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ORIGINAL ARTICLE

Volcanic Geoheritage and Geotouristic Potential of the Gegham Monogenetic Volcanic Upland (Armenia)

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Abstract
Volcanic geoheritage includes a variety of geological, environmental, and scenic landscapes that are shaped by volcanic activity and often intertwined with sites of historical and cultural significance. Armenia, a country straddling the boundary between the Eurasian, European and Arabian tectonic plates, has a rich and often unique geological past, and its post-collisional Quaternary volcanism is giving rise to numerous features that contribute to its geoheritage of local and international significance. Manifestations of Quaternary volcanism of Armenia are highly diverse and include – stratovolcanoes, calderas, monogenetic volcanic fields, and rhyolite domes. The eruption products and landforms consist of various lava flows, such as coulées and plateau basalts, along with columnar joints, thick ash fallout deposits, multiple thick ignimbrite plateaus, and world – renowned obsidian bearing lavas. The compositional diversity of Quaternary volcanic products spans from picrobasalts and basanites to rhyolites. Overall, Armenia's volcanic landscapes contain numerous significant volcanological features and phenomena. This paper aims to highlight the status of Armenia's volcanic geoheritage, with particular focus on the Gegham Volcanic Upland situated between the capital city of Yerevan and Lake Sevan. We provide an up-to-date quantitative assessment of geodiversity of this area, which categorizes the evaluation outputs for geotourism potential. Geoheritage score was developed based on the scientific, geoeducational, and geotourism values of region's geosites.

Keywords Armenia · Volcanism · Lake sevan · Obsidian · Geotourism · Gegham volcanic upland

Introduction

In recent decades, research on geoheritage, geosites, geoconservation, and geotourism has garnered significant interest within the fields of geology and environmental conservation (e.g., Ólafsdóttir 2019; Štrba et al. 2020; Williams et al. 2020; Zgłobicki et al. 2020; 2024; Khalaf 2024).

Over the past years, geotourism has become a universally valuable tool for promoting natural and cultural heritage in Armenia (e.g., https://news.am/eng/news/538889.html; https://www.armgeo.am/en/; https://hikearmenia.org/home; https://armenia.travel/). Armenia is a country with rich and well-investigated archaeology and history and blending in a geological background can provide an outstanding opportunity to further enrich traditional eco- and cultural tourism.

The idea for establishing a national geopark in Armenia was first considered by Avagyan et al. (2021, 2023). Their effort was focused on manifestations of geological phenomena that pose a certain degree of geohazard, such as active faults or volcanic eruptions, in the Gegharkunik, Vayotsdzor, Kotayk and Ararat regions (see Fig. 1 in Avagyan et al. 2023). The same initiative also included a geosite representing the Permian-Triassic mass extinction event, as well as the noteworthy hydrogeological and sediment deposition sites (Avagyan et al. 2021). The proposed Geohazard-related geopark has a limited area (Avagyan et al. 2021),

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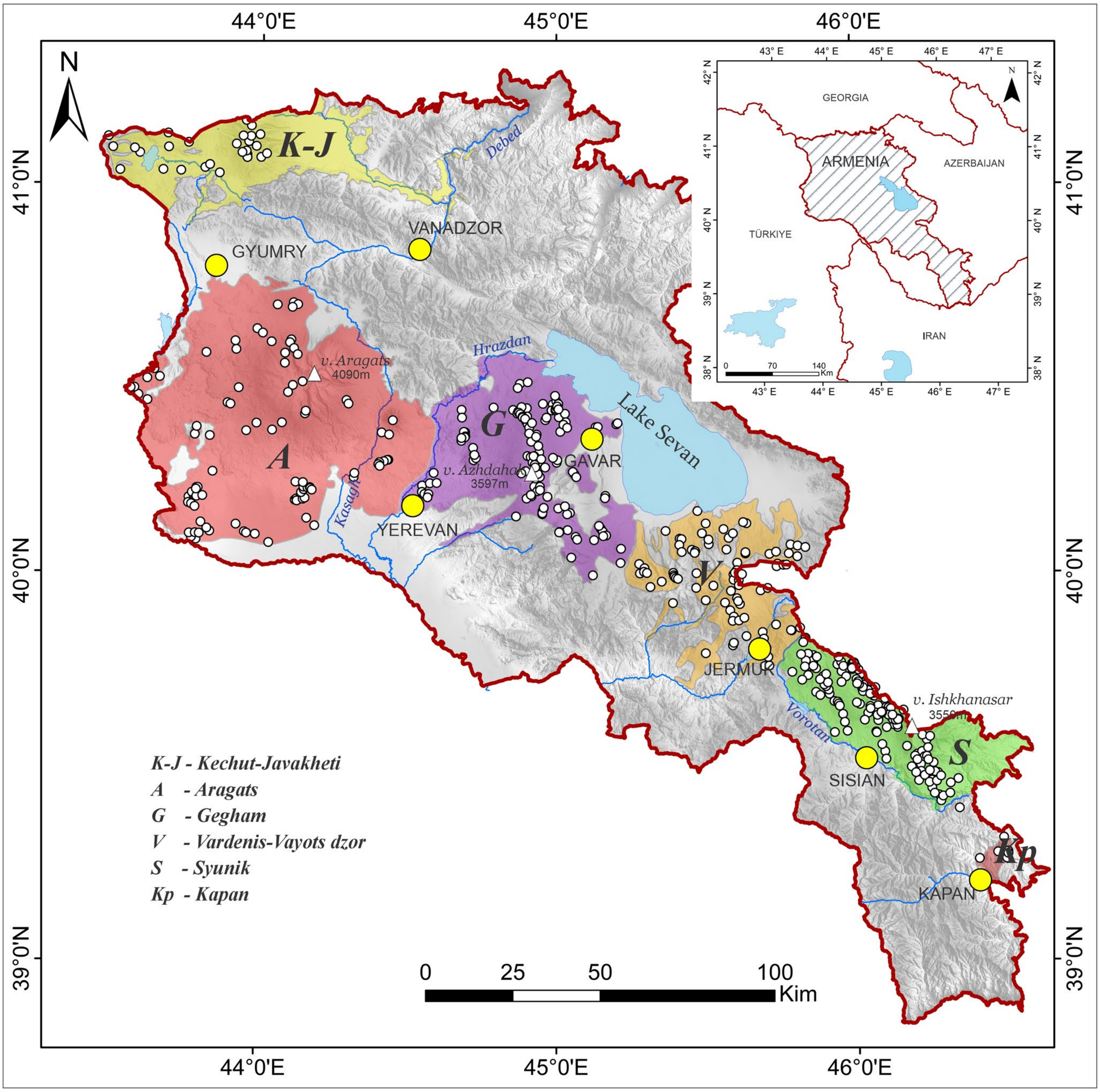


Fig. 1 Map of Armenia with surrounding countries (upper right), and a schematic map showing the volcanic regions and distribution of Quaternary volcanic products and centers of Armenia

and cannot encompass all the diversity of the Quaternary volcanism of Armenia.The geoheritage potential of such young volcanism needs more appreciation and recognition, seeing about half of the territory of the country is covered by Pliocene-Quaternary volcanic products such as lava flows and pyroclastic rocks (e.g., Karapetian et al. 2001; Halama et al. 2020; Meliksetian et al. 2021).

In this contribution, we extend the list of volcanic geosites suggested earlier for the first Armenia Geopark (Avagyan et al. 2021, 2023) with a focus on Gegham monogenetic volcanism in central Armenia monogenetic volcanism occurs as distributed volcanic fields composed of dozens to hundreds of small-volume volcanoes, exhibiting diverse eruptive styles, compositions, and geomorphologies (e.g., Nemeth and Kereszturi 2015; Smith and Nemeth 2017; Benamrane et al. 2022). Gegham Volcanic Upland (GVU) is a Pleistocene-Holocene monogenetic volcanic terrain, and is an “open book” for visitors who wish to gain an insight into a wide range of fine examples of young and well-preserved volcanic phenomena that is relatively accessible and spread over moderately short distances. It is also an area where volcanic heritage combines with sites of historical, archaeological and cultural significance. Within GVU there are well-preserved cinder cones, rhyolite domes, pyroclastic deposits, spectacular columnar joints lava flows.

The main objectives of this article are to present the volcanism of Armenia, with a particular focus on GVU, and catalogue potential geosites located within or near the recently proposed first Geopark in the Republic of Armenia, and also contribute for the further development of geotourism in Armenia.

Regional Volcanism and Ages

The Armenian Highland is located in the Arabia-Eurasia collision zone and represents intensely deformed and uplifted segment of the Alpine-Himalayan fold belt (e.g., Nikogosian et al. 2023). The complex geological structure of Armenia (Lesser Caucasus, northeastern part of the Armenian Highland) stitches together a mosaic of diverse tectonic blocks within a relatively small area, representing fragments of paleo-island arcs, continental plates, and obducted oceanic crust (ophiolites) of the Mesozoic Tethys Ocean basin (Meliksetian 2013; Sugden et al. 2019, 2021; Halama et al. 2020; Meliksetian et al. 2021; Nikogosian et al. 2023). Recent magmatism of the collision zone may be explained by partial melting of asthenospheric and lithospheric mantle, resulting from slab break-off and/or lithospheric delamination related to the southern Neo-Tethys slab (Neill et al. 2015; Halama et al. 2020; Sugden et al. 2019, 2021).

Considering regional collisional volcanism, it should be mentioned that within the orogenic plateau in eastern Türkiye, the biggest volcanic province is the Kars-Erzurum plateau (see Fig. 1 in Sugden et al. 2021). The latter borders Armenia and contains a record of very active collision-related volcanism ranging in age from Middle Miocene until the end of Pliocene (Pearce et al. 1990; Keskin et al. 1998). Also, in the region there are abundant Holocene-Historically active (including 15th and 19th AD century activity) volcanoes located north of lake Van (Bingöl, Mush, Nemrut, Süphan, Girekol), and further east Tondrak (Tendürek). Finally, the well-known and prominent in the landscape Great and Lesser Ararat volcanoes, which may have also erupted in the Holocene and even in Historical times, 2500−2400 to 700−500 BC (Karakhanian et al. 2003). Two large Quaternary stratovolcanoes are known in the northwest of Iran, namely the Sabalan (4811 m) and the Sahand (3707 m) (e.g., Ahmadzadeh et al. 2010). Javakheti Ridge in Georgia/Armenia borderlands is also characterized by Early Pleistocene volcanism, while the Samsari Ridge in southern Georgia was active in Middle Pleistocene to Holocene times (Okrostsvaridze et al. 2016).

Recent volcanism throughout the South Caucasus region can be categorized into three types: fissure (flood basaltic), younger monogenetic and polygenetic (e.g., Skhirtladze 1958; Meliksetian 2012; Jrbashyan et al. 2024).

In the Late Pliocene – Early Pleistocene, fissure volcanism produced a very large volume of sub-alkaline flood basalts and basaltic andesites (dolerites). These little differentiated mafic rocks are covering large areas in northern and central Armenia, as well as parts of southern Georgia. These regions include the Lori, and Kotayk plateaus as well as lengthy flows extending along the canyons of the Akhourian, Debed, and Hrazdan River (Neill et al. 2013, 2015; Sheth et al. 2015), the Lake Sevan basin (Kharazyan 1975) in Armenia, as well as the valleys of the Khrami, and Mashavera rivers in Georgia (Skhirtladze 1958). The age of the fissure flood basalts of the Lesser Caucasus is considered to be Upper Pliocene – Early Pleistocene and indeed the Little available ages suggest long-term volcanic activity ranging from 3.5 to 2,09 Ma (Balogh et al. 1990; Chernyshev et al. 2002; Lebedev et al. 2007, 2008a, b; Neill et al. 2015; Ritz et al. 2016). Voluminous flood basalts in Armenia, southern Georgia and Kars-Erzurum plateau discussed in terms of Pliocene–Pleistocene continental flood basalt province in the South Caucasus (Sheth et al. 2015).

Compared to the fissure eruptions and the widespread flood basalt volcanism, the monogenetic volcanism is younger. Monogenetic volcanism in Armenia is represented mainly by vents located on large elevated and prominent volcanic uplands, such as Kechut (southern part of the Javakheti ridge), Gegham, Vardenis-Vayots Dzor and Syunik), and include nearly 500 monogenetic volcanic centers, with many of them exceeding an altitude of 3000 m. Most of them are cinder cones, but as well as rhyolite domes are also present.

Central vent volcanism is related to the long-lasting magmatic activity producing large volume stratovolcanoes. From north to south such large polygenetic stratovolcanoes are: Kechut (3550 m), Aragats (4096 m), Arailer (2575 m), Ishkhanasar (3550 m) and Tskhouk (3584 m). The period of activity of these central-vent stratovolcanoes is considered to be up to 1.5 Ma (Karakhanian et al. 2003; Sugden et al. 2021). Recent high quality ^{40}Ar/^{39}Ar and K^{-}Ar dating revealed that the period of activity of the Aragats fall in the range of 1.54–0.49 Ma (Meliksetian 2012; IAEA-TECDOC 2016).

The GVU covers a high elevation area of 65 × 35 km located west of Lake Sevan and extending to the foothills of the territory of the capital Yerevan (Fig. 2). It is bounded to the north and west by the Hrazdan River Valley and to the south by the Argichy River Valley. The duration of

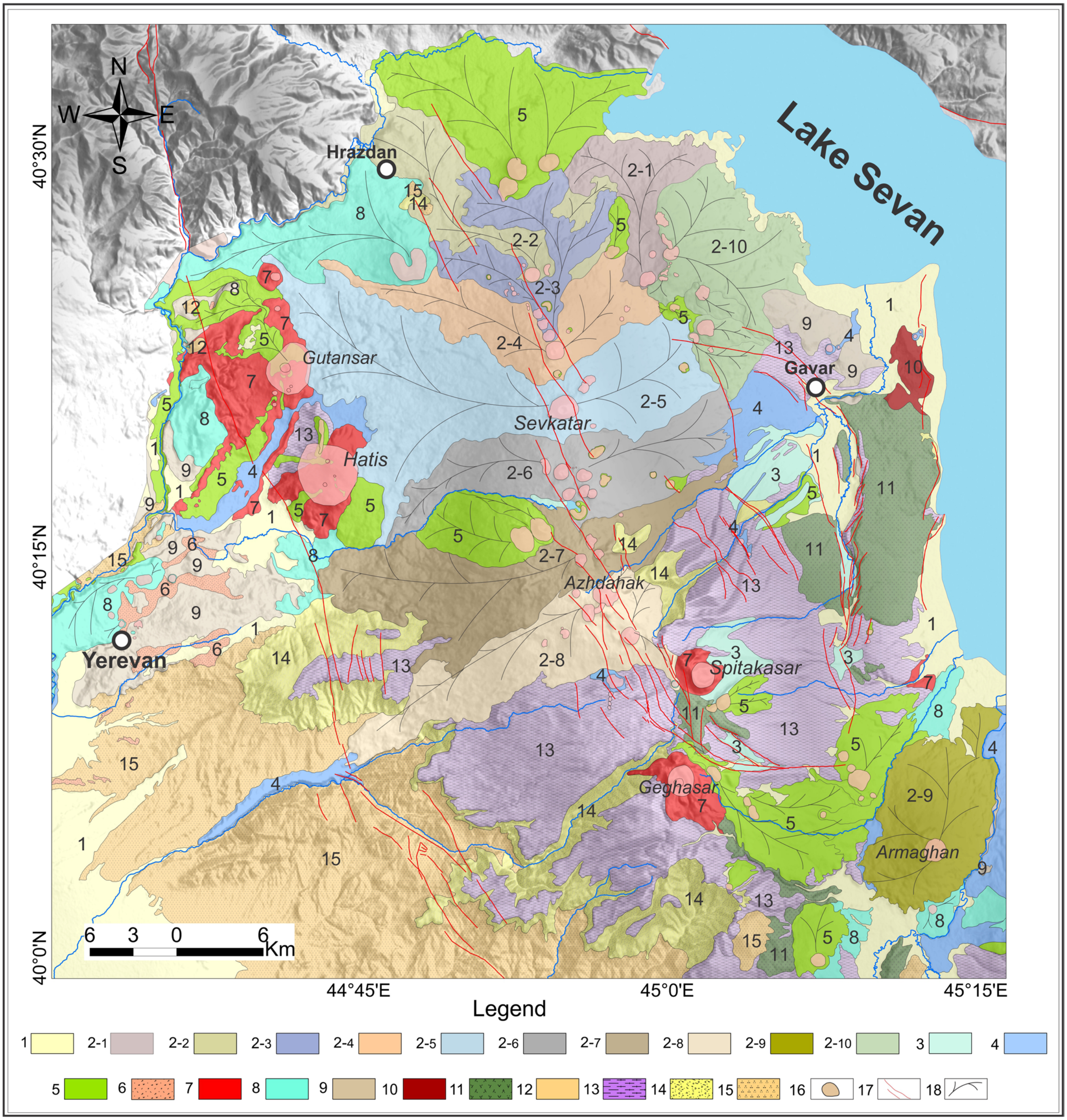


Fig. 2 Volcanological map of GVU (by K. Karapetyan, S. Karapetyan, G. Navasardyan; active faults are from Karakhanyan et al. 2017). Legend: *Upper Pleistocene-Holocene*. 1. Alluvial and colluvial sediments. 2−1. Lava flow of Norashen. 2–2. Lava flows of Tsluglukh and Srbisar volcanoes. 2–3. Lava flows of Kond, Vardanasar and etc. volcanoes. 2–4. Lava flows of Mazaz and Karmratumb volcanoes. 2–5. Lava flow of Sevkatar volcano. 2–6. Lava flows of Aknocasar and Lodochnikov volcanoes. 2–7. Lava flow of Aghusar volcano. 2–8. Lava flows of Azhdahak and Nazeli volcanoes. 2–9. Lava flow of Armaghan volcano. 2–10. Lava flows of group Eratumber volcanoes. *Upper Pleistocene*. 3. Glacial and fluvioglacial deposits. 4. Basaltic trachyandesites, trachyandesites. *Middle Pleistocene*. 5. Basaltic trachyandesites, trachyandesites. 6. Ignimbrite tuffs of Yerevan-Gyumri type. Middle-Lower Pleistocene. 7. Trachydacites and rhyolites of Gutansar, Hatis, Spitakasar, Geghasar. *Lower Pleistocene.* 8. Trachybasalts, basaltic trachyandesites, trachyandesites. Upper Pliocene. 9. Flood (doleritic) basalts, trachybasalts. 10. Volcanogenic formation. Suite of Noratus. 11. Basaltic trachyandesites, trachyandesites of Manichar lava flow. *Lower Pliocene.* 12. Rhyolites of Avazan, Gyumush volcanoes. 13. Basaltic trachyandesites, trachyandesites, trachytes. *Lower Pliocene-Upper Miocene.* 14. Volcanoclastic deposits (Voghjaberd suite). *Pre-Upper Miocene.* 15. Volcano-sedimentary rocks: sandstones, tuff breccia, Limestones, andesite lava flows. 16. Volcanic centers. 17. Active faults. 18. Directions of lava flows

volcanism within the GVU spans from the Late Miocene to the Holocene (Karakhanian et al. 2002, 2003; Lebedev et al. 2013; Sugden et al. 2021).

There are 128 monogenetic volcanic centers within the GVU and most of them are cinder cones, with 4 rhyolitic domes (Fig. 2). The highest peak in the GVU is the Azhdahak volcano (3597 m), which relative height is up to 350 m.

Sugden et al. (2021) suggested temporal and spatial relationships between polygenetic and monogenetic volcanic activity within Syuink and Vardenis-Vayots dzor volcanic uplands to the south of GVU. According to our research, based on geological evidence, such transition also occurred within GVU, which was hosting largely polygenetic eruptions during the Late Miocene and Early Pliocene and monogenetic in the Quaternary. Such transition is usually attributed to a decrease in magma supply rates and an increase in crustal extension, resulting in widely distributed clusters of volcanic vents, rather than construction of large volume stratovolcanoes (e.g., Sugden et al. 2021).

The Voghjaberd suite of Late Miocene age (e.g., Baghdasaryan and Ghukasyan 1985) reaches a thickness of up to 500 m (Milanovsky and Koronovsky 1973) and is predominantly distributed along the southwestern periphery of the GVU. It consists of volcanoclastic rocks (tuffs, volcanic breccias, tephras) and includes interstratified lava flows of andesite, partly basaltic andesite, and dacite compositions (Milanovsky and Koronovsky 1973). Volcanological characteristics and structure of the suite suggest its formation was associated with the activity of a large polygenetic volcano and, possibly, caldera-forming eruptions, as indicated by the presence of thick tuff layers and felsic tephra fallout deposits. Subsequently, Quaternary monogenic volcanism was superimposed over the caldera of Late Miocene polygenetic stratovolcano.

The Lower Pliocene on the GVU is represented by basaltic trachyandesite, trachyandesite and trachyte rocks, exposed as lava flows.

It appears that between polygenetic and monogenetic volcanism in the GVU, there was an intermediate phase characterized by the eruption of flood (dolerite) basalts from the Lower Pleistocene. Fissure volcanism in GVU, followed by monogenic volcanism, shapes the current landscape of GVU. The products of these volcanoes are spread over the upland and are a trachybasaltic to rhyolitic composition (Navasardyan 2006).

According to Karapetian et al. (2001), the felsic volcanism at the GVU is expressed by the eruption of rhyolite-trachydacite magma at Hatis and Gutansar volcanoes and of rhyolites at the Fontan, Alapars, Spitakasar and Geghasar volcanoes. Hatis and Gutansar volcanoes are cut by younger basaltic trachyandesites, suggesting a bimodal character of these volcanoes. It appears that the 600 m wide Geghasar rhyolite dome hosts mafic scoria that may be linked to the same basaltic trachyandesite eruption episodes.

Spitakasar and Geghasar are two large rhyolitic volcanoes in the central part of GVU. These volcanoes are built mainly by extrusive rocks and outcrop as obsidian flows and their devitrified perlite deposits. Spectacular and voluminous outcrops of obsidian (volcanic glass) are formed by the rapid degassing of rhyolitic magmas, which are characteristic of felsic volcanoes worldwide. Within the GVU such obsidian flows are also common at Hatis and Gutansar volcanoes (Fig. 2). Rhyolite-obsidian volcanoes of GVU contain abundant traces of prehistoric utilization (e.g., Badalyan et al. 2004). Obsidians from several Armenian volcanoes were widely used by Paleolithic, Neolithic, Chalcolithic and Bronze Age communities of the South Caucasus (Meliksetian et al. 2024). For example, the obsidians were used for making tools and weapons locally, but also were traded or exchanged over long distances (1620 km) such as - to Troy in the Aegean region (Meliksetian et al. 2024) as well as to the north Greater Caucasus Mountains and south Iran (1570 km) (Blackman et al. 1998; Chataigner et al. 2003; Badalyan et al. 2004; Frahm and Feinberg 2013; Meliksetian et al. 2024). In Armenia, obsidian is usually called "vanakat," meaning it is found in the vicinity of Lake Van, and locals also refer to it as "devil's nail." Lava flows, combined with the lack of trees and shrubs (high elevation) and the Holocene glaciations and resulting erosion (Karakhanian et al. 2003; Avagyan et al. 2020) from GVU shape the modern landscape of GVU. For example, the thick (25–37 m) lava flow sourced from the Lchasar volcano gave rise of the Lake Sevan by damming the (paleo-) Hrazdan River (Pafenholts 1959). An important stratigraphic unit is the lava flow at Garni, which stretches for 13 km, causing columnar joints in the Azat River gorge. For these (basaltic trachyandesite) lavas, Meliksetian (2018) reported ages of 127.7 ± 2.6 ka.

According to Arutyunyan et al. (2007) and Lebedev et al. (2013), both using K-Ar age determinations, the monogenetic volcanoes at GVU are exclusively younger than 1 Ma. In the western part of the GVU the monogenetic rhyolite domes and lava flows have been dated as 0.77−0.38 Ma and are relatively older than the monogenetic rhyolite domes of the central part of GVU dated as 0.20−0.10 Ma (Lebedev et al. 2013). In summary, the GVU represents a complex volcanic upland with evidences of polygenetic, flood basaltic fissure, and monogenic magmatic activity that formed between the Late Miocene and the Holocene, and that contains exceptional examples of diverse volcanic phenomena.

Methods of Volcanic Geosite Classification

Various definitions and explanations of the terms "geodiversity," "geoheritage," and "geosite" have been proposed in the literature (Brilha 2018; Gray 2018; Mariotto et al. 2023; Zakharovskyi et al. 2024). In the context of this manuscript, geodiversity is considered as a natural complex of features of geological, geomorphological and volcanic formations that arose as a result of the Quaternary volcanism of the Republic of Armenia, and their interrelation in time and space (e.g., Gray 2018). The GVU is a part of the Quaternary volcanic relief of the Republic of Armenia, is a geoheritage expressed by such reliefs of thevolcanic structures and landscapes that have scientific, educational, cultural or recreational value (e.g. Brilha 2018). Selected geosites are specific places on the GVU that can be used for geotourism, educational and research programs, and which are worthy of conservation (Zakharovskyi et al. 2024 and references therein).

Over recent decades, numerous authors (Serrano and Ruiz-Flaño 2007; Gordon et al. 2012; Gray 2013; Hjorth et al. 2015; Neches 2016; Poch et al. 2019; Dias et al. 2021; Zakharovskyi and Nemeth 2021, 2022; Albani et al. 2022; Li et al. 2023; Jon et al. 2024; Zakharovskyi et al. 2024) have developed and tested quantitative and mixed qualitative-quantitative methods for assessing the diversity of geosites. Both approaches have made significant progress in recent years and are widely adopted in geosite assessment. Examples of the application of quantitative methodology are the Brilha method (Brilha 2016), GAM (Vujicic et al. 2011), M-GAM (Tomic and Božic 2014), MCDM (Jia et al. 2023; Dede and Zorlu 2023) techniques, and GAM and MEREC-based PROMETHEE-GAIA (Zorlu et al. 2023). On the other hand, qualitative-quantitative approaches, emphasizing geomorphology and geology as core elements, have been extensively applied in various studies (e.g., Zakharovskyi and Nemeth 2021, 2022; Li et al. 2023; Zakharovskyi et al. 2024).

Table 1 The names and coordinates of geosites selected at GVU considering their volcanological and sightseeing value

Geosite code	Geosite name	Geosite coordinates	
		Lat. (*N*)	Long. (E)
G1	Geghasar volcano	40.113403	45.002163
G2	Hatis volcano	40.308260	44.725698
G3	Garni lava flow with columnar joints	40.114675	44.740836
G4	Voghjaberd Suite	40.141227	44.819220
G5	Azhdahak group of volcanoes	40.227104	44.949233
G6	Aknalich group of volcanoes	40.283038	44.919847
G7	Armaghan volcano	40.068549	45.213938
G8	Gutansar volcano	40.368219	44.684876
G9	Lchasar group of volcanoes	40.492816	44.876970

In our study, the choice of a quantitative method was driven by the fact that the primary objective of the original work was to conduct a systematic, comparable and reproducible assessment of geosites within a GVU to support a broader geosite inventory and geopark planning initiative. In this regard, the quantitative method of Brilha (Brilha 2016) was chosen for our study, which offers structured numerical assessment systems, minimizes subjectivity, allowing for transparent comparisons between geosites and adheres to international standards used in geoparks. This method has been successfully implemented in an assessment system, is widely used (e.g., Sánchez and Brilha 2017; Zwoliński et al. 2018; Albani et al. 2022; Jaya et al. 2022; Mehdioui et al. 2022; Braychevskyy et al. 2023; Elhassan et al. 2023; Khalaf 2024; Jon et al. 2024; Zorlu et al. 2024) and offers a standardized yet practical framework for assessing geosites based on four values: scientific, educational, touristic, and risk of degradation.

In contrast to the quantitative method we have chosen, the MEREC-PROMETHEE-GAIA technique, expresses the use of complex methods for the selection of geoheritage objects based on a combination of expert assessment and mathematical weighting (Zorlu et al. 2023), and the quantitative-qualitative method offers assessment studies (slope angle, age division of rocks, scale modeling, area extent: Zakharovskyi and Nemeth 2021, 2022; Li et al. 2023) that will be very effective in subsequent or late stages of assessment in GVU, but also in Armenia as a whole.

The previous assessment for potential geopark suitability in Armenia by Avagyan et al. (2023) is based on evaluation and documentation of geological significance, and integration of cultural, historical, architectural, and archaeological sites, as well as the assessment of geosite accessibility and safety. In this paper, based largely on the geological and volcanological characteristics, nine volcanic geosites were identified and defined as volcanic heritage sites (Table 1; Fig. 3).

According to Brilha (2016), the assessment of scientific value—a key factor—is based on seven main criteria, each scored with 1, 2, or 4 points. Notably, a 3-point score is intentionally omitted to enhance differentiation between geosites. Each of these criteria is weighted to reflect its importance, with the educational and tourism values playing the most crucial role for the geotourism and geoeducational development (Brilha 2016; Mariotto et al. 2023). Quantitative assessment of Potential Tourist Use (PTU) considers 13 criteria, quantitative assessment of Potential Educational

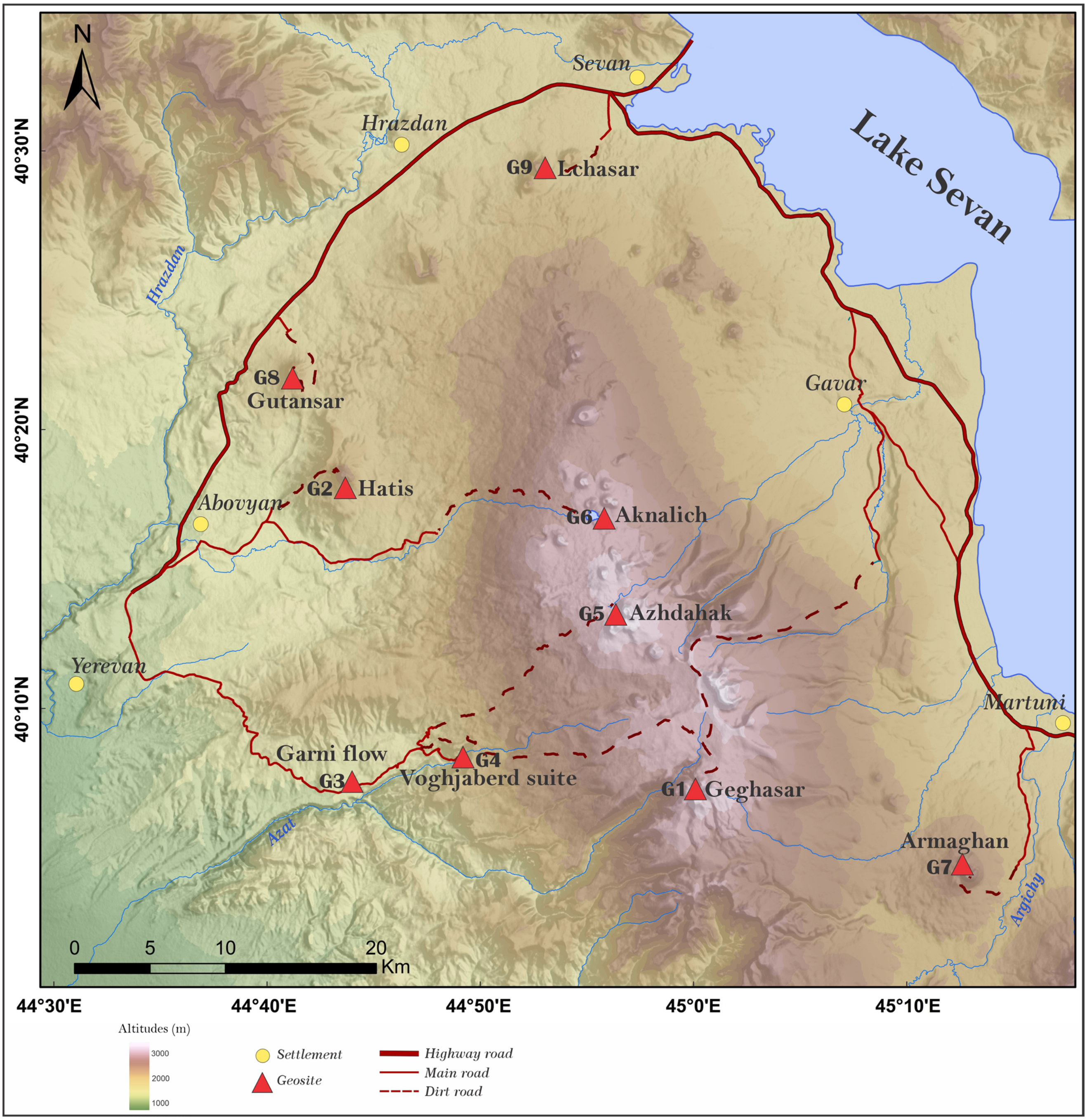


Fig. 3 Topographic map of GVU with locations of volcanic geosites selected for this study. Note that many of the geosites are relatively proximal to towns/road infrastructure

Use (PEU) is based on 12 criteria, and assessment of degradation risk is based on five criteria. The values for the different criteria have corresponding weights that are multiplied the value of quantitative assessment is obtained, which are classified according to classes: < 200 is low, 201–300 is medium, 301–400 is high (Brilha 2016).

Results

Based on volcanological features and characteristics, which include touristic and educational values, nine geosites have been selected in the GVU (see Table 1; Fig. 3).

Geosite 1: Geghasar Volcano (G1)

Geghasar volcano is located (40.113403 N; 45.002163 E) in the SE of the watershed part of the GVU, about 16 km west of the Tsovasar village of the Ghegharkunik Marz (Fig. 4). This volcano was among the goesites proposed as first Armenian geopark (Avagyan et al. 2021). The elevation of Geghasar volcano edifice over the surrounding terrain is about 350 m; its base area is 20 km^2, estimated volume of erupted rhyolites is 4.5km^3 (Fig. 4B). Volcano consist of thick lava flows towards west, east and south and are represented by a series of interlayered flows of rhyolite, obsidian and perlite extending from the central part of the volcano. In planar view, the volcano has an irregular shape elongated from northwest to southeast for about 7 km (Fig. 4C).

Geghasar volcano is a dome-shaped structure with high steep northern and gentler southern slopes, consisting of two viscous domescomposed mainly of rhyolite-obsidian lavas. On the top of the northeast dome there is crater-like feature with diameter of 150 m. The base of this dome has a diameter of 1 km, a surface area of 0.65km^2, and a volume of 0.35km^3. A second (southwest) dome with a diameter of 130 m at the base a surface area of 0.35km^2, and a volume of ~0.02km^3. The slopes of both of the domes are smoothed by talus of rhyolite-obsidian-perlite lava. A rhyolitic lava flow with obsidian extends 3 km (Fig. 4F) from the summit of the northeast dome. The volume of this flow is 0.27 km^3.

The summit of the Geghasar volcano has remnants of what appears to be mafic vent site (Nor-Geghasar), which according to Karapetian et al. (2001) may reflect interaction with possible younger dyke swarm at depth (Fig. 4B). The latter appears to bear similarity with feature at Hatis and Gutansar volcanoes and possibly relevant to the interpretation of the GVU as compositionally bimodal suite.

The age of the Geghasar rhyolites is Upper Pleistocene (K-Ar age: 0.13 ± 0.08 Ma, 0.10 ± 0.02 Ma, Lebedev et al. 2013; fission-tracks 0.042–0.082 Ma, Badalyan et al. 2001). Obsidian is a massive glassy variety of rhyolitic felsic volcanic rock with SiO_2 ranging 72–76 wt%, with a characteristic glassy luster and conchoidal fracturing, usually formed as a result of extremely fast degassing of high silica magmas (e.g., Castro et al. 2005). Obsidians of Geghasar are homogeneous and characterized by a wide range of colors: from white opaque and translucent light gray to reddish, brown, and black (Fig. 4). Reddish and brown varieties are associated with a predominance of ferric iron (Fe^{3+}), while black varieties are associated with a predominance of ferrous iron (Fe^{2+}). The silvery, white and brown varieties are usually associated with abundant microvesiculated glass and inclusions of potassium feldspars, plagioclase, magnetite, biotite and fibrous orthopyroxenes.

Geghasar volcano represents a unique opportunity to observe exquisite in quality and diverse in colors rhyolite obsidians and volcanological futures of the formation of rhyolite volcanoes, coulees, viscous lava flows, perlites and obsidian domes.

Compared to other well-known rhyolite-obsidian bearing volcanoes and geosites for instance Oki Geopark, Japan obsidian geosite (https://www.oki-geopark.jp/en/geopark-sites-features-list/2689/) Geghasar is larger, much younger and the structure of volcano and lava flows are fresh and well-preserved. Considering exposure, preservation and thickens of obsidian dome and lava flows Geghasar site is comparable to Obsidian Cliff in Yellowstone, USA (e.g., Johnson et al. 1993).

Rhyolitic lava is typically more fragile and is primarily represented by obsidian and pumice deposits, which are prone to breakage and structural instability. Due to increasing usage of the obsidian as jewellery and with the massive increase in demand due to the booming tourist growth in Armenia in the last decades, certain colourful varieties may become depleted and need to be preserved. The geosite can be reached by dirt road (about 26 km from Goght village) by off-road car or by walk. The view from the summit of the volcano provides a 360º panorama towards the entire GVU and in particular towards the less accessible summit ridges and the Spitakasar, Nazeli and Armaghan volcanoes.

Geosite 2: Hatis Volcano (G2)

Hatis is a dome-shaped volcano (40.308260 N; 44.725698 E), reaching an absolute height of 2529 m. It has a relative height of 1000 m above the village of Akunq, and a diameter of the base up to 7.5 km.

The Hatis volcano is a complex volcanic structure with ravines (Fig. 5B), consisting of several stages of rhyolite-trachydacite outcrops of obsidian, rhyolite, perlite, and pyroclastic formations (Fig. 5C). Similar to the Geghasar, he main uniqueness of this volcano also is that it has bimodal nature that is demonstrated by the clear presence of basaltic volcanic centers (basaltic trachyandesite) cutting the high SiO_2 rhyolitic dome and erupting as mafic scoria and short (0.03 km^3 in volume) lava flows. Among such volcanic features are the Tekblur (N40.310304; E44.720337), Tegh (N40.305812; E44.733067) and Kharamblur (N40.291922; E44.717908) vents (Fig. 5C). Volcanic structures of this type are a rare phenomenon worldwide as the low volume mafic magmas are usually assimilated by the older and much higher in volume rhyolites - a process usually happening at depth and rarely seen in clear relationship at the surface. In Armenia, for example, there are only three such volcanoes among 500 Quaternary volcanoes.

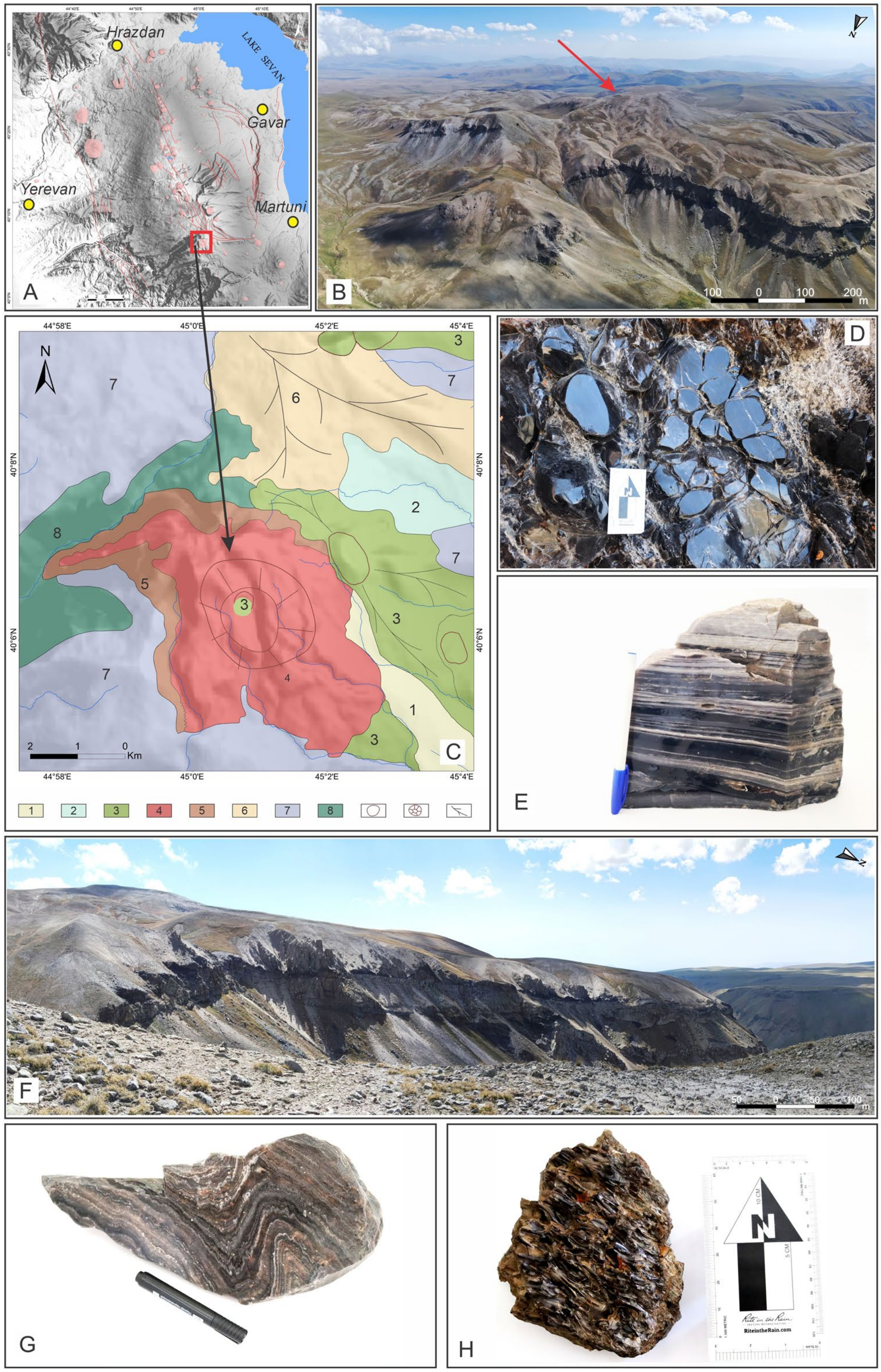


Fig. 4 **A** Schematic map of distribution volcanoes and location of Geghasar geosite in the GVU. **B** The Geghasar volcano (elev. 3346 m), on the top of which a new mafic New Geghasar volcano (the location of the vent with a red arrow). **C** Geological-volcanological map of Geghasar volcano (see legend below). **D** Obsidian-rich layer with shiny (glassy) surfaces of relatively large dense blocks of inclusion-poor black variety. **E** Striped obsidian "Obsidian onyx" (pen for scale is 14 cm long). **F** Rhyolite-obsidian laminar flow (coulee type) with black obsidian cliffs. **G** A multi-layered "rare" type of obsidian (marker for scale is 13 cm long). **H** Degassed and rapidly cooled obsidian Legend of the geological-volcanological map of Geghasar volcano. *Holocene - Upper Pleistocene.* (1) Alluvial, deluvial, eluvial and proluvial sediments, pebble, sand, sandy loam, and detritus. *Upper Pleistocene.* (2) Glacial and fluvio-glacial sediments. *Middle Pleistocene.* (3) Basaltic trachyandesites and trachyandesites of Vochkharatumb and another volcano. (4) Rhyolite-perlite lavas and breccias; (5) Rhyolites and obsidians. *Upper Pliocene.* (6) Basaltic trachyandesite and trachyandesite lavas of Manichar. *Lower Pliocene.* (7) Basaltic trachyandesites, trachyandesites, and trachytes (the Gegham stratum). *Lower Pliocene - Upper Miocene.* (8) Volcano-sedimentary formations (the Voghjaberd Suite). Dome shaped volcanic centers; Monogenetic volcanic centers; Direction of movement of lava flows

Initially, the Hatis volcano eruption activity produced rhyolite flows stretching in the southern and northeastern direction. One of them (rhyolite, obsidian, perlitic breccia) stretches 5 km in the southwest direction and is represented by obsidian "base", the thickness of which is 1–2.5 m. Along with obsidian, some vesicular rhyolites with more water contents can be observed, similar to pitchstone. Another flow is located on the northeastern slope and covered with pyroclastic perlite formation. Rhyolites of this stage can also be found on the southern slope, near the Pogos-Petros

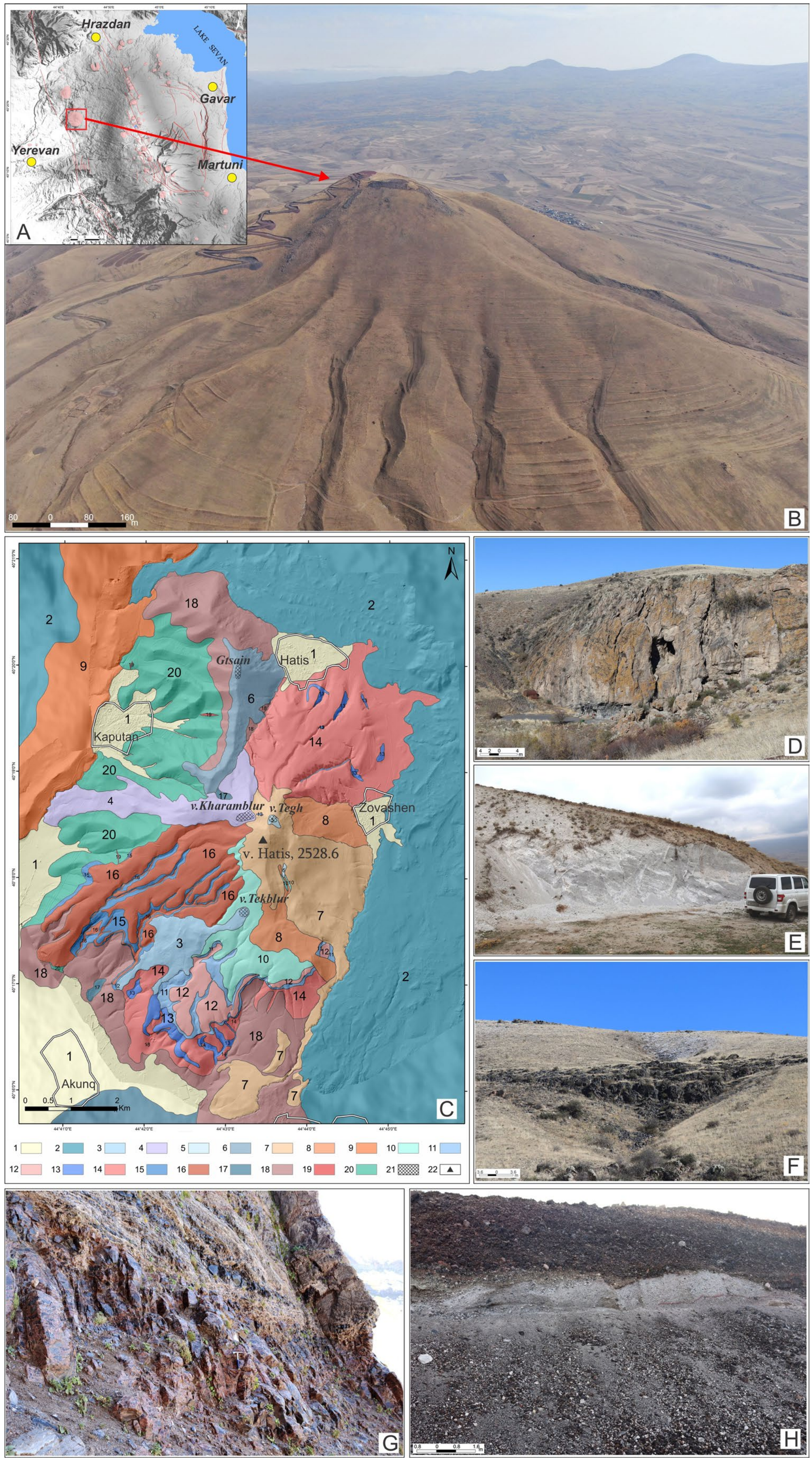


Fig. 5 **A** Schematic map of distribution volcanoes and location of Hatis geosite in the GVU. **B** Hatis volcano (elev. 2529 m). **C** Geological-volcanological map of Hatis volcano (see legend below). **D** Rhyolite-obsidian lava flows. **E** Fine-grained pyroclastic formations. **F** Obsidian cliffs in various colors. **G** Massive obsidian layer (cliff). **H** Stratigraphic relationship of basaltic scoria and rhyolite Legend of the geological-volcanological map of Hatis volcano: Holocene - Upper Pleistocene. (1) Colluvial material. (2) Young lava flows of Gegham upland. *Middle Pleistocene.* (3) Lava flows of Teqblur volcano. (4) Lava flows of Kharamblur volcano. (5) Lava flows of Tegh volcano. (6) Lava flows of Gtsain volcano. *Middle - Lower Pleistocene.* (7) Dacites. (8) Trachydacites. (9) Trachydacites of Gutansar volcano. (10) Rhyolite and obsidian of 4th stage. 11. Obsidian of 3rd stage. 12. Rhyolite of 3rd stage. 13. Obsidian of 2nd stage. 14. Rhyolite of 2nd stage. 15. Obsidian of 1 st stage. 16. Rhyolite of 1 st stage. *Lower Pleistocene - Upper Pliocene.* 17. Flood (doleritic) basalt. *Lower Pliocene.* 18. Andesitic basalt. 19. Dikes of andesite and andesitic basalt. 20. Andesite. Volcanic centers. Summit of Hatis volcano

church, and are represented by thick obsidian-rhyolite lava flows (up to 57 m thick), with black obsidians common for the lowermost 10 m of the flows (Fig. 5D).

The next stage of eruption is continuing by the formation of often complexly zoned pyroclastic flow deposits. The thickness of these pyroclastic formations in the summit part of the volcano is 35–40 m, and in the lower flanks thins down to only 1–2 m (Fig. 5E). Clustered in zones to the east and northeastern of the church outcrop a great variety of highly colorful rhyolitic obsidians (Fig. 5F).

The final eruptions of the Hatis volcano are associated with the extrusion of a diverse suite of rocks, containing a base of black-colored trachydacites and rhyolites (including obsidian) (Fig. 5G), which are locally overlain by lavas and scoria with basalt to trachyandesite composition (Fig. 5H).

The period of activity of the Hatis volcano is estimated to be 600−200 ka. The reported fission track age of obsidians is 0.21–0.4 Ma (Badalyan et al. 2004), and the K-Ar dating reveals ages bracketed between 0.66 and 0.48 Ma (Lebedev et al. 2013). The youngest manifestations of volcanic activity are associated with the basic extrusions (lava flow), dated 0.2 Ma (Lebedev et al. 2013). The length of the young lava is 3.6 km, the thickness is about 45 m, and the volume of the lava flow is 0.09 km^2.

In the structure of the Hatis volcano, with combination of acid and mafic volcanic manifestations, exposures of lavas, diverse obsidians, and pyroclastic sections that characterize the uniqueness of the volcano and can give an idea about the formation and development of the volcano.

It can be reached by paved road and by all means of transport vehicles, as well as by walk.

Geosite 3: Garni Columnar Jointed Lava Flow (G3)

Garni lava flow is located (40.114675 N; 44.740836 E) in the Azat River canyon, southwest of Garni village (Fig. 6A). This stunning lava flow is related to the voluminous post-collision (Quaternary) mafic volcanism of GVU and represents one of the most spectacular examples of thick columnar jointing in the world. Columnar jointed extend several km along the road that follows the Azat River canyon. In Armenia, it is named “Symphony of Stone” and is already recognized as Geological monument by Government decree (Fig. 6).

The lava flow is ~13 km in length, and is with an average thickness of 60 m, and covers an area of 40 km^2 and volume is 2.4 km^3. One of the important features of the site is the almost full capacity columnar separations of the lava flow and their perfect hexagonal in cross-section shapes. The hexagons formed by slow cooling of basaltic-trachyandesite in the canyon filled by lava flow, where the upper part cools faster and insulates the lower part of the flow. That led to contraction, resulting in the formation of tension cracks (Spry 1962). In particular, the lava begins to crack into regular shapes at different spots called “centers”. If those centers are evenly spaced, the forces that pull inward toward the center of each prism end up creating different chunks of cooling lava that are hexagonal in shape. The more homogeneous the magma is, the more evenly those centers will distribute the stress. This means the lava flow is more Likely to cool into hexagonal chunks, with the angles of the hexagonal prisms ranging from 100 to 150 degrees. (Fig. 6F).

The composition of Garni columnar lava flow is basaltic-trachyandesite. Lava flow is dated by $^{40}Ar/^{39}Ar$ as 127.7 ± 2.6 ka, i.e. Late Pleistocene in age (Meliksetian 2018). The columnar flow is covered by younger lava flows from Azhdahak and Tar volcanoes located in the summit area of GVU and dated by $^{40}Ar/^{39}Ar$ as young as 49.9 ± 9.2 ka (Meliksetian 2018) (Fig. 6C).

Within the GVU the Quaternary volcanic activity is represented by monogenic centers with trachybasalt, basaltic-trachyandesite, to trachyandesite composition (Navasardyan 2006 and references therein).

Given its considerable thickness and several-kilometer extent, the columnar lava flow in the Azat River canyon represents a rare geological formation and may be regarded as a geosite of international significance. Hexagonal or pentagonal columns create visually beautiful and rare landscapes not commonly found in other geological settings.

Column units may become damaged and break over time due to possible stresses on the columns (seismic and other loads). In addition, under the influence of various forces, such as water, wind and ice, erosion processes occur in the canyons, which gradually erode the surrounding rocks. As a result, columns may become unstable and prone to collapse.

This geosite can be reached by paved road and by all means of transport vehicles, as well as by a pleasant walk along the banks of Azat river.

Importantly, the Garni columnar jointed lava flow is located near the 1 st century AD Garni Hellenistic temple (40.112421 N; 44.730277 E) (Fig. 6G). In addition, in the vicinity of Garni, several Early Bronze archaeological sites and medieval monuments (Garni Fortress) with international importance add value to this geosite.

Garni Fortress and Hellenistic Temple

The area proximal to the Garni columnar jointed lava flow was first occupied in the 3rd millennium BC along easily defensible terrain at one of the bends of the Azat river. In the epoch of the Armenian rulers of the Ervandids (Orontid, 331–200 BC), Artashesids (Artaxiad, 189 BC – 12 AD) and Arshakids (Arsacid, 52–428) dynasties (since the 3rd century B.C. to the 5th century A.D.), fortification at Garni

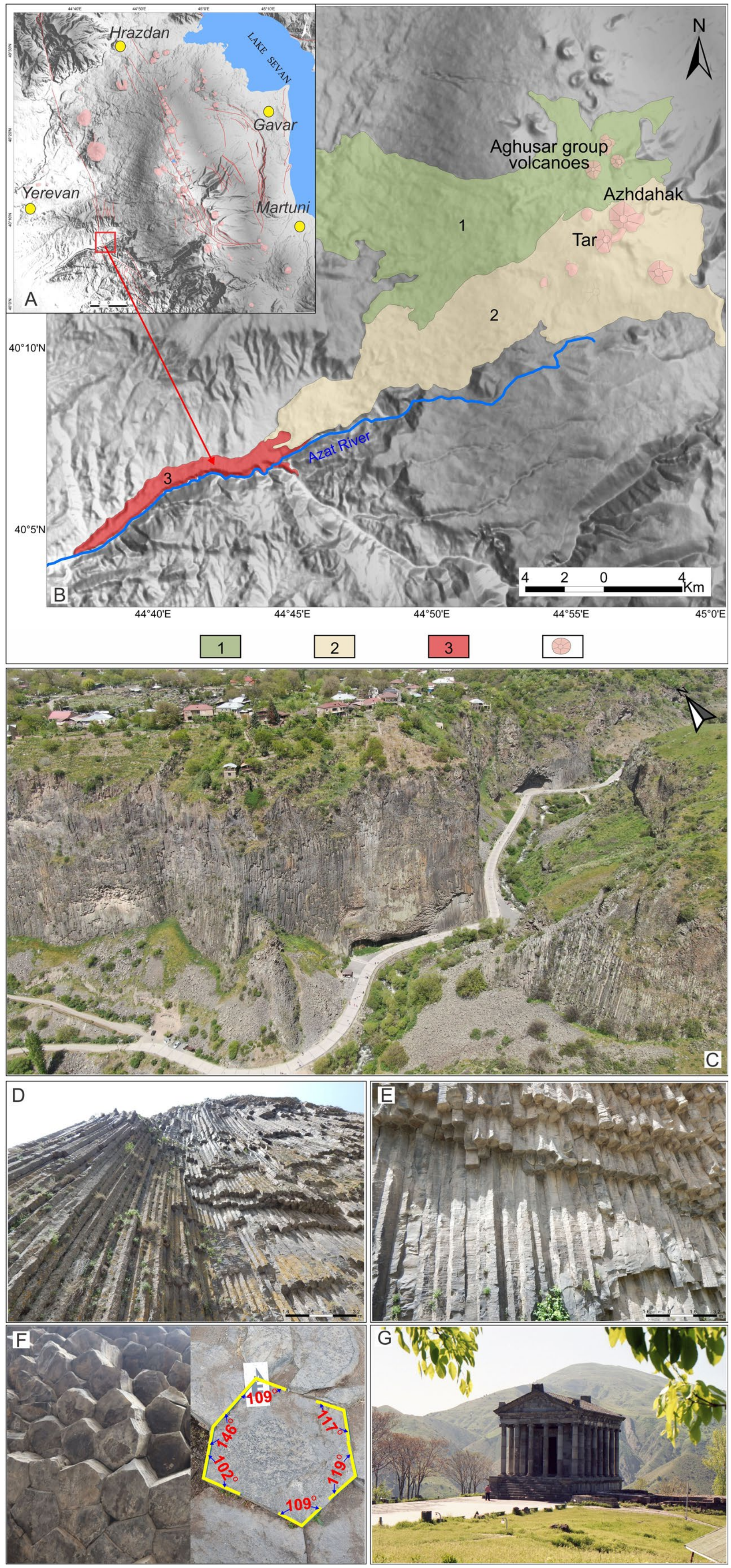


Fig. 6 **A** Schematic map of distribution volcanoes and location of Garni lava flow geosite in the GVU. **B** Stratigraphy schematic map of Garni lava flow (see legend below). **C** Azat River canyon and direction of lava flow (for scale see many homes on the top of flow). **D**, **E** The thickness and structure of columnar joints of Garni lava flow. **F** The hexagonal prisms ranging from 100 to 150 degrees. **G** Garni Hellenistic temple Legend of the stratigraphy schematic map of Garni lava flow: (1) Lava flows of Aghusar group volcanoes. (2) Lava flows of Azhdahak and Tar volcanoes. (3) Garni lava flow in Azat river gorge. (4) Volcano cones

was a summer residence of the kings and the place where their troops were stationed (Russell 1987; Tananyan 2014). The structures of Garni combine elements of Hellenistic and national culture, which evidence ancient influences and the distinct building traditions in Armenia (at that time). The temple of Garni was built by King Tiridates I in the first century AD as a temple dedicated to the god Mithra (Mihr in Armenian), the god of the sun, whose figure stood in the depth of the sanctuary (naos). After Christianity was proclaimed the state religion in Armenia in 301 AD, the temple was neither destroyed nor rebuilt as a church, unlike many other pagan temples, a common practice during the early Christian period. The Historical and Cultural Museum-Reservation of Garni (Armenia) in 2011 by UNESCO was awarded Melina Mercouri International Prize for the Safeguarding and Management of Cultural Landscapes (https://whc.unesco.org/en/culturallandscapesprize/2011/). In its style, the temple – a six-column peripteros standing on a high podium with a two-step base and surrounded by 24 Ionic columns – resembles similar structures in Asia Minor (such as the baths at Sagala and Pergamum), Syria (Baalbek) and Rome. In 1679 AD a Garni earthquake that reached a magnitude of 6.7 devastated the area, including destruction the temple (Guidoboni et al. 2003). The Hellenistic temple of Garni was reconstructed in 1975.

Geosite 4: Voghjaberd Suite (G4)

The Voghjaberd suite has a wide distribution, but its cross-section can be seen in the upper reaches of the Azat River gorge, not far from the Geghard monastery (40.141227 N, 44.819220 E). Voghjaberd volcanoclastic suite and Geghard monastery are located 4.5 km to the east of Goght village in Kotayk Marz. It can be reached by paved roads by all means of transport vehicles, and by walking 10.5 km from Garni geosite (Fig. 7).

Within the GVU, the Upper Eocene volcano-sedimentary strata are unconformably overlain by the Voghjaberd volcaniclastic suite. The age of the Voghjaberd volcaniclastic suite is Upper Miocene-Pliocene and this is supported by both geological and stratigraphic relations as well as K-Ar dating of lavas yielded 3.4–6.7 Ma (Baghdasaryan and Ghukasyan 1985).

Subsequently, the Voghjaberd suite was overlain by Pliocene trachyandesite lavas, with the groundmass dated by K-Ar method to 4.5-5.0 Ma (Karapetyan 1981). The formation of the Voghjaberd volcaniclastic suite, reaching a thickness of up to 500 m (Milanovsky and Koronovsky 1973), may have been associated with the activity of a large stratovolcano and, possibly, caldera formation, since the suite contains thick layers of ignimbrites and felsic pyroclastics, interbedded with thick volcanoclastic layers, the eruptions of which cannot be associated with monogenic volcanism. Subsequently, monogenic volcanism was superimposed on the caldera of the volcano, which is associated with the formation of cinder and lava cones, domes and intense Quaternary volcanism of the GVU.

The Voghjaberd Late Miocene-Early Pliocene volcaniclastic suite is cut through by the Gokht river (tributary of Azat river) canyon and the Geghard monastery.

Geghard Cave Monastery

Geghard is a medieval monastery (40.140425 N; 44.818511 E) partially carved into the tuffs of the Voghjaberd suite. The monastery complex was founded in the 4th century by Gregory the Illuminator on the site of a sacred spring inside a cave. The monastery became famous thanks to the relics that were kept in it for centuries. The most famous of those was the spear that wounded Christ on the Cross, allegedly brought here by the Apostle Thaddeus. Geghard means "spear" in Armenian and hence its current name Geghardavank ("Monastery of the Spear"), first recorded in a document from 1250 (Sahinian et al. 1973). Some of the churches of the monastery complex are completely excavated from the rocks, others are only caves, having both architecturally complex sections with walls and rooms deep inside the rock. The combination, together with numerous carved and free-standing khachkars, presents a unique site and is one of the most visited tourist attractions in Armenia. This place can easily be developed for geotourism purposes.

The impressive high cliffs surrounding the monastery are part of the Azat River Gorge. In 2000, the Monastery of Geghard and the Upper Gokht Valley (tributary of Azat river) were inscribed on the list of UNESCO World Heritage Sites (https://whc.unesco.org/en/list/960/). The monastery can be reached by paved road, by all means of transport, and by walk.

Geosite 5: Azhdahak (G5)

Azhdahak geosite is located (40.227104 N; 44.949233 E) in the central part of the GVU, 13 km SW of the Tshaghkashen village of the Ghegharkunik Marz and 51 km from Yerevan. This geosite includes three volcanoes Azhdahak, Kamurj and Tar that form a monogenetic volcanic system, consisting of several vents (Fig. 8A, C). Azhdahak and Tar volcanoes have beautiful craters filled by lakes, while Kamurj (bridge in Armenian) represents a ridge formed by scoria and lavas connecting Azhdahak and Tar volcanoes. To get an idea of the uniqueness of the geosite, a brief summary of the three volcanoes is provided below:

Azhdahak volcano is the highest peak of the GVU −3597 m and has a diameter of 1600 m, and a relative


A
N
LAKE SEVAN
40°30'N
40°15'N
40°0'N
6 3 0 6Km
44°45'E
45°0'E
45°15'E
Legend
Voghchaberd suite
Volcanic cones
Faults
B
0.6 0 0.6 1.2 m
N
C
16 0 16 32 m
N
D
0.4 0 0.4 0.8 1.2 m
E

Fig. 7 **A** Schematic map of the outcrop and distribution of the Voghjaberd suite and the location of geosites on the GVU. **B** Thickness of the Voghjaberd suite. **C** The boundary of the Voghjaberd suite with lava flows of Lower Pliocene. **D** Geghard Monastery in the lower part of the suite. E - Part of the church in the cave

height from its base is 350 m. The volcano is a cinder cone composed of scoria, lava fragments, volcanic ash, and ballistically discharged pyroclastic materials such as lapilli, twisted, spindle-shaped and ellipsoidal volcanic bombs that can reach up to 80 cm in length. The summit of the volcano contains a crater with a lake 150×110 m (Fig. 8B). The diameter of this crater along the ridge reaches 500 m across and its depth is up to 90 m (SE part). On the eastern slope of Azhdahak, at an altitude of 3450 m, there source of massive flows of blocky lava flows that erupted in E and NE directions. Another source of lava is located on the southern slope of the volcano. The lavas from this vent, flowing mainly to the SE, merge with the flows of the eastern crater of the neighboring Tar volcano.

Kamurj volcano (40.218898 N; 44.944782 E) has height is 3500 m, with a relative height of 200 m above its base (Fig. 8C). The volcano, elongated from northeast to southwest is a ridge connecting Azhdaak and Tar volcanoes. The cone is composed of scoria, lapilli, volcanic bombs. Fragmental blocky lavas flowed from the northeastern part of the cone and were covered by lavas from the Azhdahak and Tar volcanoes. The exposed part of Kamurj volcano's lavas covers an area of 3 km^2.

The ***Tar*** volcano (40.216159 N; 44.935866 E) is located in the central part of the GVU, southwest of Azhdahak volcano, and joins the latter through with Kamurj volcano (Fig. 8C, right side). It is a cinder cone and has 3530.0 m at sea level (with a base diameter of 1100 m and a relative height of 250 m). At the summit, there is a crater with a diameter of 300 m and a depth of up to 115 m. The crater has an outlet in the northwest, formed by the flow of fragmental lavas covering most of the cone from the crater. The cone is composed of scoria, lapilli, pumice, volcanic bombs (up to 50 cm in size), and lava fragments. From its southwest base, a 21 km long lava flow of trachyandesite composition (covering an area of over 50 square kilometers) extends, which, along with various flows, forms an instructive stratigraphic complex.

The age of this group of volcanoes is estimated to be Upper Pleistocene. Composition of lavas corresponds to trachyandesites and by petrographic characteristic contains plagioclase, clinopyroxene, orthopyroxene and olivine phenocrysts.

These lavas have an Upper Pleistocene age (49.9±9.2 ka; $^{40}Ar/^{39}Ar$, groundmass, Meliksetian 2018, covers Upper Pleistocene age Garni basalt-trachyandesite columnar lavas).

The most notable geological features in this geosite are the perfect conical shape and steep flank with a water-filled craterat the summit. Additionally, lava flows extending considerable distances from the base of the cone support the specific collisional type of magma and, in particular its well-preserved eruption characteristics (very hot, alkaline, low volatile and low viscosity nature of the magma; Sugden et al. 2019).

Cinder cones typically have steep slopes, which make them vulnerable to gravitational collapse, especially during seismic activity or heavy rainfall, which can trigger landslides or slope failures and also wind erosion. The geosite can be reached fairly easily by dirt road by off-road car or by walk from Garni, Goght and Tshaghkashen villages, a walking trail goes from the southern part of the volcanic complex towards summits and craters of Azhdahak and Tar.

Despite its relative inaccessibility, the flow of tourists to the Azhdahak geosite is quite large. The road passes through beautiful trails that open up views of an incredible landscape. Numerous prehistoric petroglyphs can be seen on the slopes of Azhdahak. The crater lake of Azhdahak changes its colors several times during the day. There is a seasonal rest house at the foot of Azhdahak.

Geosite 6: Aknalich (G6)

The Aknalich geosite is at 3038 m. at 40.283038 N, 44.919847 E, about 13 km west-southwest of Tsaghkashen village of the Ghegharkunik Marz. Aknalich geosite is part of the proposed geopark in Armenia (Avagyan et al. 2023).

The Aknalich geosite is represented by several cinder cones of Middle-Upper Pleistocene age, including Lchain, Aknalich, Paros, Western Aknotsasar and Eastern Aknotsasar and a large crater lake and represents noteworthy volcanological ad geomorphological landscape. The altitudes of the volcanoes range from 3038 m to 3260 m (Fig. 9A, B). Cinder cones are made up of layers of volcanic and scoria, as well as lava and volcanic pyroclastics (lapilli, bombs, etc.). Many of these monogenetic volcanoes have well-shaped cones and craters. One of the volcanoes, namely Lchain, has an elongated shape and a large (1.1 km in diameter) crater. The Middle Pleistocene Lchain volcano is cut through by the younger Late Pleistocene-Holocene Aknalich volcano. Lake Aknalich is of volcanic origin with an area of 0.45 km^2, located inside the crater of the Lchain volcano. The lake has a depth of 15 m. To get an idea of the shape, structure and features of volcanic cones surrounding the lake, a brief summary is given below:

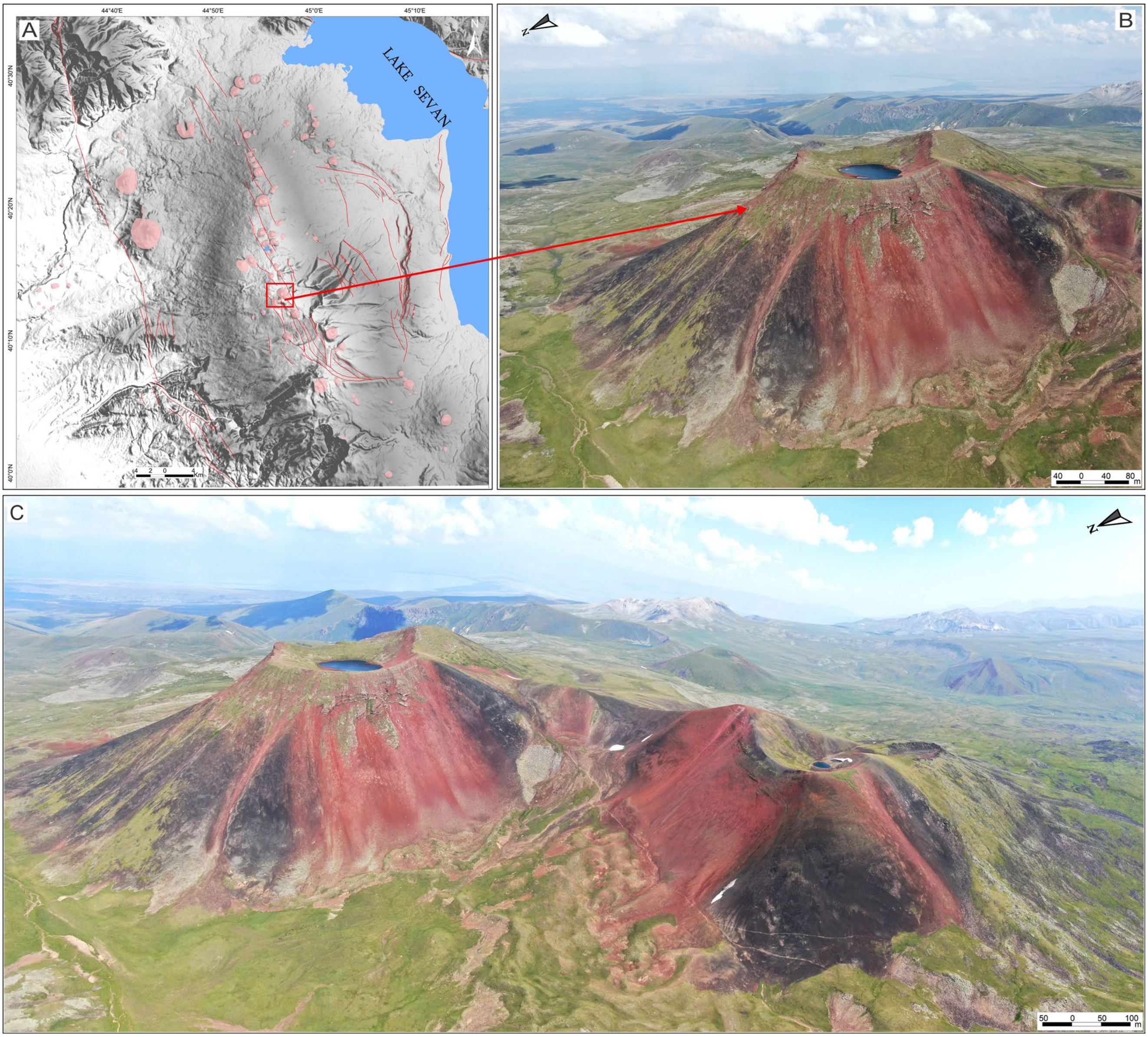


Fig. 8 **A** Schematic map of distribution volcanoes and location of Azhdahak geosite in the GVU. **B** Azhdahak volcano (elev. 3597 m); photo is not vertically exaggerated. **C** Azhdahak volcano (elev. 3397 m, left side), Tar volcano (elev. 3530 m, right side) and Kamurj volcano (elev. 3500 m, middle)

Paros Volcano

The Paros cinder cone (40.290200 N; 44.919798 E) is a well-preserved structure, elongated in the northeast direction, with a base diameter of 1100 m, a relative height of 160 m, and an absolute height of 3190 m (Fig. 9C). At the western part of the summit of the volcano, there is a crater with a lake (200 × 100 m). The crater is elongated in the northeast direction, the diameter at the top reaches up to 450 m, and the depth is up to 90 m. The Paros volcano is composed of scoria, lapilli, ash, and lava fragments, as well as a wide variety of twisted, pear-shaped, axial, and other complex volcanic bombs (up to 2 m long). The volcano is composed of pyroclastic rocks resulting from a Strombolian style mild explosive activity. The composition of the rocks is trachyandesitic. Phenocrysts are represented by plagioclase and clinopyroxene; the groundmass is hyalopilitic and microlitic.

Western Aknotsasar Volcano

Western Aknotsasar volcano (40.292108 N; 44.932219 E) is a cinder cone that is stretched in the southwest to northeast direction (Fig. 9D). The cinder cone has a base diameter of

Fig. 9 **A** Schematic map of the location of geosite, **B** Cinder cones around the Aknalich lake, **C** Paros volcano (elev. 3190 m), **D** West and East Aknotsasar volcanoes (elev. 3265 m and 3258.5 m), **E** Lchain volcano (elev. 3150 m) with crater lake and Aknalich volcano (elev. 2257 m) with small crater, **F** Aghusar volcanoes group (elev. up to 3458 m) near the Aknalich geosite

1000 m, a relative height of 130 m, and an absolute height of 3265 m. At the top of the volcano, there is a funnel-shaped crater with a diameter of 400 m and a depth of 65 m. The cone of the volcano has not been preserved and the southeastern slope, at the intersection with Eastern Aknotsasar, is flattened. Blocky lava flows with a total area of up to 38 km^2 extend in the northeastern direction. The composition of the rocks is basaltic trachyandesite. Phenocrysts are represented by plagioclase, olivine and clinopyroxene; the groundmass is hyalopilitic or microlitic.

Eastern Aknotsasar Volcano

The Eastern Aknotsasar cinder cone is with elevation of 3258.5 m and located at (40.290453 N; 44.938908 E) has a diameter of 800 m, and the relative height of 140 m (Fig. 9D). The absolute height is. At the top, there is a funnel-shaped crater with a diameter of 220 m and a depth of 70 m. The cone is composed of scoria, lapilli, volcanic ash, lemon-shaped scoria bombs (up to 45 cm long), and pieces of lava. Lava flowed out from the base of the volcano and mixed with the lava flows of Western Aknotsasar volcano. The composition of the rocks is basaltic trachyandesite. Phenocrysts are represented by plagioclase, olivine and clinopyroxene; the groundmass is hyalopilitic or microlitic.

Lchain Volcano

The Lchain volcano is a cinder cone (40.279057 N; 44.931506 E) with a base diameter of 1450 m, and a relative height of 120 m. The absolute height is 3150 m (Fig. 9E). The crater has a length of 1000 m and a depth of 120 m and has a large hole in the northwest. Lava erupted from the crater and underneath the base of the volcano. To the northwest of the volcano, there is Lake Akna of volcanic origin with an area of 0.45 km^2, a depth of which is 15 m, a height is 3038 m above sea level, but the level of the lake varies seasonally. It is noteworthy that in the north, the Lchain volcano of the Middle Pleistocene age was intersected by the Aknalich volcano of the Upper Pleistocene-Holocene age. The composition of the rocks is basaltic trachyandesite. Phenocrysts are represented by plagioclase, olivine and clinopyroxene; the groundmass is hyalopilitic or microlitic.

Aknalich Volcano

The well-defined Aknalich cinder cone (40.284735 N; 44.928010 E) has a base diameter of 550 m, a relative height of 50 m, and an absolute height of 3095 m (Fig. 9E). At the top, the funnel-shaped crater of the volcano has a diameter of 150 m and a depth of 20 m. Aknalich consists of scoria, lapilli, ash, and volcanic bombs. The composition of the rocks is basaltic trachyandesite. Phenocrysts are represented by plagioclase, olivine and clinopyroxene; the groundmass is hyalopilitic or microlitic.

From south, the Aknalich geosite is covered by the youngest lava flows of Aghusar group volcanoes (Fig. 9F).

The geosite is formed by several volcanoes with remarkable geological features. Volcanic activity has created unique and beautiful volcanic landscapes such as volcanic cones, lava flows, crater lakes, etc. This landscape provides insight into the volcanic processes that have shaped the landscape over time.

At the same time, this volcanic territory offers unique opportunities for scientific research, especially for excursions of geology students and researchers, which promotes scientific tourism. A notable feature of the monogenetic volcanism in this group of cones is also the cross-cutting of the Middle Pleistocene Lchain volcano by the younger Upper Pleistocene-Holocene Aknalich volcano (Fig. 9E).

Aknalich lake is located at an altitude of 3032 m above sea level. The area is 0.8 km^2, and the depth is 15 m. The lake is fed by snowmelt and spring waters. The lake is surrounded by mountain peaks, which are reflected in the mirror of the lake, making it even more beautiful (Fig. 9F).

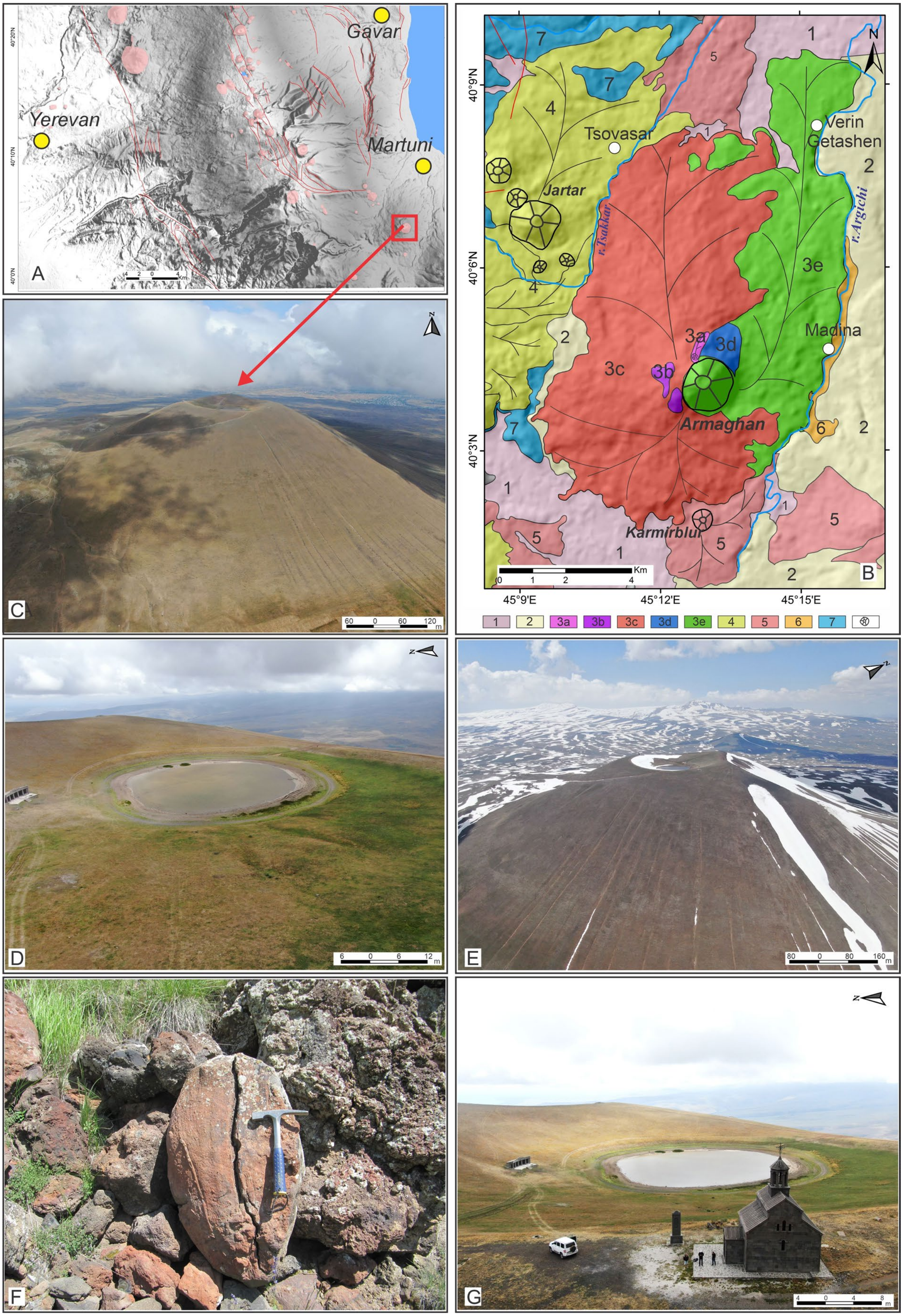
This geosite represents a remarkable opportunity for geotourism development, offering a combination of geological uniqueness, educational value and natural beauty. Its volcanic features, varied landscape and potential for eco-tourism make it a good site for geotourism.

The geosite is an ideal place for tent camping, and tourists can get there on foot, on horseback, or by all-terrain vehicle.

Geosite 7: Armaghan Volcano (G7)

Armaghan volcano is situated (40.068549 N; 45.213938 E) in the southeastern part of the GVU, southwest of Lake Sevan and 3.6 km southwest of the Madina Village of the Ghegharkunik Marz.

The absolute elevation of the Armaghan volcano corresponds to 2829.1 m and represents a well-preserved monogenetic volcano – a large cinder cone, with its base having a diameter of about 2000–2200 m and a relative height of 450 m (Fig. 10C). The crater that has been well preserved on the volcano summit has a diameter of 300 m and a depth of up to 50 m (Fig. 10D). There is a small and shallow (1.5–2 m deep) lake on the crater bottom. On the slopes of the cone, linear valleys (barrancoses) are expressed (Fig. 10E), extending from the top of the cone to the base, formed as a result of the erosive activity of water flows. The structure of the cone involves dense scoria, lapilli, ashes and twisted bombs up to 40 cm in size, which are interbedded with lava flows (Fig. 10F). From the west, high hilly ridges


Gavar
Yerevan
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A
7
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Verin Getashen
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Jartar
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r.Argichi
3e
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2
3a
3d
Madina
3c
3b
Armaghan
7
6
2
1
1
5
Karmirblur
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B
Km
0 1 2 4
40°9'N
40°6'N
40°3'N
45°9'E
45°12'E
45°15'E
1 2 3a 3b 3c 3d 3e 4 5 6 7
C
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Fig. 10 **A** Schematic map of distribution volcanoes and location of Armaghan geosite in the GVU. **B** Geological-volcanological map of Armaghan volcano (see legend below). **C** Armaghan volcano; photo is not vertically exaggerated. **D** Lake in the crater of Armaghan volcano. **E** Traces of the formation of barrancoses on the slopes of the cone because of the erosive activity of water flows. **F** Volcanic bomb. **G** The church on the top of volcano Legend of key geological features used in the map of Armaghan volcano. *Holocene - Upper Pleistocene.* (1) Alluvial, deiuvial, eluvial and proluvial sediments. (2) Trachybasalts, basaltic trachyandesites, trachyandesites; (3) Lava flows of Armaghan Volcano −3a. Secondary crater and its flow; 3b. Lava extrusion; 3c. The upper lavas; 3d. Clastic trail adjoining the base of the cone; 3e. The Lower lavas. *Middle Pleistocene.* (4) Basaltic trachyandesites, trachyandesites. *Lower Pleistocene.* (5) Trachybasalts, basaltic trachyandesites, and trachyandesites. *Lower Pleistocene - Upper Pliocene.* (6) Flood (dolerite) basalt. (7) The Manichar lavas of basaltic trachyandesite and trachyandesite compositions

of blocky lavas lean against the cone. The activity of the Armaghan volcano is classified as Strombolian, and two main phases of the eruption can be distinguished: explosive and effusive. In the explosive phase, a pyroclastic explosive eruption of the Strombolian type occurred, during which scoria and volcanic bombs were ejected, which, as a result of accumulation, formed an oval-shaped cinder cone. Later, in the effusive phase, lava flows of the Armaghan volcano are associated with meridional fissures at the base of the cone in the western part. A side crater with a depth of up to 2–3 m and a diameter of up to 25 m was noted, over the edge of which a flow of blocky lava up to 800 m long flows. The total area covered by block lavas of the Armaghan volcano reaches 95 km^2. The composition of the rocks is trachyandesitic (Fig. 10B). The age of the volcano is Middle–Upper Pleistocene (K-Ar; 0.16 ± 0.03 Ma, Lebedev et al. 2013).

The structure and formations of the Armaghan volcano indicate its uniqueness, showing the stages of formation of the volcano and the features of its development. The volcano summit is also a pilgrimage site and a new Saint John (Saint Hovhannes) church was built on the western side of the volcano summit a few years ago (Fig. 10G). This geosite represents an interesting combination of several values: geological, religious heritage and educational, which makes a great site for geotourism. The combination of the crater lake, church, landscape, and panoramic view provides many opportunities for exploration, education and recreation, increasing the geotourism potential of the region.

The geosite can be reached fairly easy by dirt road by off-road car or by walk from Madina village.

Geosite 8: Gutansar Volcano (G8)

Gutansar volcano is located (40.368219 N; 44.684876 E) in the western part of the GVU, about 3 km S of the Fantan village of the Kotayk Marz. The dome-shaped volcanic building has a rounded plan, slightly elongated in the meridional direction. At the top of the cone, there is a crater funnel elongated in the same direction, open to the south. The diameter of the base is approximately 3000 m, and the relative height is 350–400 m (Fig. 11B). Gutanasar is a rather complex volcanic structure, characterized by bimodality. According to some authors (Karapetian S. 1972; Jrbashyan et al. 2024), the structure of the volcano is dominated by rhyolite - trachydacite lavas, and on the northern and western slopes, predominantly perlites are exposed (Fig. 11C). In the initial stages of activity, volcanic activity was explosive with the formation of rhyolite–obsidian zonal flows (stage 1), followed by outpourings of perlite–pumice rocks of agglomerate structure (stage 2), and finally outpourings of rhyolite–trachydacite lavas (stage 3). Later, due to new volcanic activity in the area, Gutansar, like Hatis, was pierced by volcanoes of the main composition - lavas, and scorias. The latter, like a black wall, are exposed on the northeastern slopes of Gutansar (Fig. 11F). Among such volcanoes are Nor Gutansar, Tsakhkot, Poqr Tsakhkot, Menak, Poqr Menak.

Rhyolite-obsidian zonal flow (stage 1) with a thickness of 70–80 m from bottom to top is represented by lower rhyolite, then transitional rhyolite-obsidian, and at the highest – obsidian (Fig. 11E). The obsidian zone sometimes forms steeply falling (60-80^{o}) cornices, with a height of 4–6 m to 10–15 m. They are represented mainly by black and brown banded varieties, sometimes turning into very original breccia varieties.

Perlite–pumice agglomerate material (stage 2) starts from the slopes and foot and is located around the volcano. In the eastern and northern directions, its length does not exceed 1–1.5 km, and in the western and southwestern directions, it reaches 6–7 km. The volume of erupted material is about 1-1.5 km^3.

Rhyolite–trachydacite lavas (stage 3) also form well-defined flows extending in southern directions (Fig. 11D). These rocks are characterized by clearly defined fluidity, often forming kinks, flexure-like “plications” and corrugations.

The Gutansar volcano is a very interesting and unique structure, where it is possible to see the stages of its development, expressed by different types of formations. The spread of beautiful obsidian is particularly noteworthy. The volcano also has a bimodal nature, and the youngest manifestations of volcanic activity are associated with basic composition of lava eruptions, the height of which is about 3 m. According to Meliksetian (2018), the lava flow of the Nor Gutansar volcano is 0.31 ± 0.02 Ma ($^{40}Ar/^{39}Ar$).

Gutansar volcano can be reached by an asphalt road. The crater and “Black Scoria Wall” can be reached by dirt road as well as by foot. The latter is very popular among tourists, which is a good opportunity to develop geotourism in this area.

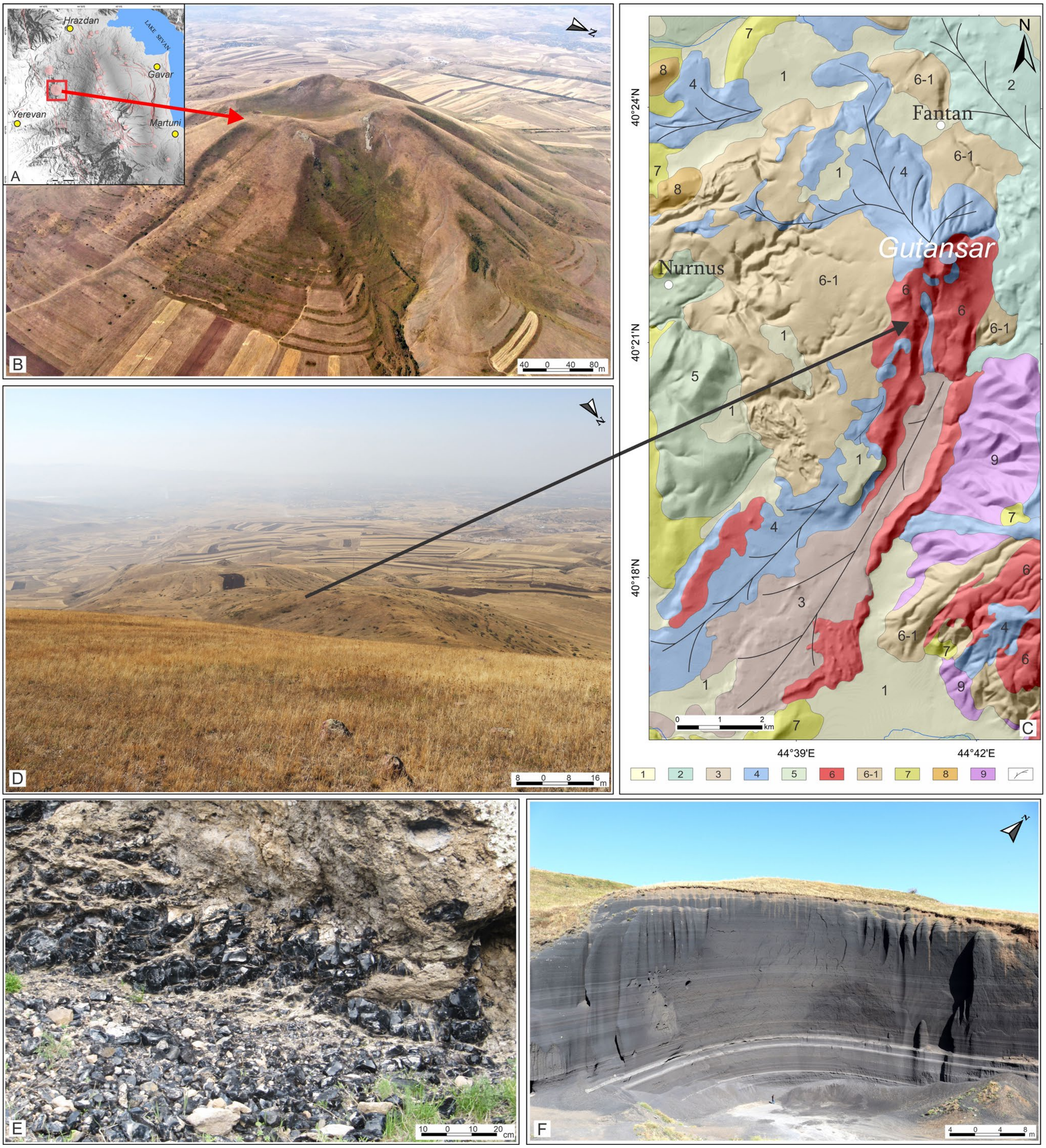


Fig. 11 **A** Schematic map of distribution volcanoes and location of Gutansar geosite in the GVU. **B** Gutansar volcano. **C** Geological-volcanological map of Gutansar volcano (see legend below). **D** Rhyolite–trachydacite lava flow extending in southern directions. **E** Massive thickness of obsidian in the footwells of Gutaansar volcano. **F** Homogeneous thickness of black volcanic scoria, "black wall" Legend of the map of the Gutansar volcano. *Holocene - Upper Pleistocene.* (1) Alluvial, deluvial, proluvial deposits; (2) Basaltic trachyandesite lavas of the watershed part of the Gegham upland. *Upper Pleistocene.* (3) Basaltic trachyandesites and trachyandesites. *Middle Pleistocene.* (4) Basaltic trachyandesites; (5) Trachybasalts, basaltic trachyandesites, trachyandesites. *Middle-Lower Pleistocene.* (6) Trachydacites and rhyolites (obsidians) of the Gutansar and other volcanoes; 6−1. Perlite-pumice and agglomerate lavas with obsidians. *Lower Pleistocene - Upper Pliocene.* (7) Doleritic trachybasalts. *Lower Pliocene.* (8) Rhyolitic, trachydacite lavas of the extrusive dome-shaped volcanoes Gyumush and Avazan: (9) Basaltic trachyandesites, trachyandesites, trachytes (trachyandesite formation). Direction of lava flows

The geosite can be reached fairly easy by dirt road by off-road car or by walk from Fantan village.

Geosite 9: Lchasar (G9)

The Lchasar geosite is located (40.492816 N; 44.876970 E) in the northern part of the GVU, approximately 1 km southwest of the village of Lchashen, Gegharquniq Marz. The Lchasar geosite is represented by three volcanoes of Middle Pleistocene age: Small Lchasar, Big Lchasar, Eastern Lchasar, and is located at an altitude of 1950–2300 m above sea level (Fig. 12). These volcanoes form an arc-shaped chain, convexly facing northwest. Monogenic volcanoes have beautifully shaped craters (Fig. 12C). Volcanic cones are composed of scoria, lapilli, as well as twisted, spindle-shaped bombs and lava fragments. Lava flows of a blocky structure emerge from under the base of the cones, which dammed the northwestern part of Lake Sevan. In the eastern wing of the Eastern Lchasar volcano, a large thickness of volcanic ash with a thickness of about 20 m is exposed (Fig. 12D). According to Jrbashyan et al. (2024), it is composed mainly of lapilli and ash. Completely unchanged loose material is composed of hundreds of layers 2–35 cm thick, each of them characterized by normal grading. All this material erupted in three phases. This geosite is very educational and attractive both from a volcanological point of view and for the development of geotourism. Geosite is an ideal place for tourism development, which can be reached on foot or by any means of transport or by walk from Lchashen village (Fig. 13).

Thick layers of scoria at the Gutansar and Lchasar geosites are characterized by signs of Strombolian-type eruptions. According to Houghton and Gonnermann (2008), the activity of such eruptions consists of long sequences of impulsive short-term explosions lasting several tens of seconds and is accompanied by fragmentation of basaltic magma.

In this geosite, there are also non-homogeneous thicknesses of volcanic ash (Fig. 12E), which indicates that the volcanic activity took place in different stages with a certain change in the intensity of eruption.

Discussion

Assessment of Scientific Values (SV)

Armenia has significant Quaternary volcanic activity linked to continental collision regional geodynamic setting. One of the types of volcanism is distributed monogenetic activity, manifested by strombolian eruptions of hundreds of vents. Gegham volcanic upland with unique volcanic landscapes and crater lakes is coupled with important archaeological and historical heritage. With the publications of Avagyan et al. (2021, 2023), this study is the first attempt to describe volcanic geoheritage aiming to promote geotourism and geoeducation.

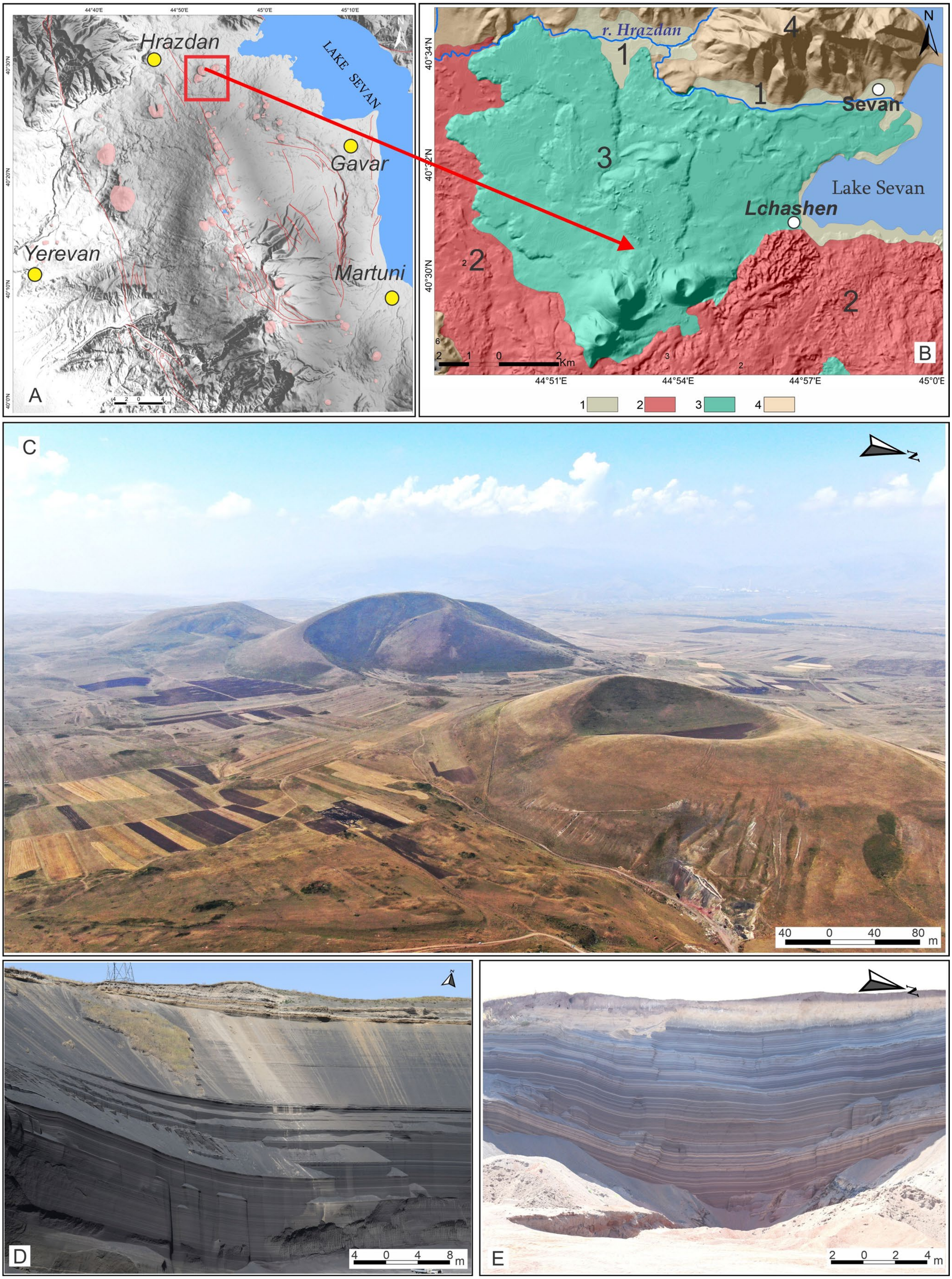
Fig. 12 **A** Schematic map of distribution volcanoes and location of Lchasar geosite in the GVU. **B** Geological-volcanological map of Lchasar group volcanos (see legend below). **C** Lchasar group volcanos. **D** Homogeneous thickness of black volcanic scoria. **E** Inhomogeneous thickness of the volcanic ash layer Legend of the Geological-volcanological map of Lchasar group volcanos. *Holocene - Upper Pleistocene.* (1) Alluvial and colluvial sediments. (2) Young lava flows from the volcanoes of the watershed of the Gegham upland. *Middle Pleistocene.* (3) Basaltic trachyandesites of Lchasar group volcanos. *Pre - Upper Miocene.* 6. Volcano-sedimentary rocks: sandstones, tuff breccia, limestones, andesite lava flows

SV assessment (Table 2) shows that 5 of the selected geosites (G1, G2, G3, G6 and G8) have a high scientific value (>300) and 4 have a medium scientific value (G4, G5, G7 and G9), which confirms that the GVU has valuable volcanological features and new opportunities for study. Such high scientific values can be of interest to researchers to understand the history of the upland, formation and geological development, and tectonic events. One of the important features for scientific values is the well-preserved nature of the volcanoes, lava flows and thick tephra layers. In all this, Garni columnar jointed lava flows are a unique scientific value not only for Armenia, but also in the region.

At the same time, all geosite will create a very good opportunity for the development of geotourism potential.

Assessment of Tourism Value (potential Tourism use)

The results of a quantitative assessment of tourism value (Table 3) show that geosites G2, G3 and G4 are close and have high tourism potential due to the uniqueness of the object, accessibility, safety, logistics, association with other values and attractiveness. These features make it possible to organize tourist routes, during which tourists can enjoy beautiful scenery and visit religious places around those geosites. The remaining 6 geosites (G1, G5, G6, G7, G8 and G9) have moderate potential for geotourism in terms of accessibility, logistics and association with other values. There is still work to be done to develop geotourism at these sites, perhaps primarily in terms of accessibility and safety. The development of geotourism in all mentioned geositess can provide a significant flow of tourism, which will have a certain positive impact on the socio-economic condition of residents of nearby areas, further ensuring the sustainable development of geotourism.


A
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Gavar
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2 1 0 2 Km
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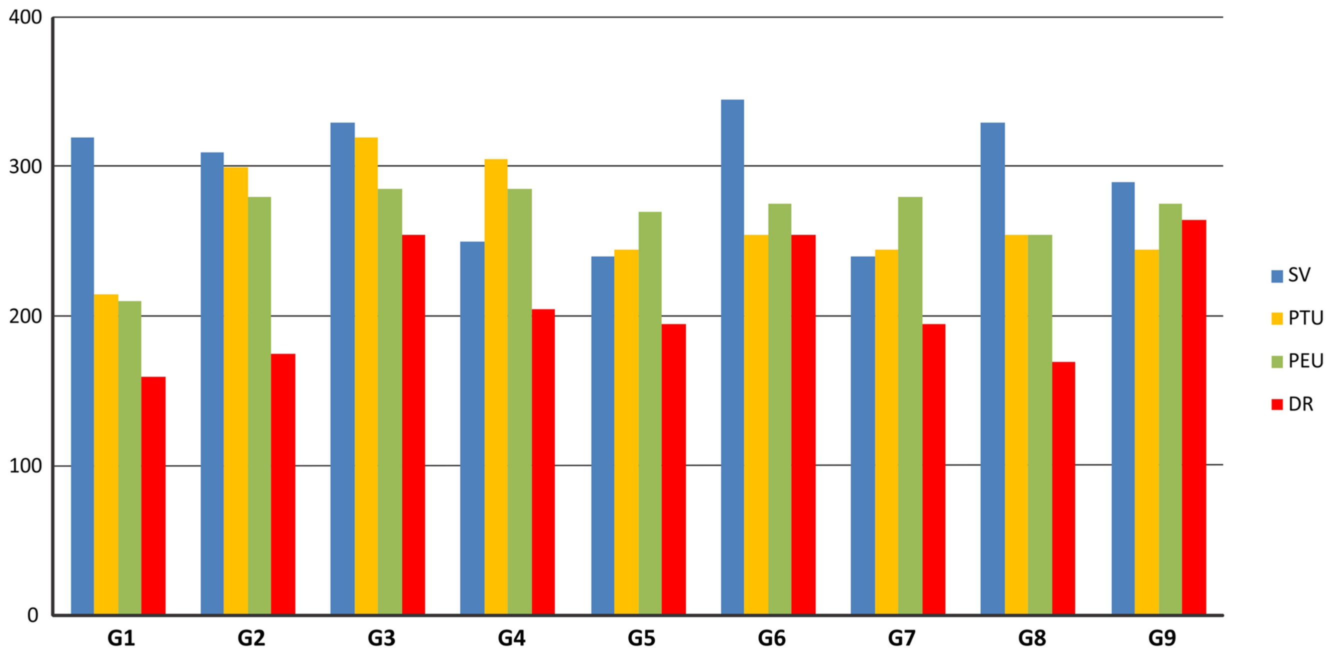

Fig. 13 Histogram of the quantitative assessment of each geosites of GVU by scientific value (SV), potential tourist use (PTU), potential educational use (PEU), and degradation risk (DR)

Assessment of Educational Value (potential Educational use)

The results of the assessment of potential educational use (Table 4) for all geosites have a medium value, which indicates that there is still some potential for the educational use of geosites. As sites of geological and volcanological significance, they provide the opportunity for educational field trips and research. The medium value indicates that although these opportunities exist and may be beneficial, they may not be universally recognized or fully utilized, possibly due to factors such as accessibility, availability of nearby residences, didactic potential, or uniqueness priorities.

Degradation Risk Assessment

The degradation risk assessment (Table 5) showed that 4 of the geosites (G1, G2, G5, and G7) have a low degradation risk value, and 3 (G3, G4, and G6) have a medium degradation risk value. The low values are mainly due to the inaccessibility of the site and the absence of nearby settlements, although these geosites are highly prone to natural erosion factors due to their geological structure. The medium risk of degradation, in this case, is due mainly to the disruption of the structure and aesthetics of geosites as a result of human activity.

Comparing the quantitative assessment of the values of all geosites (Fig. 11), it is noticeable that the scientific value of geosites G1, G2, G3, G6, G8 and G9 is higher compared to other values, and also that geosites G4, G5 and G7 are inferior in value to tourism and educational use. But in terms of tourism significance, only three geosites (G2, G3, G4) have high values, and educational ones - everything is in between. Geosites G3, G6 and G9 have the highest degradation risk. These data reflect that each geosite, according to various assessments, needs to be developed and promoted to the public through press, advertising, television, phone applications and other methods, always mentioning the risks of degradation and the need to take measures to reduce them. For example, in G6, potential tourism use and degradation risk have the same weight.

Conclusion

The GVU is partly the area of the planned first Armenian geopark (research project funded by the Government of Armneia, see Avagyan et al. 2021, 2023 for more detail) and the geosites identified in it area of great importance for the development and presentation of their significance. The results of the evaluation of geosites using Brilha's method (2016) prove that geosites identified in the Gegham upland have scientific, educational, and touristic potential. Some geosites, combined with religious and historical-cultural values, reflect their importance in educational development. Selected geosites can be important geotourism sites in the future, creating a complex environment for recreation, education and training.

Table 2 Assessment of the scientific value (SV) of the selected geosites in GVU

Scientific value	Weight%	G1		G2		G3		G4		G5		G6		G7		G8		G9	
		point	total	point	total	point	total	point	total	point	total	point	total	point	total	point	total	point	total
Representativeness	30	4	320	4	310	4	330	2	250	2	240	4	345	2	240	4	330	4	290
Key locality	20	2		2		2		2		2		2		2		2		2	
Scientific knowledge	5	4		4		2		2		4		4		4		4		2	
Integrity	15	4		2		4		4		4		4		4		4		4	
Geological diversity	5	2		4		4		2		1		1		1		4		2	
Rarity	15	2		4		4		2		1		4		1		2		2	
Use limitations	10	4		2		2		4		4		4		4		4		2	

Garni hellenistic temple, Azat River gorge and Geghard monastery are visited by a large number of tourists who have the opportunity to get information about the cultural/religious heritage. Due to the large tourist flow, it will be easy to present the geological heritage in those locations: the columnar separations, their formation features (G3), the volumes and distribution of the Voghjaberd thickness formations (G4) and contribute to the development of geotourism. These geosites attract local and foreign international visitors due to their high tourism potential, accessibility, and lack of barriers and restrictions on use.

Unlike the two geosites mentioned above, the Hatis (G2), Armaghan (G7) and Gutansar (G8) geosites do not have a large international tourist flow, but local tourists visit these sites simply for mountaineering or pilgrimage purposes, as well as a nice landscape. The Hatis and Gutansar Geosites, with its bimodal feature, and the Armaghan volcano, with its crater lake, are classic volcanic structures that can serve for scientific, educational, and geotourism purposes. Geghasar (G1), Azhdahak (G5) and Aknalich (G6) geosites are located in the watershed area of the plateau, they are difficult from the point of view of accessibility, so the flow of tourists is not large, but with their landscapes, structure, layering of volcanic formations, with great scientific and educational values, they have the potential for the development of geotourism especially on May to September.

It is necessary to separate geosites with clear boundaries, subsequently placing signs with geological explanations in several languages, drawing up and building tourist routes, creating safe approach roads and trails to these geosites.

Geosite Lchasar (G9) is also a great place for geotourism and education. There is a classic construction of volcanic cones and the exposure of tens of meters of scoria formations like a Strombolian type eruption. It is accessible in terms of logistics, but there is scoria mining going on there.

Along with all this, the protection of designated areas is very important, such as geosite management, improvement of tourism infrastructure, security conditions, prevention of illegal mining.

According to (Sobhani et al. 2022), in line with other studies, in the development of tourism, from the point of view of environmental, socio-cultural and economic dimensions, local residents have a crucial role. However, the development of tourism should not lead to the distortion of geosites and the natural environment.

Table 3 Assessment of the potential tourism use (PTU) of the selected geosites in GVU

Potential Touristic Use	Weight%	G1		G2		G3		G4		G5		G6		G7		G8		G9	
		point	total	point	total	point	total	point	total	point	total	point	total	point	total	point	total	point	total
Vulnerability	10	3	215	3	300	1	320	4	305	3	245	3	255	3	245	2	255	2	245
Accessibility	10	1		1		4		4		1		1		1		2		2	
Use limitations	5	4		4		2		1		4		4		4		4		2	
Safety	10	1		4		4		4		2		2		3		2		2	
Logistics	5	3		4		4		4		3		3		3		4		4	
Density of population	5	1		1		1		1		1		1		1		1		1	
Association with other values	5	1		4		4		4		1		1		3		4		4	
Scenery	15	2		4		4		2		4		4		2		2		1	
Uniqueness	10	3		3		4		3		1		2		1		4		3	
Observation conditions	5	4		4		4		4		4		4		4		4		4	
Interpretative potential	10	3		2		3		3		4		4		4		2		4	
Economic level	5	1		1		1		1		1		1		1		1		1	
Proximity of recreational areas	5	1		4		4		4		1		1		3		3		4	

Table 4 Assessment of the potential educational use (PEU) of the selected geosites in GVU

Potential Touristic Use	Weight%	G1		G2		G3		G4		G5		G6		G7		G8		G9	
		point	total	point	total	point	total	point	total	point	total	point	total	point	total	point	total	point	total
Vulnerability	10	3	210	3	280	1	285	4	285	3	270	3	275	3	280	2	255	2	275
Accessibility	10	1		1		4		4		1		1		1		2		2	
Use limitations	5	4		4		2		1		4		4		4		4		2	
Safety	10	1		4		4		4		2		2		3		2		2	
Logistics	5	3		4		4		4		3		3		3		4		4	
Density of population	5	1		1		1		1		1		1		1		1		1	
Association with other values	5	1		4		4		4		1		1		3		4		4	
Scenery	5	2		4		4		2		4		4		2		2		1	
Uniqueness	5	3		3		4		3		1		2		1		4		3	
Observation conditions	10	4		4		4		4		4		4		4		4		4	
Didactic potential	20	1		1		1		1		4		4		4		1		4	
Geological diversity	10	3		4		4		3		2		2		2		4		2	

Table 5 Assessment of the degradation risk (DR) of the selected geosites in GVU

Degradation risk	Weight%	G1		G2		G3		G4		G5		G6		G7		G8		G9	
		point	total	point	total	point	total	point	total	point	total	point	total	point	total	point	total	point	total
Deterioration of geological elements	35	1	160	2	195	3	255	1	205	2	195	2	255	2	195	2	170	3	265
Proximity to areas/activities with potential to cause degradation	20	1		4		1		1		1		4		1		1		4	
Legal protection	20	4		1		3		4		4		4		4		2		2	
Accessibility	15	1		1		4		4		1		1		1		2		2	
Density of population	10	1		1		1		1		1		1		1		1		1	

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Declarations

Competing Interest The authors confirm that they have no known financial interests or personal relationships that could have influenced the work presented in this paper.

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