Unveiling the Pasqale Avalanche: A Perilous Prehistoric Landslide Proximity to Tehran's Metropolis in Darband Valley, Iran

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Abstract

This research introduces the Pasqale rock/debris avalanche, an occurrence of a prehistoric landslide in the upstream region of Darband Valley in northern Tehran metropolitan that is exemplified as an instance of a high-risk geohazard encountered in the proximity of a metropolitan area. Its initiation as a slide from a steep scarp, with an elevation of approximately 3000 m, nestled within Eocene volcanic rocks and tuff, is noted. The local geology and geomorphology of the Pasqale landslide are described in this paper, relying on topographical data, satellite imagery, and field observations. Through various considerations and the utilization of high-resolution satellite data, the total volume of the landslide is estimated to be in the range of 800,000 m^3. Remarkably, the occurrence of this landslide is found to be influenced by intense fracturing and hydrothermal alterations of the Eocene pyroclastic rocks. Moreover, the seismic aspect of the region is emphasized, with particular attention given to the likelihood of a large earthquake being the most probable triggering factor for the Pasqale avalanche, originating from the Mosha or North Tehran faults. The significance of the cascading hazards that may be brought about following a major earthquake event in the northern Tehran metropolitan area is featured in this paper.

Keywords

Coseismic landslide, earthquake hazard, Central Alborz, Tehran, Pasqale

1- Introduction

Landslide is the movement of a mass of rock, earth or debris materials down a slope of a mountain (Cruden, 1991). Landslides are natural phenomena that can cause disruptions and damages to the built environment and human societies in their path. For example, landslides can damage the transportation routes and in mountain valleys which is a source of considerable economic losses. Additionally, rapid landslides can lead to large fatalities in local environments (e.g. Turner, 2018). Landslides constitute a significant geohazard in emerging mountainous regions globally, spanning from the Alp-Himalaya belt in Eurasia to the Andes in South America, as well as surrounding the mountain ranges of New Zealand (e.g., Glade 2003; Crozier 2005; Dortch et al. 2009; Hasegawa et al. 2009; Zerathe et al. 2014; Shoaei 2014; Wood et al. 2015; Aslan et al. 2020; Grima et al. 2020; Delgado et al. 2020). Landslide volumes (V) exhibit remarkable diversity, ranging from a few hundred to several billion cubic meters, with the latter being termed giant or mega landslides ($V > 10^8$ m^3). Examples of Earth's largest terrestrial landslides include the Seimareh landslide in the Zagros (Shoaei and Ghayoumian, 1998), the 1792 Unzen-Mayuyama mega-slide in Japan (Wang et al. 2019), and the TsergoRi landslide in Nepal (Weidinger et al. 1996), among others.

Korup et al. (2007) conducted an extensive review of giant landslides, exploring their relationship with topography and erosion based on the analysis of 300 cases. Their findings reveal that nearly two-thirds of giant landslides occurred within the steepest 5% of land surfaces, predominantly in deeply incised valleys, along the peripheries of active mountain belts (i.e., fault-bounded fringes), and in volcanic arcs. These distributions align with regions characterized by elevated long-term erosion rates (~ 4 mm yr- 1), affirming the role of giant landslides in expedited mountain denudation. Significantly, most eroded landslide deposit volume is concentrated in the slightest yet steepest sections of mountain belts and volcanic arcs.

Pánek et al. (2016) identified giant landslides in the Caspian Sea region of western Kazakhstan, where more than 100 slope failures mobilized volumes exceeding 10^8 m^3, even along basal failure planes with gradients as low as ∼5°. These events primarily occurred during Pleistocene Caspian Sea-level high stands or during the Holocene, as substantiated by C_{14} dating, and were characterized by lateral rock spreads involving competent limestones covering weak claystone beds.

Rowberry et al. (2023) recently compiled a database of giant landslides on volcanic islands, expanding our understanding of these phenomena. Pánek et al. (2012) introduced the seismic-induced giant Uspenskoye landslide in the Kuban River valley in the Northern Caucasus (Russia). This landslide is believed to have originated catastrophically as a rotational block slide combined with earthflow. Subsequent Kuban River erosion of the landslide toe triggered secondary collapses, resulting in multiple rotational landslides. Strom and Wang (2022) undertook a comprehensive review of rockslides in Central Asia, describing several giant rock slides in the Pamir, Tien Shan, and Djungaria mountains triggered by large historical and instrumental earthquakes.

Despite the long history of geological investigations, giant landslides only sometimes present clear and readily identifiable features to experts. The Alborz Mountains in northern Iran constitute a ~2000 km long belt of folded Paleozoic to Cenozoic rocks, connecting the Caucuses and Hindukush mountains to the northwest and northeast, respectively. This polyorogenic folded belt, evolving during Cimmerian and Alpine orogeny, serves as the focus of active deformation and has witnessed significant historical and instrumental earthquakes.

Historical accounts and recent studies underscore the pivotal role of coseismic land sliding in the Alborz Mountains, affecting both the belt's geomorphological evolution and its socioeconomic landscape. Nevertheless, many landslides in the Alborz Mountains still need to be studied, warranting further efforts to establish a comprehensive database. This paper introduces the Pasqale giant landslide, situated in the upper slopes of the Darband Valley in the north of the Tehran metropolitan area, for the first time

2- Methods

Given the Pasqale landslide geohazard significance and proximity to Tehran, this study offers preliminary insights derived from field observations, satellite imagery, and GIS analysis. Measurement on the area was based on field observations and analysis of high resolution satellite data from Google Earth, Bing data and Sentinel satellite data. Topographic profiles and measurements was done by preparing a Digital Elevation Model (DEM) of the slide zone that was generated using 1:25,000 topographic data with a contour interval of 10 m (Figures 1&2)

3- Observations

3-1- Geological setting and geomorphology of Pasqale landslide

The Pasqale landslide is situated within the Darband Valley's upper reaches, located north of Tehran, in the southern flanks of the Central Alborz Range (Figure 1a). The geological formations exposed in the entire landslide region and its associated deposits are belonging to the Eocene Karaj Formation. Figure 1b illustrates the broader geological context of the study area, adapted from the 1:100,000 geological map of Tehran (Emami et al. 1993). The upper levels of the slide zone, comprising the scarp and an exposed rupture surface, consist of dacitic to andesitic lava and rhyodacitic pyroclastic rock types (E1da). In the middle section of the landslide zone, the composition shifts to include dacitic to andesitic lava with tuff breccia (E1a) and andesitic to basaltic lava flow and breccia (E1b). Notably, these rock units exhibit varying degrees of alteration to the south of the slide zone.

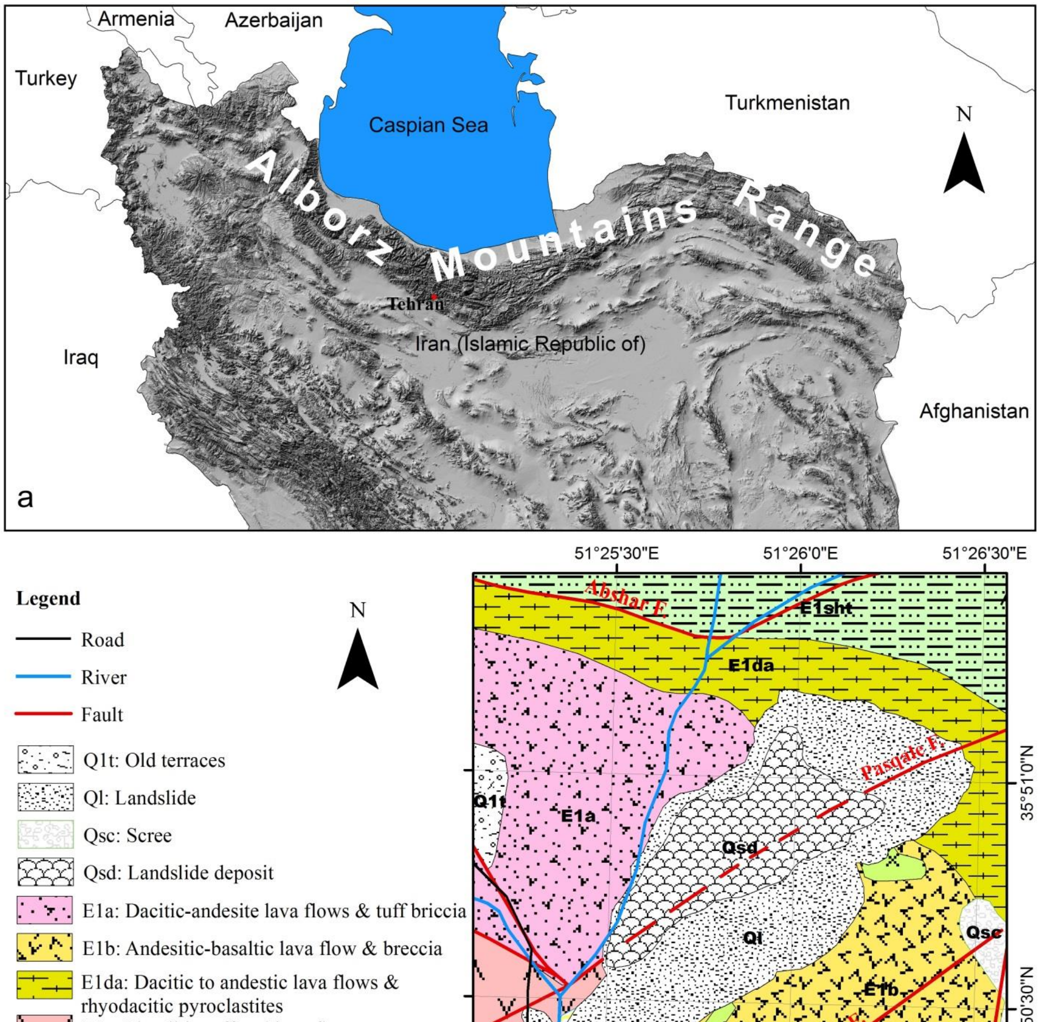

Figure 1. a) SRTM shaded relief map showing the general trend of the Alborz Mountains Range in the north of Iran. The red dot shows the location of the area of study; b) Geology map of Pasqale study area in the northern Tehran. The landslide district in the map includes volcanic rocks, green tuffs and shales of Eocene Karaj Formation. The geology map is modified after Emami et al. (1993).

The topographic contrast between the upper levels of the landslide scarp (>3000 m) and the current level of the slide mass is about 1000 m. Figure 2b illustrates the spatial position of the slide zone with major fault strands and the location of four lines along with topographic profiles. Figure 2c provides the original topographic map employed for making DEM. The plotted topographic profiles encompass one longitudinal and three transverse profiles traversing the slide zone (Figure 3). The longitudinal profile (profile 1 in Figure 3) reveals a nearly vertical slope on the higher levels of the slide zone, corresponding to the prominent Pasqale landslide scarp, with the surface of the rupture only partially exposed. The transverse profiles 3 and 4 (Figure 3) capture secondary topographic undulations attributable to the slide body, inclusive of slide deposits.

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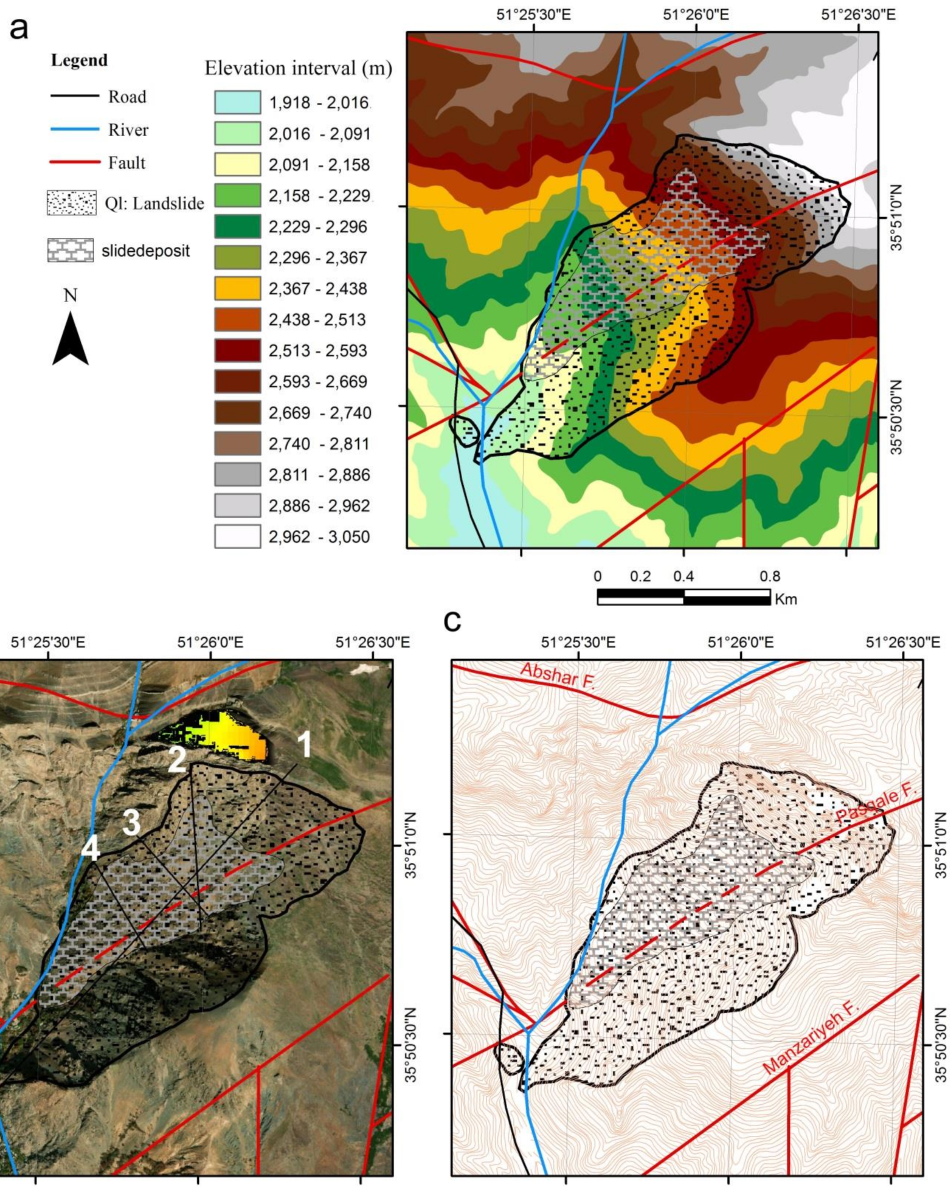

Figure 2. a- Digital elevation model (DEM) of the Pasqale landslide and surrounding area study area that produced from 10 m intervals topographic map using GIS. Boundary of landslide zone and its deposit with major faults have marked on the DEM; b- satellite image of the same area (Bing Images, 2023) on which the location of four topographic profiles (in Figure 3) is shown by white lines. c- Original topographic data that was used for DEM generation (achieved from National Cartographic Center of Iran).

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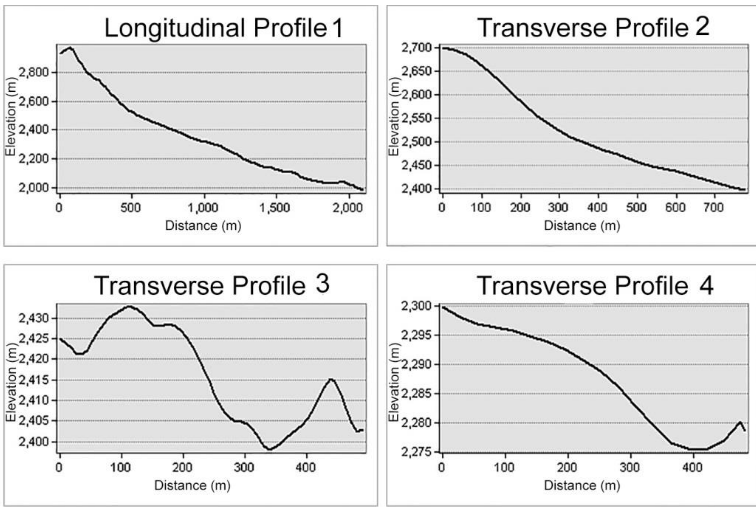

Figure 3. Topographic profiles across the Pasqale landslide based on DEM (10 m); profile 1 is longitudinal and 3 others are transverse. Locations of topographic profiles are shown in Figure 2b by white lines. The horizontal axes of profiles shows the distance (m) from the starting points of profiles that marked by their profile number in Figure 2b. In Profile 1note to the higher slope gradient in the upper scarp; the topographic difference between transverse profiles (profiles 2, 3 and 4) is mainly due to accumulation of the slide deposit.

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While Figures 1b and 2 delineate major fault strands in the study area, Figures 4a and 4b depict a densely fractured system within the exposed rocks of the uppermost segment of the original rock mass. Figure 4a provides an on-site view of the primary scarp (MS) and the exposed surface of rupture (SOR) of the Pasqale landslide. Conversely, Figure 4b presents an annotated satellite image of the region (Bing, 2023), revealing densely fractured rock units in the northern portion. The Pasqale landslide was initiated from the north and northeastern slopes of the Darband Valley, as indicated by the arrows in Figure 4b. However, it remains reasonable that the Darband Valley may have experienced prior landslides from other slopes, necessitating a geophysical survey to ascertain basal rock mass variations beneath the current Pasqale slide deposits.

3-2- Rough estimation of landslide volume

Estimating the volume of the Pasqale landslide is challenging due to the absence of original topographic data predating the landslide event and limited subsurface information from the slide deposit.

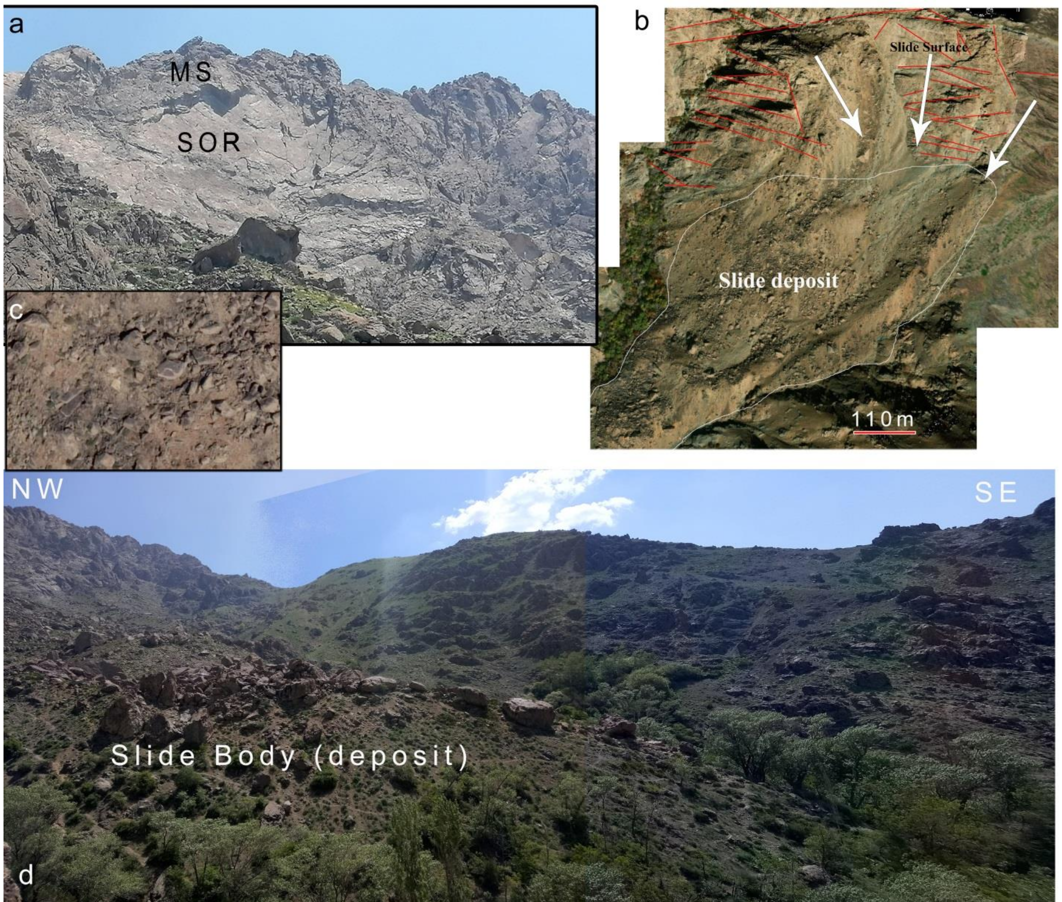

Figure 4.a- Field photograph of the Main scarp (MS) and Surface of Rupture (SOR) of the Pasqale landslide; topographic height at the top of main scarp is ~2980 m.; b- photomap of the Pasqale landslide prepared by the satellite image from Google Earth (2023) that shows the boundary of slide deposit (white polygon), movement direction (white arrows) and slide surface c- a sample of satellite image with high spatial resolution provided by Bing (2023) that was used for measuring the size of rock blocks; d- field photograph showing the panorama view of slide body in which rock blocks are variable is size. The slide deposit is bounded by tall white poplar trees Sepidar in Persian, *Populus alba*).

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Nonetheless, to gain a preliminary rough estimation of the landslide volume, a volumetric measurement of exposed rock blocks on the surficial slide deposit was conducted using high-resolution satellite images and GIS (Figures 4c and 4d). By this approach, rock blocks are classified as cube, spherical, or ellipsoid shapes. While satellite images are inherently two-dimensional, certain assumptions were made to estimate rock block volumes. Specifically, measurements were taken for the long and minor axes for cube and ellipsoid shapes, with the third axis considered equivalent to the middle axis. For spherical rock blocks, only the radius was necessary for volume calculations. While this method is approximated, it provides an estimate of rock block volumes. Figure 5a illustrates the share and volume size distribution of measured rock blocks within the Pasqale landslide deposit categorized by their shape (spherical, cube, and ellipsoid). Figure 5b offers comparative histograms of volume size distributions for the different rock block types. The data reveals that cube-shaped rock blocks predominate in terms of occurrence, whereas ellipsoid shapes contribute to larger blocks. Classification by size indicates that small to medium cubes and small spherical rock blocks are more common. In contrast, ellipsoid rock blocks feature more prominently in the larger block category.

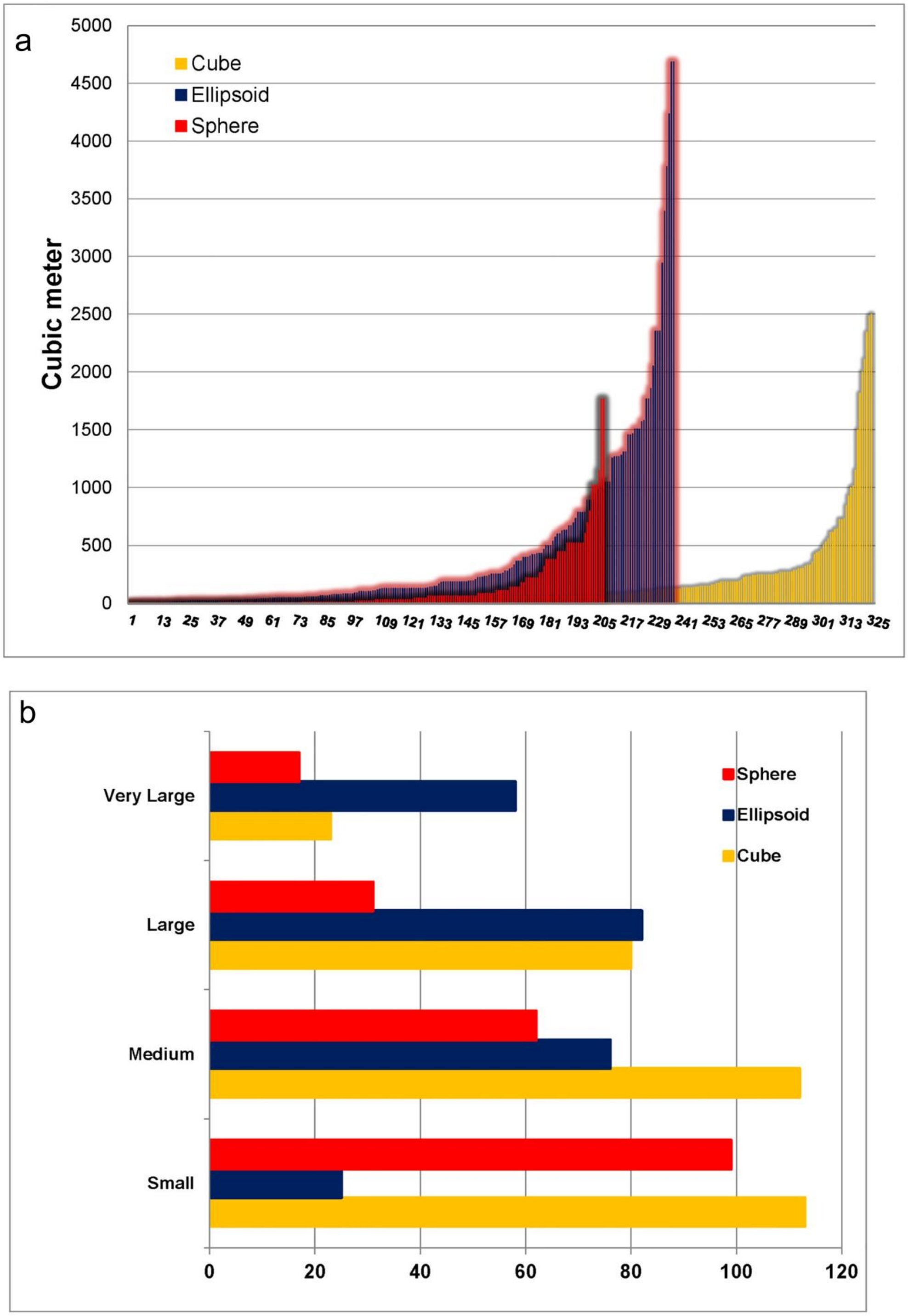

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Figure 5. a- shape and volume size distribution of measured rock blocks of Pasqale landslide deposit by their type (spherical, cube and ellipsoid); b- comparative histogram of volume size distribution of measured rock blocks.

The roughly estimated volume of surficially exposed rock blocks within the Pasqale landslide is approximately ~200,000 m^3. Currently, the timing of the Pasqale landslide remains undetermined, and the extent of fine-grain slide deposits that fluvial processes may have eroded remains uncertain. However, various observations, such as the presence of thriving vegetation around the deposit (Figure 4d), the distinct surface rupture, and known cascades along the flowing Darband River, suggest that the landslide likely occurred during the Holocene. Nevertheless, it is reasonable to assume that a substantial portion of the slide deposit has been eroded, while a significant proportion of fine-grained deposits remain. The erosion time series of landslide deposits is related to several factors such as climate, local topographic condition, lithology, size and cohesion of slide mass, proximity to river and fluvial system etc. the true measurement of this time series requires profound interdisciplinary studies on landscape evolution with geochemical analysis, dating and provenance or fingerprinting studies of slide deposits (e.g. Chang and Zhang, 2010; Gan et al., 2018; Del Vecchio et a., 2018; Chen et al., 2022). However, in various cases for landslides deposits are dated back to several hundreds to more than 1000 years ago, between 10 to 30% of slide deposits still remained uneroded (Del Vecchio et a., 2018; Chen et al., 2022; Koshimizu and Uchida, 2023). Consequently, the estimated volume of the debris mass may be between four to six times the measured volumes of rock blocks. Accordingly, the total roughly estimated volume of the Pasqale landslide ranges from 800,000 to 1,400,000 ± 200,000 m^3. Of course, this amount is the total volume before the start of erosion. Therefore, it is possible that the current value of the volume of the landslide mass is the same number as 800,000 cubic meters.

4- Discussion

The Pasqale landslide, introduced for the first time in this study, is a substantial landslide situated within the Darband Valley on the southern slopes of the Central Alborz Mountains. The slide zone primarily comprises weathered and altered volcanic rocks and tuff belonging to the Eocene Karaj Formation. Notably, the slope gradient between the slide scarp and the toe is remarkably steep, with an elevation difference of approximately 1000 m. The Darband Valley may have a history of older landslides, thus representing a paleolandslide zone that warrants further investigation. Extensive fracturing of higher slopes of landslide area provided required condition for disintegration of rock blocks, where the several sets of fractures intersect with each other (Fig. 6).

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Of course, this amount is the total volume before the start of erosion. Therefore, it is possible that the current value of the volume of the landslide mass is the same number as 800,000 cubic meters.

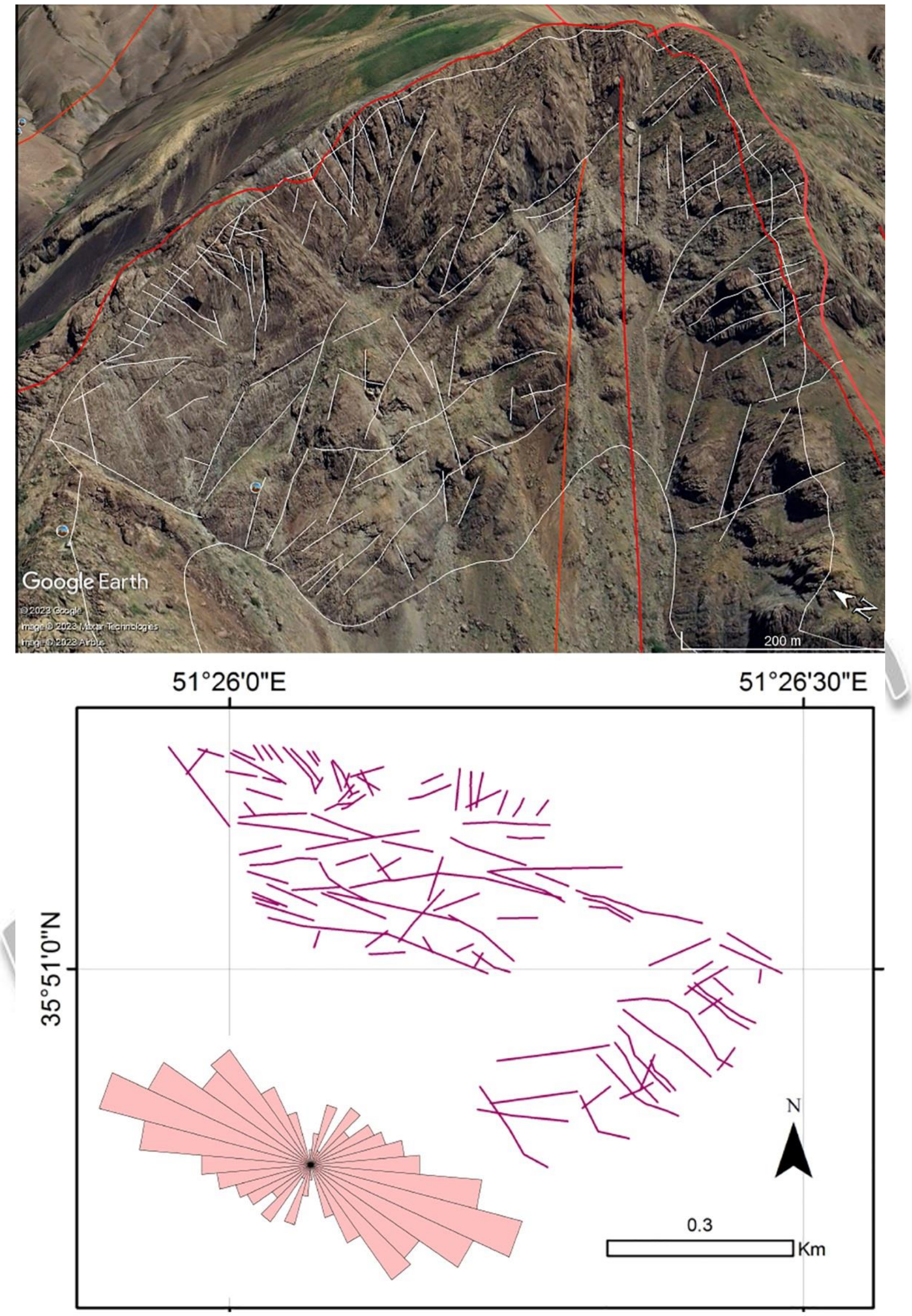

Figure 6. More detailed map of fracture distribution on the top portion of Pasqale landslide with their rose diagram showing several sets of available fractures that are more frequently ~E-W. Intersection fracture sets provided suitable condition of rock blocks to destabilize.

At this stage, we estimate the volume of the Pasqale landslide to range from 800,000 to 1,400,000 ± 200,000 m^3. While the Pasqale landslide does not meet the criteria of a giant landslide, it is still reasonably classified as a large-scale landslide. Based on observations of the exposed sliding surface, the high steep gradient, and the overall morphology, it is inferred that the Pasqale landslide was likely initiated as a rock-debris slide. However, it experienced a transition to a rock/debris avalanche due to the following key observations:

1. The exposed slide surface discontinues downward (Figure 4a), indicating that the slide body is entirely detached from the slide surface after minimal movement.
2. Of greater significance, rock blocks of considerable size, comparable to the dimensions of a room or small building and evaluating several hundred tons, were pushed several kilometers from their original positions. Such occurrences align with the characteristics of rock avalanches, which are recognized globally as coseismic landslides (e.g., Keefer 1984; Jibson et al. 2006; Dunning et al. 2007). Rock avalanches represent one of the most common fatal landslide types in the Alborz and Zagros regions (Roberts and Evans 2013; Ehteshami-Moinabadi 2019; Gutiérrez et al. 2023).

As previously mentioned, Korup et al. (2007) identified that nearly two-thirds of giant landslides are concentrated within the steepest 5% of land surfaces, particularly in deeply incised valleys, along the peripheries of active mountain belts (fault-bounded fringes), and in volcanic arcs. The conditions prevailing in the Darband Valley, characterized by its steep and deeply incised terrain, align with the criteria observed for giant landslides.

From an active tectonic and seismotectonic perspective, the Mosha and North Tehran faults represent two major seismic faults that have experienced historical and pre-historical large earthquakes (M>7.0) (Fig 7). These faults are located north and south of the study area, respectively (e.g., Berberian and Yeats 1999, 2001, 2017; Ritz et al. 2012; Talebian et al. 2016). While a detailed discussion of the seismotectonic aspects of the region is beyond the scope of this paper due to length constraints, interested readers are directed to the aforementioned references and additional works such as Berberian et al. (1985), Landgraf et al. (2009), Solaymani-Azad et al. (2011), Ghassemi et al. (2014), Solaymani-Azad (2023), Ehteshami-Moinabadi and Nasiri (2023) and Ehteshami-Moinabadi et al., (2023).

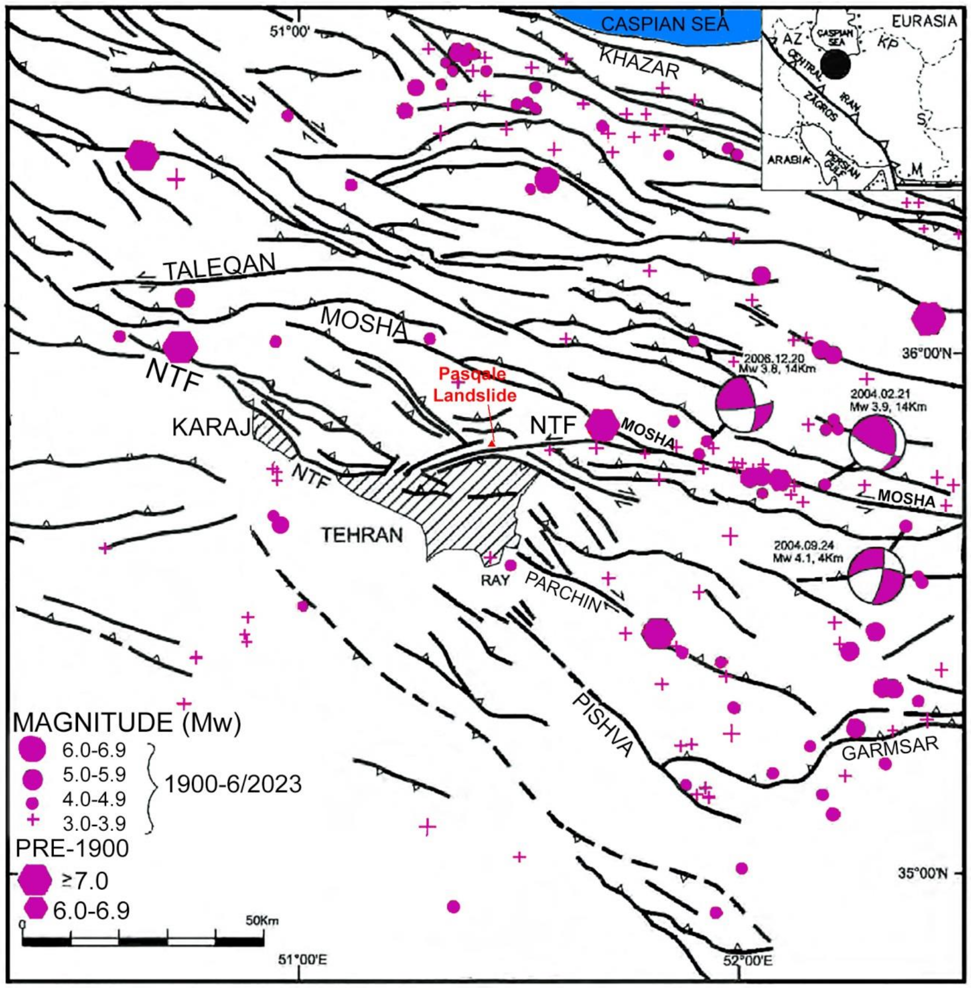

Figure 7. Map showing the historical and instrumental seismicity of the Tehran region and surrounding area; instrumental seismic data achieved from Iranian Seismological Center. Historical seismicity and faults based on Berberian and Yeats (2017). The location of Pasqale Landslide is marked by red triangle.

Given the well-established relationship between earthquakes and large landslides in the Alborz Mountains (e.g., Berberian et al. 1992; Asadi and Zare 2014; Ehteshami-Moinabadi and Nasiri 2019), and considering the proximity of the North Alborz and Mosha faults to the Pasqale landslide, it is reasonable to assert that an earthquake represents the most probable triggering mechanism for this landslide. Further research and investigation are essential to refine our understanding of the specific seismic conditions and factors that led to the initiation of the Pasqale landslide.

5- Conclusion

In conclusion, the Pasqale landslide represents a significant prehistoric event characterized as a large rock/debris avalanche originating from a slide in the Darband Valley's upper reaches, situated north of Tehran. The rough estimated volume of this landslide falls within the range of 800,000 to 1,400,000 ± 200,000 m^3. Notably, the composition of thrown rock blocks varies in size, ranging from a few cubic meters to several hundreds of cubic meters, with some exceptionally large blocks.

The geological components contributing to this event primarily comprise volcanic rocks and tuff, characterized by intense fracturing. Additionally, the upper surface of the landslide exhibits a near-vertical slope. Moreover, the Darband Valley exhibits feature consistent with the potential occurrence of paleolandslides, warranting further investigation.

From a seismotectonic viewpoint, the study area is identified as an active area. In this context, the most plausible triggering factor for the Pasqale landslide is a significant earthquake originating from either the Mosha or North Tehran faults. This observation underscores the significance of the Pasqale landslide as an illustrative example of the hazards associated with coseismic mass movements in the northern vicinity of the Tehran metropolitan area. The implications of such events on the safety and preparedness of this densely populated urban region are of paramount concern, highlighting the need for continued research and assessment in geohazard mitigation and disaster management.

6- Declarations

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Author contributions

All authors contributed to the study conception and design. Material preparation, data collection and analysis were performed by [Mohsen Ehteshami-Moinabadi] and [Elahe Feizabadi]. The first draft of the manuscript was written by [Mohsen Ehteshami-Moinabadi] and all authors commented on previous versions of the manuscript. Shahram Nasiri read the draft and made contribution on final revisions. The original idea about this landslide was inspired by Mohsen Ehteshami-Moinabadi and Shahram Nasiri. All authors read and approved the final manuscript.

Conflicts of interests (CEI)

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper. The authors have no conflicts of interest to declare. All co-authors have seen and agree with the contents of the manuscript and there is no financial interest to report. We certify that the submission is original work and is not under review at any other publication.

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