

Article

Volcanic Hazard Assessment of a Monogenetic Volcanic Field with Sporadic and Limited Information: Deterministic Approach for Harrat Lunayyir, Saudi Arabia

Károly Németh ^{1,2,3,*} , Abdulrahman Sowaigh ², Mahmoud Ashor ¹, Mostafa Toni ^{1,4} and Vladimir Sokolov ¹ 

¹ Saudi Geological Survey, National Program of Earthquakes and Volcanoes, Jeddah 21514, Saudi Arabia; ashor.ms@sgs.gov.sa (M.A.); mostafa.toni@science.helwan.edu.eg (M.T.); sokolov.v@sgs.gov.sa (V.S.)

² Institute of Earth Physics and Space Science, HUN-REN Fluids by Depth Program, 9400 Sopron, Hungary; sowaigh.ag@sgs.gov.sa

³ Volcanic Risk Solutions, Massey University, Palmerston North 4442, New Zealand

⁴ Geology Department, Faculty of Science, Capital University, Cairo 4037120, Egypt

* Correspondence: nemeth.k@sgs.gov.sa

Abstract

Saudi Arabia is experiencing interactions between ongoing urbanization, tourism growth, infrastructure projects in western regions along the Red Sea, and volcanic hazards. The area contains extensive monogenetic volcanic fields with hundreds of volcanoes formed during the Quaternary period. The large scale of the region often limits and fragments volcanological research, resulting in insufficient age and chemical data to understand the spatial and temporal development of many volcanic fields. Increased tourism has created a need for volcanic hazard assessments, particularly since some volcanic fields are considered possible tourist destinations. Harrat Lunayyir, in northwestern Saudi Arabia, is an example where such assessments have been conducted. Hazard assessments seek to provide information about potential future eruption types, locations, and impacts over timeframes relevant to urban planning and risk management. Due to rapid local development, these assessments may be required on short notice for specific small areas within larger volcanic fields, even when geological data are limited. This report presents a deterministic, scenario-based method for addressing such requests in the Lunayyir Volcanic Field. Results indicate a young Holocene eruption site characterized by a complex scoria cone associated with lava spattering, Strombolian, violent Strombolian activity and extensive transitional-type lava effusion.

Keywords: volcanic field; monogenetic; scoria; lava spatter; ash; lapilli; fissure; Rifting; Arabian Shield; Red Sea; lava flow inundation; pāhoehoe; Geoheritage; Geotourism



Academic Editor: Thomas R. Walter

Received: 4 January 2026

Revised: 17 February 2026

Accepted: 3 March 2026

Published: 4 March 2026

Copyright: © 2026 by the authors.

Licensee MDPI, Basel, Switzerland.

This article is an open access article distributed under the terms and

conditions of the [Creative Commons Attribution \(CC BY\)](https://creativecommons.org/licenses/by/4.0/) license.

1. Introduction

Monogenetic volcanic fields are a common form of volcanism on Earth, especially within intracontinental regions [1–3]. They produce many small-volume volcanoes that usually erupt on short timescales, generating less than 1 km³ of dense rock equivalent (DRE) over their lifetimes [2]. Future eruptions typically occur at sites distant from previous vent locations. However, regions with ongoing melting anomalies may see later eruptions on top of older volcanic structures [4,5]. When eruption recurrence intervals are geologically short, distinguishing individual eruptive units within such complexes becomes difficult because erosional or sedimentological markers are absent. These overlapping volcanoes may still

be considered monogenetic if each is fed by a distinct conduit, with residual magma in the conduit crystallizing before subsequent eruptions nearby. The spatial distribution of monogenetic vents varies widely, from random to clustered or structurally aligned patterns, often interpreted as reflecting subsurface melting anomalies and crustal structure [6,7]. Volcanic hazards in monogenetic volcanic fields—characterized by small volumes, mainly basaltic composition, absence of central magma chambers, dispersed volcanoes over large areas, vent distribution dictated by geology, and brief eruption durations, while the overall activity can last hundreds of thousands of years—pose significant challenges from a probabilistic standpoint. Often, there is limited age data or large error margins, making it difficult to predict where and when volcanoes form and erupt accurately; these two aspects are distinct, as shown by Harrat Lunayyir (Figure 1), one of the smallest Neogene–Quaternary monogenetic volcanic fields just about 300 km to the NW from the city of Al Madinah, where many volcanoes are complex vent structures that can become active rapidly but are supplied by different magma sources from separate melting events. In summary, monogenetic volcanoes display a complexity that surpasses their small size and brief eruption periods, reflecting their links to various lithospheric processes occurring across different spatial and temporal scales. This complexity complicates the assessment of volcanic hazards in these regions. Key hazard considerations include the location and timing of potential future eruptions, as well as the nature of possible volcanic events. Effective hazard management requires probabilistic assessments of the temporal and spatial patterns of volcanism, supported by comprehensive volcano models that can be integrated into spatiotemporal prediction frameworks. To build such models, three essential components are needed: (1) a comprehensive event library with accurate geochronology spread evenly across the volcanic field; (2) a detailed catalog of vents, including an understanding of vent distributions ideally placed within event chronology; and (3) a simplified volcano model capable of capturing and synthesizing the sequence of volcanic activity observed at individual volcanoes. The accuracy of hazard estimates is thus directly affected by the quality and completeness of these parameters, requiring minimum threshold values for practical probabilistic approaches. For example, if the event age database is incomplete, unevenly distributed, or characterized by significant uncertainties, whether due to methodological errors or challenges in establishing field-based stratigraphy, the reliability of probabilistic models is greatly diminished. Similarly, a limited understanding of vent distributions or the lack of a comprehensive vent catalogue can pose significant obstacles to model development. An additional complication arises from the frequent occurrence of multi-event or nested volcanoes [8,9], in which multiple eruptions form new edifices over relatively short timescales, further complicating the accuracy of probabilistic modeling in these systems.

A significant challenge in developing probabilistic models is that eruption prediction timelines are often much shorter than those supported by geological records. This expectation is influenced by public familiarity with more frequent hazards, such as earthquakes, floods, or landslides. These events occur on timescales—ranging from years to centuries—that align with human planning horizons and are reflected in probability estimates for disaster preparedness. In contrast, volcanic eruptions—especially in association with distributed volcanic fields—typically have recurrence intervals far longer than 50–200 years, creating a paradox between expectations and reality [8–22]. No definitive solution exists yet. In this report, we offer a narrative to illustrate these challenges and suggest possible methods for addressing them elsewhere.

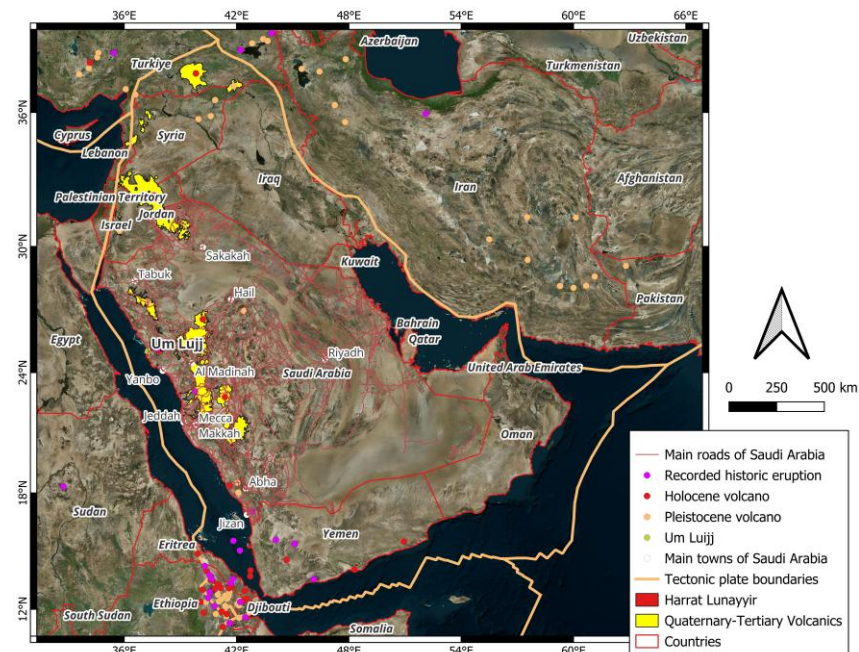


Figure 1. Cenozoic volcanic fields of Saudi Arabia. Harrat Lunayyir is located near the Red Sea Coast, near the local service center of Um Lujj. The map displays the most recent volcanoes and records volcanic eruptions in the Middle East, sourced from the Smithsonian Institution’s Global Volcanism Program database. River outlines are from the World River Database. The Volcanic fields (harrats) are based on the USGS Geological Map of the Arabian Peninsula data source [<https://www.arcgis.com/home/item.html?id=c364d4f44caf4d49af12eb18eac0867e>, accessed on 30 October 2025].

The study area, referred to as the Option 4 area (Figure 2), is situated in the center of Harrat Lunayyir. It has been designated as high-risk for both seismic and volcanic hazards, as well as potential cascading events such as mass movements. This understanding of the hazard profile at the proposed tourism development site in the Option 4 area prompted an assessment focused on volcanic risks in this region. The evaluation was requested under two main constraints: (1) completing the report in approximately six months, and (2) providing suggestions regarding the likelihood of volcanic eruptions and their impact over a 50- to 200-year span. Significant development initiatives along the Red Sea coast focus on adventure tourism [23–26] amid the striking landscapes of the Arabian Shield, characterized by dark basaltic lava flows and relatively young volcanic formations that sit atop light-colored Precambrian crystalline basement rocks. While Cenozoic volcanic fields are widespread across western Arabia (Figure 1), current infrastructure limitations restrict the growth of niche tourism in the region. Harrat Lunayyir, located approximately 300 km northwest of Al Madinah and near Um Lujj, is a key destination for specialized tourism activities (Figure 1).

During the planning stage, tourism development centered on the so-called Option 4 region (Figure 2), which includes a young scoria cone (Target Volcano), its surrounding plain, and a complex lava flow that extends over 10 km from the cone. Precambrian basement rocks emerge, creating a landscape of steep basement hills and flat-bottomed Quaternary valley networks that follow major structural elements [27]. These valleys are the geomorphological features that host most of the Cenozoic volcanics. Geological information is compiled from the available 1:250,000 geological map of the region [GM-053—Wadi al’ Ays sheet] and an updated, interim dataset of ongoing 1:100,000 geological mapping (Figure 2). We differentiate lava flow horizons (and associated explosive pyroclastic eruptions) by identifying an older part of the area, labeled the Qj lithostratigraphic unit, inferred to have formed in the Late Pliocene to Pleistocene and primarily cropping out in the southern part

of the volcanic field. Younger volcanism from the Pleistocene to Holocene is distinguished by sporadic radiometric age dating (with unreliable K-Ar and sporadic Ar-Ar data) [27–40], morphology [41], and geological mapping based on relative stratigraphy, labeled from Qm1 to Qm6 from older to younger. The study area is primarily composed of the youngest Qm6 lava flows, with small remnants of Qm5 nearby and some older eruptive products modified by erosion (Figure 2).

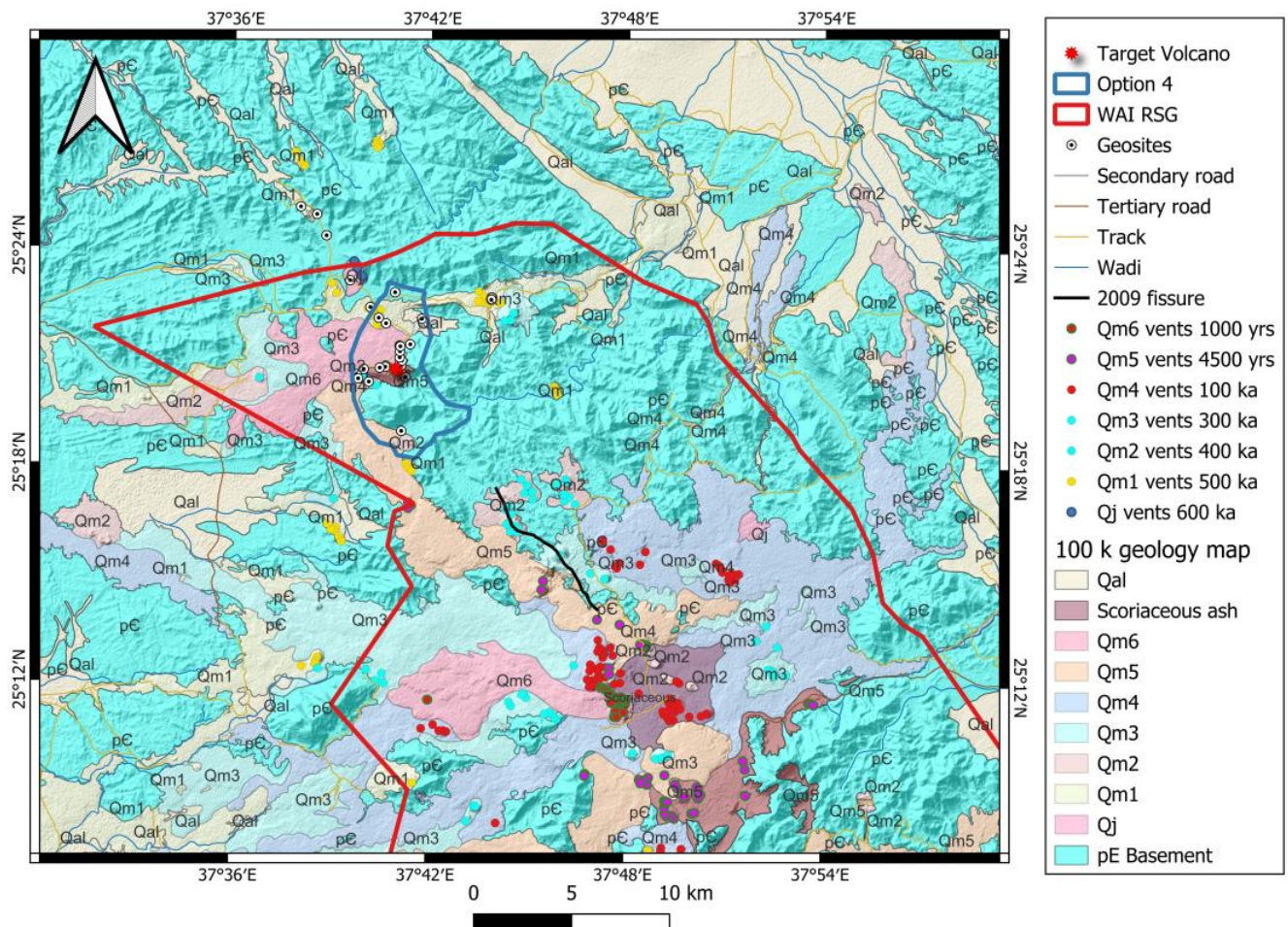


Figure 2. A geology map of the study area also shows 26 significant geosites [28]. A blue outline marks the Option 4 research area. At the same time, the boundaries of the Wider Area of Interest of the Red Sea Global tourism development are indicated by thick red lines (WAI RSG).

Preliminary research, however, shows that Option 4 is exposed to significant natural hazards, mainly seismic and volcanic risks [28]. Seismic data since 2007 (Figure 3), including a notable 2009 unrest [29–34], reveal ongoing low-intensity earthquake swarms along a NW-SE belt, associated with shallow crustal structures and possible faults. The 2009 event—possibly a failed eruption—is valuable for anticipating future volcano–seismic activity and understanding warning signs of eruptions. Probabilistic and deterministic assessments indicate generally low earthquake intensity in the area, but similar events remain possible. The region also faces highly irregular hazards, such as rockfalls and flash floods. Option 4 lies within a zone of high volcanic vent density and includes the youngest volcanoes, as indicated by their youthful morphological appearance, suggesting potential for future eruptions even on a century timescale.

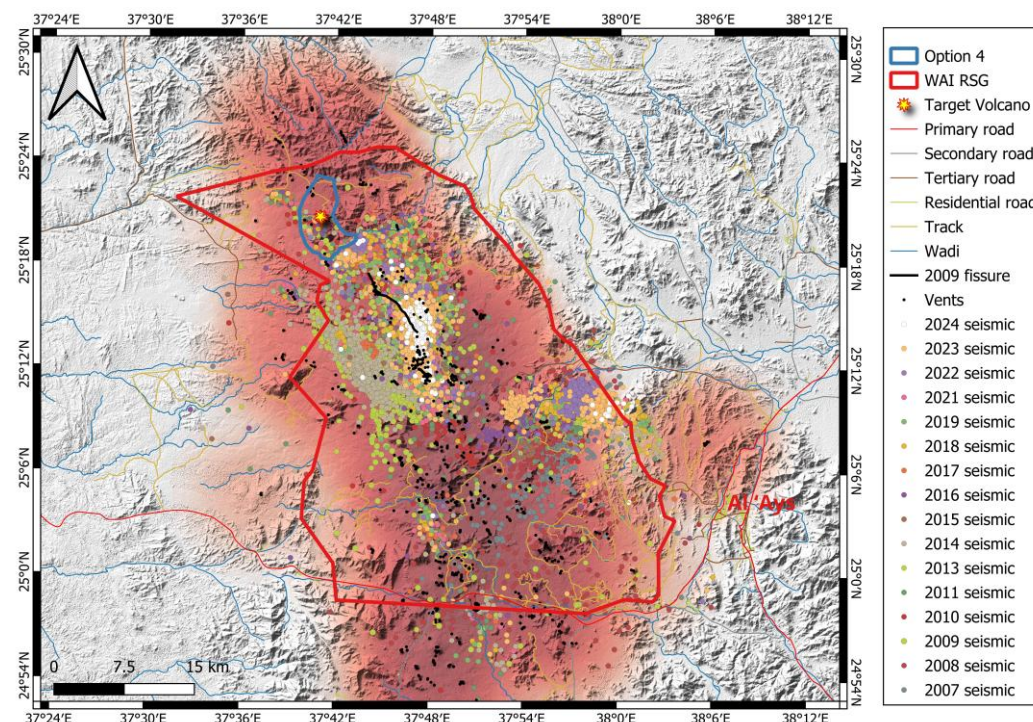


Figure 3. Total seismicity recorded by the Saudi Geological Survey seismic network since 2007, and the fissure opened during that event just south of the Option 4 area. The vent distribution is shown in a heat map, which indicates a strong correlation between seismicity and vent locations. WAI RSG—Wider Area of Interest—Red Sea Global; Option 4—main development area.

At Harrat Lunayyir, critical geological data remain unavailable; information on the ages, compositions, and eruption styles of the volcanoes is limited and unevenly distributed. Although interest in developing an eruptive history database grew after the 2009 volcano–seismic events, current data remains sparse and inconsistent, making probabilistic hazard estimates for the desired timeframes more complicated. To address these issues, a systematic approach was used to identify key volcanic hazards that require further attention. This report outlines the initial conceptual framework for the region, which was later developed into a detailed geological model. It also includes recommendations for risk mitigation and, as necessary, monitoring strategies.

2. Materials and Methods

The methodology is divided into two main approaches. The first step outlines the main types of volcanic hazards associated with the volcanic history of northern Harrat Lunayyir. These hazards are linked to specific eruption styles, as shown by the volcanic deposits that can be mapped in the field. This section provided a narrative summary of the identified volcanic geologic features and their implications for the volcanic hazard description. The section is structured by major volcanic-hazard types that can be linked to the observed geological features. The second approach used a deterministic volcanic hazard overview that involved terrain analysis of digital elevation models, lava-flow inundation simulation, and combined lava-flow volume estimates based on textural, mapping, and distributional information. Finally, eruption scenarios are outlined in a hazard matrix that summarises the most likely impacts of the identified hazards, their mitigation strategies, and stages from onset through the sustained period of activity to post-event mitigation.

Digital elevation models were used to calculate eruptive volumes, identify units, and characterize landscape features. The overall geomorphological assessment employed the ALOS-PALSAR Digital Elevation Model (DEM) at 12.5 m resolution, which is ade-

quate for capturing general volcanic geological details and useful for lava-flow inundation simulations with the Q-LavHA 3.0 software in QGIS environments [11,35–37].

Q-LavHA is a freeware plugin that simulates the probability of lava-flow inundation from one or regularly distributed eruptive vents on a Digital Elevation Model (DEM) [35]. The probabilistic steepest-slope constraint limits spatial propagation. Corrective factors are included to allow the flow simulation to overcome small topographical obstacles and to fill pits, implying an input parameter defining the average thickness of the flow based on direct field observations (H_c) and an estimated value introduced to fill pits on the DEM, likely resulting from errors in generating the DEM (H_p) [35]. The terminal length of the flow simulation can be determined using a fixed length value, a statistical length probability function, or the thermo-rheological properties of an open-channel lava flow, such as the FLOWGO algorithm [35]. As most lava flows observed in the field clearly follow flat-based valley networks, their length appears fixed; hence, the fixed-length method was selected in the simulations, as in other lava-field cases elsewhere [38–41]. Lava flow simulations were performed with input parameters including a conservative 15 m lava thickness (observed in most areas) and a 25 m buffer (which allows the simulation to overcome obstacles up to 25 m high), providing a minimum estimate of the affected area. Any location with a non-zero probability in the simulation is considered at hazard. Because the terrain is flat, a flow length of 50 km was set, following Q-LavHA recommendations for flat surfaces [35,36], consistent with known flows in Harrat Lunayyir. The longest observed lava flows are about 30 km from their source, as confirmed by mapping. These flows apparently expose complex flow structures and surface textures, commonly engulfing some cones to near-complete destruction, suggesting that they might be composite systems rather than single flows. While the decision to distinguish these features is not the subject of this work, here we treat these values as the maximum possible flow lengths and, consequently, the modeling results as the maximum lava-inundation input parameters. As recommended for Q-LavHA lava flow inundation simulations, the flow distances observed were multiplied by at least 1.5 for a realistic simulation, as has been recommended, for instance, from the Paricutin (Mexico) lava flow field evolution simulations [36]. We fixed the values to 50 km in the simulations. This value was scaled to the longest lava flows observed and preserved in the field. The Manhattan technique, in which flow propagation simulation was prioritized along the local topography and its channel network, enabled the identification of directional valleys typical of the region.

Red Relief Surface Maps (RRSM) [<https://www.rrim.jp/en/>, accessed on 30 October 2025] were generated by combining Red Slope Angle Maps and Differential Openness maps derived from the DEMs [42,43]. RRSM proved helpful for delineating lava flow boundaries, enabling the identification of individual lava lobes [44–48].

Eruptive and edifice volumes were calculated from the DEMs using the QGIS Volume tool, Tamsweg, Austria, which operated with the lowest and average pixel elevations along identified lava flow contacts. Field observations and GPS elevation measurements revealed that most emplacement surfaces are remarkably flat, dipping less than 1.5 degrees (approximately a 300 m drop over 12,000 m). This slight dip is unlikely to significantly impact volume calculations, except in areas where topography drops sharply—mainly along suspected structural lines where lava flows cascade. These zones were identified in the distal parts of the study area, where flows narrow and thin, contributing minimally to the total estimated volumes.

For the ash-fall distribution, direct field measurements of ash-fall thickness were performed, and a simplified isomap was generated. To assess the potential ash dispersal, the values from the USGS Ash3D tool, Vancouver, WA, USA were used with estimated eruption-plume height parameters to evaluate the dispersal. Finally, a combined hazard

map was generated to highlight the diverse hazards the region faces in the event of a future eruption.

3. Results

3.1. Field Observations

3.1.1. Spatter and Scoria Cones

Fire or lava fountaining eruptions happen when jets of low-viscosity magma shoot molten fragments, called spatters, into the air [49,50]. These sometimes-episodic events, which can look like water hose blasts, last from hours to days and are usually linked to fissures hundreds of meters long before focusing into point-source eruptions. Fountain heights often go beyond 200 m, so a 500 m exclusion zone is advised to stay clear of hot pyroclasts [49,50]. Main products include large spatters around vents, forming cones, and new lava flows that can cover older volcanic features. In the lava fields west of the Target Volcano, volcanic spattering has covered previous landforms (Figure 4).



Figure 4. Partially engulfed former lava spatter ramparts (located in the middle of the view) within the main channel of the youngest lava flow mapped west of the Target Volcano (visible on the left side of the view) within Option 4 area ($25^{\circ}21'1.50''$ N, $37^{\circ}40'46.81''$ E). View looking toward the SE.

Weak convective plumes above magma fountains only lift fine ash particles a few hundred meters, while larger fragments quickly fall out [49,50]. Fountaining often occurs alongside or shifts into effusive activity, creating interconnected lava flows and mild explosive hazards. Lava fountains typically feed flow both directly and by depositing spatter clasts, resulting in alternating agglutinates and clastogenic lava, with clastic textures remaining visible. Volcanoes that mainly emit mafic, low-silica magmas are characterized by periods of open vent activity. During these times, explosive eruptions typically occur in rapid, individual bursts of spatter—called Strombolian-style (*sensu stricto*) explosive events—separated by intervals ranging from seconds to several hours. Explosion durations typically last from a few seconds to several tens of seconds [50–52]. These events produce rapid sprays of mostly fluidal spatter, scoria, volcanic bombs, and small amounts of ash. The deposits build up within a few hundred meters of the vent, gradually creating landforms known as scoria (cinder) cones [53].

Due to localized pyroclast dispersion during typical Strombolian eruptions, most eruptive products directly contribute to cone development. From a volcanic hazard standpoint, Strombolian-style explosions can disperse pyroclasts up to 1000 m from the eruption site; this distance provides a helpful guideline for exclusion zones near active scoria cones. These eruptions mainly produce spatter cones, ramparts, and coarse *Scoriaceous lapilli* and bomb-rich deposits. When smaller but sustained eruption columns occur, larger scoria cones composed of fine lapilli and coarse ash can form, with localized fallout deposits

building up within approximately one kilometer. Strombolian eruption columns or spray heights typically range from a few tens of meters to under 200 m, ejecting several hundred cubic meters of pyroclastic material per burst. The area shows deposits and lava associated with low-intensity Strombolian events, which are often part of larger eruption sequences characterized by occasional higher-intensity explosions and the gradual development of scoria cones (Figure 5). The cone-building pyroclastic succession at the Target Volcano in Option 4 illustrates these deposit types.



Figure 5. The Target Volcano ($25^{\circ}20'33.69''$ N, $37^{\circ}41'5.89''$ E), with its young scoria cone morphology (Qm6 vent), is visible in this view due to Strombolian-style explosive eruptions and associated tephra deposits. An older scoria cone ($25^{\circ}22'21.57''$ N, $37^{\circ}40'5.94''$ E), located at the left front of the Target Volcano, is part of the oldest volcanism in the volcanic field (Qm1). Its preserved volcanic slope is not as steep as that of the Target Volcano (dark, fresh cone in the mid-left far side of the image). View looking toward the SE about 5 km away from the Target Volcano.

3.1.2. Lava Flows

The formation of a solid crust on lava flows depends on how cooling influences viscosity over time, compared to the lava's shear rate [54]. In low-viscosity basalts, such as pāhoehoe, the viscoelastic layer absorbs strain, allowing the smooth crust to remain intact even when lava beneath flows rapidly, sometimes exceeding 10 m/s. This crust also remains preserved at low strain rates, such as when lava moves slowly across flat valley floors west of the Option 4 area. When strain rates on developing crust increase—due to steep slopes, sudden changes in slope angle, higher lava input, or increased eruption rates—the crust experiences plastic failure, resulting in surface textures that signal complex brittle–elastic deformation. This process leads to clinker, slabby, and ultimately aa-type lava flows (Figure 6).

As lava viscosity increases in distal regions and flow slows, its crystallinity rises, causing it to resemble 'a'ā lava [54]. Transitional surface textures often appear between smooth pāhoehoe and clinker-rich 'a'ā, creating hybrid forms like shelly, slabby, and rubbly pāhoehoe—commonly seen in the study area (Figure 7) [55,56]. These transitions are also typical of the harrats in western Saudi Arabia [57]. When lava crusts form over a channel and stay intact, they create an underground lava tube, offering an alternative to open lava channels. In the Option 4 area, collapsed tube roofs reveal entry cavities (Figure 7), and nearby depressions, up to 10–15 m deep, indicate extensive tube networks along the main systems. Lava tubes are also observed in other parts of Harrat Lunayyir, featuring short, well-developed tubes with visible openings in the central region and near vents within the Option 4 area. Usually, tubes and open channels form complex distributary systems, found both near and away from volcano vents, especially where terrain slopes change. Smooth

lava surfaces with fractured plates, as seen on satellite images, suggest the presence of complex tube networks extending several meters underground.



Figure 6. Rubbly or slabby pāhoehoe surface texture in the main feeding arteries of the lava field just west of the Target Volcano. The location coordinates are 25°21′19.48″ N, 37°41′5.03″ E, and the view is roughly south–north, from left to right.



Figure 7. Collapsed roof of a pāhoehoe lava field over a master tube below. Note that the collapsed feature (dark rubbly zone in the middle view) is about 10 m deep, with large slabs of pāhoehoe crusts, several meters across, from solidified and ripped-up lava flow surfaces. In these ponded zones, we can estimate a potential lava flow (25°21′48.70″ N, 37°38′39.16″ E). The view is looking toward the south.

Large lava tubes, such as those in Harrat Khaybar, can extend over a kilometer and serve as underground passages, allowing lava to travel great distances. The roof may collapse if the lava supply decreases or after eruptions, when lava drains away, leaving partially empty tubes. Fluctuations in lava output can add to surface complexity, blending collapsed tube roofs with active molten channels and viscous flows. This results in rugged terrain, as seen at Option 4’s proximal lava fields. Skylights over lava tubes form during eruptions, offering views of moving molten lava; after cooling, they become deep cavities linked to tube networks. These tubes, ranging from less than 1 m to over 30 m in diameter and 15 m in height, can channel lava over hundreds of kilometers beneath a mostly solid surface [58]. Surface features, such as pāhoehoe slabs, skylights, and updoming, indicate meter- to tens-of-meters-wide tubes along major lava pathways. Large roof collapses and extended tube openings suggest long, narrow tubes formed where lava accumulated behind barriers or in depressions. Lava stored in these main zones later traveled farther than expected. Tube-fed pāhoehoe flows can extend much farther than comparable a’a flows, making tube formation a key consideration in assessing lava flow hazards. A solid, insulating crust in pāhoehoe lavas enables flow inflation when magma accumulates beneath the rigid surface, as the volumetric flow rate exceeds the advance rate, often at slope breaks [59,60]. This results in surface uplifts and can cause lava breakouts. Although

most common in pāhoehoe, inflation and breakouts also occur in a'a lavas when their fronts slow due to cooling or gentler slopes. The resulting autobreccia increases resistance and thickens the flow. Pressure buildup behind stationary fronts may trigger bright breakouts along the margins or at the surface, a scenario typical in the study area and a hazard to consider during eruptions and recovery efforts.

3.1.3. Ash Plains

Explosive eruptions from low-viscosity, typically water-rich (3–5 wt %) basalts form subduction settings, as observed at Mexico's Parícutin volcano (1943–1952), can produce large amounts of fine ash [61]. The initial phase of Parícutin's eruption began on 20 February 1943, quickly forming a 167 m-high scoria cone with up to 18 explosions per minute and a plume reaching roughly 5 km. Parícutin serves as a valuable comparison for the Target Volcano in Option 4 because of its similar sequence and structure. Between 18 March and 9 June 1943, the eruption intensified, producing more ash and a convective plume that reached 6 km and was carried downwind [61]. The eruption style was characterized by frequent explosions, with a magma eruption rate estimated at 10^4 – 10^5 kg/s. Ash deposits extend up to 250 km from the volcano, resulting in continuous tephra coverage; lapilli-sized fragments were transported several kilometers from the vent [62]. Inevitable scoria fall and cone-building deposits with high fragmentation and dispersal rates are commonly defined as “violent Strombolian” [63,64], highlighting the episodic nature of these explosions despite differences from classic strombolian eruptions. Extensive ash and lapilli fields within Option 4, associated with the Target Volcano, suggest that violent Strombolian explosive eruptions have occurred in the region, indicating a potential volcanic hazard. Recent assessments suggest using the term “violent Strombolian” specifically for eruptions that produce columns typically under 8 km and generate sizable fallout deposits with limited stratification [61]. However, vertical variations in grain size can occur, as seen in ash and fine lapilli deposits approximately 3.5 km from the Target Volcano (Figure 8). These eruptions are characterized not only by their column height but also by sustained, pulsatory explosive activity that creates cone-shaped, stratified deposits rich in fine ash. In contrast, micro-Plinian eruptions tend to be more continuous and produce larger, more extensive deposits, such as coarse scoria cones and widespread massive deposits [49]. Individual explosions can resemble discrete fire fountain sprays. Later phases could involve more sustained activity, produce a buoyant eruption column and depositing coarse, massive scoria near the vent, as well as localized fall deposits downwind. This event provides an analog to interpret potential eruption types and scales for the Target Volcano, informing future scenarios in the study area.



Figure 8. A pyroclastic succession approximately 20 cm thick (black coarse ash and fine lapilli) is located about 3.5 km from the source (Target Volcano) on a steep slope of an older scoria cone (25°22'19.99" N, 37°40'16.67" E). The view is looking toward SE.

3.2. Volcanic Hazard Types

After outlining the major eruption styles, we identify the key volcanic hazards in the area. Using analogies and observations, we summarize these hazards and suggest mitigation measures in a table. We describe the precursory phase as the time of geophysical warnings, followed by hazard-specific onset stages, established eruptive processes, and post-event outcomes.

Large volumes and widespread lava flows indicate the importance of volcanic hazards associated with lava effusion. These can be classified by lava characteristics, such as pāhoehoe and transitional flows that evolve into aa-type lava. Such hazards usually move slowly and are considered manageable, but they can cause significant long-term landscape changes and result in destruction. Volcanic hazards can also arise from a range of explosive eruption styles, including: (1) the formation of lava spatter cones with associated lava fountaining; (2) the development of scoria cones; (3) Strombolian or mafic sub-Plinian explosive eruptions; and (4) deposition of ballistic projectiles. Additionally, volcanic degassing and vog (volcanic gas fog) are often observed alongside extensive lava flow emplacement, especially after the formation of scoria cones. Based on field observations and considerations, eight different types of volcanic hazards can be identified. Each of them is documented in (Supplementary Tables S1–S8) in detail, such as

- (1) Pāhoehoe lava flow outpouring;
- (2) Transitional lava flow outpouring;
- (3) Lava spatter cone formation and lava fountaining;
- (4) Scoria (cinder) cone birth and growth;
- (5) Ballistic impact;
- (6) Cone collapse and cone rafting;
- (7) Sub-Plinian explosive eruption and associated ash fall;
- (8) Volcanic degassing and vog formation.

3.3. Eruption Scenario Simulations

Eruption scenarios are concise, realistic narratives that summarize potential eruption types, timelines, and impacts, facilitating clear information transfer in volcanology, especially when probabilistic methods are impractical. Due to limited geological data available for Harrat Lunayyir, hazard-based models were developed using direct observations and desktop analysis. Two scenario types—localized point eruptions and fissure eruptions—have both occurred over the past 600,000 years, with fissure eruptions being more common and likely in future events. Three potential eruption sites were identified: vent 1 NW outside Option 4; vent 2 near the Target Volcano (Figure 9); and vent 4 SW inside the Option 4 area. The results are presented in Supplementary (Figures S1–S5). Fissure vents were located at the same sites previously considered for point-source vents (Figures S1–S5), with additional fissure settings simulating a particularly long fissure in the southwest of the region, aligned with the main structural feature of the area. In each scenario, the scoria cone footprint was fixed at a 500 m radius, while ballistic impacts were estimated within 1000 m of the vent. Fissure vent simulations were necessary for hazard assessments because most volcanoes in the Lunayyir volcanic field formed through fissures of different lengths. Short fissures, approximately a hundred meters long, often form elongated structures, while longer fissures extend several kilometers and feature aligned vents. One test modeled a 15 km NW-SW-trending fissure, like the 2009 event, with lava effusion simulated by Q-LavHA using emission points spaced at 90 m intervals along its length (Figures S1–S5). Each model included a 500 m buffer to represent areas where lava spatter cones and fountaining could deposit material near the active vents. Finally, a combined worst-case scenario summarized the main lava inundation models,

applying long-fissure simulations and the development of lava spatter cones along fissures (Figure 10), excluding cone-base and ballistic-impact visualizations, as their effects are much less significant. We used the lava inundation zone as a proxy to identify areas where development would be at high risk, which also aligns with previously recognized vent clusters, alignment zones, and graben features marked by structural weaknesses.

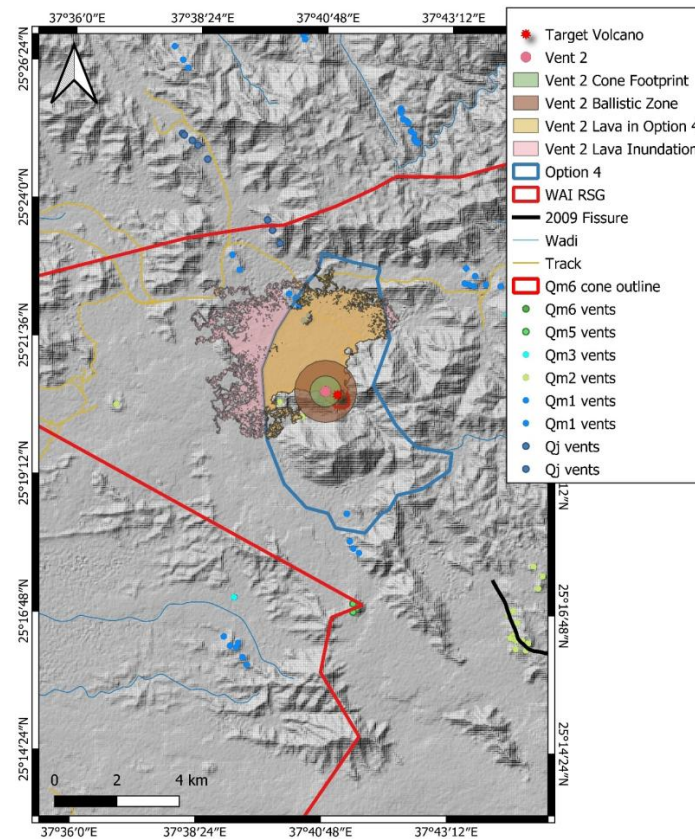


Figure 9. Eruption scenario with the vent opening adjacent to the Target Volcano. Note that approximately 30% of the surface area of the Option 4 region will be directly affected. WAI RSG—Wider Area of Interest—Red Sea Global; Option 4—main development area.

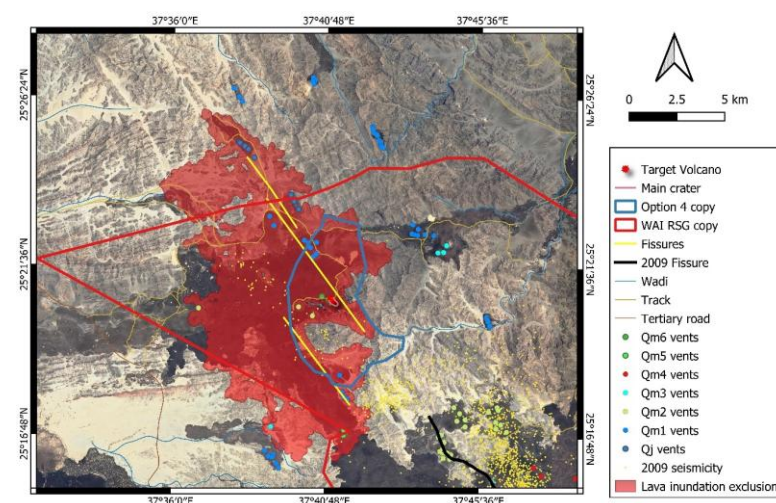


Figure 10. The total lava inundation exclusion zone map shows the areas where the maximum expected lava flow inundation would occur. This map was created by combining three lava inundation simulations along three long fissures (marked yellow lines) that follow the same structural pattern as the overall area. This pattern aligns with the vent alignment (various vents are shown with color codes

indicating their relative strati-graphic age) and the recorded seismicity locations (marked by yellow dots). In areas marked in red, lava flow impact is expected and could cause significant property damage if an eruption occurs. WAI RSG—Wider Area of Interest—Red Sea Global; Option 4—main development area.

3.4. Lava Flow Volume Estimate

Estimating lava flow volume is key to understanding volcanic hazards. However, in our study area, no features suitable for accurate stratigraphic assignment or age dating were identified due to time and resource constraints. As a result, we relied on existing maps, limited remote sensing data, and targeted field surveys to delineate the most probable extent of a young lava flow in northern Harrat Luinayyir. Comprehensive mapping of the nearly 100 km² region was not feasible within the project timeline, so surveys focused on key locations. Our findings, along with previous lava flow maps, showed varying interpretations of the youngest lava effusion in the area (Figures 11 and 12).

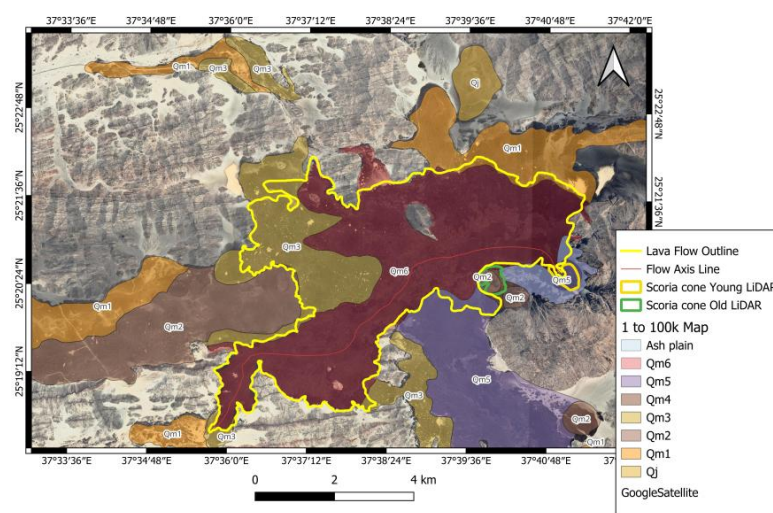


Figure 11. Lava flow mappings of the region revealed three distinct patterns, underscoring the challenges of precise lava flow mapping when a large volume of lava forms complex lava fields. The map shows the interim 1:100k-scale geology map, with lithostratigraphic units ranked by lava flows from Qj and Qm1 to 6. The flow outline has been revised to separate the youngest flow field into distinct zones. The latest revision shows slightly different patterns in the western edge of the flow fronts.

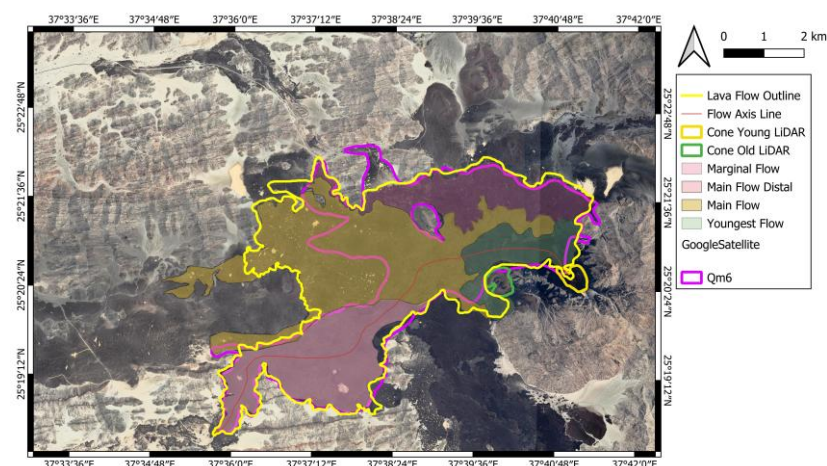


Figure 12. One of the latest surveys distinguishes Main Flow, Main Flow Distal, Marginal Flow, and Youngest Flow within the young lava field. In this work, the volume calculations followed a slightly revised pattern where in a thin distal areas has been excluded due to the heavily erosion modified

nature of the region where basaltic rocks forming dissected cover on the desert flow that can also be interpreted as some redistribution of rocks from thin lava flows hence we focused only those regions where the lava front is distinct and characteristic.

The flow boundary delineation discrepancies were more apparent in the distal regions, where distinguishing the main flow arteries, channels, and thin, squeezed-out lava surfaces was difficult. Red Image Surface Maps have also been used, based on ALOS-PALSAR DEMs. As the DEM resolution is only 12.5 m, the resulting maps were only helpful for discerning the internal textures of the main lava bodies (Figure 13), confirming the separation of lava sections within the flow field and allowing slightly more restricted lava-flow coverage, as previous mappings indicated.

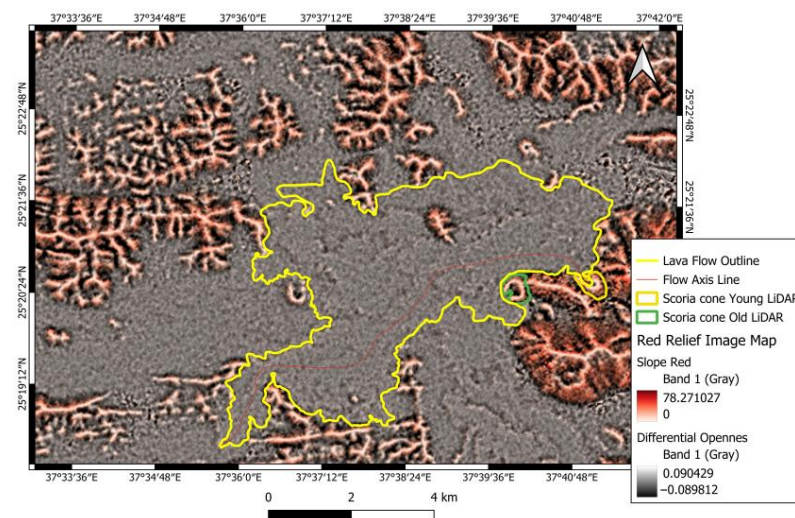


Figure 13. Although the DEM resolution is low, the Red Relief Image Map still shows a distinct pattern of flow lobes and fronts, which has been assigned to the youngest lava flow field in the study area.

For the lava volume calculation, the emplacement surface was generated from elevation data around the flow margins using linear interpolation in QGIS. This surface is generally flat, with step-like drops in elevated areas and a gentle westward slope (Figure 14). The estimated thickness map indicates that the flow margins are thin, and the interior rarely exceeds a few tens of meters in thickness. The relative thickness map highlights key accumulation zones within the field (Figure 15). Assuming a uniform thickness of 10 m and an area of 30.616 km², the total lava volume is approximately 0.3 km³. Using an average lava thickness of about 30 m and uniform coverage, the total erupted lava volume would be around 1 km³. When accounting for voids, lava tubes, and high vesicularity, the dense rock equivalent (DRE) is approximately 30% of this volume, yielding a range of 0.09 to 0.3 km³, based on estimates of 10 or 30 m of lava thickness, respectively. These values are comparable to those of the well-documented Paricutin (Mexico) eruption [65], where the average flow thickness estimates ranged from 8 to 25 m. At the same time, the covered area was calculated to range from 1.892 to 12.317 km², yielding erupted volumes of 0.01 to 0.3 km³ without DRE corrections. DRE corrections would lower the eruptive volumes by approximately 20–30%. Because Paricutin's activity occurred between February 1943 and March 1952 in 23 distinct eruptive phases [36], we can assume that the formation of the Qm6 lava flow field likely occurred in multiple stages and could have lasted several months or more. It appears that our study area has not exhibited the complex, numerous eruptive episodes (23) observed elsewhere and is likely to have experienced only a few, based on the lava flow mapping so far. This suggests that the eruption rate there might be estimated

as higher than that of Paricutin. In a shorter period with fewer eruptive phases, a larger volume of lava was produced. Volume calculations using GIS-based volume counts appear to overestimate values by approximately 1.6–3.3 km³, reflecting uncertainty in defining the emplacement surface, the GIS-based calculation methods, and the resolution (12.5 m) of the available DEM.

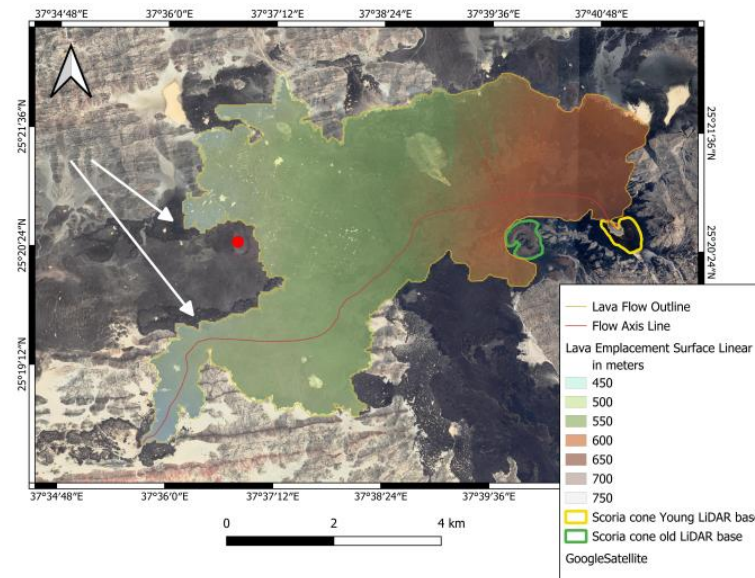


Figure 14. Lava flow surface elevation map based on Linear interpolation techniques of the elevations collected outside of the lava flow areas. White arrows point to places where thin lava squeeze-outs and erosional modification are suspected, making it difficult to assign the area to a specific flow. The red dot marks an older scoria cone that served as an obstacle to stop and divert the flow.

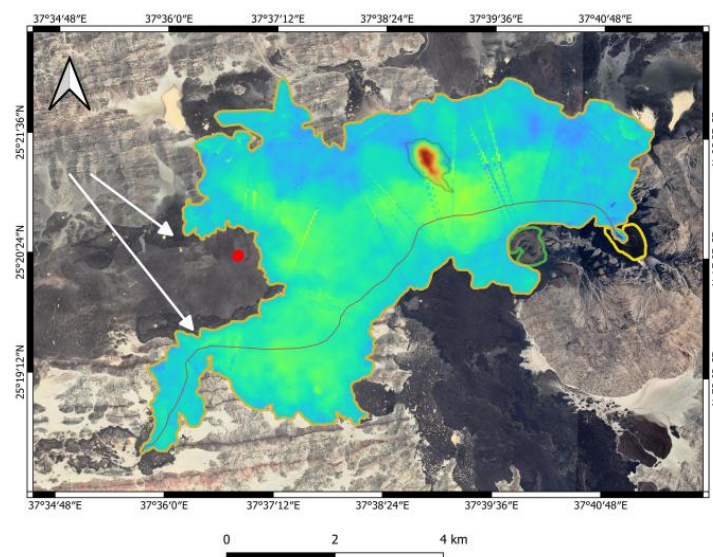


Figure 15. Lava flow thickness model map calculated from the generated lava flow base surface and the terrain DEM data. Note that the image is only indicative for areas with thick lava flows (yellow-orange color), while thin lava flows are deep blue. The absolute thickness range is suspected to be in a few meters to a few tens of meters. The basement hill, marked in blue, also indicates its elevation above the top of the lava flow field. White arrows point to places where thin lava squeeze-outs and erosional modification are suspected, making it difficult to assign the area to a specific flow. The red dot marks an older scoria cone that served as an obstacle to stop and divert the flow.

3.5. Ash Fall Hazards

Ash fall hazards in Saudi Arabia's Quaternary volcanic fields receive less attention than lava flow risks, mainly because ash deposits—often fine lapilli to fine ash—are rarely well-mapped. This is due to their preservation as mixed aeolian and pyroclastic layers, making mapping challenging (Figure 16).

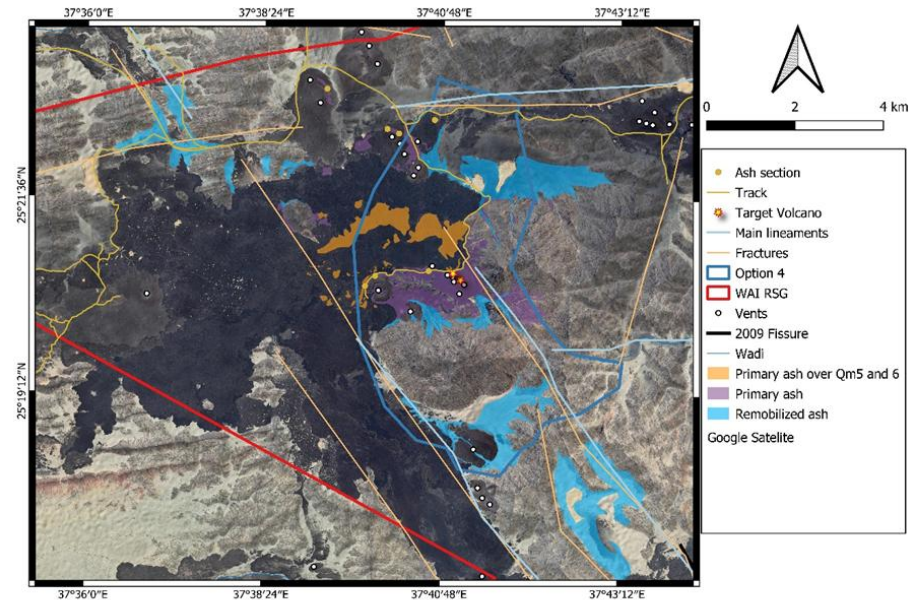


Figure 16. A rough estimate of the potential ash cover is based on measurements from a few spots' thickness and satellite image analysis to identify remote traces of ash. Use this map as a preliminary estimate of ashfall distribution, which should be mapped more accurately in a separate study later. Based on limited spot measurements (due to access or preservation potential), a rough isopach map of tephra distribution has been created (Figure 17). WAI RSG—Wider Area of Interest—Red Sea Global; Option 4—main development area.

The United States Geological Survey (USGS) uses the Ash3D simulation tool to predict the spread (ash clouds) and deposition (ash fall) from volcanic eruptions, primarily during Plinian eruption conditions (USGS Ash3D). This three-dimensional model simulates volcanic ash movement by factoring in time-varying wind patterns and other weather data to estimate ash transport under both current and past atmospheric conditions. The online tool provides near-real-time forecasts of ashfall centered on Harrat Lunayyir, using data from the Smithsonian Global Volcanism Program Holocene Volcanoes catalog. The vent is located near the center of the volcanic field, approximately 20 km southeast of the Option 4 area, near recent eruption sites. The model considers the estimated magma volume involved—specifically the tephra—and the height of the eruption column above sea level. Harrat Lunayyir sits about 1300 m above sea level, so an eruption column reaching roughly 8700 m above sea level corresponds to a 10 km plume in the model that is an average value for sub-Plinian eruptions [66,67]. An initial simulation was run for an ash-producing eruption on 19 July 2024, using real-time wind data, with a plume height of 7 km above sea level (around 5.7 km above the volcano) and a total eruptive volume of 0.005 km³ DRE, with 5% of the volume airborne at the vent (Figure 18). The results suggest that central Harrat Lunayyir would receive between 1 and 3 cm of ash over an area three times larger than in Option 4. These modeled values are much lower than those observed in the field and may reflect only a single phase of the eruption rather than the total effect across all stages.

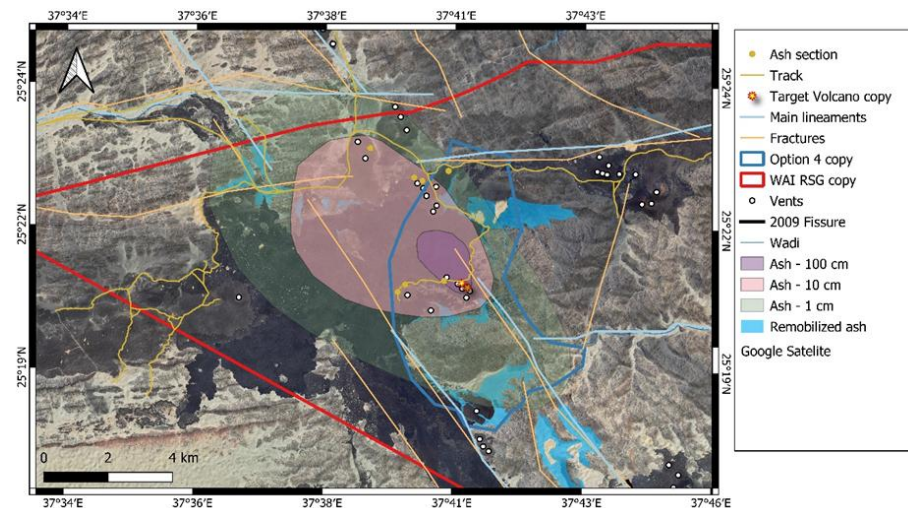


Figure 17. Ash fall simulation using the USGS Ash3D tool with input parameters of a 7 km plume, 0.005 km^3 DRE magma input, and an eruption duration of approximately 6 h. WAI RSG—Wider Area of Interest—Red Sea Global; Option 4—main development area.

Ash fall hazard was identified during field mapping, with primary ash layers approximately 2 mm thick located about 8 km northwest of the youngest cone (Target Volcano). This distribution pattern indicates that a Strombolian- or sub-Plinian-style explosive eruption dispersed ash through the atmosphere over this distance. Based on these findings, an average ash distribution pattern can be constructed, assuming eruptions occur along the central axis or along a fissure aligned with the observed structural trend in the field. This approach provides a visual representation of the maximum extent, while the ashfall hazard should also be considered. Since the impact of this hazard is generally low, it is recommended to acknowledge its presence, especially in spatially restricted areas where its effect could be more significant (such as potential roof collapses). Figure 19 illustrates this zone.

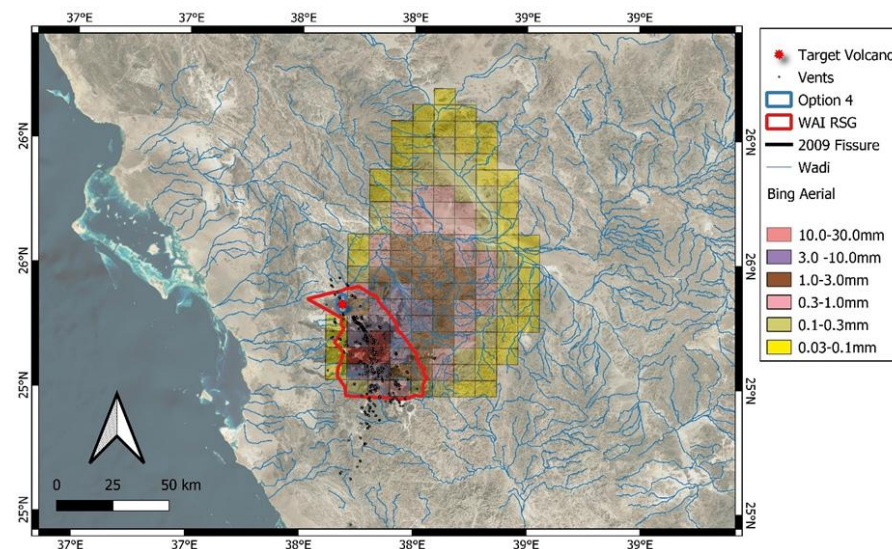


Figure 18. An area where 2 mm ash fall may occur if the vent opening is anywhere along the marked long fissure. The actual spread pattern will depend on the wind during the eruption. Keep in mind that this is a relatively low-impact hazard, and it can be avoided by staying about a kilometer away from the vent. WAI RSG—Wider Area of Interest—Red Sea Global; Option 4—main development area.

Ash fall can significantly impact buildings and their critical operational components. Inside, ash contamination may pose health risks to occupants (www.ivhbn.org), directly

damage sensitive equipment such as electronics, and cause abrasion damage to flooring surfaces. Abrasive damage to roofing, cladding, and flooring materials during ash removal is often unavoidable, even with minimal ash buildup, which increases recovery costs. Ash fall may also disrupt essential building services, including electricity and water systems. Construction planning should consider the use of appropriate non-structural elements to reduce ashfall risks. Gutter systems, when installed, can collect ash from roofs, reducing drainage capacity and adding to structural loads; blockages in gutters and downpipes can lead to localized flooding and damage, especially to roofs, drainage networks, and ceiling spaces. Internal gutters are particularly vulnerable and often hard to clean. Metal roofs, fastenings, and claddings may be prone to corrosion, as ash deposits containing salt can accelerate deterioration. Painted surfaces and artistic features are at risk from acid leachates, which can cause rapid and significant damage, especially for tourism facilities that depend on aesthetic appeal. Structural concerns include potential roof deformation and collapse due to excessive ash loading. However, very thick deposits (>100 mm, more often >300 mm) are uncommon except within 5 km of the vent; they remain a design consideration. Field measurements recorded ash thicknesses of 300 mm at 4 km and 10 mm at 8 km from the source. Long-span, low-pitched roofs should generally be avoided, as they are most vulnerable to ash loading. Assuming an average basalt density of 2900 kg/m³ and approximately 75% vesicularity observed in the study area, roof designs should be able to withstand up to 500 mm of ash cover (about 362 kg/m²), which is relevant within 2 km of a vent where lava inundation could occur within days. While simultaneous rainfall and ashfall are unlikely in this arid environment, the possibility cannot be ruled out. The overall impact level depends on these interconnected factors, as buildings function as integrated systems. Mitigation strategies, such as prompt and regular ash removal when safe to do so, can lessen or even prevent adverse effects. Cleaning building exteriors and interiors after ashfall can be costly and time-consuming and may require ongoing effort due to recurring ash or wind- and water-driven remobilization. Taking key steps before, during, and after ashfall can help minimize damage. Protective gear is essential during cleanup, as roofs may be slippery or collapsed, especially if water blasting increases the ash's weight. Fine ash removal creates dust that can cause discomfort, and all collected ash should be disposed of where it will not be remobilized later.

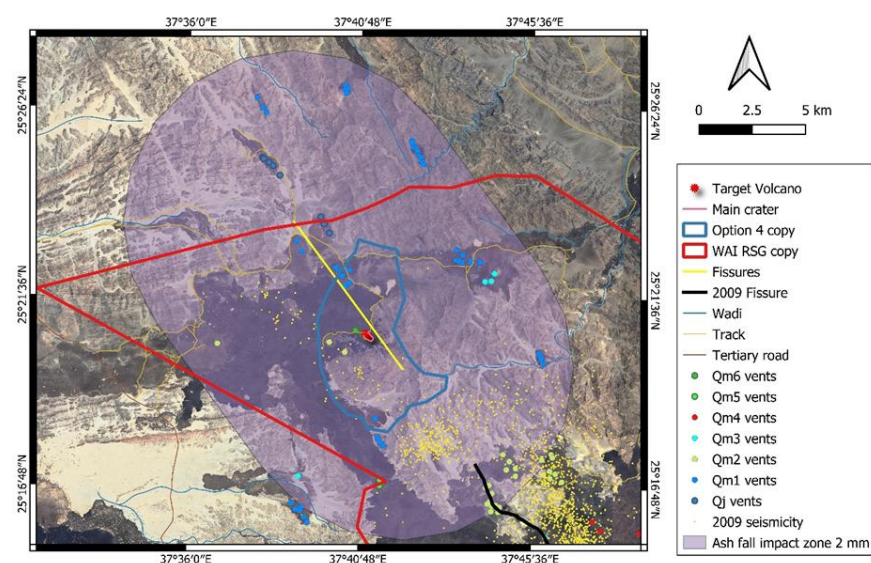


Figure 19. Simplified isopach map showing 1, 10, and 100 cm thick ash tephra layers inferred from spot measurements collected during reconnaissance mapping of the region for ash fall. WAI RSG—Wider Area of Interest—Red Sea Global; Option 4—main development area.

4. Discussion

Geological studies and simulations indicate that Option 4 lies within a region highly prone to volcanic hazards, primarily lava flows, with eruptions potentially reaching VEI 4 and dispersing ash over tens of kilometers. The likely eruption patterns closely resemble those observed in Iceland over the past thousand years, owing to similar rift-related processes, basaltic sources, and fissure vent formation. Recent well-documented eruptions in Iceland have generated spatter cones, mild explosive phases, and steady, low-viscosity lava flows, providing valuable insights for hazard mitigation in Harrat Lunayyir.

Volcanic hazards in the Option 4 area and surrounding regions are classified as low to moderate risk, although they can still cause significant impacts. Identifying safe zones in this region is challenging, as approximately 80% of the Option 4 area is exposed to one or more types of volcanic hazards (Figure 20). In addition to lava flows, ashfall poses a significant threat, and an eruption could reach VEI 3 or VEI 4, producing extensive ash plains that may block access and mobility. Ashfall also increases the risk of total loss of facilities, roads, and equipment planned for development and use in Option 4.

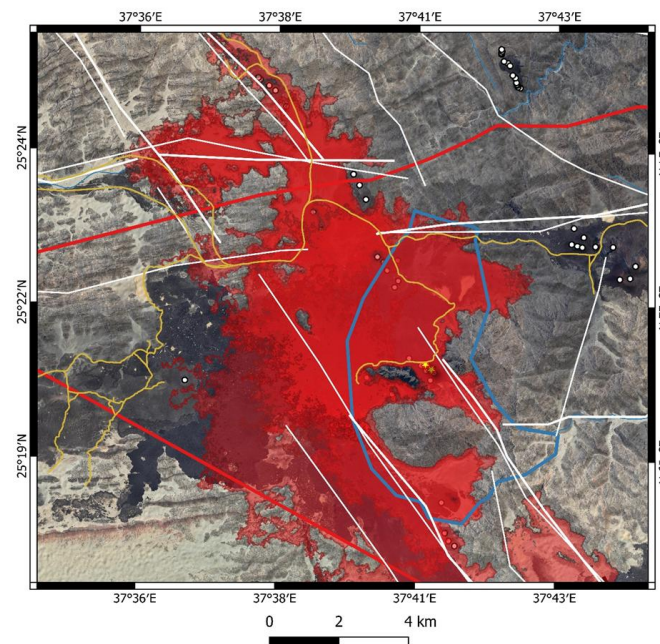


Figure 20. A map shows the lava flow risk in the area. It appears that if eruptions occur within the NW-SE zone, most of the Option 4 region would face immediate and ongoing danger, which could be life-threatening if the eruption occurs at an inconvenient time, such as at night. The chances of being cut off by lava blocking access roads are high. There is no point in marking safe zones, as lava would probably reach the access roads within hours. The safest place right now is on higher ground along the northern access road. However, that area would then be cut off from the local service town in the Um Lujj region.

There is currently no established industry practice for mitigating volcanic hazards associated with monogenetic volcanism, especially in Saudi Arabia, where no modern volcanic eruptions have been observed. The most recent confirmed eruption occurred in 1256 CE southeast of Al Madinah City [68]. Stratigraphic evidence also suggests that eruptions within Harrat Lunayyir may date back to the Holocene, with an estimated age range of 4500 to 1000 years ago at the Target Volcano, which could be among the youngest sites in the region. However, these age estimates are uncertain, and the likely recurrence interval probably falls well outside a typical 50-year timeframe. This estimate is based on the number of vents—usually five to ten per volcanic complex—leading to an average

recurrence rate of decades to centuries. However, this method highlights the limitations of current models. Industry practices have generally addressed volcanic hazards from monogenetic volcanism only at high-sensitivity sites, such as nuclear power plants, dams, major infrastructure, or high-risk waste repositories, where design criteria must consider hazards identified over thousands of years. For instance, high-level waste repositories (usually for nuclear waste) require hazard assessments spanning about 50,000 years—a period during which multiple vents can form in volcanic fields with eruption recurrence rates over thousands of years, as seen in the Auckland Volcanic Field (New Zealand) [16,69–71], Yucca Mountain (Nevada) [72–74], and Southern Armenia [14,75,76]. Studies in these regions have focused on urbanization and lifeline exposure (Auckland), planning for high-level power plants (Armenia), or designing waste repositories (Yucca Mountain). These studies were conducted within appropriate time frames and supported by high-resolution, evenly distributed age dating across the fields. In contrast, predicting volcanic hazards for Harrat Lunayyir over a 50-year period is currently not feasible due to data and technical limitations. Even the most precise Ar-Ar radiometric dating methods have errors that surpass the resolution needed for this timescale. Consequently, the approach shifted from probabilistic estimates to a deterministic method that systematically considers all identified volcanic hazards. This involves preparing for any documented hazards throughout the entire field (~600,000 years of records), with a particular focus on Qm5 and Qm6 vent locations.

For industry applications, each identified volcanic hazard type should be considered a potential scenario at any location where vents have historically formed. Design solutions should be scaled accordingly: for example, structures should be designed to withstand lava flow inundation, considering fire hazards and mechanical stress, and to account for potential economic losses from such incidents; roofs should be designed to support at least 10 cm of ash accumulation, ideally up to 50 cm; and precautions should be implemented to protect sensitive equipment from fine ash infiltration, such as air conditioners, vehicle and generator filters, sewage systems, and drinking water supplies. Hazard zones were identified based on three simulated long fissure lava flows, using the orientation and length of the 2009 fissure (~15 km) as a model. The lava inundation maps were combined and smoothed with a 100 m buffer to define the ORANGE zone, indicating moderate volcanic hazard from lava flows. The RED zone, representing the highest hazard, was established by adding a 1000 m buffer around the fissures, where immediate edifice formation and pyroclastic activity are primary threats. YELLOW zones denote lower-risk areas mainly affected by ash fall up to 1 cm, as shown in Figure 21.

High-hazard zones are defined as the area immediately surrounding each fissure, including a 2000 m buffer to account for potential proximal hazards such as ash fall, ballistic projectiles, lava fountain reach, and scoria cone growth. Low-hazard zones extend up to 8000 m from the identified fissures, where an ash accumulation of at least 1 cm is anticipated. Field studies and mapping support this threshold and serve as reliable indicators of potential volcanic ash hazard, particularly if a future sub-Plinian eruption occurs—a scenario with a significant likelihood given the area's geological history. Although ash fall may still pose a significant hazard, it does not materially change the overall hazard classification for Option 4. Additionally, this map does not include information on secondary or cascading hazards, such as remobilized ash or potential flash-flood routes, nor does it address extremely distal, thin lava-flow inundation. Thin lava flows are considered low hazard, while comprehensive modeling of flash flood risks requires further research focused explicitly on sedimentary gravity flows. Generally, flash-flood channels or alluvial fans are located along steep valley slopes or near the foothills of major mountain ranges. Estimating eruption probability remains uncertain at this stage due to limited precise knowledge about volcanic event sequences, which mainly relies on approximate assessments based on relative

stratigraphy. The total activity of the volcanic field spans approximately 600,000 years, encompassing over 700 vent openings across around 150 multi-vent volcanoes. This age estimate is supported by 17 high-precision Ar-Ar radiometric ages, mostly from older lava flows, though the dataset is geographically and temporally uneven [77]. Previously, the total lifespan of the volcanic field was estimated at 2.8 million years, further increasing uncertainty in probability calculations. The average recurrence rate for vent openings over the 600,000-year period would be roughly one event every 857 years, which can be rounded to a 1000-year recurrence interval if events were evenly spaced—although this uniform distribution is unlikely. Therefore, the 1000-year vent-opening interval should be viewed as a conservative estimate, with actual recurrence rates likely being higher. Given an estimated 150 volcanoes, the recurrence rate would be about 4000 years. Based on these figures, it is reasonable to expect that complex, multi-vent eruptions could happen roughly every 4000 years, as indicated by geological mapping throughout the entire field, regardless of age or location. Assuming Qm5 began 4500 years ago, and Qm6 began 1000 years ago, there were 33 vents during Qm6 and 71 during Qm5. This indicates volcanic events occurred, on average, every 50 years during Qm5 and every 30 years during Qm6. Combined, the recurrence rate is approximately 1 event every 43–50 years, assuming each vent represents a separate event. Many vents are part of complex structures, often erupting simultaneously along fissures that can be up to 3 km long. For example, six closely spaced vents in the youngest Qm6 phase formed along a NW-SE fissure matching recent earthquake patterns. If an average of five vents defines an eruption episode, the true recurrence rate doubles to roughly every 100 with ten vents per event, it's about every 200 years. These rates have remained steady since Qm3, despite uncertainties in the timing of older eruptions.

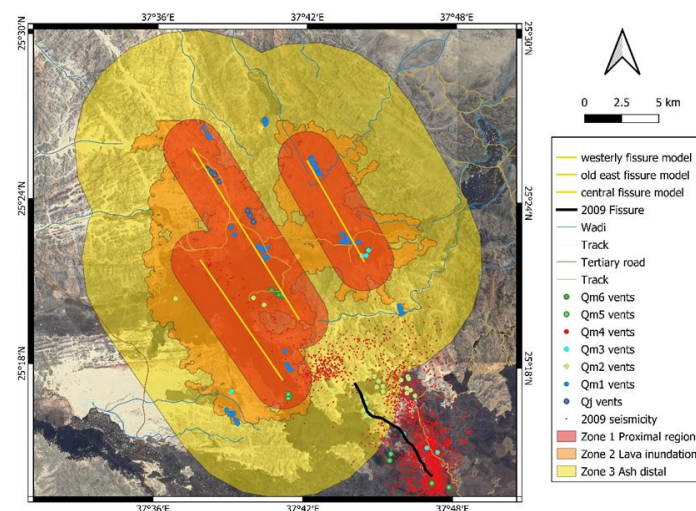


Figure 21. A simplified hazard zonation map derived from lava flow inundation simulations based on three extended fissure scenarios. The fissure lengths reflect the parameters observed during the failed 2009 eruption and subsequent fissure activity. Zone 2, or the medium hazard zone, represents the combined inundated areas from all three simulations. The primary NW-SE structural trends in the region, documented vent alignments, and the broader geological framework of greater Harrat Lunayyir informed the selection of fissure locations.

After conducting both a desktop study and an on-site reconnaissance mapping of volcanic features throughout the Lunayyir Volcanic Field, we have found that a volcanic eruption would likely unfold through a specific sequence of events observed at most of the studied locations. These eruptive processes generally follow a predictable pattern, resulting in a series of cascading volcanic hazards that should be included in any hazard assessment. We identified this chain of events and ranked its likelihood using a straightforward four-tier

system. Table 1 presents the potential progression of cascading volcanic hazards along with estimated likelihoods. It is important to note that this analysis is based on rapid assessment and does not reflect a detailed or quantitative evaluation involving precise counts of cases, eruptive volumes, or durations within individual eruption periods. In Table 2 the identified volcanic hazard estimates are demonstrated within the target area.

Table 1. Volcanic hazard types and their likelihood and duration ranking.

Chain of Volcanic Hazards/Cascading Hazards If an Eruption Starts	Likelihood Ranking	Estimated Duration
Fissure opening–Lava fountaining–Pāhoehoe lava outpour–Transitional flow field development–Inflation/deflation zone development–Scoria cone edifice growth–Ballistic bombardments–Small-scale rafting–Lava outpour repetition–Sub-Plinian/violent Strombolian explosive event with moderate ash dispersal–Cone regrowth–Slight lateral fissure shifting–Major paroxysmal sub-Plinian explosive event–Major ash dispersal–Longitudinal fissure rupture–Additional vent formations through the entire length of the fissure–Paired eruptions and compound volcanic edifice formation–Major rafting and collapse events	LOW	DAYS to YEARS
Fissure opening–Lava fountaining–Pāhoehoe lava outpour–Transitional flow field development–Inflation/deflation zone development–Scoria cone edifice growth–Ballistic bombardments–Small-scale rafting–Lava outpour repetition–Sub-Plinian/violent Strombolian explosive event with moderate ash dispersal–Cone regrowth–Slight lateral fissure shifting	MODERATE	DAYS to MONTH
Fissure opening–Lava fountaining–Pāhoehoe lava outpour–Transitional Flow field development–Inflation/deflation zone development–Scoria cone edifice growth–Ballistic bombardments–Small-scale rafting	HIGH	DAYS to MONTH
Fissure opening–Lava fountaining–Pāhoehoe lava outpour–Transitional Flow field development–Inflation/deflation zone development	CERTAIN	DAYS to WEEKS

Table 2. Volcanic hazard categorization.

	Category 1 (Likelihood/Expectation During Lifetime of Project)	Category 2 (Likelihood/Expectation During Lifetime of Project)	Category 3 (Likelihood/Expectation During Lifetime of Project)
Example/s	Ash fall/dispersion in distal areas, well beyond the geometrical footprint of the base of the volcano, typically over the distance where the ash fall thickness falls below 1 cm (in Lunayyir over 5 km from source).	Lava inundation of medial to distal regions from volcanic eruption site(s), likely about 3 km from the vent to the longest runout distance, in the Lunayyir case, about 30 km.	Complex eruption scenario of proximal regions where volcanic edifice grows (within the typical footprint of a volcanic edifice, commonly within 3 km from the vent), proximal lava outpouring occurs, and heavy ash fall can be accompanied by volcanic edifice instability (rafting and collapse).

Table 2. *Cont.*

	Category 1 (Likelihood/Expectation During Lifetime of Project)	Category 2 (Likelihood/Expectation During Lifetime of Project)	Category 3 (Likelihood/Expectation During Lifetime of Project)
Severity/Impact	(x) Manageable	(x) Manageable	(x) Unmanageable, built environment suffers irreparable and unrecoverable damage
Mitigation Through Design	1—Design buildings and roofs to support 1–2 m of ash accumulation. 2—Design accessibility and escape routes to exit the hazard zone.	1—Install detection systems and monitoring services that alert all people in the development vicinity to prepare for evacuation. (Warning signs before any risk to humans can be potentially ensured.) 2—Design escape routes. 3—Accept potential loss of assets and design to limit asset loss as much as possible.	Mitigation should focus on quick evacuation, minimizing delays in complete access, and the rapid removal of valuable items from the premises. This latter process must be pre-designed to achieve maximum efficiency of the rescue operation.
Information	Ash zonation modeling	Lava flow modeling	Model scenario of events

5. Conclusions

Although volcanic and seismic threats are rated as low to medium in intensity, they still pose significant risks, including potential economic impacts if tourism development proceeds to construct permanent visitation centers and frequent visitation, allowing multi-day potential exposure to the identified volcano–seismic hazards. A substantial portion of the Option 4 site is situated within zones unsuitable for safe development due to persistent, high-impact hazards and the absence of feasible methods to delineate secure areas. Exclusion zones have been established in areas with high volcanic seismic activity. It is recommended to place development projects outside these sensitive areas. Multi-night stays should be avoided; instead, daytime visits may be allowed only when volcano-seismic conditions are stable. A comprehensive mitigation plan (Table 3) will help reduce potential economic losses from geological hazards and enable quick interventions during visits.

Recurrence rates for eruptions vary from 50 to 4000 years, depending on the period examined. These numbers include only actual eruptions, excluding failed ones, which are difficult to track due to the limited availability of historical seismic data. Since events like the 2009 failed eruption may influence future risk, it is wise to include them in probabilistic models despite data gaps. Using conservative estimates, if the 2009 event is incorporated into a model starting from 2024 and assuming a 50-year recurrence interval, an eruption could occur within the next 35 years. This should be regarded as a worst-case scenario. Locating future events in a monogenetic volcanic field, such as Harrat Lunayyir, is challenging because new eruptions are likely to occur outside known vent areas but still within the overall zone. As volcanic fields develop and more vents form, future eruptions may break through existing volcanoes, forming complex mashups—a pattern seen in western Saudi Arabia’s harrats, where younger volcanoes sometimes overlap older ones with large gaps in between.

Table 3. Identified volcanic hazard types and their risk estimates.

Volcanic Hazard	Low Risk	Moderate Risk	High Risk
	Areas may experience ashfall that is 1 cm or less thick.	Lava flow zones beyond vent areas.	Potential vent zones are identified by analyzing the combination of structural elements, vent alignments, and age constraints.
Pāhoehoe lava flow	Use fire-resistant materials and avoid flammable items. Ensure the building design does not encourage accidental lava diversion; avoid holes, tunnels, or underground chambers.	Use fire-resistant exterior materials, minimize the use of materials prone to accidental ignition and capable of transferring fire into the building, and design clear escape routes with procedures to ensure evacuation within 24 h.	Use fire-resistant materials in construction. Strengthen the building frame to endure mechanical pressure and include a survival chamber stocked with at least 24 h of supplies for the typical number of occupants.
Transitional lava flow	Ensure the exterior is structurally sound and mostly perpendicular, capable of resisting lava flow and withstanding pressure from up to 2 m of lava, even with some overhang.	Use durable, sloped exterior materials to divert incoming lava. Design a complex outer structure to split a lava flow for cooling and to form a natural barrier. Build stone fences to slow lava and spread it into smaller, more manageable areas.	Construct a durable, insulated structure with a sealed environment and life support systems—including gas and air filters, as well as a water supply for the expected number of occupants—so that they can endure at least 24 h if trapped. Incorporate helipads or elevated, lava-safe landing zones for rescue within the first 24 h.
Lava spatter eruption	All relevant precautions for lava flows are deemed suitable for handling lava spattering events.	Ensure the building includes shelters that withstand heat and protect against incoming debris weighing several kilograms, impacting at speeds of several tens of meters per second.	Design buildings with simple geometry to minimize spatter buildup and secondary flow inside the structure.
Scoria cone formation and growth	In low-risk zones, the likelihood of scoria cone formation is very low, and no preventive measures are recommended aside from being prepared to handle possible ashfall.	Scoria cones could form in this area, which is completely overgrown by pre-existing buildings and structures; during the cone's growth stage, in its vicinity, follow ashfall safety measures.	Scoria cone formation is anticipated in this area, so all recommendations regarding roof reinforcement are relevant, potentially providing time to delay complete evacuation and to rescue material before the cone completely engulfs the built environment.

Table 3. Cont.

Volcanic Hazard	Low Risk	Moderate Risk	High Risk
Ballistic impact	In areas marked as low risk on the map, the risk of ballistic impact is minimal.	In regions with moderate risk, the likelihood of ballistic impact is low; it is advisable to use reinforced roof structures that may include elastic components capable of absorbing impact energy and reducing the likelihood of fracturing.	Ballistic impacts are likely in the red zone due to the vent locations. Buildings here must have reinforced walls and windows capable of withstanding 100 kg projectiles moving at up to 100 m/s.
Scoria cone collapse and rafting	No specific measures are needed.	No specific measures are needed; an adaptive mitigation strategy has been implemented.	In this area, proximity to scoria cones and major lava outflow sites poses a moderate-to-high risk of cone collapse. It is advisable to build structures in areas where cone collapse and direct proximal lava inundation are expected, on a continuous, reinforced foundation designed to move as a unit in the event of a nearby gravity-induced collapse, helping the structure stay intact and be transported atop the collapsing material along the lava flow surface.
Sub-Plinian to violent Strombolian eruption style	In these areas, a sub-Plinian eruption may cause fine ash fallout. Air filters and air conditioning systems should be ready to handle this, and facilities must be prepared for quick cleaning and disposal of fine ash.	Sub-Plinian eruptions are likely to occur in this zone, with moderate ash accumulation expected. Facilities must have real-time ash cleanup plans and accessible tools. Roofs should be able to support up to 10 cm of ash in the long term when ash accumulation is rapid and continuous removal is hindered.	There is a high likelihood that this intense phase of explosive volcanic activity will occur once an eruption begins. This area may experience significant ash fall; therefore, the original roof structures of buildings planned should be designed to support approximately 50 cm of ash buildup, with maximum levels potentially reaching up to 2 m within 1 km of the source. Building designs must ensure that controlled roof collapse does not endanger human life, while also maintaining the building's functionality and keeping external access points available for emergency response.

Table 3. Cont.

Volcanic Hazard	Low Risk	Moderate Risk	High Risk
Volcanic degassing, vog formation	This area is away from the lava field, and vog levels depend on wind conditions. Buildings should have personal air filter kits available in case of high gas concentrations.	The risk of vog exposure is considered moderate to high. Intense vog formation is expected in areas where lava collects, such as depression or behind physical barriers.	There is a high risk of vog, which can be particularly dangerous near vents and lava flows. All visitors are required to carry their own personal dust and respiratory filter equipment during visitation, to be ready for the highest-hazard scenario. Permanent visitor centers and buildings (hotels and service buildings) must have such gear ready for deployment in the event of a nearby eruption.

Supplementary Materials: The following supporting information can be downloaded at: <https://www.mdpi.com/article/10.3390/geohazards7010033/s1>, Table S1. Pahoehoe lava flow outpour, Table S2. Transitional lava flow outpouring, Table S3. Lava spatter cone formation and lava fountaining, Table S4. Scoria (cinder) cone formation and growth, Table S5. Ballistic impact, Table S6. Cone collapse and cone rafting, Table S7. Sub-Plinian explosive eruption and associated ash fall, Table S8. Volcanic degassing and vog formation, Figure S1. Cone formation and lava effusion from vent 1 in the NW outskirts of the Option 4 area, Figure S2. Vent opening simulation in the SW part of the Option 4 area, Figure S3. Fissure 1 simulation and hazard impact characterization. Note that this situation would not directly affect the Option 4 area but would cut off the development site via the westbound access road, leaving only escape routes toward the east, which would take considerable time to reach remote villages, Figure S4. Fissure 2 simulation involves a fissure opening approximately 2 km long, with the same strike direction as the vent alignments identified near the Target Volcano, Figure S5. An extensive fissure eruption along the SW edge of the Option 4 area could cause significant destruction and landscape changes, impacting about 27% of the area. The lava probably will not reach the development site, but its secondary effects could lead to the site being abandoned. In this case, the access road would likely stay open.

Author Contributions: Conceptualization, K.N., M.T. and V.S.; methodology, K.N.; software, K.N. and A.S.; validation, K.N. and M.T.; formal analysis, K.N., M.T. and A.S.; investigation, K.N.; resources, A.S.; data curation, A.S.; writing—original draft preparation, K.N.; writing—review and editing, M.T., V.S. and M.A.; visualization, K.N. and A.S.; supervision, K.N. and M.T.; project administration, A.S. and M.A.; funding acquisition, A.S. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by the Red Sea Global contract to the Saudi Geological Survey, grant Number, C00O00 BlackDesrt SW.

Data Availability Statement: The original contributions presented in this study are included in the article/Supplementary Material. Further inquiries can be directed to the corresponding author.

Acknowledgments: The Authors acknowledge the Saudi Geological Survey's logistical support in conducting the research under the strict time constraints.

Conflicts of Interest: The authors declare no conflicts of interest.

References

1. Németh, K. Monogenetic volcanic fields: Origin, sedimentary record, and relationship with polygenetic volcanism. *Spec. Pap. Geol. Soc. Am.* **2010**, *470*, 43–66. [\[CrossRef\]](#)
2. Smith, I.E.M.; Németh, K. Source to surface model of monogenetic volcanism: A critical review. In *Geological Society Special Publication*; Geological Society Publishing House: Bath, UK, 2017; Volume 446, pp. 1–28.
3. Németh, K.; Kereszturi, G. Monogenetic volcanism: Personal views and discussion. *Int. J. Earth Sci.* **2015**, *104*, 2131–2146. [\[CrossRef\]](#)
4. Kshirsagar, P.; Aviles, R.M.; de Puy y Alquiza, M.J.; Chako Tchamabe, B.; Dominguez, A.J.C. Case study of a cluster of simple and complex monogenetic volcanoes in the north-east part of the Michoacan–Guanajuato Volcanic Field, Central Mexico: Nomenclature implications. *Geol. J.* **2024**, *59*, 2750–2771. [\[CrossRef\]](#)
5. Chako Tchamabe, B.; Youmen, D.; Owona, S.; Ohba, T.; Németh, K.; Ngapna, M.N.; Asaah, A.N.E.; Aka, F.T.; Tanyileke, G.; Hell, J.V. Eruptive history of the Barombi Mbo Maar, Cameroon volcanic line, Central Africa: Constraints from volcanic facies analysis. *Cent. Eur. J. Geosci.* **2013**, *5*, 480–496. [\[CrossRef\]](#)
6. Le Corvec, N.; Bebbington, M.S.; Lindsay, J.M.; McGee, L.E. Age, distance, and geochemical evolution within a monogenetic volcanic field: Analyzing patterns in the Auckland Volcanic Field eruption sequence. *Geochem. Geophys. Geosyst.* **2013**, *14*, 3648–3665. [\[CrossRef\]](#)
7. Le Corvec, N.; Spörli, K.B.; Rowland, J.; Lindsay, J. Spatial distribution and alignments of volcanic centers: Clues to the formation of monogenetic volcanic fields. *Earth-Sci. Rev.* **2013**, *124*, 96–114. [\[CrossRef\]](#)
8. Martí, J.; Ricci, J.; Planagumà, L.; Aguirre-Díaz, G.J. The Quaternary La Garrotxa volcanic field (NE of Iberia): A geochronological approach. *Quat. Sci. Adv.* **2025**, *17*, 100267. [\[CrossRef\]](#)
9. Zimmerer, M.J. A temporal dissection of late Quaternary volcanism and related hazards within the Rio Grande rift and along the Jemez lineament of New Mexico, USA. *Geosphere* **2024**, *20*, 505–546. [\[CrossRef\]](#)
10. Zarazúa-Carbajal, M.C.; Mendoza-Rosas, A.T.; Caballero-Jiménez, G.V.; Gómez-Vázquez, Á.; De la Cruz-Reyna, S. The spatiotemporal evolution of monogenetic scoria cones in the Paricutin-Tancitaro region, Mexico: Results from a Morpho-chronological analysis and its consequences on the distributed volcanic hazard. *J. Volcanol. Geotherm. Res.* **2024**, *451*, 108111. [\[CrossRef\]](#)
11. Vilches, M.; Ureta, G.; Grosse, P.; Németh, K.; Aguilera, F.; Aguilera, M. Effusion rate estimation based on solidified lava flows: Implications for volcanic hazard assessment in the Negros de Aras monogenetic volcanic field, northern Chile. *J. Volcanol. Geotherm. Res.* **2022**, *422*, 107454. [\[CrossRef\]](#)
12. Schmidt, C.; Laag, C.; Whitehead, M.; Profe, J.; Tongwa Aka, F.; Hasegawa, T.; Kereszturi, G. The complexities of assessing volcanic hazards along the Cameroon Volcanic Line using spatial distribution of monogenetic volcanoes. *J. Volcanol. Geotherm. Res.* **2022**, *427*, 107558. [\[CrossRef\]](#)
13. Foote, A.; Németh, K.; Handley, H. The interplay between environmental and magmatic conditions in eruption style transitions within a fissure-aligned monogenetic volcanic system of Auckland, New Zealand. *J. Volcanol. Geotherm. Res.* **2022**, *431*, 107652. [\[CrossRef\]](#)
14. Meliksetian, K.; Neill, I.; Barfod, D.N.; Milne, E.J.M.; Waters, E.C.; Navasardyan, G.; Grigoryan, E.; Olive, V.; Odling, N.; Karakhanian, A. Pleistocene–Holocene volcanism at the Karkar geothermal prospect, Armenia. *Quat. Geochronol.* **2021**, *66*, 101201. [\[CrossRef\]](#)
15. Pedrazzi, D.; Kereszturi, G.; Lobo, A.; Geyer, A.; Calle, J. Geomorphology of the post-caldera monogenetic volcanoes at Deception Island, Antarctica—Implications for landform recognition and volcanic hazard assessment. *J. Volcanol. Geotherm. Res.* **2020**, *402*, 106986. [\[CrossRef\]](#)
16. Ang, P.S.; Bebbington, M.S.; Lindsay, J.M.; Jenkins, S.F. From eruption scenarios to probabilistic volcanic hazard analysis: An example of the Auckland Volcanic Field, New Zealand. *J. Volcanol. Geotherm. Res.* **2020**, *397*, 106871. [\[CrossRef\]](#)
17. Nieto-Torres, A.N.; Martín-Del-Pozzo, A.L. Spatio-temporal hazard assessment of a monogenetic volcanic field, near Mexico City. *J. Volcanol. Geotherm. Res.* **2019**, *371*, 46–58. [\[CrossRef\]](#)
18. Marrero, J.M.; García, A.; Berrocoso, M.; Llinares, Á.; Rodríguez-Losada, A.; Ortiz, R. Strategies for the development of volcanic hazard maps in monogenetic volcanic fields: The example of la Palma (Canary Islands). *J. Appl. Volcanol.* **2019**, *8*, 6. [\[CrossRef\]](#)
19. Osorio-Ocampo, S.; Macías-Vázquez, J.L.; Pola, A.; Cardona-Melchor, S.; Sosa-Ceballos, G.; Garduño-Monroy, V.H.; Layer, P.; García-Sánchez, L.; Pertón, M.; Benowitz, J. The eruptive history of the Pátzcuaro Lake area in the Michoacán Guanajuato Volcanic Field, central México: Field mapping, C-14 and $^{40}\text{Ar}/^{39}\text{Ar}$ geochronology. *J. Volcanol. Geotherm. Res.* **2018**, *358*, 307–328. [\[CrossRef\]](#)
20. Kereszturi, G.; Bebbington, M.; Németh, K. Forecasting transitions in monogenetic eruptions using the geologic record. *Geology* **2017**, *45*, 283–286. [\[CrossRef\]](#)
21. Bebbington, M.S. Assessing spatio-temporal eruption forecasts in a monogenetic volcanic field. *J. Volcanol. Geotherm. Res.* **2013**, *252*, 14–28. [\[CrossRef\]](#)

22. Cronin, S.J.; Neall, V.E. Impacts of volcanism on pre-European inhabitants of Taveuni, Fiji. *Bull. Volcanol.* **2000**, *62*, 199–213. [\[CrossRef\]](#)
23. Filippi, L.D.; Mazzetto, S. Comparing AlUla and The Red Sea Saudi Arabia's Giga Projects on Tourism towards a Sustainable Change in Destination Development. *Sustainability* **2024**, *16*, 2117. [\[CrossRef\]](#)
24. Amal, M.O.T.; Sahide, A.; Bustami, M.R. Saudi arabia's diversification strategy through the red sea project in facing the international petroleum competition. *Jurisdiction J. Huk. Syariah* **2024**, *15*, 380–411. [\[CrossRef\]](#)
25. Robitzsch, V.; Kattan, A.; Dunne, A.; Coker, D.J. *Saudi Arabia Case Study: The Development of Saudi Arabia's Red Sea Coastline: Challenges Facing Sustainable Resource Use*; Springer Nature: Berlin/Heidelberg, Germany, 2023; pp. 73–93.
26. Alyusuf, A. Sustainable tourism development in the red sea of the kingdom of Saudi Arabia: Threats and opportunities. In Proceedings of the International Conference on Tourism Research, Lisbon, Portugal, 20–21 May 2021; pp. 36–43.
27. Németh, K.; Toni, M.; Sokolov, V.; Sowaigh, A.; Ashor, M.; Moqem, F. Eruption Scenarios of a Monogenetic Volcanic Field Formed Within a Structurally Controlled Basement Terrain: Harrat Lunayyir, Saudi Arabia. In *A Comprehensive Study of Volcanic Phenomena*; Németh, K., Ed.; IntechOpen: Rijeka, Croatia, 2024.
28. Németh, K.; Sowaigh, A.; Toni, M.; Sokolov, V.; Moqem, F. Volcanic hazard assessment of northern Harrat Lunayyir, Kingdom of Saudi Arabia: Volume 5 of 5. In *Saudi Geological Survey Project Contract Report*; Saudi Geological Survey (SGS): Jeddah, Saudi Arabia, 2025; Volume 5, p. 68.
29. Pallister, J.S.; McCausland, W.A.; Jónsson, S.; Lu, Z.; Zahran, H.M.; El Hadidy, S.; Aburukbah, A.; Stewart, I.C.F.; Lundgren, P.R.; White, R.A.; et al. Broad accommodation of rift-related extension recorded by dyke intrusion in Saudi Arabia. *Nat. Geosci.* **2010**, *3*, 705–712. [\[CrossRef\]](#)
30. Mukhopadhyay, B.; Mogren, S.; Mukhopadhyay, M.; Dasgupta, S. Incipient status of dyke intrusion in top crust—Evidences from the Al-Ays 2009 earthquake swarm, Harrat Lunayyir, SW Saudi Arabia. *Geomat. Nat. Hazards Risk* **2013**, *4*, 30–48. [\[CrossRef\]](#)
31. Zahran, H.M.; El-Hady, S.M. Seismic hazard assessment for Harrat Lunayyir—A lava field in western Saudi Arabia. *Soil Dyn. Earthq. Eng.* **2017**, *100*, 428–444. [\[CrossRef\]](#)
32. Zahran, H.M.; El-Hady, S.M.; Abuelnaga, H.S. Aeromagnetic data over Harrat Lunayyir and surrounding areas, western Saudi Arabia. *Arab. J. Geosci.* **2017**, *10*, 63. [\[CrossRef\]](#)
33. Al Shehri, A.; Gudmundsson, A. Thermal mapping of the 2009 dyke emplacement at Harrat Lunayyir, Saudi Arabia. *Arab. J. Geosci.* **2019**, *12*, 602. [\[CrossRef\]](#)
34. Saibi, H.; Mogren, S.; Mukhopadhyay, M.; Ibrahim, E. Subsurface imaging of the Harrat Lunayyir 2007–2009 earthquake swarm zone, western Saudi Arabia, using potential field methods. *J. Asian Earth Sci.* **2019**, *169*, 79–92. [\[CrossRef\]](#)
35. Mossoux, S.; Saey, M.; Bartolini, S.; Poppe, S.; Canters, F.; Kervyn, M. Q-LAVHA: A flexible GIS plugin to simulate lava flows. *Comput. Geosci.* **2016**, *97*, 98–109. [\[CrossRef\]](#)
36. Becerril, L.; Larrea, P.; Salinas, S.; Mossoux, S.; Ferrés, D.; Widom, E.; Siebe, C.; Martí, J. The historical case of Parícutin volcano (Michoacán, Mexico): Challenges of simulating lava flows on a gentle slope during a long-lasting eruption. *Nat. Hazards* **2021**, *107*, 809–829. [\[CrossRef\]](#)
37. Németh, K.; Moufti, M.R. Lava Flow Hazard and Its Implication in Geopark Development for the Active Harrat Khaybar Intracontinental Monogenetic Volcanic Field, Saudi Arabia. *Land* **2023**, *12*, 705. [\[CrossRef\]](#)
38. Rodríguez-Gonzalez, A.; Aulinas, M.; Mossoux, S.; Perez-Torrado, F.J.; Fernandez-Turiel, J.L.; Moreno-Medina, C. Lava flow modelling of Pico de Bandama volcano (Gran Canaria, Canary Islands). *Geogaceta* **2019**, *65*, 19–22.
39. Prieto-Torrell, C.; Rodríguez-Gonzalez, A.; Aulinas, M.; Fernandez-Turiel, J.L.; Cabrera, M.; Criado-Hernandez, C.; Perez-Torrado, F.J. Modelling and simulation of a lava flow affecting a shore platform: A case study of Montaña de Aguarijo eruption, El Hierro (Canary Islands, Spain). *J. Maps* **2021**, *17*, 502–511. [\[CrossRef\]](#)
40. Ramayanti, S.; Achmad, A.R.; Jung, H.C.; Jo, M.J.; Kim, S.W.; Park, Y.C.; Lee, C.W. Measurement of surface deformation related to the December 2018 Mt. Etna eruption using time-series interferometry and magma modeling for hazard zone mapping. *Geosci. J.* **2022**, *26*, 749–765. [\[CrossRef\]](#)
41. Martín-Raya, N.; Díaz-Pacheco, J.; López-Díez, A.; Dorta Antequera, P.; Cabrera, A. A lava flow simulation experience oriented to disaster risk reduction, early warning systems and response during the 2021 volcanic eruption in Cumbre Vieja, La Palma. *Nat. Hazards* **2023**, *117*, 3331–3351. [\[CrossRef\]](#)
42. Chiba, T.; Kaneta, S.; Suzuki, Y. Red relief image map: New visualization method for three dimensional data. *Int. Arch. Photogramm. Remote Sens. Spat. Inf. Sci.* **2008**, *37*, 1071–1076.
43. Chiba, T.; Kaneta, S.; Ohashi, M. Digital Terrain Representation Methods and Red Relief Image Map, a New Visualization Approach. In Proceedings of the International Cartographic Association, 29th International Cartographic Conference (ICC 2019), Tokyo, Japan, 15–20 July 2019; Volume 2. [\[CrossRef\]](#)
44. Gałaś, A.; Lewińska, P.; Aguilar, R.; Nowak, Ł. Remote sensing data applied to the reconstruction of volcanic activity in the Valley of the Volcanoes, Central Volcanic Zone, Peru. *J. Geodyn.* **2023**, *156*, 101972. [\[CrossRef\]](#)

45. Ulusoy, İ.; Diker, C.; Şen, E.; Aydın, E.; Akkaş, E.; Gümüş, E.; Çubukçu, H.E.; Erkut, V. Surface expressions of morphostructural features at Hasandağ stratovolcano on DEM datasets. *Mediterr. Geosci. Rev.* **2021**, *3*, 175–191. [\[CrossRef\]](#)
46. Karátson, D.; Yepes, J.; Favalli, M.; Rodríguez-Peces, M.J.; Fornaciai, A. Reconstructing eroded paleovolcanoes on Gran Canaria, Canary Islands, using advanced geomorphometry. *Geomorphology* **2016**, *253*, 123–134. [\[CrossRef\]](#)
47. Favalli, M.; Fornaciai, A. Visualization and comparison of DEM-derived parameters. Application to volcanic areas. *Geomorphology* **2017**, *290*, 69–84. [\[CrossRef\]](#)
48. Özpolat, E.; Yildirim, C.; Görüm, T. The Quaternary landforms of the Büyük Menderes Graben System: The southern Menderes Massif, western Anatolia, Turkey. *J. Maps* **2020**, *16*, 405–419. [\[CrossRef\]](#)
49. Giordano, G.; Cas, R.; Wright, J.V. Explosive Eruption Styles, Columns, and Pyroclastic Fallout Deposits. In *Volcanology: Processes, Deposits, Geology and Resources*; Cas, R., Giordano, G., Wright, J.V., Eds.; Springer International Publishing: Cham, Switzerland, 2024; pp. 519–691.
50. Taddeucci, J.; Edmonds, M.; Houghton, B.; James, M.R.; Vergnolle, S. Chapter 27—Hawaiian and Strombolian Eruptions. In *The Encyclopedia of Volcanoes*, 2nd ed.; Sigurdsson, H., Ed.; Academic Press: Amsterdam, The Netherlands, 2015; pp. 485–503.
51. Houghton, B.F.; Wilson, C.J.N.; Smith, I.E.M. Shallow-seated controls on styles of explosive basaltic volcanism: A case study from New Zealand. *J. Volcanol. Geotherm. Res.* **1999**, *91*, 97–120. [\[CrossRef\]](#)
52. Houghton, B.F.; Gonnermann, H.M. Basaltic explosive volcanism: Constraints from deposits and models. *Geochemistry* **2008**, *68*, 117–140. [\[CrossRef\]](#)
53. Németh, K.; Kereszturi, G. Monogenetic Basaltic Volcanoes: Genetic Classification, Growth, Geomorphology and Degradation. In *Updates in Volcanology—New Advances in Understanding Volcanic Systems*; Németh, K., Ed.; IntechOpen: London, UK, 2012.
54. Cas, R.; Wright, J.V.; Giordano, G. Basaltic and Other Low-Viscosity Lavas. In *Volcanology: Processes, Deposits, Geology and Resources*; Cas, R., Giordano, G., Wright, J.V., Eds.; Springer International Publishing: Cham, Switzerland, 2024; pp. 229–309.
55. Harris, A.; Latutrie, B.; Van Wyk de Vries, B.; Saubin, É.; Foucher, M.; Gurioli, L.; Zanella, E.; Médard, E.; Nauret, F. Emplacement of monogenetic lava flows on eroded terrain, Part II: The case of the Artière valley (Grave Noire, France). *J. Volcanol. Geotherm. Res.* **2023**, *438*, 107812. [\[CrossRef\]](#)
56. Latutrie, B.; Harris, A.; Van Wyk de Vries, B.; Gurioli, L.; Médard, E. Emplacement of lava flows on eroded terrain, part I: The case of the Tiretaine valley (Chaîne des Puys, France). *J. Volcanol. Geotherm. Res.* **2023**, *438*, 107808. [\[CrossRef\]](#)
57. Murcia, H.; Németh, K.; Moufti, M.R.; Lindsay, J.M.; El-Masry, N.; Cronin, S.J.; Qaddah, A.; Smith, I.E.M. Late Holocene lava flow morphotypes of northern Harrat Rahat, Kingdom of Saudi Arabia: Implications for the description of continental lava fields. *J. Asian Earth Sci.* **2014**, *84*, 131–145. [\[CrossRef\]](#)
58. Brown, C.; Bryan, S.E.; Gust, D.A.; Dalton, H. Insights into the development of small-volume long lava flows: A case study of the Coalstoun Lakes Volcanic Field, southeast Queensland, Australia. *J. Volcanol. Geotherm. Res.* **2024**, *451*, 108115. [\[CrossRef\]](#)
59. Self, S.; Keszthelyi, L.; Thordarson, T. The importance of pāhoehoe. *Annu. Rev. Earth Planet. Sci.* **1998**, *26*, 81–110. [\[CrossRef\]](#)
60. Self, S.; Thordarson, T.; Keszthelyi, L. Emplacement of continental flood basalt lava flows. In *Geophysical Monograph Series*; American Geophysical Union: Washington, DC, USA, 1997; Volume 100, pp. 381–410.
61. Pioli, L.; Erlund, E.; Johnson, E.; Cashman, K.; Wallace, P.; Rosi, M.; Delgado Granados, H. Explosive dynamics of violent Strombolian eruptions: The eruption of Parícutin Volcano 1943–1952 (Mexico). *Earth Planet. Sci. Lett.* **2008**, *271*, 359–368. [\[CrossRef\]](#)
62. Foshag, W.F.; Gonzalez, R.J. Birth and development of Parícutin volcano. *U.S. Geol. Surv. Bull.* **1956**, *965*, 355–489.
63. Walker, G.P.L. Explosive volcanic eruptions—A new classification scheme. *Geol. Rundsch* **1973**, *62*, 431–446. [\[CrossRef\]](#)
64. Valentine, G.A.; Gregg, T.K.P. Continental basaltic volcanoes—Processes and problems. *J. Volcanol. Geotherm. Res.* **2008**, *177*, 857–873. [\[CrossRef\]](#)
65. Larrea, P.; Salinas, S.; Widom, E.; Siebe, C.; Abbitt, R.J.F. Compositional and volumetric development of a monogenetic lava flow field: The historical case of Parícutin (Michoacán, Mexico). *J. Volcanol. Geotherm. Res.* **2017**, *348*, 36–48. [\[CrossRef\]](#)
66. Cioni, R.; Pistolesi, M.; Rosi, M. Chapter 29—Plinian and Subplinian Eruptions. In *The Encyclopedia of Volcanoes*, 2nd ed.; Sigurdsson, H., Ed.; Academic Press: Amsterdam, The Netherlands, 2015; pp. 519–535.
67. Nakada, S.; Nagai, M.; Kaneko, T.; Suzuki, Y.; Maeno, F. The outline of the 2011 eruption at Shinmoe-dake (Kirishima), Japan. *Earth Planets Space* **2013**, *65*, 475–488. [\[CrossRef\]](#)
68. Camp, V.E.; Hooper, P.R.; Roobol, M.J.; White, D.L. The Madinah eruption, Saudi Arabia: Magma mixing and simultaneous extrusion of three basaltic chemical types. *Bull. Volcanol.* **1987**, *49*, 489–508. [\[CrossRef\]](#)
69. Bebbington, M.S. Spatio-volumetric hazard estimation in the Auckland volcanic field. *Bull. Volcanol.* **2015**, *77*, 39. [\[CrossRef\]](#)
70. Hayes, J.L.; Wilson, T.M.; Deligne, N.I.; Lindsay, J.M.; Leonard, G.S.; Tsang, S.W.R.; Fitzgerald, R.H. Developing a suite of multi-hazard volcanic eruption scenarios using an interdisciplinary approach. *J. Volcanol. Geotherm. Res.* **2020**, *392*, 106763. [\[CrossRef\]](#)

71. Hopkins, J.L.; Smid, E.R.; Eccles, J.D.; Hayes, J.L.; Hayward, B.W.; McGee, L.E.; van Wijk, K.; Wilson, T.M.; Cronin, S.J.; Leonard, G.S.; et al. Auckland Volcanic Field magmatism, volcanism, and hazard: A review. *N. Z. J. Geol. Geophys.* **2021**, *64*, 213–234. [[CrossRef](#)]
72. Valentine, G.A.; Perry, F.V. Volcanic risk assessment at Yucca Mountain, NV, USA: Integration of geophysics, geology and modeling. In *Volcanic and Tectonic Hazard Assessment for Nuclear Facilities*; Cambridge University Press: Cambridge, UK, 2009; pp. 452–480.
73. Wetmore, P.H.; Hughes, S.S.; Connor, L.J.; Caplinger, M.L. Spatial distribution of eruptive centers about the Idaho National Laboratory. In *Volcanic and Tectonic Hazard Assessment for Nuclear Facilities*; Cambridge University Press: Cambridge, UK, 2009; pp. 385–405.
74. Gallant, E.; Cole, L.; Connor, C.; Donovan, A.; Molisee, D.; Morin, J.; Walshe, R.; Wetmore, P. Modelling eruptive event sources in distributed volcanic fields. *Volcanica* **2021**, *4*, 325–343. [[CrossRef](#)]
75. Sugden, P.; Meliksetian, K.; Savov, I.P.; Barfod, D.; Wilson, M.; Connor, C.; Navasardyan, G.; Grigoryan, E.; Manucharyan, D. Post-collisional shift from polygenetic to monogenetic volcanism revealed by new $^{40}\text{Ar}/^{39}\text{Ar}$ ages in the southern Lesser Caucasus (Armenia). *J. Volcanol. Geotherm. Res.* **2021**, *412*, 107192. [[CrossRef](#)]
76. Connor, L.J.; Connor, C.B.; Meliksetian, K.; Savov, I. Probabilistic approach to modeling lava flow inundation: A lava flow hazard assessment for a nuclear facility in Armenia. *J. Appl. Volcanol.* **2012**, *1*, 3. [[CrossRef](#)]
77. Duncan, R.A.; Al-Amri, A.M. Timing and composition of volcanic activity at Harrat Lunayyir, western Saudi Arabia. *J. Volcanol. Geotherm. Res.* **2013**, *260*, 103–116. [[CrossRef](#)]

Disclaimer/Publisher’s Note: The statements, opinions and data contained in all publications are solely those of the individual author(s) and contributor(s) and not of MDPI and/or the editor(s). MDPI and/or the editor(s) disclaim responsibility for any injury to people or property resulting from any ideas, methods, instructions or products referred to in the content.