



The Potential for a Geohazard-Related Geopark in Armenia

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Abstract

The territory of the Republic of Armenia (RA) stands out in its complex geological structure and diversity of formations due to its complex geodynamic history and the country being located in the axial part of the Arabian and Eurasian continental collision zone. The selected geohazard-related geosites of regional and international interest allow us to propose the creation of a geopark, focused on geohazards. The Armenian geohazard-related geopark will encompass 26 geosites with various geological hazards concerning active faults and surface ruptures, recent volcanism and related lava flows, stratigraphic evidence of mass extinction events, saturated with carbon dioxide subaquatic gas emissions related to buried active fault segment and a borehole of a pulsating water fountain, coastal transgression and regression of various intervals from several thousand to about three hundred million years, active geodynamic processes and related ophiolite obduction, earthquake-related active slope processes, causing destruction and deformation of historical monuments, among others. Some geosites are exceptionally rich in archaeological monuments affected by geological phenomena. From the perspective angle, the results of this study will benefit management of the land environment, historical and cultural heritage, raising awareness of natural hazards and increasing population resilience. The study's results can have wide-ranging implications, including improved geoheritage education, development of conservation ethics, better land management practices, enhanced understanding of historical and cultural heritage, increased awareness of natural hazards, and the promotion of sustainable development through the proposed Armenian Geopark.

Keywords Geohazard-related geopark · Geosites · Geological heritage · Geotourism · Armenian Highland

Introduction

The objective of this paper is to highlight the potential of the specialized geohazard-related geopark in the Republic of Armenia. It is expected that the establishment of a geopark in Armenia would essentially promote geoconservation efforts, improving the management of protected areas and spreading Dynamic Earth Science knowledge and education across Armenia and beyond it.

In general, the natural major event probability reduction is nearly impossible; however, one of the risk reduction factors can be educating the population about geological

hazards and providing effective communication between science and local and central authorities. Geoparks can serve as one of the informative and educational centers for learning the dynamic history of the Earth. There are examples of such geoparks worldwide. Many of Japan's geoparks, like the Shirataki Geopark, focus on geological features related to earthquakes or active volcanoes events (e.g., Nakada 2013). The Katla UNESCO Geopark shows the wonderland of active volcanism in Iceland and related hazards (e.g., Oppenheimer 2011). The Qingchuan Geopark in Sichuan Province of China is an example of an earthquake relic geopark (e.g., Wang and Tian 2014; Yin et al. 2010).

Knowledge of Earth Dynamic Geology and geological hazards is important for all people living in areas prone to geological hazards including the territory of the Republic of Armenia. The tectonically and volcanically active territory of Armenia, located in the Arabia-Eurasia continent–continent collision zone, is characterized by a complex geological

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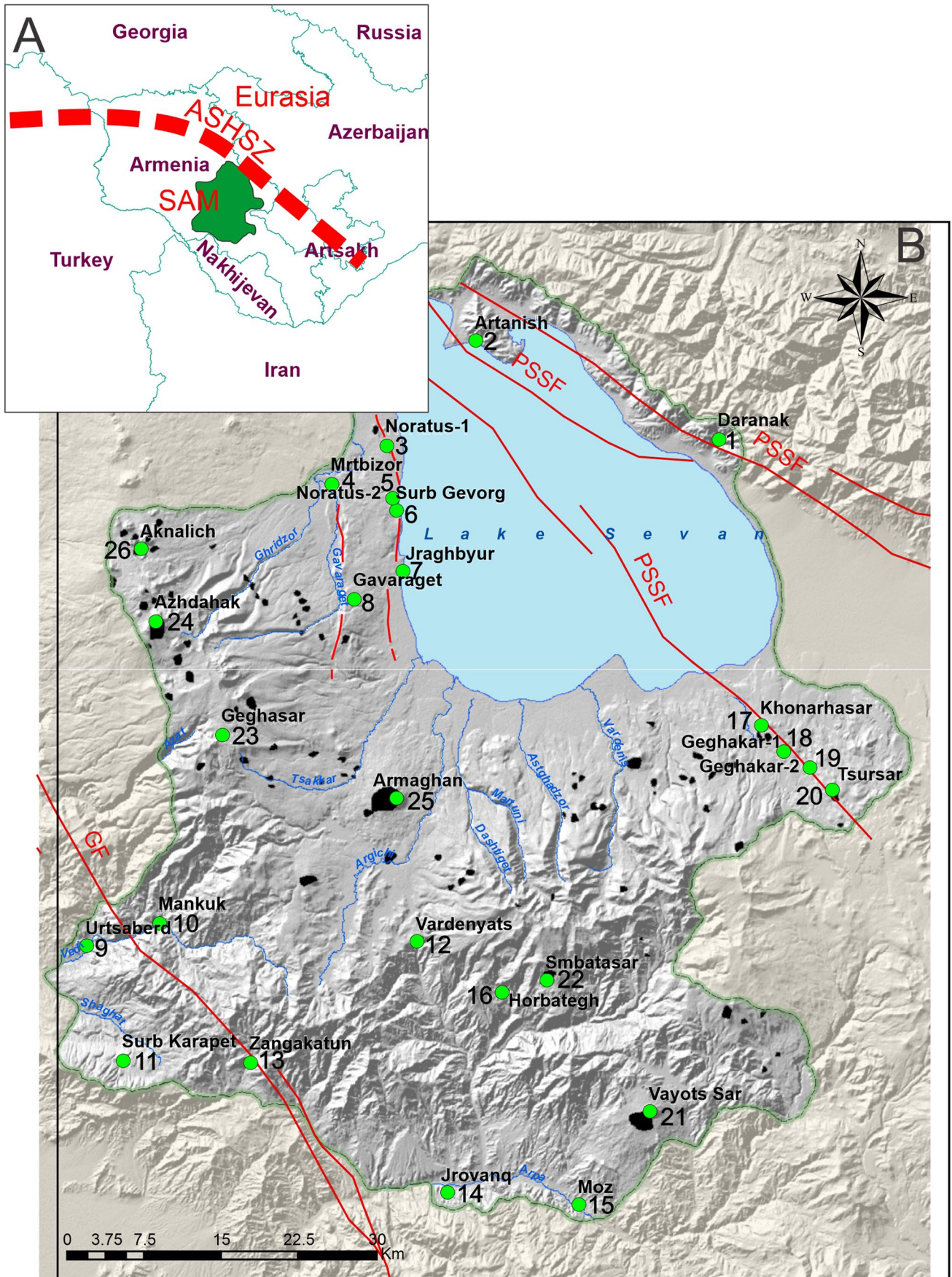


Fig. 1 **A** Schematic map showing the location of Armenia, the territory of the Geopark in green color. ASHSZ—Amasia-Sevan-Hakari suture zone, SAM—South Armenian Microcontinent. **B** Territory of the first Armenian Geopark on the landscape. Green circles indicate geosites, black polygons indicate volcanoes. PSSF—Pambak-Sevan-Sunik fault, GF—Garni fault

history and presence of a mosaic of different geological blocks and terranes, for instance, continental blocks, ophiolites, and arcs merged together by long-lasting convergent plate geodynamics, the latter manifested by various geological hazards.

Having analyzed the rich geological heritage, as well as the international experience of geoparks, the authors propose to establish a geopark of specialized geological hazards. The Armenian one will include 26 geosites of various geological hazards in a relatively limited area (active faults and surface ruptures, recent volcanism and related hydrothermalism, subaquatic gas emission related to buried active fault segment, stratigraphic evidences of mass extinction events, coastal transgression and regression, etc.). Several geosites will certainly have regional and international value. In addition, the development of geotourism, combined with historical, archaeological, cultural components, will make the first geopark of Armenia a place of high international interest.

Geological Setting

The territory of the Republic of Armenia is part of the Alpine-Himalayan Mountain belt, distinguished by a variety of geological formations and complex tectonic structures. Throughout its long geological history, it has been subject to various geodynamic processes; the manifestations of which are presented in various geological formations and structures (Fig. 1A). The structural setting of the NW–SE trending Lesser Caucasus orogenic belt (partially corresponding to the territory of RA) has been controlled by the northward (as a dominant view) subduction of Neotethys oceanic crust beneath the Eurasian margin during Mesozoic times. The collision of the Gondwana-derived South Armenian Microplate (SAM) and the active southern Eurasian margin followed from the Late Cretaceous (e.g., Hässig et al. 2013; Sosson et al. 2016). Intense shortening of the area occurred after another continental collisional event further south: the collision of the Arabian Plate with the southern margin of the SAM, which was finally accreted to the Eurasian margin (Fig. 1A) during Late Eocene–Early Oligocene (e.g., Sosson et al. 2010). Due to this later collision, the ASHSZ (Amasia-Sevan-Hakari ophiolite suture zone) (Galoyan and Melkonyan 2011) was reactivated by a zone of major thrusts and strike-slip faults called Pambak-Sevan-Sunik fault (PSSF, Avagyan et al. 2005). Generally, the studied

region is enclosed between mainly rigid plates (i.e., Arabia and Eurasia), escaping secondary blocks or microplates (Iran and Taurides–Anatolides), and the Armenian Highland in the middle (e.g., Sosson et al. 2010; Avagyan et al. 2010; 2017; Hässig et al. 2016).

A series of sedimentary basins (including the recent Sevan one) is developed during the collision whose axes are parallel to the uplifting Greater and Lesser Caucasus Mountain belts (e.g., Phillip et al. 1989). Sedimentary sequences have been preserved, serving as evidence of several mass extinction events that occurred in the Late Devonian (375–360 Ma), in the Permian–Triassic (~252 Ma that was the largest known extinction in the history of the Earth), in the Paleocene-Eocene (thermal maximum, 56 Ma), and in the Eocene–Oligocene boundary (abrupt cooling 33.9 Ma).

The analyses of the structural setting demonstrate their formation due to regional N-S shortening since Late Cretaceous. Related compression continues to control the tectonic regime at the present time (e.g., Avagyan et al. 2018).

One of the main geological characteristics of the Armenian Highland and the territory of RA in it is the presence of a dense active fault network of various strikes (e.g., Jackson & McKenzie 1984; Rebai et al. 1993; Philip et al. 2001; Trifonov et al. 2002). Various coeval kinematic types of neotectonic major faults are present that comprise NE trending sinistral strike-slip faults, NW trending dextral strike-slip faults, east-trending thrusts, and north-trending normal faults (Philip et al. 1989; Karakhyanian et al. 2004; Avagyan et al. 2005, 2010; Karakhyanian et al. 2013, 2017a). The fault activity in the Armenian Highland and surroundings is indicated by the numerous evidences of historical seismicity (old cities and capitals of historical Armenia such as Yerevan, Dvin, Ani, and actual capital Yerevan were repeatedly ruined by strong earthquakes) and instrumental damaging earthquakes occurred in the region (e.g., Chaldiran (1976, $M=7.1$), Norman (1983, $M=7.1$), Spitak (1988, $M=6.9$), Racha (1991, $M=7.1$), and Van (2011, $M=7.2$)).

In Armenia, magmatic activity has been manifested from the Early-Middle Jurassic to date. Jurassic to Late Cretaceous volcanism was mostly arc type caused by Tethyan subduction (Adamia et al. 1981; Innocenti et al. 1982; Philip et al. 1989; Galoyan et al. 2018). The products of later magmatism (Eocene to Quaternary) incorporated into the regional Paleogene “andesitic” belt (60–27 Ma), the Late Oligocene–Early Miocene magmatism (20–15 Ma), and the Late Miocene–Quaternary volcanic belt (6–0 Ma). It is noteworthy that Armenia represents one of the densest clusters of volcanoes on Earth: there are 516 volcanoes over the area of ~30,000 km² (e.g., Innocenti et al. 1982; Karapetian et al. 2001; Karakhyanian et al. 2002; Sugden et al. 2021; Meliksetian et al. 2021). Recent volcanism in the territory of RA is presented in Sunik, Vardenis, and Gegham volcanic highlands, Aragats stratovolcano, and Javakhq (Javakheti) volcanic ridge (Karakhanian

et al. 2002; Avagyan et al. 2003; Meliksetian 2013; Gevorgyan et al. 2018). Most of the Quaternary volcanic monogenetic centers form clusters, showing space distribution relative regularity in accordance with the general N-S compression axes. The majority of the clusters of monogenetic volcanic centers demonstrate NW–SE alignment (Avagyan et al. 2005). Some of the volcanoes in Armenia are very young and erupted a few thousand years ago. Also, in total about 200 thermal and mineral springs exist in Armenia and part is associated with young volcanism and active faults (Fig. 1B).

The mountainous relief, climatic and seismic factors have strongly contributed to slope-failure potential in the territory of RA. More than 3500 mapped landslides affected about 4% of the territory of RA (e.g., Matossian et al. 2020).

The aforementioned, and sometimes interacting, natural phenomena lead to the fact that the relatively limited territory of RA is subject to various geological hazards.

To develop the geopark, spectacular geological monuments (geosites) of high scientific, educational, intellectual, and aesthetic-touristic value have been selected using international, as well as local experience of the geosite criteria.

A detailed literature review and preliminary fieldwork have been carried out in all the geosites before their selection. Initially, the existing lists of natural and geological monuments were analyzed including the list of the Republic of Armenia Natural Monuments (decree of the Government of RA-2013, <https://ace.aua.am/hy/gis-and-remote-sensing/maps/natural-monuments/>).

Areas proposed for inclusion in the geopark are situated mainly in Gegharkunik and Vayots Dzor provinces of the RA. However, in the course of work, small neighboring parts from Ararat and Kotayk provinces have been incorporated as well to include a few more objects of regional and international significance. Analyzing the rich geological heritage of the country and the international experience, we have proposed to create a geohazard-specialized geopark. The proposed Armenian Geopark will be distinguished by its outstanding geosites of various geological hazards (active faults and related surface ruptures and liquefactions, recent volcanism and volcanic landforms, stratigraphic records of mass extinction events, subaquatic gas emissions, identifying burred segments of active fault and boreholes of pulsating water fountains, transgression and regression in the coastal zones, active geodynamic processes and related ophiolite obductions of the geological past, slope active processes, etc.) in a relatively limited area.

Materials and Methods

The following methodological scheme was implemented for the selection of geosites: (a) initial assessment, (b) geosite selection, (c) evaluation and documentation, (d) involvement

of cultural, historical-architectural, and archaeological monuments, and (e) estimation of the geosite accessibility and safety. A large number of existing publications, reports, and communications have been cross-analyzed. The local and international experience of legislation is considered and mentioned in the “Introduction.” For additional information, the classic approaches of different domains of the geology have been used in the field. Landsat/Copernicus, Digital Globe, Google Earth satellite, and various aerial images have been used for remote sensing.

Drones have been widely used to create 3D images of terrain and evaluate the sites. The aerial photographs used in the paper are newly made and published for the first time. An extended GIS database was developed to summarize all existing geological data related to studied geosites.

The geological phenomena that are active today, with a correlation of different hazards and triggering processes, are presented. These geosites will include processes which occurred during the early stage of the geological history of the Lesser Caucasus evidencing active geodynamic processes with a combination of catastrophic events that have affected the geological formations up to 360 Ma old. The list of geosites will feature cultural, historical-architectural, and archaeological monuments, which often have a geological context or are located on the territory in the vicinity of geosites. These circumstances will convey additional significance to the first Armenian Geopark making it more recognizable.

Geosite Selection Criteria, Classification, and Passportization

Geosite selection and management might be based on the conservation ethic by developing educational programs through interpretation, understanding, appreciation, and protection (Tormey et al. 2022). The protection and conservation strategies of valuable geoheritage include built environment and remains of archaeological objects (e.g., Gizzi et al. 2019). A case study for geosite criteria and environmental and social issues is the Mexico City geosite in an active continental volcanic arc (Guilbaud et al. 2021). These geosites include valuable objects addressing issues such as nature preservation, environmental sustainability, social inequalities, and natural hazards. All the abovementioned aspects concerning conservation ethic through the complex education, involvement of built environment that have geological context, and the social issue conducting to sustainable development are considered during the selection of Armenian geosites.

Geological heritage of Armenia includes a number of key small and large geosites. Some of them represent landscapes associated with geological hazards. Standards that include

internationally recognized criteria, described in IUCN (International Union for Conservation of Nature) Protected Areas Category or in Operational Guidelines for the Implementation of the World Heritage Convention, have been used. In general, geological monuments will be considered objects of inanimate nature that have scientific, educational-cognitive, and aesthetic-touristic significance, which will be rare, high-value, and spectacular.

Certain international examples have been studied for the classification of geosites (Ruban 2010; Ruban and Kuo 2010; Wimbledon et al. 1998; Massoli-Novelli 1999; García-Cortés et al. 2000; Gray 2004; Prosser et al. 2006; Bruschi and Cendrero 2009; De Wever et al. 2014; Lapo et al. 1993; Karpunin et al. 1998). The significance of creating an accurate nomenclature of geological heritage sites is addressed by Prosser et al. (2006), Ruban (2010), Bradbury (2014), and Habibi et al. (2018). Obviously, some objects can be linked to a variety of geological domains.

There are different approaches depending on countries. Thus, in the UK, Spain, and Portugal, the classification of geosites focuses on global geological context, according to geological time intervals and the key events in the history of the Earth (Wimbledon et al. 1995; García-Cortés et al. 2000; García-Cortés and Carcavilla 2009; Pereira et al. 2012). On the other hand, the classification in Italy, France, Russia, and Armenia is based on different disciplines of geology (Mulqijanyan 1975; Karpunin et al. 1998; Lapo et al. 1993; Melik-Adamyan et al. 2019; Kiselev et al. 2003; Vdovets 2009; Giovagnoli 2012; Bruno et al. 2014). Geosites of the first Armenian Geopark will have some peculiarities due to

its specialization, and the classification with phenomena-based approach is carried out in function of geohazard types (faulting, earthquake, surface rupture, liquefaction, eruption, landslide, mass extinction, etc.).

Based on international approaches (e.g., García-Cortés et al. 2000; De Wever et al. 2014) and the experience in the Republic of Armenia, a version of the “geosite identification form” is proposed. It includes the name, type of classification, assessment in a different point scale, according to its rarity, geological significance, educational, aesthetic, touristic values, accessibility, and related risks. It will include geographic, scientific data, information about the presence of historical and architectural monuments, figures, maps, and schemes. These are in the base of the site evaluation (Fig. 2).

Geosite Examples: New Results

General Description of Geosites

As previously mentioned, the selected geosites are associated with various important geodynamic and hazardous processes. After multiple analyses, 26 sites have been selected (Table 1) (Avagyan et al. 2021a). It is worth noting that the number of geosites is not finalized, as a new “candidate” may be proposed during the exploitation of the geopark.

Several sites concern active faults and are related to surface ruptures (Noratus 1, Mrtbizor, Sub Gevorg, Jraghbyur, Gavaraget, Khonarhasar, Geghakar 2, Tsursar, Urtsaber, and

Fig. 2 Evaluation of geosites on the example of Jrovanq

The name of Geosite	Jrovanq				Total	81
Type of geological branches	Stratigraphy, paleontology, geodynamics					
Type of geological hazards	Earthquakes, surface rapture, mass extinction					
General rating	Local (20 points)	Republican (30 points)	Regional (40 points)	International (50 points)	50	
	-	-	-	50		
5 point rating scale	Rarity	Geological importance	Educational and scientific popularity	Spectacularity and aesthetic value	20	
	5	5	5	5		
Rating of availability/ Touristic value	Road type	Transport means	Existence of risks	5 point rating scale of tourism	13	
	asphalt-3, roadway-2, footpath -1	Bus-4, SUV-3, horse racing/cycling-2, pedestrian-1	Safe -3, Relatively safe-2, risky-1			
Existence of historical and cultural monuments (corresponding rating will be given according to the quantity)	Architectural	Historical	Archaeological	Ethnographic	8	
	4	-	4	-		

Surb Karapet). Volcanoes have a significant number of geosites including those of Pleistocene–Holocene activity (Khonarhasar, Azhdahak, Vayots Sar, Armaghan, Smbatarar) (Fig. 1B). Three examples relate to the important geodynamic episodes in the geological history of the area; they were accompanied by geologically active processes. Two of them belong to ophiolites: one is exposed in the suture zone in Sevan Basin (Daranak), and the other is obducted on the South Armenian Block (Mankuk). The third is an important angular unconformity with an absence of about 320 Ma history, indicating a major change in the geodynamic phase (Jrovanq, Fig. 3). Two geosites evidence the slope active processes (Vardenyats, Surb Karapet). Both of them are conducted to architectural monument destructions and deformations. Single examples indicate seismic triggered liquefaction (Noratus 2), stratigraphic evidence of Permian/Triassic mass extinction (Zangakatun), and recent fluctuations in lake water levels (Artanish). Two geohydrological sites are included: one of them is underwater gas emission (enriched by carbon dioxide) alongside the buried active fault segment (Jraghbyur) and the second is a borehole of pulsating water fountain (Horbategh).

It is worth pointing out that some geosites are related to complex geological phenomena. For example, the sites of Khonarhasar, Geghakar 2, and Tsursar are related to volcanism and active tectonics, and the sites of Urtsaberd and Surb Karapet are related to tectonic rupture and landslide. The geosites of Surb Karapet and Vardenyats are related to both seismicity and landslide. Jrovanq is related to both active tectonics and underground water and gas circulation (Avagyan et al. 2020).

It is obvious that there is little possibility to describe all geosites due to their quantity as well as the restricted volume of the paper. Some of them are well described in international publications, especially related to ophiolites (e.g., Galoyan et al. 2009; Sosson et al. 2010; Rolland et al. 2020), volcanism (e.g., Karapetian et al. 2001; Sugden et al. 2021; Meliksetian et al. 2021), active tectonics, landslide, water and gas circulation (Avagyan et al. 2018, 2020), or mass extinction events (e.g., Sahakyan et al. 2017; Friesenbichler et al. 2018; Joachimski et al. 2019). In this paper, some geosites will be briefly addressed.

Jrovanq Geosite

Jrovanq geosite is located in a secondary valley formed by the Jrovanq tributary of the Arpa river (Fig. 1B) in Vayots Dzor province. Here, the Upper Devonian terrigenous sediments and the discordantly overlying organogenic-clastic (nummulitic) limestone of the late Upper Eocene (NP17) are exposed. Distortions of late Upper Eocene sediments are caused by thrust faults, back-thrust and normal faults, which result from the stress field of horizontal compression along

the NNW–SSE axis (Vardanyan 2014). This episode evidence of important regional tectonic stress regime change has conducted to crust thickening and sea regression.

The geosite includes ruins and tombs of the village Ertych dating back to the 12th–fourteenth centuries AD. A castle is situated on top of Nummulitic clastic limestone cliff.

In the upper part of the stream, near the spectacular waterfall, a karstic cave is located containing stalactites and stalagmites and a rock-cut chamber (Fig. 3B) (Dan et al. 2022).

Khonarhasar and Tsursar Geosites

Khonarhasar and Tsursar geosites are located in the Khonarhasar segment of Pambak-Sevan-Sunik fault (Fig. 1B). This fault is the most important active structure in the Lesser Caucasus and it is associated with the strongest paleoearthquakes (e.g., Avagyan 2001; Philip et al. 2001; Karakhanyan et al. 2004; Ritz et al. 2016; Karakhanyan et al. 2017a). Khonarhasar volcano was split and displaced by PSSF and has a dextral offset of 750 ± 50 m (Fig. 3) (Philip et al. 2001). The average slip rate of the Khonarhasar segment is estimated at 0.53 ± 0.04 mm/year over an interval of 1.4 Ma (the age of Khonarhasar volcano determined by K–Ar method (Philip et al. 2001, Fig. 4)). Tsursar volcano is situated about 9 km SSE from Khonarhasar volcano, which has an offset of 350–400 m shown in Fig. 4. Both Khonarhasar and Tsursar volcanoes are partly surrounded by recent lava flows of more than 24 km length related to Porak volcanic system (Figs. 4 and 5).

Several paleoseismological trenches are dug to study evidences of strong paleoearthquakes. It is most evident in the Geghakar 2 geosite (Fig. 1B) where the surface rupture and seismic shaking deformed the tumulus with the burial chamber of Late Bronze–Early Iron Ages (12th–ninth centuries BC) (Karakhanyan et al. 2017b).

Evidence of Porak's volcanic eruption can be related to the historical events during 782–773 BC (Philip and Karakhanyan 1999; Harutyunyan 2001) and revealed by the petroglyph which was found and interpreted as a volcanic eruption (discovered by A. Avagyan, about 11 km southeast of Porak volcano along the Khonarhasar fault segment) (Avagyan 2001, 2003; Avagyan et al. 2005; Bousquet 2018).

The Khonarhasar segment of Pambak-Sevan-Sunik fault crosscuts the archaeological site of Geghakar 1. In particular, it affects the wall of Bronze Age that preserves a horizontal right lateral offset of about 1.80 ± 0.2 m. This pre-Urartian (Bronze Age) large city is a considerable archaeological monument which occupies several hectares in the vicinity and on the Holocene lava flows.

The monastery of Makenyats Vanq, located in Khonarhasar geosite on a Holocene lava flow, was a major cultural and educational center of medieval Gegharkunik,

Table 1 General parameters of the geosites

The name of geosite	Coordinates (N, E) Average H-m (asl)	Area (ha)	Type of geological branches	Type of geological hazards	Historical and cultural monuments
1 Daranak	N 40.379029° E 45.582886° H-2150	446	Geodynamic, active tectonic	Earthquake, surface rapture	Not available
2 Artanish	N 40.492634° E 45.288868° H-1940	678	Geoarchaeology, stratigraphy	Lake transgression, regression	Available
3 Noratus 1	N 40.368541° E 45.205959° H-1922	587	Seismotectonic, stratigraphy, geodynamic	Earthquake, surface rapture, volcanism	Available
45 Mrtbidzor	N 40.342972° E 45.141853° H-1985	3	Geoarchaeology, active tectonic	Earthquake, surface rapture	Available
5 Surb Gevorg	N 40.319768° E 45.215704° H-1959	21	Active tectonic, geoarchaeology	Earthquake, surface rapture	Available
6 Noratus 2	N 40.330863° E 45.211182° H-1916	19	Seismotectonic, sedimentology	Earthquake, liquefaction	Available
7 Jraghbyur	N 40.266206° E 45.220922° H-1900	5	Hydrogeology, hydrochemistry, tectonic	Earthquake, surface rapture, tsunami	Not available
8 Gavaraget	N 40.230168° E 45.159648° H-2218	1688	Active tectonic, seismology	Surface rapture, earthquake	Available
9 Urtsaberd	N 39.939499° E 44.867176° H-1178	15	Sedimentology, tectonic	Earthquake, surface rapture	Available
10 Mankuk	N 39.961515° E 44.942469° H-1437	44	Lithology, geodynamic	Earthquake, dynamic movement	Available
11 Surb Karapet	N 39.844232° E 44.906011° H-1959	21	Stratigraphy, geodynamic	Earthquake, landslide	Available
12 Vardenyats	N 39.949398° E 45.236030° H-2265	73	Dynamic geology, stratigraphy, active tectonic	Earthquake, landslide	Available
13 Zangakatun	N 39.841954° E 45.050688° H-1814	19	Sedimentology, stratigraphy, tectonic	Volcanism, mass extinction	Available
14 Jrovanq	N 39.722893° E 45.268222° H-1148	54	Stratigraphy, geodynamic	Earthquake, surface rapture, mass extinction	Available
15 Moz	N 39.718815° E 45.415811° H-1220	96	Geoarchaeology, volcanology, active tectonic	Earthquake, volcanism	Available
16 Horbategh	N 39.901687° E 45.332158° H-1917	1	Volcanology, geodynamic, active tectonic	–	Available
17 Khonarhasar	N 40.131901° E 45.639622° H-2246	737	Volcanology, geodynamic, active tectonic	Surface rapture, earthquake, volcanism	Available
18 Geghaqar-1	N 40.110715° E 45.647544° H-2299	338	Active tectonic, archaeology, volcanology	Surface rapture, earthquake, volcanism	Available

Table 1 (continued)

The name of geosite	Coordinates (N, E) Average H-m (asl)	Area (ha)	Type of geological branches	Type of geological hazards	Historical and cultural monuments
19 Geghaqar-2	N 40.096533° E 45.679948° H-2357	61	Geoarchaeology, active tectonic	Surface rapture, earthquake,	Available
20 Tsursar	N 40.072435° E 45.703978° H-2590	273	Volcanology, geodynamic, active tectonic	Surface rapture, earthquake, volcanism	Not available
21 Vayots Sar	N 39.797329 E 45.496504 H-2496	524	Volcanology	Volcanism	Not available
22 Smbatarar	N 39.928692° E 45.388486° H-2648	1957	Volcanology	Volcanism	Not available
23 Geghasar	N 40.113403 E 45.002163 H-3142	3103	Volcanology	Volcanism	Not available
24 Azhdahak	N 40.227104 E 44.949233 H-3436	505	Volcanology	Volcanism	Not available
25 Armaghan	N 40.068549 E 45.213938 H-2806	867	Volcanology	Volcanism	Not available
26 Aknalich	N 40.283038 E 44.919847 H-3082	660	Volcanology	Volcanism	Not available

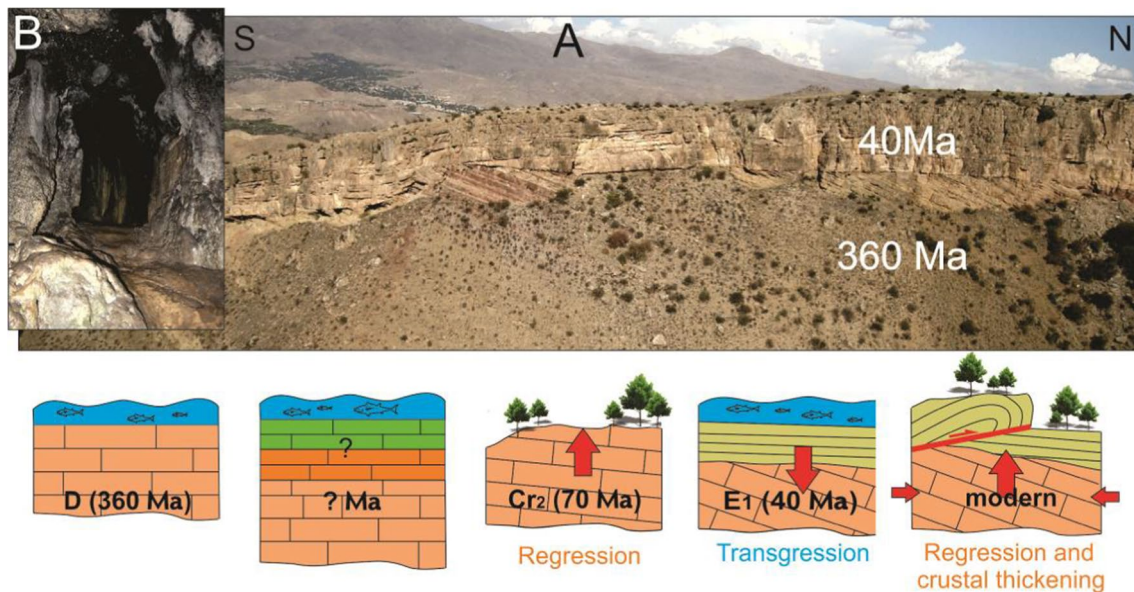


Fig. 3 Jrovanq geosite (see Fig. 1B). **A** Angular unconformity between Upper Devonian and late Upper Eocene formations with the geologic evolution below. **B** View of the entrance to Jrovanq chamber. Photo by M. Sosson

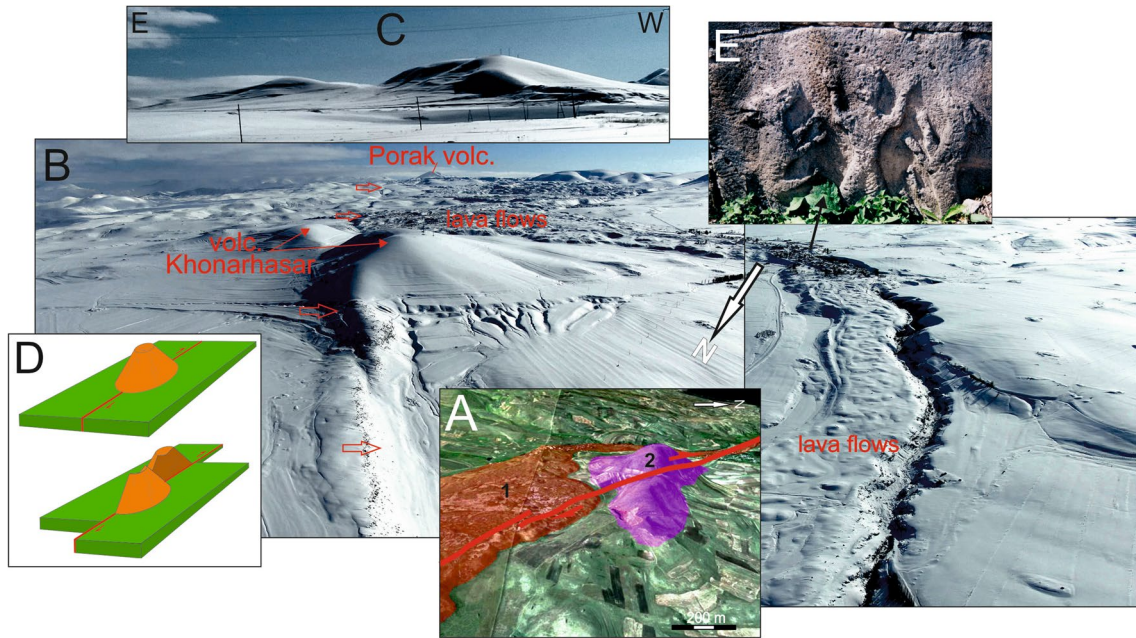
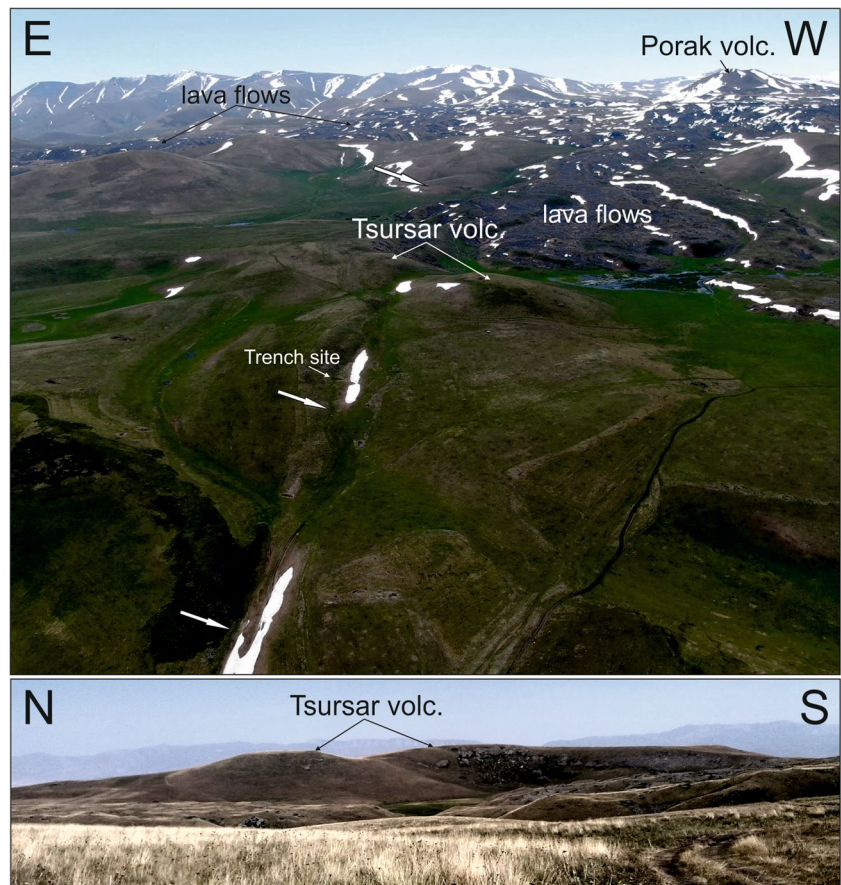


Fig. 4 Khonarhasar geosite (see in Fig. 1B). **A** Porak's Holocene lava flows (1) and Khonarhasar volcano displaced by active fault (2), the same in **B** (active fault is indicated by red arrows) and **C**, **D** schematic

chart of the volcano displacement, **E** eroded and damaged bas-relief of the pagan goddess. Photos by A. Avagyan

Fig. 5 Tsursar geosite (see in Fig. 1B), Porak's Holocene lava flows (1) and Tsursar volcano displaced by active fault. The active fault is indicated by white arrows; the paleoseismological trench site is also indicated in the same way. Photos by A. Avagyan



with structures dating from the 9th to thirteenth centuries AD. Numerous khachkars (cross-stones) and sculptures have been placed along the walls of the church. One of them is an eroded and damaged bas-relief of the pagan goddess (Fig. 4E).

Aknalich Geosite

The Aknalich geosite (Fig. 1B) represents a unique volcanic landform and is located at the axial part of Gegham volcanic ridge. It represents a dense cluster of 127 monogenetic volcanoes, encompassing Middle to Late Pleistocene and Holocene ages within a 65 km long and 35 km wide oval-shaped area of $\sim 2100 \text{ km}^2$ (Karakhian et al. 2003; Sugden et al. 2021) (Fig. 5).

The described geosite is located within a group of cinder cones of Upper Pleistocene-Holocene age, namely, Lchayin 1, Lchayin 2, Paros, Aknocasar, Lodochnikov, west Aknocasar, east Aknocasar, and Arcruni, as well as Aghusar, south Aghusar, and western Aghusar with elevations ranging 3084–3458 m asl (Fig. 6). Lchayin 1 volcano exhibits an elongated shape and a large crater of $\sim 1.1 \text{ km}$ in diameter on its long side. Aknalich is a lake of volcanic origin with an area of 0.45 km^2 . It filled the crater of Lchayin 1 volcano; the lake depth is about 15 m, 3038 m asl, but its level exhibits seasonal fluctuations. All cinder cones are composed of layers of volcanic scoria, as well as lavas and volcanic bombs. A noteworthy feature of monogenetic volcanism of the described group of cones is the cross-cutting of Middle Pleistocene Lchayin 1 volcano by a younger, Upper Pleistocene-Holocene Lchayin 2 volcano (Fig. 6). According to recent volcano-seismological research (Sargsyan et al. 2021), seismic swarms of volcano-tectonic origin periodically occur beneath the cluster of Lodochnikov-Lchayin volcanoes, indicating active magmatic and hydro-geothermal processes beneath the Gegham ridge. Most of the mentioned monogenetic volcanoes have nice shaped craters (Fig. 6). It is suggested that Aknalich geosite, in addition to its aesthetic value, will also serve as scientific and educational site, since it provides a vivid example of monogenetic volcanism, clustering of volcanoes, and age relationships of cinder cones.

Artanish Geosite

Due to geological, climatic, anthropogenic factors, the water level of Lake Sevan has shown significant shoreline fluctuations (transgression and regression) affecting the coastal ecosystem and sedimentation processes as well as human activity over the past millennia.

In Fig. 6, schematic 3D maps of lake level fluctuations in the Artanish geosite (Fig. 1B) for over 5000 years are presented, based on the results of geoarchaeological research (Hovhannisyan et al. 2022). Approximately by 5000 BC (Middle Holocene), shallow lake conditions had formed in

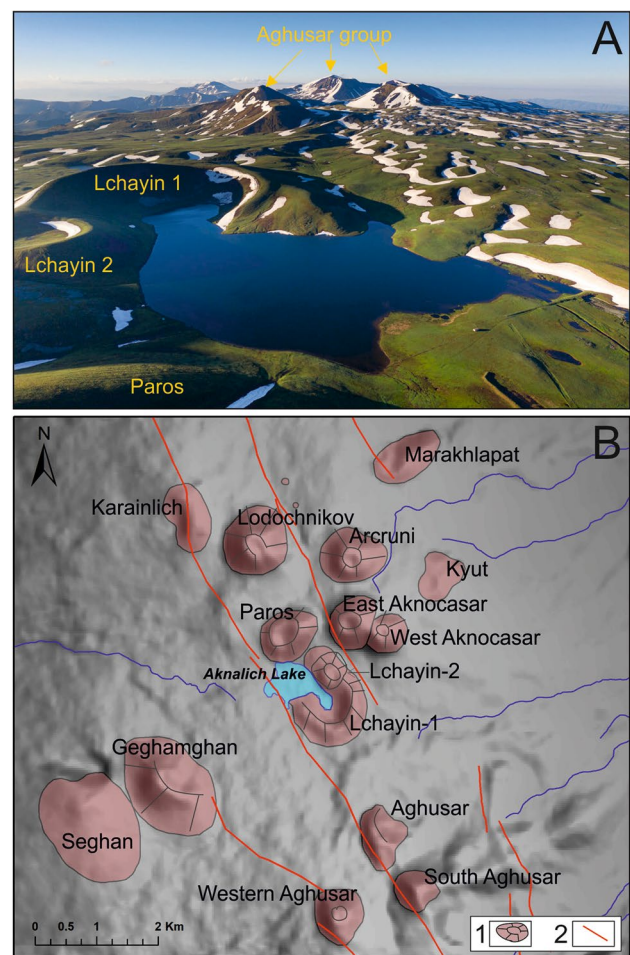


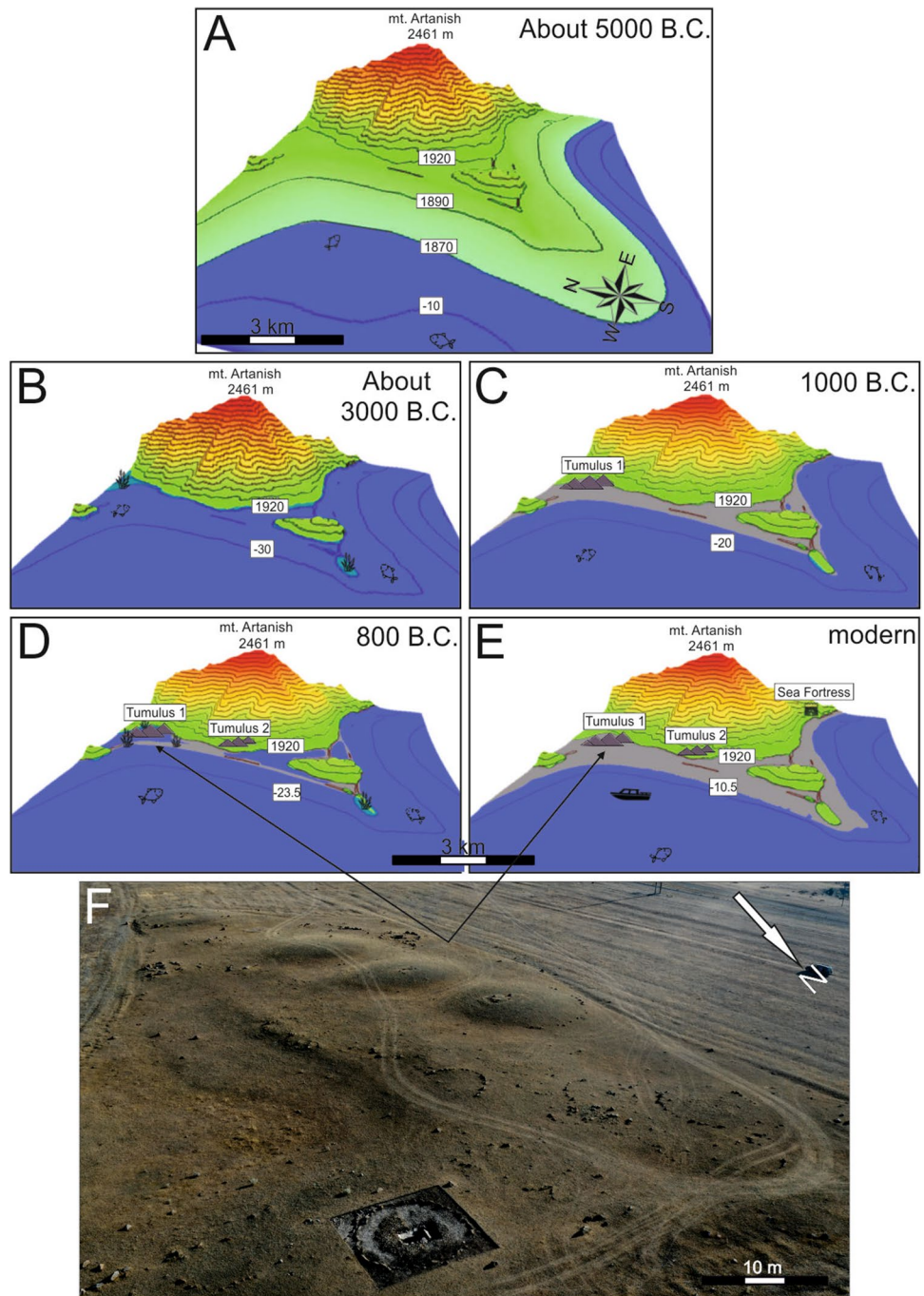
Fig. 6 **A** Aerial drone image of Aknalich crater lake and volcanoes: Paros, Lchayin 1 and 2, and Aghusar group of cinder cones (aerial photo by A. Keshishyan). **B** Schematic map of distribution of monogenetic vents and active faults (after Karakhian et al. 2003)

the Greater Lake Sevan. The following general warming of climate and intensive melting of glaciers started of Lake Sevan transgression. Approximately in 3000 BC, the maximum level of Lake Sevan corresponded to the elevation of 1917–1920 m (Fig. 7B). Lake sediments had been accumulating intensely. About 1000 BC, regression lowered the lake level to 1910 m (Fig. 7C, F). The Iron Age tombs were built in areas of land that emerged due to water retreat. In 800 BC (Fig. 7D), lake level elevation corresponded to 1916.5 m, and as the transgression led to bogging of the old burial grounds, new burial grounds were built in higher elevation areas and the remains were re-buried. The current water level of Lake Sevan corresponds to the elevation of 1900.4 m asl.

Vardenyats Geosite

Orbelian Caravanserai was built in 1332 by Prince Chesar Orbelian on the southern side of Vardenyats Mountain

Fig. 7 Artanish geosite (see in Fig. 1B). **A–E** Sevan Lake water level at different times, based on the work of Hovhannisyan et al. (2022). **F** Archaeological site with tumuli built by Sevan Lake sediments. Photo by A. Hovhannisyan

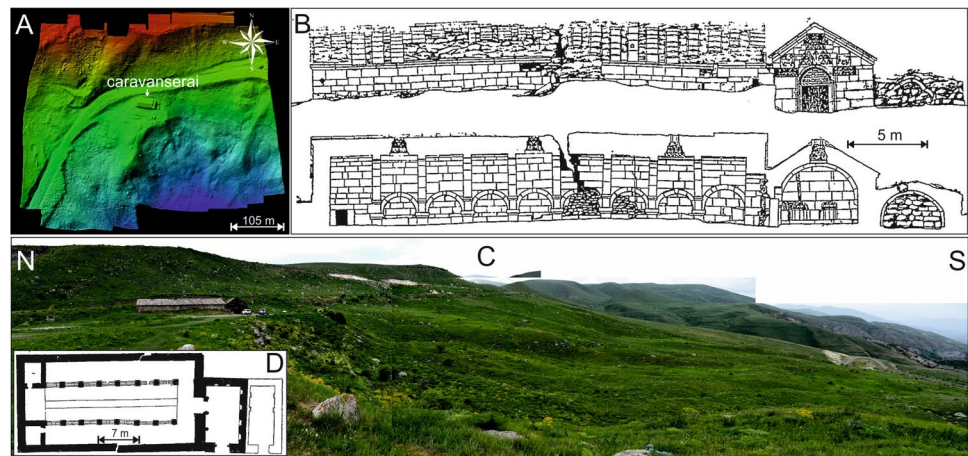


Pass at a height of 2410 m above sea level, to accommodate weary travelers and their animals as they crossed from or into the mountainous Vayots Dzor province (Fig. 8). Orbelian’s Caravanserai is the best-preserved caravanserai in the entire country. Orbelian’s Caravanserai was damaged because of landslides triggered by an earthquake in 1840 (Ter-Hovhannisyan 2003). Figure 8B shows the caravanserai’s southern face and inner cross section. Figure 8D shows its plan presented by Harutyunyan (1960) before reconstruction. The southern wall and roof of the structure have been

restored. However, many deformations remain unrepaired. Our observations of the site, as well as the analysis of the drawings before reconstruction (Harutyunyan 1960), suggest that the main destruction of the structure took place in a short period of time (Fig. 8B).

The western and eastern parts of the caravanserai roof were subsided in comparison with the central part; the western one was subsided by about 0.6 m. Western and eastern parts are tilted at 2.8° W and 2.9° E, respectively. The angle of general deformation is 5.7°. The horizontal

Fig. 8 Vardenyats geosite (see in Fig. 1B). **A** 3D model realized by drone, the main landslide scarp, and terrace with Orbelian Caravanserai of XIV century on it. **B** Caravanserai before reconstruction, after Harutyunyan (1960). **C** Field photography of the caravanserai site landslide. **D** Plan of the caravanserai with faulted and displaced walls and colonnade after Harutyunyan (1960). Photo by A. Avagyan



movement of the landslide is evidenced by the displacement of the southern columns and the eastern part of the southern wall, which is clearly visible in the plan. The latter is shifted about 25 cm to the south (Fig. 8D).

The geosite of the Vardenyats Mountain Pass provides evidence related to geodynamics, stratigraphy, and active tectonics and to geohazards represented by earthquakes and landslides with the affection on Orbelian Caravanserai.

Gavaraget Geosite

Geosite Gavaraget is located in a picturesque mountainous area rich in unique geological features and biodiversity. The site helps to demonstrate the danger of large earthquakes with surface rupture, which can displace the huge blocks and change the river flow direction (Fig. 9) (Avagyan 2001; Karakhanyan et al. 2017a, b; Avagyan et al. 2021b). On the schematic block diagram (Fig. 9E), the evolution of events is demonstrated, where the riverbed situated on the footwall of the normal fault is abandoned. A temporary lake was formed in front of a huge fault scarp of 250 m vertical cumulated displacement (Avagyan 2001; Avagyan et al. 2010).

Archaeological sites are situated along the banks of the abandoned river segment. The archaeological complex is represented by huge wall fragments and a bridge (Avagyan et al. 2021b).

The geosite presents an example of river channel distortion resulting from fault activation, when one block was downthrown relative to the other (by normal faulting). The extraordinary and spectacular landscape of the clearly manifested fault, distinct offset of the river channel, and the pattern of an abandoned river segment on the footwall of the fault scarp considered all together might rank this geosite among those of international value.

Urtsaberd Geosite

The Urtsaberd geosite is located in the Ararat province (Fig. 1B) within a Paleogene flexural basin. The geosite is presented by folded Paleogene sediments, due to Urtsaberd fault strong dynamic activity (Fig. 10) (Avanesyan 2007). The fault is in continuation of Lanjanist fault, which has a post-Oligocene activation (Avanesyan 2007; Avagyan et al. 2018). NNW part of the section, late Upper Paleocene marls is drag folded, and layers are exposed in a nearly vertical position next to the main fault. At the SSE part of the section, late Upper Eocene volcanoclastic sedimentary green-gray deposits are exposed (Fig. 10).

The geosite displays evidence related to sedimentology and tectonics, as well as geological hazards of earthquakes and surface ruptures. This is an excellent example of folding of sedimentary formations determined by fault dynamics. As a result of the Earth's crust shortening, reverse-faulting and thrusting developed drag folds.

Jraghbyur Geosite

More than three dozen points of subaqueous water sources and gas emissions points have been identified linearly striking north–south over > 8 km (Fig. 11) (Avagyan et al. 2020). In some cases, gas emission forms craters in the sand with diameters that can reach up to 0.9 m (Fig. 11D). Gas emissions are represented by almost pure carbon dioxide (up to 96%) that are analogues to mineral spring sources analyzed on Lake Sevan shores (Shahinyan et al. 2019). The carbon dioxide enrichment is associated with volcanic magma chambers (Avagyan et al. 2020).

The geosite displays field evidence related to hydrogeology, hydrochemistry, and tectonics and to geological hazards such as earthquakes, surface ruptures, and high lake waves in case of an earthquake. The geosite is intended for studies and near-shore observations of the spectacular underwater emission of gas and water (also through diving).

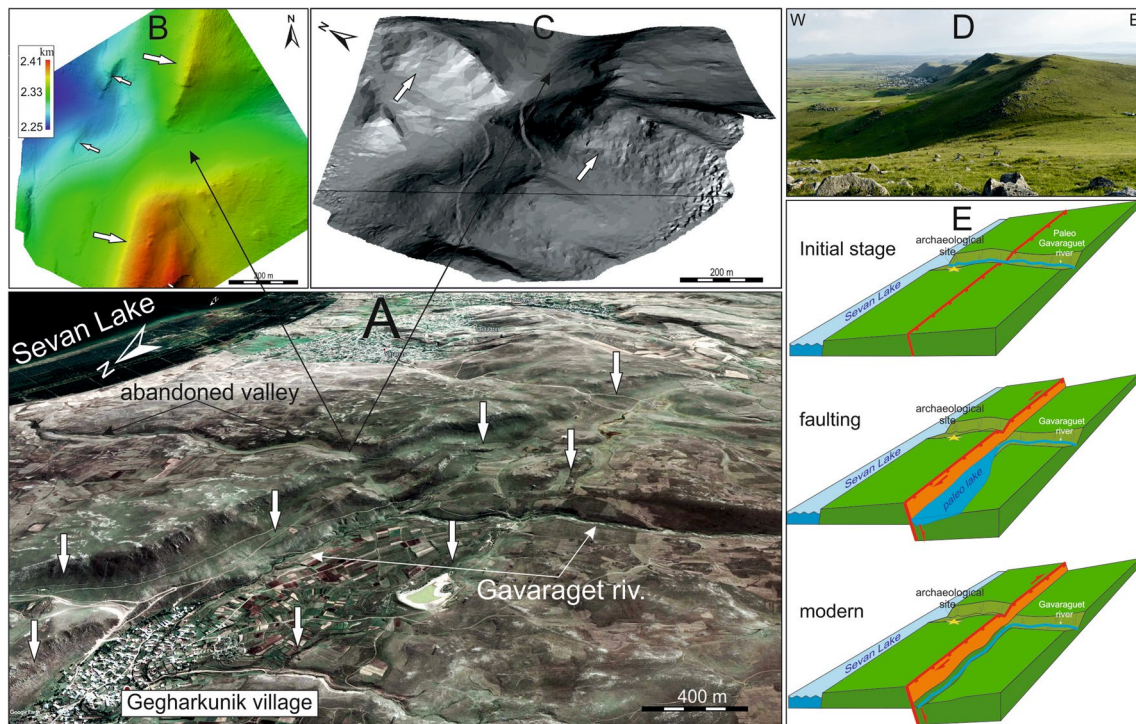


Fig. 9 Gavaraget geosite (see in Fig. 1B). **A** Geosite on the Google map, the fault is indicated by white arrows. **B**, **C** 3D model of the river cut area by fault. **D** North view of the fault scarp of about 250 m

formed by normal fault. **E** Schematic block diagram showing succession of events. Photo by A. Avagyan

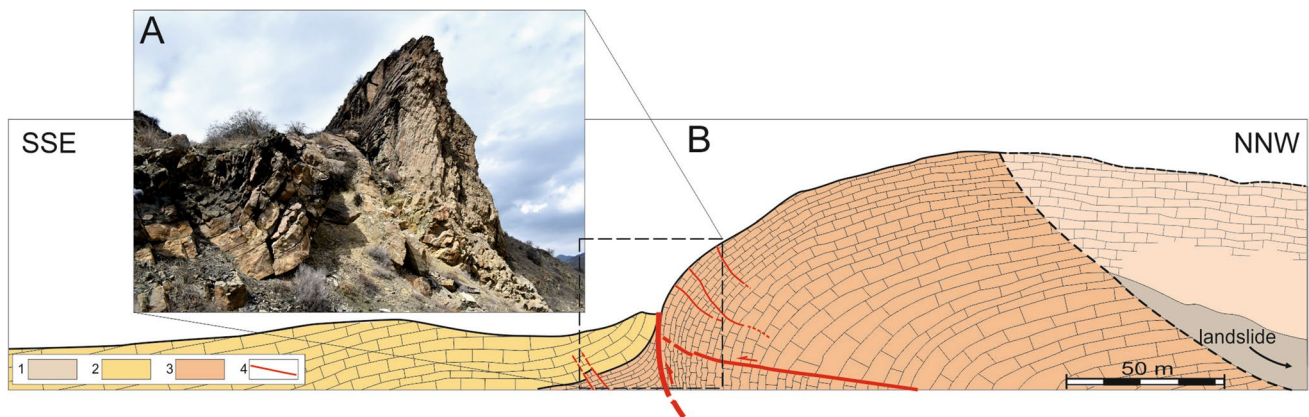


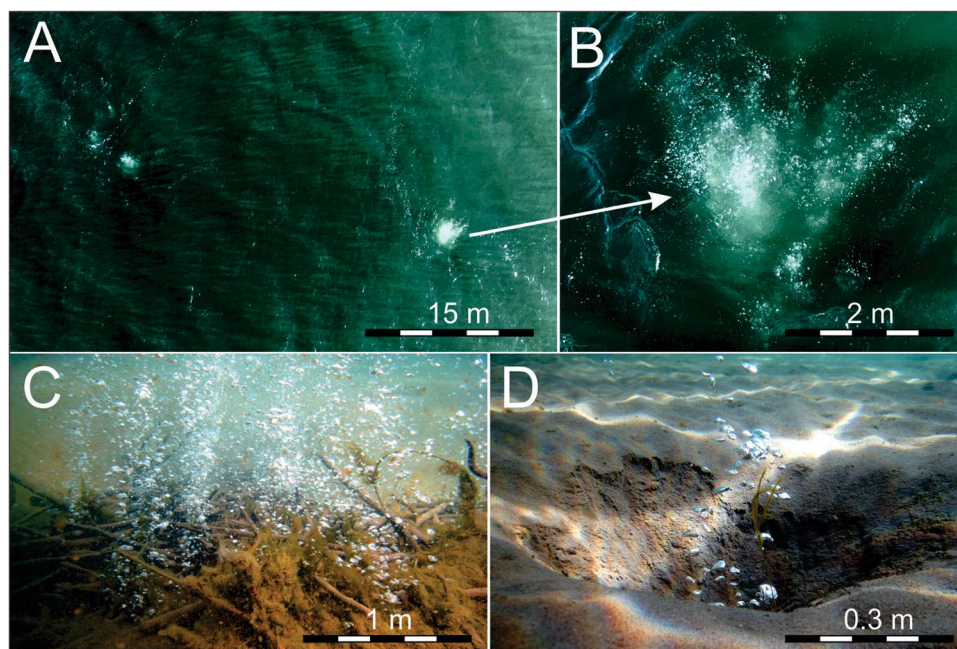
Fig. 10 **A** Urtsaberd geosite main fault field photography. **B** Geological cross section of Urtsaberd reverse and trust faults. 1: landslide mass, 2: late Upper Eocene volcanoclastic deposits, 3: early Upper Paleocene marls, 4: faults. Photo by L. Sahakyan

Discussion and Conclusion

Some features of the geological structure and history of its development have made Armenia a unique country, despite its relatively small territory, especially from the point of view of geological hazards. Given the presence of active faults, volcanoes, and volcano-tectonic interactions, clear evidence of geological disasters, such as surface ruptures, recent volcanism, tectonically induced landslides, mass

extinction, geothermal activity, and many other features, it has been proposed to establish a geopark that would focus on the geological hazards. In a limited area where outstanding geological heritage is coupled and interfingered with a rich archaeological and historical-architectural context, we have presented geosites of regional and international value, which allows us to specialize the Armenian Geopark to be hazard-related and evaluate human resilience over long, pre-historical and historical timescales.

Fig. 11 Jraghbyur geosite (see in Fig. 1B) of the subaqueous water sources and gas emissions. **A, B** Drone aerial photography from the height of 50 and 5 m. **C, D** Underwater photographs. Photos by A. Avagyan (**A, B**) and by ACUR (Armenian Center of Underwater Research) (**C, D**)



By establishing this geopark, several important outcomes can be expected: (a) the geopark will serve as a platform to promote geoconservation efforts in Armenia; (b) the establishment of a specialized geopark focused on geohazards will contribute to better management of protected areas in Armenia; (c) the geopark will play a crucial role in spreading dynamic Earth science knowledge and education both within Armenia and beyond; (d) by showcasing Armenia's geological heritage and its efforts in geohazard management, the geopark can attract international attention and participation.

The population education in geological hazards and the facilitation of communication between scientific experts, local communities, and central authorities are crucial factors in risk reduction.

Geohazard-related geoparks become more substantial, being useful for the mitigation of disaster risks and for the development of informed and protected communities. Stakeholders and policymakers can promote the development of educational programs, interpretive materials, and guided tours to enhance the educational value of geosites. This can include partnerships with educational institutions, training for guides and educators, and the creation of interactive exhibits and signage. Stakeholders and policymakers should focus on infrastructure development and capacity-building initiatives for local communities. Encouraging community involvement, promoting local businesses, and ensuring the equitable distribution of tourism benefits can contribute to the long-term sustainability of geosites as tourist destinations.

The proposed Armenian geohazard-related geopark is set to encompass 26 geosites related to diverse geological

processes that are mainly geohazard-related. Some of these processes result in the destruction and deformation of archaeological constructions, historical monuments, and medieval churches. The impact of geohazards on cultural heritage requires additional research aimed to assess risks and conservation. The awareness about geohazard history for the local people and visitors is important knowledge, helping effectively respond to potential geological hazards, predict and prevent them, and evaluate human resilience over long timescales. The selected geosites possess scientific quality, rarity, and aesthetic appeal and can serve for environmental, educational, and multidisciplinary research, on the one hand, and for geotourism favorizing sustainable economic development, on the other hand.

It is essential to monitor the socioeconomic impacts of the geopark, including its contribution to local economies and community development. This can involve assessing visitor satisfaction and evaluating the effectiveness of sustainable tourism practices and the vulnerability of geosites to erosion and their conservation. Future collaborations with other geoparks, scientific institutions, and organizations working in the field of geohazards will promote knowledge exchange and contribute to global efforts in geohazard mitigation and conservation.

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Declarations

Competing Interests The authors declare no competing interests.

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