98 (Supplementary Table 3). To further verify the correlation of the dilute PDC deposits, the componentry of samples D52-D59-D55-D88 was investigated. As seen in Fig. 7, samples D52-55-59 are almost similar in

terms of the type and abundance of minerals, with all three containing 30-40% pyroxene and 28-34% plagioclase (Supplementary Table 5). However, D88 is different and about 50% of its particles are lithics. The correlation of D88 with Polour Phase is thus not very strong, also due to the absence of underlying dense PDC deposits. However, as mentioned above, it has a strong geochemical similarity with the D39-51-54 samples (SC=0.96 to 0.97) and so we also consider it to belong to the Polour Phase.

5.8. Fireh1 Phase

The upper part of outcrop DM010 on the eastern flank (Unit 4) consists of pumice lapilli (D78) and coarse ash fall (D79) deposits (Fig. 3g, i, Table 2). The base of this deposit is probably an alluvium deposit (layer F in Fig. 3g). Petrographic observations show that D79 ash is not comparable with any of the other ash fall deposits sampled in this study, and we attribute it to a separate eruption, called Fireh 1 Phase (Fig. 7 and Supplementary Table 5). From a geochemical point of view, the pumice lapilli fall D78, directly underneath ash fall D79 (not geochemically analyzed), is similar to pumice lapilli D87 from a PDC deposit in outcrop DM013 on the southern flank (Supplementary Fig. 4e, 8). These samples (D78-87) show high SC values (~0.93; Supplementary Table 3 and have very similar SiO₂ and K₂O contents (D78: 62.61 wt% SiO₂ and 4.13 wt% K₂O; D87: 62.56 wt% SiO₂ and 4.17 wt% K₂O), however their Na₂O and Al₂O₃ contents are different (Fig. 6 and Supplementary Table 2). Therefore, we cautiously correlate the D87 PDC deposit with the Fireh1 Phase (Fig. 8).

5.9. Fireh4 and Fireh5 Phases

On the eastern flank of Damavand, in section DM011, a dilute PDC deposit (unit B, sample D82) is placed on top of a dense PDC deposit (unit A, sample D81; Fig. 8). There is a distinct erosional discontinuity between units A and B (Fig. 3a). The pumice lapilli from unit A (D81) are geochemically different from the pumice lapilli of unit B (D82). D81 is more evolved and has higher SiO₂ (62.15 wt%) and lower MgO (2.29 wt%) contents, compared to D82 (60.9 and 3.19 wt%, respectively; Fig. 6 and Supplementary Table 2). Therefore, we relate them to different eruptions: Fireh4 (unit A, sample D81) and Fireh5 (unit B, sample D82) Phases (Fig8). These two units (A and B) are different from other PDC deposits and cannot be correlated elsewhere. At the base of unit A (in Fireh4 Phase), a dilute PDC deposit (sample D80; Fig. 3b) occurs, and which has a different componentry from other ash samples in other sections of Damavand (Fig. 7). It has a relatively high amphibole content (~7%), which is not observed elsewhere (Fig 7 and Supplementary Table 5). This is also consistent with the interpretation that Fireh4, including its dilute PDC deposit at the base, represents a distinct eruption (Fig. 8).

5.10. Malar Phase

On the NE flank of Damavand, at the base of section DM001, and at a distance of 12.9 km from the vent, a ~ 120 cm thick pumice lapilli fall (D21) is observed and which is covered by a massive lapilli-tuff PDC deposit with a thickness of ~ 4 meters (Fig. 4b, c and Table1). The pumice lapilli fall deposit shows primary grain size variations, attributed to varying eruption intensities. The pumice of D21 is geochemically similar to sample D27 (61.86-61.85 wt% SiO₂), from a 40 cm thick pumice lapilli fall deposit in outcrop DM002 (Supplementary Fig. 3) on the eastern flank (Fig. 6), at a distance of about 7 km from the crater. In sample D27, the size of the largest pumice is 3.5 cm, whereas in sample D21, at a distance ~ 13 km from the crater, it is about 2.5 cm (Table1 and Supplementary Table 1). Pumice lapilli fall D27 in outcrop DM002 is underlain by an ash fall deposit (D26) that is considered part of the same eruption. Since the base of the pumice lapilli fall D21 in outcrop DM001 was not reached, we do not know how widespread the underlying ash fall deposit is. We consider the entire pyroclastic fall and PDC deposit sequence in the DM001 outcrop (NE flank) to be correlative with the ash fall (D26), pumice lapilli fall (D27) and PDC deposit (D28) in outcrop DM002 (E flank) and group them as the Malar Phase (Fig. 8).

5.11. Malar1 Phase

Above the Malar Phase in outcrop DM002, another ash fall (D29) and pumice lapilli fall deposit (D30) appears (Supplementary Fig. 3). More than 38% of the particles of ash fall D29 consists of lithic volcanic fragments, much more than ash fall D26 in the same outcrop (4.5 %; Fig. 7 and Supplementary Table 5). The pumice lapilli fall (D30) is also coarser-grained (maximum 5 cm) than the pumice lapilli fall of Malar Phase (D27; maximum 3.5 cm; Supplementary Fig. 3 and Table 1). Geochemical data show significant differences in SiO₂ (D29: 59.2 wt%; D27: 61.85 wt%) and MgO contents (D29: 3.76 wt%; D27: 2.69 wt%; Fig. 6 and Supplementary Table 2) between the two pumice and ash fall deposits. Based on different physical and geochemical characteristics, we thus introduce a new phase for D29-D30, called Malar1 Phase.

6. Discussion

6.1 A history of repeated explosive activity at Damavand

Based on field observations, major and trace element geochemistry and ash componentry, fourteen different explosive phases have been identified on different flanks of Damavand (Fig. 8).

Our whole rock geochemical data are significantly helpful in recognizing and distinguishing different PDC facies. However, in some cases their correlation is difficult and therefore some facies (Polour, Fireh 1-2, Rineh 1, Malar, and Larijan Phases) are shown with dashed lines in Fig. 8. For example, the Larijan Phase consists of two different facies (pumice lapilli fall deposit vs PDC deposit in DM009 and DM012 outcrops) which are located on two different flanks (eastern vs western; Fig. 8). However, they show similar geochemical compositions. In the Polour Phase, dilute PDC deposits in outcrop DM013 are geochemically similar to dilute PDC deposits in outcrops DM007 and DM006 (Fig. 6, 8), however they have different particle componentry (about 7-18% vs 49% lithic volcanic; Fig. 7 and Supplementary Table 5). Therefore, the correlation between dilute PDC deposits in outcrop DM013 and those in DM007 and DM006 is treated with caution (Fig. 8).

In some cases, we tentatively attributed units to the same Phase based on strong geochemical similarity, despite showing differing emplacement mechanisms. For instance, underneath the Polour Phase in DM003, around 10 mm of fine-grained ash (D61) is geochemically different from the overlying pumice lapilli fall but is instead very similar to PDC deposit Unit C in DM010, and is thus cautiously considered to belong to a different Phase, Fireh2 (Fig. 8).

Because the facies have only limited overlapping sequences, it is complicated to reconstruct the relative stratigraphy. Due to the absence of adequate pieces of charcoal or other dateable material, absolute chronological data could not be obtained either. Therefore, to construct our composite stratigraphy (Fig. 8), our field observations and geochemical analyses were as much as possible combined with previous preliminary work (Mortazavi et al., 2009) and radiometric ages that were obtained on some pyroclastic samples by Davidson et al (2004).

The oldest explosive event identified in this paper is represented by pumice fall and the dilute PDC deposits of the Mon Phase, located on the SE flank and which sits on the 280 ka Ask Ignimbrite (Davidson et al., 2004). The other identified phases are found topographically higher than the Mon Phase (Supplementary Table 1) and are therefore assumed to be younger than it.

After the Mon Phase, the pumice and ash fall deposits of the Amir Abad 1 Phase are deposited on the SE flank. Since the Rineh1 Phase on the E flank occurs at the same elevation as the Amir Abad1 Phase (Supplementary Table 1), it is difficult to constrain their relative order after the Mon Phase.

The Larijan Phase on the eastern flank was presumably deposited after the Amir Abad Phase, because at the base of the Larijan Phase, thick alluvial sediments are found (Supplementary Fig. 2f, g and Fig. 8). Following these sediments on the eastern flank, it was observed that they were deposited above the Amir Abad Phase (Supplementary Fig. 2a and Fig. 8). Pumice from a location near section DM012

was dated by Davidson et al. (2004) using (U-Th)/He dating on apatite, and yielded an age of 177.2 ka, which we thus consider as the age of the Larijan Phase. Pumice samples taken from an outcrop near DM006, where we described the Polour Phase, were dated at 177.9 ka (Davidson et al., 2004). Davidson et al. (2004) interpret this pumice and the one near DM012 as the result of a single explosive eruption and consider the difference in the absolute age (177.2 and 177.9) of these two samples to be related to the measurement error. However, the tephrostratigraphic and geochemical evidence provided here suggests that they belong to two different phases, that thus presumably occurred within a relatively short time interval.

If sample D61 at the base of the Polour Phase is related to Fireh2 Phase, this also constrains the minimum age of the latter and of Rineh1. This is consistent with the Polour Phase occurring topographically higher than the Rineh1 Phase.

Above Rineh1 and Fireh2, at least five more explosive eruptions occur, most of which represent relatively small, on the order of VEI 3, eruptions (see Section 6.2): Rineh2 Phase probably represents weak explosive activity that occurred shortly after the Rineh1 Phase (Fig. 8). Another weak explosive eruption (Fireh3 Phase) is interpreted shortly after the Fireh2 Phase (Fig. 8). Units D, 3 and E of section DM010 were not sampled due to lack of access. However, in the upper part of the DM010 section, another deposit of an explosive eruption called Fireh1 Phase was emplaced, and the deposits of this phase can be observed on both the eastern (DM010 section) and southern flanks (DM013 section) of the volcano. The Fireh1 Phase in the DM013 outcrop is located on the southern flank and is discontinuously placed on the Polour Phase (Fig. 8). It is only covered by a few centimeters of soil with limited vegetation (Supplementary Fig. 4e), and for this reason we consider it the youngest phase in our sequence.

Finally, because outcrop DM002 on the eastern flank is topographically located above the DM011 outcrop on the same flank, we assume that the Malar and Malar1 Phases are younger than the Fireh4 and Fireh5 Phases.

Explosive phases of Damavand are thought to have sometimes happened one after the other with only short time interval, since almost no traces of paleosol can be seen between their deposits. For example, successive PDC deposits in outcrop DM010 are related to Rineh1, Fireh 2, Fireh3, Unites D, 3 and E, and Fireh1. However sometimes the explosive eruptions of Damavand have occurred only after a long-time interval. For example, at the base of the Mon Phase, there is thick alluvium deposit (unknown thickness), and then the underlying Ask ignimbrite (Fig. 8). This ignimbrite can be seen only on the eastern flank of Damavand near Haraz River (Fig. 1), and its thickness reaches 100 m. It has moderate to severe welding features and is a columnar-jointed at the base in some places. As the Ask ignimbrite occurs on the edge of the Haraz River, its frontal part has probably been removed by erosion and it is not possible to say exactly how far away from the

crater it reached. Davidson et al. (2004) suggest that the origin of this ignimbrite is related to the Young Damavand crater and that its origin is unrelated to the caldera formation or sector collapse of Old Damavand. The traces of that latter caldera and the remains of Old Damavand are marked with arrows in Fig. 1. Ask ignimbrite is deposited on lava with an age of 445 ka, which is the oldest known unit of the Young Damavand lava flows (Davidson et al., 2004).

6.2. Eruption magnitudes and implications for volcanic hazards

All of the identified explosive phases at Damavand are younger than 280 ka and at least 14 eruptive facies were identified, indicating various styles of explosive activity with different intensity and magnitude. Dilute PDC deposits are observed at distances of more than 10 km from the crater (e.g., Mon Phase in outcrop DM004, near Mon village) and dense PDC deposits can be observed at distances of up to 13 km from the crater (e.g., Malar Phase, outcrop DM001, near Haji Dela village; Fig. 9a and Supplementary Table 1). This means that villages as far as 15 km from the crater are at risk from PDCs.

Pumice lapilli in the Malar Phase, from the largest Sub-Plinian-style fall deposit in the sequence, can be up to 2.5 cm in size and are found in a deposit over 1 meter thick located about 13 km from the crater (Table 1 and Fig. 9a, 4b). Since the deposits is only firmly identified in two localities, we cannot constrain an isopach or isopleth map. Following the method of Legros (2000), we obtain however a minimum deposit volume of $V_{\min} \sim 0,45 \text{ km}^3$, corresponding to a VEI 4 and sub-Plinian eruption ($V_{\min} = 3.69TA$, with T: Thickness and A: Area enclosed within an isopach). This Malar Phase fall deposit is exposed less than 2 kilometers from Haji Dela village (Fig. 9a). Other phases of presumably similar magnitude include: Malar1 ($V_{\min} \sim 0,11 \text{ km}^3$), Larijan ($V_{\min} \sim 0,10 \text{ km}^3$), Mon ($V_{\min} \sim 0,18 \text{ km}^3$), Amir Abad ($V_{\min} \sim 0,13 \text{ km}^3$). These phases, as shown in Fig. 8, may have occurred shortly one after the other (Malar and Malar1) given the lack of clearly developed soil horizons. They may therefore present a period of relatively intense explosive activity in Damavand's history. However, due to the lack of chronometric dating of these pyroclastic deposits, we do not know the absolute age of the eruptions and it is not possible to say how long this intense period would have lasted.

We also identified deposits considered to result from relatively weak eruptions. For example, Rineh2 Phase in outcrop DM005 shows a limited thickness (on the order of 10cm) and grain size (fine pumice lapilli; Table 1) of the deposit relative to its distance to the vent (ca. 9 km; Supplementary Table 1). Using the same approach as above, based on Legros (2000), we constrain a minimum volume for Rineh2 Phase of $V_{\min} \sim 0,02 \text{ km}^3$, and so this would correspond to a VEI 3 eruption.

On the S-SE flank of the volcano, we can observe coarse-grained ash fall (Polour Phase), which was deposited at about 5 km from Polour village (Fig. 9a). The thickness of the ash fall on the southeastern-eastern flank sometimes reaches up to 20 cm (Amir Abad Phase), which is exposed less than 2 kilometers from Larijan village (Fig. 9a). It seems like most explosive eruptions in Young Damavand's history were event of the order of VEI 3 to 4.

There are many villages (more than 65) around the volcano that are located at distances of 8 to 20 km from the crater, and some of them on the edifice (Fig. 9b). The villages are thus located at distances of the volcano that are easily subject to volcanic ash fall in case of another VEI 3-4 eruption. According to the 2016 census of the Statistics Center of Iran (<https://www.amar.org.ir/>), the population of villages around Damavand (medial to proximal areas) reaches up to 9,000 people, but the size of this population varies in different seasons and usually multiplies significantly (to ~70,000 people) in spring and summer (April to August) due to an influx of tourists, seasonal workers and gardeners.

Moreover, most of these villages are often built in valleys and could thus be affected by PDCs and lahars in case of explosive eruptions. In case of reawakening of the volcano, due to the presence of glaciers on the eastern flank (area ~2 km²) and the northern flank (area ~3.5 km²), and snowfall during the autumn, winter and spring seasons, a significant risk may exist from lahar generation. The occurrence of lahars at this volcano in the past can be observed in the Malar 1 and Mon phases (Fig. 8). The lahar deposits that covers the Malar1 Phase (~7 km from crater, Supplementary Table 1) is composed of scattered rocks with a maximum diameter of 2 m. Other fragments include pumice and lithic bombs, lapilli and ash. Lahar deposits can be observed on all flanks of the volcano, but it is difficult to determine to which phase they belong.

Fallout of ash and pumice and also PDC deposits can block roads and make the road surface slippery and hinder the movement of vehicles and cause problems for emergency services during and after the eruption of a volcano (e.g., Barnard, 2009; Blake et al., 2017; Wardman et al., 2012). The main roads connecting villages around Damavand volcano are the Haraz and Rineh roads, and along which large-scale PDC deposits are found, e.g., from the Polour Phase (Fig. 9a).

Distal ash fall could also impact Tehran city (with more than 13 million inhabitants), located at a distance of 60 km to the south-west of Damavand. In addition, at least 300,000 people live to the south and southwest within 30 kilometers away from the volcano (Fig. 9b). The arrival of ash in these areas would depend on the intensity of the eruption and the height of the eruption column. Meteorological data used in Mortazavi et al. (2009) show that at an altitude of 10 to 15 km in the atmosphere, the wind direction is mainly from the west in all

seasons. At higher altitudes (20 to 25 km), the wind direction in June, July and August is from the east (i.e., from the volcano approximately towards the city of Tehran). Therefore, depending on eruptive and meteorological conditions, fine ash may reach Tehran city even in case of a moderate-size explosive eruption.

7. Conclusions

Here we have presented a detailed stratigraphy of the Late Quaternary activity of Young Damavand volcano, which, based on tephrostratigraphy and geochemical studies, eventually revealed 14 explosive eruptions (phases). Field studies show that the explosive phases may have occurred one after the other, sometimes with only a short time interval between them, as almost no traces of paleosol can be seen between them. It has been observed that explosive eruptions of varying intensity have occurred in the history of this volcano, which is confirmed by field measurements of the thickness and dimensions of pumice lapilli fall deposits and their distance from the crater. At least 5 explosive eruptions are interpreted to have a VEI of 4 (Malar, Malar1, Larijan, Mon and Amir Abad Phases). The largest eruption in the sequence is the Malar Phase, with a minimum deposit volume of $V_{\min} \sim 0,45 \text{ km}^3$. Like is the case for the Malar Phase, most explosive eruptive phases were characterized by the emplacement of PDCs along with pyroclastic fallout. However, sometimes only ash and pumice fall products are observed during explosive eruptions (e.g., Amir Abad and Amir Abad 1 Phases). The presence of pyroclastic fall, dense PDC and dilute PDC deposits in residential areas around the volcano shows the importance of studying volcanic hazards at Damavand.

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Figure captions:

Fig 1. a and b, Location of Damavand volcano in map (a) and 3D topography (b) view of the Alborz mountains; elevation data from Shuttle Radar Topography Mission (SRTM) at 3 arcsecond resolution (Earthexplorer.usgs.gov) (c) Location of studied outcrops around the volcano and remains of Old Damavand, background map: Landsat 8 satellite image. (ig: ignimbrite-Ask ignimbrite). Gray lines are topographic contours at 200 meter intervals and dashed line marks Damavand volcano between Alborz mountains.

Fig 2. Field images and schematic lithologs of a selection of outcrops on the SSE flank of Damavand. (a) wide view of facies at outcrop DM003; (b) ash of upper part of dilute PDC deposits; (c) ash and pumice deposits; (d) schematic litholog; (e) Dense and dilute PDC deposits at outcrop DM007; (f) Close view and the boundary between dilute and dense PDC deposit; (g) Schematic view of the facies. Legend at the bottom right applies to subsequent Figures 3-4 and Supplementary Figures 1-4.

Fig 3. Field images of the E flank facies of Damavand at outcrop DM010 and DM011 and schematic images of them. (a) wide and (b, c) close-up view of thick package of PDC and fall deposits; person for scale; (d) Schematic view of the outcrop stratigraphy. (e) wide and (f, g, h) close-up view of thick package of PDC and fall deposits; person for scale; (i) Schematic view of the outcrop stratigraphy.

Fig 4. Field images of the NE and W flank facies of Damavand volcano (outcrops DM001 and DM012 respectively) and schematic images of them (a and b) showing PDC and pumice lapilli fall deposits at the base (c) Schematic view of the facies (d) PDC deposit (e) Schematic view of the facies.

Fig 5. a) K_2O versus SiO_2 classification diagram of volcanic rocks, after Peccerillo and Taylor (1976). The samples are placed in high-K calc-alkaline and shoshonitic series. b) Total alkali versus silica (TAS) classification diagram of volcanic rocks, after Le Maitre, (2002). Data from Davidson et al., (2004), Liotard et al. (2008), Mirnejad et al. (2010), and Eskandari et al. (2020) are plotted for comparison (black circles).

Fig 6. Variation diagrams for Damavand pyroclastic units. The colored squares in the lower right of the figure are the names of the explosive phases.

Fig 7. Pie charts showing abundance and type of minerals in ash fall and ash from dilute PDC deposits in different stratigraphic deposits; abundance calculated based on point counting of >300 particles from the <2 mm fraction, prepared as polished thin sections and observed under petrographic microscope. More details are shown in Supplementary Table 5. Ash fall deposits are shown in brackets at the bottom of the pie charts. Pie charts sorted from young to old, from left to right and top to down.

Fig 8. Schematic logs of pyroclastic deposits on different flanks of Damavand and related phases constrained by stratigraphic correlation. A summary of the explosive phases and the sequence of their occurrence, schematically and without

thickness scale of each facies, is shown at the bottom of the figure. Radiometric ages that were obtained by Davidson et al (2004).

Fig 9. a) Proximal-medial sequences of dense PDC, dilute PDC and tephra fall deposits and main villages. The spatial position of all phases is given. b) Scattered villages and main cities in proximal and distal areas of Damavand. Background Image is from Landsat 8 data and courtesy of the U.S. Geological Survey.

Supplementary Figure captions:

Supplementary Fig 1. Field images of the SE facies of Damavand volcano and schematic images of them (a) PDC and in the pumices fall in the upper part and the base of the flow (b) more detailed view of pumice fall deposit with reverse grading (c) schematic view of facies (d) sequence of fall and Dilute PDC deposits (e) Schematic view of the facies.

Supplementary Fig 2. Field images of the ESE facies of Damavand volcano and schematic images of them (a) two distinct pumice and ash fall deposits; (b) Upper pumice lapilli and ash fall; (c) Bottom pumice and ash fall; (d) more detailed image of the base that shows a sequence of fine and coarse ash and pumice fall units (e) Schematic view of the facies (f) Pumice lapilli fall separated into two parts by a thin layer of ash (g) Schematic view of the facies.

Supplementary Fig 3. Field images of the E facies of Damavand volcano and schematic images of them. (a) massive PDC deposit in bottom third of the exposed sequence and alluvium/landslide at the base. (b) more detailed view of fall and PDC facies (c) Schematic view of the facies.

Supplementary Fig 4. Field images and schematic lithologs of a selection of outcrops on the SSE and S flank of Damavand (a) Dense and dilute PDC deposits with lenses of pumice blocks (closed dotted lines) (b) close-up of dilute PDC deposits; (c) elutriation pipes (d) is a schematic view of the facies (e) dense PDC deposit; (f) dilute PDC deposit; (g) schematic view of facies.

Table captions:

Table 1. Field observations and facies description of pyroclastic deposits found on different flanks of Damavand. PDC: pyroclastic density current

Supplementary Table captions:

Supplementary Table 1. Coordinates, elevation and distance to Damavand summit crater for studied outcrops.

Supplementary Table 2. Whole-rock major and trace element compositions of pumice -ash samples and determined by ICP-OES. Weight % values of major element oxides normalized to 100 wt%. Sample names with a * are dark-colored pumice. Fe₂O₃* is total iron.

Supplementary Table 3. The similarity coefficients (SC) method and results.

Supplementary Table 4. The ratios of high field strength elements (HFSE) to Th

Supplementary Table 5. Proportion and type of particles in ash fall (highlighted in green) and ash from dilute PDC deposits, determined by optical petrography and point counting on >300 particles per sample.

Supplementary Table 6. Explanation of terminology used throughout the manuscript.

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Table 1. Field observations and facies description of pyroclastic deposits found on different flanks of Damavand. PDC: pyroclastic density current

										Emplacement Mechanism					
Location	Section Name	Phase Name	Sample	Thickness	Grain size	Sorting	Sedimentary Structures	Pumice Shape	Additional Description	Dense PDC	Dilute PDC	Pumice Fall	Ash Fall	Figure	
SE Flank	DM003	No	D63	Unknown	Fine silt	Very poorly sorted	Massive		Orange layer at the base of the DM003 section is paleosol (Fig2c). In this unit, only lithic clasts of different type and very low abundance and in size 1 to 3 cm, can be seen.					Fig2(a-b-c-d)	
		Fireh2	D61	10 mm	Very fine ash	Well sorted	Non-graded						X		
		Polour	D36	5 cm	Fine pumice lapilli, 5-8 mm	Well sorted	Non-graded	Angular				X			
		Polour	D64	2 cm	Coarse ash	Well sorted	Non-graded								X
		Polour	D39	>2 m	2 -15 cm pumice and lithic clasts; fine ash matrix	Very poorly sorted	Massive	Rounded			X				
		Polour	No	5-10 cm	0.5 - 1 cm pumice and lithic clasts; medium ash matrix	Poorly sorted	Low-angle cross bedding			Cm-thick layer of Dilute PDC above unit D39 (200 meters away from the sampling site) with a low abundance of rounded pumice and angular lithics of 0.5-1 cm in size (Fig2b).		X			
	DM013	Fireh1	D87	2 m	up to 40 cm	Very poorly sorted	Massive	Rounded	Pumice and lithic bombs, blocks and lapilli	X				Supplementary Fig4(e)	

	Polour	D88	30 cm	coarse ash	Poorly sorted	Low-angle cross bedding to parallel bedding		Coarse ash with cross stratification; more than 48% (Based on petrography) studies of the ash particles are composed of lithic volcanics (Fig7), which are mainly composed of fine-grained microlites in an otherwise glassy groundmass.		X			
DM005	Rineh1	D65	50 cm	maximum pumice size 4-5 cm; maximum lithic size 3.5-4 cm	Well sorted	Reverse grading	Angular				X		Supplementary Fig1 (a-b-c)
	Rineh1	D66	1.5 m	4-5 cm pumice and lithic clasts, fine ash matrix	Poorly sorted	Massive	Subrounded		X				
	Rineh2	D67	10 cm	Fine pumice lapilli, 4-6 mm	Very Well sorted	Non-graded	Angular				X		
DM006	Polour	D54	4 m	3 - 5 cm pumice and lithic clasts; fine ash matrix	Very poorly sorted	Massive with lenses	Rounded	Pumice and lithic bombs, blocks and lapilli; pumice displays white and dark grey streaks. Fossil fumarole pipes can be seen in parts of the massive deposit (Supplementary Fig4c). Lenses (3 to 5 meters diameter) are present across different levels of the deposit (Supplementary Fig4a).		X			Supplementary Fig4(a-b-c-d)

		Polour	D55	60 cm	1 - 2 cm pumice and lithic clasts; fine ash matrix	Poorly sorted	Low-angle cross bedding	Subrounded			X			
	DM007	Polour	D51	2 m	2 - 40 cm pumice and lithic clasts; fine ash matrix	Poorly sorted	Massive	Rounded	2-40 cm rounded pumice; lithic fragments from 2 cm to 30 cm. Most of the deposit consists of pumice blocks. The matrix is composed of coarse-grained ash.	X				Fig2(e-f-g)
		Polour	D52	80 cm	fine ash, pumice lapilli, mm-sized lithic clasts	Poorly sorted	Low-angle cross bedding	Subrounded	Lower part of the deposit shows cross bedding; the top is more massive.		X			
		Polour	D59	20 cm	fine ash, pumice lapilli, mm-sized lithic clasts	Poorly sorted	Massive	Subrounded	Mm-scale gypsum layer separating D52 from D59		X			
W Flank	DM012	Larijan	D85	2 m	2 - 20 cm pumice and lithic clasts; fine ash matrix	Poorly sorted	Massive	Rounded	The pumice is highly vesicular and mostly has a light to white cream color, but sometimes also dark grey. Lithic fragments occur in a variety of colors and lithologies, and are up to 15 cm in size. Pumice clasts are smaller at the base than in the middle and upper parts of the deposit.	X				Fig4 (d-e)
N Flank	DM001	Malar	D22	3-4 m	pumice lapilli and ash	Poorly sorted	Massive	Rounded	Massive lapilli-tuff with pumice lapilli lenses (10 to 50 cm diameter)	X				Fig4 (a-b-c)

	Malar1	D30	1 m	maximum pumice size 5 cm; maximum lithic size ca. 1 cm	Well sorted	Non-graded	Angular					X		
DM008	Amir Abad	D48	55 cm	maximum pumice size 3.5 cm; maximum lithic size ca. 2.5-3.0 cm	Well sorted	Normal grading	Angular	Low abundance of lithic clasts; pumice has a light gray color and is very vesicular				X		Supplementary Fig2 (a-b-c-d-e)
	Amir Abad	D49	20 cm	Medium to coarse ash	Well sorted	Non-graded							X	
	Amir Abad1	D84	1 m	pumice lapilli (~1cm), fine-coarse ash	Well sorted	Rhythmic bedding	Angular	Package of coarse and fine ash alternating with pumice lapilli on cm-dm-scale. Most units are reversely graded				X	X	
DM009	Larijan	D50	50 cm	maximum pumice size 3.5-4.0 cm; maximum lithic size ca. 2.5-3.0 cm	Well sorted	Non-graded	Angular	Low abundance of lithic fragments, which are mostly angular to sub angular. A thin ash layer halfway separates this deposit in two.				X		Supplementary Fig2(f-g)
DM010	Rineh1	A	>3 m	fine ash, pumice lapilli and bombs; lithic lapilli	Poorly sorted	Reverse grading				X				Fig3(e-f-g-h-i)

Rineh1	1	30 cm	2-3 cm pumice lapilli	Well sorted	Non-graded	Subangular				X	
Rineh1	B (D74)	3 m	fine ash, pumice lapilli and bombs; lithic lapilli	Poorly sorted	Massive	Rounded	Rounded to sub-rounded pumice lapilli, bombs and sub-angular lithic fragments. A 2 to 5 cm thick clay layer exists between units B and C.	X			
Fireh2	C (D76)	2 m	fine ash, pumice lapilli and bombs; lithic lapilli	Poorly sorted	Massive	Rounded	Rounded to sub-rounded pumice lapilli, bombs and sub-angular lithic fragments. 30 cm thick deposit of coarse ash and fine pumice lapilli with low-angle cross bedding at the base	X			
Fireh3	2 (D77)	5-50 cm	Fine pumice lapilli, 2-5 mm and coarse ash	Poorly sorted	Low-angle cross bedding to parallel bedding	Subrounded	In the middle of the deposit there are two layers of fine-grained ash (layers D77a and D77b). Graded bedding can be observed in the upper and lower parts of the D77a and D77b ash. The contact between unit 2 and units C and D is continuous.		X		
No	D	1-2 m	fine ash, pumice lapilli and bombs; lithic lapilli	Poorly sorted	Massive	Rounded		X			
No	3	40 cm	1-2 cm pumice lapilli	Well sorted	Non-graded	Angular				X	

	No	E	0.5-1 m	fine ash, pumice lapilli; mm-sized lithics	Poorly sorted	Massive to cross bedding and parallel bedding	Subrounded	Unit E consists of an alternation of pumice lapilli and ash deposits representing both fall and small-scale PDC deposits. There are two fall deposit horizons (E1 and E2) in the middle of the unit.	X	X		
	No	F	1 m		Poorly sorted	Massive						
	Fireh1	4 (D78)	60 cm	maximum pumice size 2.5-4.0 cm; maximum lithic size ca. 2.5-3.5 cm	Well sorted	Normal grading	Angular				X	
	Fireh1	4 (D79)	5 cm	coarse ash	Well sorted	Non-graded						X
DM011	Fireh4	D80	2 cm	Medium to coarse ash	Moderately sorted	Low-angle cross bedding to parallel bedding				X		
	Fireh4	A (D81)	4 m	fine ash, pumice lapilli and bombs; lithic lapilli	Poorly sorted	Massive	Rounded	At the base of unit A, there are fine-grained pumice lapilli (0.5-1cm) with a relatively good sorting and 10 cm thickness	X			
	Fireh5	(D83)B	3 m	Medium to coarse ash	Moderately sorted	Low-angle cross bedding to parallel bedding	Subangular	Unit B is divided into two units B1 and B2. Also, in this section 1 to 3-meter blocks of pumice and lithics clasts appear. 20 cm of ash rests on top of unit B. Units B1 and B2 are normally graded.		X		
												Fig3(a-b-c-d)

		Fireh5	(D82)D	15 cm	1-2 cm pumice lapilli	Well sorted	Non-graded	Angular				X	
		No	C	30 cm	2-3 cm pumice lapilli	Well sorted	non-graded	Angular	Ca. 5 cm coarse ash on top of unit C			X	X
		No	E	3 m	pumice lapilli and ash	Poorly sorted	Massive			X			
		No	F	20 cm	2-3 cm pumice lapilli	Well sorted	Non-graded	Angular				X	
	DM004	Mon	D41	80 cm	Maximum pumice size 3-4 cm; maximum lithic size ca. 2-2.5 cm	Well sorted	Non-graded	Angular				X	
		Mon	A	170 cm	Very fine Pumice lapilli and coarse ash	Poorly sorted	low-angle cross bedding to parallel bedding	Subangular	It consists of laminated of coarse-grained ash and very fine pumice, which are slightly rounded		X		
													Supplementary Fig1 (d-e)

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